University of Sussex

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NOvA Oscillation Results

European Research Council
Established by the European Commission

Jeff Hartnell
University of Sussex

NOvA

Imperial College Seminar

5th October 2016

Introduction

- Why study neutrinos?
- Neutrino oscillations

- NOvA experiment and physics goals
  - NuMI beam
  - NOvA detectors

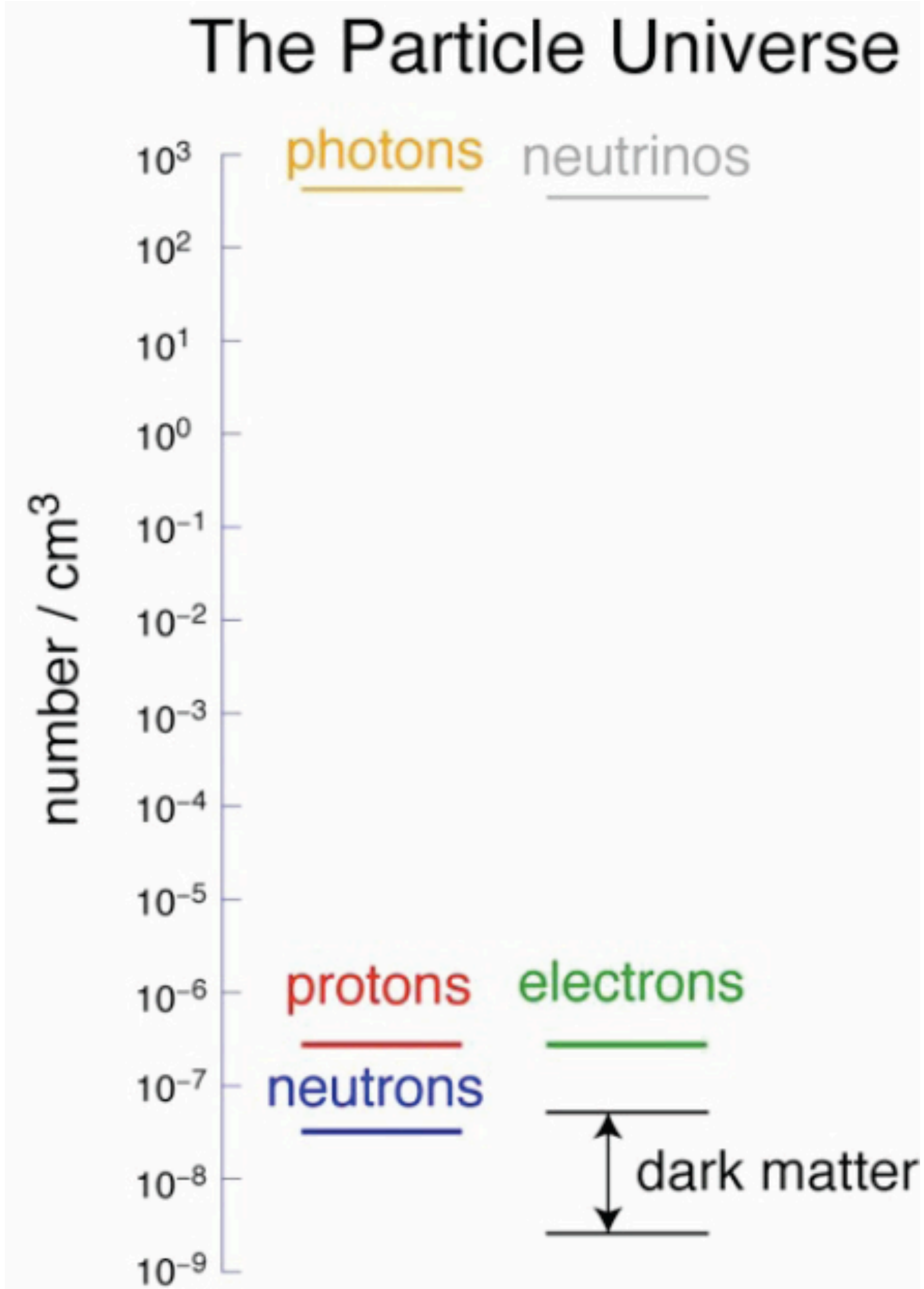
- Muon neutrino disappearance
- NC analysis
- Electron neutrino appearance

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 θ_{13}


The Particle Universe
number / cm³
10³
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
photons
neutrinos
protons
electrons
neutrons
dark matter

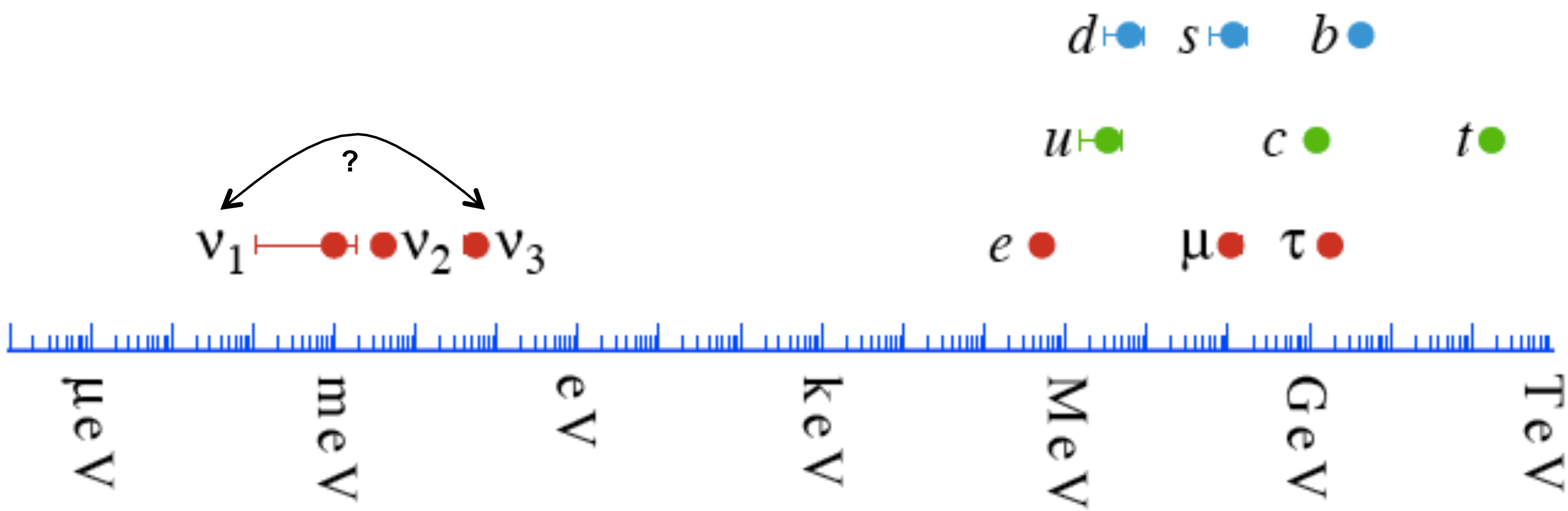
Two Major Questions

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

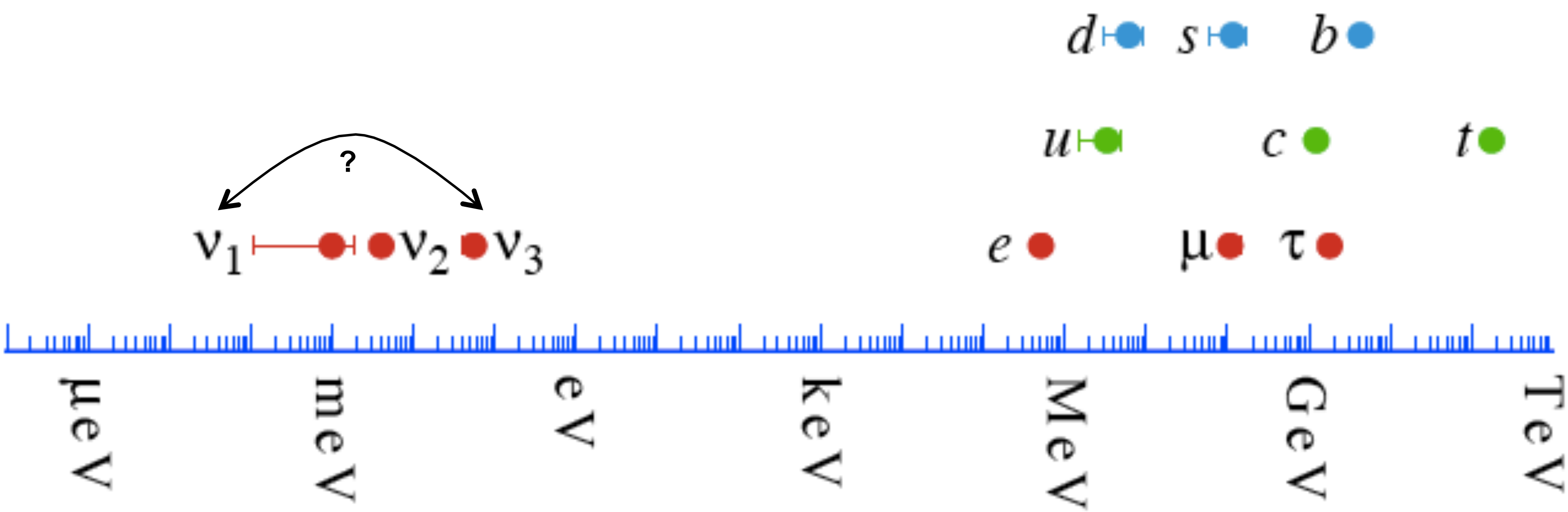
- Neutrinos ⟷ leptogenesis

- Neutrino oscillations can test CP
  - NOvA has some sensitivity, DUNE/Hyper-K much more

Is there a pattern to the masses?

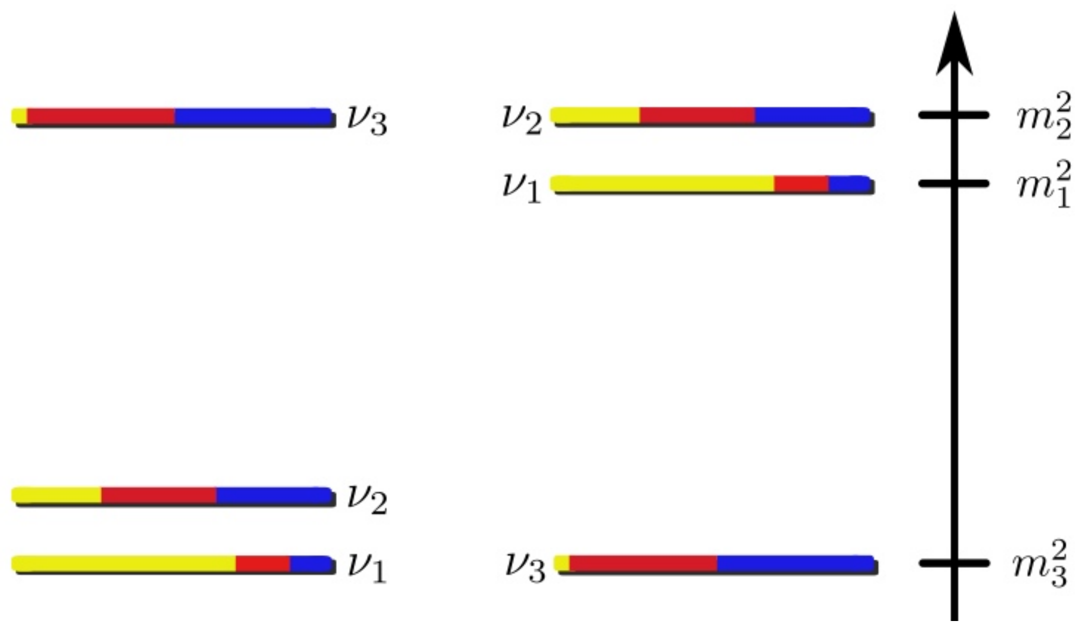


Is there a pattern to the masses?



Two heavy and one light?

NOvA has sensitivity to the mass hierarchy

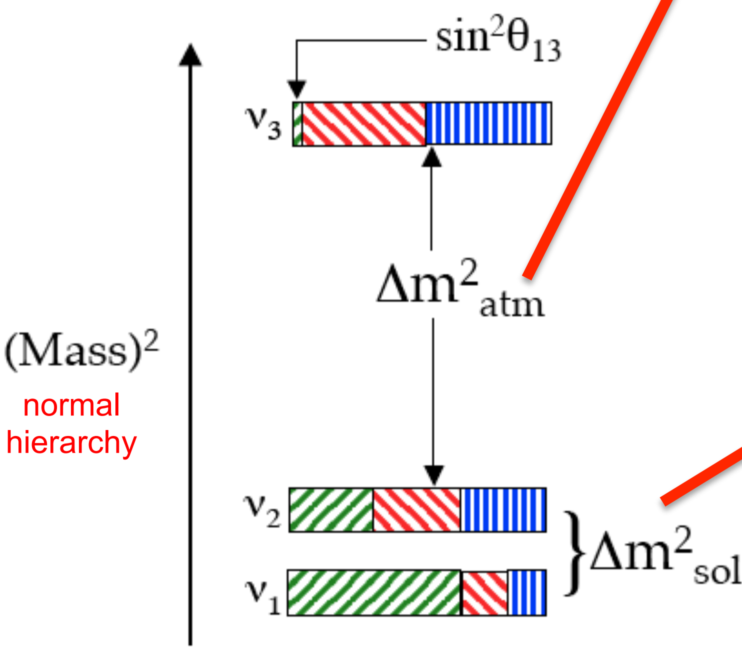


Theory Overview

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

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

Subdominant term



$\Delta m^2_{31} = m_3^2 - m_1^2$, L/E≅500 km/GeV

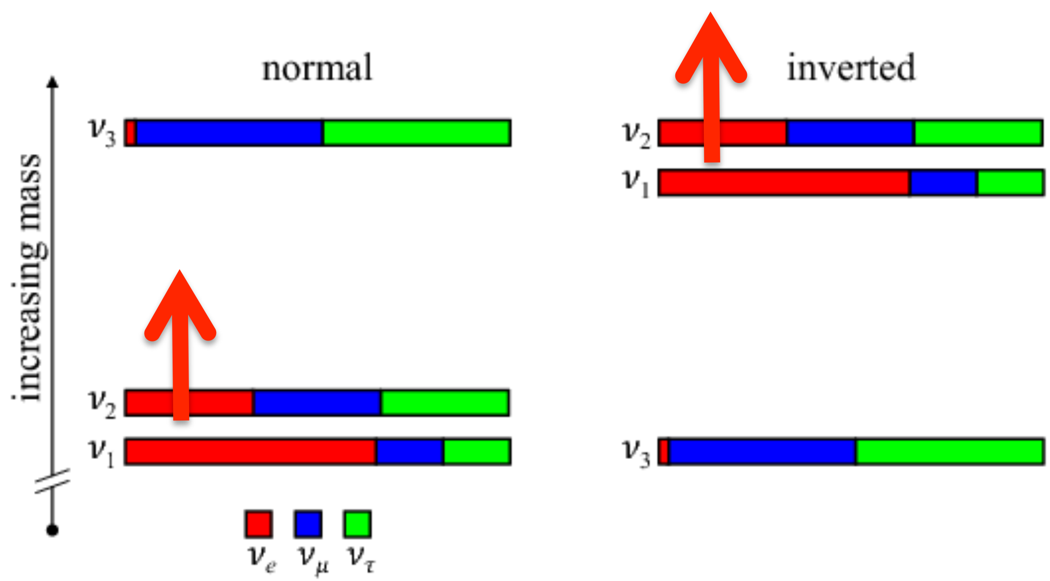
$\Delta m^2_{32} = m_3^2 - m_2^2$, L/E≅500 km/GeV

(≅0.5 km/MeV)

$\Delta m^2_{21} = m_2^2 - m_1^2$, L/E≅15000 km/GeV

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 ν_e and $\bar{\nu}_e$ interactions with electrons so different amplitudes



Arrows flip for antineutrinos

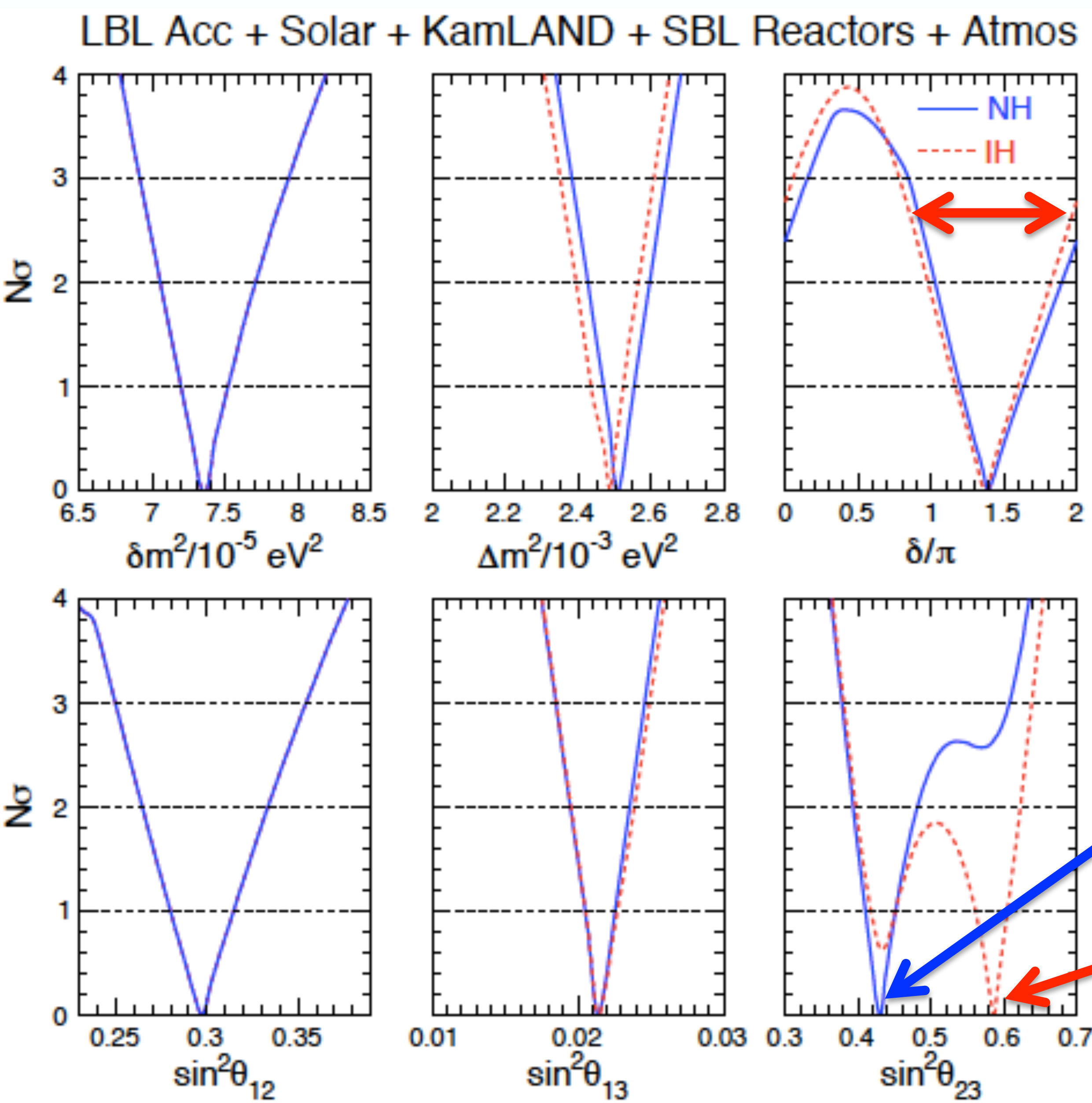
It's hard to overstate…

- The past few years have seen a major breakthrough in neutrino physics
  - Our measurement of θ_{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 θ_{23}

Reactor Experiments Provided the Breakthrough on θ_{13}

- Daya Bay, RENO and Double Chooz

What we know and don't know



Three "Unknowns"

Wide range of δ_{CP} values possible (1)

Slight preference for **NH** (ΔX^2=3.2, suppressed in plot) (2)

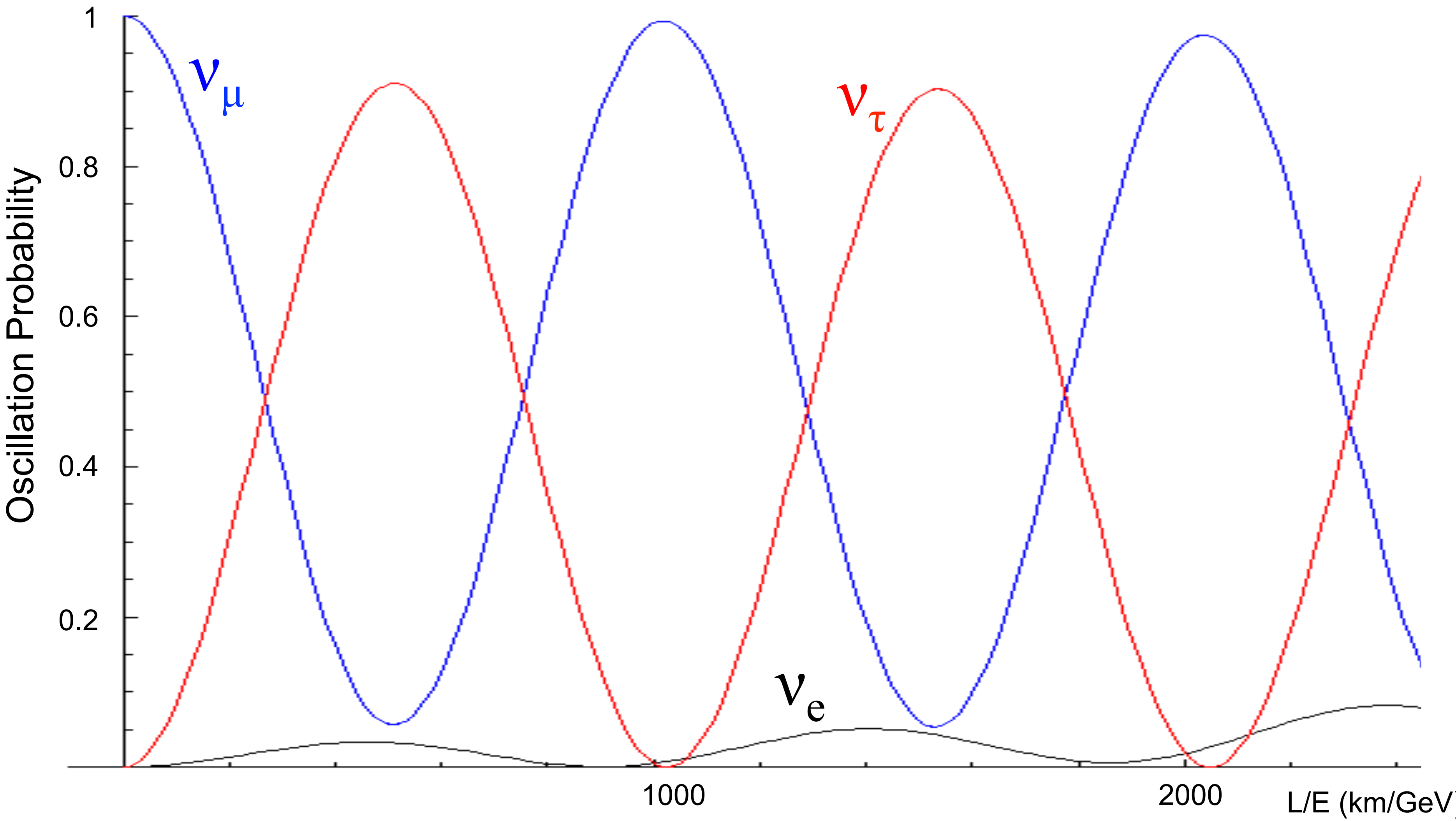
Preference for non-maximal θ_{23} mixing

Lower Octant, NH preferred.

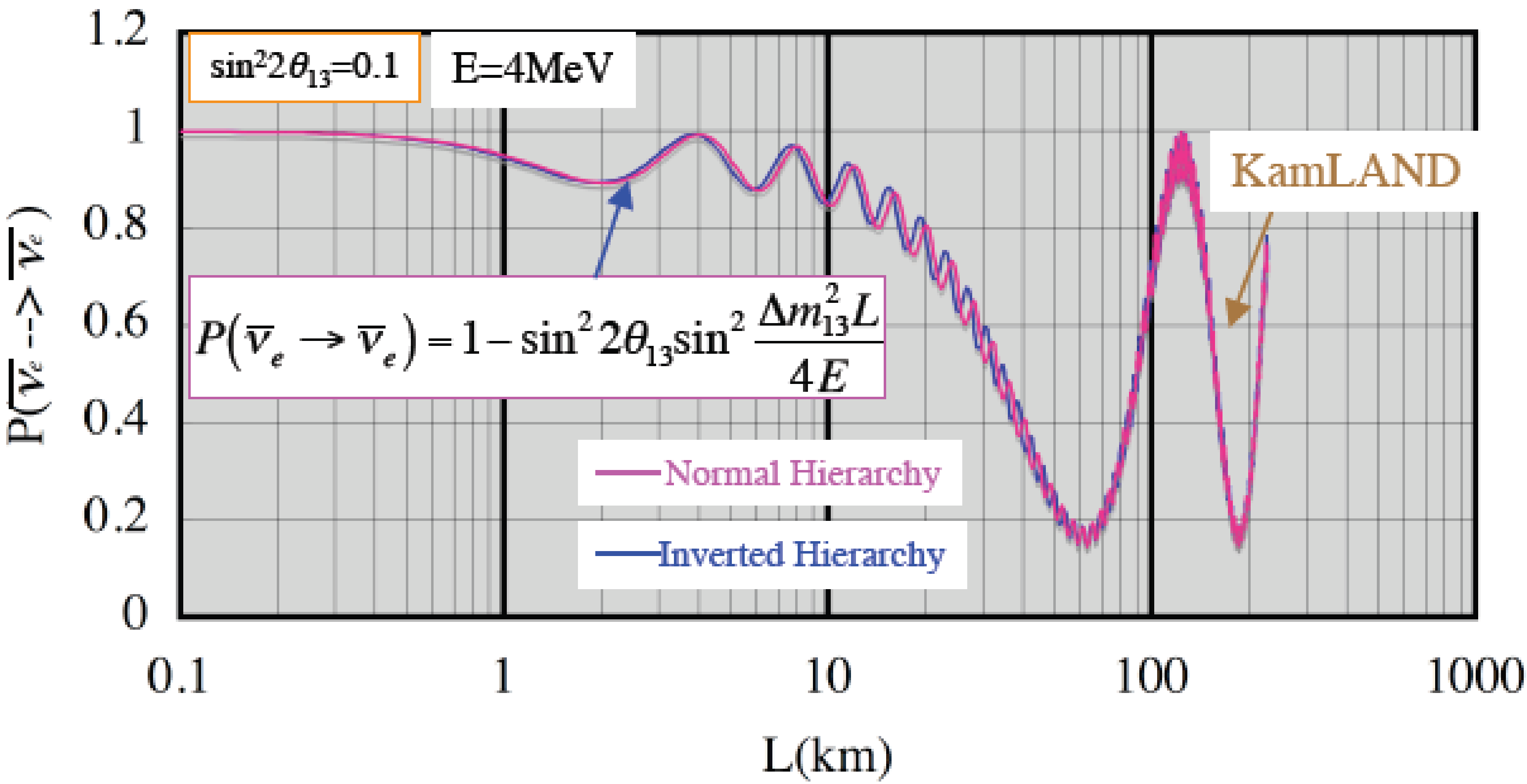
Upper Octant, IH a viable solution (3)

[Ferruccio Feruglio, NOW]

Starting with ν_μ



Starting with ν_e



Long-baseline neutrino oscillations

ν_μ disappearance:

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

...to leading order

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

➡ **Need a leap in precision on θ_{23} (and Δm^2_{32})**

ν_e appearance:

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \underbrace{\sin^2 2\theta_{13}} \sin^2(\Delta m^2_{32} L/4E)$$

Daya Bay reactor experiment:
$\sin^2(2\theta_{13}) = 0.084 \pm 0.005$

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

Long-baseline $\nu_\mu \to \nu_e$

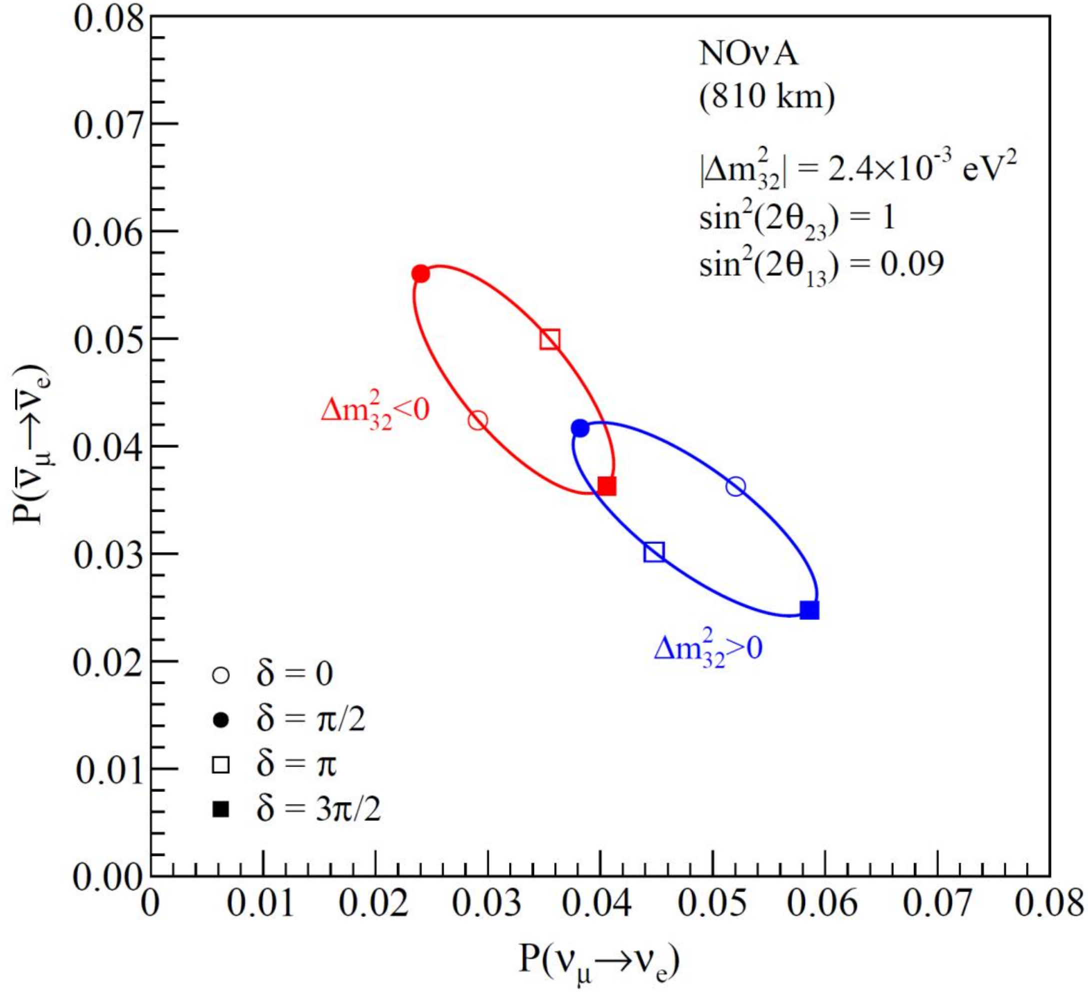
A more quantitative sketch…

At right:

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

plotted for a single neutrino energy and baseline

For fixed L/E = 0.4 km/MeV



Long-baseline $\nu_\mu \to \nu_e$

A more quantitative sketch…

At right:

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

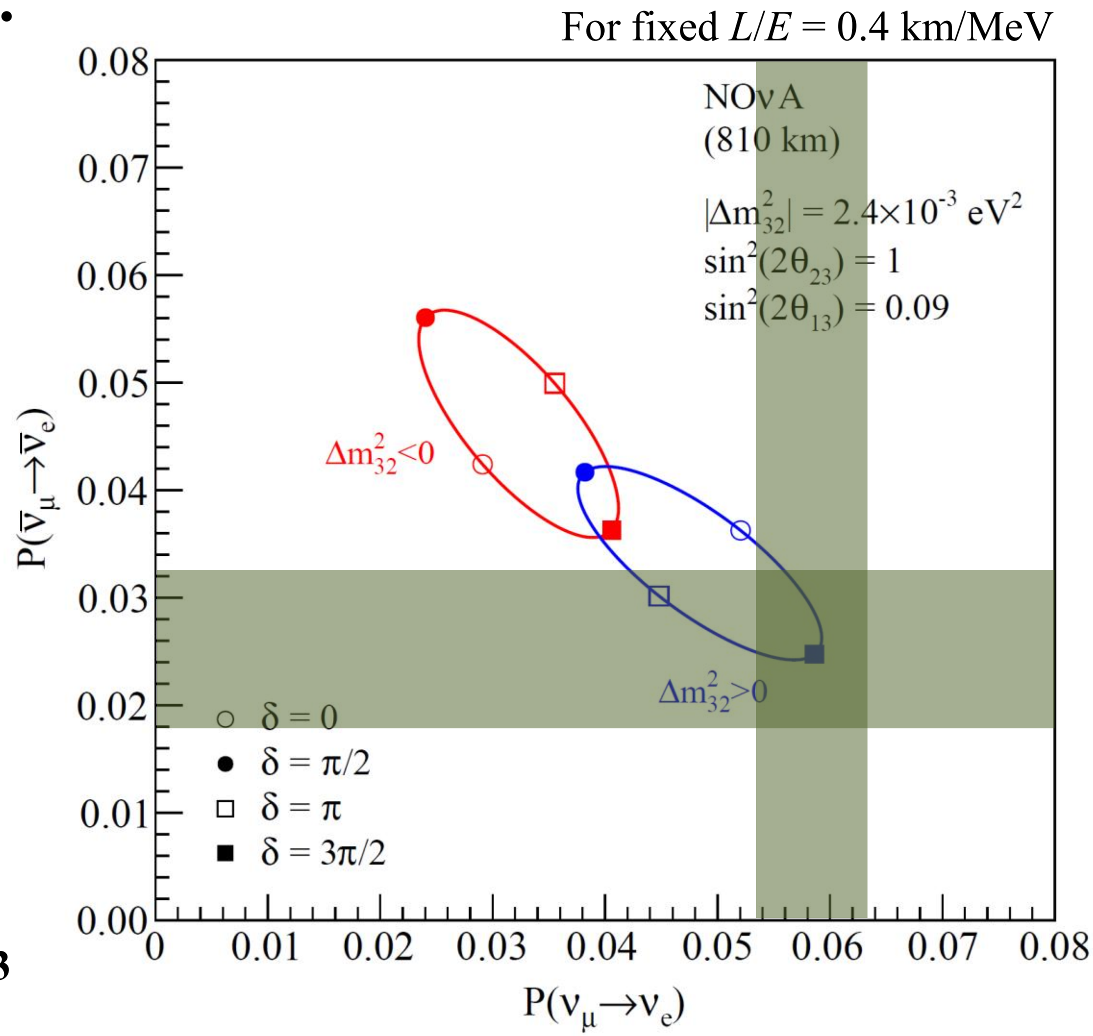
plotted for a single neutrino energy and baseline

Measure these probabilities

(an example measurement of each shown)

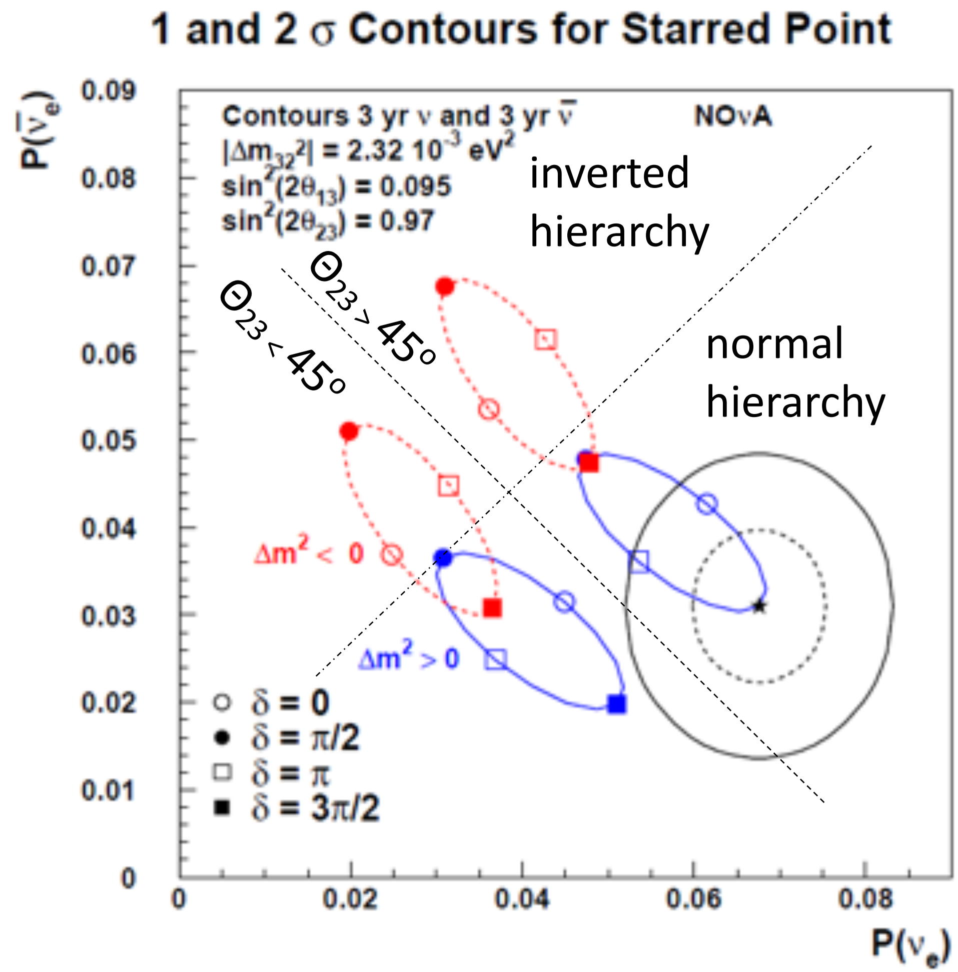
Also:

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



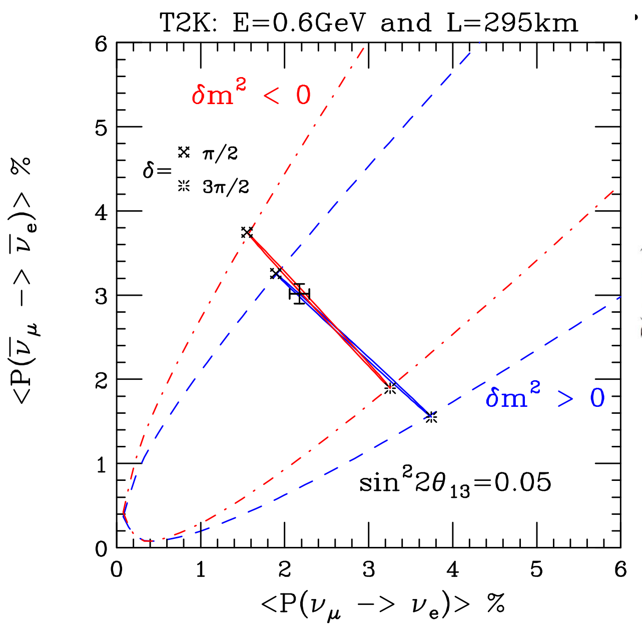
Non-maximal mixing scenario

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



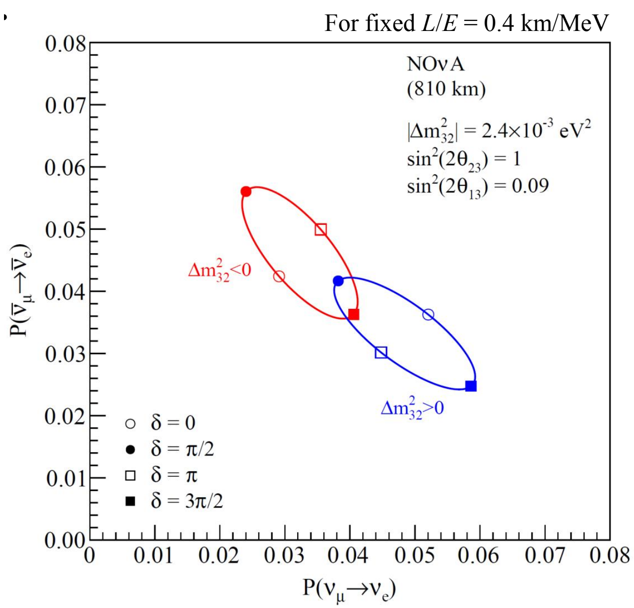
Effect of Increasing Energy

T2K



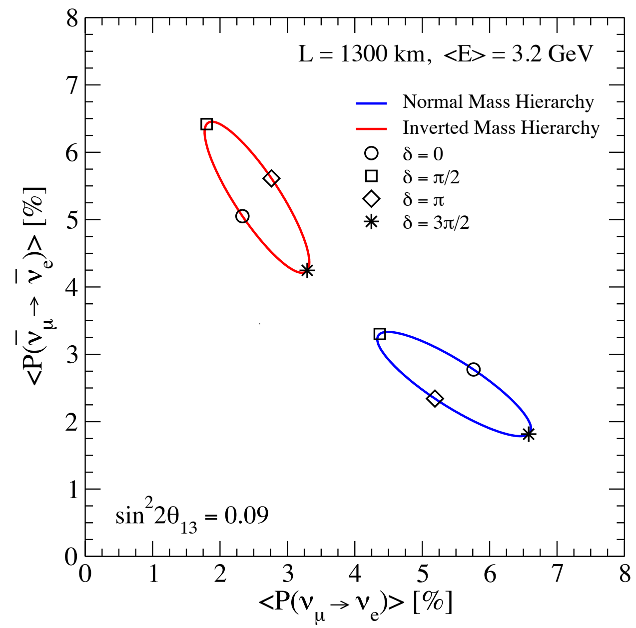
0.6 GeV

NOvA



2 GeV

DUNE



3 GeV

Increasing Energy

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

T2K ν_e Appearance

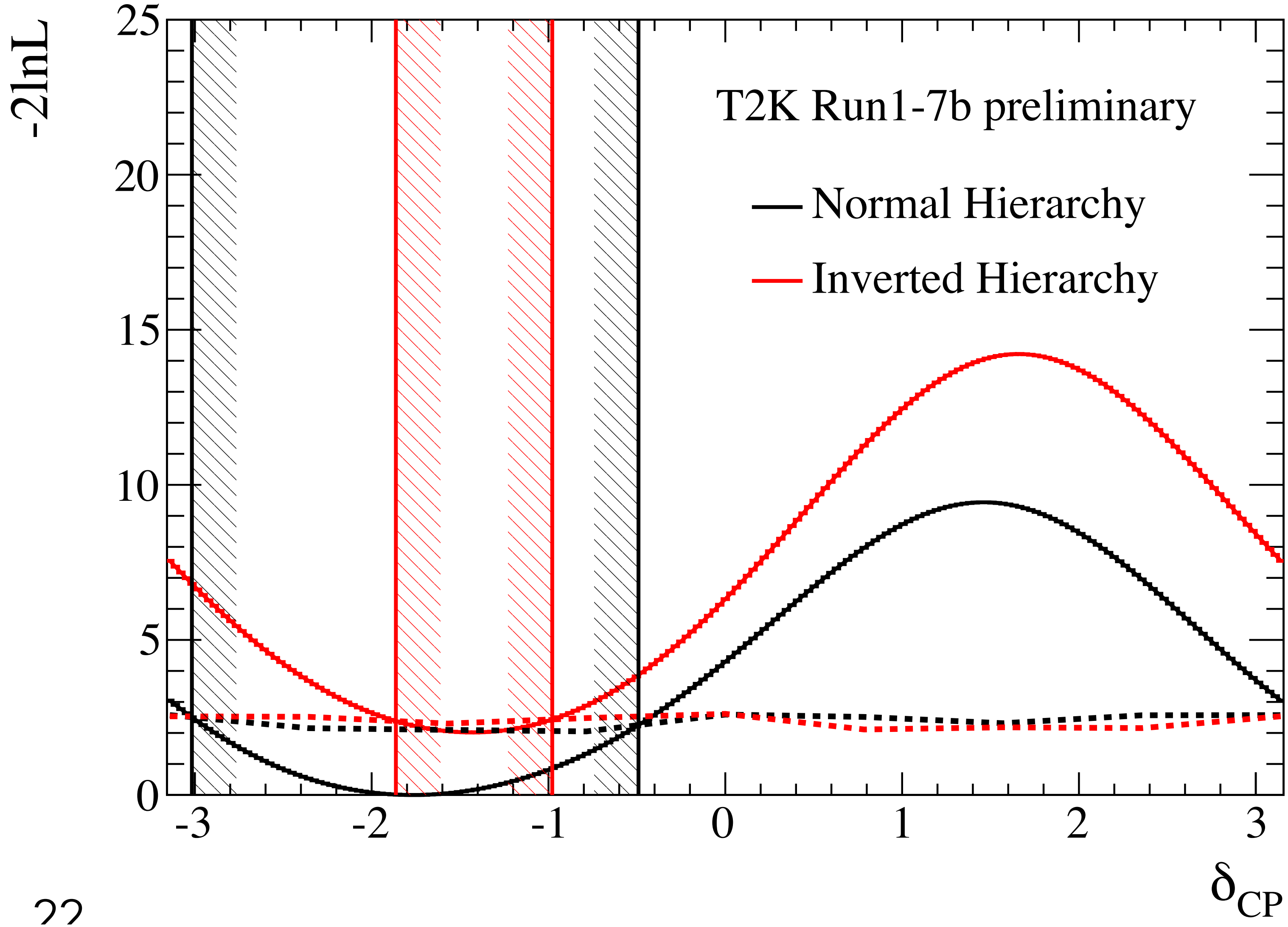
		EXPECTED (NH, $\sin^2\Theta_{23}$=0.528)				
	OBS.	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$	Bkg
ν_e	32	27.0	22.7	18.5	22.7	5.0
$\bar{\nu}_e$	4	6.0	6.9	7.7	6.8	3.2

Favoured scenario, -pi/2

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

[Tanaka, Neutrino]

T2K Results on δ_{CP} (fixed hierarchy)



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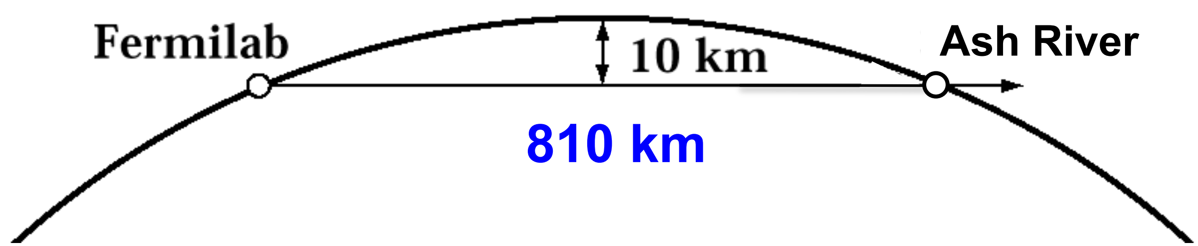
NOvA Overview

- "Conventional" beam
- Two-detector experiment:

- Near detector
  - measure beam composition
  - energy spectrum

- Far detector
  - measure oscillations and search for new physics



The NOvA Collaboration

www-nova.fnal.gov

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

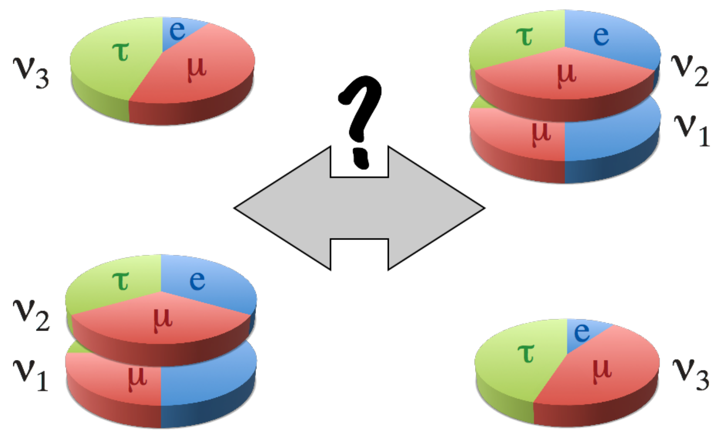
234 Collaborators
41 institutions
7 countries

Physics Goals

Results from 3 different oscillation analyses

- Disappearance of ν_μ CC events
  - clear suppression as a function of energy
  - 2015 analysis results Phys.Rev.D93.051104

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



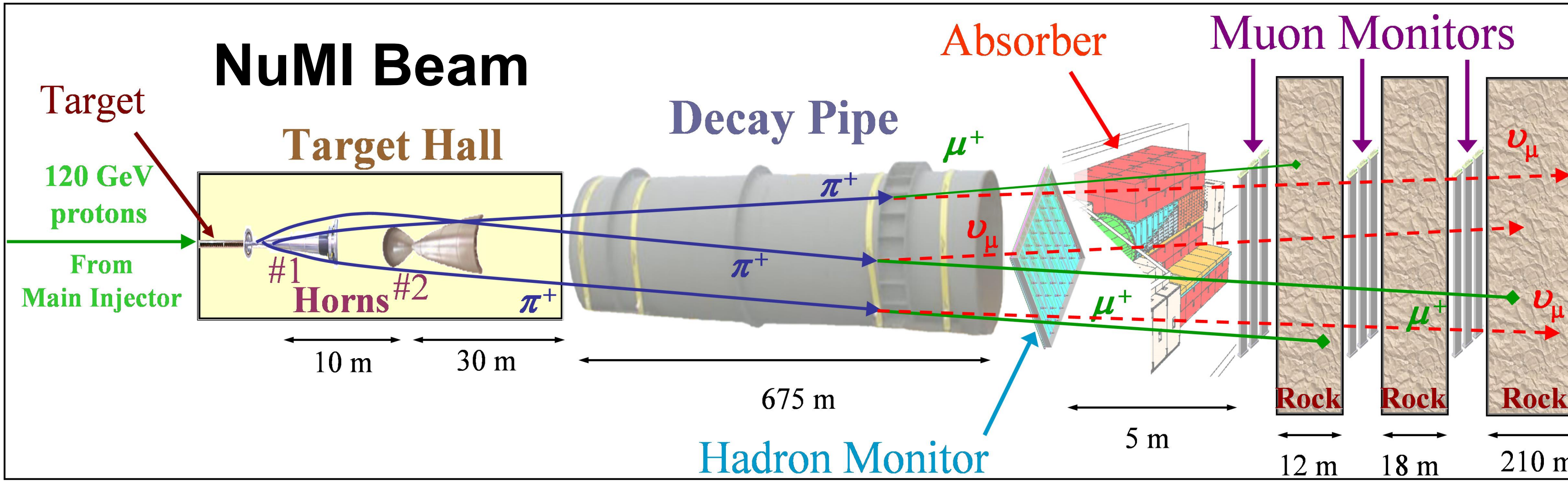
- Appearance of ν_e CC events

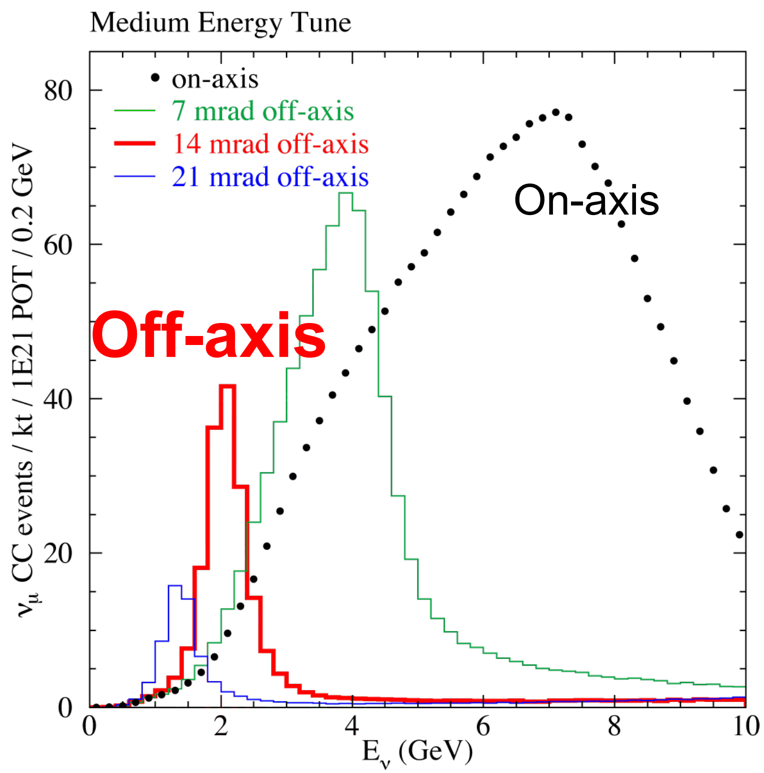
$\theta_{13}, \theta_{23}, \delta_{CP},$ and Mass Hierarchy

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

- Deficit of NC events?
  - suppression of NCs could be evidence of oscillations involving a sterile neutrino
  - Fit to 3+1model
  - new!

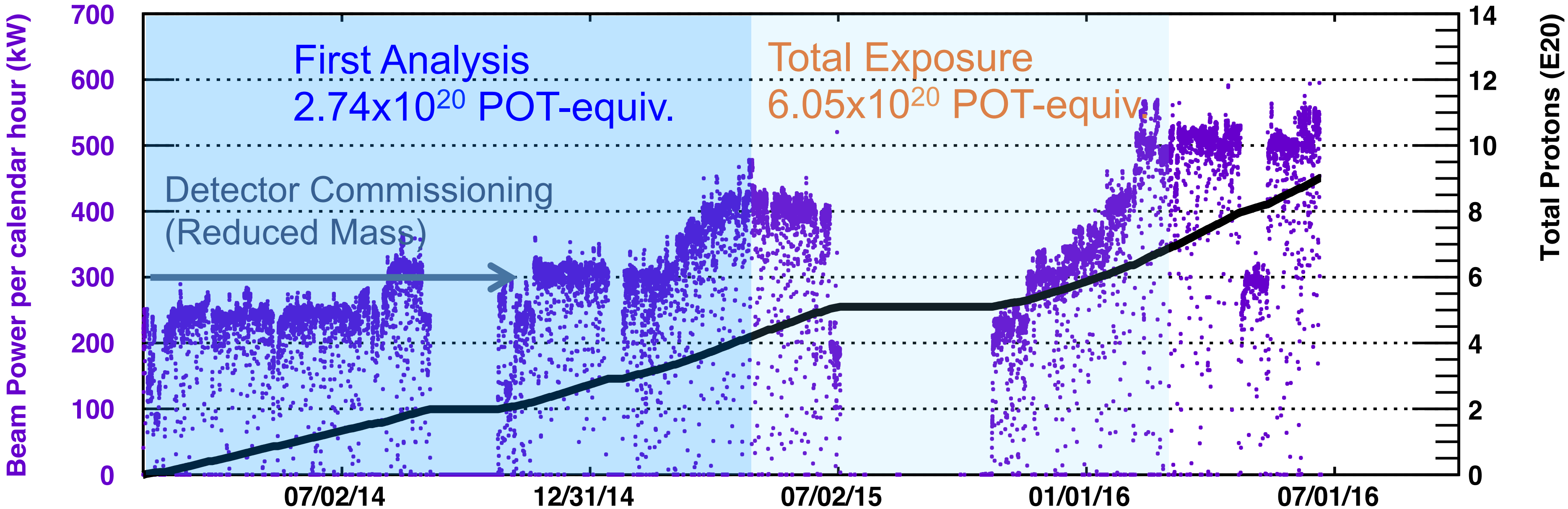
$$\Delta m^2_{41}, \theta_{34}, \theta_{24}$$


NuMI Beam
Target
Target Hall
120 GeV protons
From Main Injector
#1
Horns
#2
Decay Pipe
Absorber
Muon Monitors
Hadron Monitor
Rock
Rock
Rock
10 m
30 m
675 m
5 m
12 m
18 m
210 m


Medium Energy Tune
on-axis
7 mrad off-axis
14 mrad off-axis
21 mrad off-axis
On-axis
Off-axis
ν_μ CC events / kt / 1E21 POT / 0.2 GeV
E_ν (GeV)

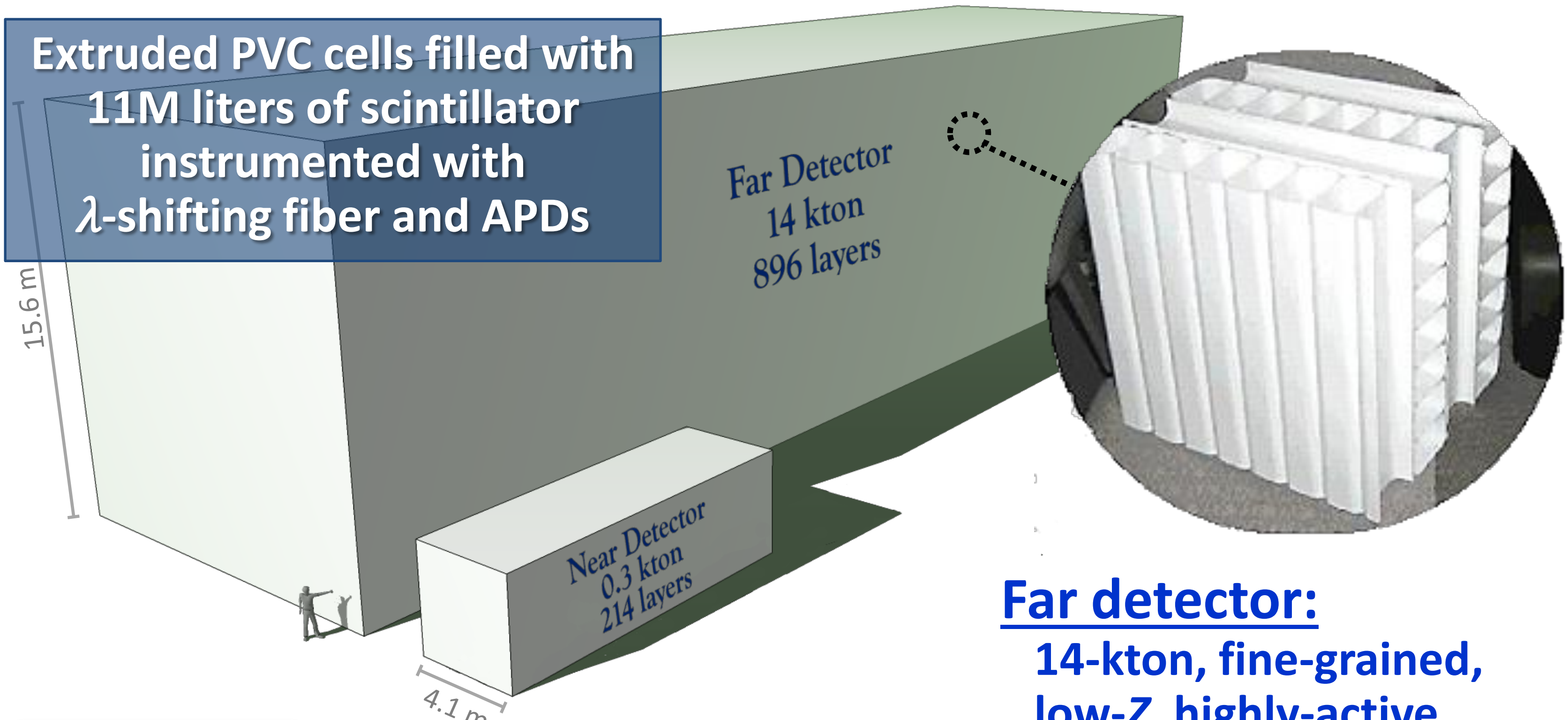
Beam Performance

- 6.05×10^{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)

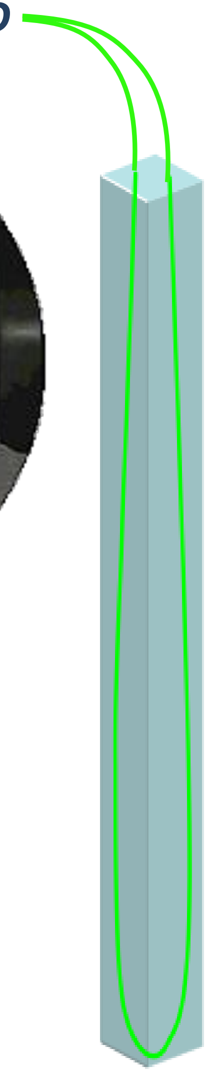


NOνA detectors

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



A NOνA cell

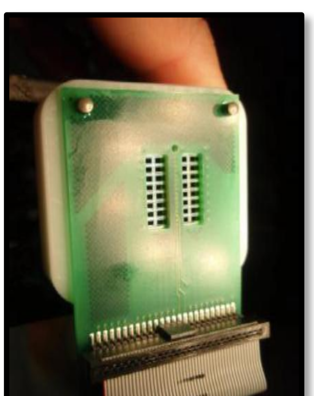


Far detector:

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

Near detector:

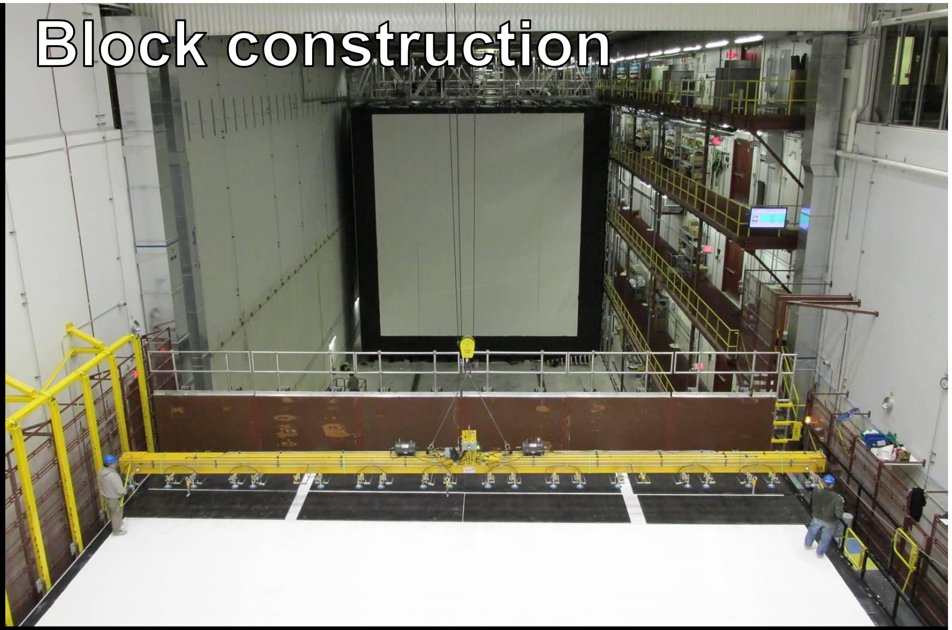
0.3-kton version of the same
→ *20,000 channels*



32-pixel APD ←

Fiber pairs from 32 cells →

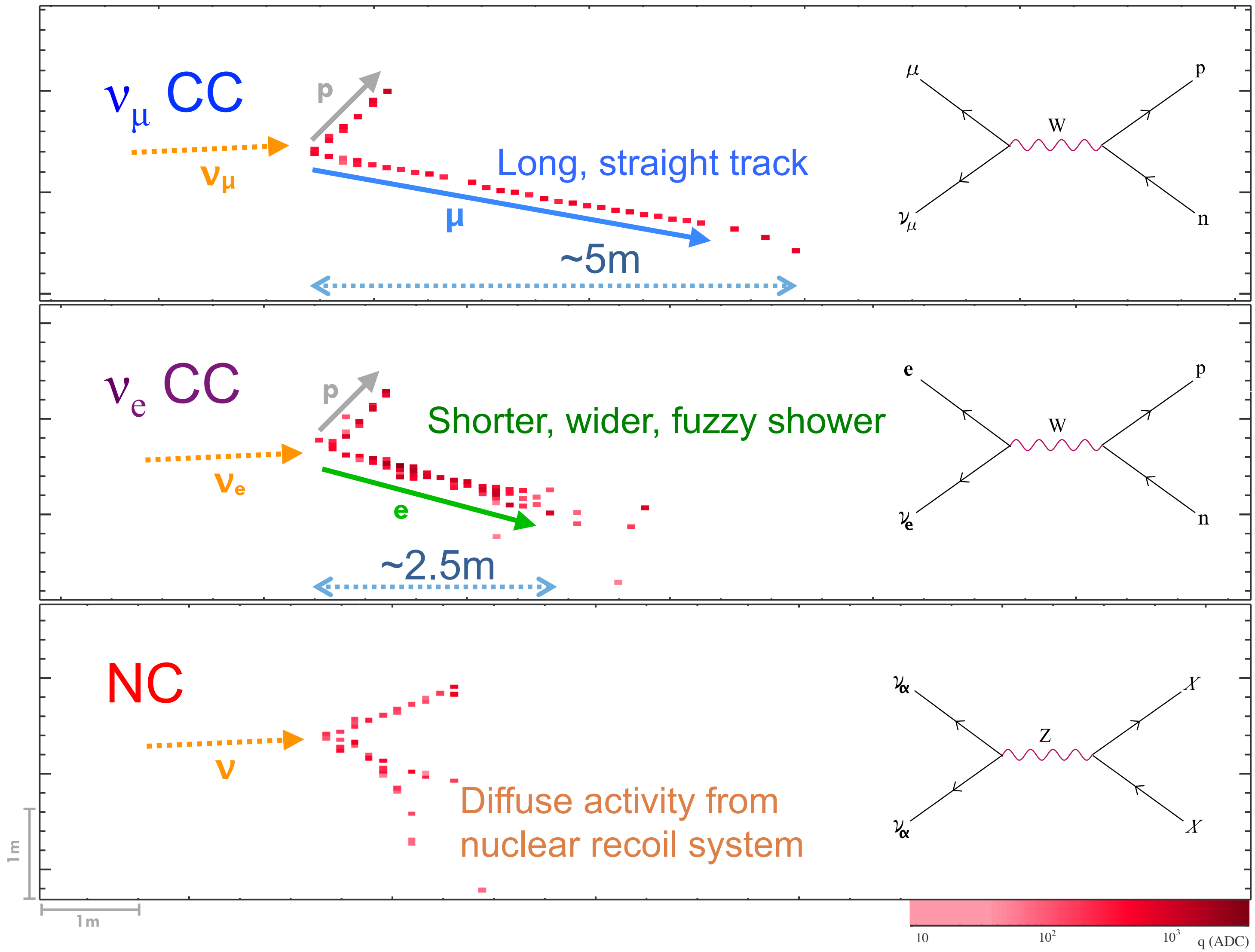

Far Detector site


Block construction


Outfitted Far Detector

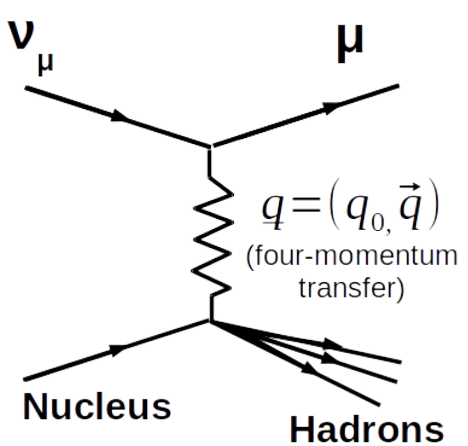

Near Detector

Event Selection

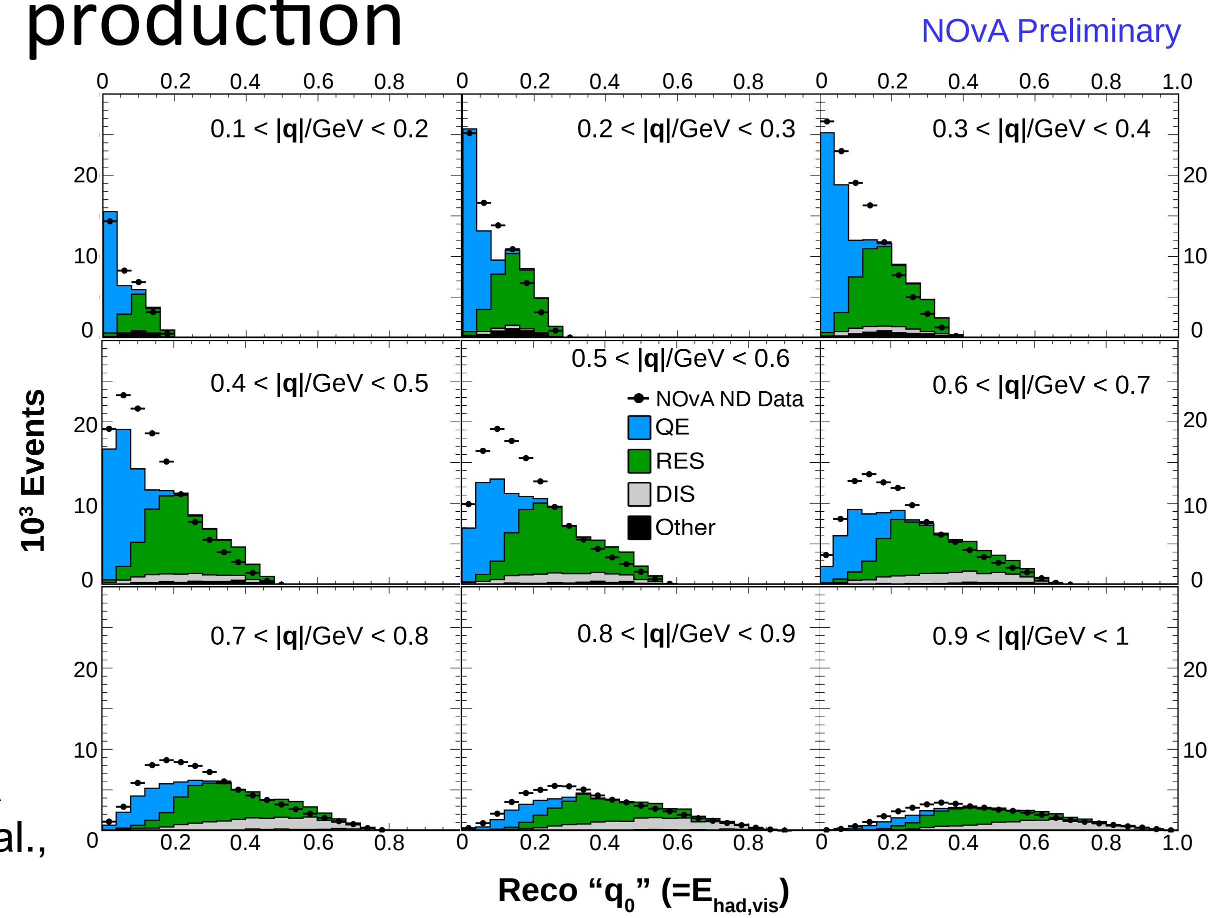


Scattering in a Nuclear Environment

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

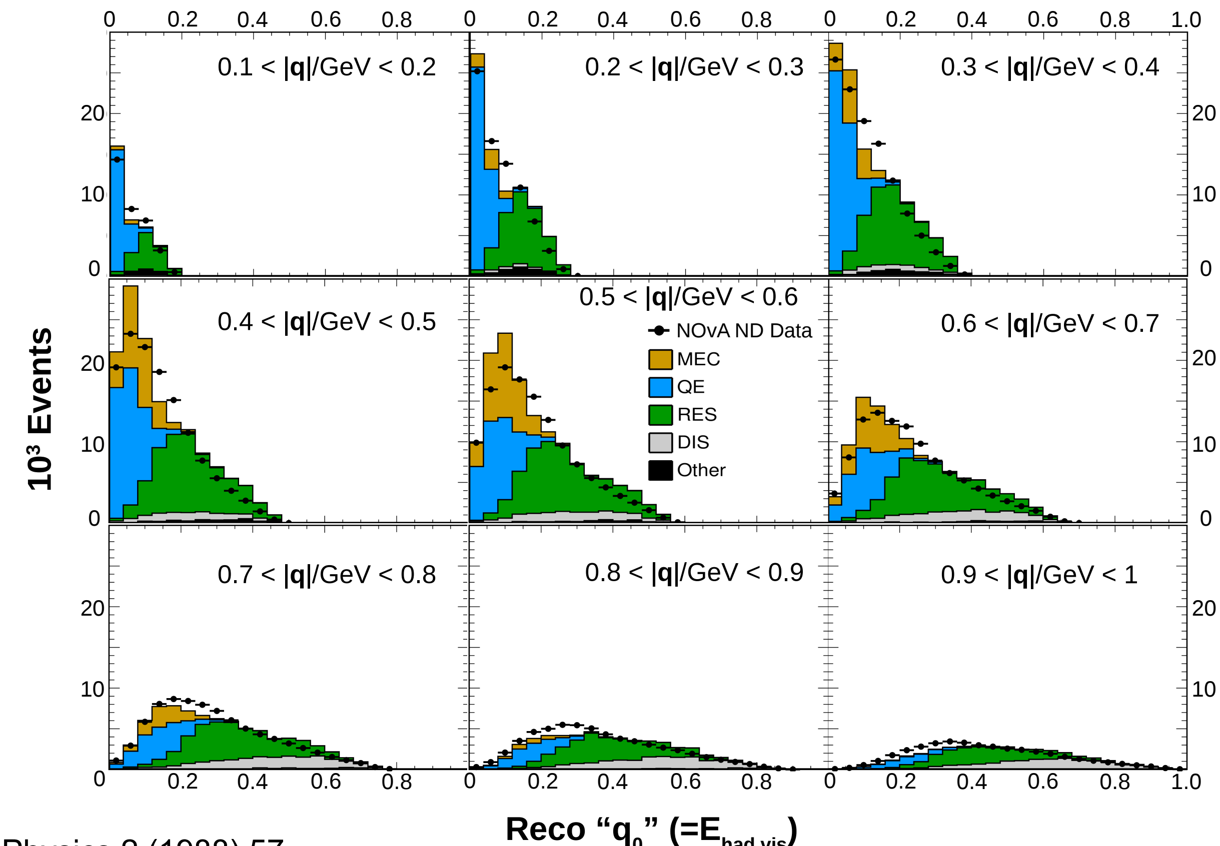


Similar conclusions from MINERvA data reported in P.A. Rodrigues et al., PRL 116 (2016) 071802



Scattering in a Nuclear Environment

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

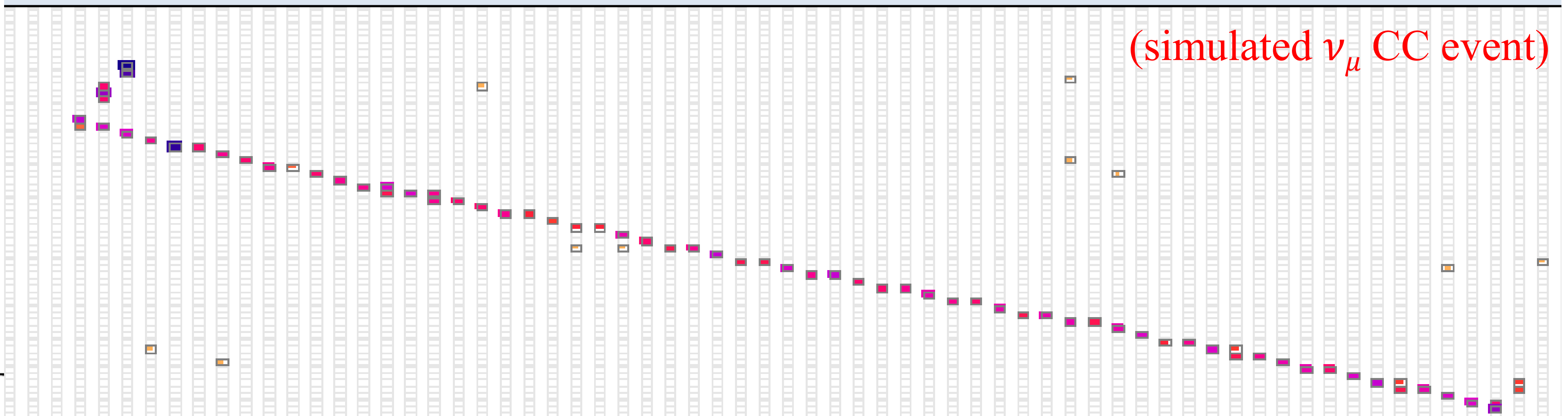


- 50% systematic uncertainty on MEC component
- Reduces largest systematics
  - hadronic energy scale
  - QE cross section modeling
- Reduce single non-resonant pion production by 50% (P.A. Rodrigues et al, arXiv:1601.01888.)

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

ν_μ disappearance

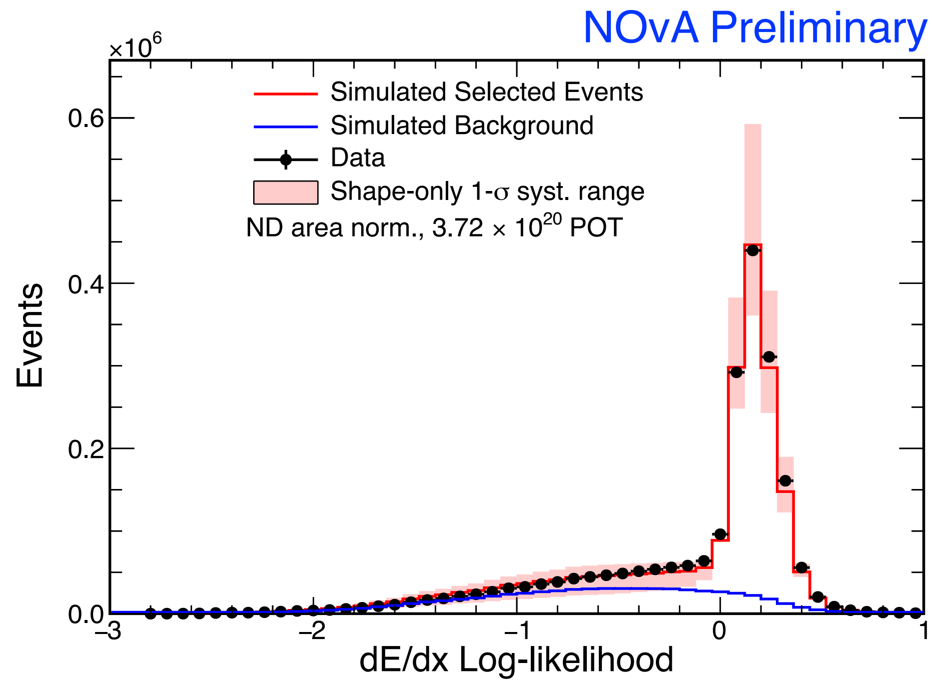
- Identify **contained ν_μ CC events** in each detector
- Measure their **energies**
- Extract oscillation information from differences between the **Far and Near energy spectra**

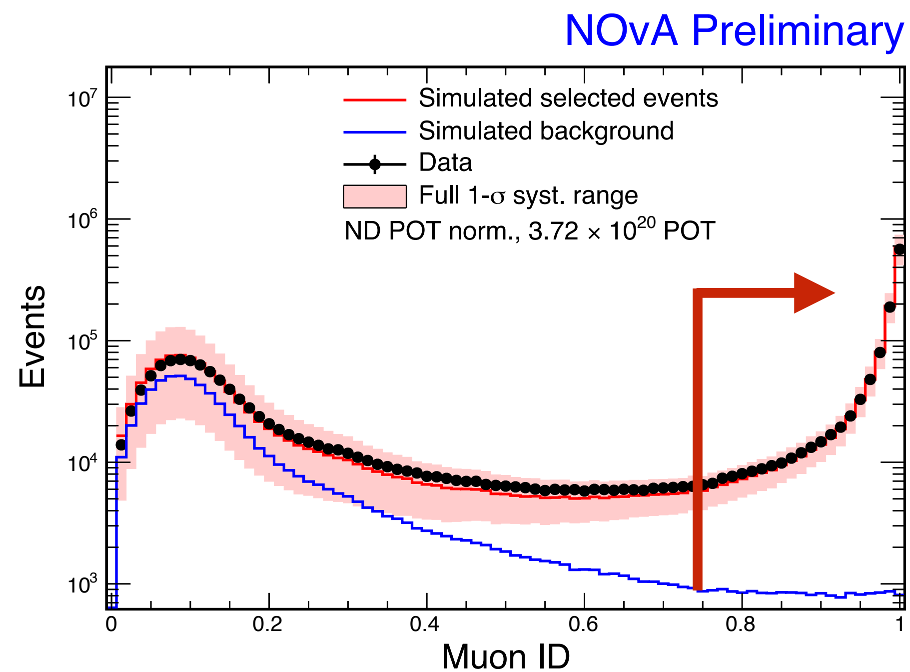


(simulated ν_μ CC event)

ν_μ Event Selection

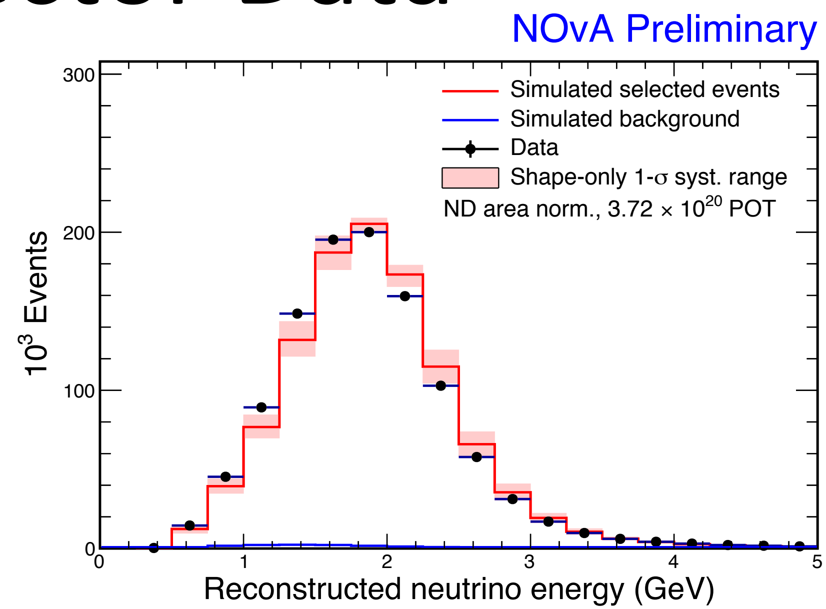
- Goal: Isolate a pure sample of ν_μCC events less than 5GeV
  - Select events with long tracks
  - Suppress NC and cosmic backgrounds
- 4-variable kNN used to identify muons
  - track length
  - dE/dx along track
  - scattering along track
  - track-only plane fraction
- ND data matches simulation well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

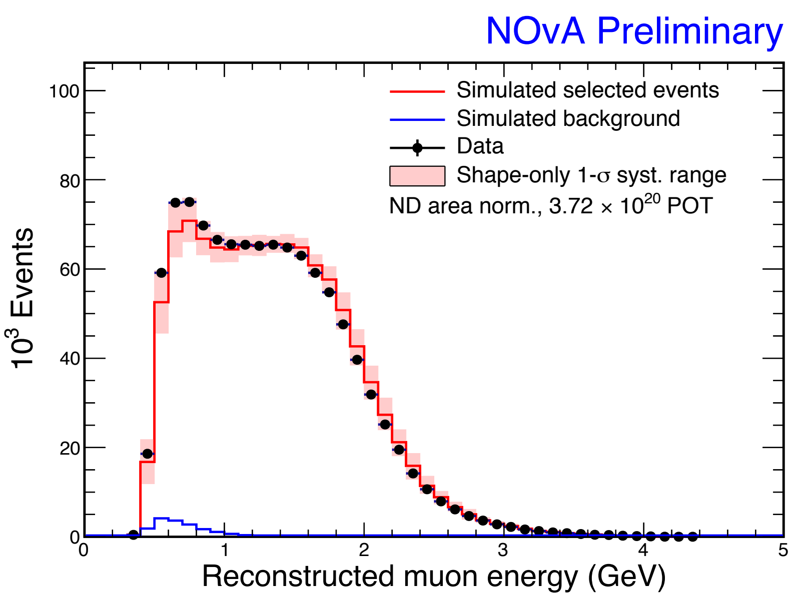


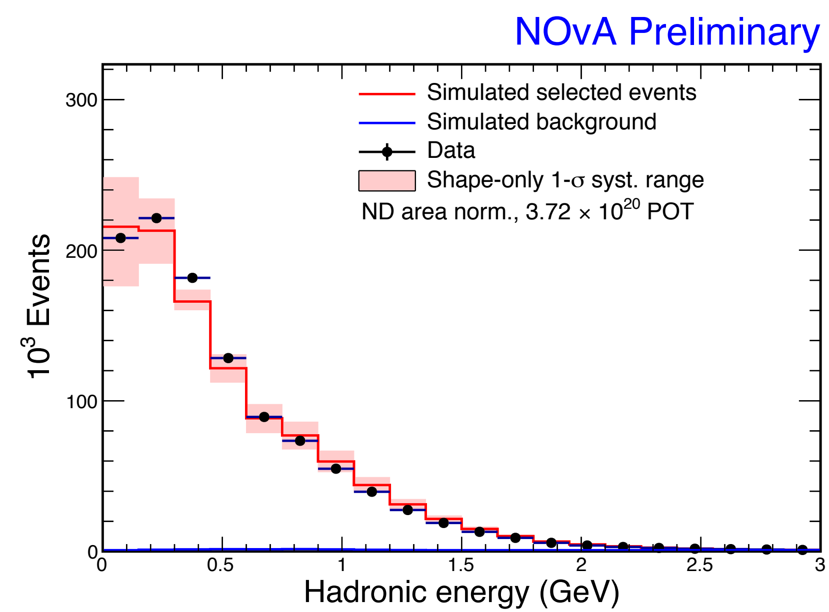


ν_μ Near Detector Data

- 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

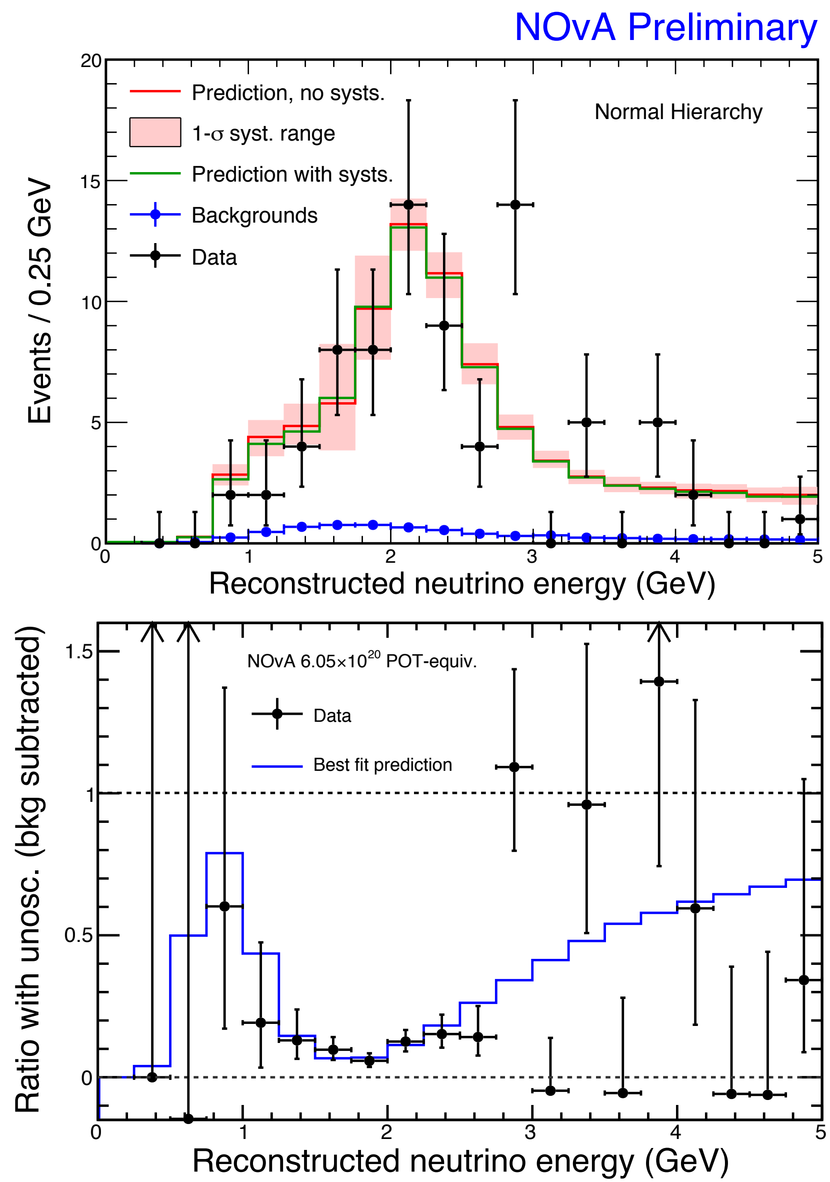




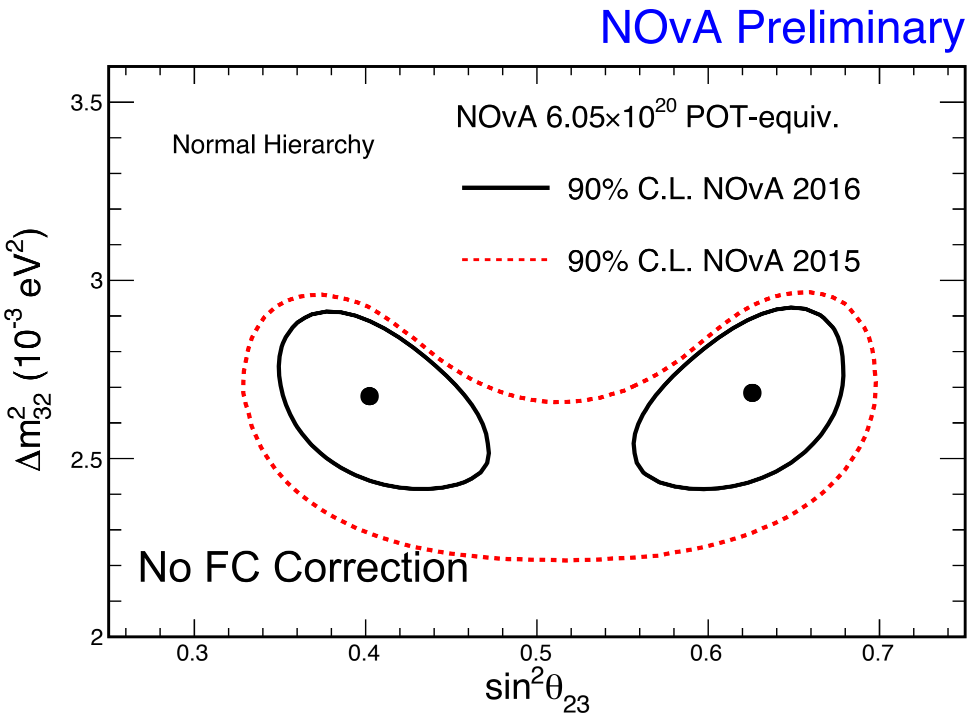


ν_μ Far Detector Data

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



Contours



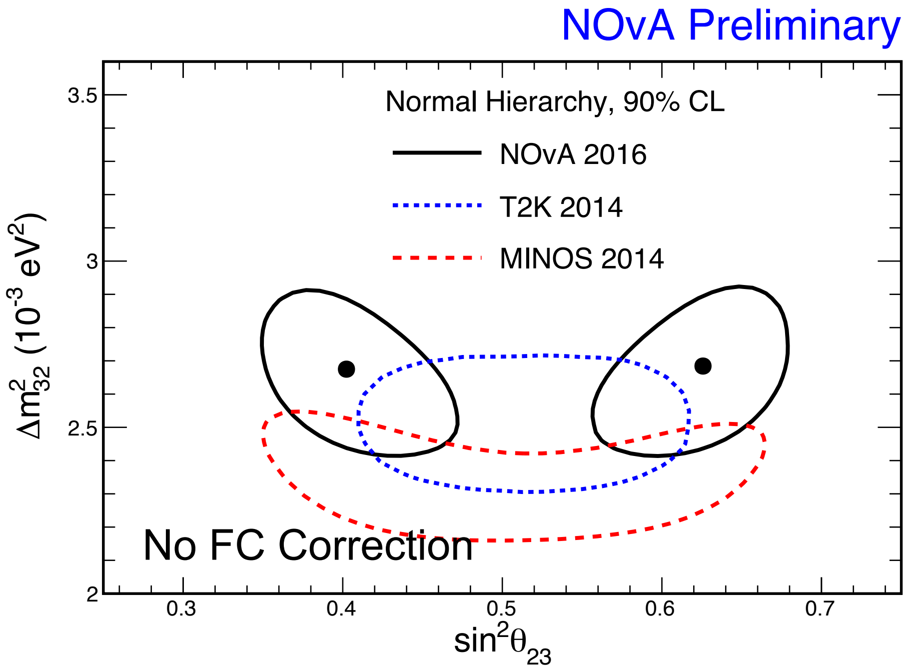
- Fit for Δm^2 and $\sin^2\theta_{23}$
- Dominant systematic effects included in fit:
  - Normalization
  - NC background
  - Flux
  - Muon and hadronic energy scales
  - Cross section
  - Detector response and noise

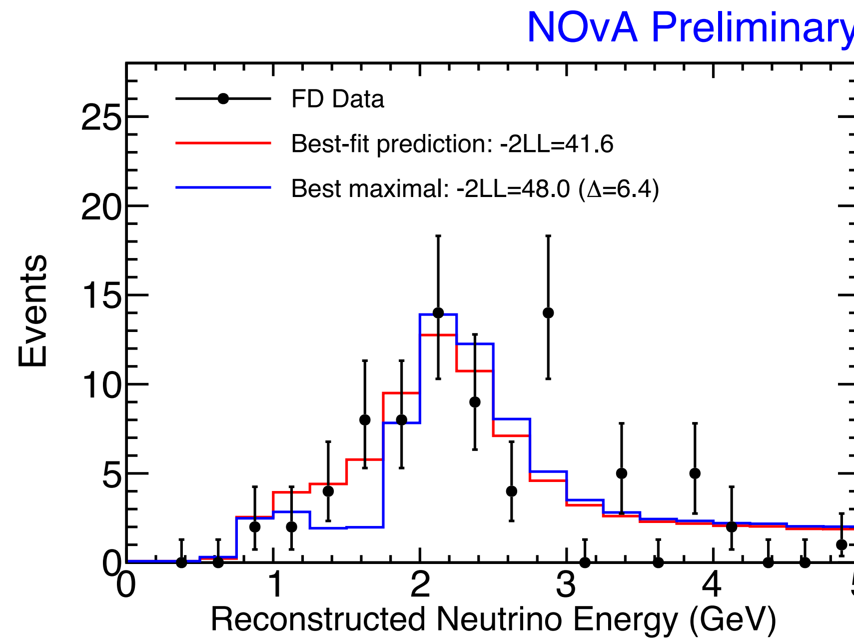
Best Fit (in NH):

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

Maximal mixing excluded at 2.5σ

Contours Compared





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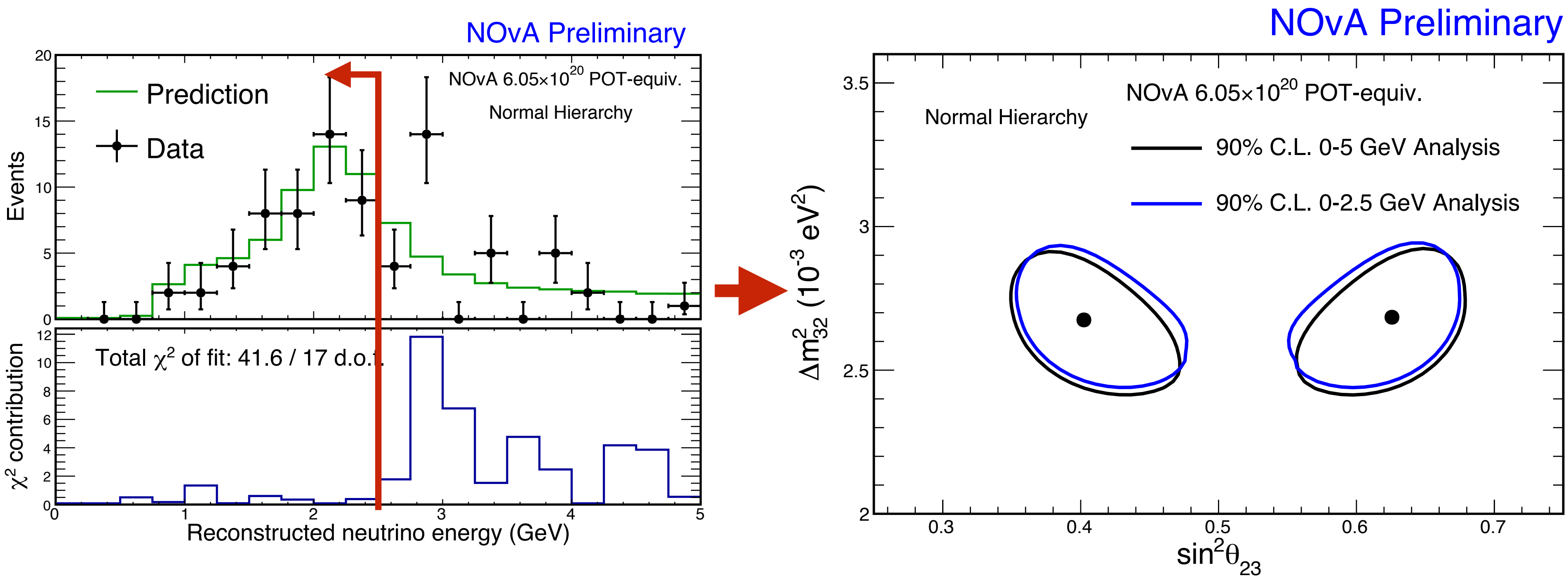
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02} (0.63^{+0.02}_{-0.03})$$

Maximal mixing excluded at 2.5σ

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

$$\Delta m^2_{32} = (2.46) \times 10^{-3}\mathrm{eV}^2$$

Goodness of fit



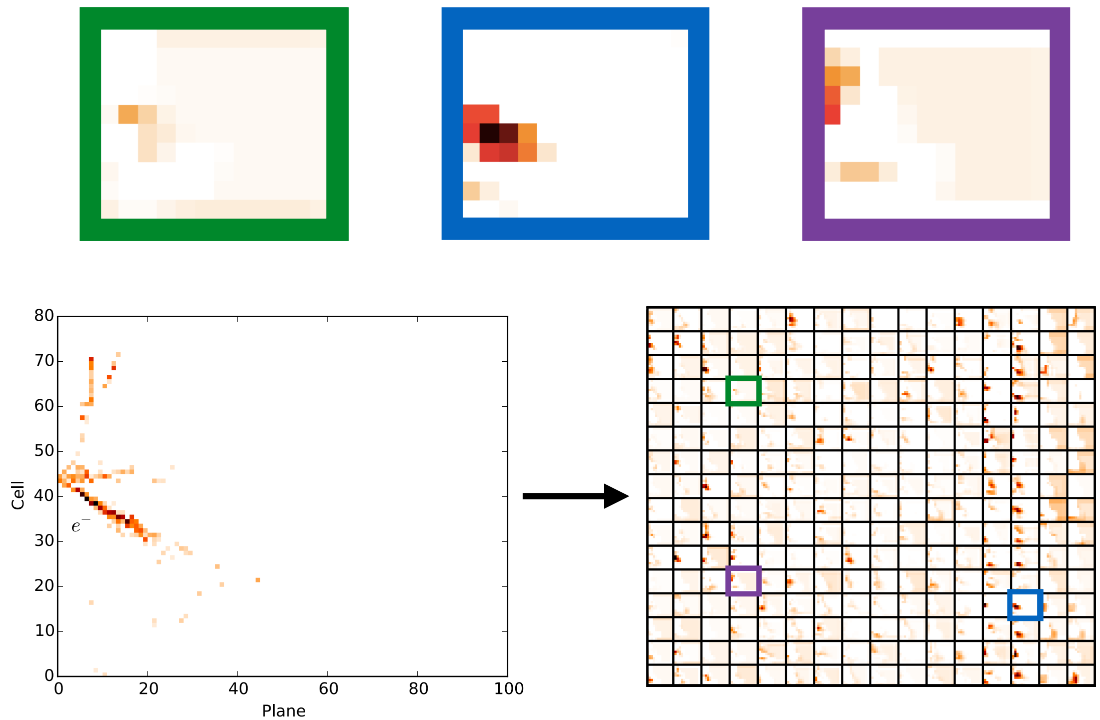
There is no significant pull in the oscillation fit from bins in the tail

Neutral Current & ν_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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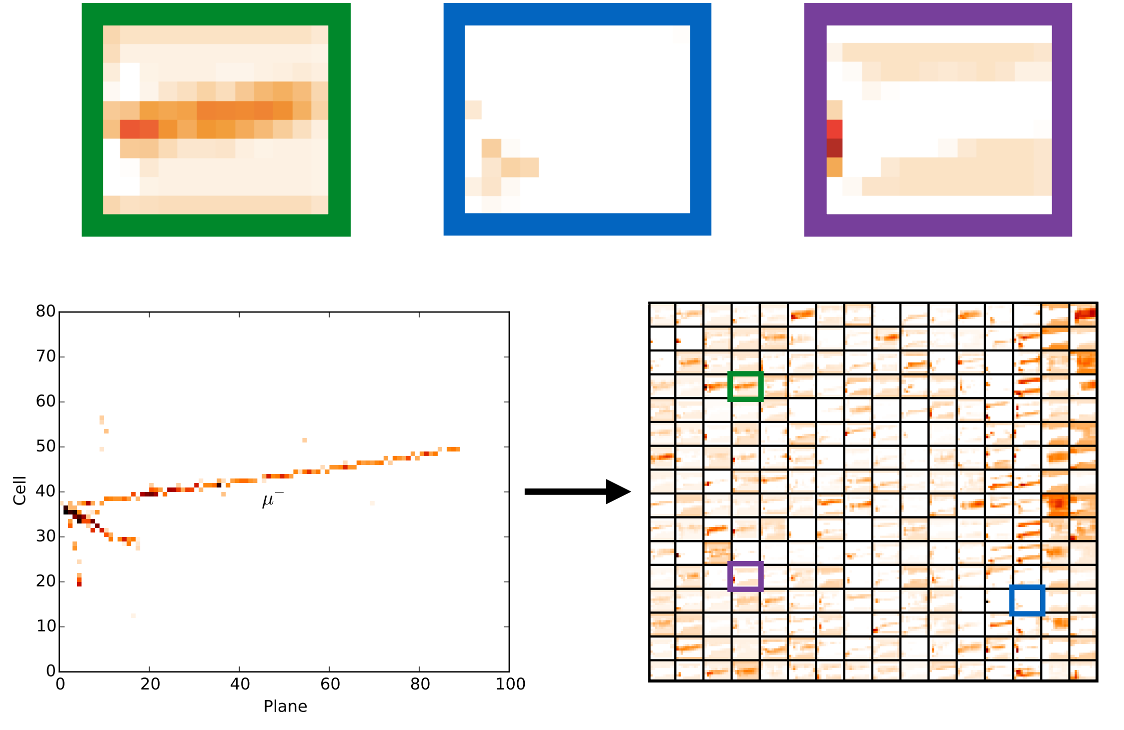

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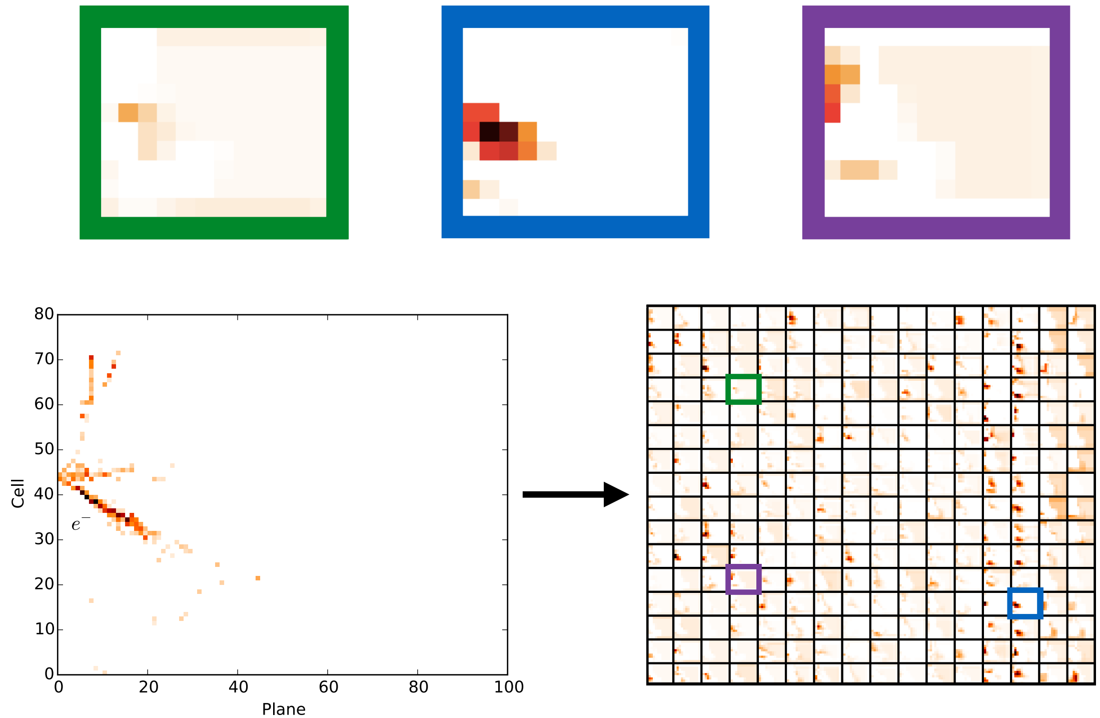
- □ Extracted features used as inputs to a conventional neural network to classify the event

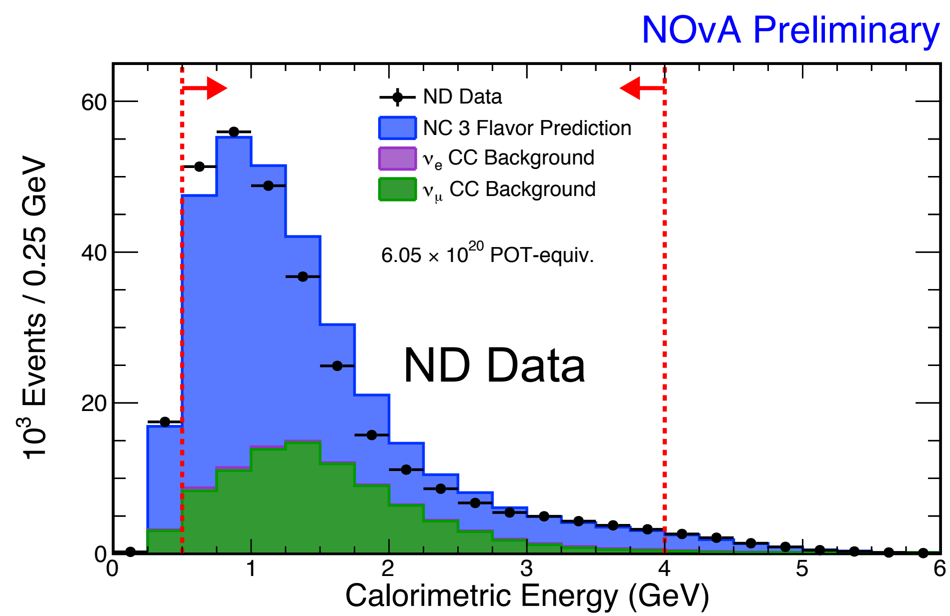


Improvement in sensitivity from CVN equivalent to 30% more exposure

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

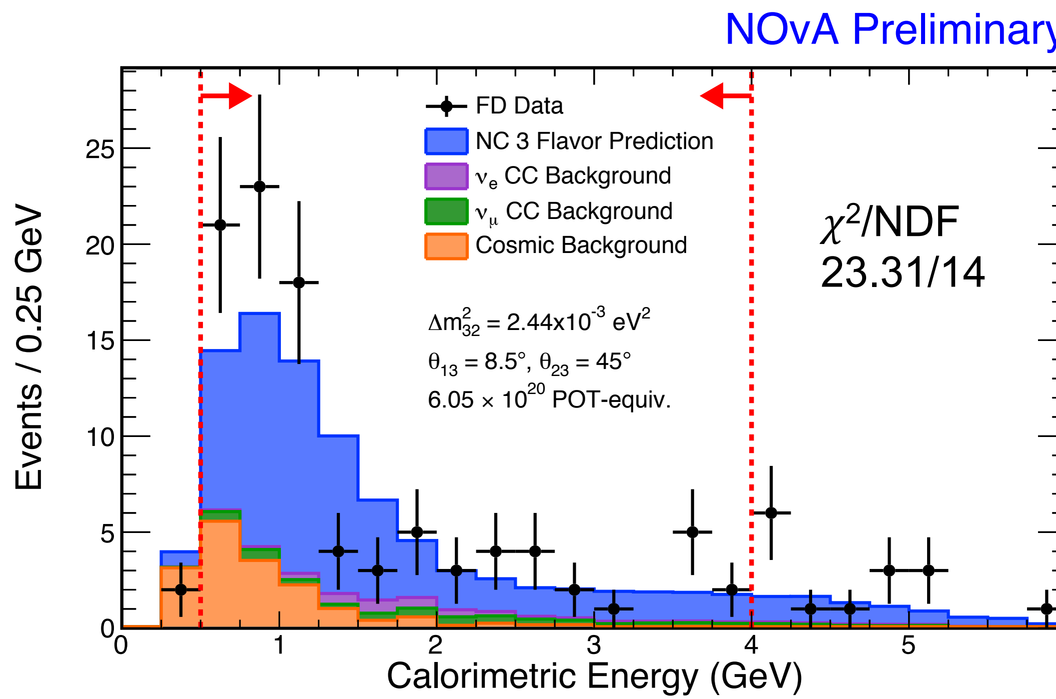


Extrapolation of ND data using F/N in reconstructed energy gives a prediction

Total	NC	ν_μ CC	Beam ν_e	Cosmics
83.7±8.3	60.6	4.8	3.6	14.3

NC Far Detector Data

- Observe 95 events
- No evidence of oscillations involving steriles



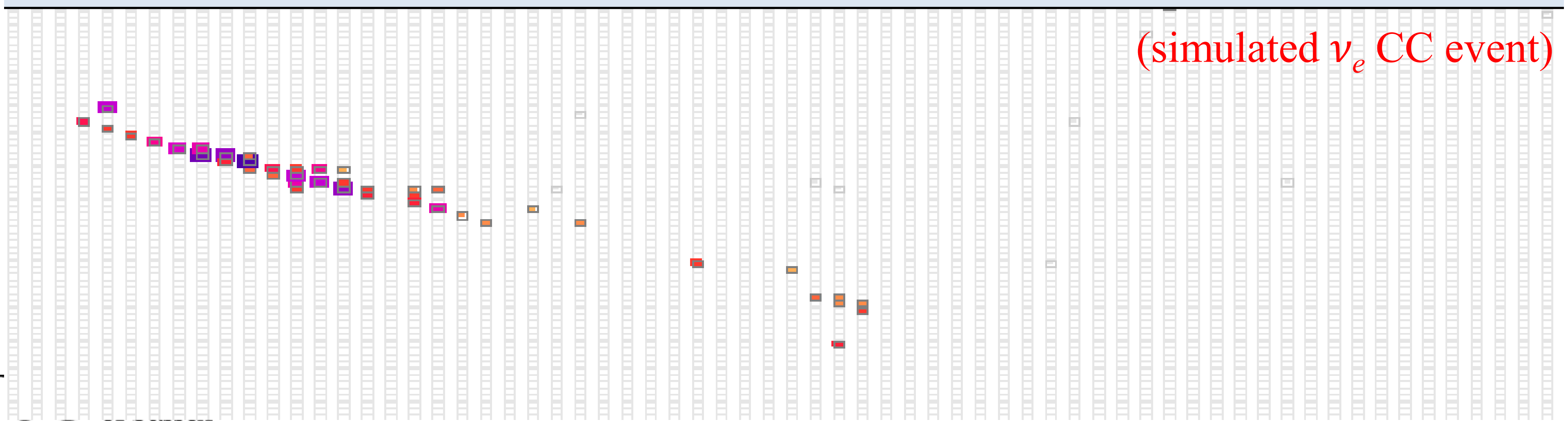
$$\text{For } 0.05 \text{ eV}^2 < \Delta m^2_{41} < 0.5 \text{ eV}^2$$

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

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

ν_e appearance

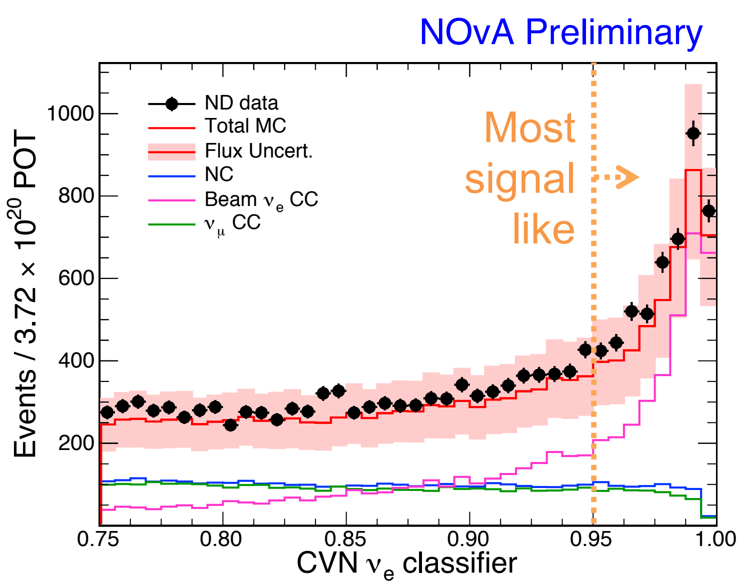
- Identify **contained ν_e CC candidates** in each detector
- Use Near Det. candidates to **predict beam backgrounds** in the Far Detector
- Interpret any **Far Det. excess** over predicted backgrounds as ν_e appearance

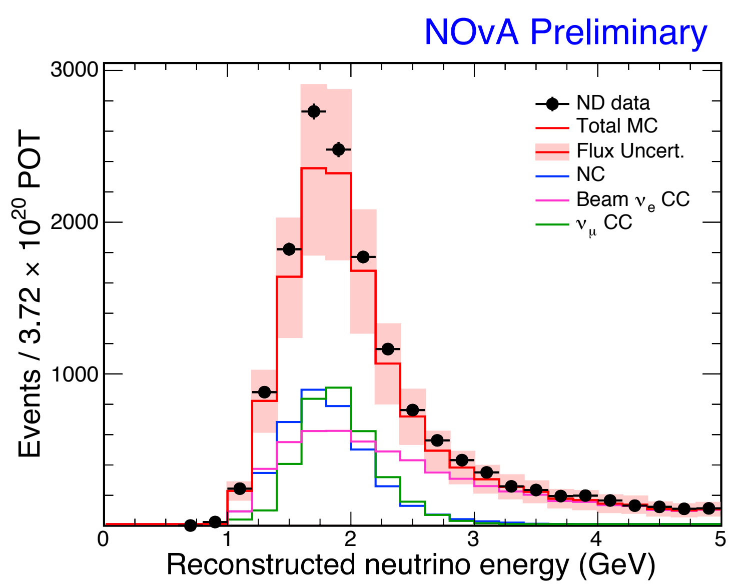


ν_e Near Detector Data

- 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 ν_e each propagate differently
  - constrain beam ν_e using selected ν_μ CC spectrum
  - constrain ν_μ CC using Michel Electron distribution

beam ν_e up by 4%
NC up by 10%
ν_μ CC up by 17%



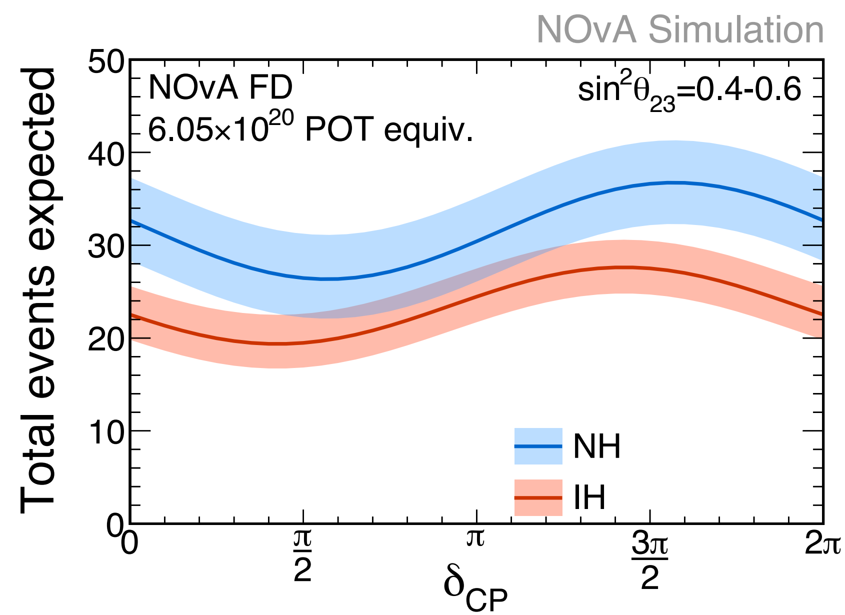


Prediction

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

Signal events
(±5% systematic uncertainty):

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

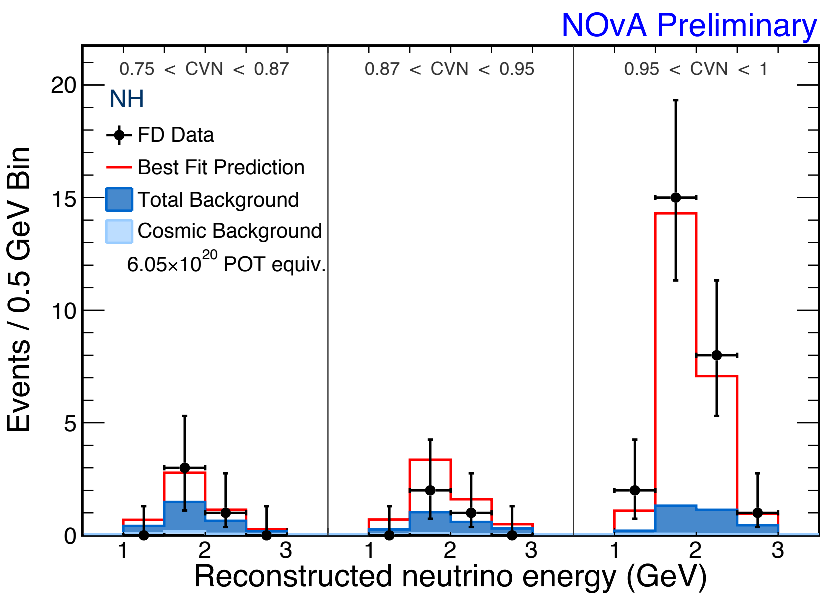


Background by component
(±10% systematic uncertainty):

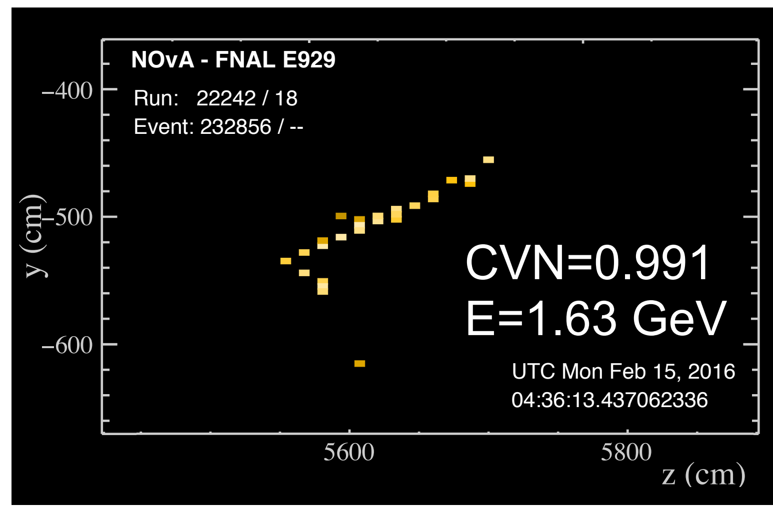
Total BG	NC	Beam ν_e	ν_μ CC	ν_τ CC	Cosmics
8.2	3.7	3.1	0.7	0.1	0.5

ν_e Far Detector Data

>8σ electron neutrino appearance signal



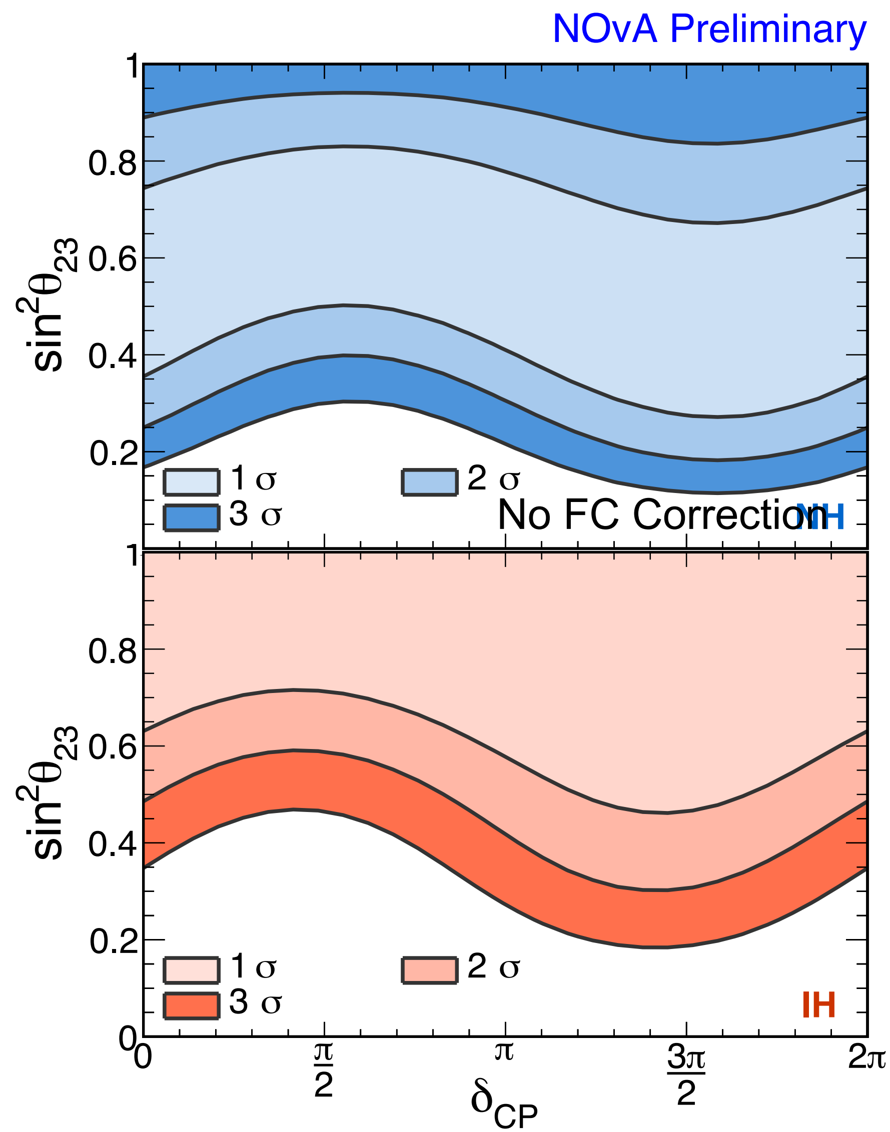
- Observe 33 events in FD
  - background 8.2±0.8



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

Contours

- Fit for hierarchy, $\boldsymbol{\delta}_{CP}$, $\sin^2\theta_{23}$
  - Constrain $\sin^2(2\theta_{13})=0.085\pm0.05$
  - Constrain $\Delta m^2=2.44\pm0.06\text{x}10^{-3}$ eV^2 (-2.49±0.06x10^{-3} eV^2, IH)
  - Systematic effects included as nuisance parameters (normalization, flux, calibration, cross section, and detector response effects)

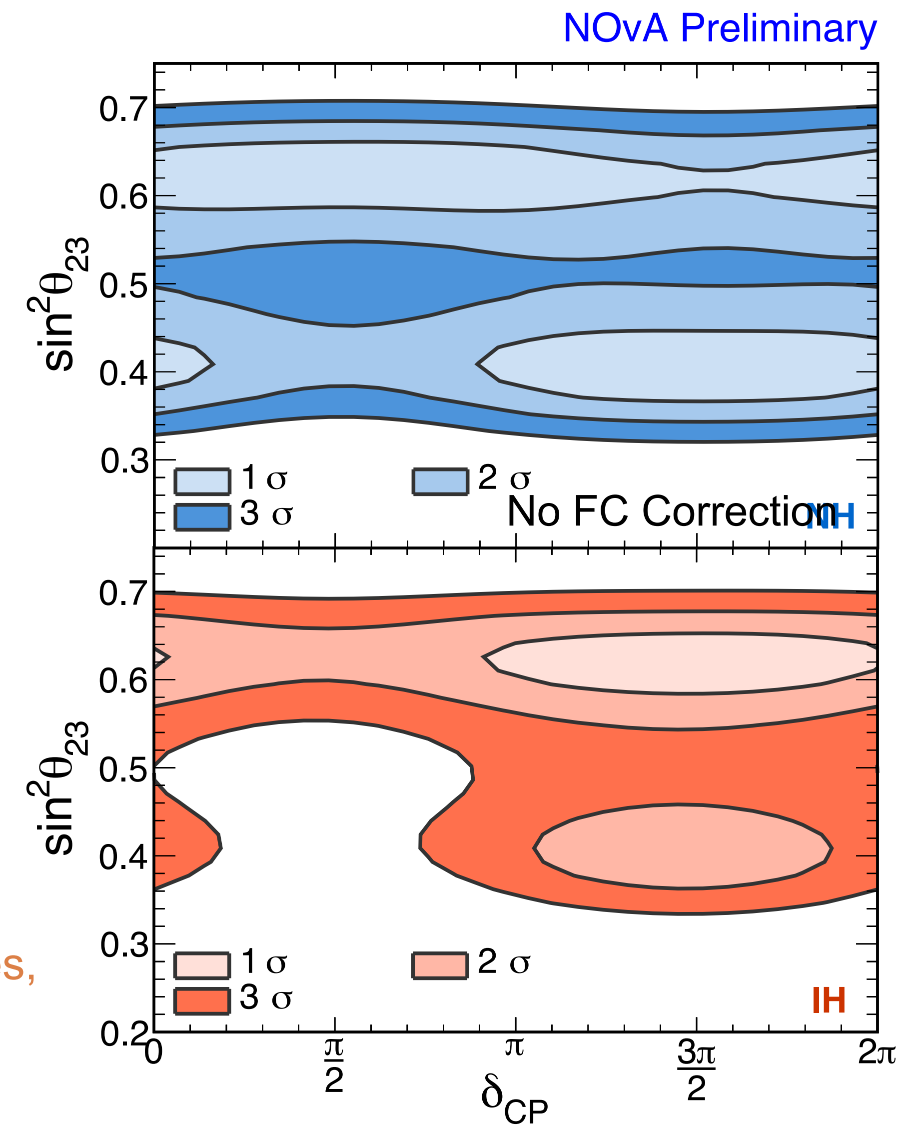


Contours

- Fit for hierarchy, δ_{CP}, $\sin^2\theta_{23}$
  - Constrain Δm^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 1σ
  - 3σ 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 6.05×10^{20} POT, NOvA finds:

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

Backup slides

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

[PDG, 2014]

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

Here

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

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

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

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

where

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}\,,\;\;\Delta = \frac{\Delta m^2_{31}\,L}{4E}\,,\;\;A = \sqrt{2}G_F N_e^{man}\,\frac{2E}{\Delta m^2_{31}}\,,$$

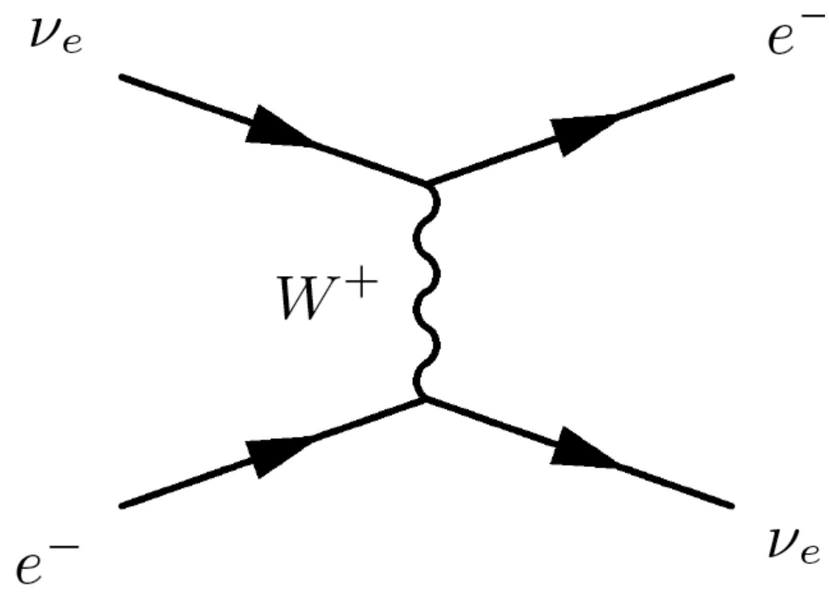
and $\cot\delta = J_{CP}^{-1}\mathrm{Re}(U_{\mu3}U^*_{e3}U_{e2}U^*_{\mu2})$, $J_{CP} = \mathrm{Im}(U_{\mu3}U^*_{e3}U_{e2}U^*_{\mu2})$.

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 ν_e and $\bar{\nu}_e$ interactions with electrons...

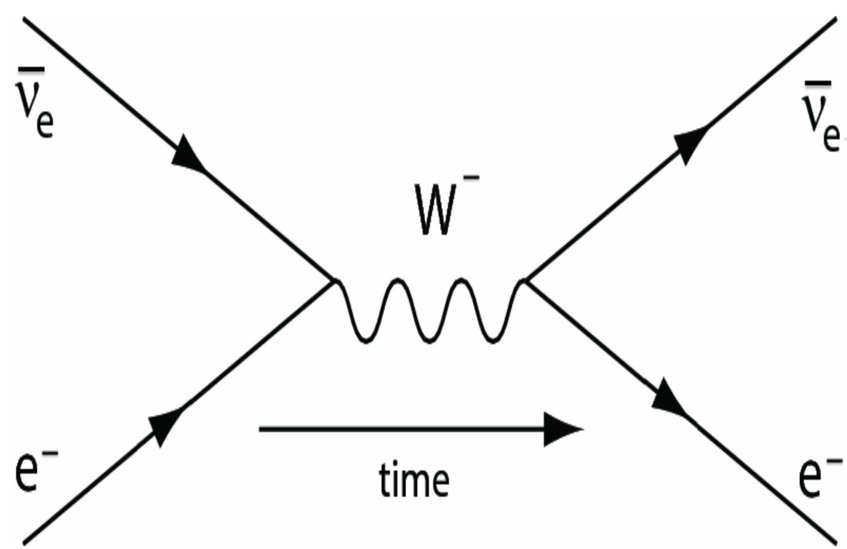
Different Feynman Diagrams

- Amplitude for electron **neutrino** interaction with an electron



- is not equal to...

- Amplitude for electron **antineutrino** interaction with an electron

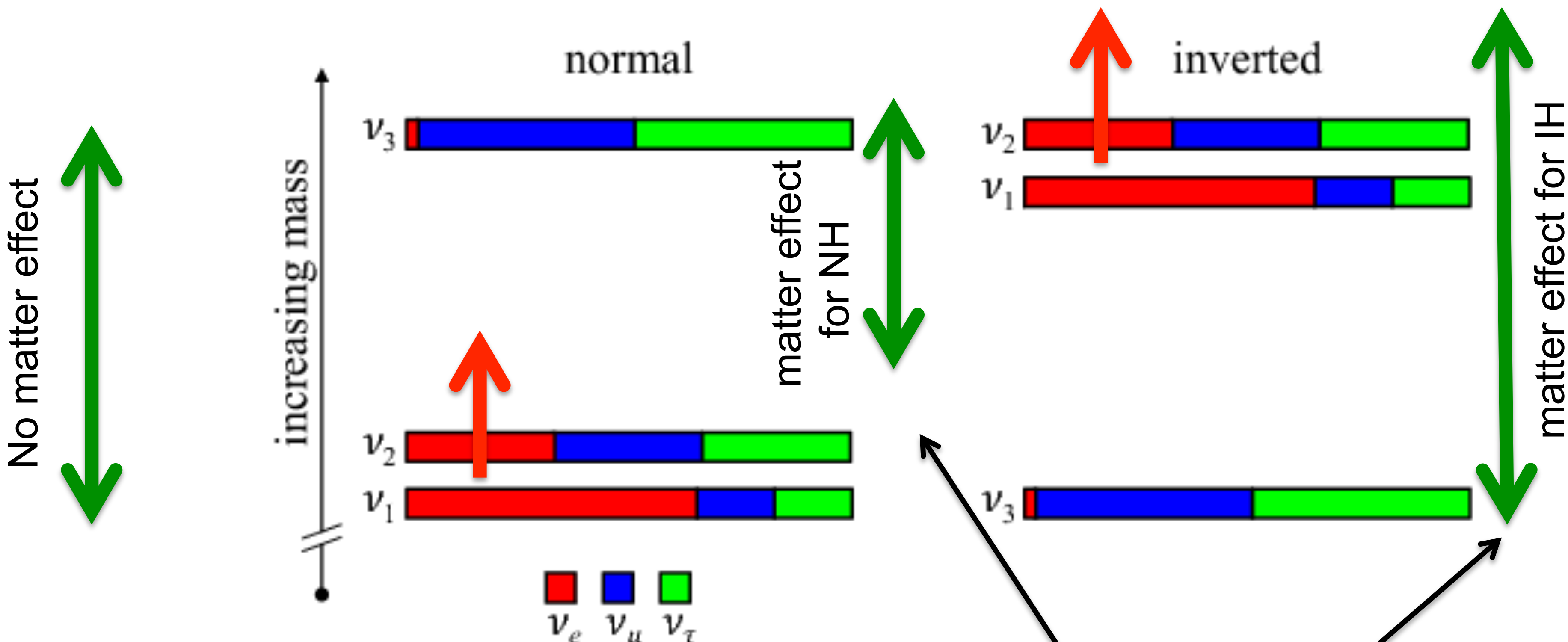


Electron neutrinos and antineutrinos are affected differently by interactions with matter → **fake** CP violation

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

Matter effect (neutrino case)

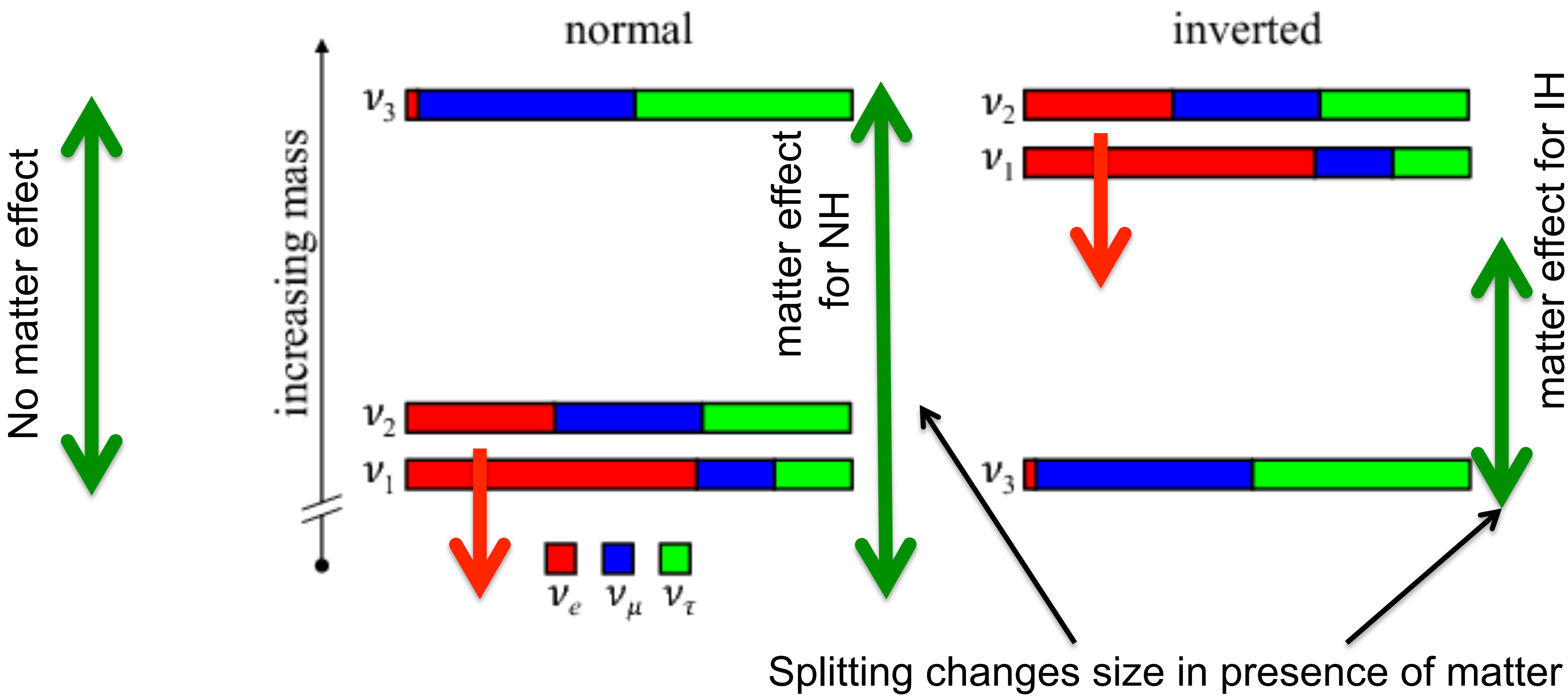
- Matter effect raises (or lowers) the energy state of the **mass eigenstates**
  - strength depends on electron neutrino content of each mass eigenstate



Splitting changes size in presence of matter

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 (θ_M) are modified by the mass squared splitting in matter (Δm^2_M)
  - e.g. simple 2-flavour case:

$$\sin 2\vartheta_{\mathrm{M}} = \frac{\Delta m^2 \sin 2\vartheta}{\Delta m^2_{\mathrm{M}}}$$

  - 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 Δm^2_{32}
Normalisation	± 1.0%	± 0.2 %
Muon E scale	± 2.2%	± 0.8 %
Calibration	± 2.0 %	± 0.2 %
Relative E scale	± 2.0 %	± 0.9 %
Cross sections + FSI	± 0.6 %	± 0.5 %
Osc. parameters	± 0.7 %	± 1.5 %
Beam backgrounds	± 0.9 %	± 0.5 %
Scintillation model	± 0.7 %	± 0.1 %
All systematics	**± 3.4 %**	**± 2.4 %**
Stat. Uncertainty	**± 4.1 %**	**± 3.5 %**

In each case:

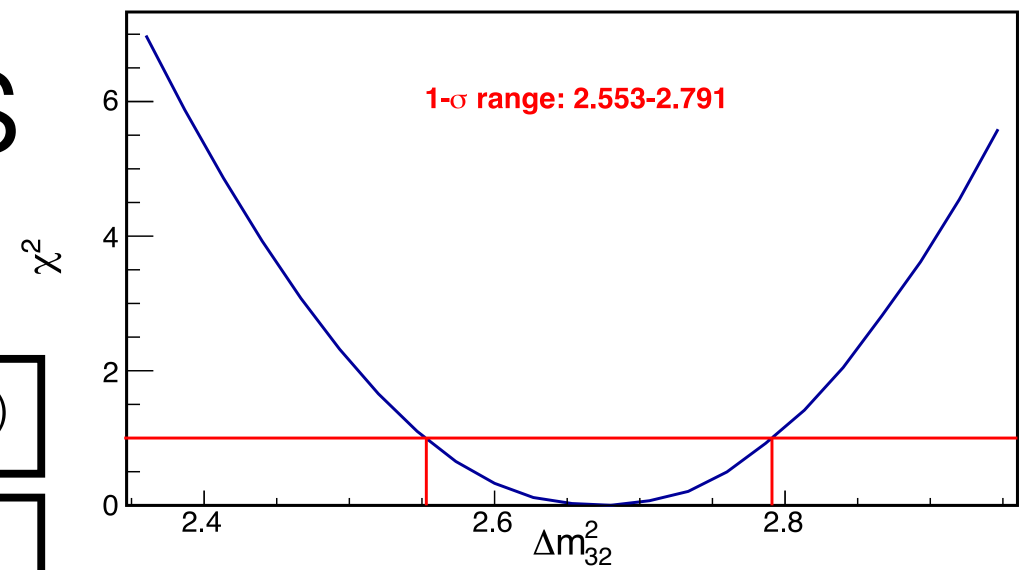
- The effect is propagated through the extrapolation
- We include those effects as pull terms in the fit
- The increase (in quadrature) of the parameter measurement error is recorded

1-D Profiles

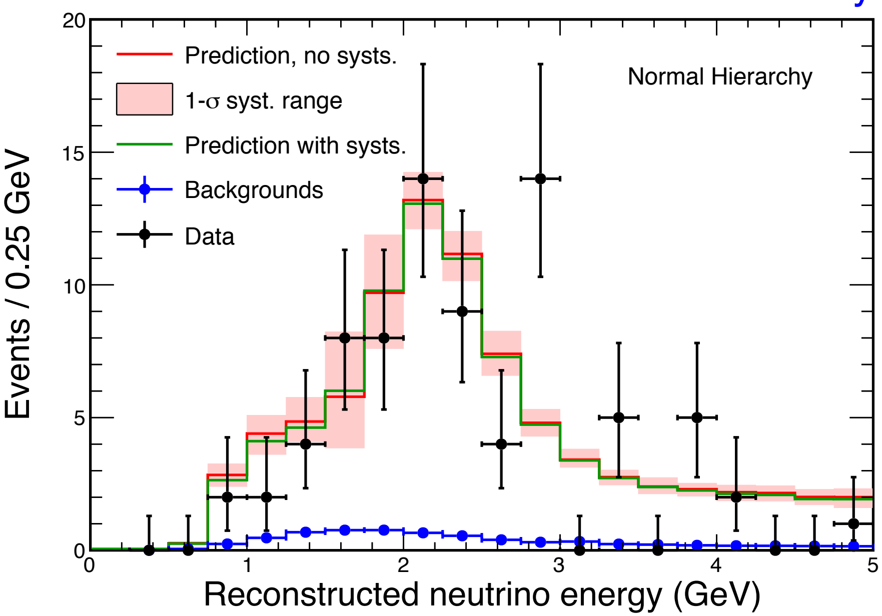
Recall our best fit:

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

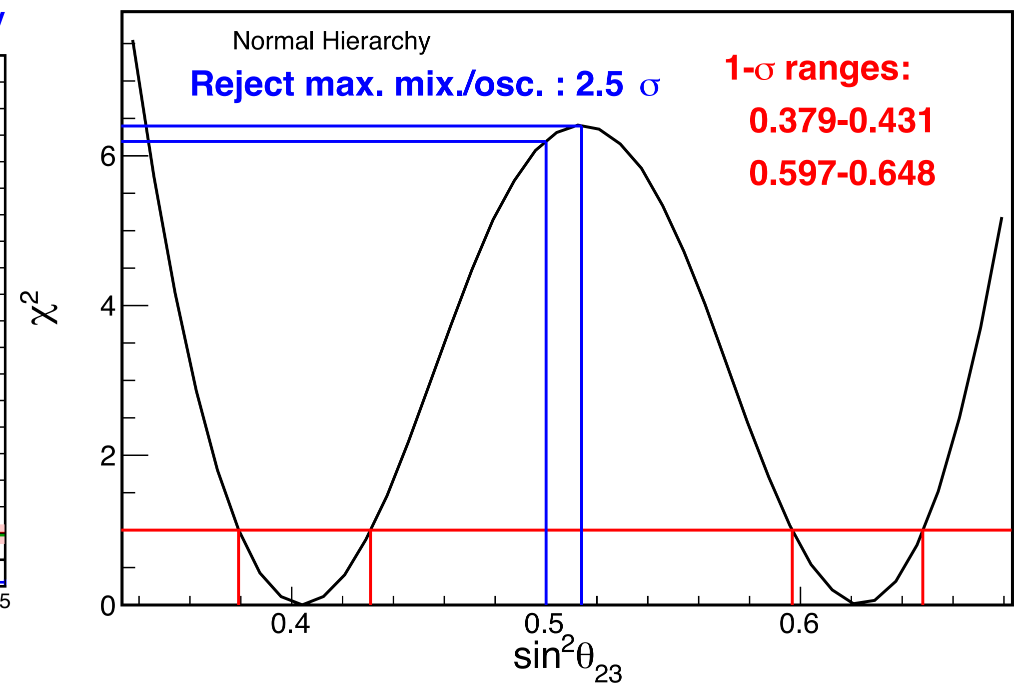
$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}\ (0.63^{+0.02}_{-0.03})$



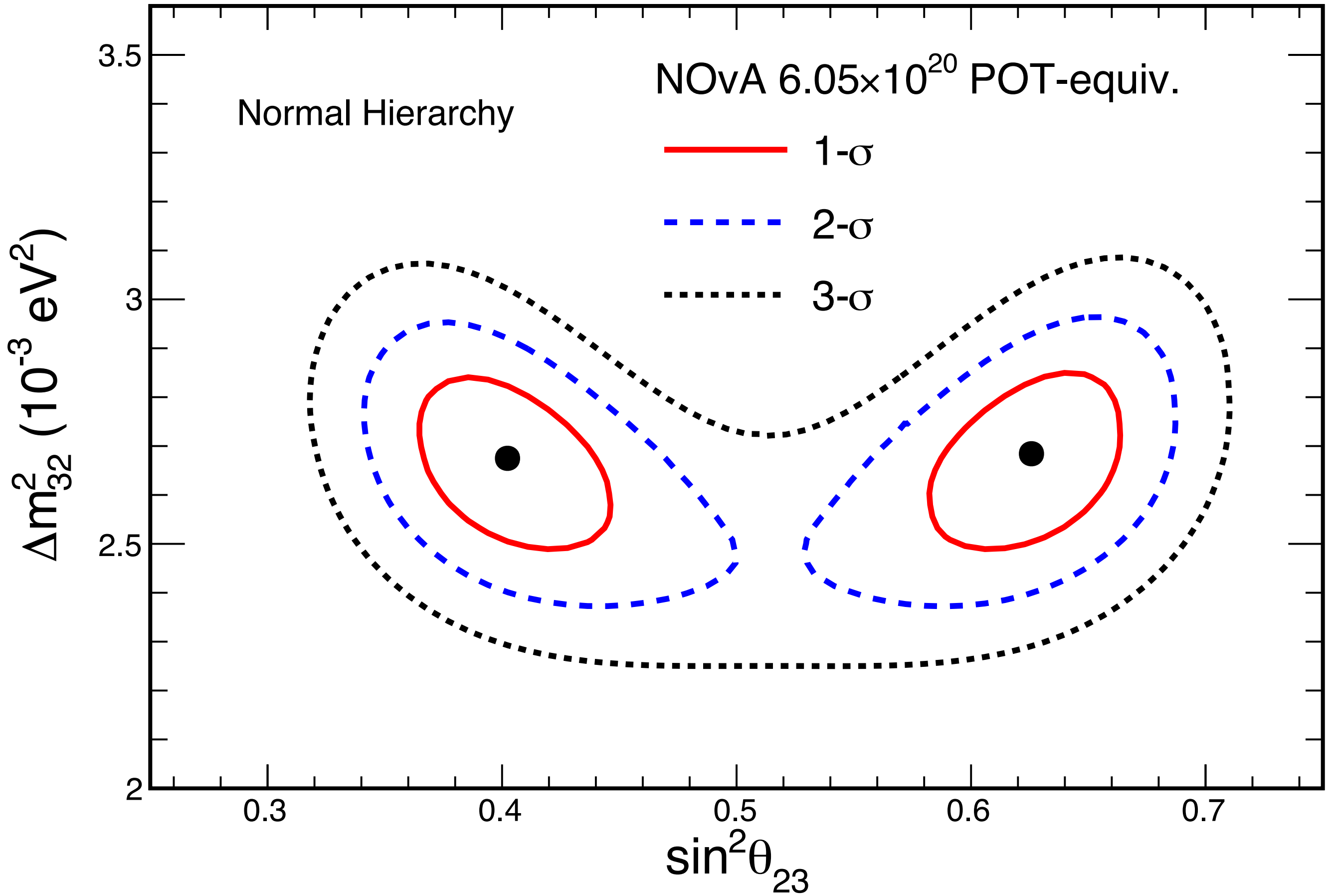
NOvA Preliminary



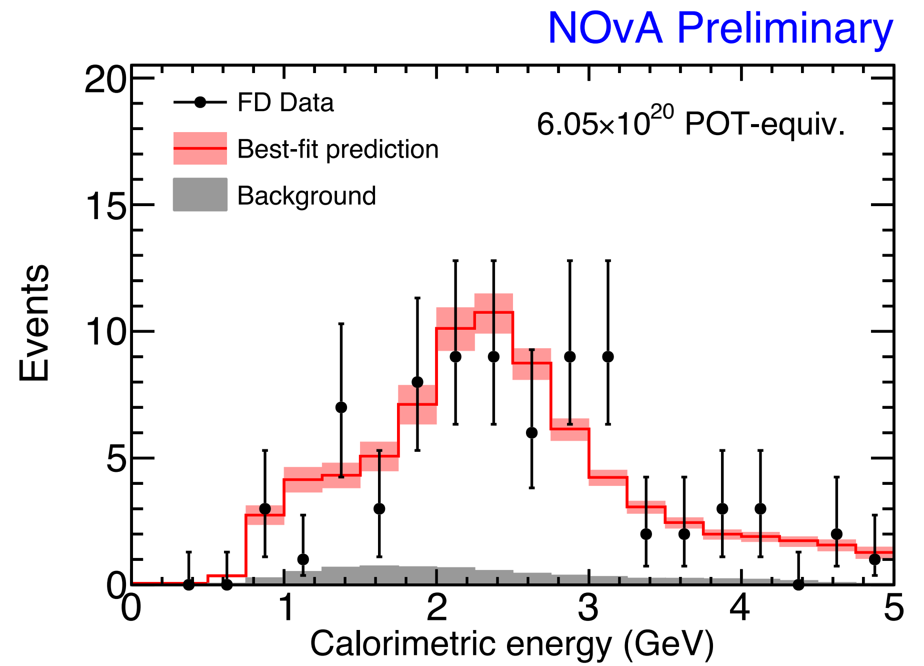
NOvA Preliminary

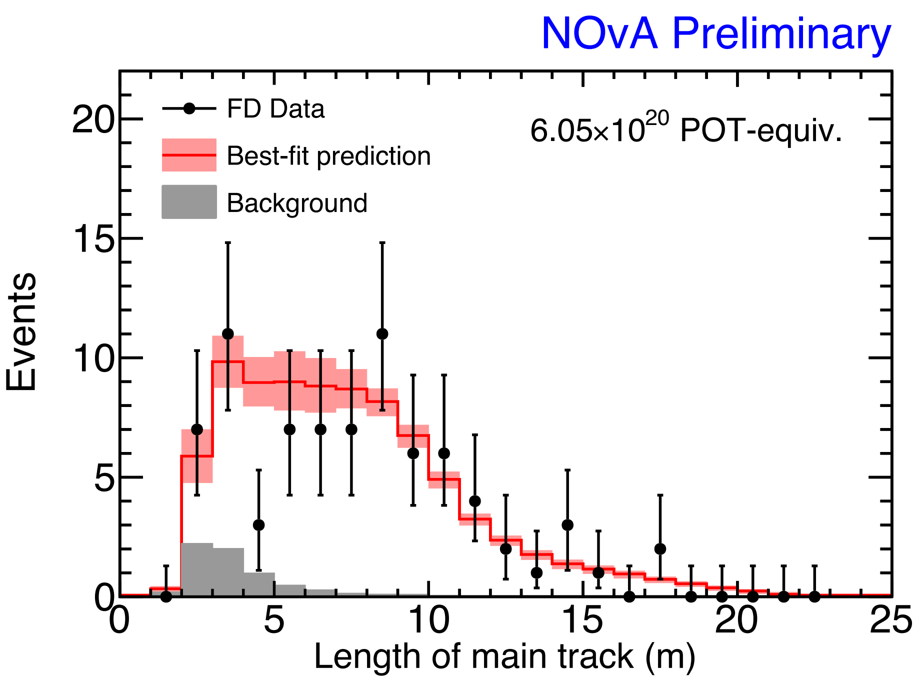


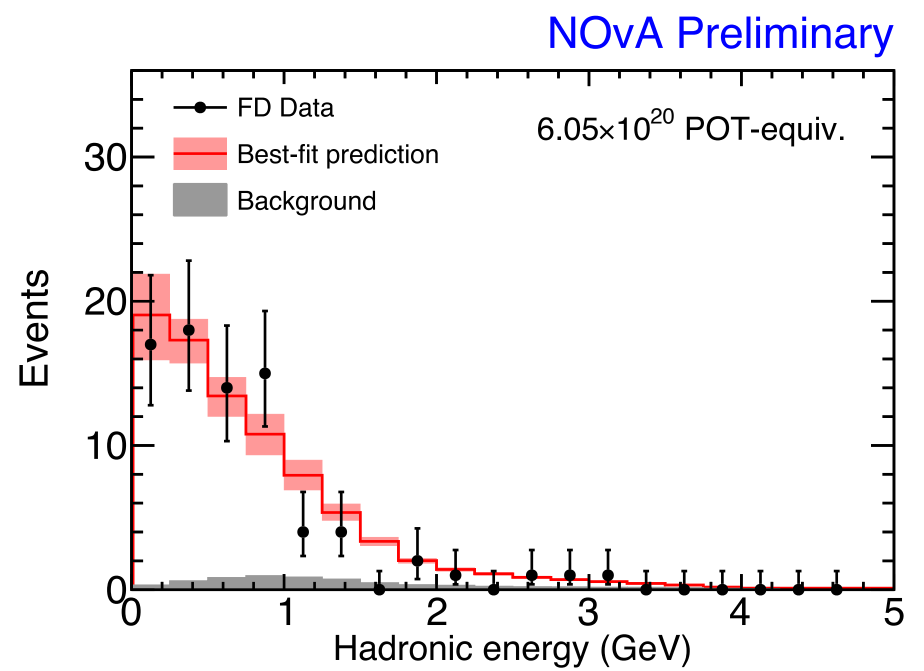
NOvA Preliminary

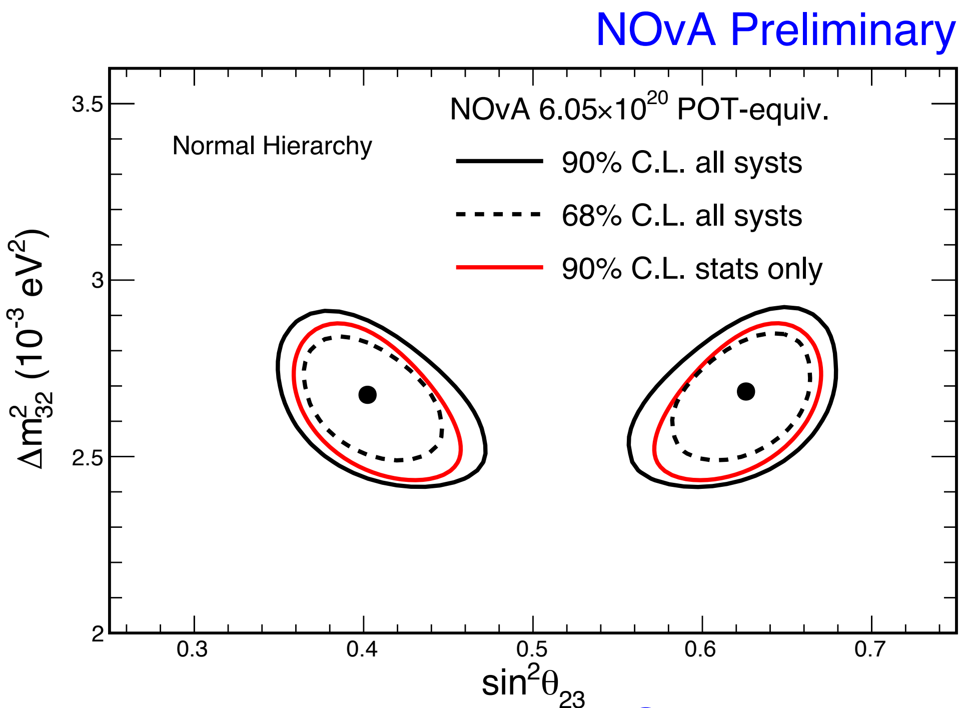


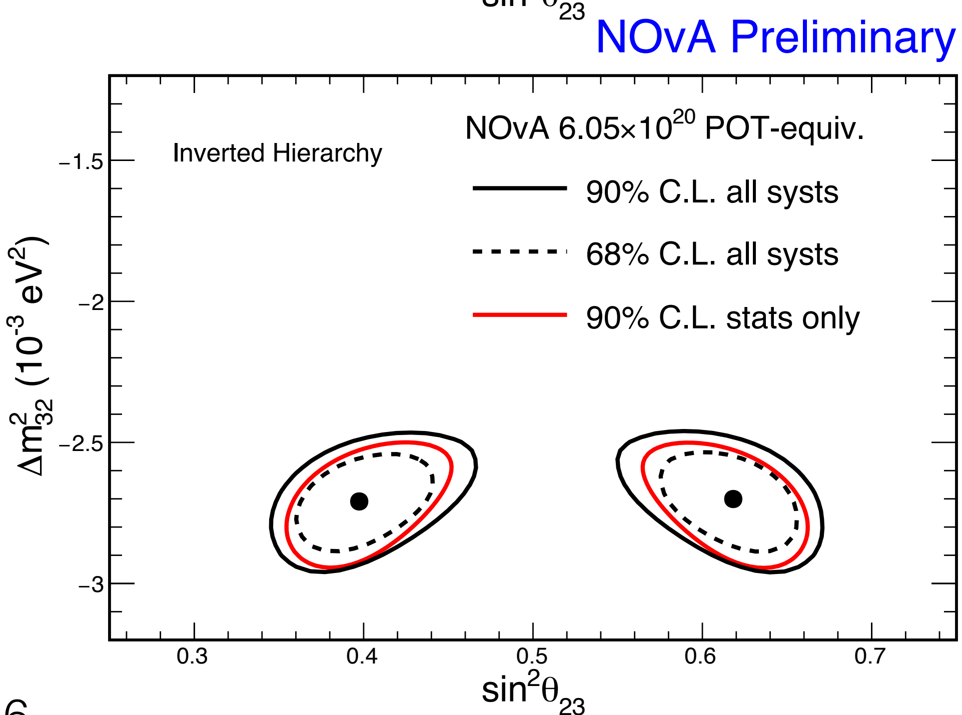
Our best fit oscillation prediction matches other distributions well








NOvA Preliminary
NOvA 6.05×10^20 POT-equiv.
Normal Hierarchy
90% C.L. all systs
68% C.L. all systs
90% C.L. stats only
Δm²32 (10^-3 eV²)
sin²θ23

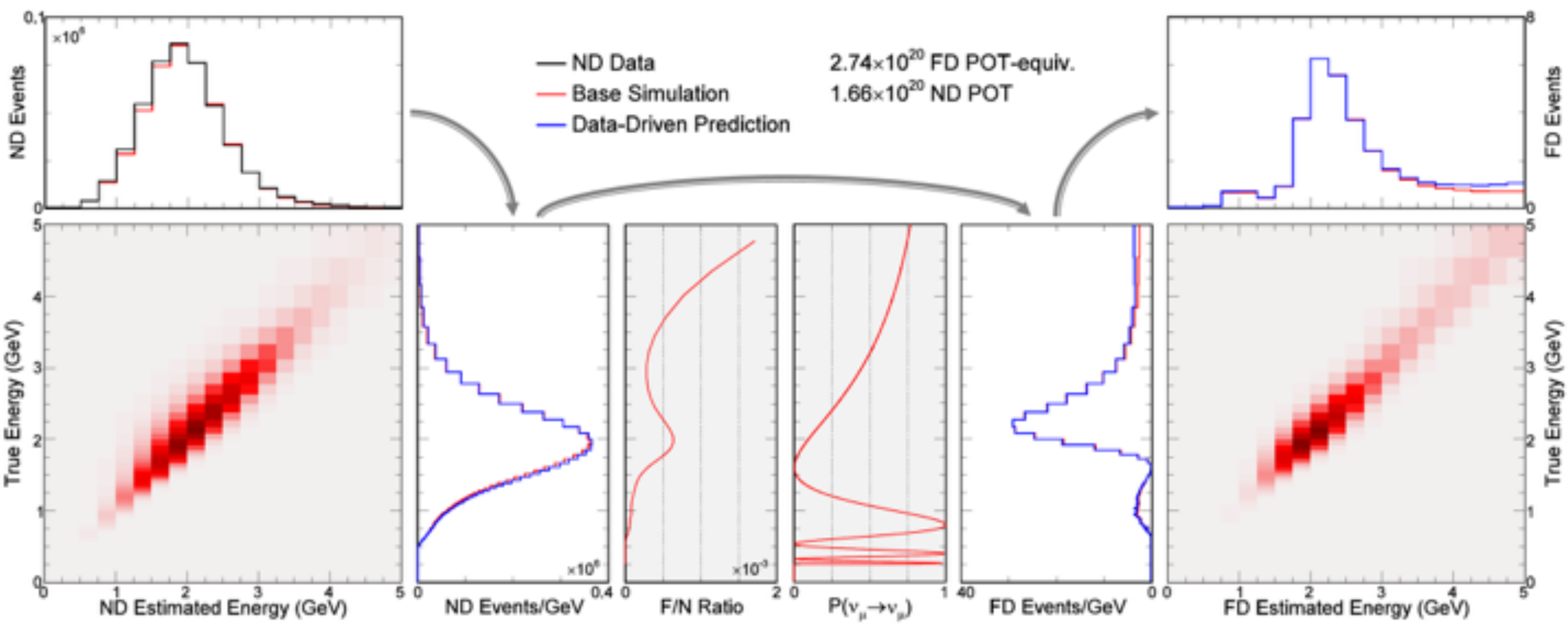

NOvA Preliminary
NOvA 6.05×10^20 POT-equiv.
Inverted Hierarchy
90% C.L. all systs
68% C.L. all systs
90% C.L. stats only
Δm²32 (10^-3 eV²)
sin²θ23

(1) Estimate the underlying **true energy distribution** of selected ND events

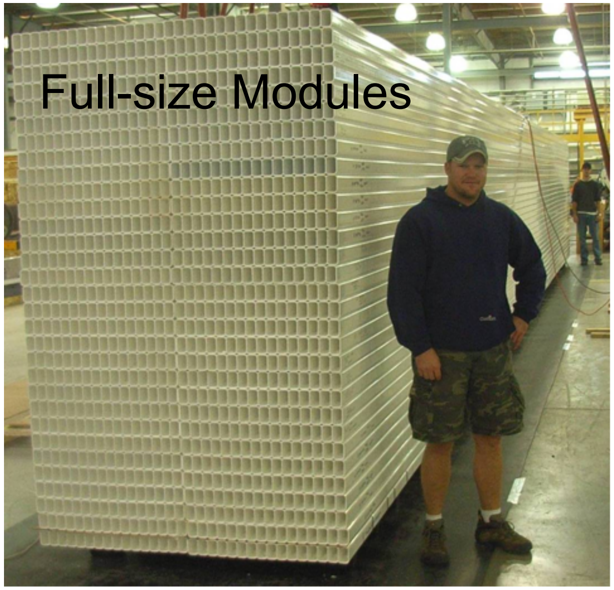
(2) Multiply by expected **Far/Near event ratio** and $\nu_\mu \rightarrow \nu_\mu$ **oscillation probability** as a function of true energy

(3) Convert FD true energy distribution into **predicted FD reco energy distribution**

Systematic uncertainties assessed by **varying all MC-based steps**

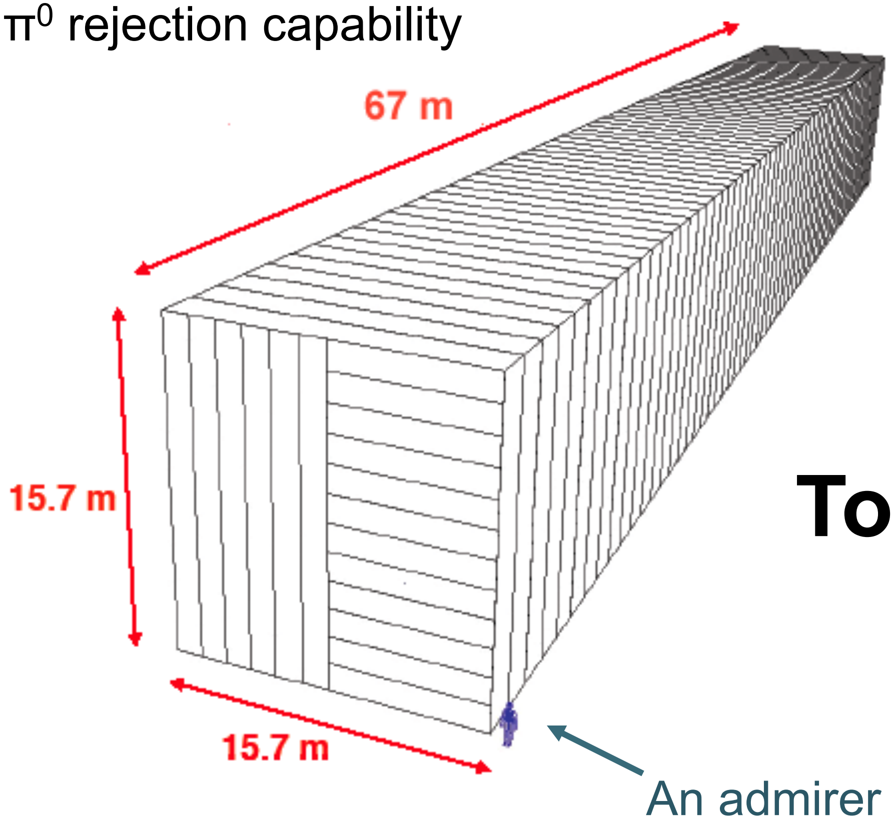


NOvA Far Detector



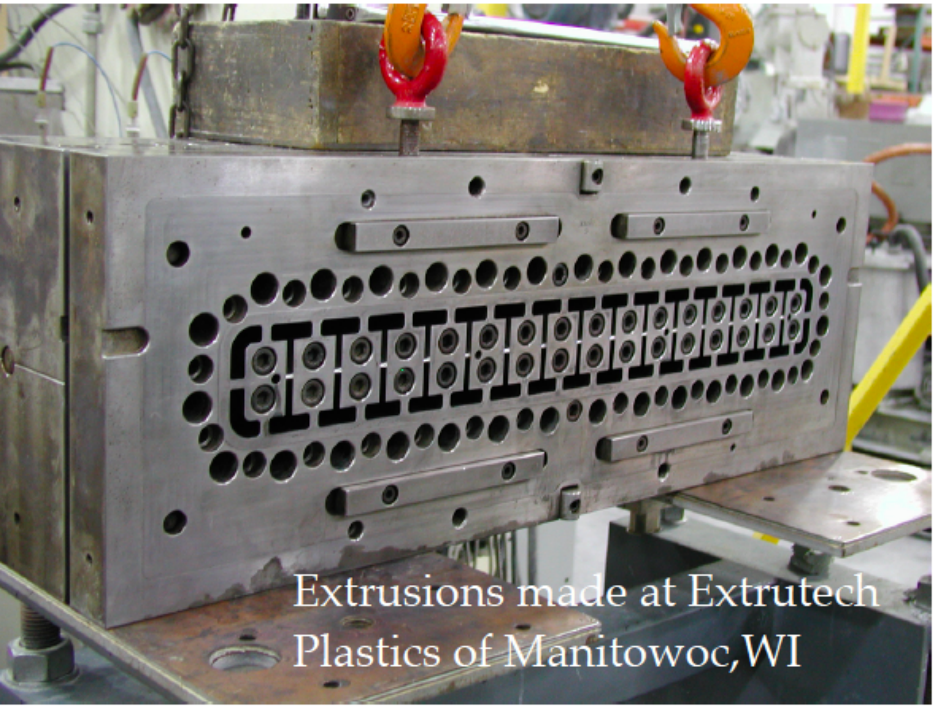
TASD: Totally Active Scintillator Design

Longitudinal sampling is ~0.15 X_0, which gives:
-- excellent μ-*e* separation
-- π^0 rejection capability



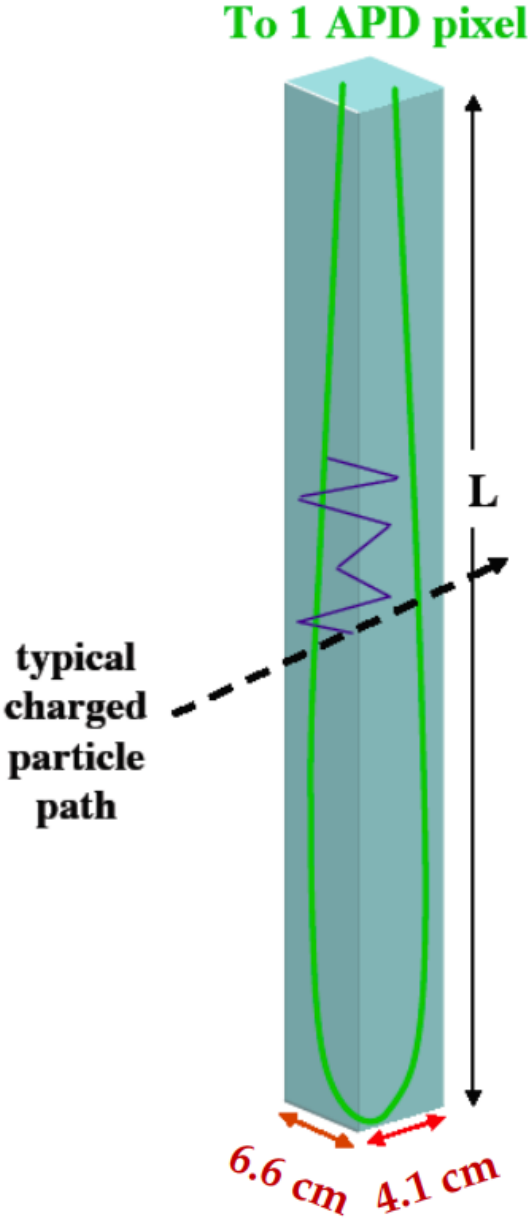
Total mass of 14 ktons

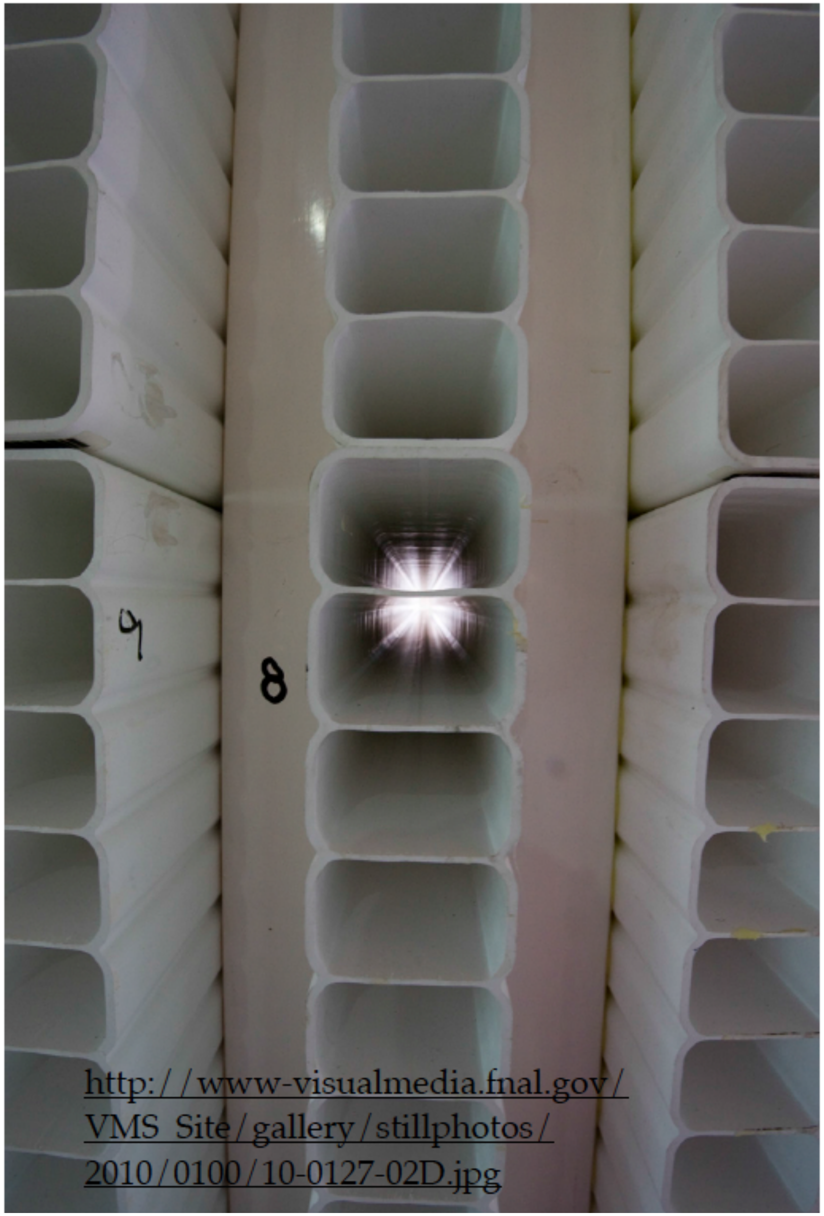
Extrusions



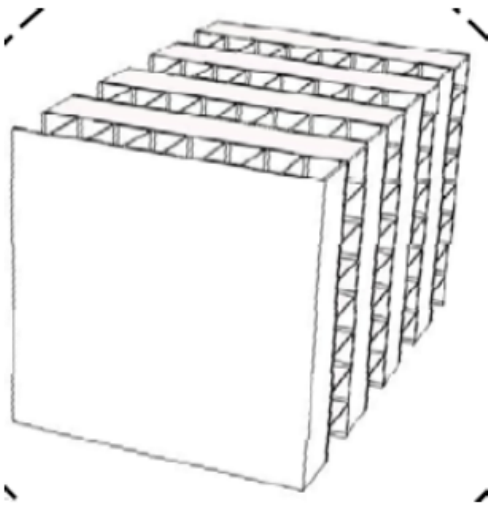
- PVC extruded through die to form 15.7m extrusions
- ~24,000 required for Far Detector.

Detector Elements

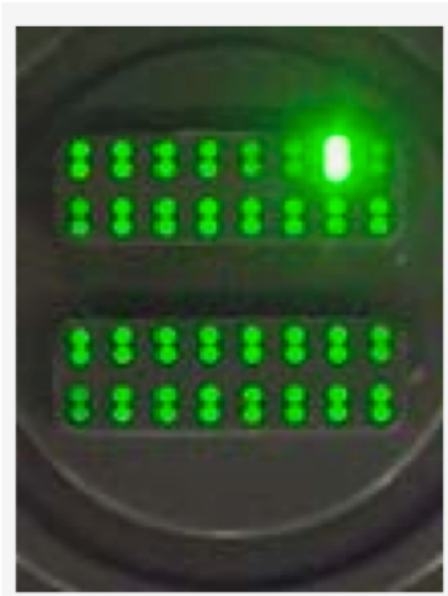


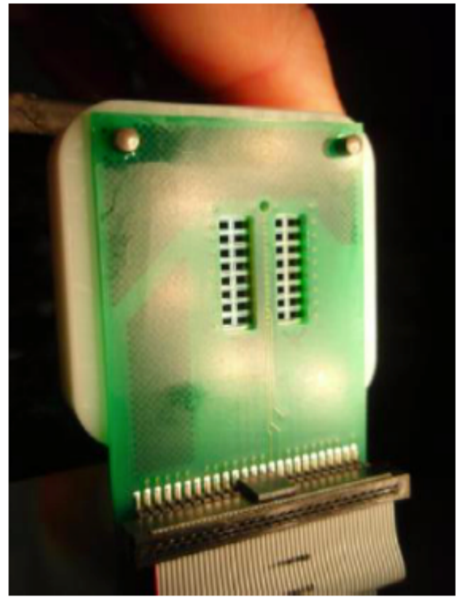


- Cells with liquid scintillator grouped into alternating planes



[L. Corwin]





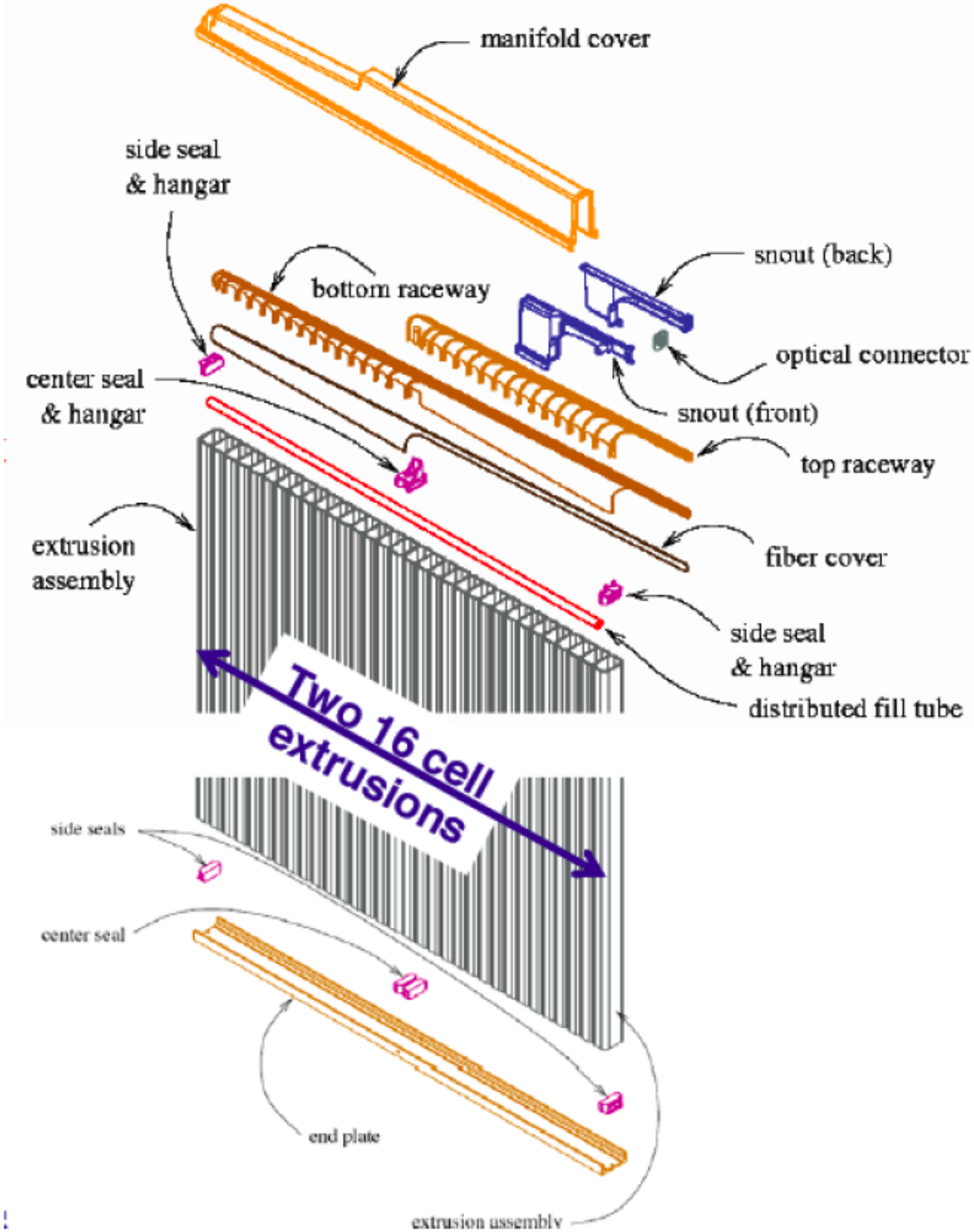
Scintillation light travels along wavelength shifting fibers to end of manifold

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

[L. Corwin]

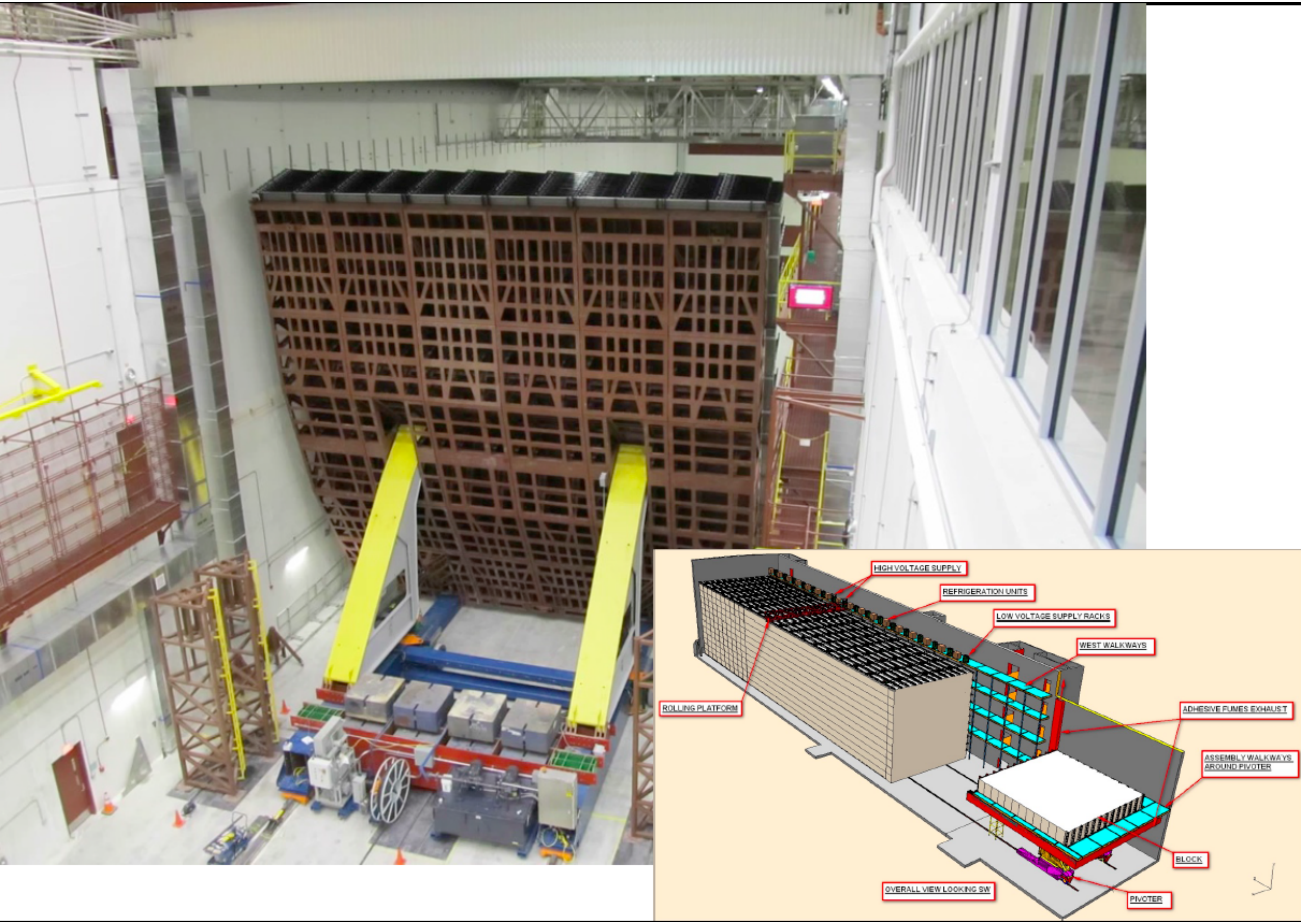
Modules

- 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

[L. Corwin]



HIGH VOLTAGE SUPPLY
REFRIGERATION UNITS
LOW VOLTAGE SUPPLY RACKS
WEST WALKWAYS
ROLLING PLATFORM
ADHESIVE FUMES EXHAUST
ASSEMBLY WALKWAYS AROUND PIVOTER
BLOCK
OVERALL VIEW LOOKING SW
PIVOTER

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