

# NOvA Oscillation Results



**European Research Council**

Established by the European Commission

**Jeff Hartnell**  
University of Sussex



CERN EP Seminar  
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# Introduction

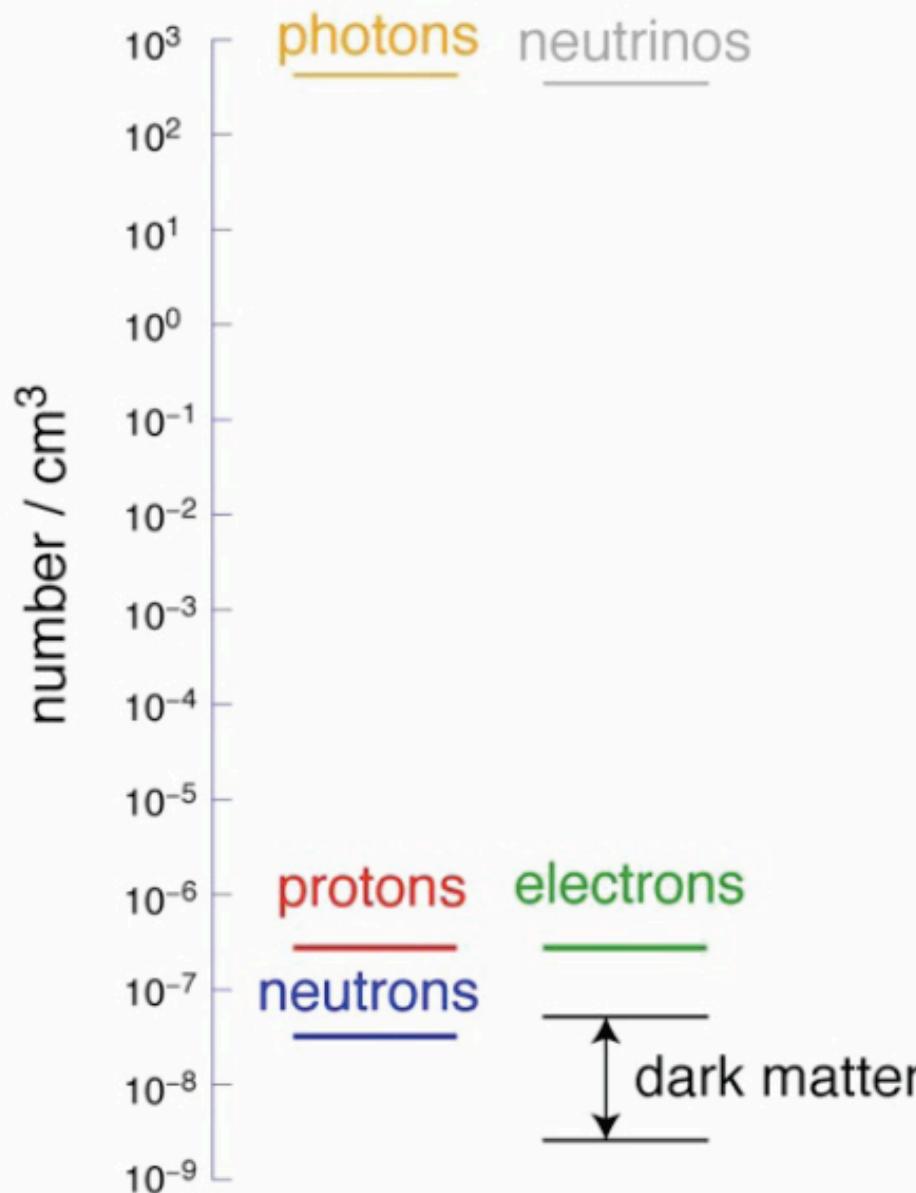
- Why study neutrinos?
- Neutrino oscillations
- NOvA experiment and physics goals
  - NuMI beam
  - NOvA detectors
- Muon neutrino disappearance
- NC analysis
- Electron neutrino appearance

# Why study neutrinos?

# Neutrinos

- Physics beyond the standard model
  - 20,000 neutrino papers since 1998
  - Nobel Prize for neutrino oscillations in 2015!
- New doors opened by recent discovery of  $\theta_{13}$

# The Particle Universe

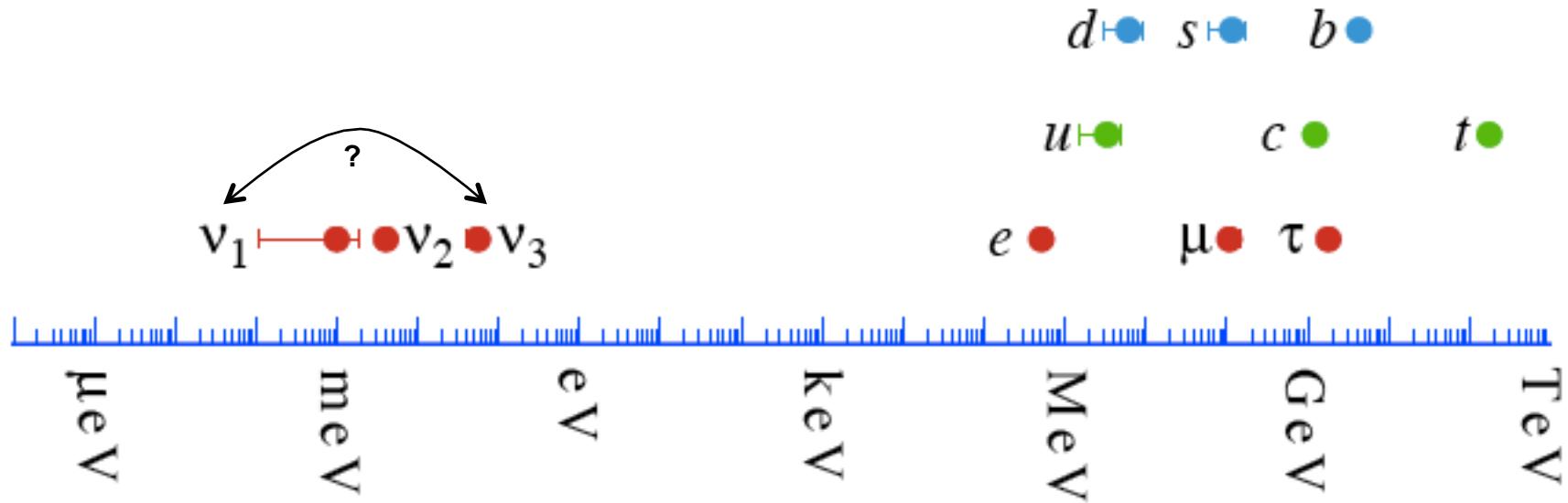


# Two Major Questions

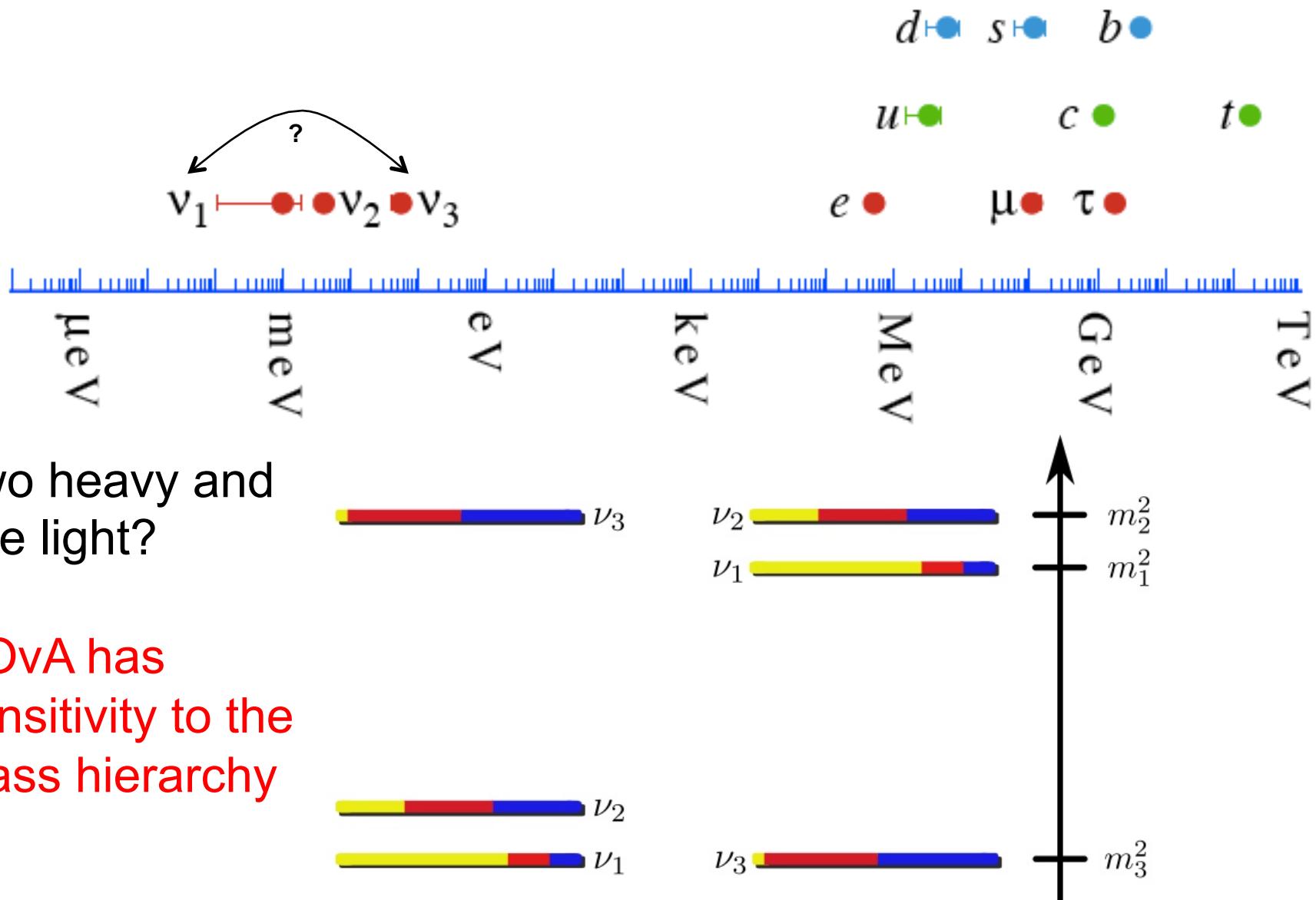
# Why is the matter – antimatter asymmetry of the universe so large?

- Neutrinos  $\longleftrightarrow$  leptogenesis
- Neutrino oscillations can test CP
  - NOvA has some sensitivity, DUNE/Hyper-K much more

# Is there a pattern to the masses?



# Is there a pattern to the masses?

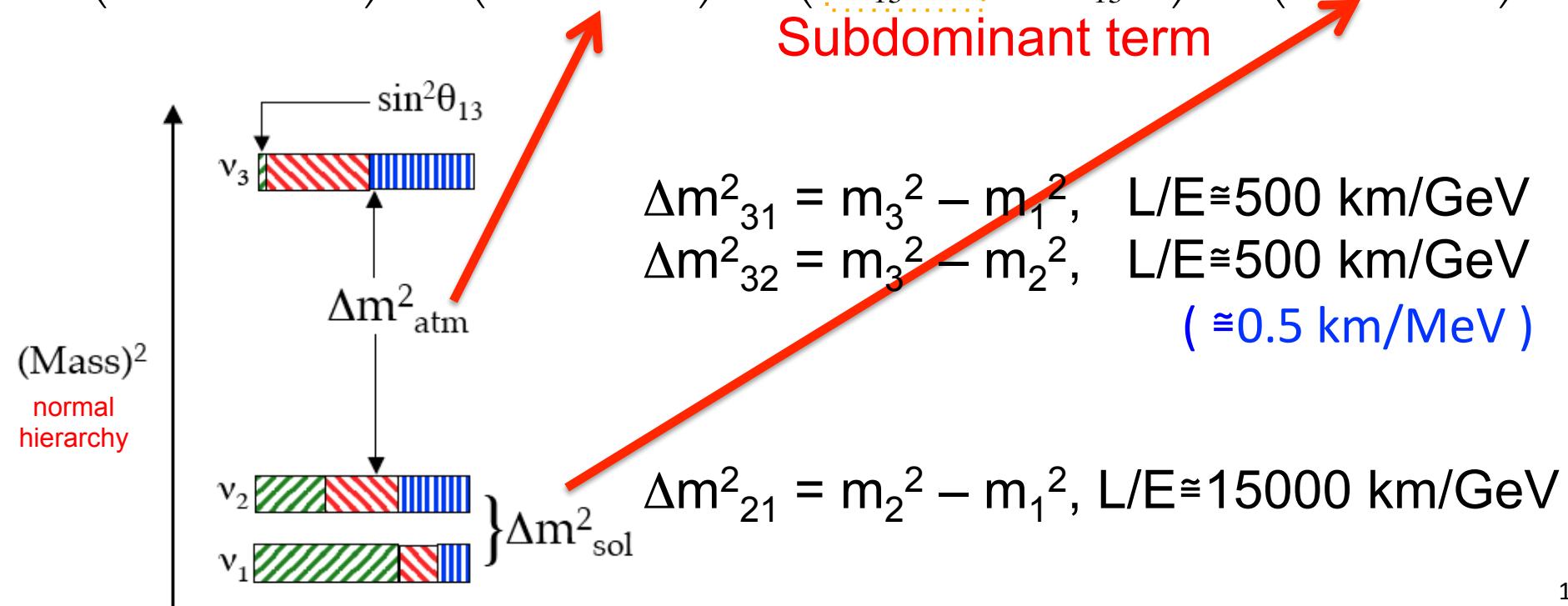


# Theory Overview

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

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

**Subdominant term**



# How does the mass hierarchy come into play?

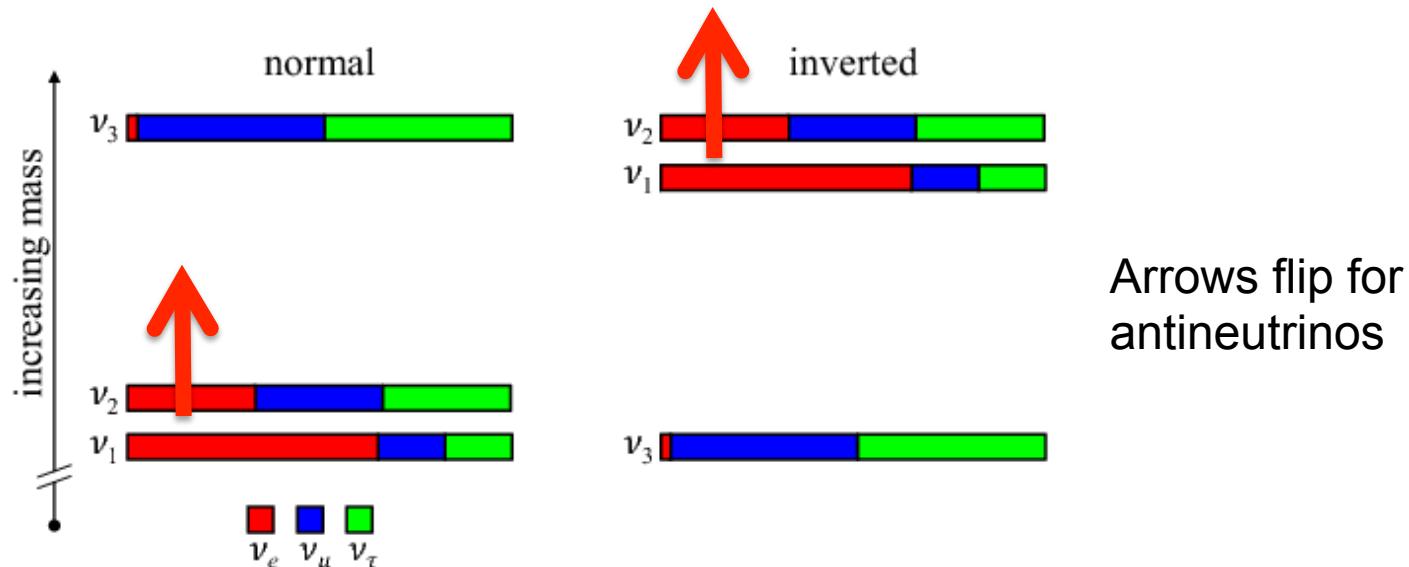
$\Delta m^2_{31}$  and  $\Delta m^2_{32}$  differ by 3%

Small effect

JUNO's planned measurement involves this

# Matter Effect & Mass Hierarchy

- Neutrinos (and antineutrinos) travel through matter not antimatter
  - electron density causes asymmetry (fake CPv!)
    - via specifically **CC** coherent forward elastic scattering
  - different Feynman diagrams for  $\nu_e$  and  $\bar{\nu}_e$  interactions with electrons so different amplitudes



# Where have we got to?

# It's hard to overstate...

- The past few years saw a major breakthrough in neutrino physics
  - Our measurement of  $\theta_{13}$  has gone from just an upper limit to one of the best measured
- A new door has been opened to probing **CP violation**, **mass hierarchy** and **octant of  $\theta_{23}$**

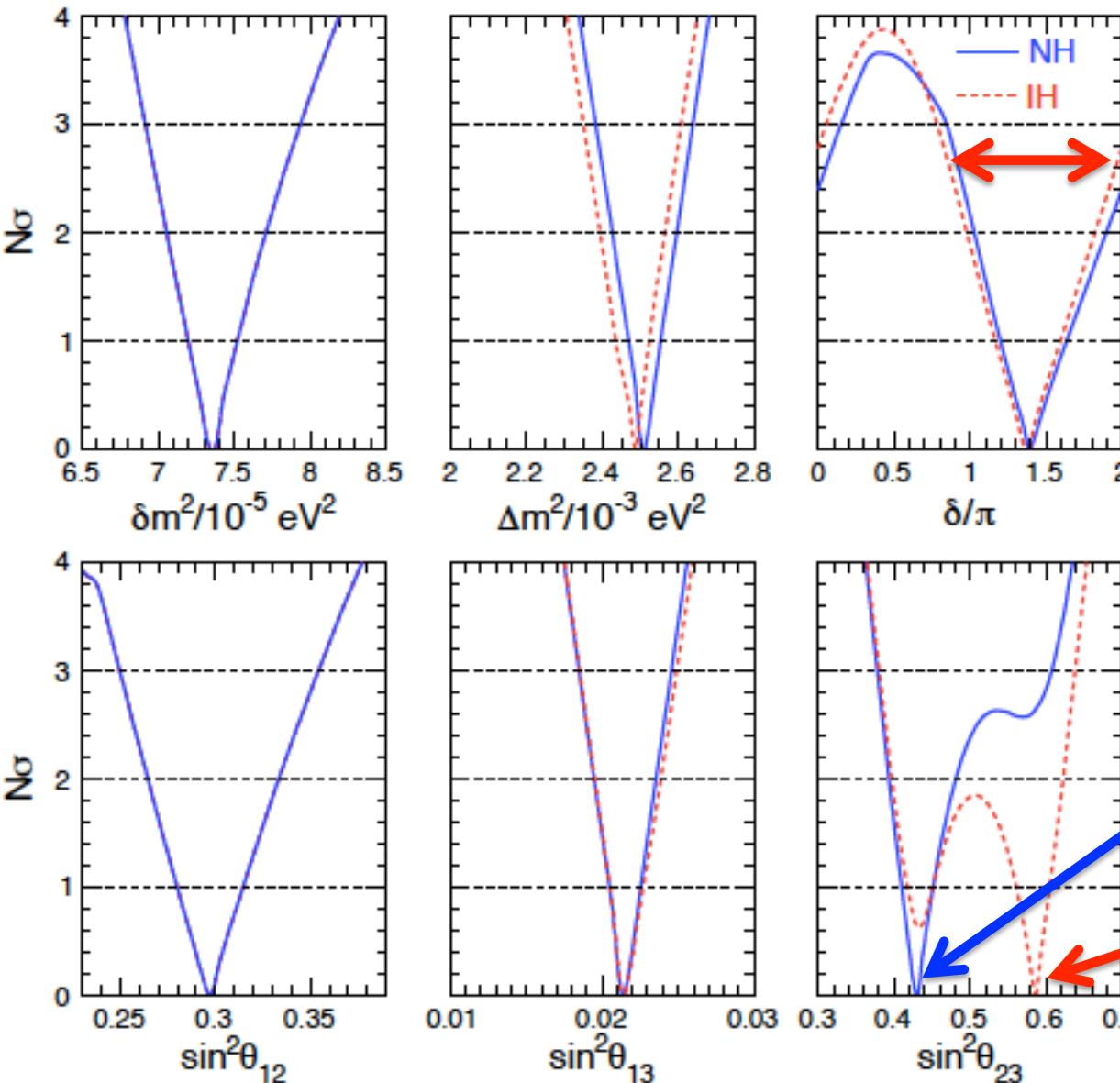
# Reactor Experiments Provided Breakthrough on $\theta_{13}$

- Daya Bay, RENO and Double Chooz



# What we know and don't know

LBL Acc + Solar + KamLAND + SBL Reactors + Atmos



## Three “Unknowns”

Wide range of  $\delta_{CP}$  values possible (1)

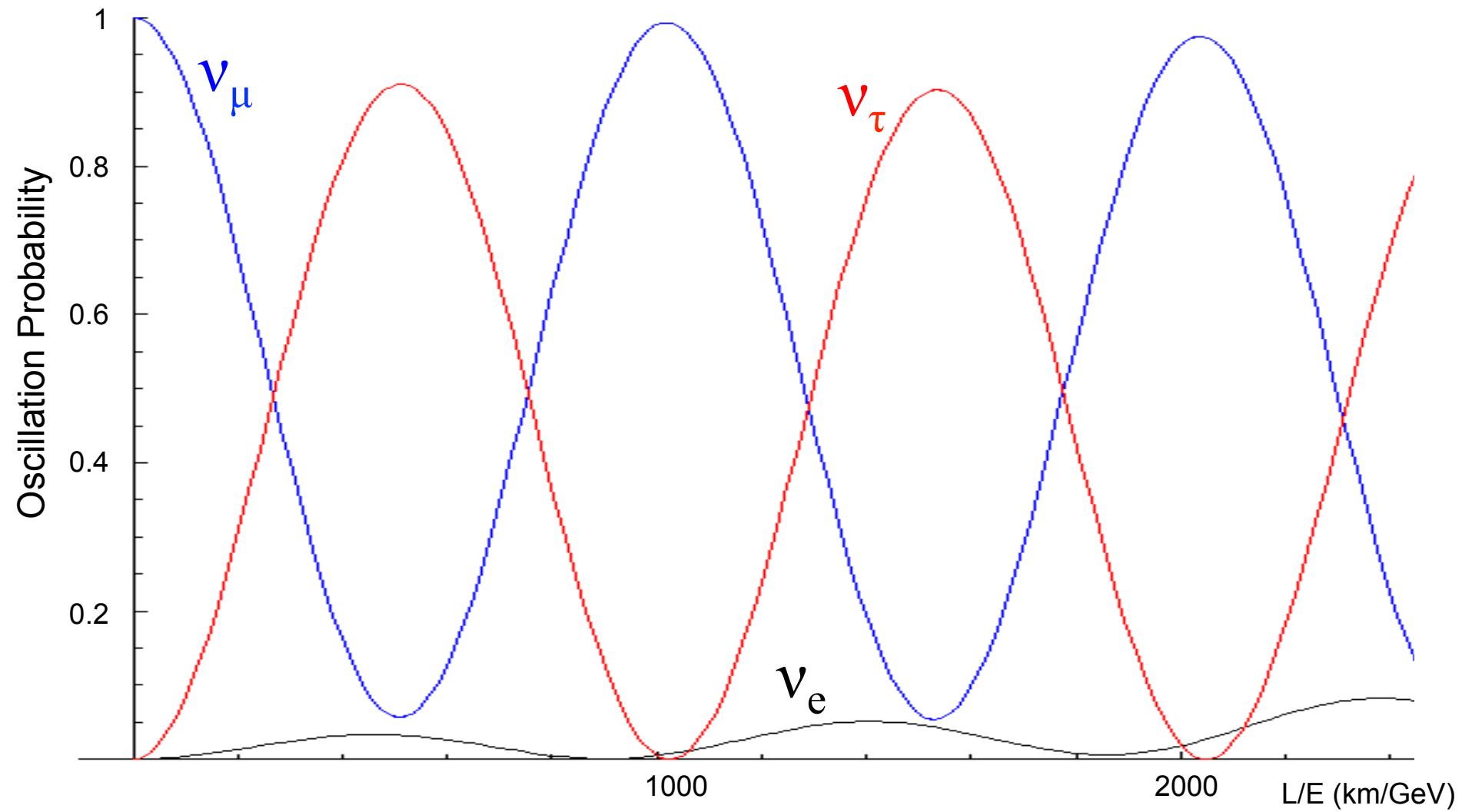
Slight preference for NH ( $\Delta\chi^2=3.2$ , suppressed in plot) (2)

Preference for non-maximal  $\theta_{23}$  mixing (3)

Lower Octant, NH preferred.

Upper Octant, IH a viable solution

# Starting with $\nu_\mu$



# Long-baseline neutrino oscillations

$\nu_\mu$  disappearance:

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

experimental data are **consistent with unity**  
("maximal mixing")

→ Need a leap in precision on  $\theta_{23}$  (and  $\Delta m_{32}^2$ )

$\nu_e$  appearance:

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \underbrace{\sin^2 2\theta_{13}}_{\text{Daya Bay reactor experiment: } \sin^2(2\theta_{13}) = 0.084 \pm 0.005} \sin^2(\Delta m_{32}^2 L / 4E)$$

*...plus potentially large CPv and matter effect modifications!*

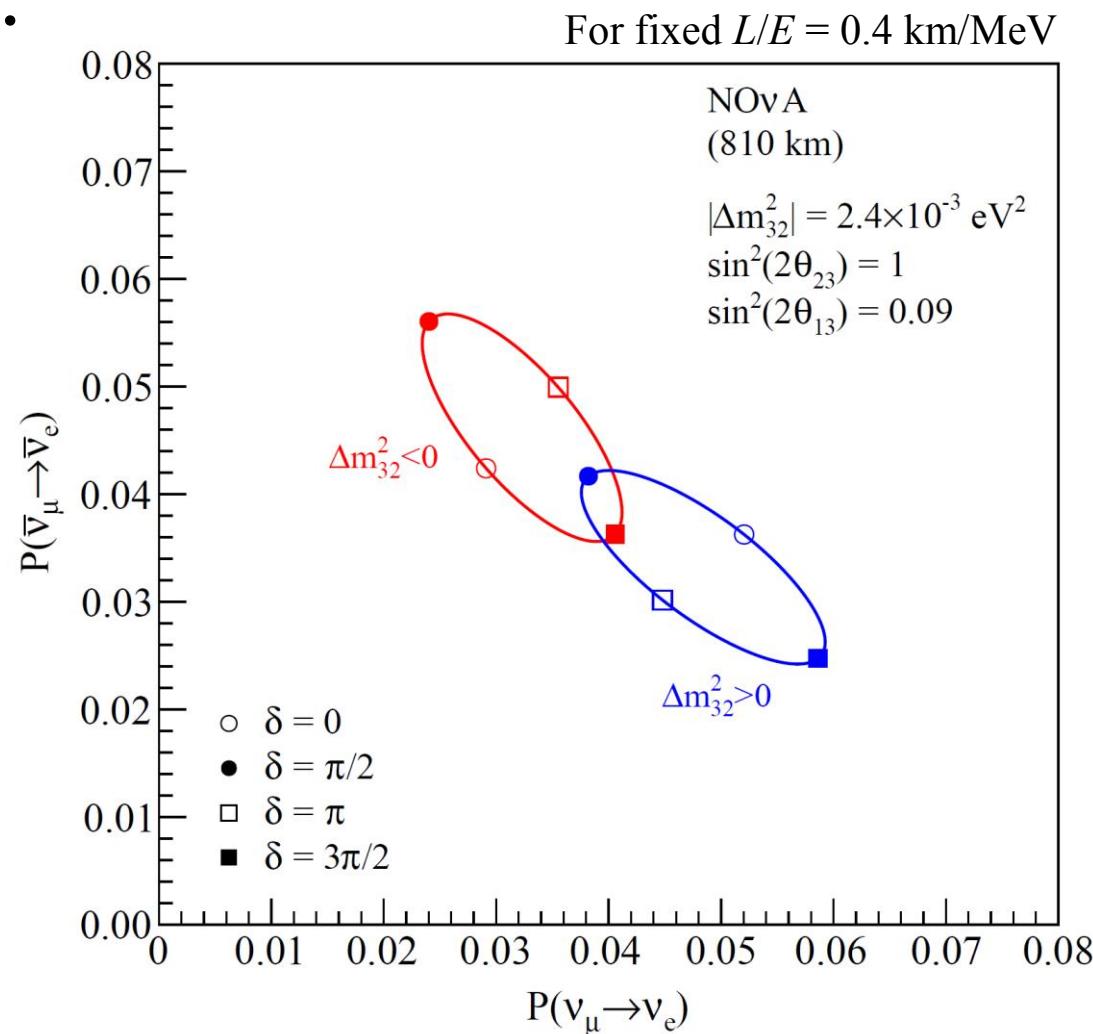
# Long-baseline $\nu_\mu \rightarrow \nu_e$

A more quantitative sketch...

At right:

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$  vs.  $P(\nu_\mu \rightarrow \nu_e)$

plotted for a single neutrino energy and baseline



# Long-baseline $\nu_\mu \rightarrow \nu_e$

A more quantitative sketch...

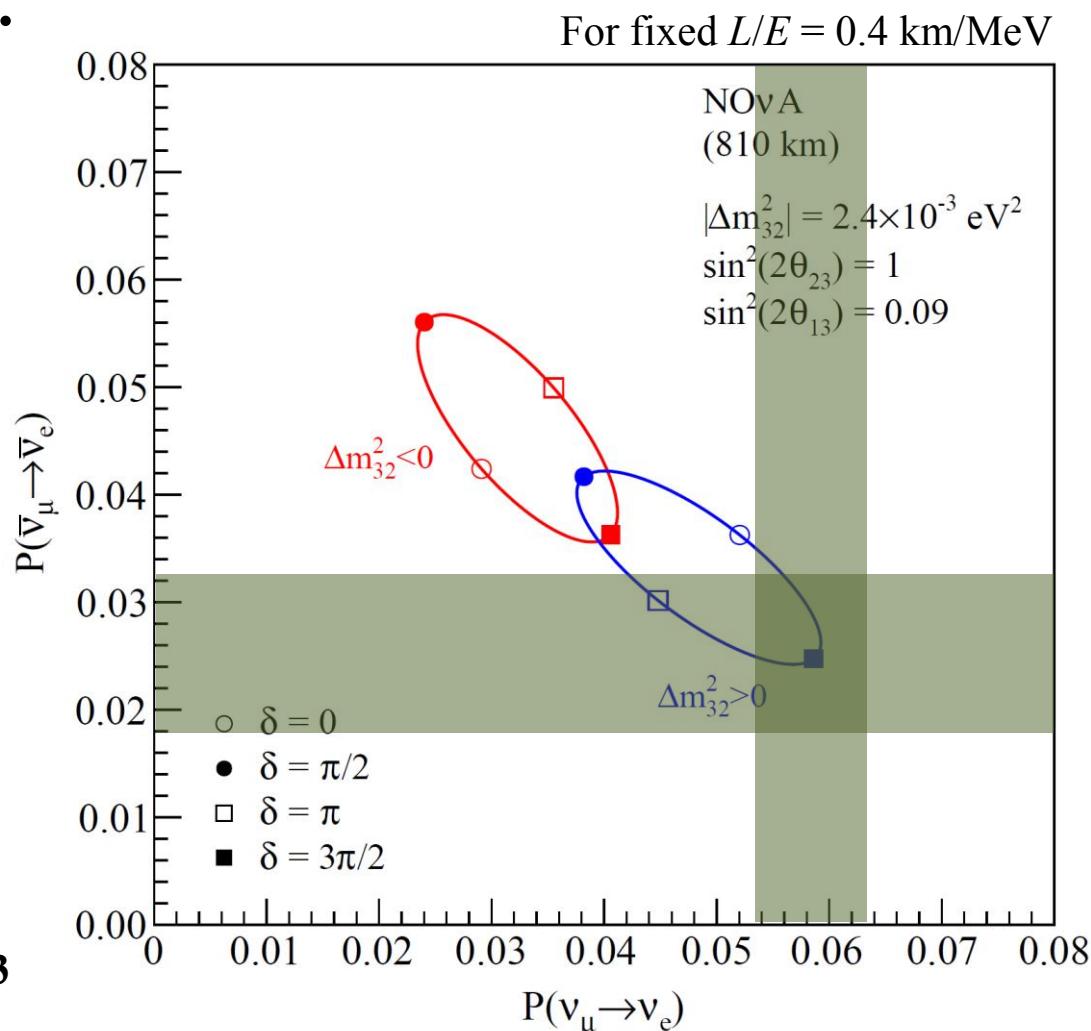
At right:

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$  vs.  $P(\nu_\mu \rightarrow \nu_e)$   
plotted for a single neutrino  
energy and baseline

Measure these probabilities  
(*an example measurement  
of each shown*)

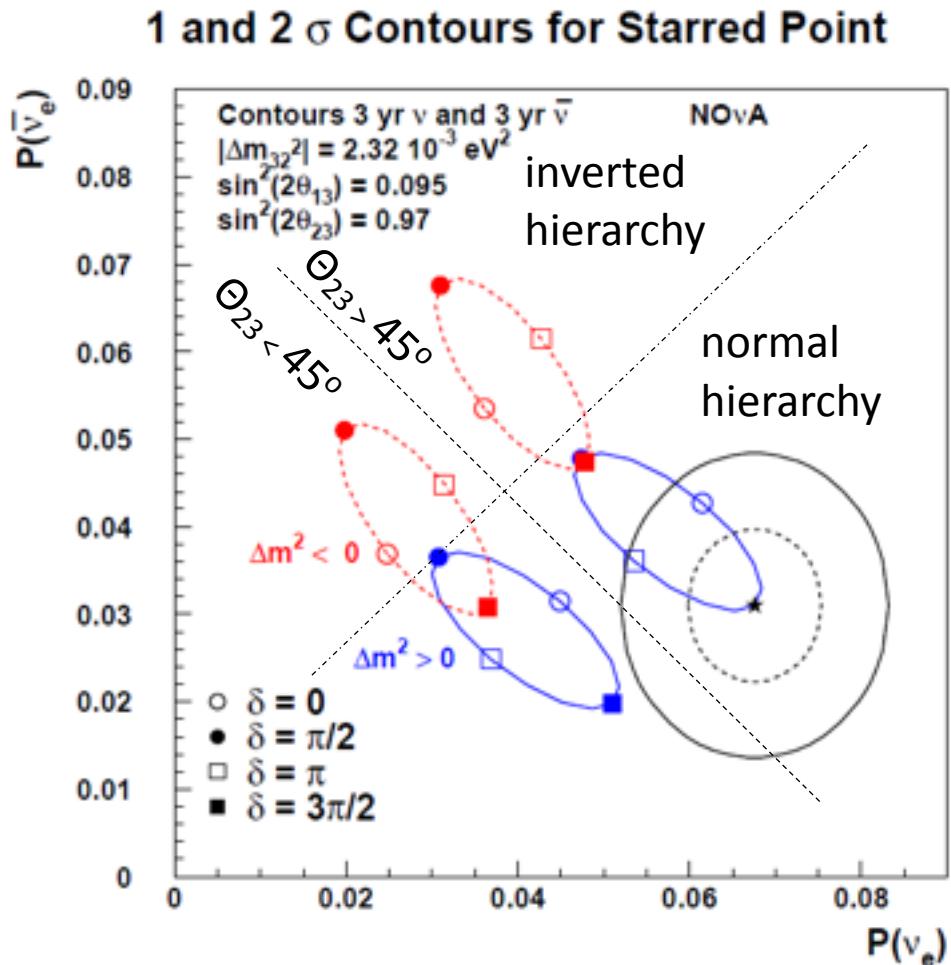
Also:

Both probabilities  $\propto \sin^2 \theta_{23}$



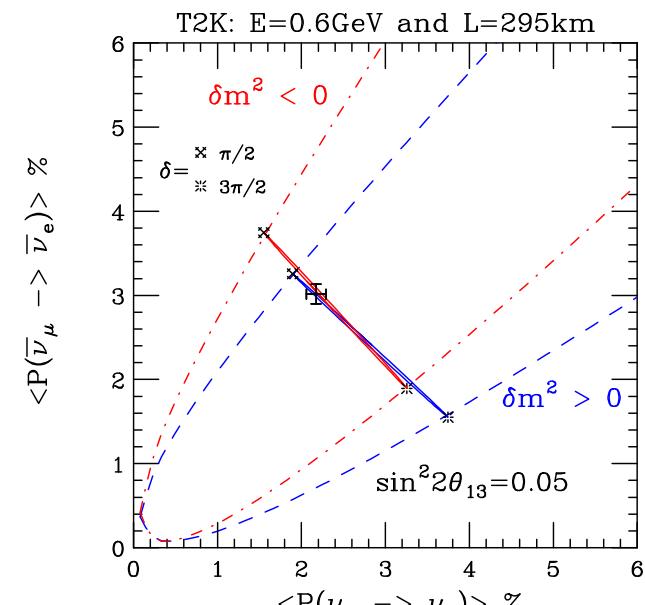
# Non-maximal mixing scenario

- If  $\theta_{23}$  non-maximal then effect of octant is important
- Big effect, +/- 20%



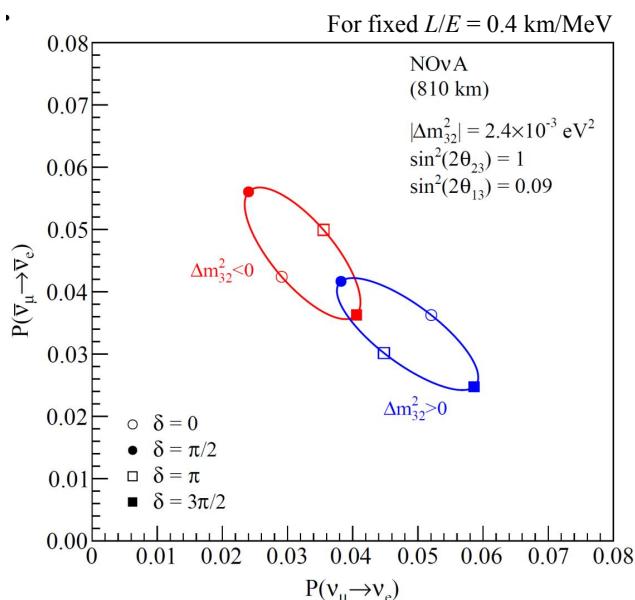
# Effect of Increasing Energy

**T2K**



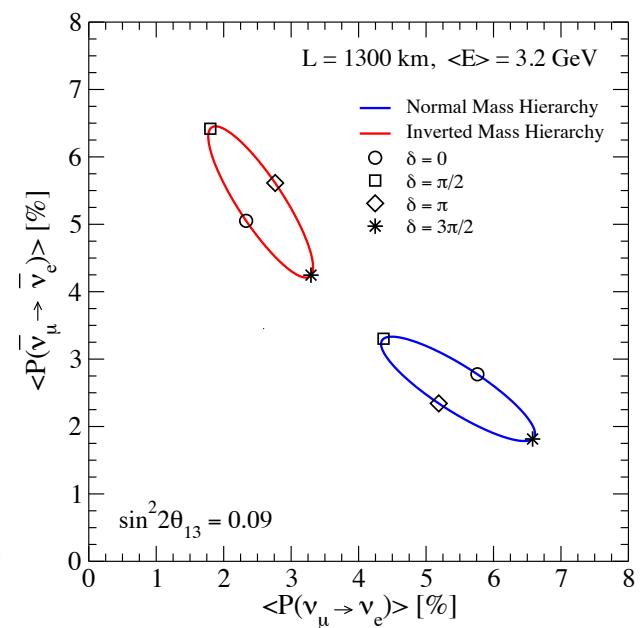
**0.6 GeV**

**NOvA**



**2 GeV**

**DUNE**



**3 GeV**

**Increasing Energy**

[→ bigger matter effect and hence bigger fake CP violation]

# T2K $\nu_e$ Appearance

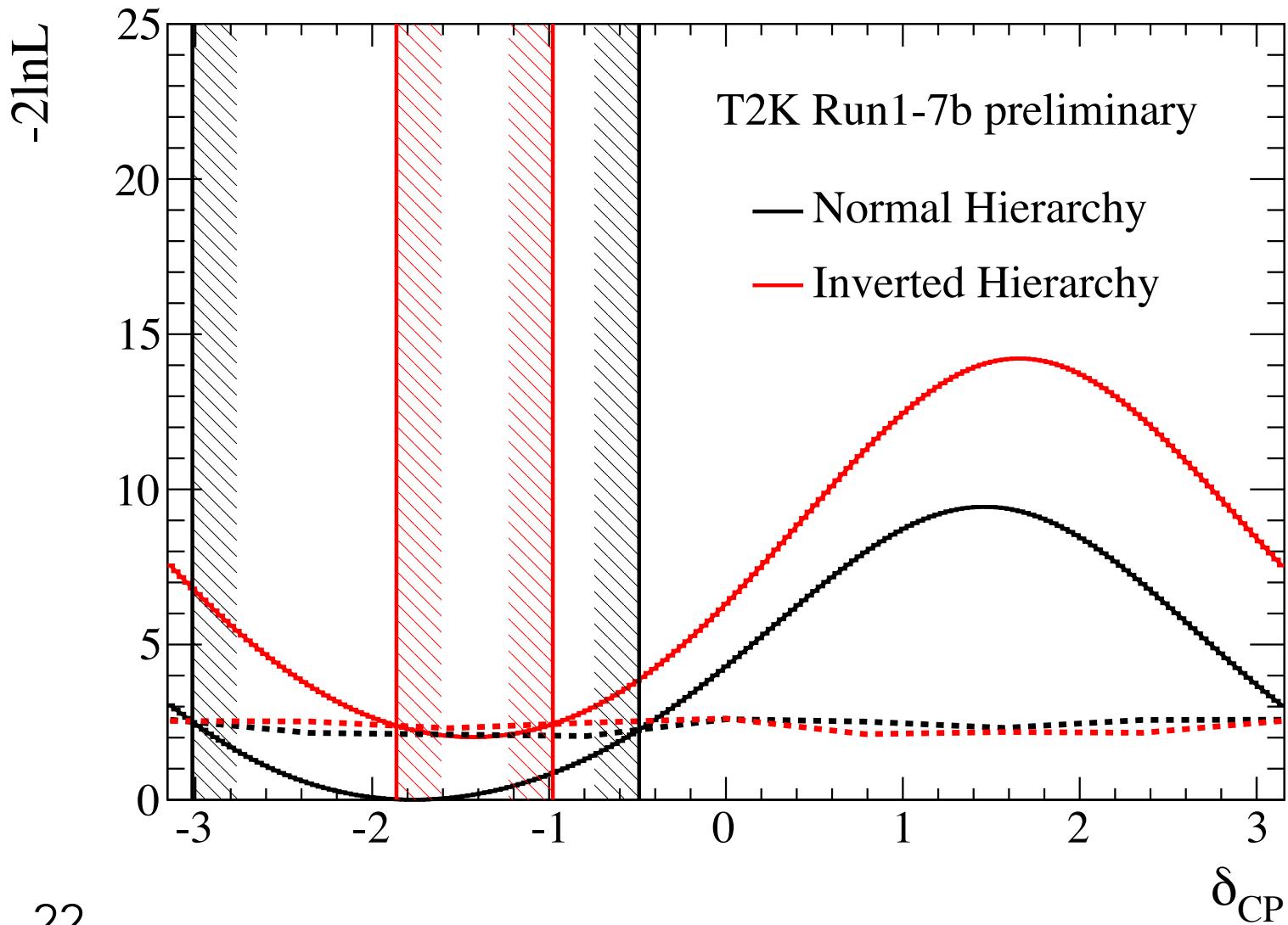
		EXPECTED (NH, $\sin^2\Theta_{23}=0.528$ ) <b>(Signal + Bkg)</b>				Bkg
		OBS.	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$
$\nu_e$	32	27.0	22.7	18.5	22.7	5.0
$\bar{\nu}_e$	4	6.0	6.9	7.7	6.8	3.2



Favoured  
scenario,  $-\pi/2$

Some small tension:  
Neutrinos too high (upper octant?)  
Antineutrinos too low

# T2K Results on $\delta_{CP}$ (fixed hierarchy)

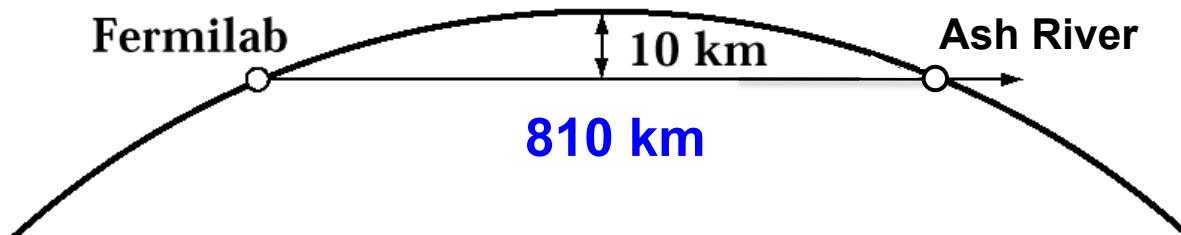


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# NOvA Overview

- “Conventional” beam
- Two-detector experiment:
- **Near detector**
  - measure beam composition
  - energy spectrum
- **Far detector**
  - measure oscillations and search for new physics



# The NOvA Collaboration

Argonne, Atlantico, Banaras Hindu University, Caltech, Cochin, Institute of Physics and Computer science of the Czech Academy of Sciences, Charles University, Cincinnati, Colorado State, Czech Technical University, Delhi, JINR, Fermilab, Goiás, IIT Guwahati, Harvard, IIT Hyderabad, U. Hyderabad, Indiana, Iowa State, Jammu, Lebedev, Michigan State, Minnesota-Twin Cities, Minnesota-Duluth, INR Moscow, Panjab, South Carolina, SD School of Mines, SMU, Stanford, Sussex, Tennessee, Texas-Austin, Tufts, UCL, Virginia, Wichita State, William and Mary, Winona State



234 Collaborators  
41 institutions  
7 countries

# Physics Goals

## Results from 3 different oscillation analyses

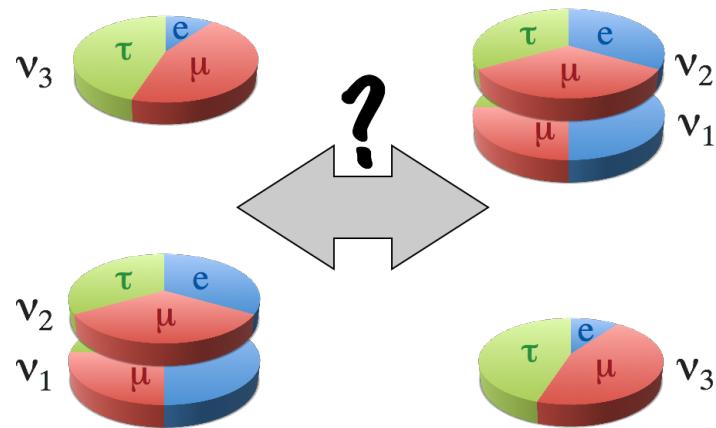
### □ Disappearance of

$\nu_\mu$  CC events

- clear suppression as a function of energy

- 2015 analysis results  
Phys.Rev.D93.051104

$$|\Delta m_{32}^2| \sin^2(2\theta_{23})$$



### □ Deficit of NC events?

- suppression of NCs could be evidence of oscillations involving a sterile neutrino

- Fit to 3+1 model

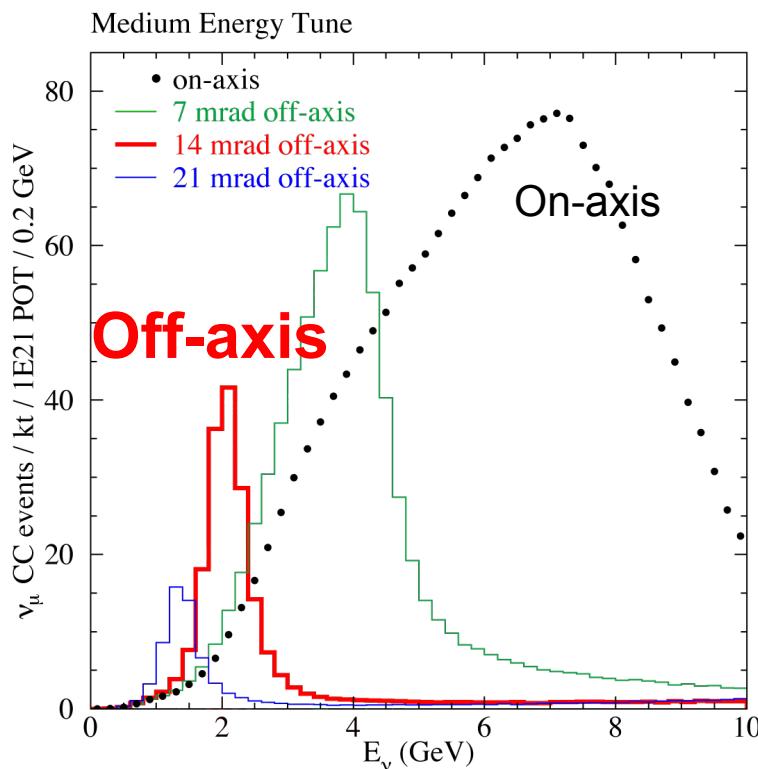
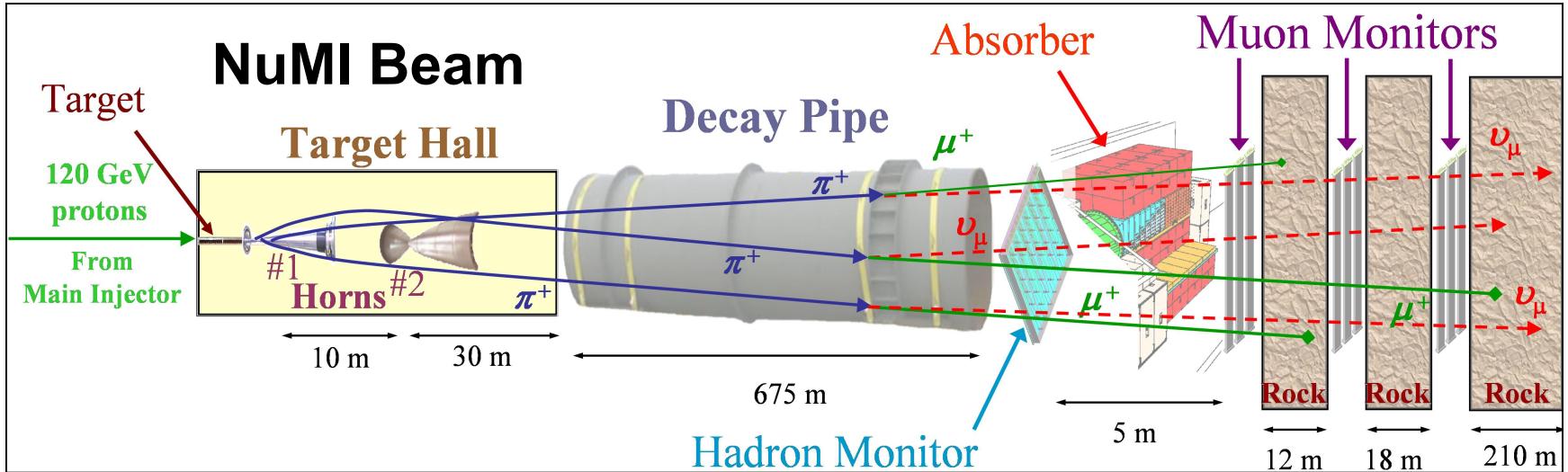
- new!

$$\Delta m_{41}^2, \theta_{34}, \theta_{24}$$

### □ Appearance of $\nu_e$ CC events

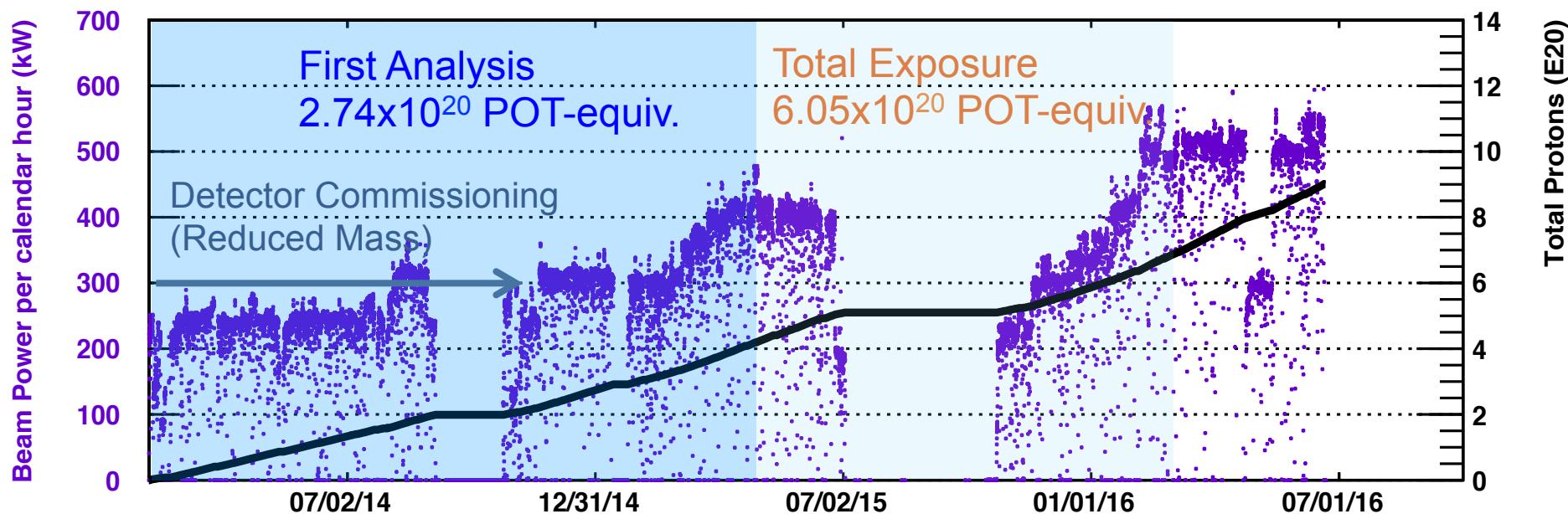
$\theta_{13}, \theta_{23}, \delta_{CP}$ ,  
and Mass Hierarchy

- 2 GeV neutrinos enhances matter effects
- $\pm 30\%$  effect
- 2015 analysis results in PRL.116.151806



# Beam Performance

- $6.05 \times 10^{20}$  POT in 14 kton equivalent detector
  - More than double exposure of 2015 analysis
- Averaged 560 kW before present shutdown
- Achieved 700 kW design goal in tests (June13)

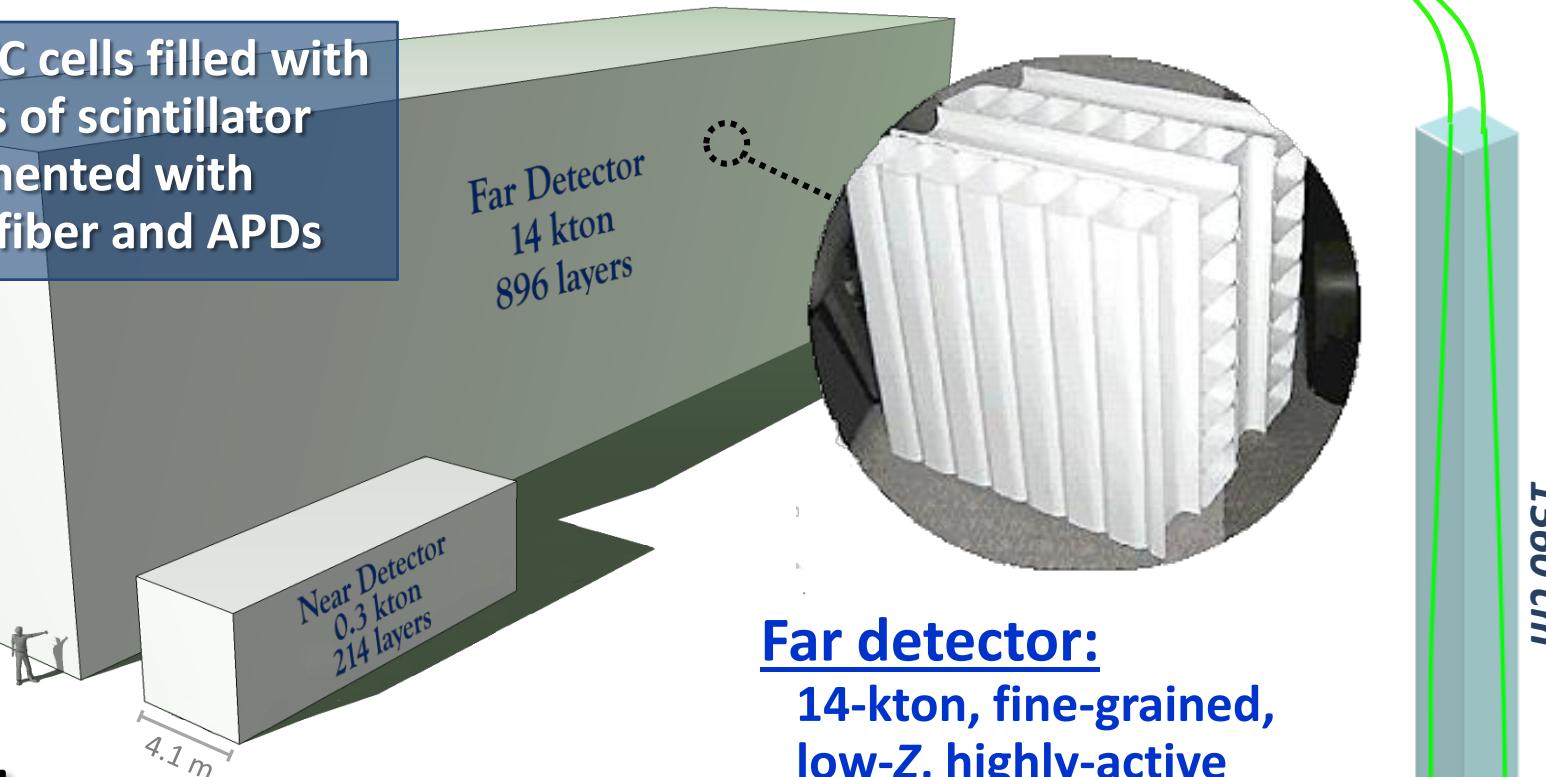


# NO $\nu$ A detectors

## A NO $\nu$ A cell

Extruded PVC cells filled with  
11M liters of scintillator  
instrumented with  
 $\lambda$ -shifting fiber and APDs

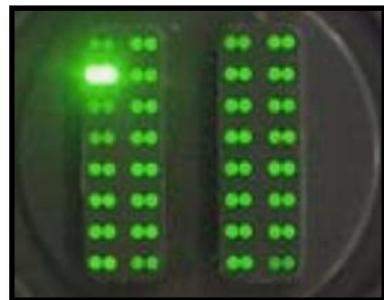
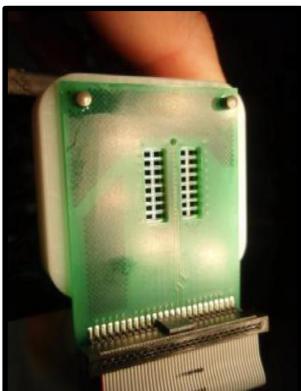
15.6 m



**Far detector:**  
14-kton, fine-grained,  
low-Z, highly-active  
tracking calorimeter  
→ 344,000 channels

**Near detector:**  
0.3-kton version of  
the same  
→ 20,000 channels

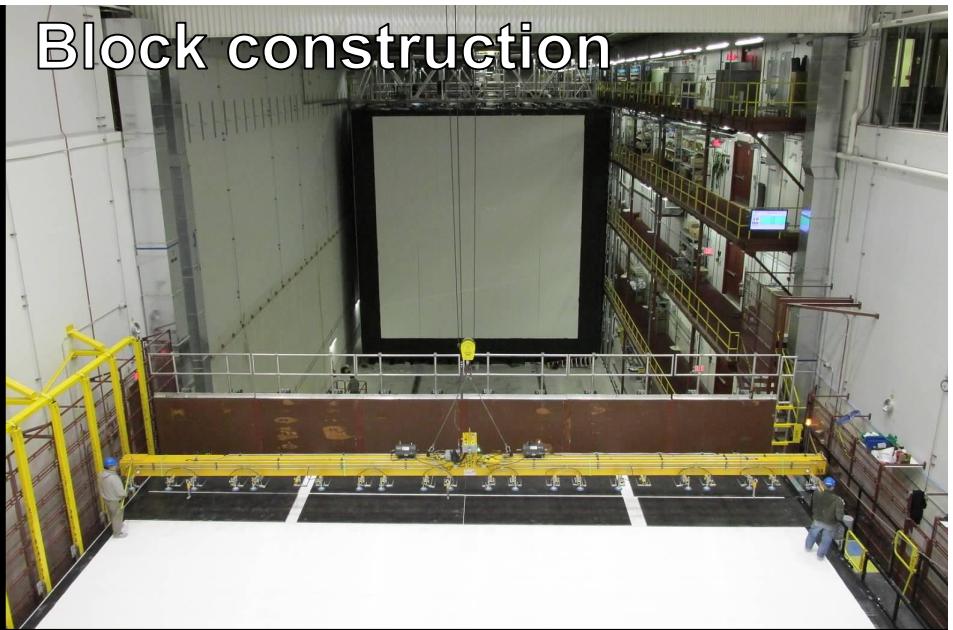
32-pixel APD  
←  
Fiber pairs  
from 32 cells →



## Far Detector site



## Block construction



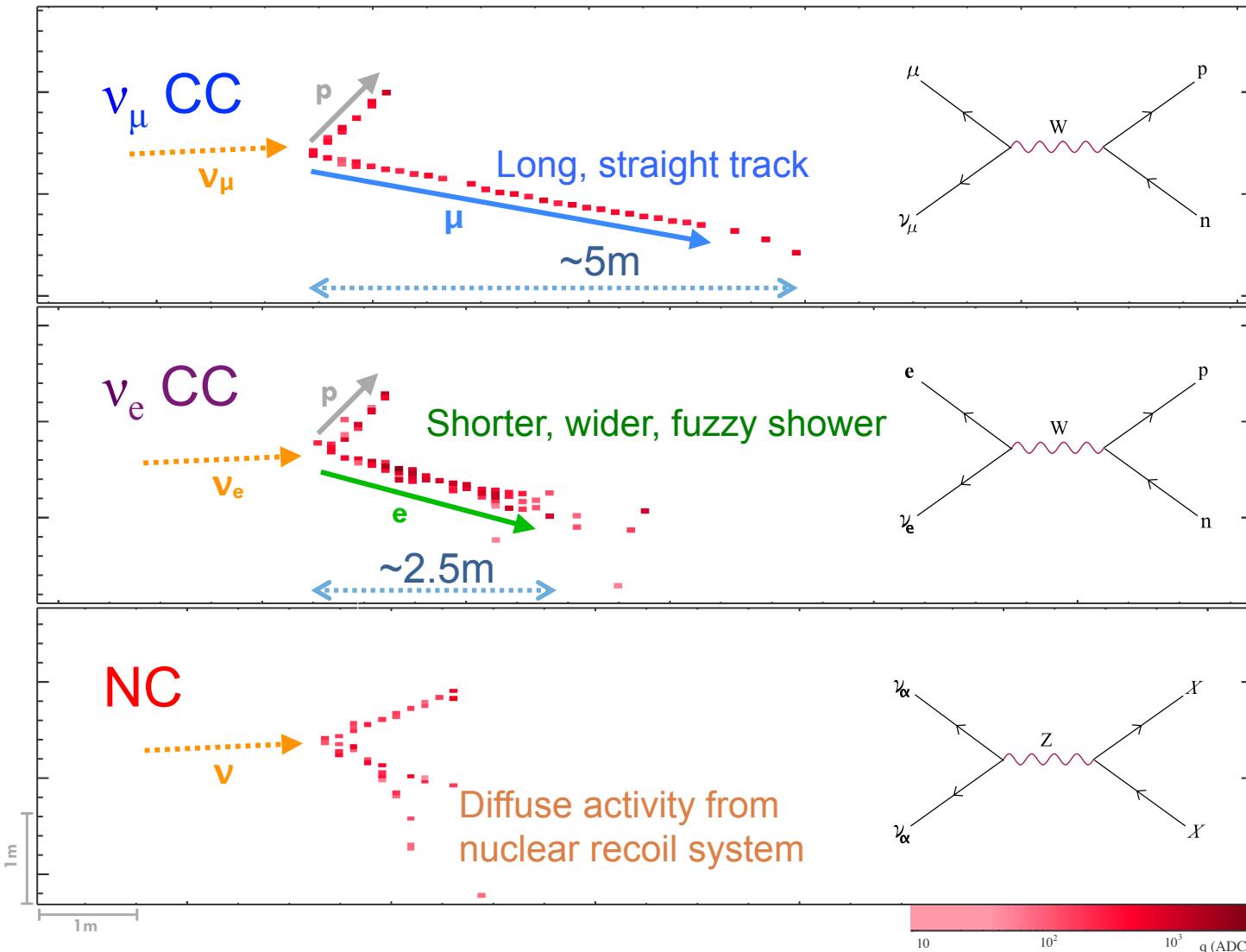
## Outfitted Far Detector



## Near Detector

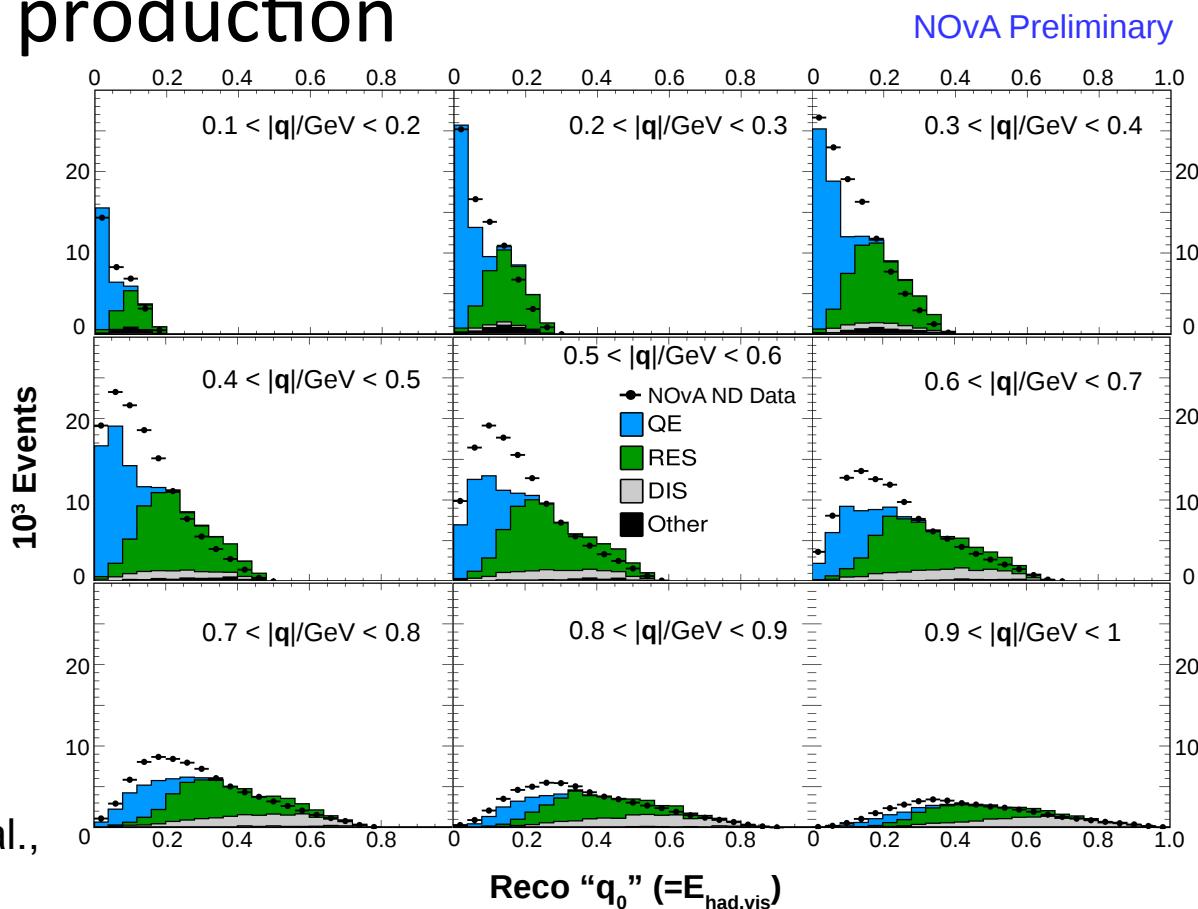
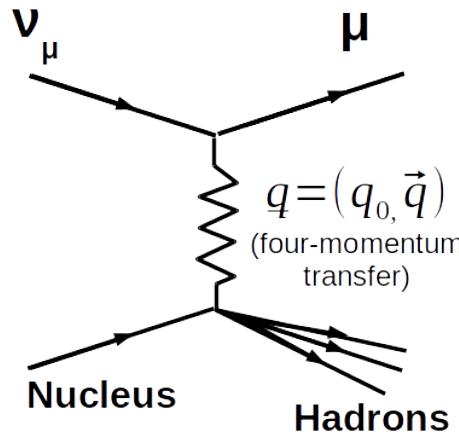


# Event Types



# Scattering in a Nuclear Environment

- Near detector hadronic energy distribution suggests unsimulated process between quasi-elastic and delta production

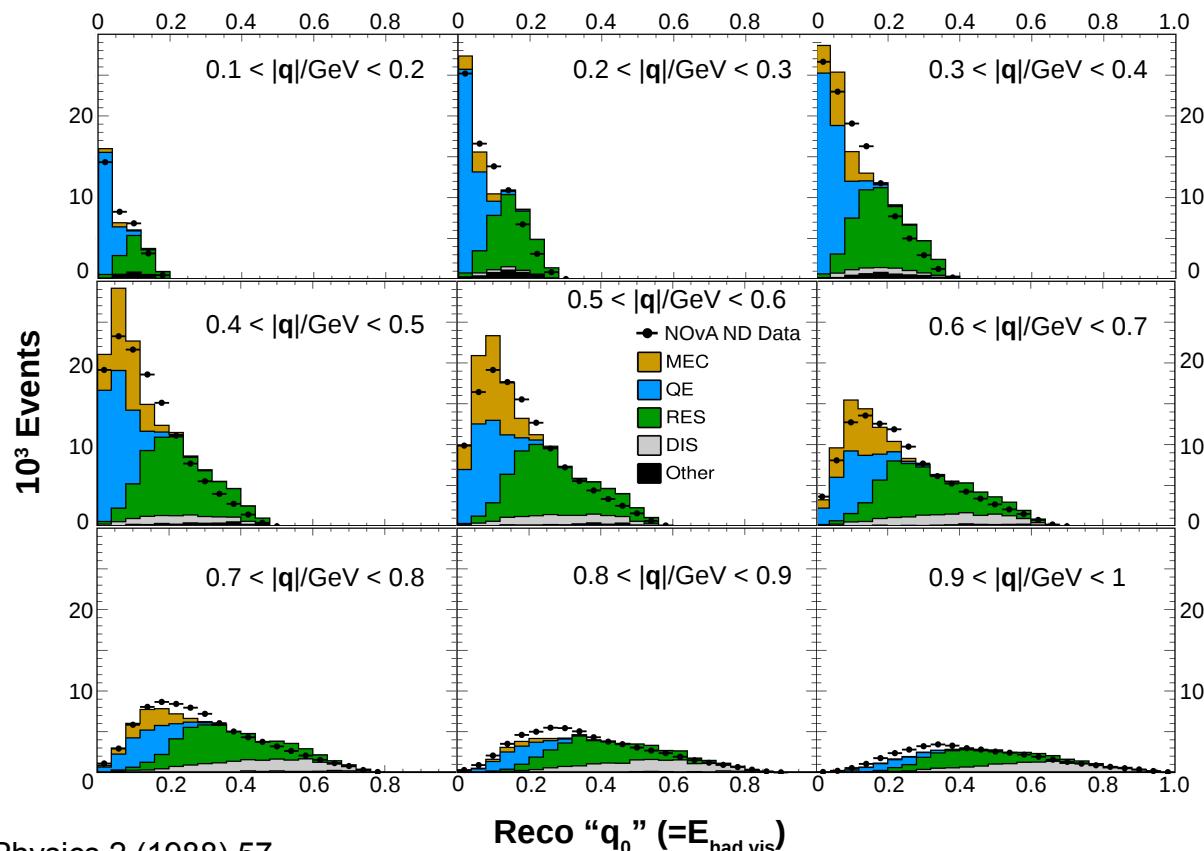


Similar conclusions from MINERvA data reported in P.A. Rodrigues et al.,  
PRL 116 (2016) 071802

# Scattering in a Nuclear Environment

- Enable GENIE empirical Meson Exchange Current Model
- Reweight to match NOvA excess as a function of 3-momentum transfer

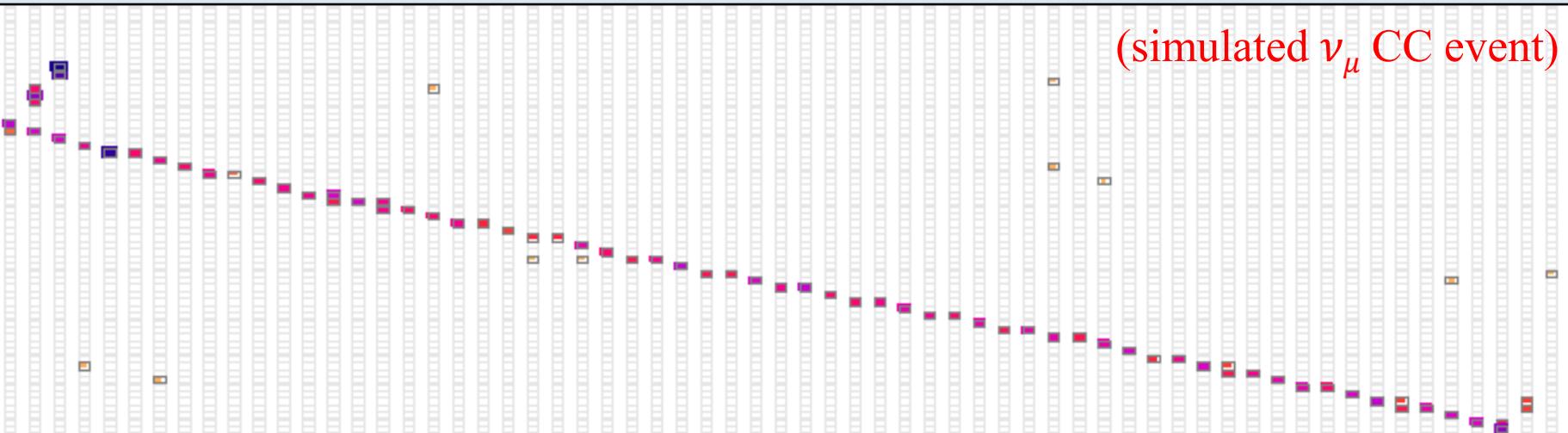
- 50% systematic uncertainty on MEC component
- Reduces largest systematics
  - hadronic energy scale
  - QE cross section modeling
- Reduce single non-resonant pion production by 50%  
(P.A. Rodrigues et al,  
arXiv:1601.01888.)



MEC model by S. Dytman, inspired by  
J. W. Lightbody, J. S. O'Connell, Computers in Physics 2 (1988) 57.

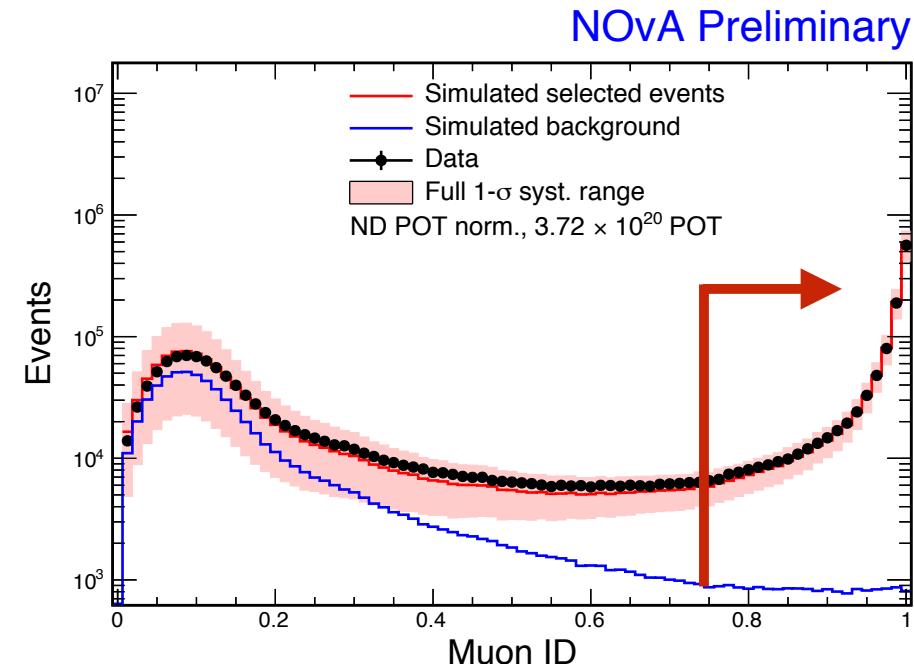
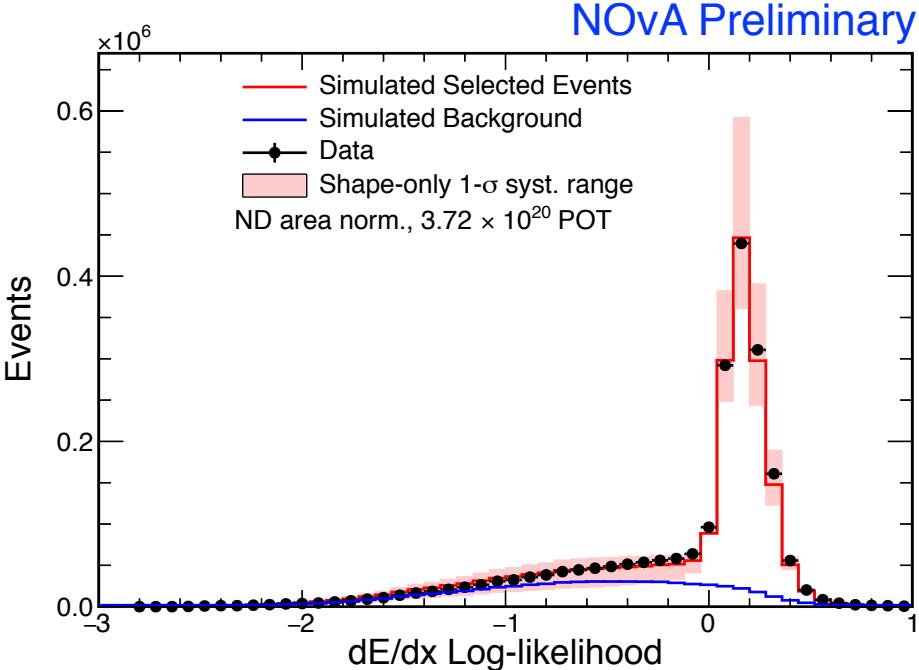
# $\nu_\mu$ disappearance

- Identify **contained  $\nu_\mu$  CC events** in each detector
- Measure their **energies**
- Extract oscillation information from differences between the **Far and Near energy spectra**



# $\nu_\mu$ Event Selection

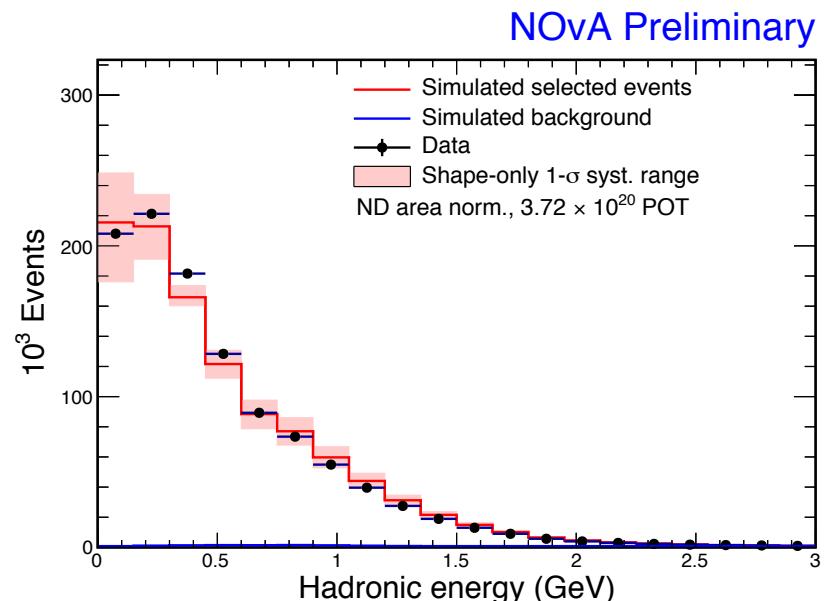
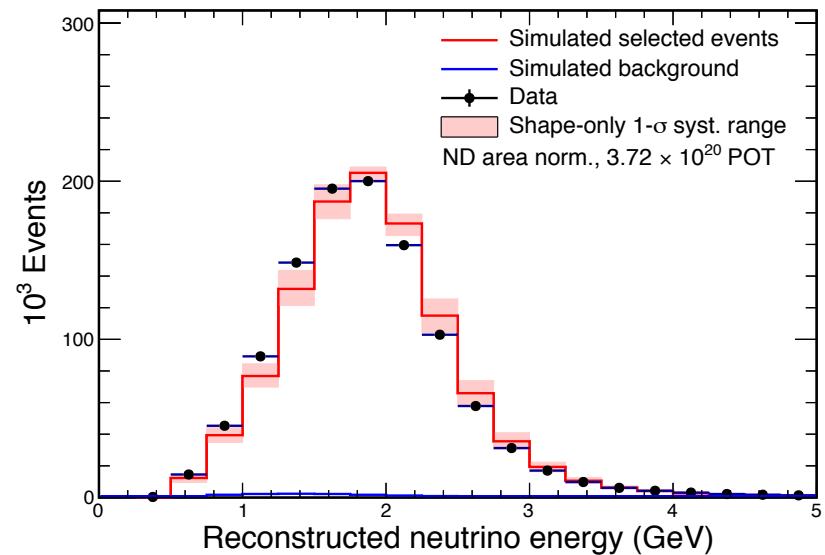
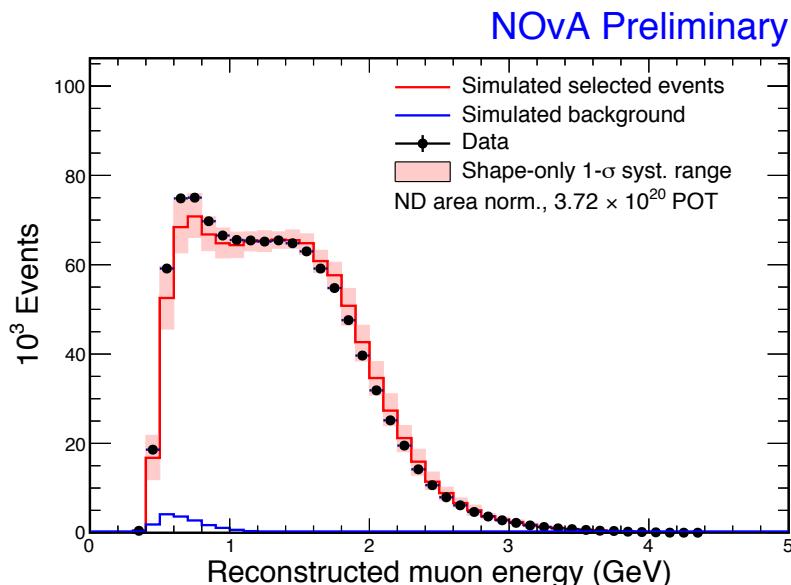
- Goal: Isolate a pure sample of  $\nu_\mu$  CC events less than 5GeV
  - Select events with long tracks
  - Suppress NC and cosmic backgrounds
- 4-variable kNN used to identify muons
  - track length
  - $dE/dx$  along track
  - scattering along track
  - track-only plane fraction
- ND data matches simulation well for muon variables



# $\nu_\mu$ Near Detector Data

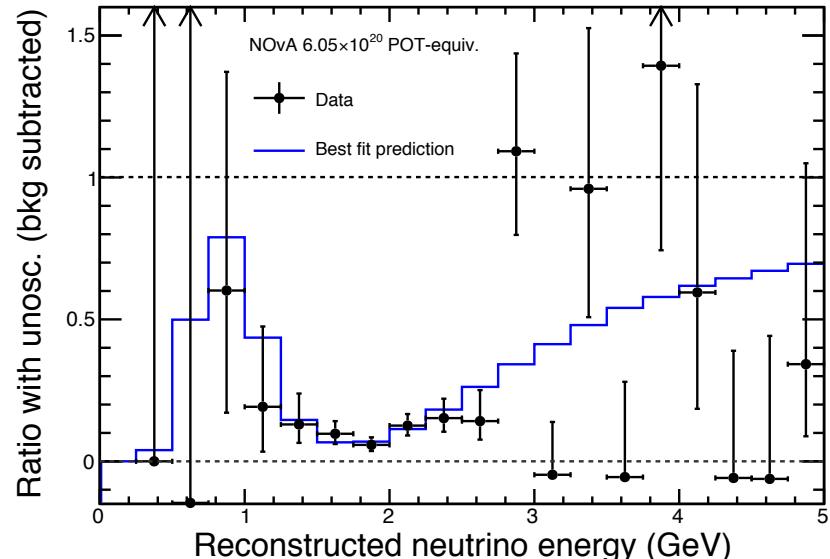
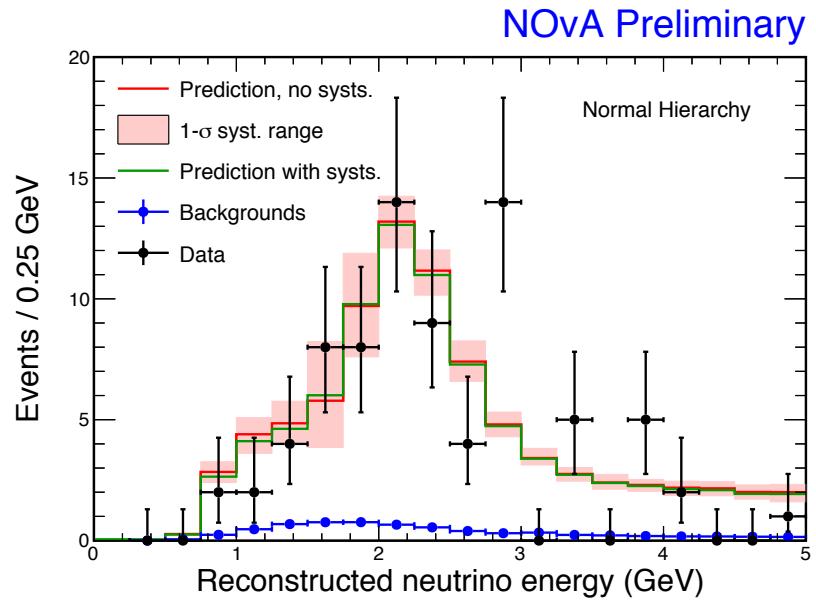
NOvA Preliminary

- Addition of MEC events substantially improves simulated hadronic energy distribution
  - hadronic energy scale uncertainty reduced (14% to 5%)
- Reconstructed neutrino energy unfolded, true Far/Near ratio used to extrapolate ND data for a FD prediction



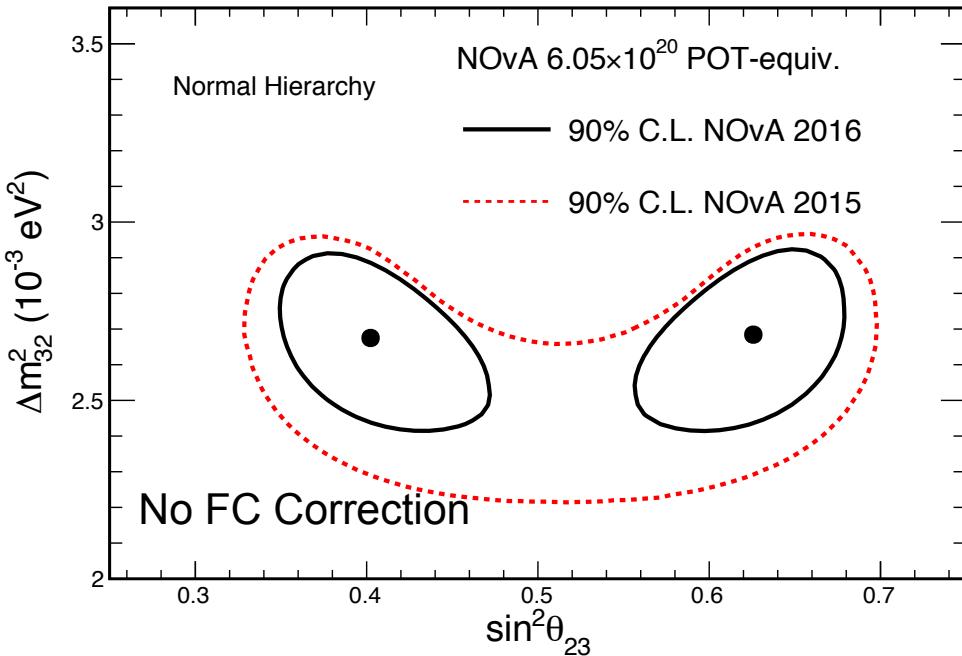
# $\nu_\mu$ Far Detector Data

- **78 events** observed in FD
  - **$473 \pm 30$  with no oscillation**
  - 82 at best oscillation fit
  - 3.7 beam BG + 2.9 cosmic



# Contours

NOvA Preliminary



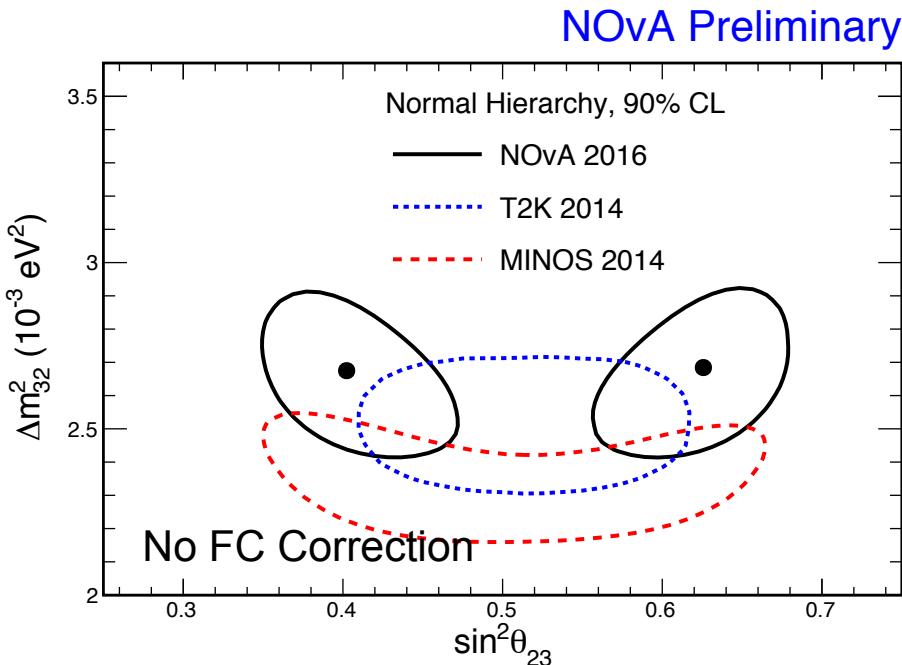
- Fit for  $\Delta m^2$  and  $\sin^2\theta_{23}$
- Dominant systematic effects included in fit:
  - Normalization
  - NC background
  - Flux
  - Muon and hadronic energy scales
  - Cross section
  - Detector response and noise

Best Fit (in NH):

$$|\Delta m^2_{32}| = 2.67 \pm 0.12 \times 10^{-3} \text{ eV}^2$$
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02} (0.63^{+0.02}_{-0.03})$$

Maximal mixing  
excluded at  $2.5\sigma$

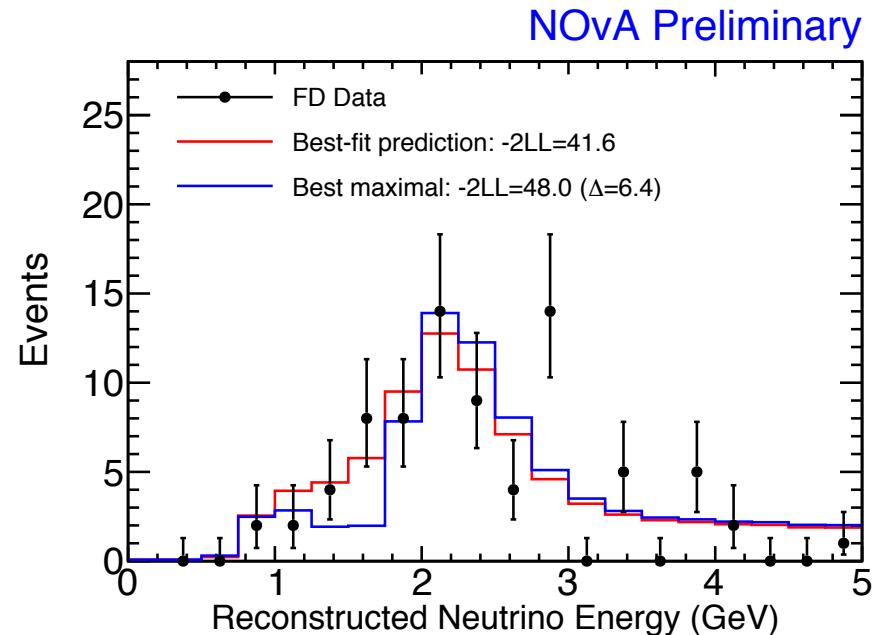
# Contours Compared



Best Fit (in NH):

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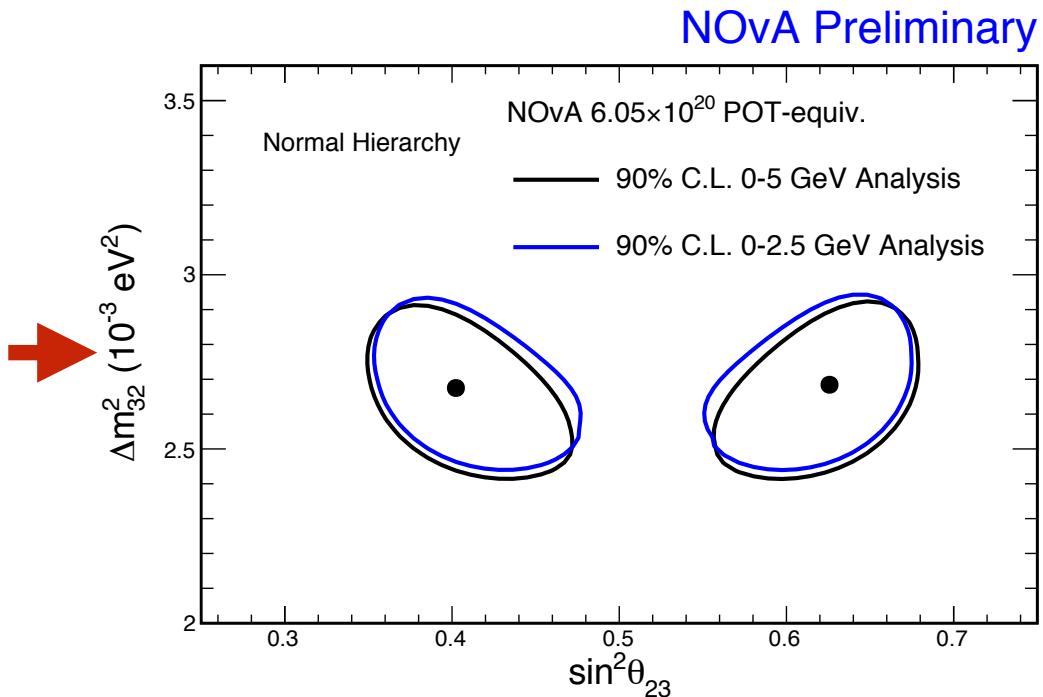
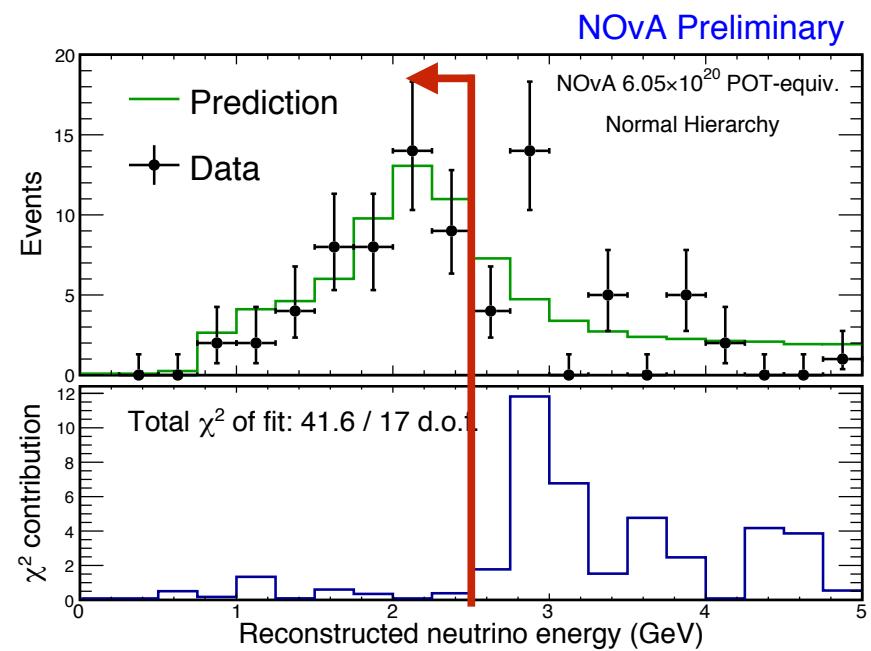


Maximal mixing  
excluded at  $2.5\sigma$

Driven by bins in oscillation dip (1-2 GeV).  
Forcing maximal mixing gives:

$$\Delta m_{32}^2 = (2.46) \times 10^{-3} \text{ eV}^2$$

# Goodness of fit



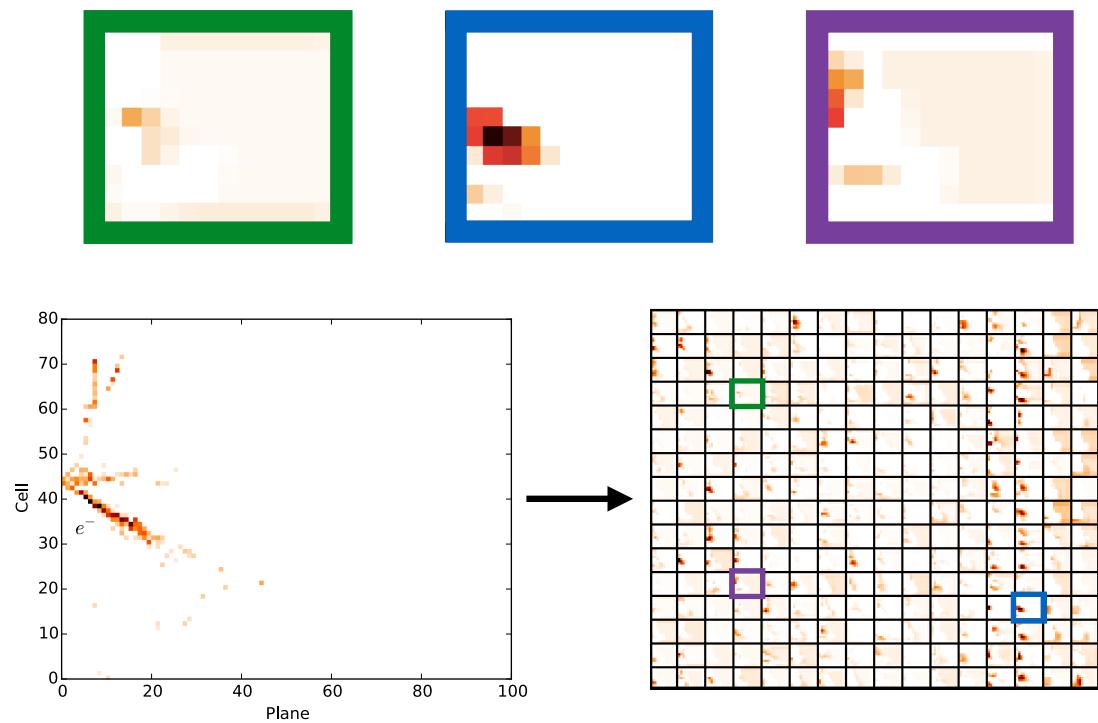
There is no significant pull in the oscillation fit  
from bins in the tail

# Neutral Current & $v_e$ Results

# Improved Event Selection

- This analysis features a new event selection technique based on ideas from computer vision and deep learning

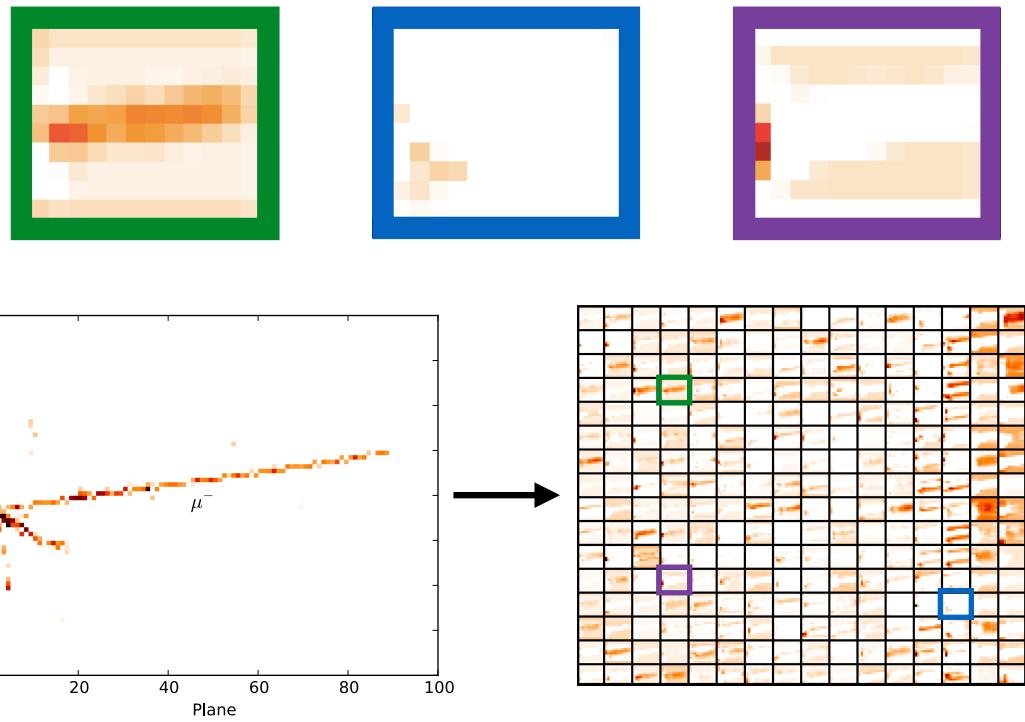
- Calibrated hit maps are inputs to Convolutional Visual Network (**CVN**)
- Series of image processing transformations applied to extract abstract features
- Extracted features used as inputs to a conventional neural network to classify the event



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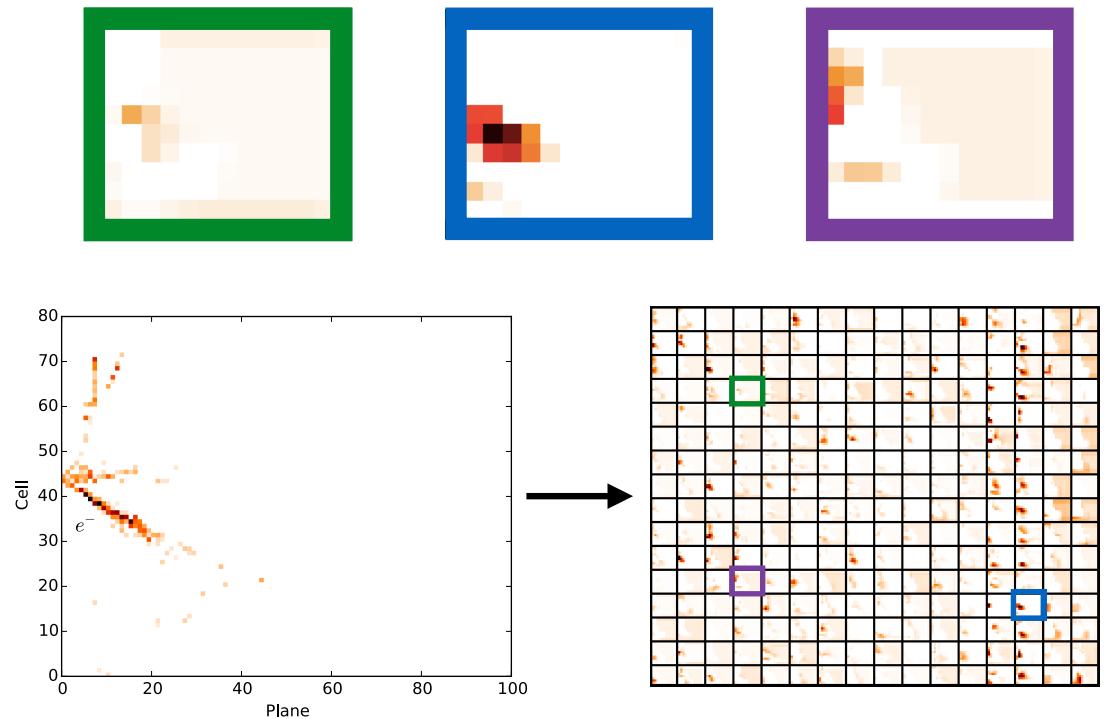
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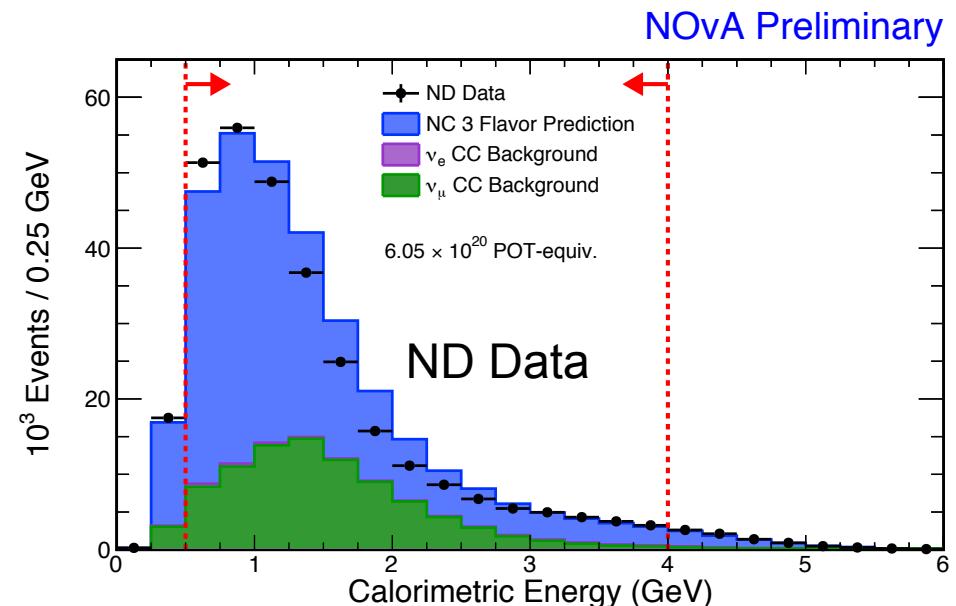


Improvement in sensitivity from CVN equivalent to 30% more exposure

# Neutral Current Result

# NC Near Detector Data

- Events classified using CVN
- Normalization agrees well
- Data shifted to lower energy relative to MC
  - No MEC model for NC events
  - Large uncertainties on NC cross section

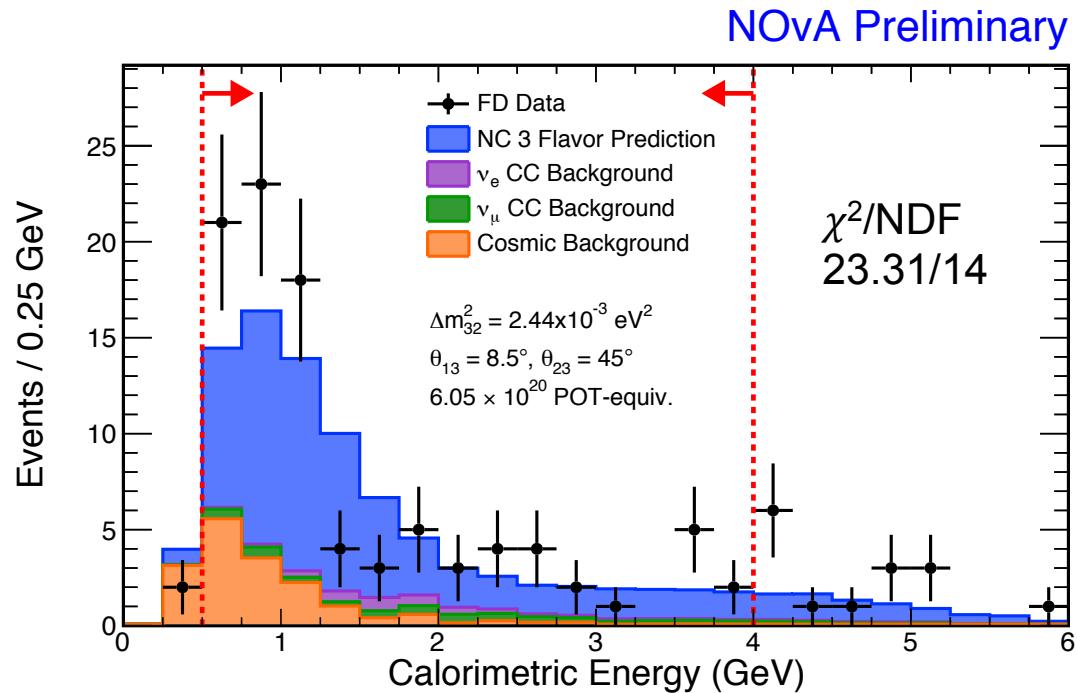


Extrapolation of ND data using F/N in reconstructed energy gives a prediction

Total	NC	v <sub>μ</sub> CC	Beam v <sub>e</sub>	Cosmics
$83.7 \pm 8.3$	60.6	4.8	3.6	14.3

# NC Far Detector Data

- Observe 95 events
- No evidence of oscillations involving steriles



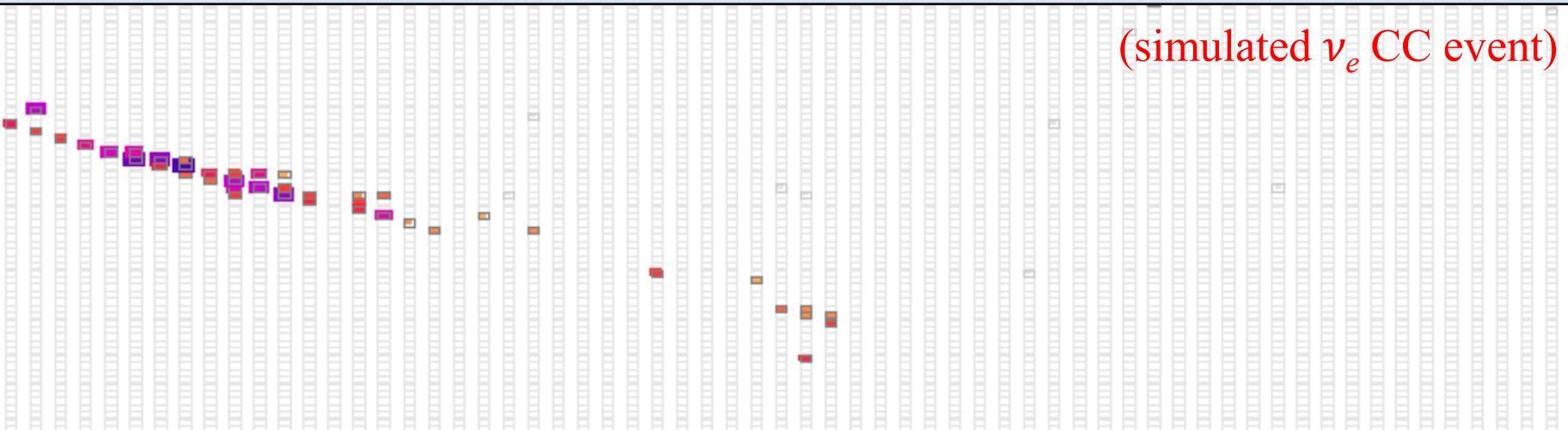
For  $0.05 \text{ eV}^2 < \Delta m_{41}^2 < 0.5 \text{ eV}^2$

$\theta_{34} < 35^\circ, \theta_{24} < 21^\circ$  (90% C.L.)

Excellent NC efficiency (50%) and purity (72%) promise strong future limits on  $\theta_{34}$

# $\nu_e$ appearance

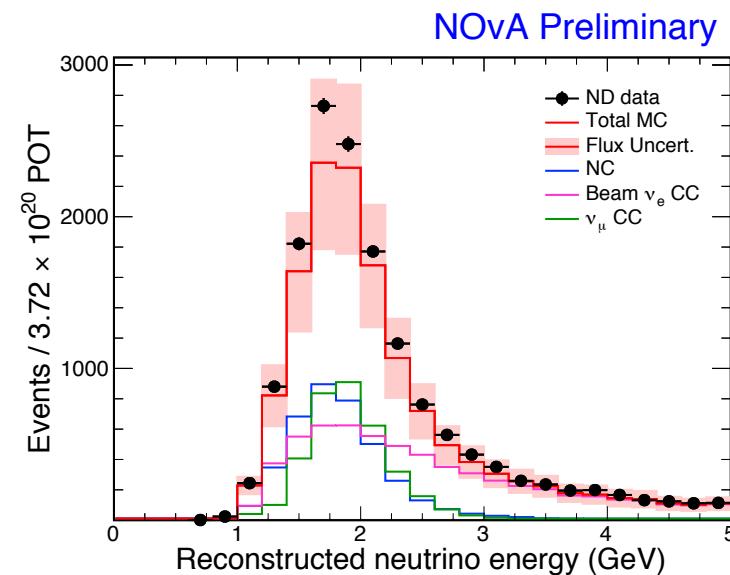
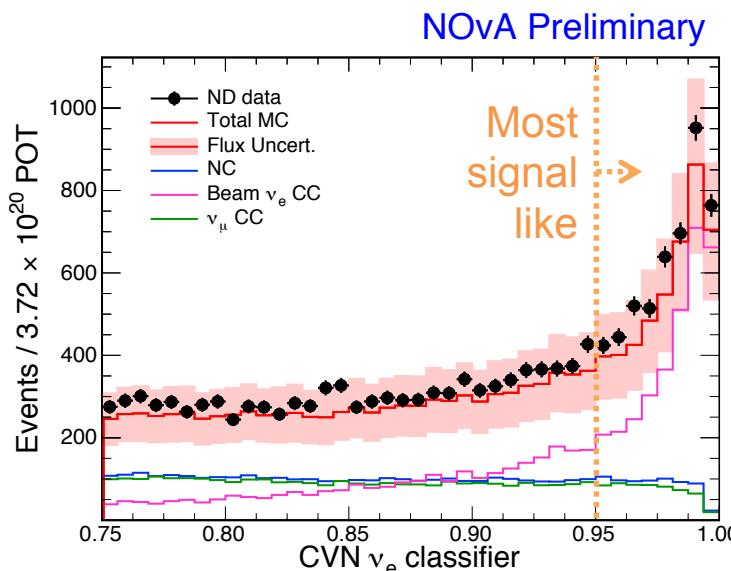
- Identify **contained  $\nu_e$  CC candidates** in each detector
- Use Near Det. candidates to **predict beam backgrounds** in the Far Detector
- Interpret any **Far Det. excess** over predicted backgrounds as  $\nu_e$  appearance



# $\nu_e$ Near Detector Data

- Selection reoptimized to favor parameter measurement
  - both cosmic rejection and classifier cut
  - increased signal efficiency, including lower purity bins
- Use ND data to predict background in FD
  - NC, CC, beam  $\nu_e$  each propagate differently
  - constrain beam  $\nu_e$  using selected  $\nu_\mu$  CC spectrum
  - constrain  $\nu_\mu$  CC using Michel Electron distribution

beam  $\nu_e$  up by 4%  
NC up by 10%  
 $\nu_\mu$  CC up by 17%



# Prediction

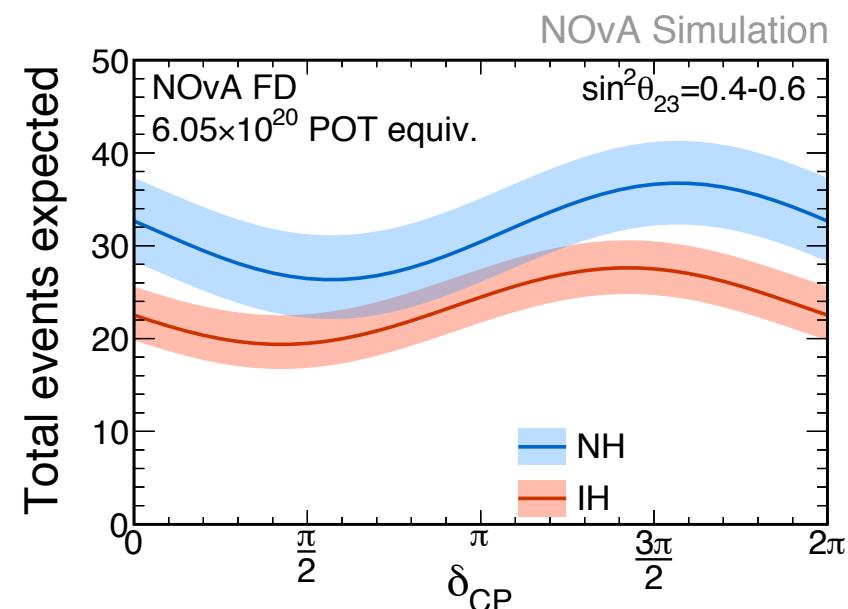
- Extrapolate each component in bins of energy and CVN output
- Expected event counts depend on oscillation parameters

Signal events  
( $\pm 5\%$  systematic uncertainty):

NH, $3\pi/2,$	IH, $\pi/2,$
28.2	11.2

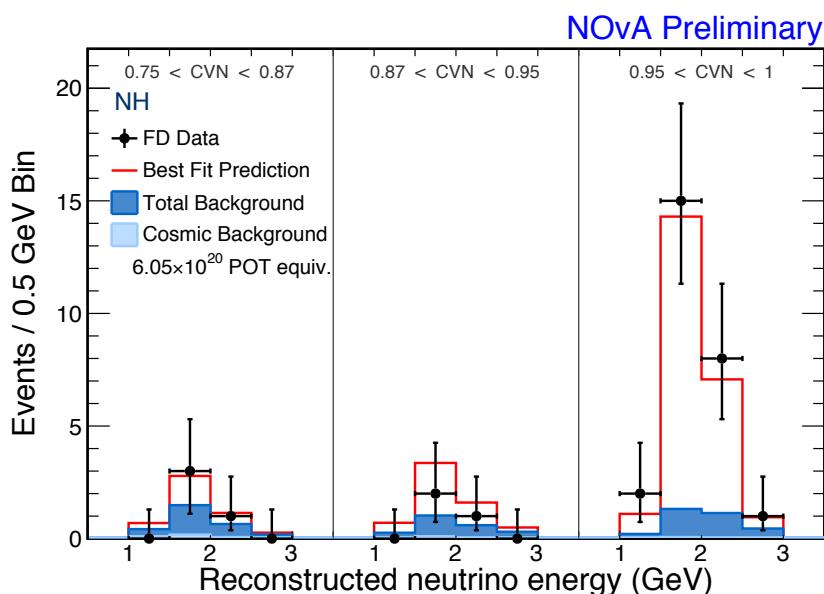
Background by component  
( $\pm 10\%$  systematic uncertainty):

Total BG	NC	Beam $\nu_e$	$\nu_\mu$ CC	$\nu_\tau$ CC	Cosmics
8.2	3.7	3.1	0.7	0.1	0.5

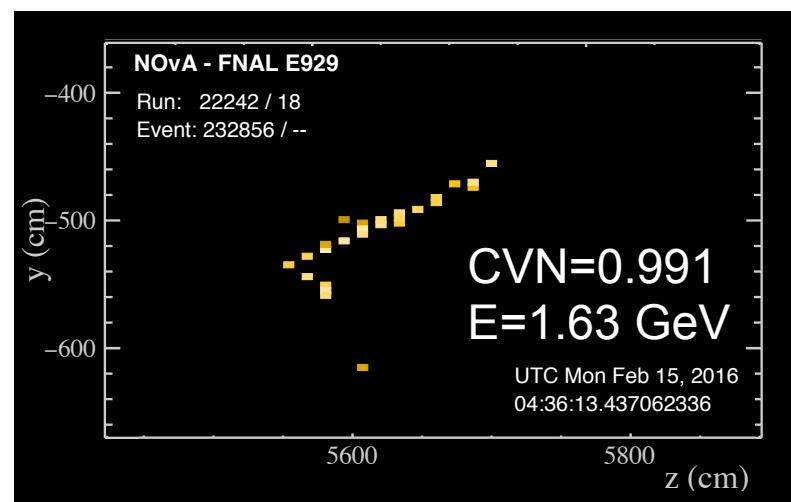


# $\nu_e$ Far Detector Data

>8 $\sigma$  electron neutrino appearance signal



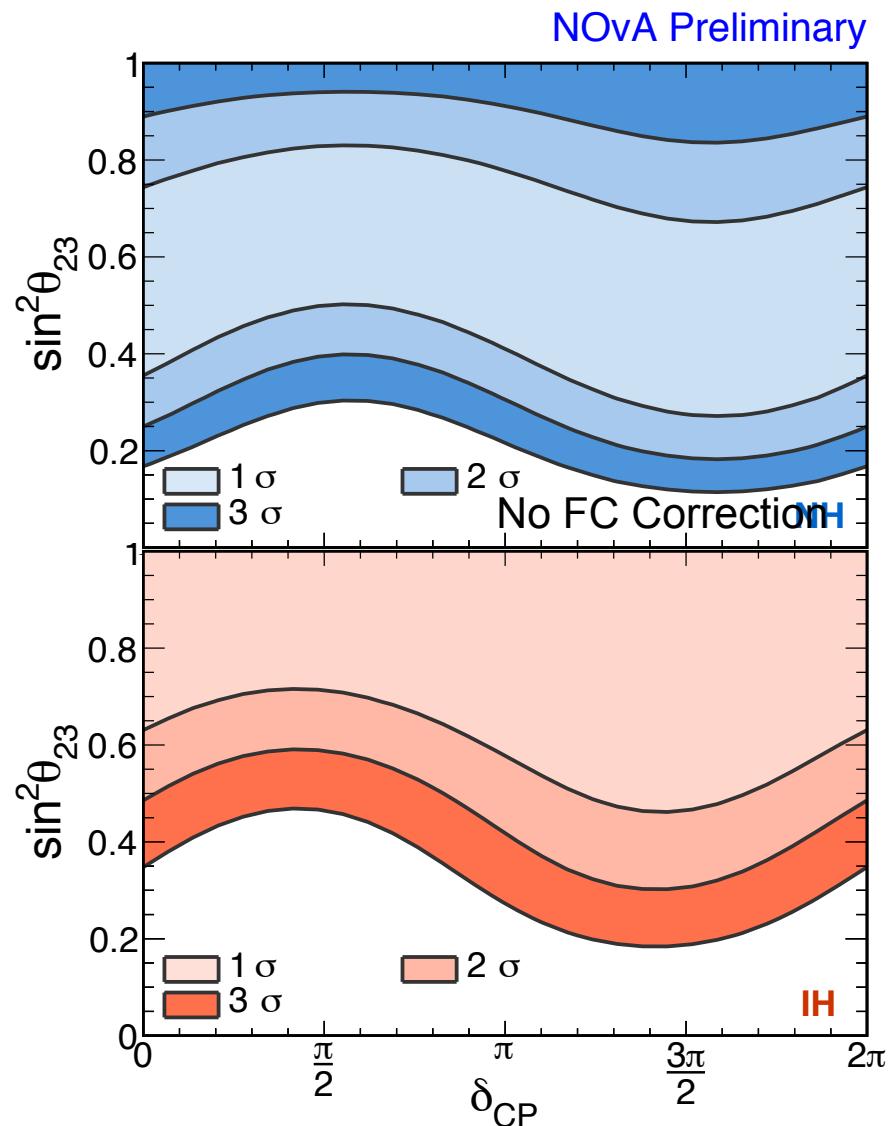
- Observe 33 events in FD
  - background  $8.2 \pm 0.8$



Alternate selectors from 2015 analysis show consistent results  
LID: 34 events,  $12.2 \pm 1.2$  BG expected  
LEM: 33 events,  $10.3 \pm 1.0$  BG expected

# Contours

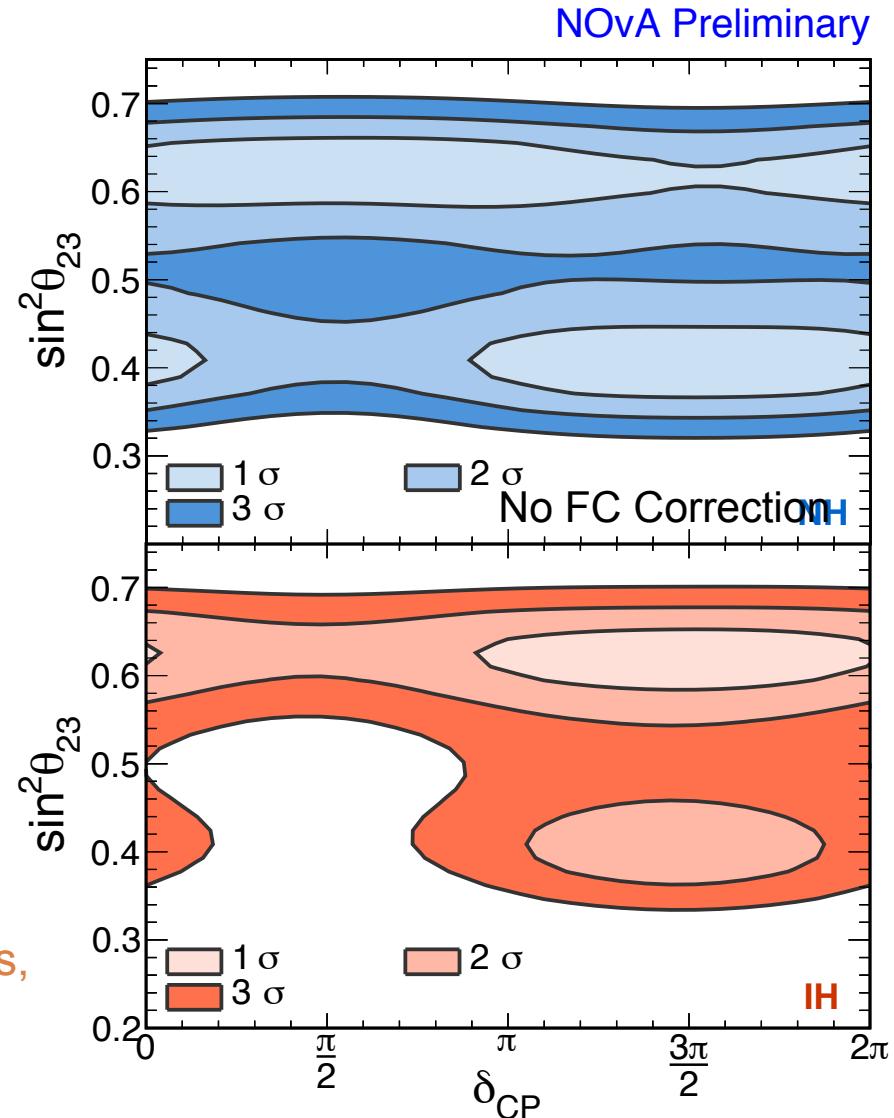
- Fit for hierarchy,  $\delta_{CP}$ ,  $\sin^2\theta_{23}$ 
  - Constrain  $\sin^2(2\theta_{13})=0.085\pm0.05$
  - Constrain  $\Delta m^2=2.44\pm0.06\times10^{-3}$  eV<sup>2</sup>  
( $-2.49\pm0.06\times10^{-3}$  eV<sup>2</sup>, IH)
  - Systematic effects included as nuisance parameters (normalization, flux, calibration, cross section, and detector response effects)



# Contours

- Fit for hierarchy,  $\delta_{CP}$ ,  $\sin^2\theta_{23}$ 
  - Constrain  $\Delta m^2$  and  $\sin^2\theta_{23}$  with NOvA disappearance results
  - Not a full joint fit, systematics and other oscillation parameters not correlated
- Global best fit **Normal Hierarchy**
$$\delta_{CP} = 1.49\pi$$
$$\sin^2(\theta_{23}) = 0.40$$
  - best fit IH-NH,  $\Delta\chi^2=0.47$
  - both octants & hierarchies allowed at  $1\sigma$
  - $3\sigma$  exclusion in IH, lower octant around  $\delta_{CP}=\pi/2$

Antineutrino data will help resolve degeneracies,  
particularly for non-maximal mixing  
**Planned for Spring 2017**



# Conclusions

With  $6.05 \times 10^{20}$  POT, NOvA finds:

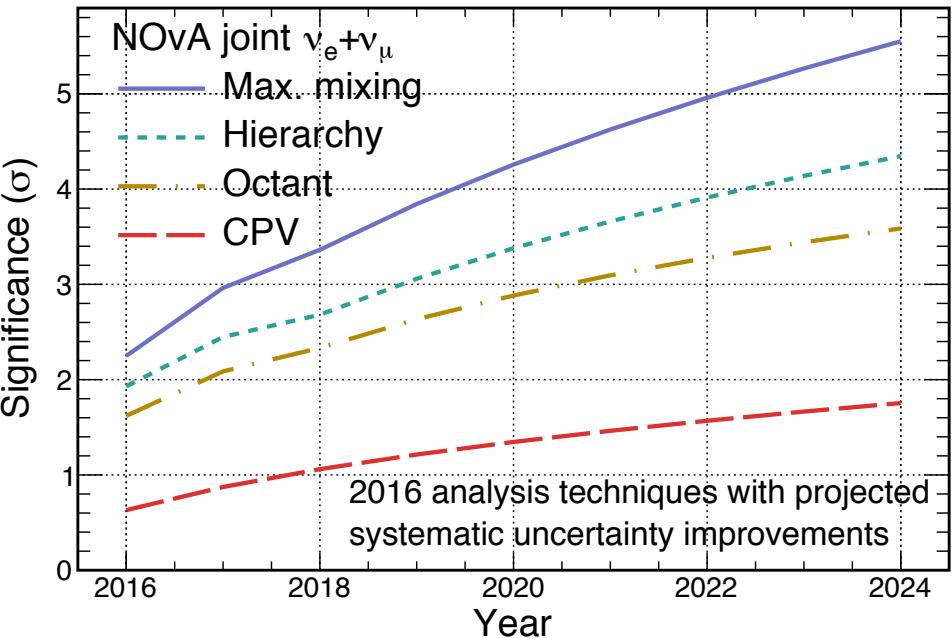
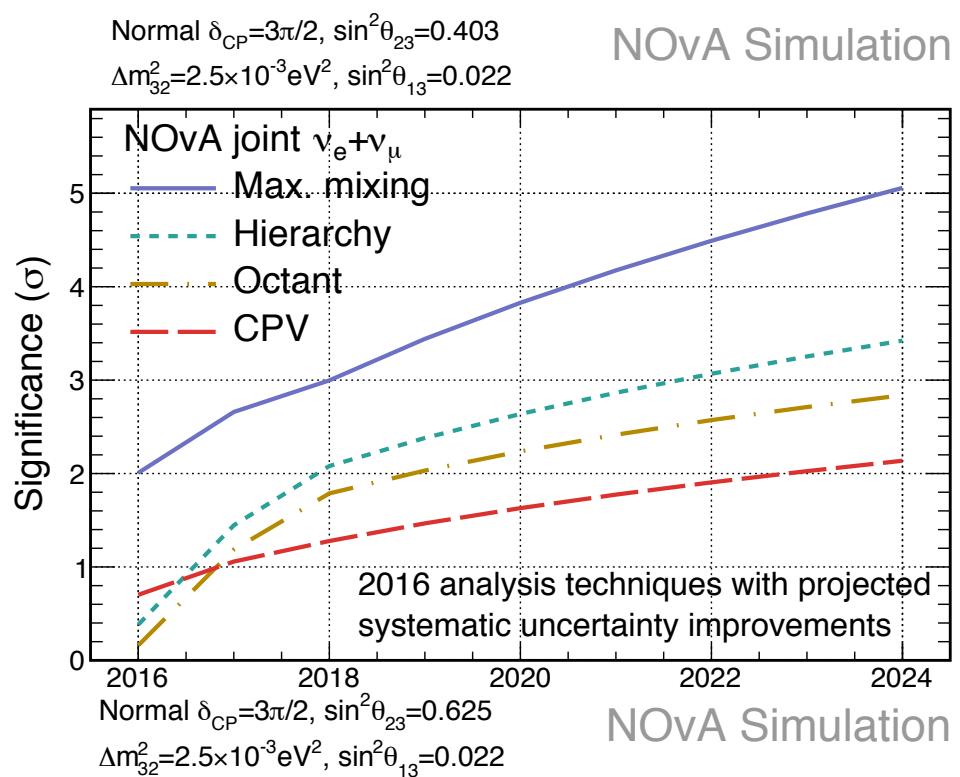
- Muon neutrinos disappear
  - Best fit is non-maximal
  - Maximal mixing excluded at  $2.5\sigma$
- Neutral current event rate shows no evidence of steriles
  - With more data, expect strong limits on  $\theta_{34}$
- Electron neutrinos appear
  - Data prefers NH at low significance
  - IH, lower octant,  $\delta_{CP} = \pi/2$  region excluded at  $3\sigma$
- Looking forward to more neutrinos
- Antineutrino running planned, spring 2017
- Stay tuned!

# Backup slides

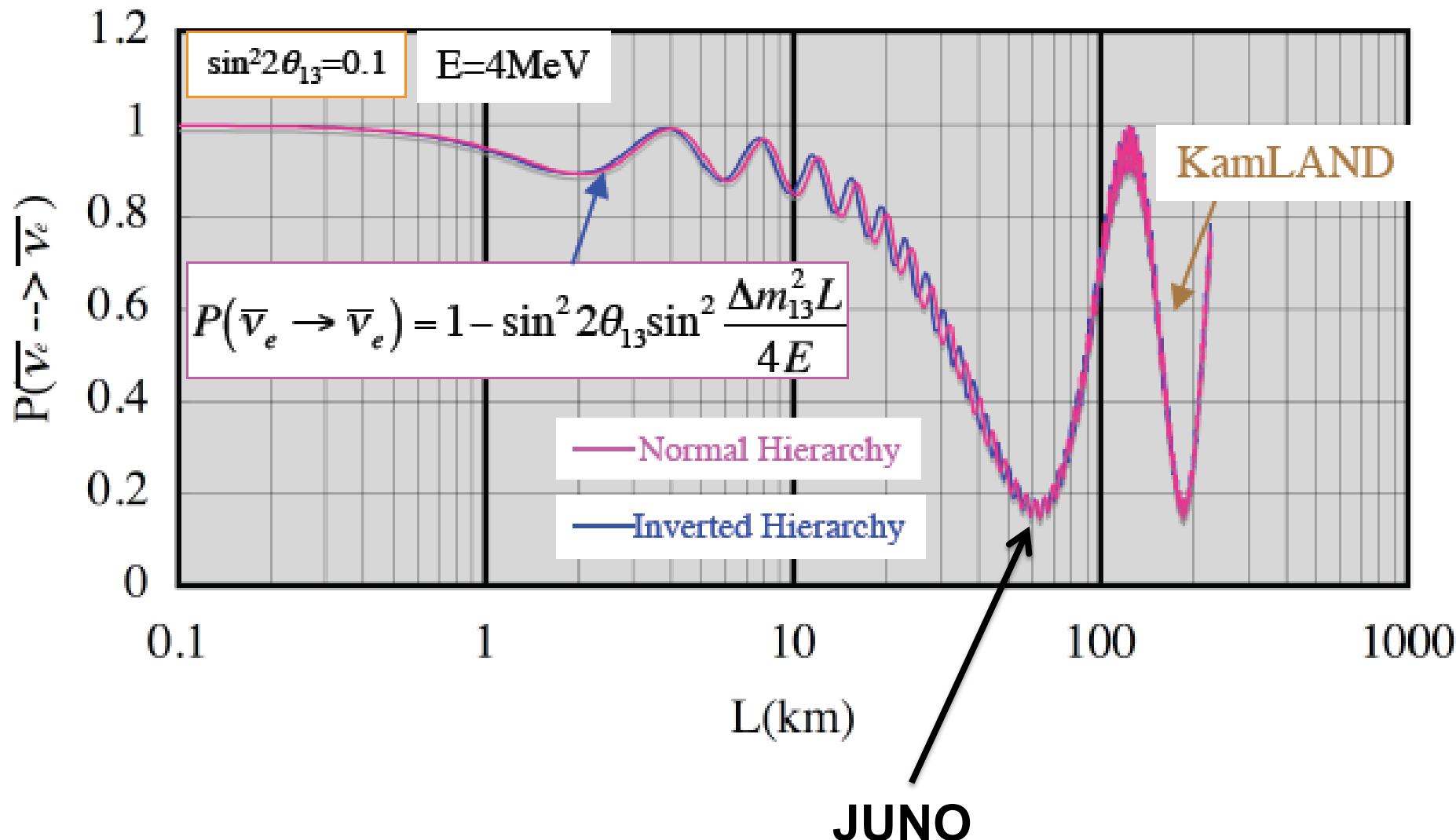
# Future Sensitivity

Lower Octant

Upper Octant



# Starting with $\nu_e$



# $\nu_\mu \rightarrow \nu_e$ appearance probability

[PDG, 2014]

$$P_m^{3\nu \text{ man}}(\nu_\mu \rightarrow \nu_e) \cong P_0 + P_{\sin \delta} + P_{\cos \delta} + P_3.$$

Here

$$P_0 = \sin^2 \theta_{23} \frac{\sin^2 2\theta_{13}}{(A-1)^2} \sin^2[(A-1)\Delta]$$

$$P_3 = \alpha^2 \cos^2 \theta_{23} \frac{\sin^2 2\theta_{12}}{A^2} \sin^2(A\Delta),$$

$$P_{\sin \delta} = -\alpha \frac{8 J_{CP}}{A(1-A)} (\sin \Delta) (\sin A\Delta) (\sin[(1-A)\Delta]),$$

$$P_{\cos \delta} = \alpha \frac{8 J_{CP} \cot \delta}{A(1-A)} (\cos \Delta) (\sin A\Delta) (\sin[(1-A)\Delta]),$$

where

$$\alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}, \quad \Delta = \frac{\Delta m_{31}^2 L}{4E}, \quad A = \sqrt{2} G_F N_e^{\text{man}} \frac{2E}{\Delta m_{31}^2},$$

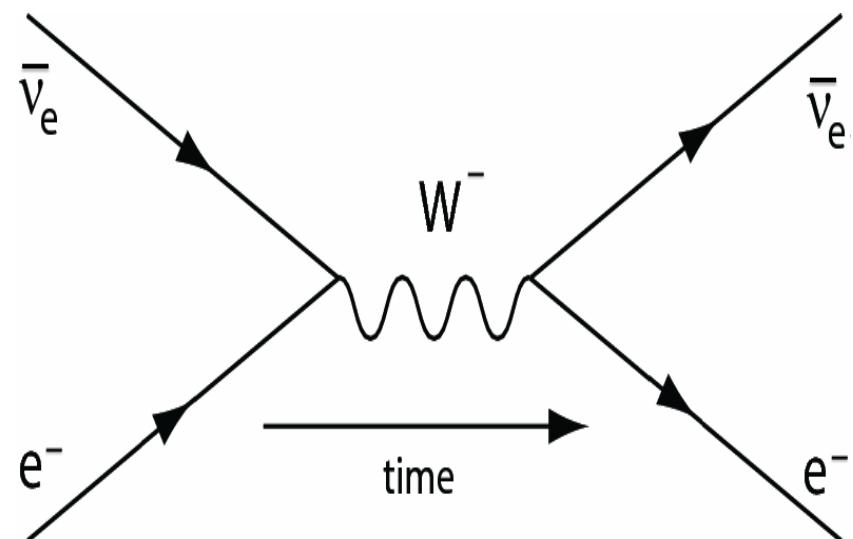
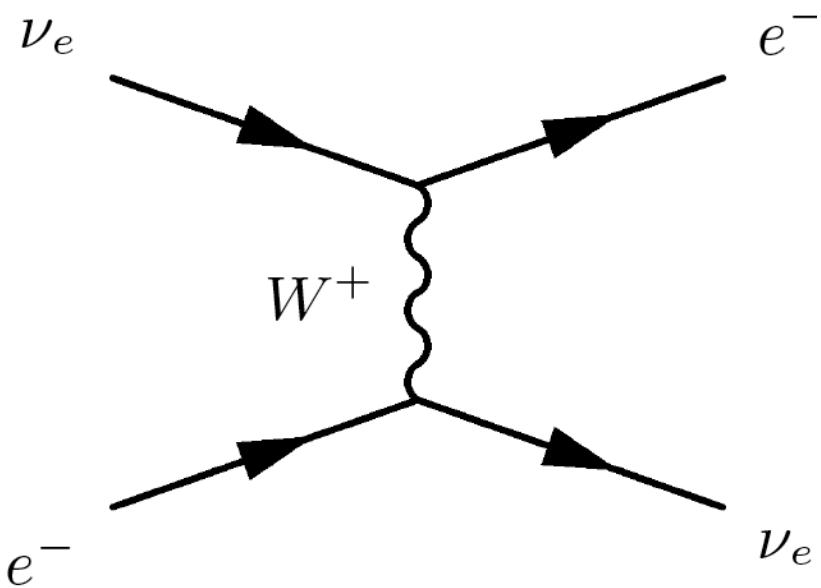
and  $\cot \delta = J_{CP}^{-1} \text{Re}(U_{\mu 3} U_{e3}^* U_{e2} U_{\mu 2}^*)$ ,  $J_{CP} = \text{Im}(U_{\mu 3} U_{e3}^* U_{e2} U_{\mu 2}^*)$ .

# Matter Effect & Mass Hierarchy

- Coherent forward elastic scattering
- Neutrinos (and antineutrinos) travel through matter not antimatter
  - electron density causes the asymmetry
    - via specifically **CC** coherent forward elastic scattering
  - different Feynman diagrams for  $\nu_e$  and  $\bar{\nu}_e$  interactions with electrons...

# Different Feynman Diagrams

- Amplitude for **electron neutrino** interaction with an **electron**
- is not equal to...
- Amplitude for **electron antineutrino** interaction with an **electron**

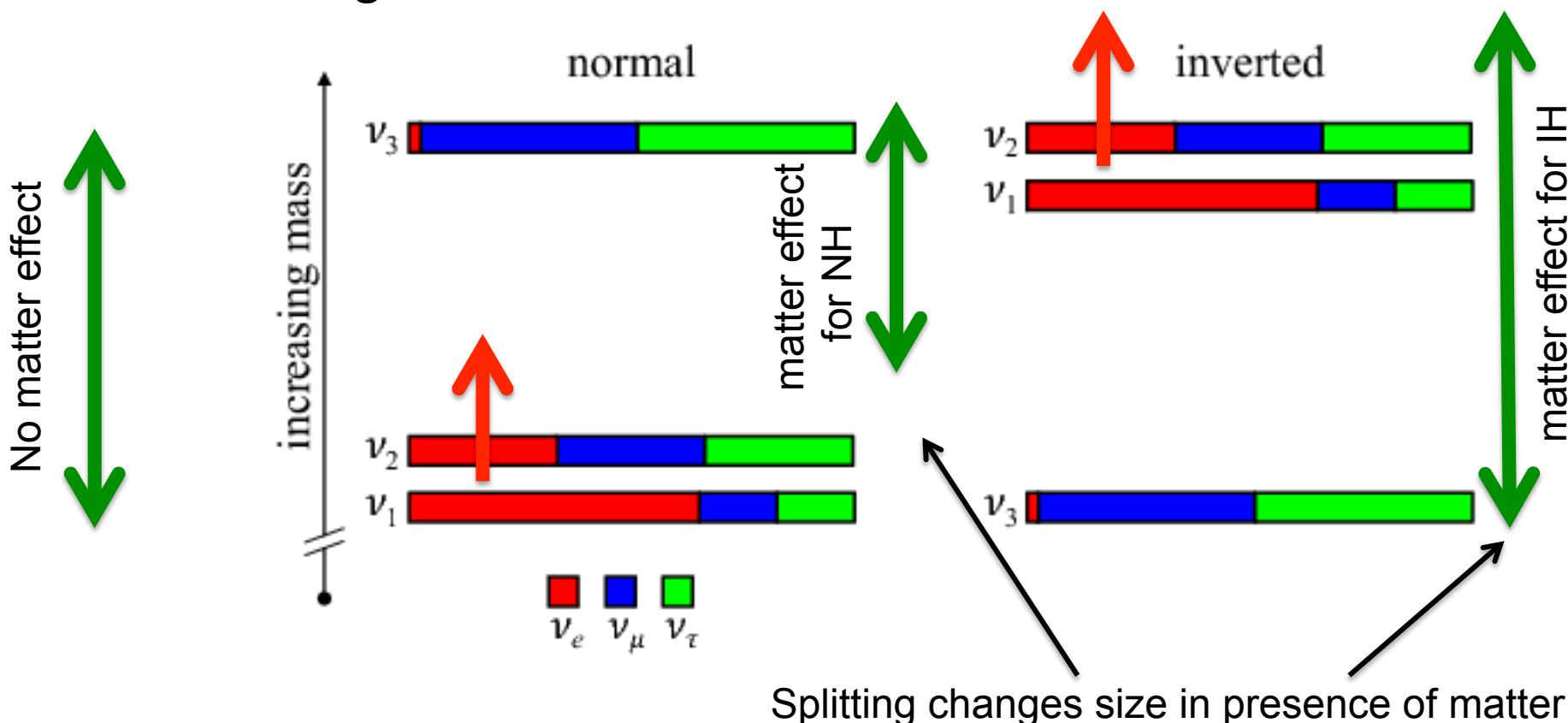


Electron **neutrinos** and  
antineutrinos are affected  
differently by interactions with  
matter → **fake CP violation**

Why does the **mass hierarchy**  
affect oscillations involving  
electron (anti)neutrinos?

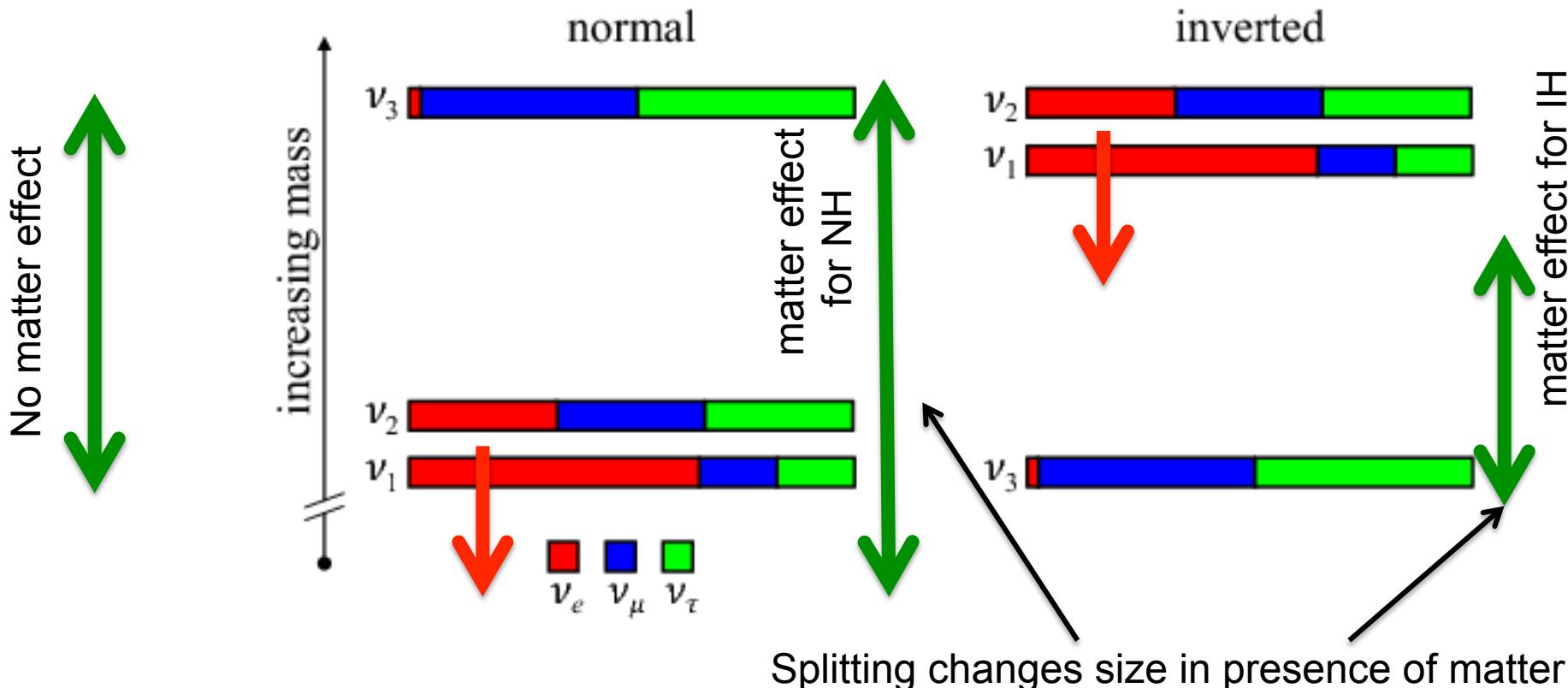
# Matter effect (neutrino case)

- Matter effect raises (or lowers) the energy state of the **mass eigenstates**
  - strength depends on electron neutrino content of each mass eigenstate



# Antineutrino case

- Matter effect raises (or lowers) the energy state of the **mass eigenstates**
  - strength depends on electron neutrino content of each mass eigenstate



# Splittings **and** mixing angles affected

- Mixing angles in matter ( $\theta_M$ ) are modified by the mass squared splitting in matter ( $\Delta m^2_M$ )
  - e.g. simple 2-flavour case:

$$\sin 2\vartheta_M = \frac{\Delta m^2 \sin 2\vartheta}{\Delta m_M^2}$$

- Also see it in full 3-flavour equations (a few slides back)

# We consider multiple possible sources of systematic error

Systematic	Effect on $\sin^2(\theta_{23})$	Effect on $\Delta m^2_{32}$
Normalisation	$\pm 1.0\%$	$\pm 0.2\%$
Muon E scale	$\pm 2.2\%$	$\pm 0.8\%$
Calibration	$\pm 2.0\%$	$\pm 0.2\%$
Relative E scale	$\pm 2.0\%$	$\pm 0.9\%$
Cross sections + FSI	$\pm 0.6\%$	$\pm 0.5\%$
Osc. parameters	$\pm 0.7\%$	$\pm 1.5\%$
Beam backgrounds	$\pm 0.9\%$	$\pm 0.5\%$
Scintillation model	$\pm 0.7\%$	$\pm 0.1\%$
<b>All systematics</b>	<b><math>\pm 3.4\%</math></b>	<b><math>\pm 2.4\%</math></b>
<b>Stat. Uncertainty</b>	<b><math>\pm 4.1\%</math></b>	<b><math>\pm 3.5\%</math></b>

In each case:

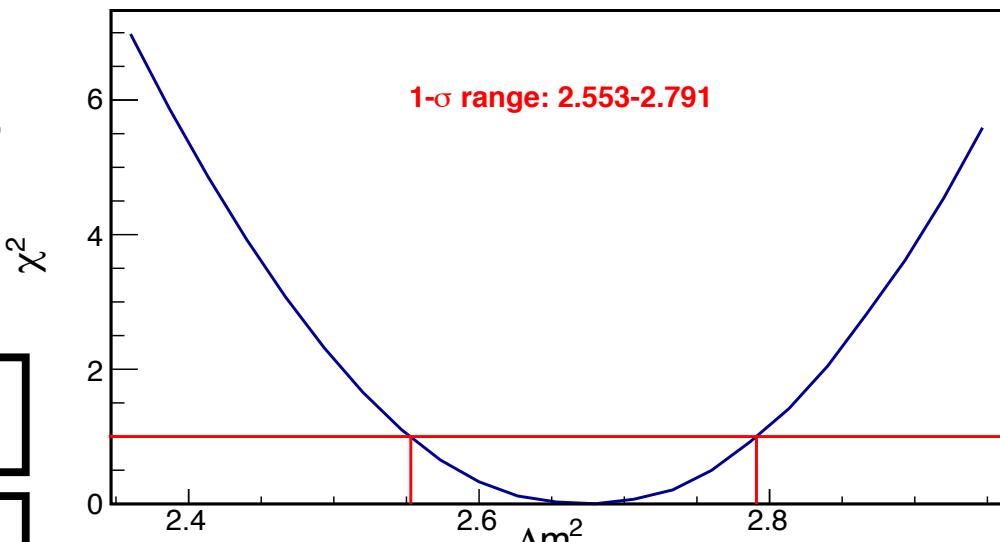
- The effect is propagated through the extrapolation
- We include those effects as pull terms in the fit
- The increase (in quadrature) of the parameter measurement error is recorded

# 1-D Profiles

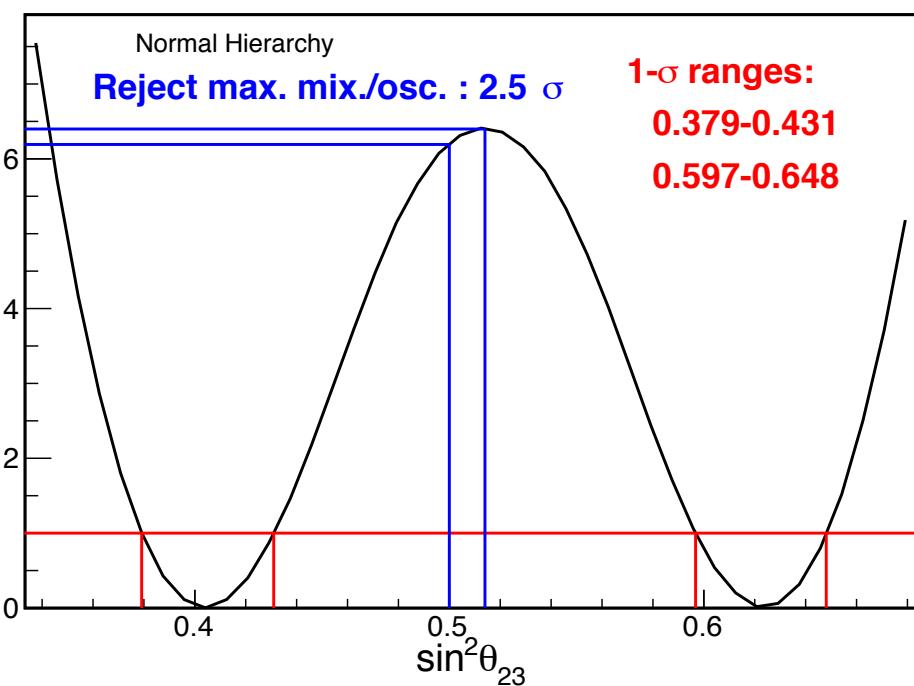
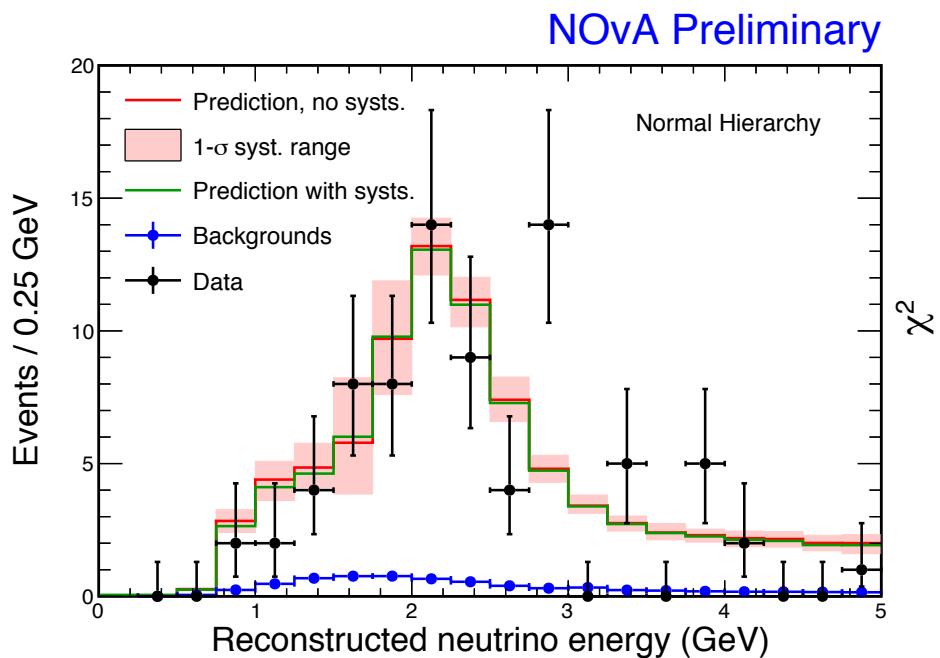
Recall our best fit:

$$\Delta m_{32}^2 = (2.67 \pm 0.12) \times 10^{-3} \text{ eV}^2 \text{ (NH)}$$

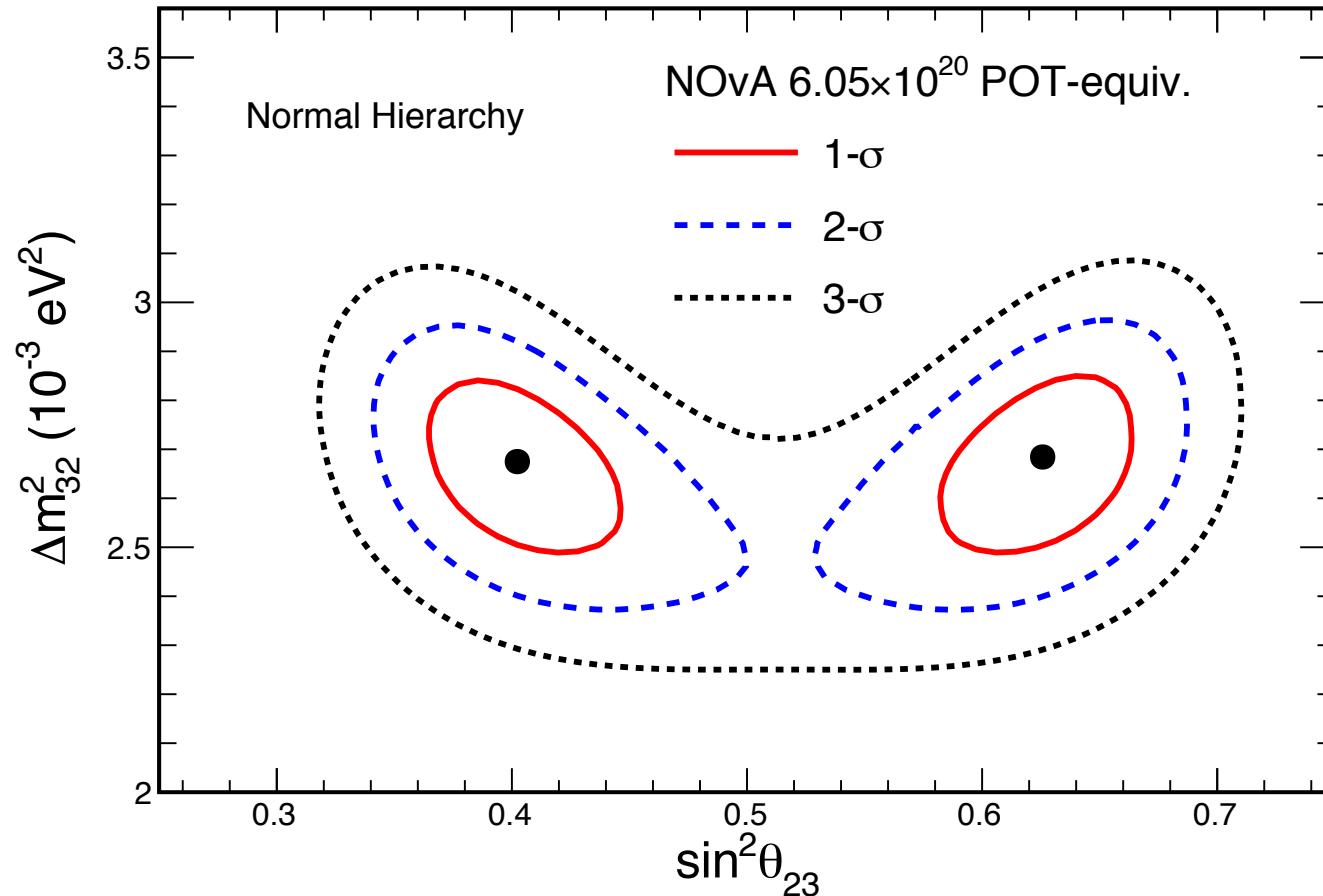
$$\sin^2 \theta_{23} = 0.40^{+0.03}_{-0.02} \quad (0.63^{+0.02}_{-0.03})$$



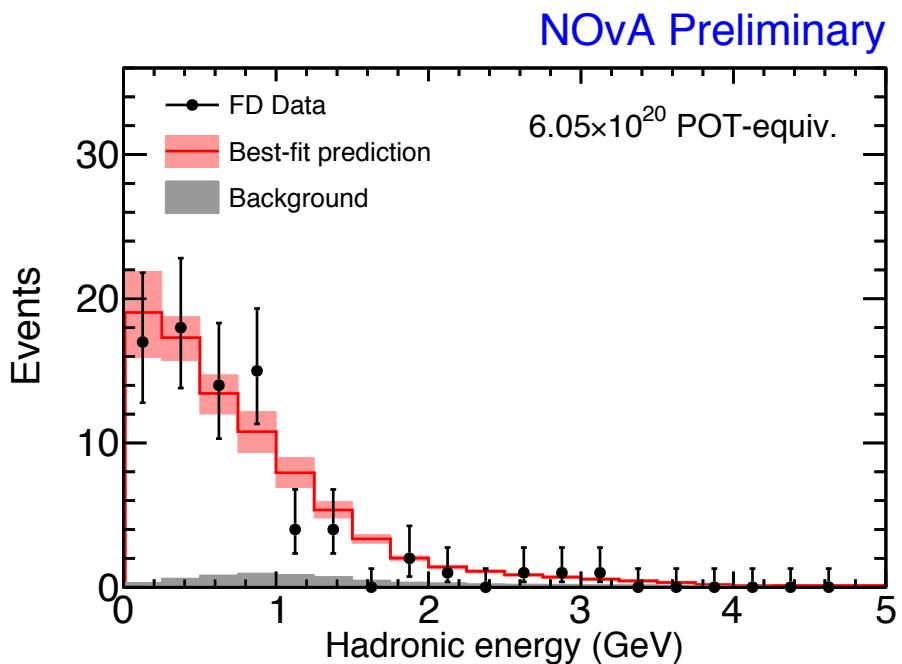
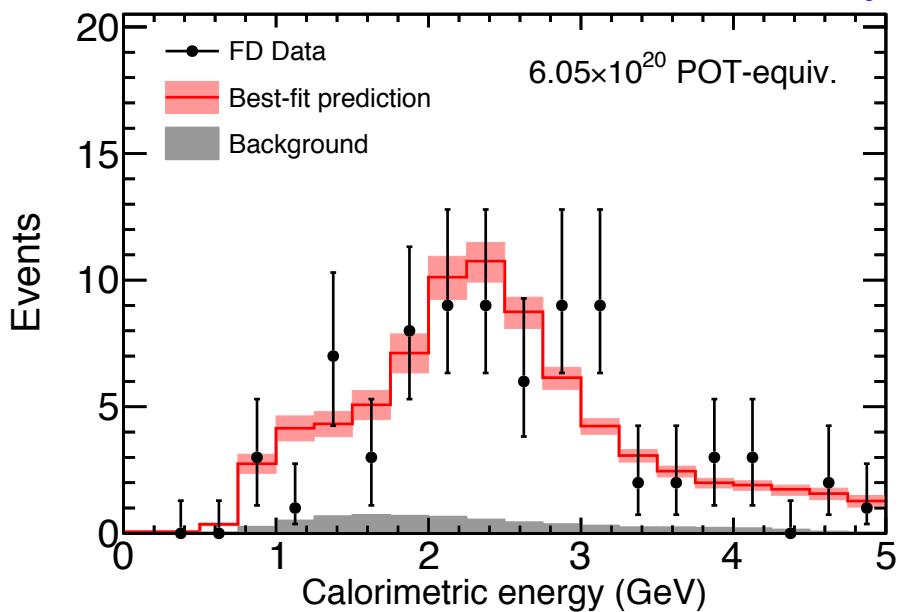
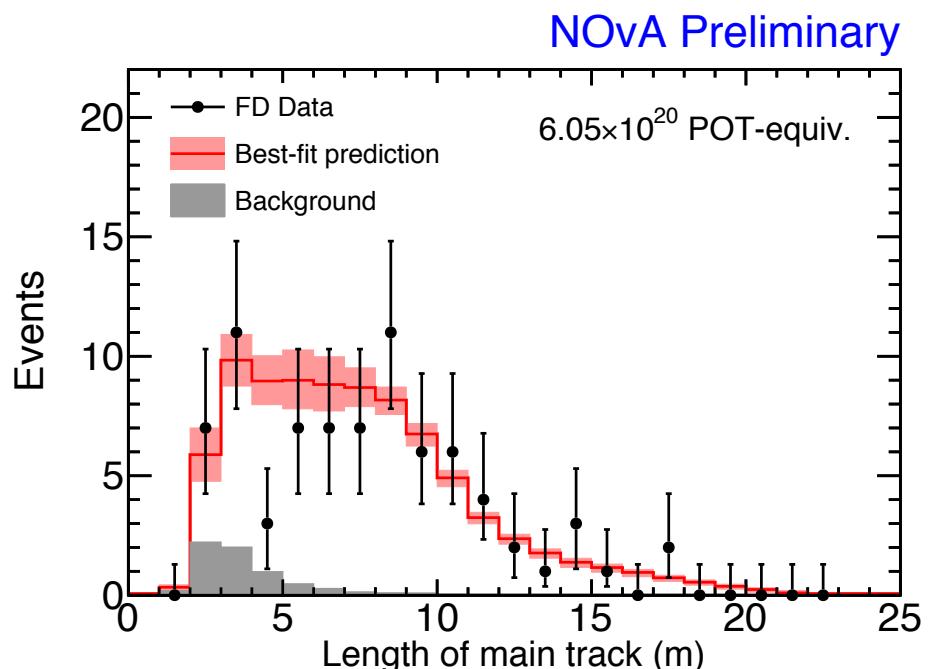
NOvA Preliminary

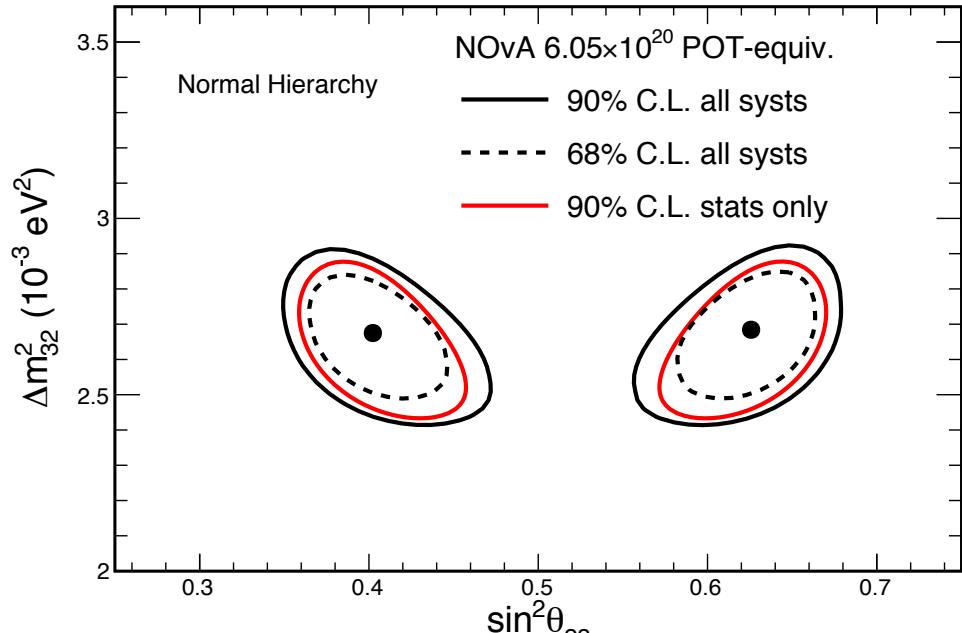


## NOvA Preliminary

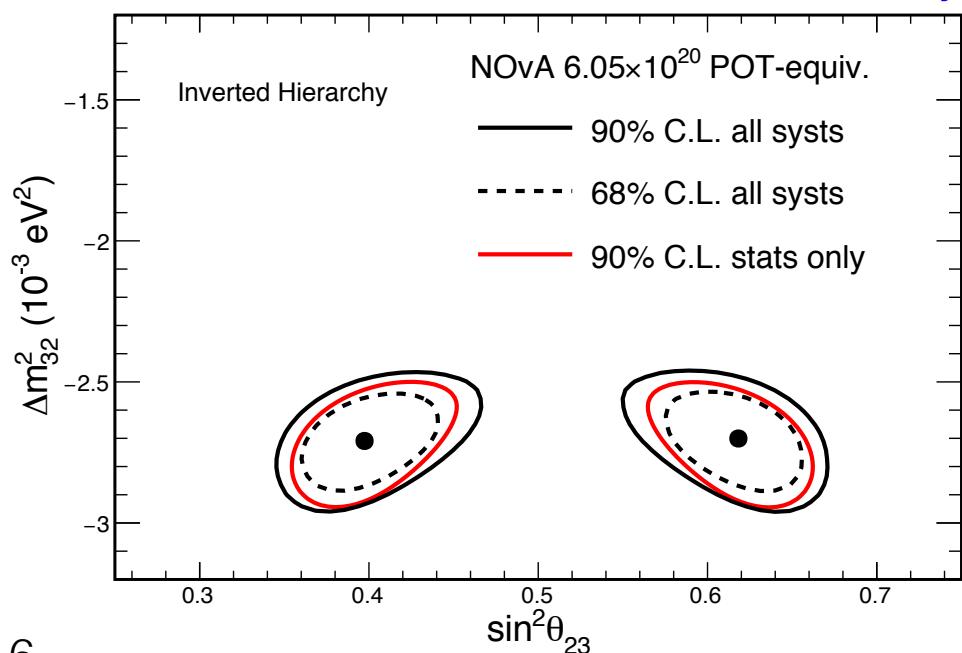


Our best fit oscillation prediction matches other distributions well

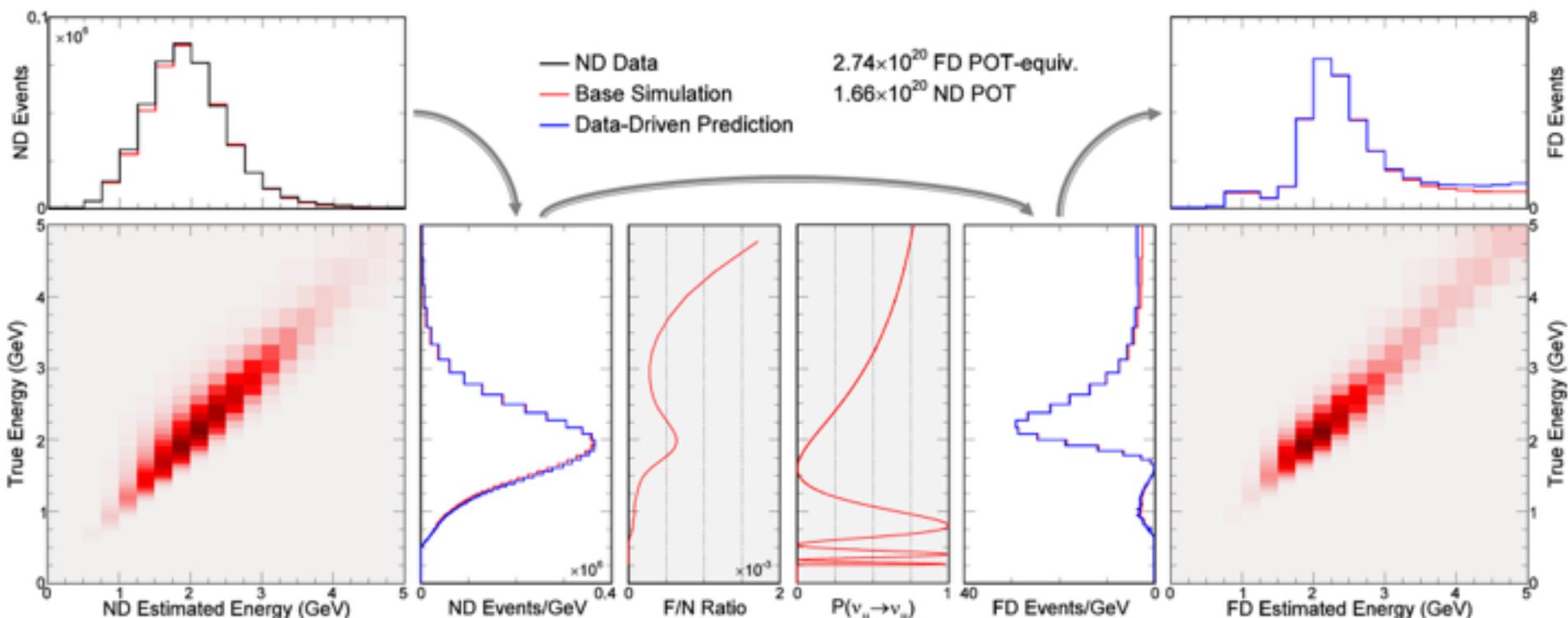




NOvA Preliminary



- (1) Estimate the underlying **true energy distribution** of selected ND events
  - (2) Multiply by expected **Far/Near event ratio** and  $\nu_\mu \rightarrow \nu_\mu$  oscillation probability as a function of true energy
  - (3) Convert FD true energy distribution into **predicted FD reco energy distribution**
- Systematic uncertainties** assessed by varying all MC-based steps

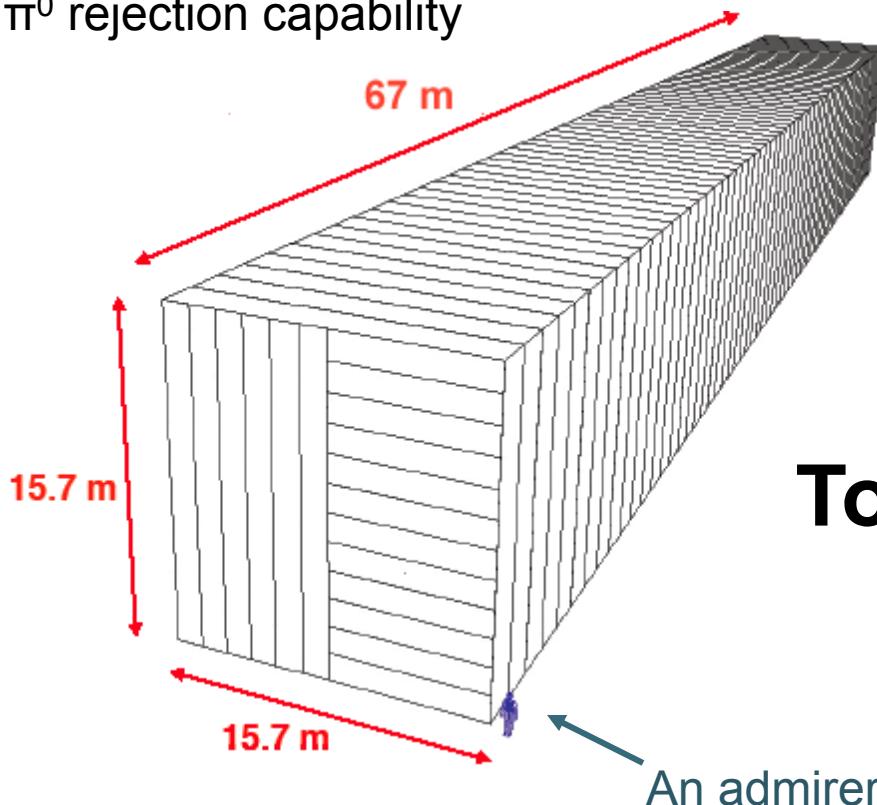


# NOvA Far Detector

## TASD: Totally Active Scintillator Design

Longitudinal sampling is  $\sim 0.15 X_0$ , which gives:

- excellent  $\mu$ -e separation
- $\pi^0$  rejection capability



**Total mass of 14 ktons**

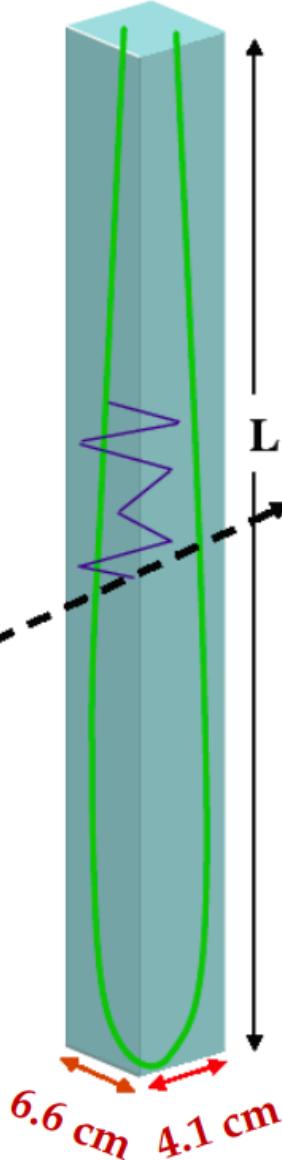
# Extrusions



- PVC extruded through die to form 15.7m extrusions
- ~24,000 required for Far Detector.

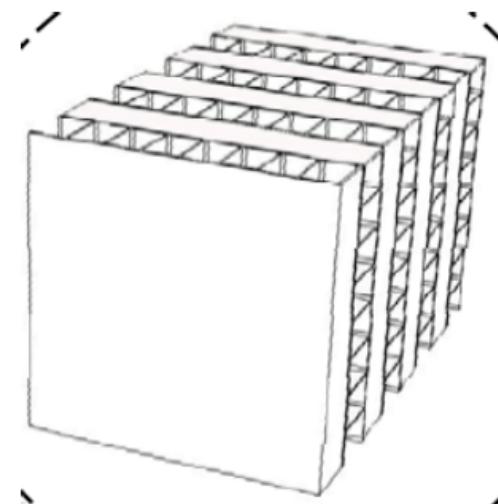
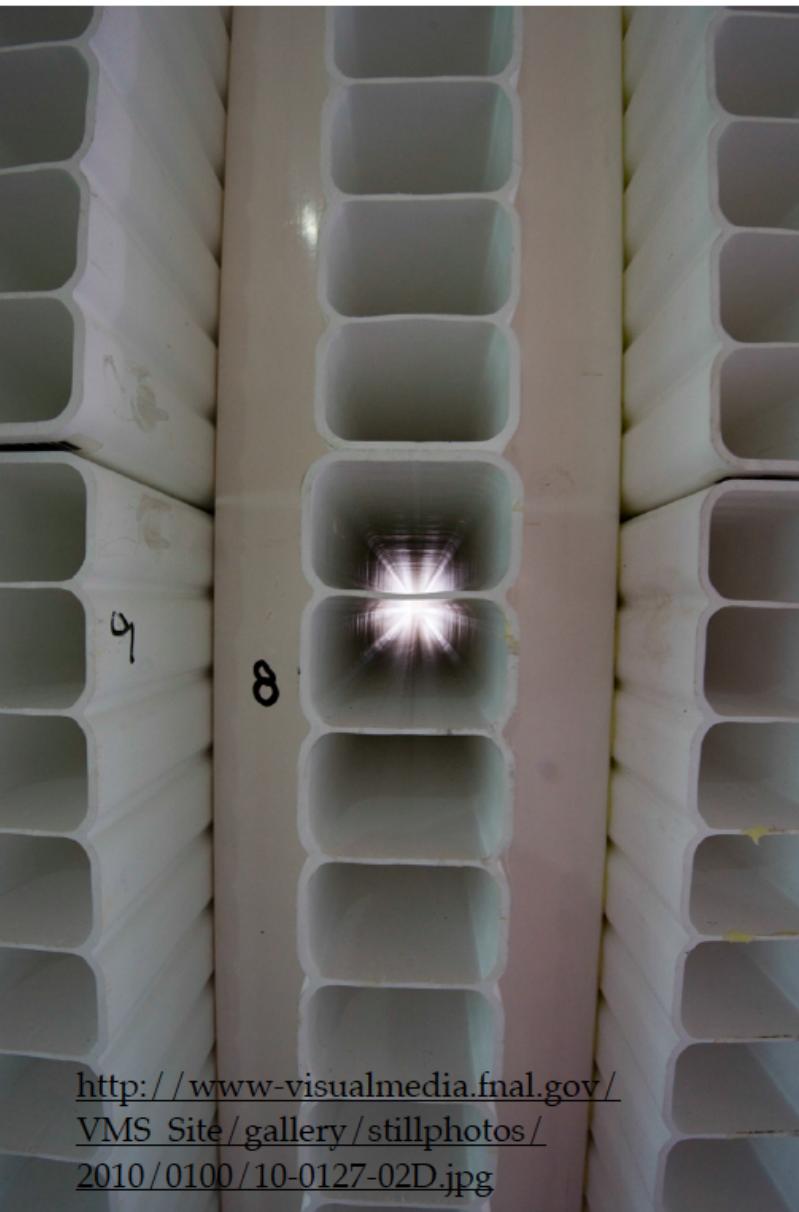
To 1 APD pixel

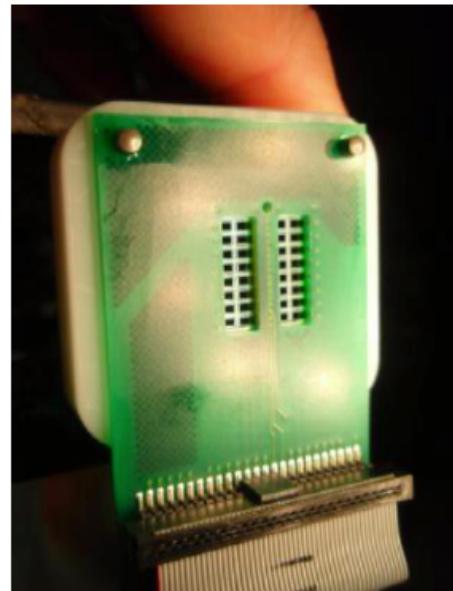
typical charged particle path



# Detector Elements

- Cells with liquid scintillator grouped into alternating planes



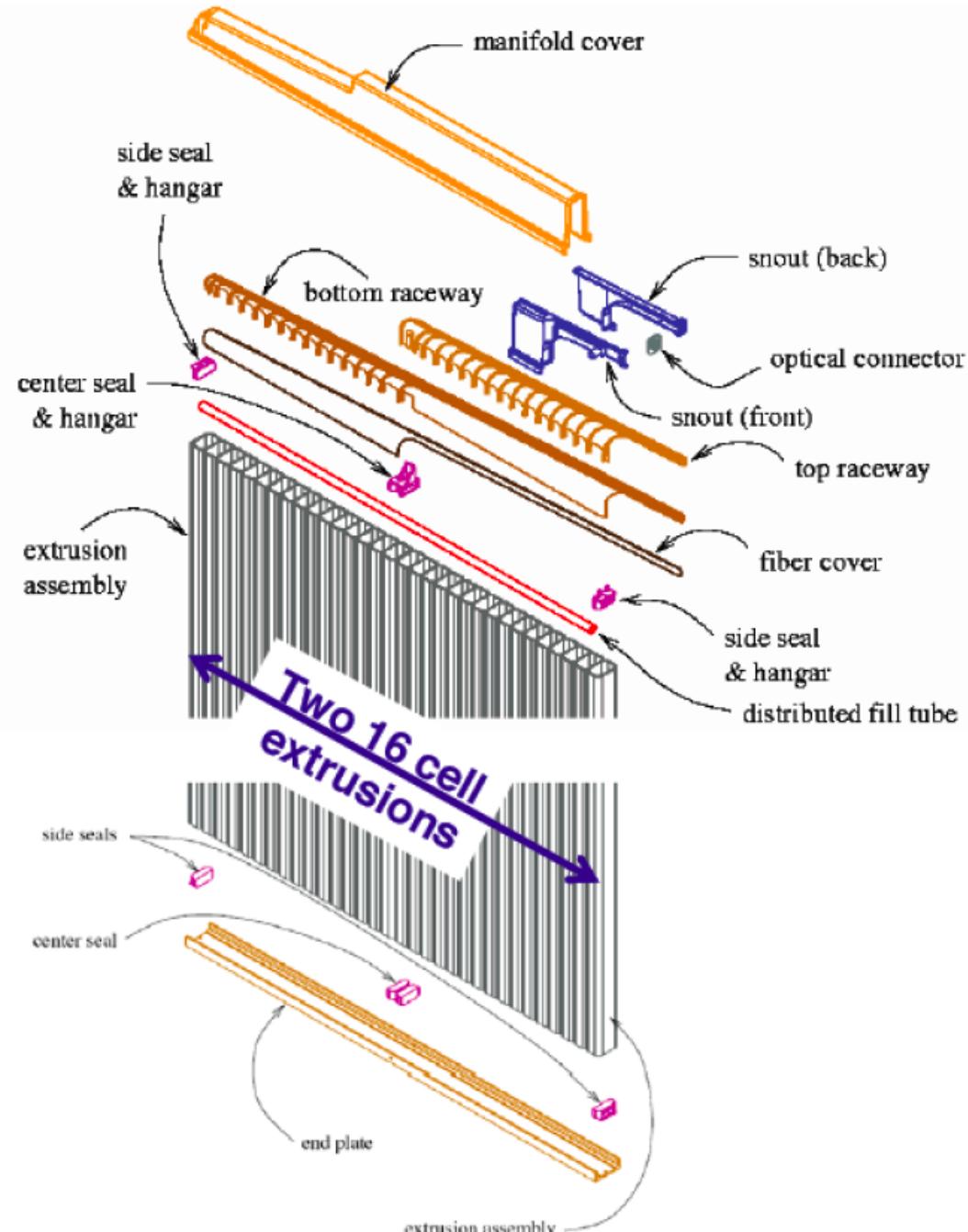


Scintillation light travels along wavelength shifting fibers to end of manifold

Light detected in by avalanche photodiodes (APDs) that are sealed, cooled (to -15 °C) and mated to the detector data acquisition system.

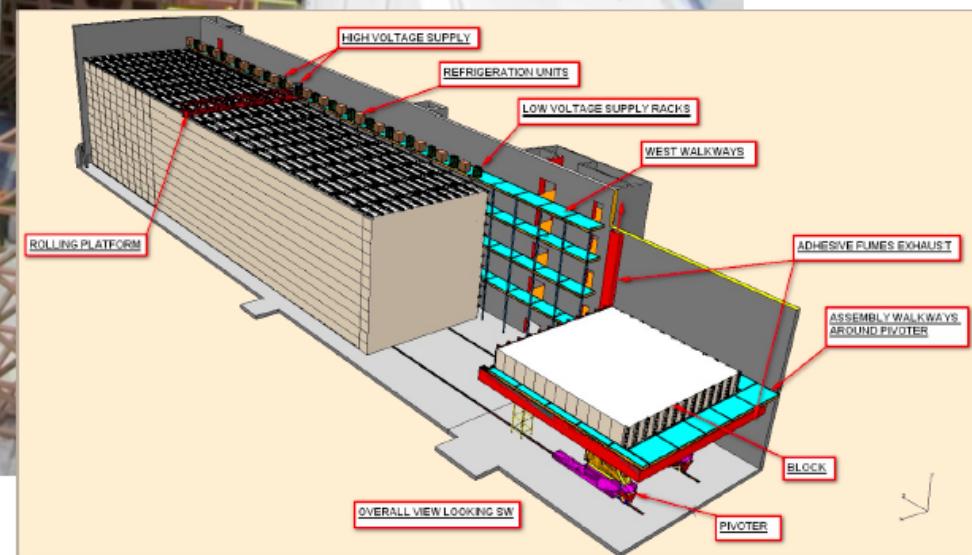
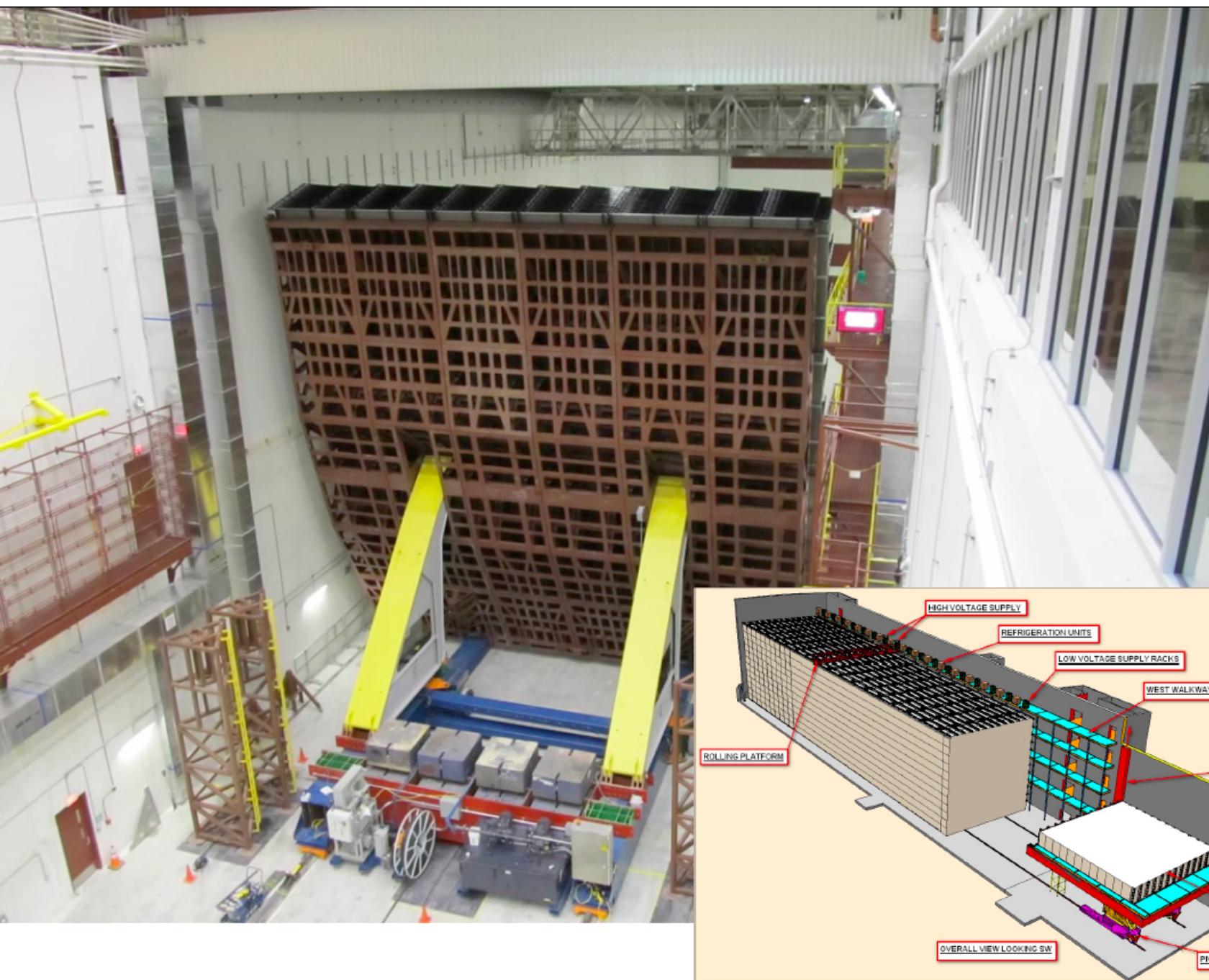
# Modules

- Many pieces must be brought together to form an active detector module
- Many undergrads working at module factory at the U of MN
- Cell interiors must be very reflective so scintillation light is not lost.



# Assembly







## Block Zero Installed

September 10, 2012



Very cool time lapse video: <http://www.youtube.com/watch?v=gFpK00WJI90&sns=tw>