

# The NOvA Neutrino Experiment

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# NuMI Off-axis electron neutrino [ $\nu_e$ ] Appearance



# Neutrino Mixing Matrix and Masses

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{-i\delta} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

atmospheric  $\nu$ 
Mixed Term
solar  $\nu$

Sometimes around '2010



# Neutrino Mixing Matrix and Masses

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \text{atmospheric } \nu & \text{Mixed Term} & \text{solar } \nu \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{-i\delta} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric:  $\Delta m_{31}^2 = (2.45 \pm 0.009) \times 10^{-3} eV^2$

$$\sin^2 \theta_{23} = 0.51 \pm 0.06$$

Solar:  $\Delta m_{21}^2 = (7.59_{-0.18}^{+0.20}) \times 10^{-5} eV^2$

$$\sin^2 \theta_{12} = 0.312_{-0.015}^{+0.017}$$

*arXiv:1108.1376*



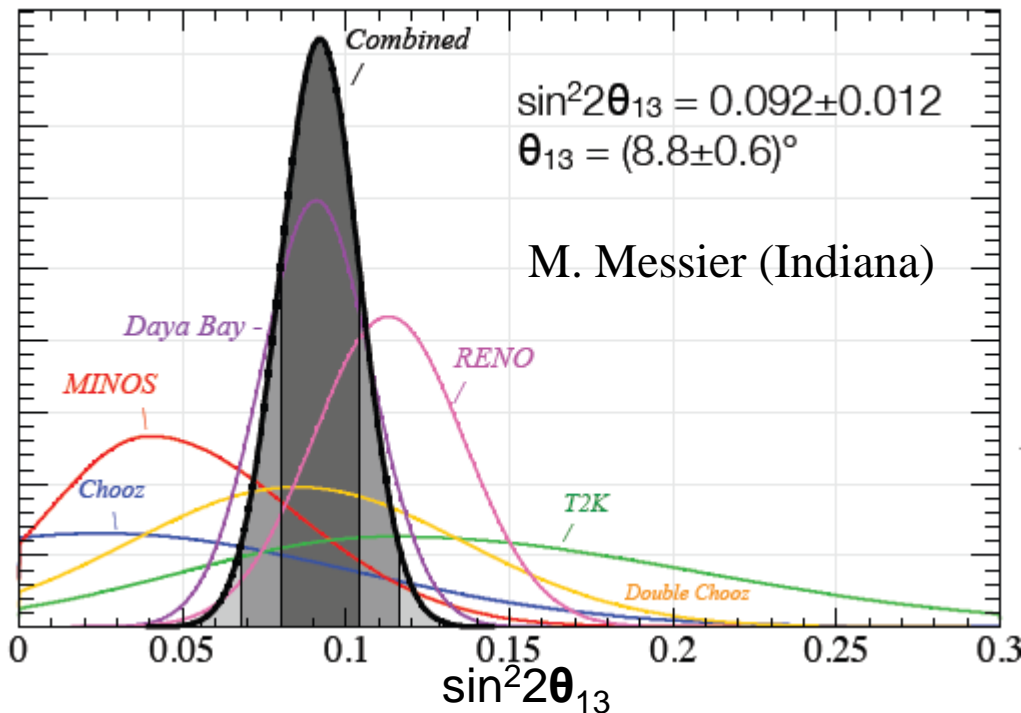
# Neutrino Mixing Matrix and Masses

atmospheric  $\nu$

Mixed Term

solar  $\nu$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{-i\delta} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



- Daya Bay  $0.092 \pm 0.017$   
 ✓ arXiv:1203.1669v2 [hep-ex]
- RENO  $0.113 \pm 0.023$  (revised)  
 ✓ arXiv:1204.0626v2 [hep-ex]
- Reactor Average (2012)  
 ✓  $0.099 \pm 0.014$
- Current Combined Average**  
 ✓  **$0.085 \pm 0.005$**



# Open Questions In Neutrino Physics

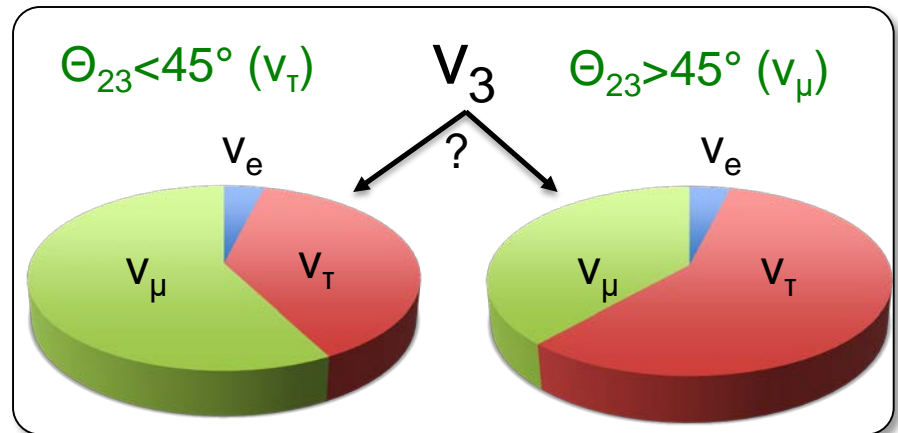
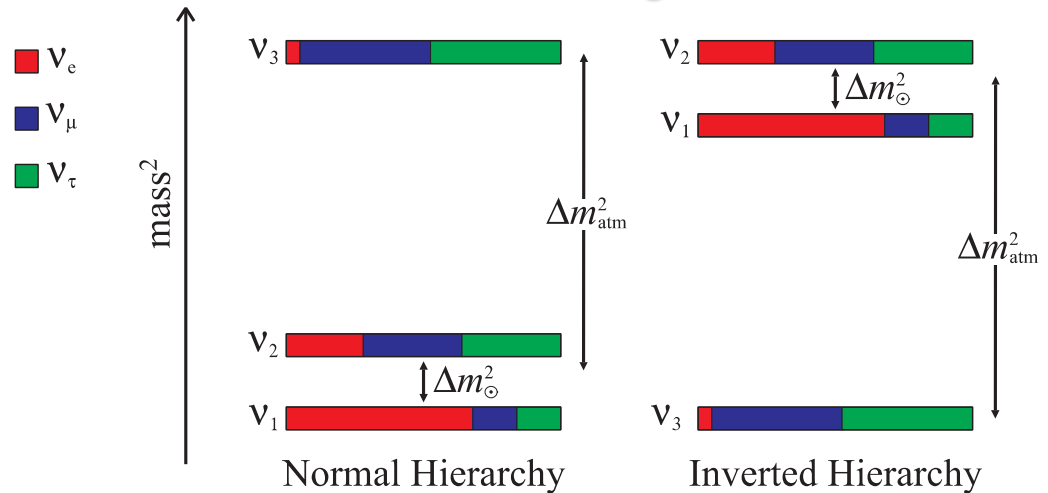
□ Mass hierarchy?

□ Nature of  $\nu_3$  -  $\theta_{23}$  octant?

□ Is CP violated?

Might neutrinos play an important role in anti/matter symmetry?

□ Is anything beyond this picture??



# NOvA experiment

The **NOvA** experiment is a **long-baseline neutrino** experiment designed to make measurements to determine **the neutrino mass hierarchy**, neutrino **mixing parameters** and **CP violation** in the neutrino sector.

The NOvA collaboration has designed and built a highly **distributed, synchronized, continuous digitization and readout system** that is able to acquire and correlate data from the Fermilab accelerator complex (**NuMI**), the NOvA **near detector** at the **Fermilab** site and the **NOvA far detector** which is located **810 km** away at Ash River, MN..



# Neutrino Oscillation/Transition in NOvA Exp

$$\begin{aligned}
 \begin{matrix} P(\nu_\mu \rightarrow \nu_e) \\ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \end{matrix} &\approx \underbrace{\sin^2(2\theta_{13})}_{\text{blue}} \underbrace{\sin^2(\theta_{23})}_{\text{orange}} \underbrace{f^\pm(L, E, \Delta m_{31}^2)}_{\text{cyan}} \\
 &+ \left\{ \underbrace{\cos \delta_{\text{CP}}}_{\text{green}} \cos \frac{\Delta m_{31}^2 L}{4E} \mp \underbrace{\sin \delta_{\text{CP}}}_{\text{green}} \sin \frac{\Delta m_{31}^2 L}{4E} \right\} \\
 &\times 2 \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \sin(\theta_{13}) g^\pm(L, E, \Delta m_{31}^2, \theta_{12}, \theta_{23})
 \end{aligned}$$

$\pm$  neutrino mode

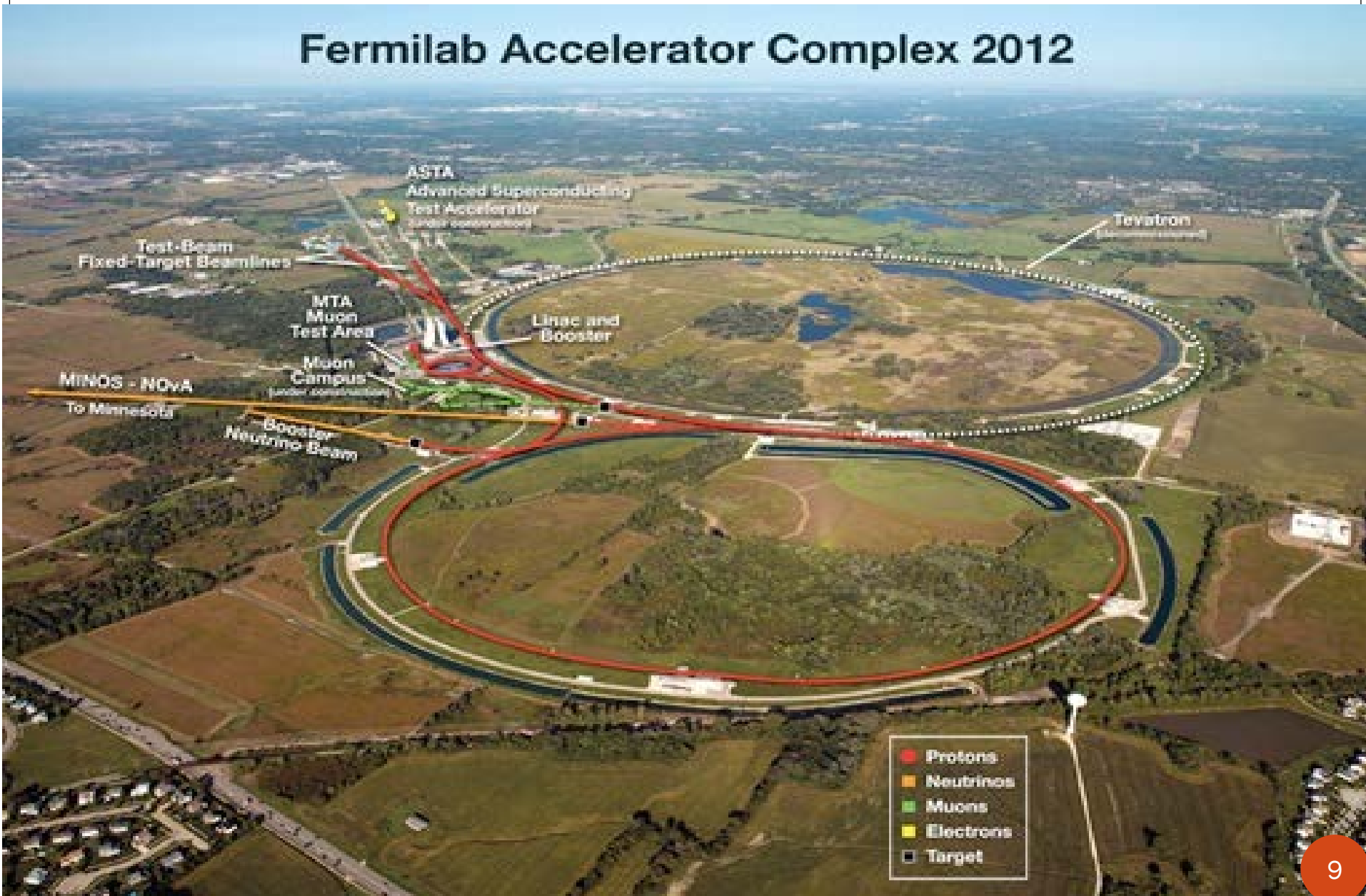
$\pm$  anti-neutrino mode

- ❑ The **NOvA baseline** ( $L = 810$  km) and **neutrino beam energy** ( $E = 2$  GeV) place our detector at the first  $\nu_\mu \rightarrow \nu_e$  oscillation peak.
- ❑  **$\sin^2 2\theta_{13}$** : the leading term in this equation has already been measured and it is large!
- ❑  **$\sin^2 \theta_{23}$** : we get information about the  $\theta_{23}$  octant from the leading term.
- ❑  **$\delta_{\text{CP}}$** : we have sensitivity to the CP-violating phase angle.
- ❑ **mass hierarchy**: depending on the sign of  $\Delta m_{31}^2$  ( $\sim \Delta m_{32}^2$ ), the oscillation probability is either enhanced or suppressed.

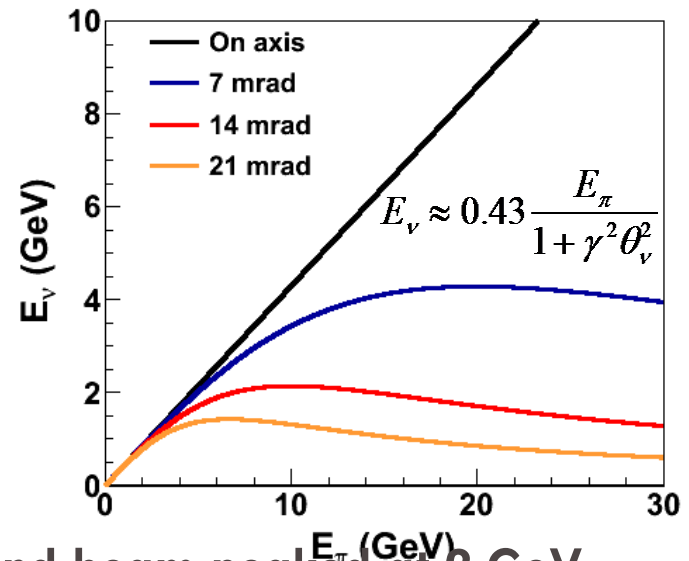
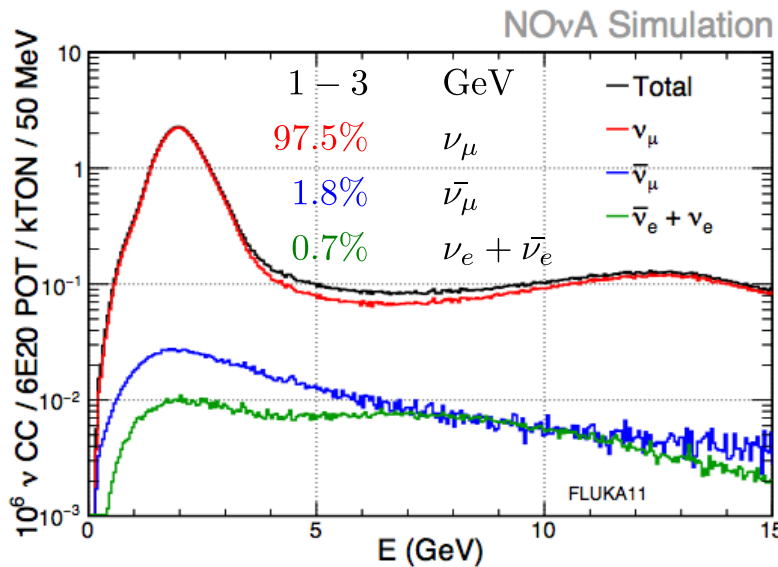
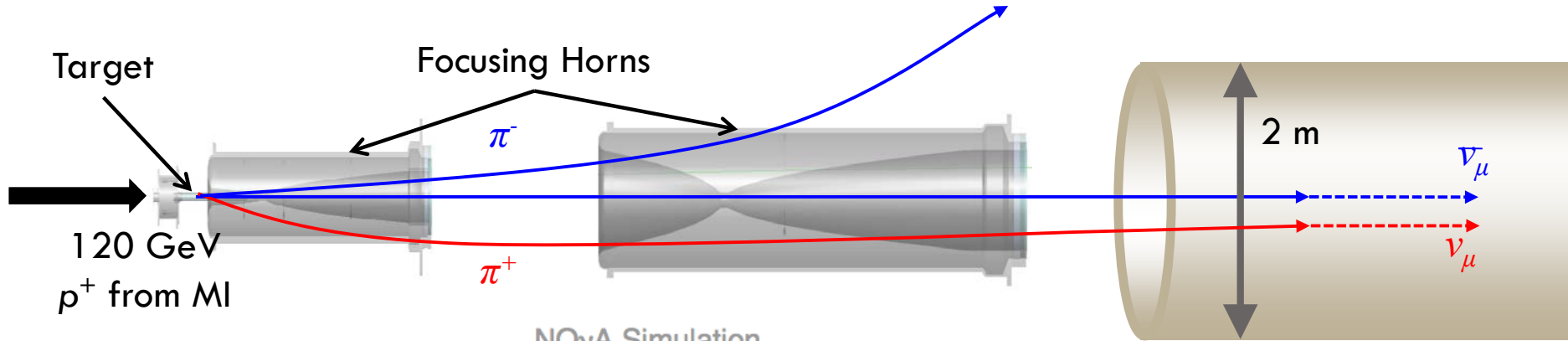


# Fermilab Accelerators

## Fermilab Accelerator Complex 2012

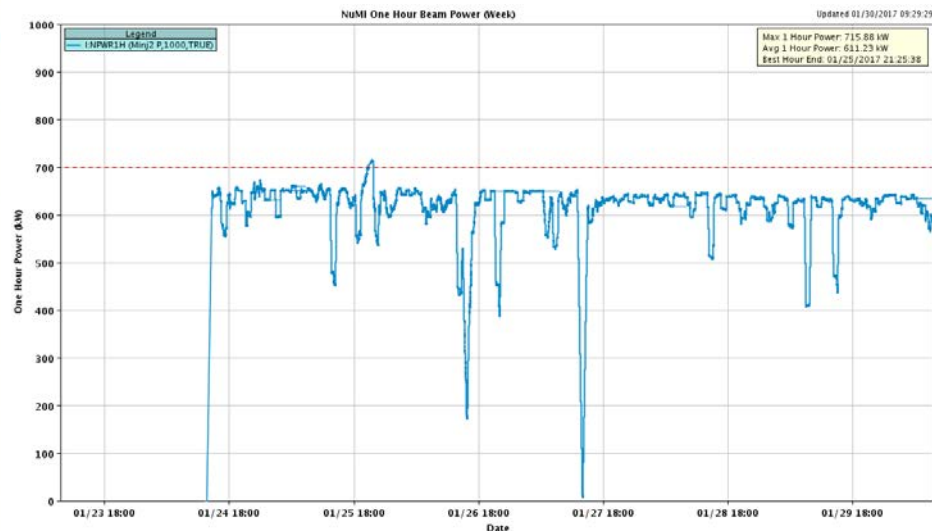
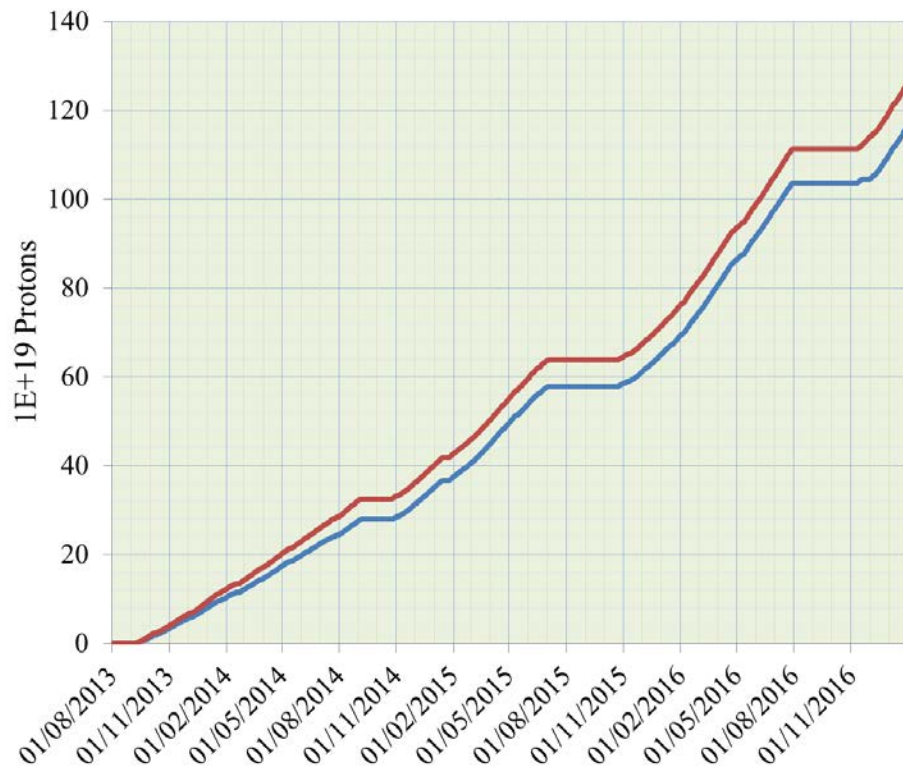


# Making an off-axis neutrino beam



- At 14 mrad off-axis, narrow band beam peaked at 2 GeV
- ▣ Near oscillation maximum
- ▣ Few high energy NC background events

# Beam Delivered



□ 635.6kW NuMI with SY => 700 KW NuMI only

□ 1 hour beam power record: 715.88 kW (1/25/17 20:25 to 21:25)

Congratulations and thank you to all at Fermilab that helped achieve this significant milestone and continued excellent beam delivery

# NOvA instrumentation

Far Detector site



Block construction



Outfitted Far Detector



Near Detector





# Block Zero Installed

September 10, 2012



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

# FarDet: LAST BLOCK IN PLACE



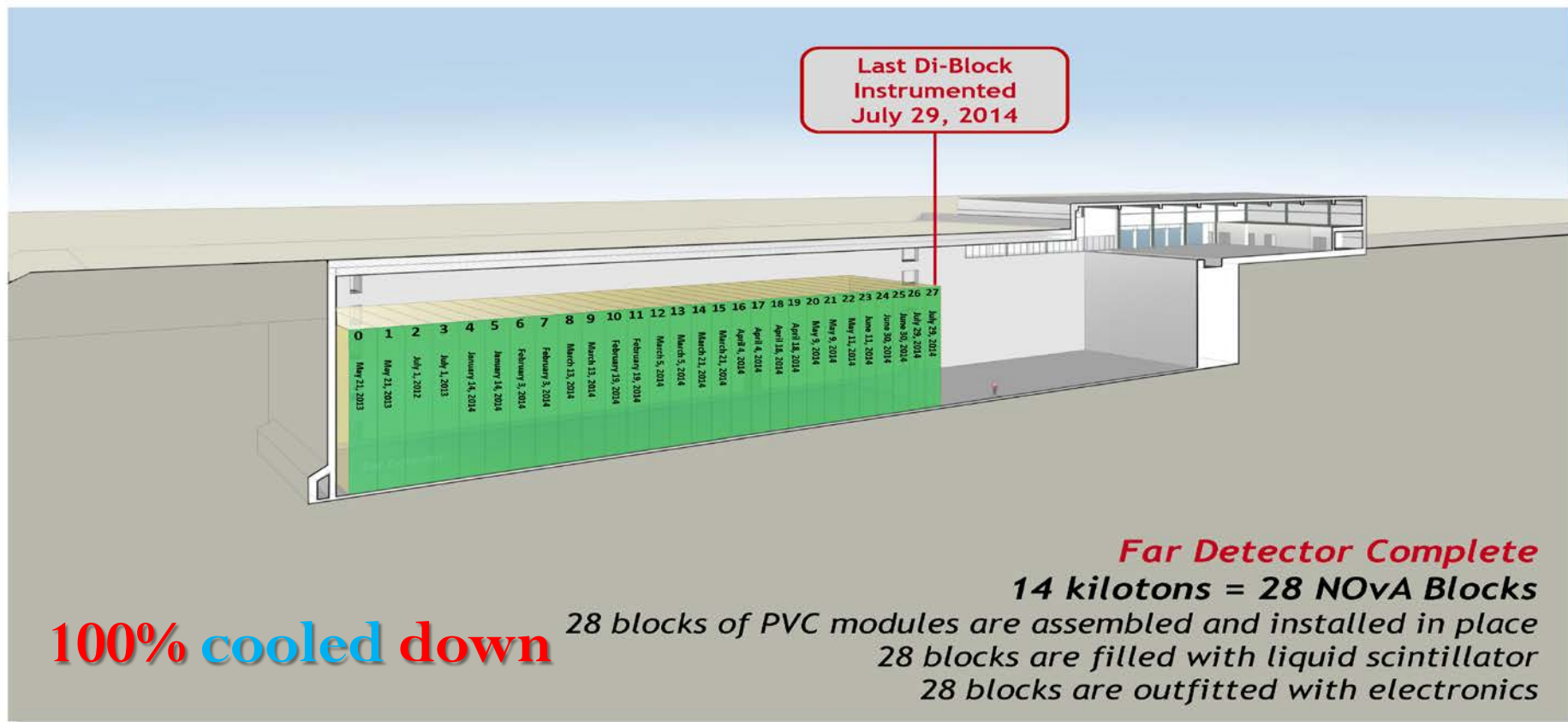
**Milestone:**  
**Last Block in place**  
**Feb 26, 2014 at 4:55PM**

# FD: Detector Assembly Progress

The Intensity Frontier

## NOvA Far Detector Assembly Progress

Status Date: 29 JUL 14



✓ Done! May 2013 – July 2014

➤ We came in to the Retrofitting phase

# NOvA Far and Near Detectors



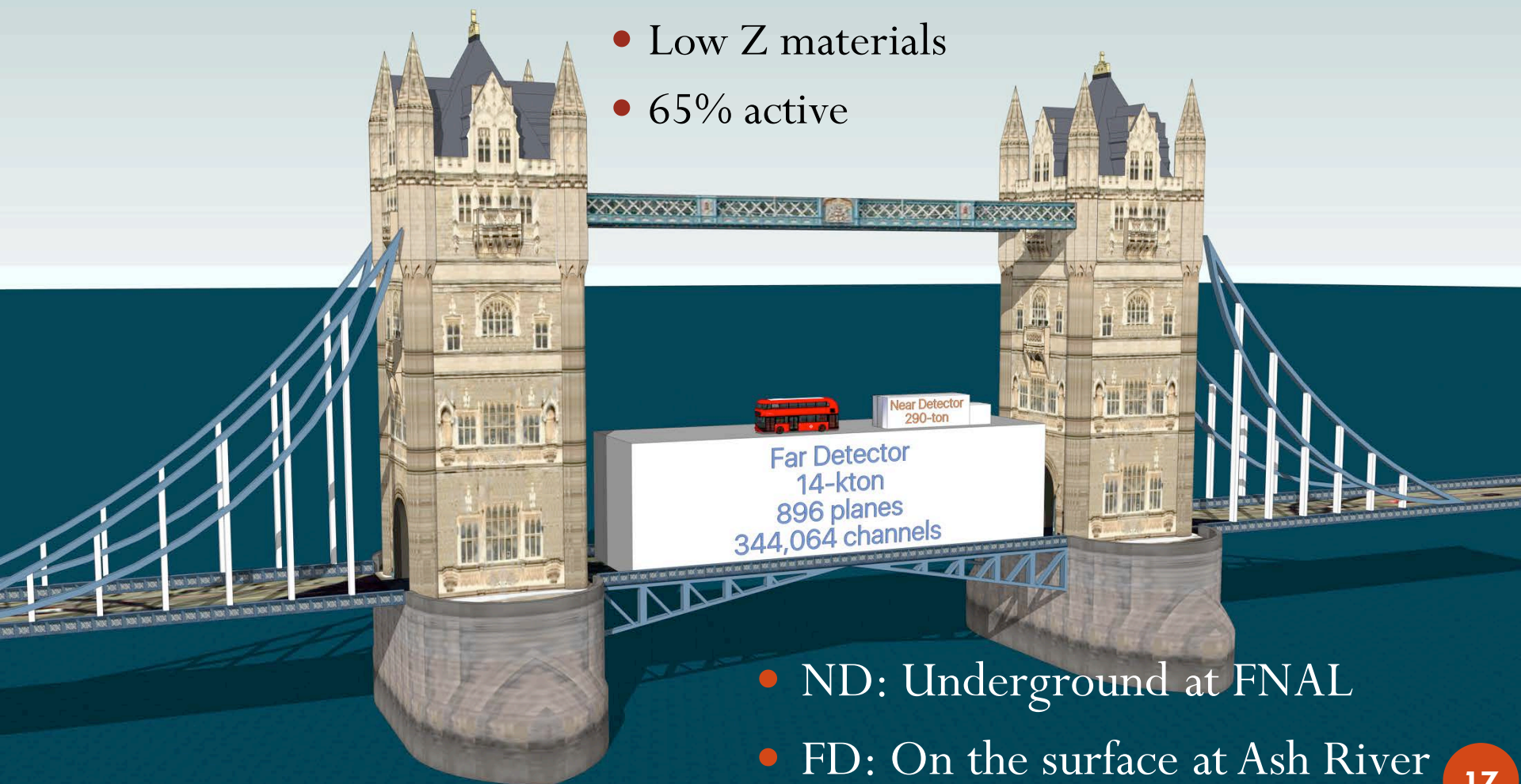
- A large 14+ kton Far Detector
- A smaller
- Functionally equivalent Near Detector
  - ▣ Reduced systematic uncertainties
- Highly segmented (alternating X/Y)
- 65% Active Volume
- Low Z materials (PVC and Oil)
  - ▣ Radiation length  $\sim 40$  cm





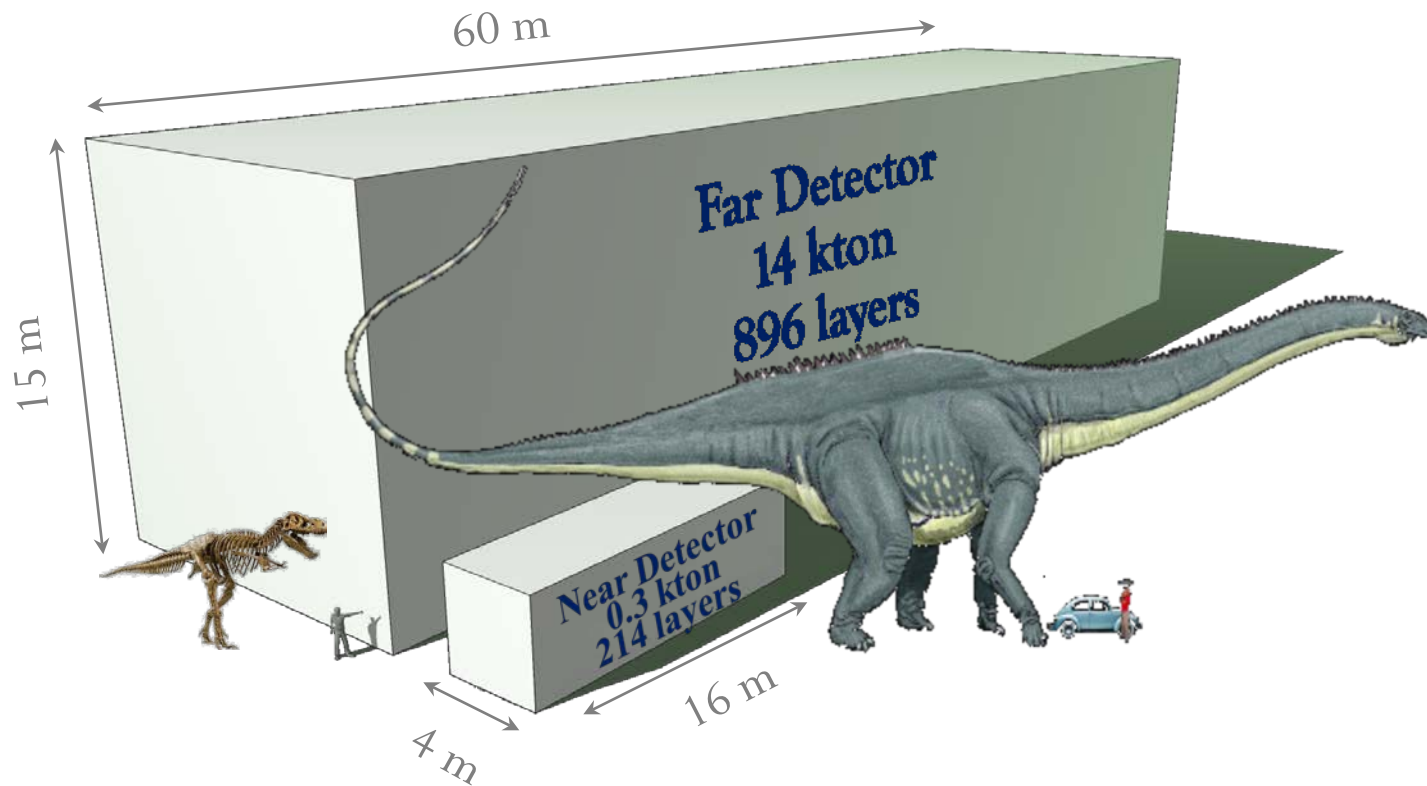
# NOvA Far and Near Detectors

- Designed for electron ID
- Low Z materials
- 65% active



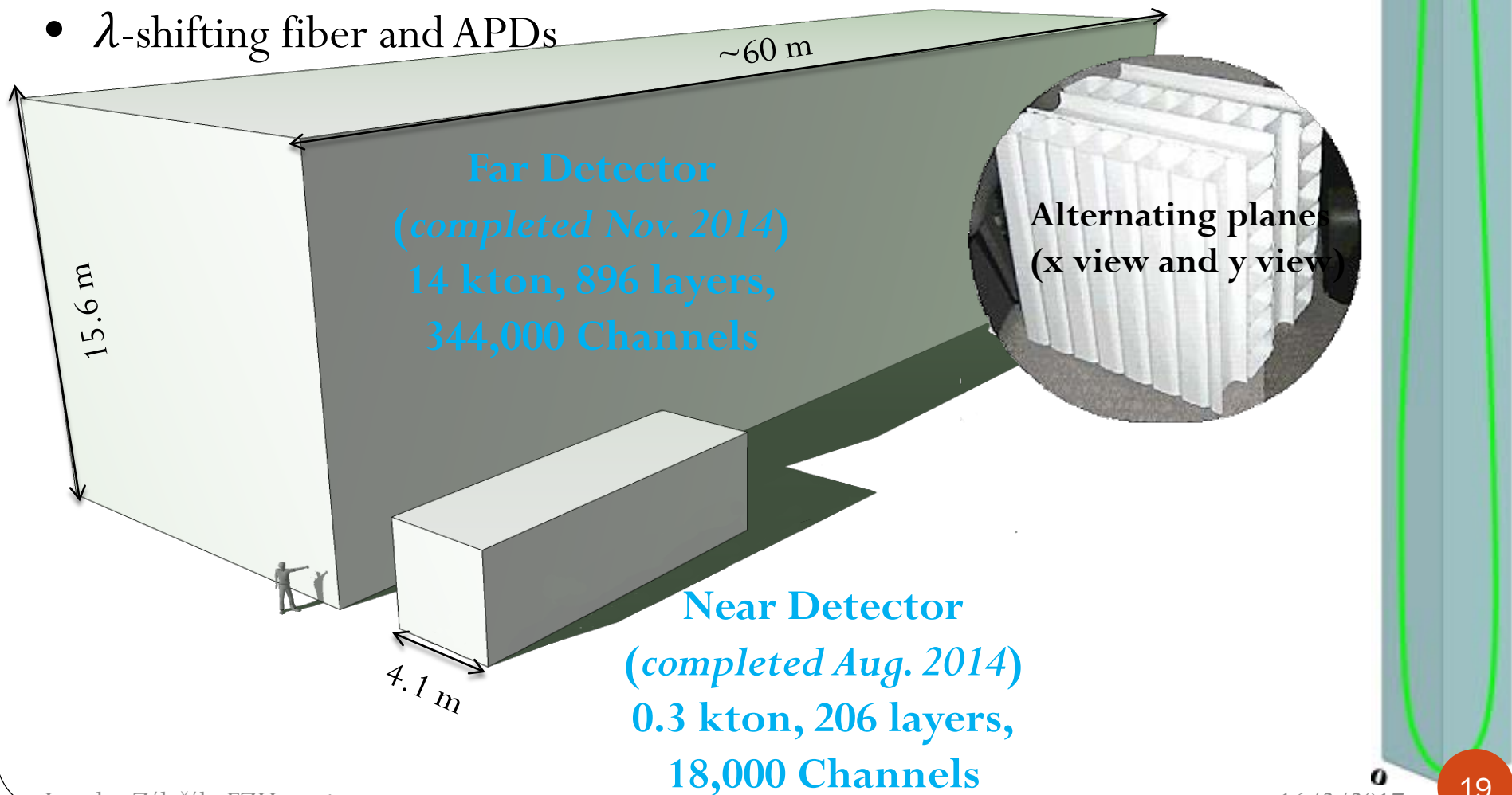
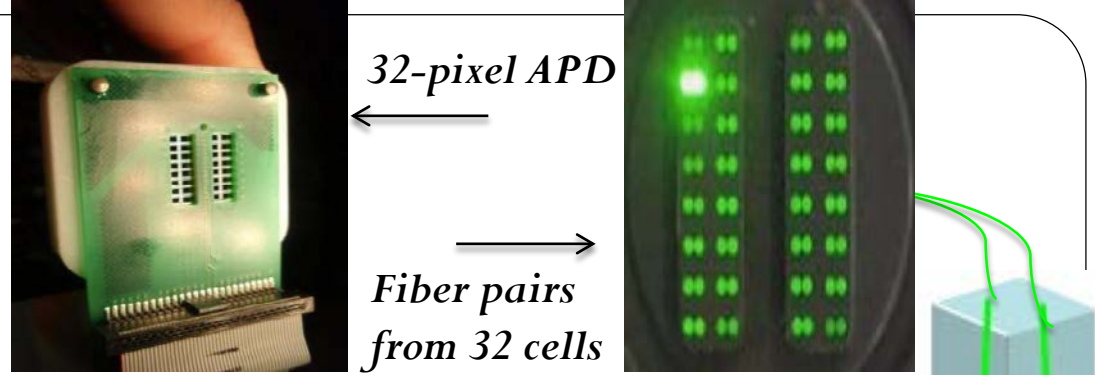
- ND: Underground at FNAL
- FD: On the surface at Ash River

# NOvA Far and Near Detectors



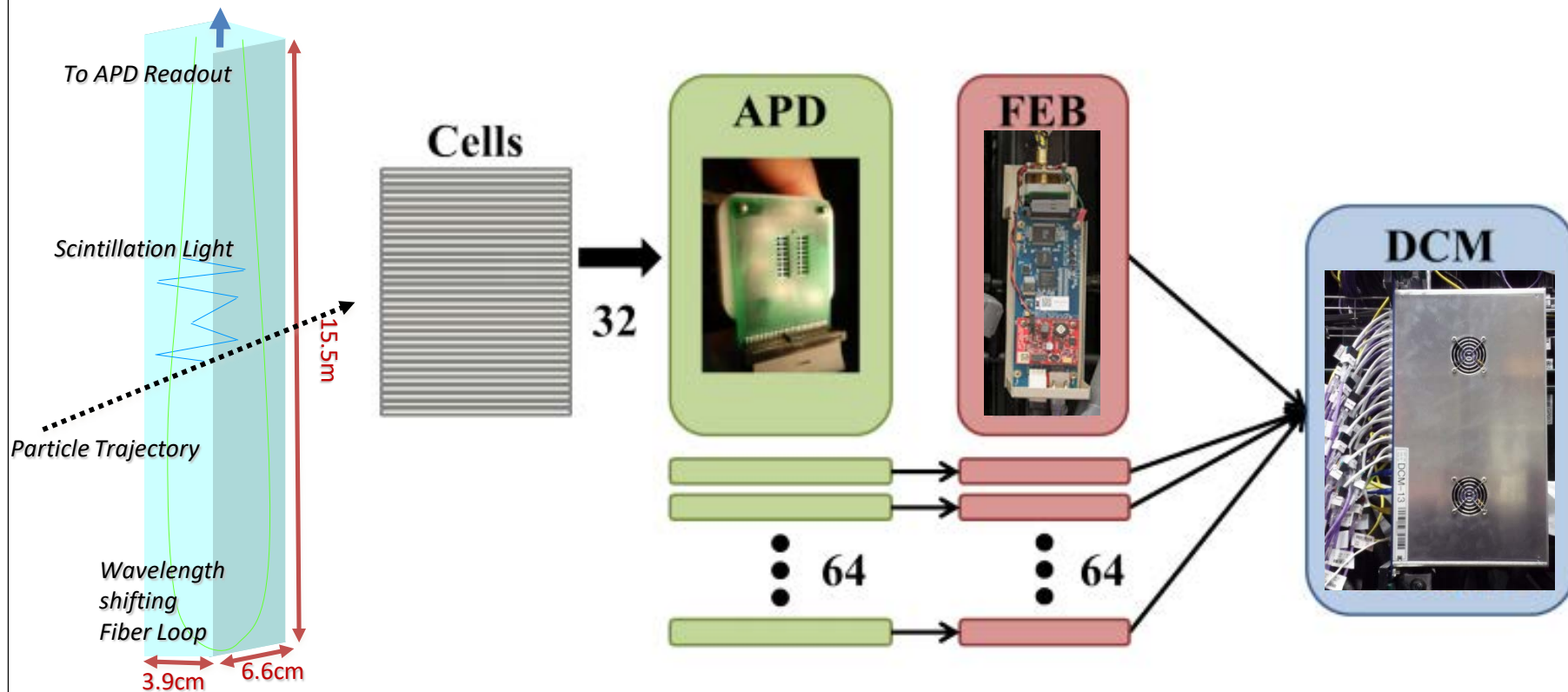
# NOvA detectors

- Fine-grained, low-Z, highly-active tracking calorimeters
- 11 M liters of scintillator
- $\lambda$ -shifting fiber and APDs

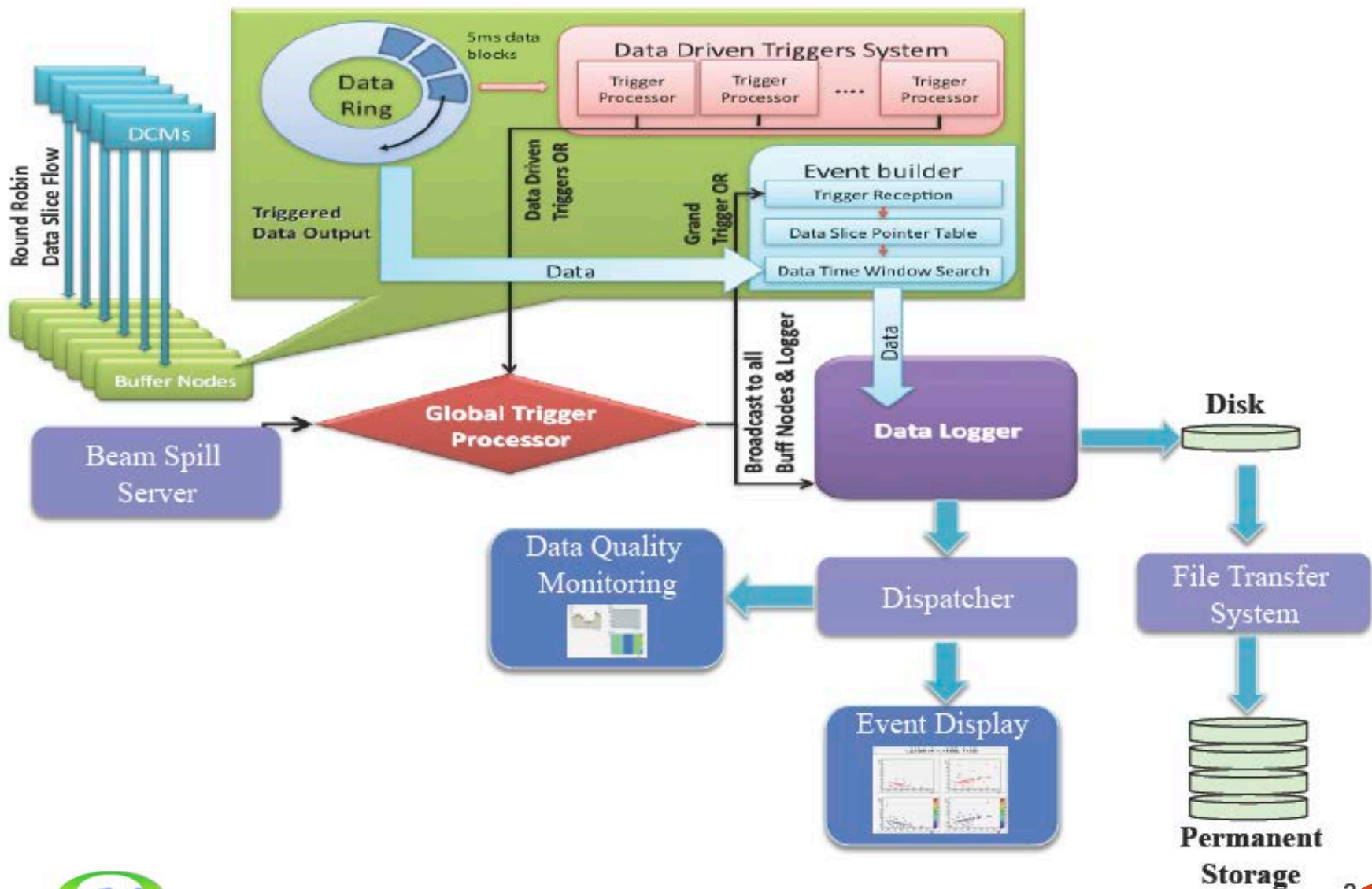


# The Detector Technology

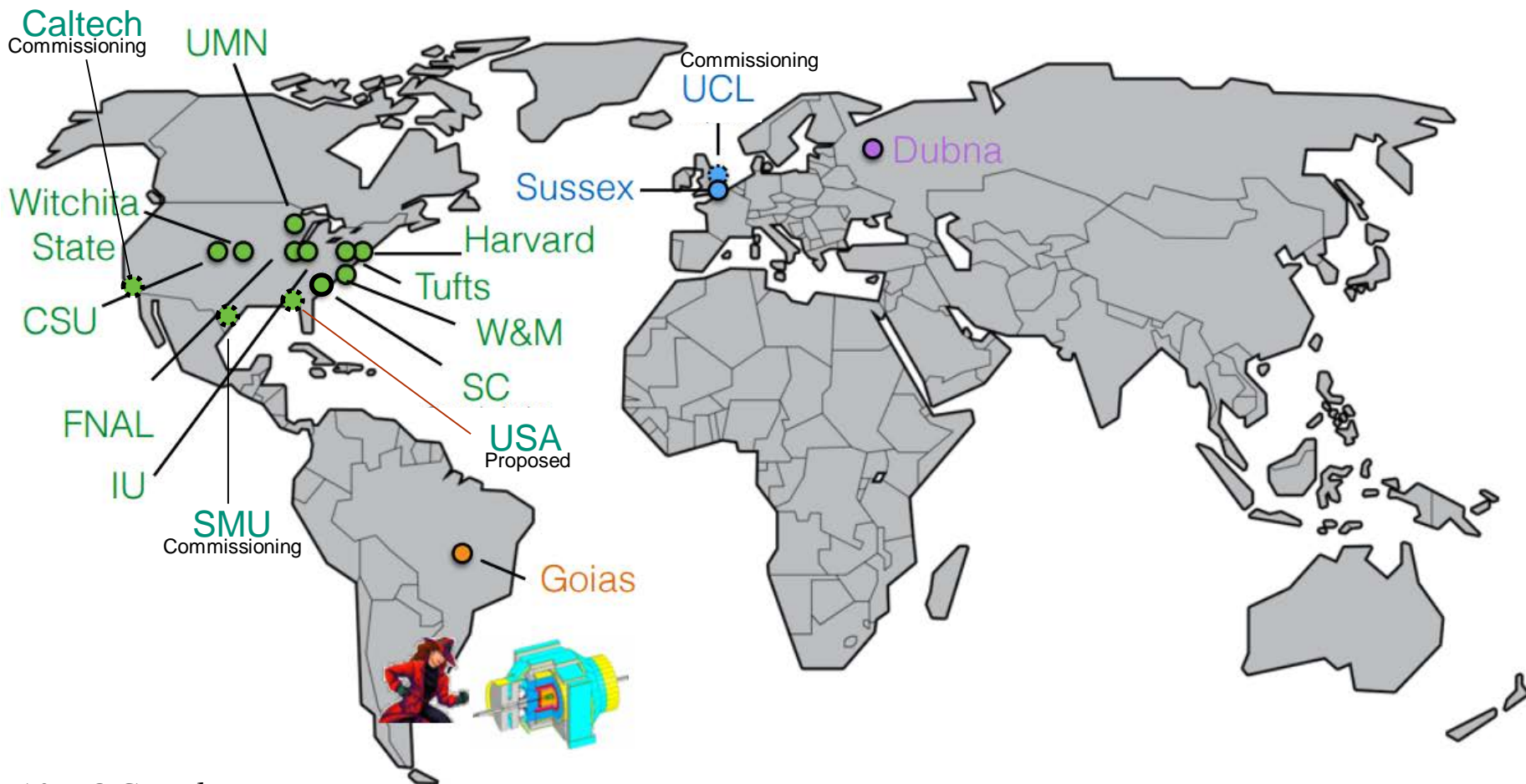
- Light is generated by charged particles and collected by wavelength-shifting fiber.
- Each avalanche photodiode (APD) reads out 32 cells.
- Each APD is connected to a Front End Board (FEB).
- The FEB digitizes signal, sends it to a Data Concentrator Module (DCM).
- Each DCM can read 64 FEBs.



# Data Acquisition System



# Remote Operation Centres



12 ROCs online.

ROC-SoCal (Caltech), ROC-UCL, ROC-SMU commissioning. ROC-USA proposed

# NOvA Physics Goals

## Results from 3 different oscillation analyses

### Disappearance of $\nu_\mu$ CC events

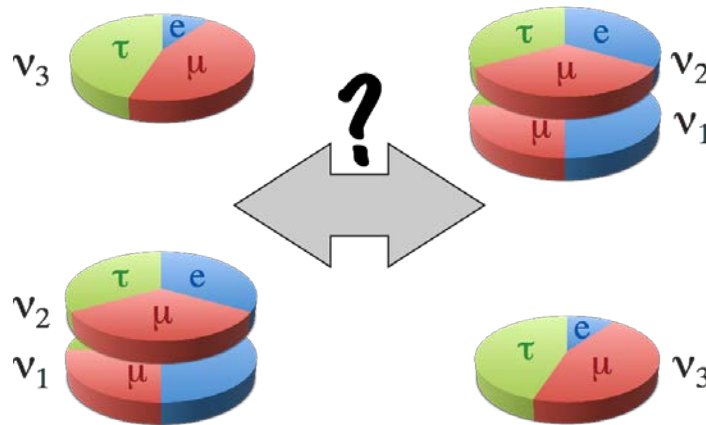
- clear suppression as a function of energy
- 2015 analysis results [Phys.Rev.D93.051104](#)
- **NEW** in [ArXiv1701.0589](#)

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

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

### Deficit of NC events?

- suppression of NCs could be evidence of oscillations involving a sterile neutrino
- Fit to 3+1 model



### Appearance of $\nu_e$ CC events

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

- 810 km baseline enhances matter effects
- $\pm 30\%$  effect
- 2015 analysis results in [PRL.116.151806](#)

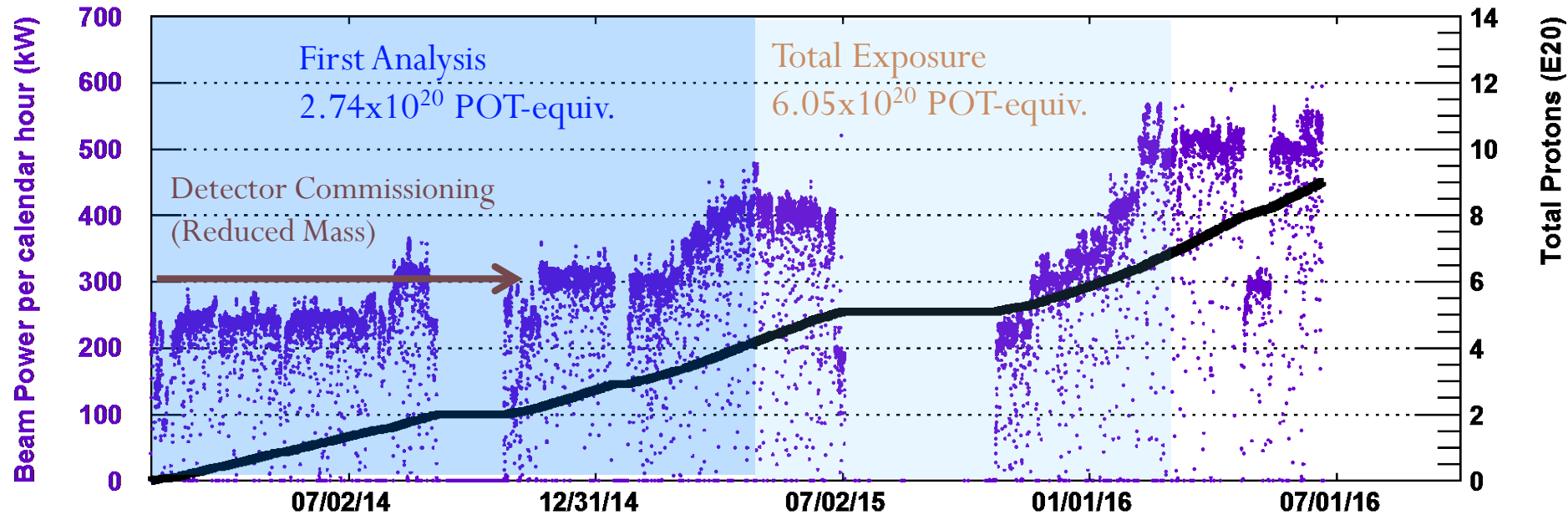
# NLO of NOvA Physics Goals

## Beyond Oscillation Physics

- ❑ Neutrino Cross Sections
- ❑ Neutrino Magnetic Moment
- ❑ Sterile Neutrinos
- ❑ Dark Matter
- ❑ Magnetic Monopoles
- ❑ Supernova
- ❑ WIMPs
- ❑ And More!



# NuMI Beam Exposure

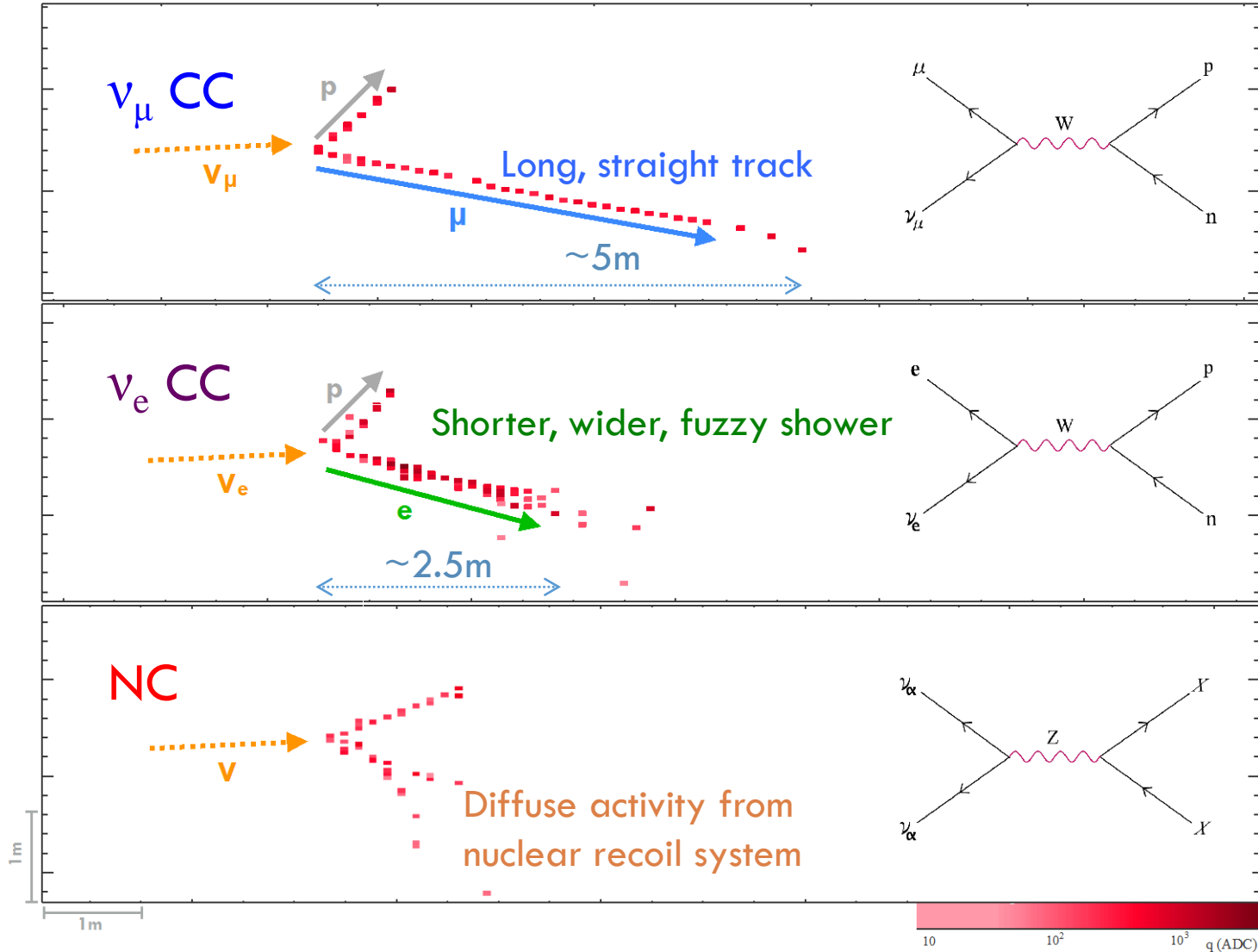


Beam is currently operating at  $\sim 640$  kW

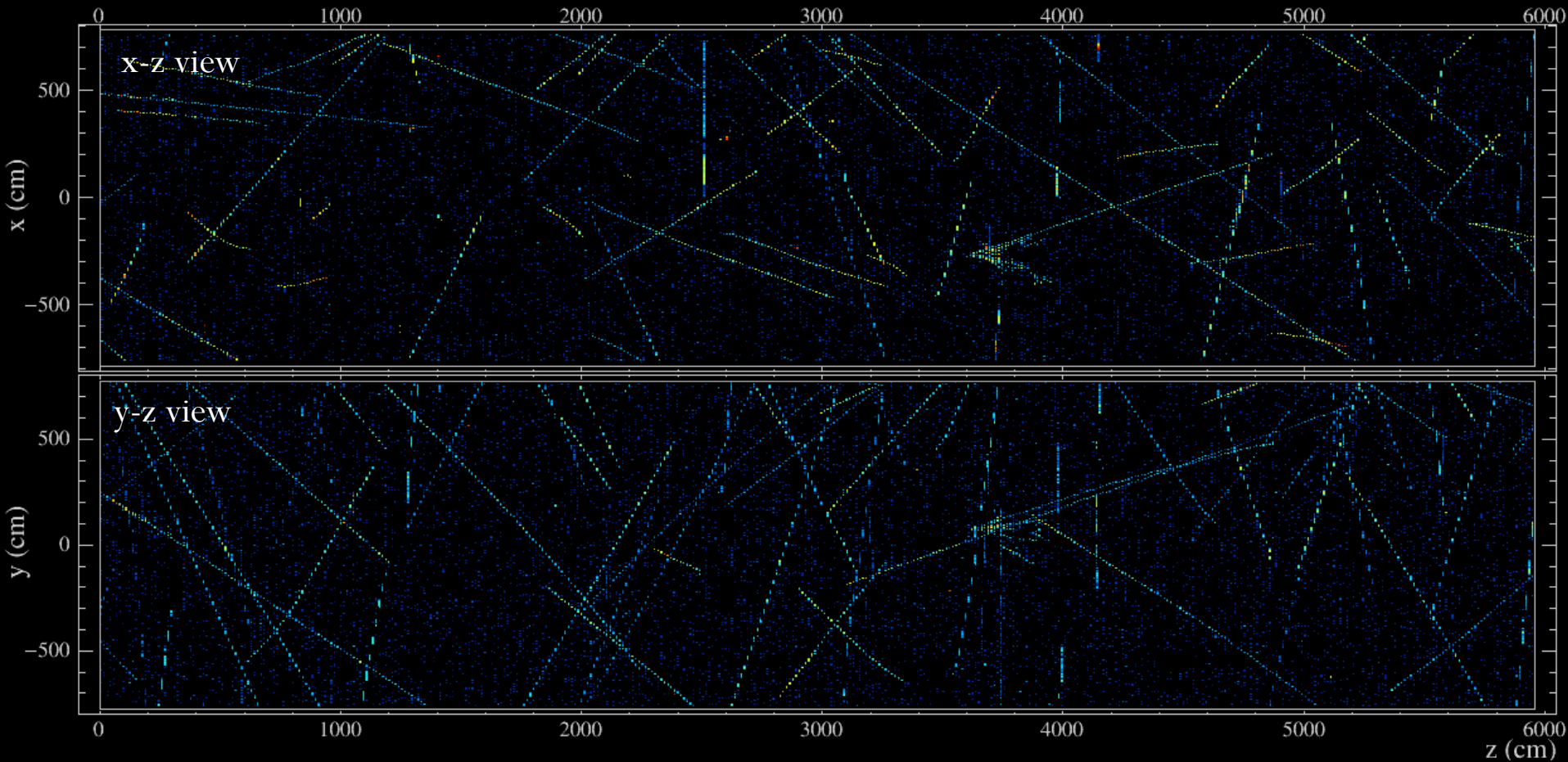
Record of **more than 700 kW** on Jan. 25, 2017!

**Scaling to full 14 kton-equivalent exposure, current results have  $6.05 \times 10^{20}$  POT.**

# Event Selection



# Data Event Display of Far Detector



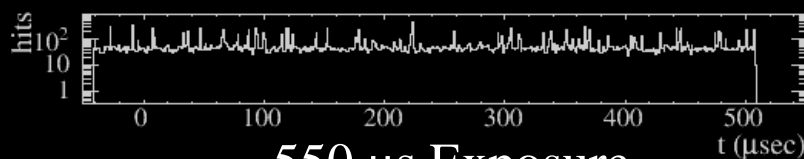
NOvA - FNAL E929

Run: 18620 / 13

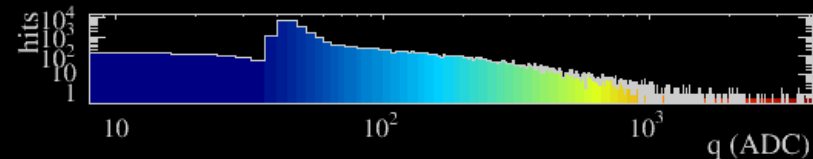
Event: 178402 / --

UTC Fri Jan 9, 2015

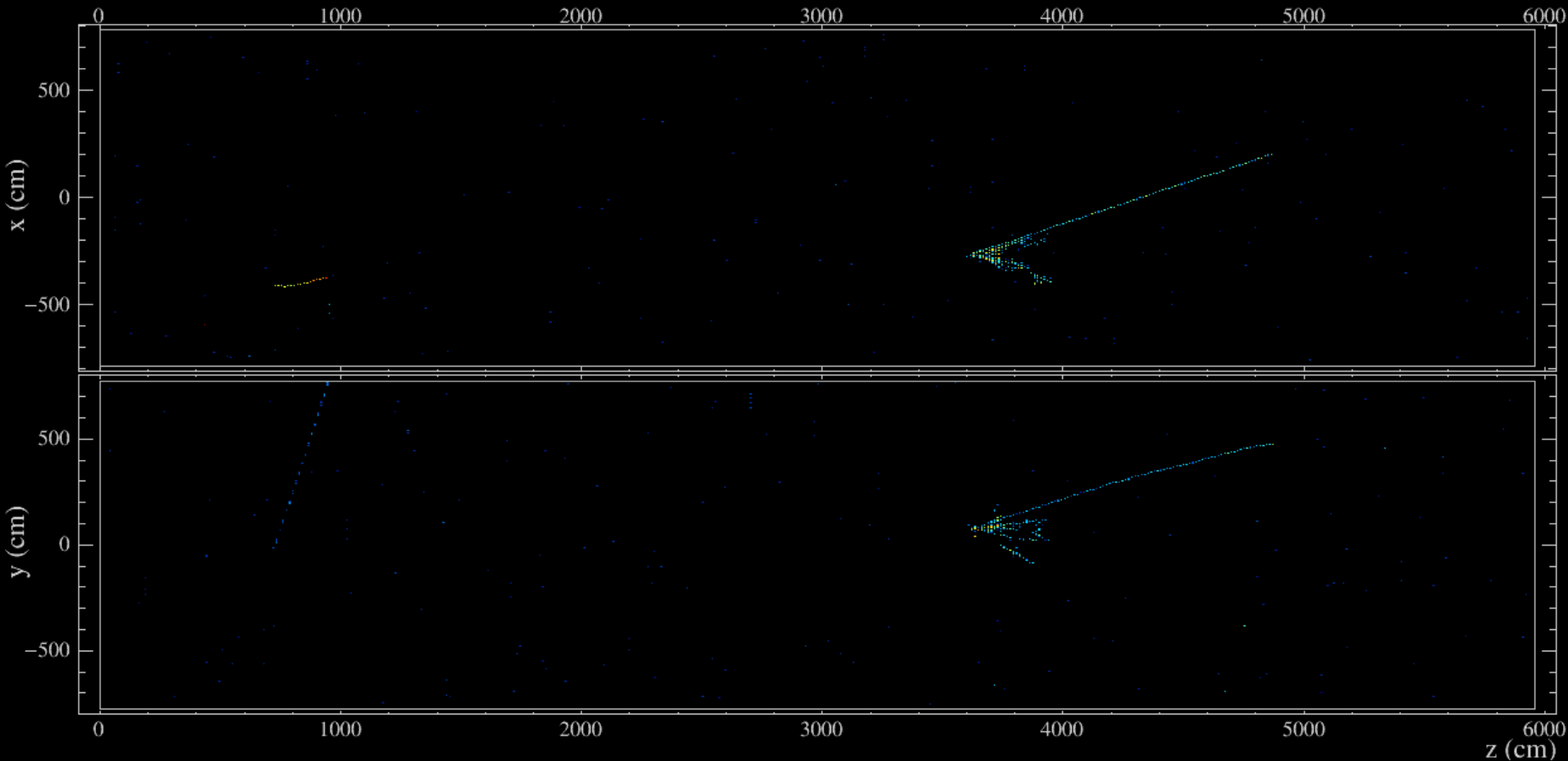
00:13:53.087341608



550  $\mu$ s Exposure



# Time Zoom on NuMI Beam Pulse



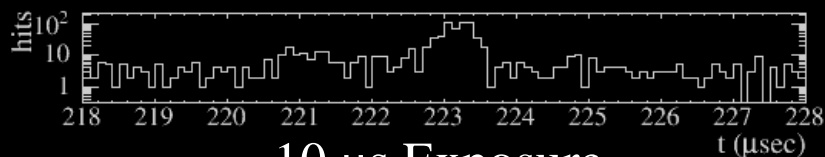
NOvA - FNAL E929

Run: 18620 / 13

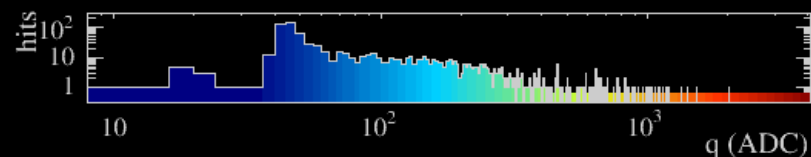
Event: 178402 / --

UTC Fri Jan 9, 2015

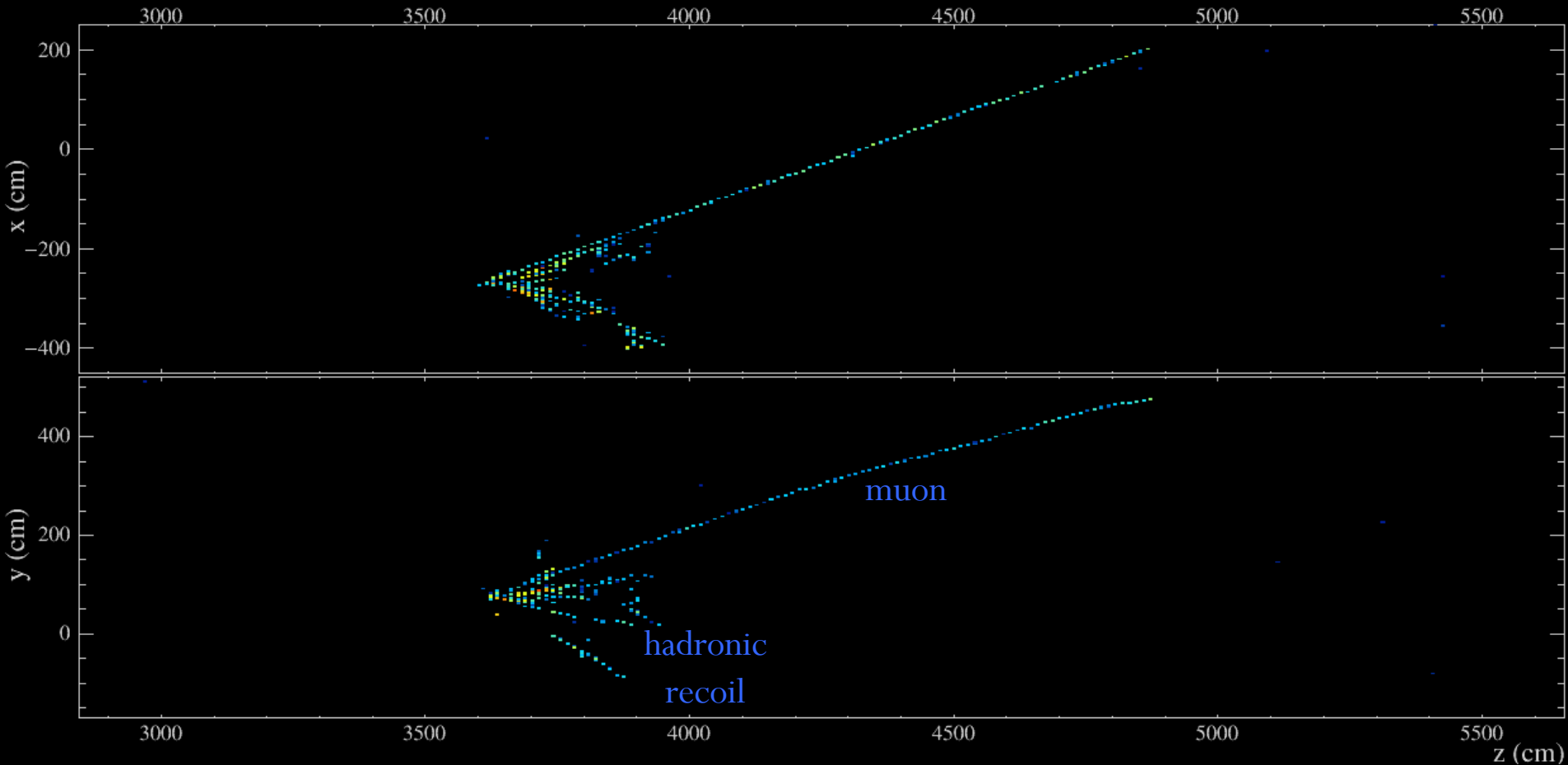
00:13:53.087341608



10  $\mu\text{s}$  Exposure



# Close-Up of Neutrino Interaction



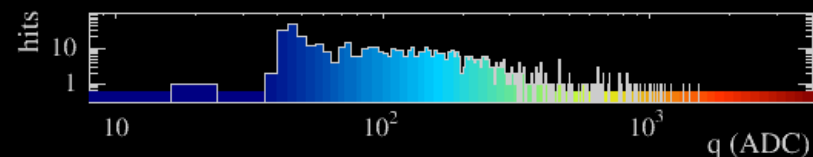
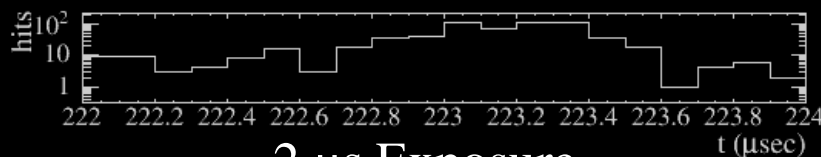
NOvA - FNAL E929

Run: 18620 / 13

Event: 178402 / --

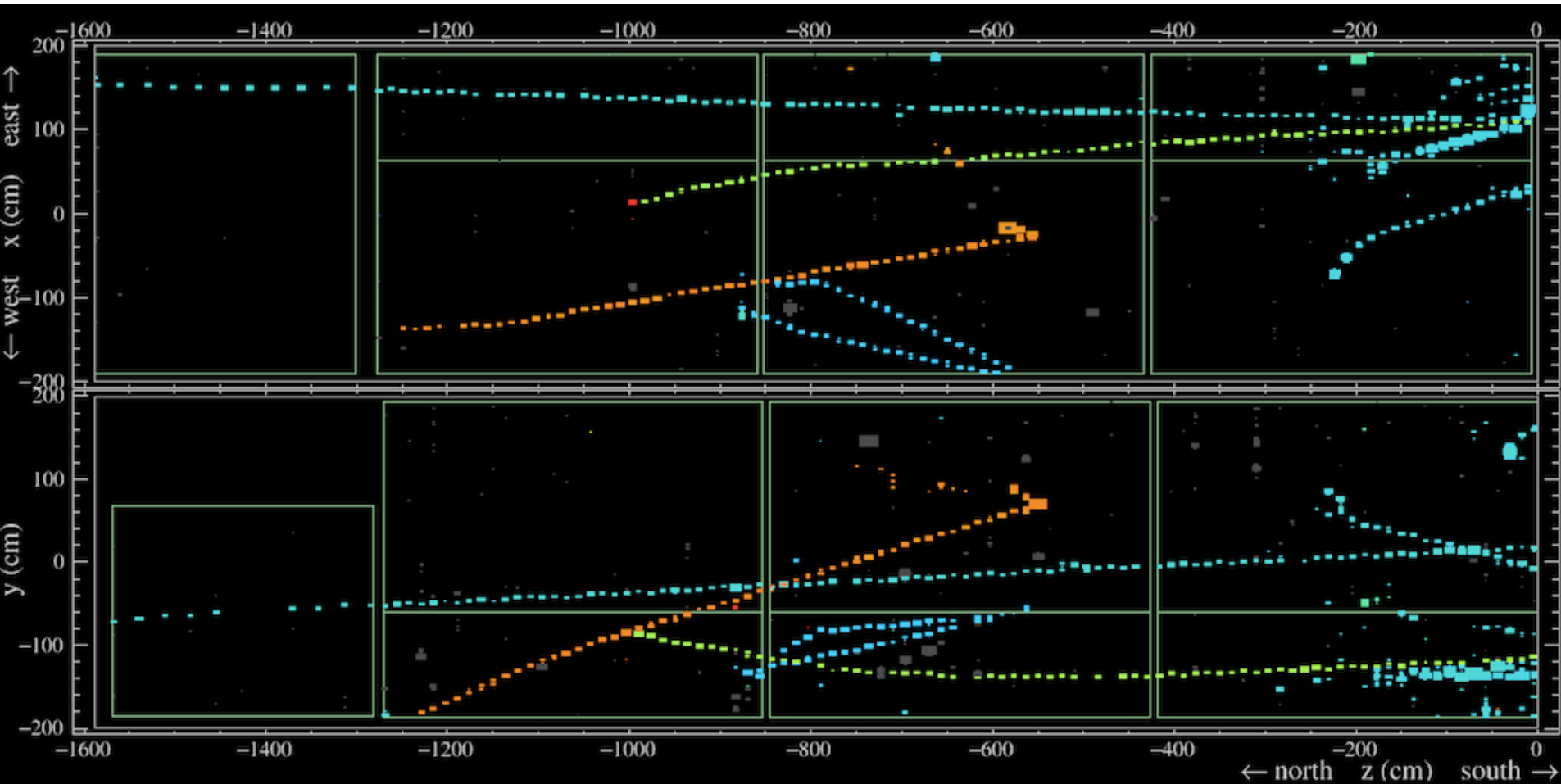
UTC Fri Jan 9, 2015

00:13:53.087341608



2  $\mu\text{s}$  Exposure

# Neutrinos “pile up” in the Near Detector!



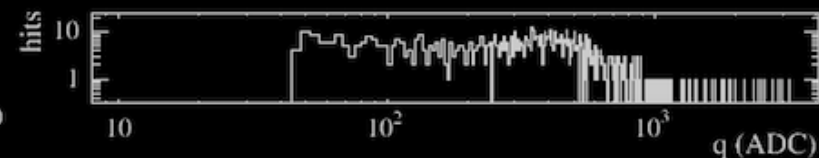
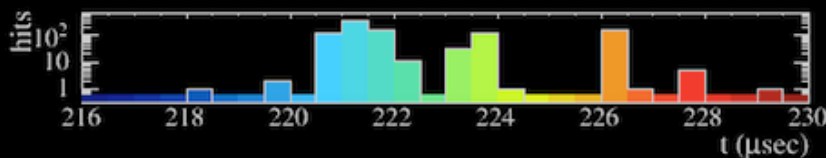
NOvA - FNAL E929

Run: 11381 / 17

Event: 3353617 / --

UTC Mon Jan 18, 2016

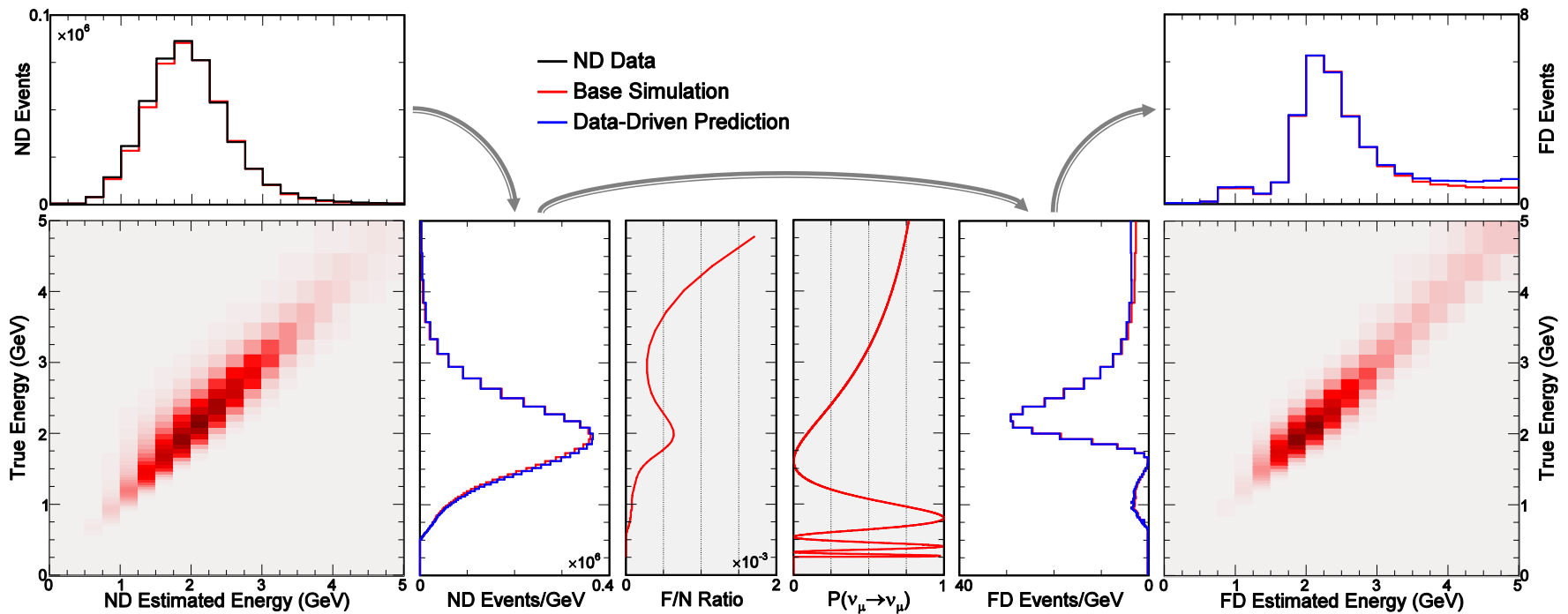
07:37:7.880560384



# Far Detector neutrino prediction

□ We use a data-driven technique to extrapolate the neutrino events in the near detector to the far detector:

1. Estimate true energy distribution of near detector events.
2. Multiply by expected far/near event ratio and oscillation probability.
3. Convert far detector true energy into reconstructed energy.

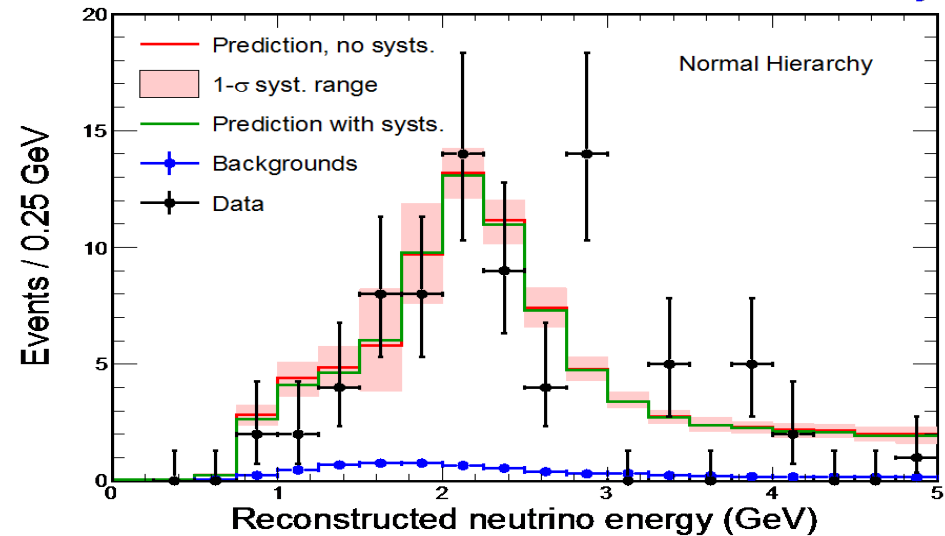


# Muon Neutrino FD Data

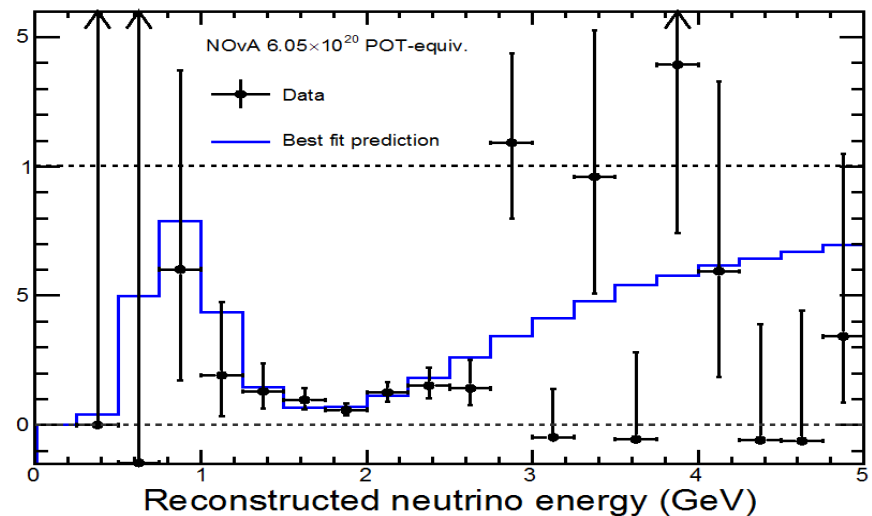
- 78 events observed in FD
  - $473 \pm 30$  with no oscillation
  - 82 at best oscillation fit
  - 3.7 beam BG + 2.9 cosmic

$\chi^2/\text{NDF} = 41.6/17$   
Driven by fluctuations in tail,  
no pull in oscillation fit

NOvA Preliminary



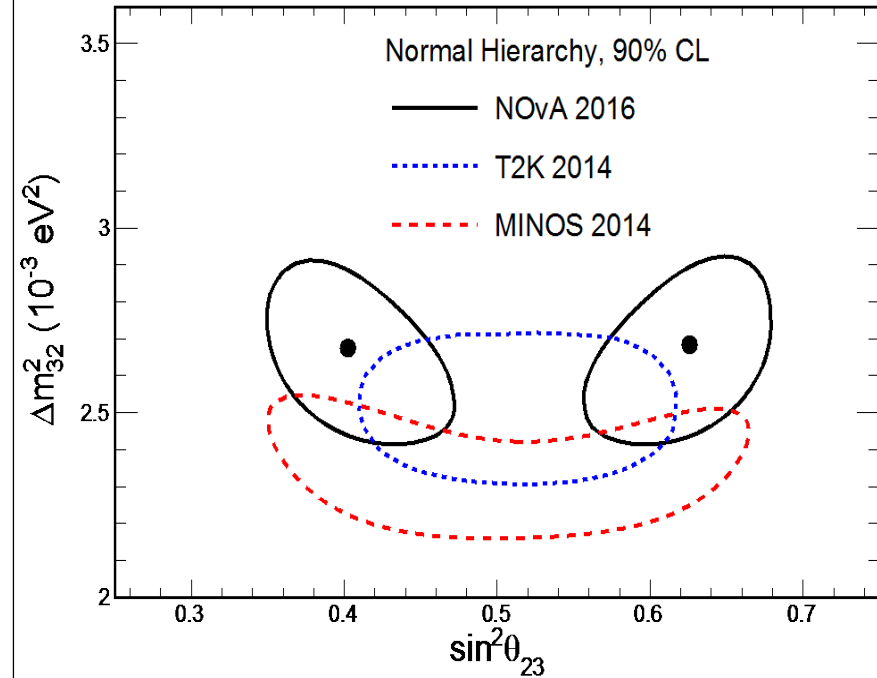
NOvA Preliminary





# Contours

NOvA Preliminary

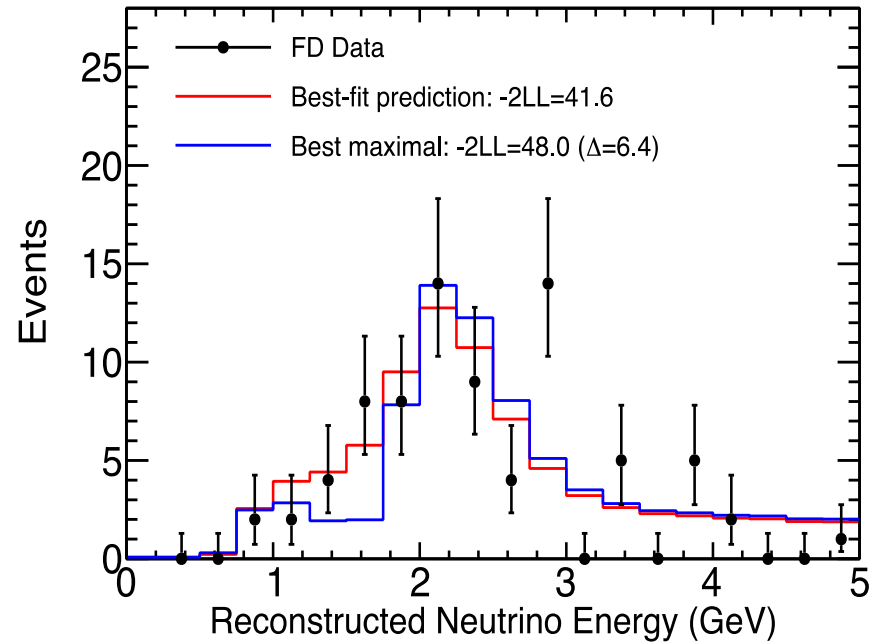


Best Fit (in NH):

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

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

NOvA Preliminary

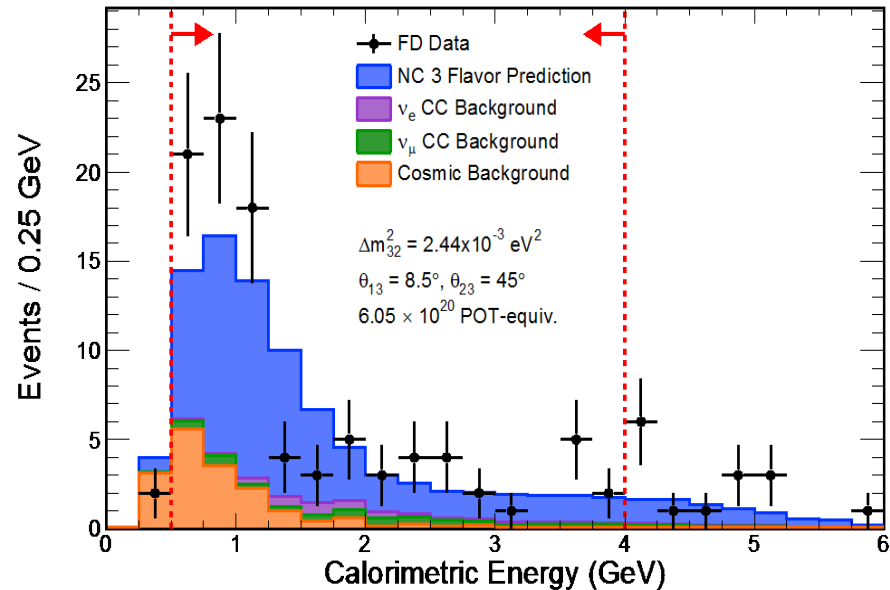


Maximal mixing excluded at  $2.5\sigma$

# Neutral Current FD Data

NOvA Preliminary

- Observe 95 events
- No evidence of oscillations involving steriles



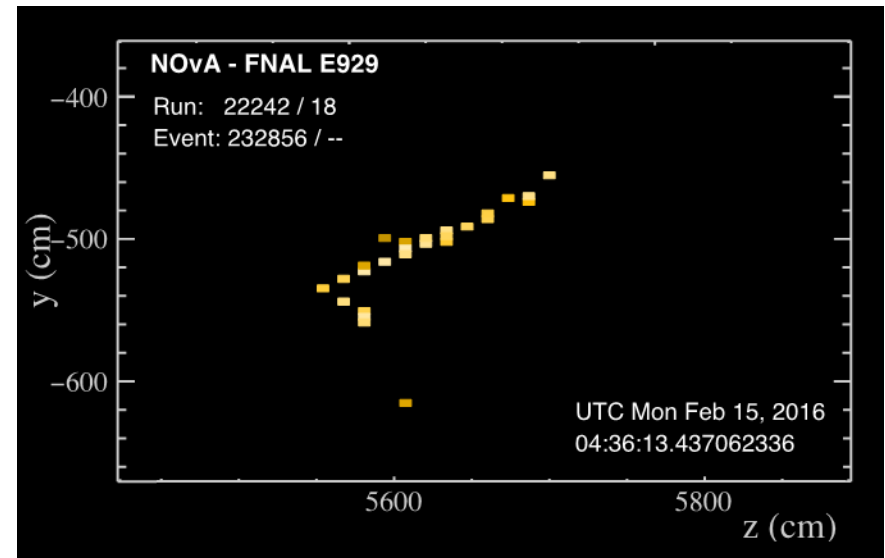
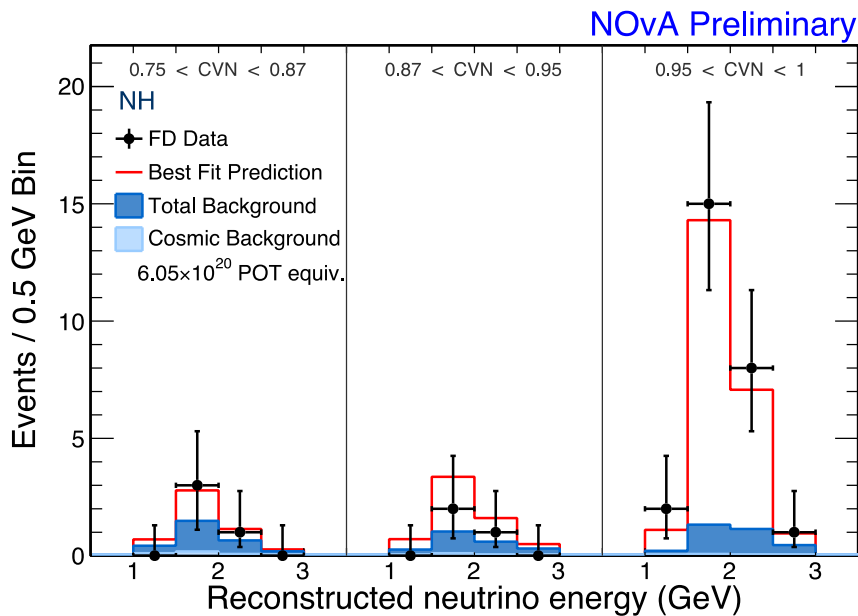
$$\text{For } 0.05 \text{ eV}^2 < \Delta m_{41}^2 < 0.5 \text{ eV}^2$$
$$\theta_{34} < 35^\circ, \theta_{24} < 21^\circ \text{ (90\% C.L.)}$$

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

# Electron Neutrino FD Data

>8 $\sigma$  electron neutrino appearance signal

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



# Contours

- Fit for hierarchy,  $\delta_{CP}$ ,  $\sin^2\theta_{23}$ 
  - Constrain  $\Delta m^2$  and  $\sin^2\theta_{23}$  with NOvA disappearance results
- Global best fit **Normal Hierarchy**

$$\delta_{CP} = 1.49\pi$$

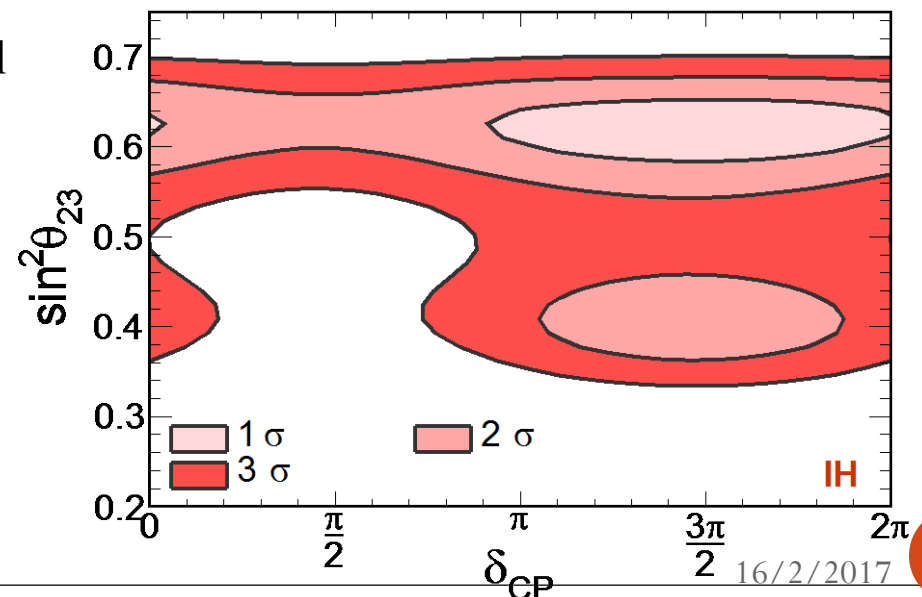
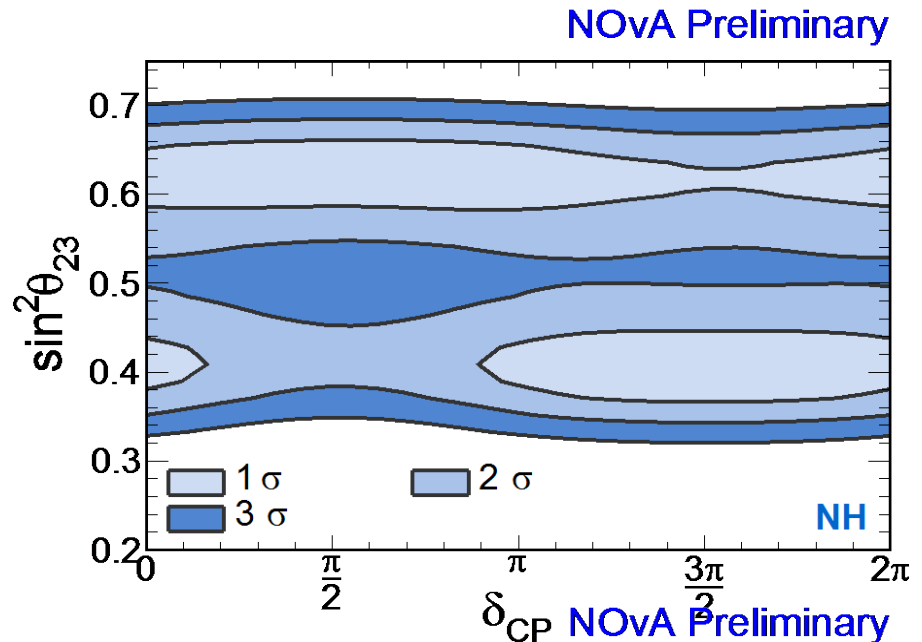
$$\sin^2(\theta_{23}) = 0.40$$

(0.74 $\pi$ /0.62 2<sup>nd</sup> degenerate NH fit )

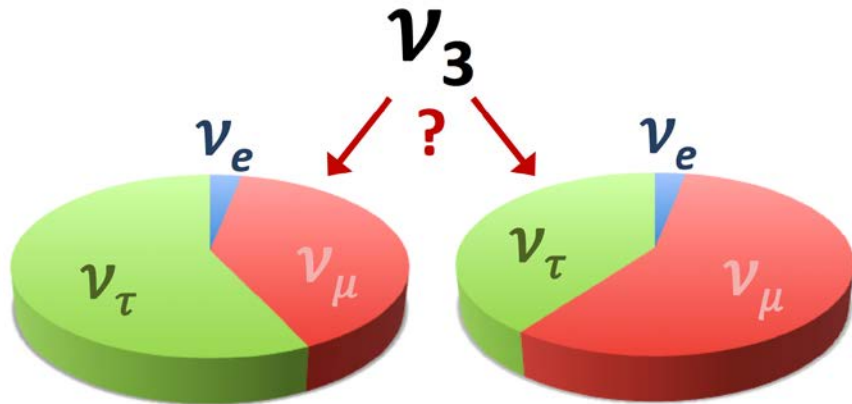
  - both octants and hierarchies allowed at 1 $\sigma$
  - 3 $\sigma$  exclusion in IH, lower octant around  $\delta_{CP}=\pi/2$

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

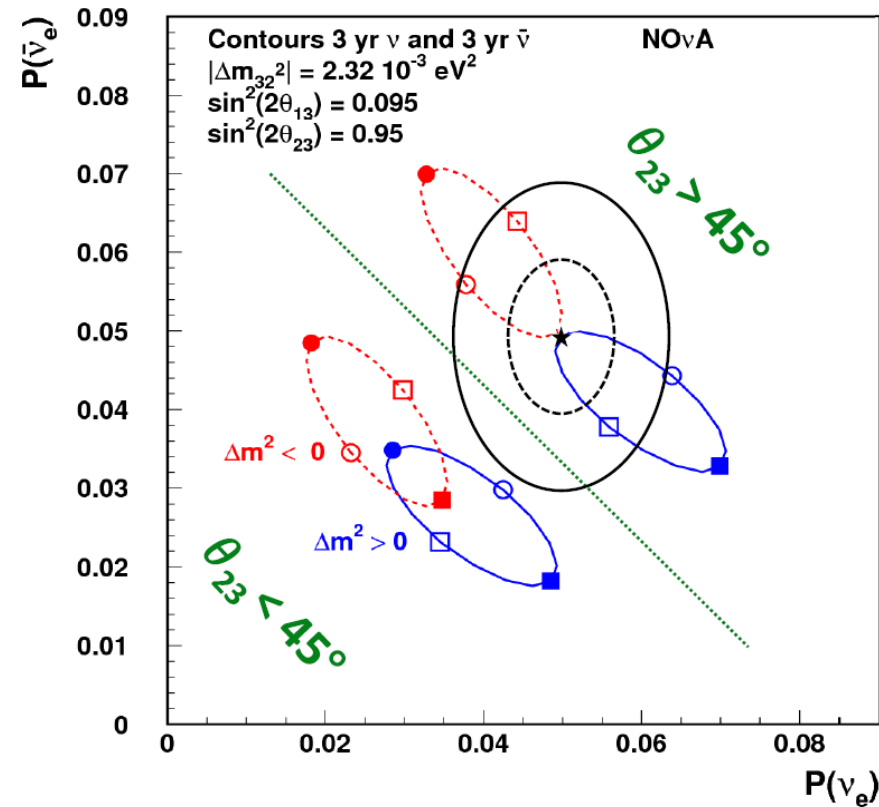
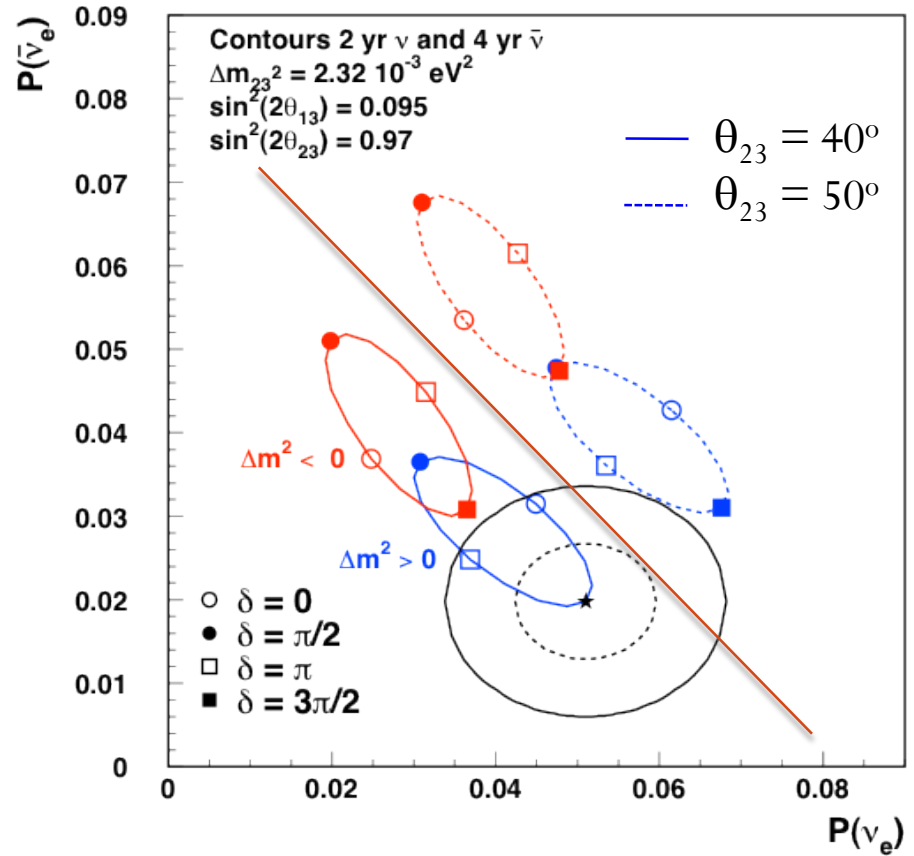
**Planned for Feb 20, 2017**



# $\bar{\nu}_e$ Appearance



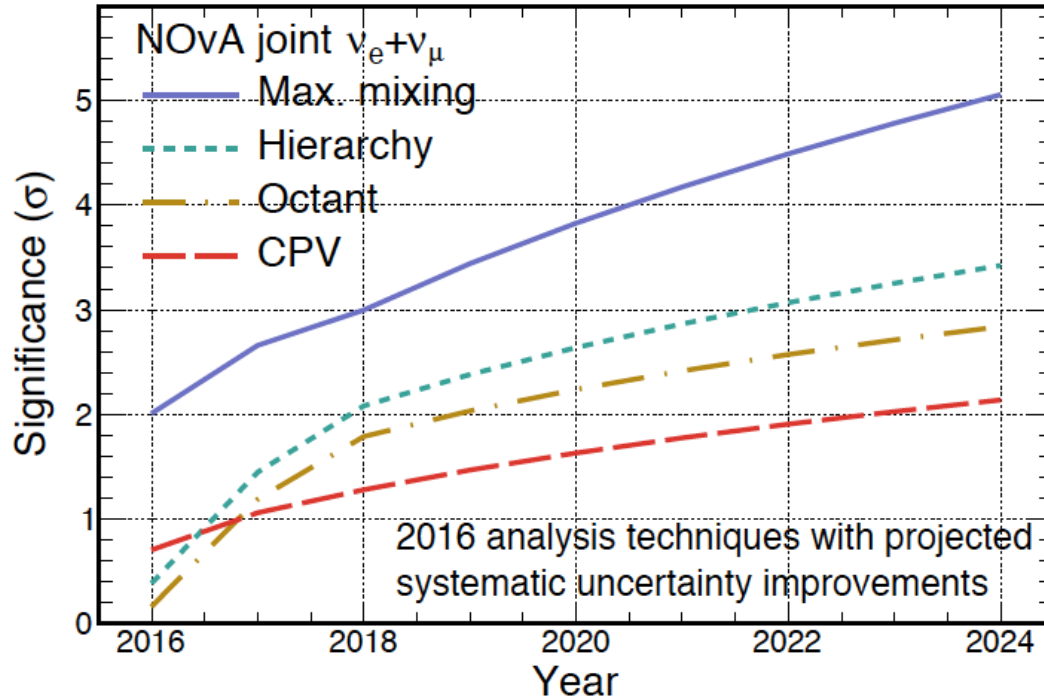
## 1 and 2 $\sigma$ Contours for Starred Point



# Projections

Normal  $\delta_{CP}=3\pi/2$ ,  $\sin^2\theta_{23}=0.403$   
 $\Delta m_{32}^2=2.5\times 10^{-3}\text{eV}^2$ ,  $\sin^2\theta_{13}=0.022$

NOvA Simulation



Assuming  $6\times 10^{20}$  POT/year.

The accumulated exposure is divided between FHC and RHC mode as:

- $6\times 10^{20}$  FHC by 2016
- $9\times 10^{20}$  FHC +  $3\times 10^{20}$  RHC by 2017
- $9\times 10^{20}$  FHC +  $9\times 10^{20}$  RHC by 2018
- 50\% FHC + 50\% RHC after that.

**“It's tough to make predictions, especially about the future.”**

**-- Yogi Berra**

# Summary

With  $6.05 \times 10^{20}$  POT, NO $\nu$ A 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
  - Region in IH, lower octant around  $\delta_{CP} = \pi/2$  is excluded
- Looking forward to more neutrinos and antineutrino running planned, switch over Feb 20, 2017.

# Run Coordinator – official version

- **3 Mar 2014 – 11 Jul 2016:** NOvA experiment
  - Till 6 Jul 2015 one person responsibility (after tripartite)
- Run Coordinator (staying at Fermi National Laboratory, USA)
  - Charged with optimizing the use of the near and far detectors to meet the physics goals of the experiment.
  - Directing and deciding the priority and scheduling of detector systems development and maintenance.
  - Responsible for reports to the weekly All Experimenters' Meeting.
- Ex officio member of the IB and EC at NOvA experiment.
- During my duty:
  - 74 All Experimenter's Meeting (a Director watch)
  - 59 weekly reviews to the collaboration
  - 9 Plenary talks (plus ~ IB reports) at Collaboration meetings
  - 137 Operations meetings leadership (main report on each)



# Run Coordinator – unofficial version I

## The Varied Neuroses of Mildly-Successful Run Coordinators

A guide to being Run Coordinator

*Authors:*

Versions 1.0-1.1: Keith Matera

Version 1.2 (added Gavin): Evan Niner





NOvA DocDB 15206

So, you've been handed the mantle of Run Coordinator.

Weighted heavy by history and by responsibility, shall it hang upon shoulders lifted with pride? Or broken by its heft? Only you know the answer to this, my friend. In these pages, I hope to help you find your answer.

It is said that the first Run Coordinator sprang fully-formed from a barrel of scintillator oil that had been lost by UPS and wound up in Brazil.

# Run Coordinator – unofficial version II

	<p><b>Steve Magill</b> ANL</p> <p>Years active: 2013-2014</p>	<p>The Bobblehead</p> <p>Cast into ceramic by the Spokes for standing in front of the NearDet and absorbing a dark matter particle that was detected in 99% of all alternate universes.</p>
	<p><b>Jaroslav Zalesak</b> <i>(First Form)</i> Prague</p> <p>Years active: 2014-2015</p>	<p>The Eternal</p> <p>Ok! So. Forever bound to his duty. NOvA's longest running Run Coordinator.</p>
	<p><b>Louise Suter</b> ANL</p> <p>Years active: 2015-2015</p>	<p>The Near Warden</p> <p>Interim Run Coordinator while Jaroslav was in metamorphosis. Pictured here at the helm of the HMS NOvA.</p>
	<p><b>Gavin Davies</b> IU</p> <p>Years active: 2015-2015</p>	<p>The Warm Body</p> <p>In NOvA's time of need, with all RCs either on holiday or detained fighting the creatures beneath, the Spokes cast about in desperation and settled on the first person in eyesight, just as prophesy foretold.</p>

	<p><b>Jaroslav Zalesak</b> <i>(Second Form)</i> FNAL</p> <p>Years active: 2015-Present (Tripartite)</p>	<p>The Relieved Eternal</p> <p>Much happier in his second form.</p>
	<p><b>Keith Matera</b> FNAL</p> <p>Years active: 2015-2016 (Tripartite)</p>	<p>The Candyman</p> <p>Personally responsible for over sixty pounds of collaborator weight.</p>
	<p><b>Evan Niner</b> FNAL</p> <p>Years active: 2015-Present (Tripartite)</p>	<p>The Timelord</p> <p>Has actually never been seen without his glasses.</p>
	<p><b>Matt Strait</b> UMN</p> <p>Years active: 2016-Present (Tripartite)</p>	<p>The Neutron Star</p> <p>Is going to correctly model neutrons in the NearDet <i>and</i> die trying.</p>

# RC: AEM Summary Aug 18, 2014

**A milestone:** the Project (CD1-4 fulfillment) to Operations phase changeover of the NOvA experiment

## FarDet:

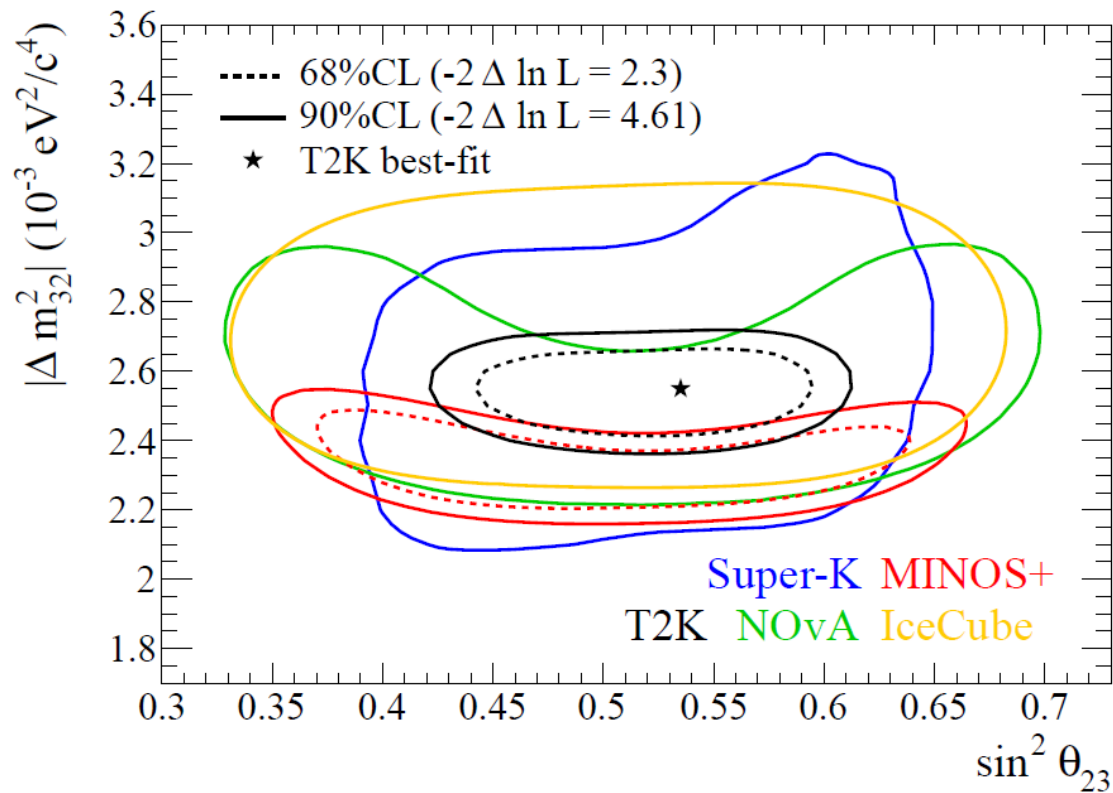
- Far detector completed and running 14-diblock with final configuration over 3 days.
- Now we have started a new phase: the retrofitting.
- We have closed the book of the Far detector assembly and are just opening the doors to retrofitting which should eliminate water leaks in future.

## NearDet:

- Near detector completed and running 3-diblock (+MC) with final configuration over 3 days.
- Waiting for evaluation of its performance and perhaps some repair works will be done this week.

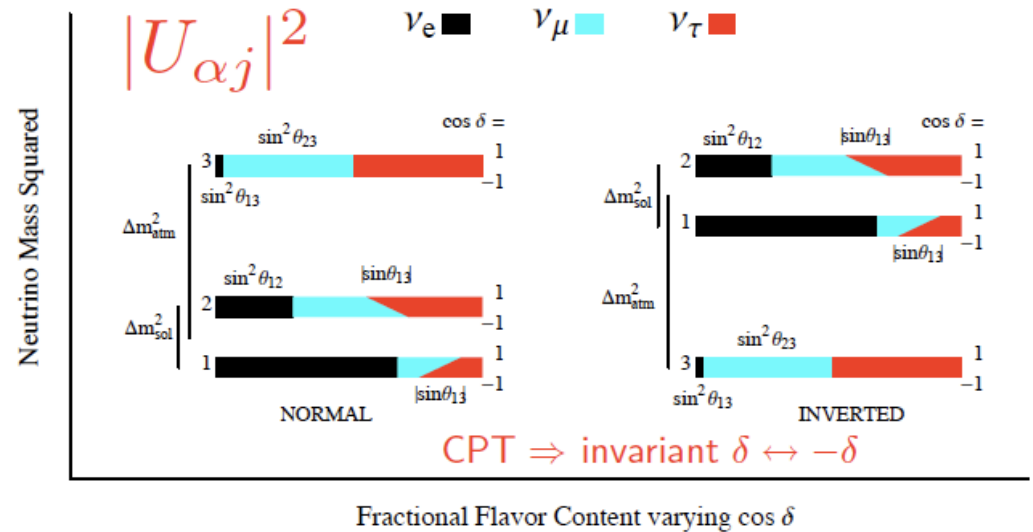
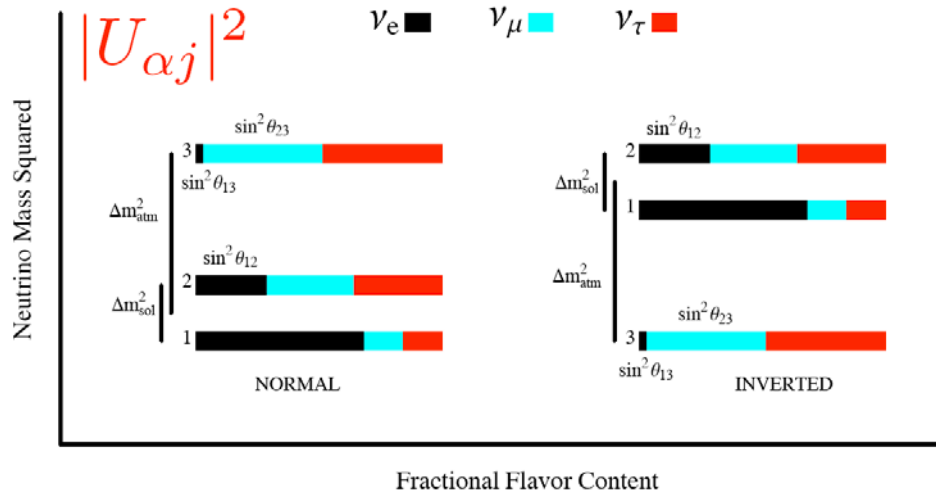
# Competitors & Successors

- ❑ T2K
- ❑ Daya Bay
- ❑ Others
  
- ❑ DUNE
- ❑ JUNO
- ❑ T2HK
- ❑ Others



# BACK UP

# Mass Hierarchy



## $\bar{\nu}_e$ Appearance

- NOvA measures the probability of  $\bar{\nu}_e$  appearance in a  $\nu_\mu$  beam:

$$\begin{aligned}
 P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) &\approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2} \\
 &+ 2\alpha \sin \theta_{13} \sin \delta_{\text{CP}} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin \Delta \\
 &+ 2\alpha \sin \theta_{13} \cos \delta_{\text{CP}} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos \Delta
 \end{aligned}$$

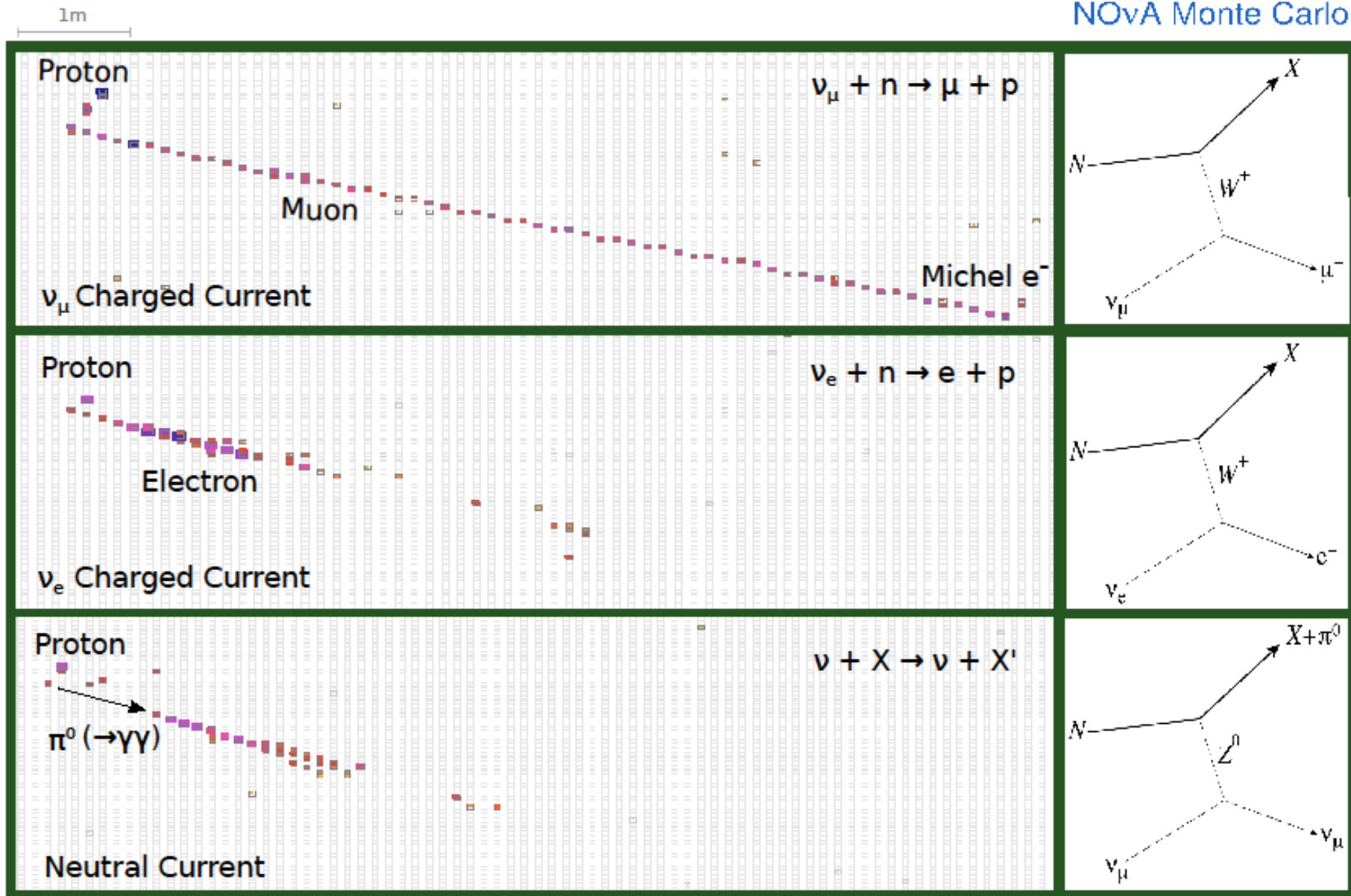
$$\alpha = \Delta m_{21}^2 / \Delta m_{31}^2 \quad \Delta = \Delta m_{31}^2 L / (4E) \quad A = \frac{(-)}{+} G_f n_e L / (\sqrt{2}\Delta)$$

- $\sin^2(2\theta_{13})$  has been measured which allows us to make measurements of  $\delta_{\text{CP}}$  and mass hierarchy.
- Note that we can improve  $\theta_{23}$  measurement from  $\nu_\mu$  disappearance.
- Probability is enhanced or suppressed due to **matter effects** which depend on the mass hierarchy, i.e the sign of  $\Delta m_{31}^2 \sim \Delta m_{32}^2$  as well as neutrino vs. anti-neutrino running.



# Event Topologies

NOvA Monte Carlo

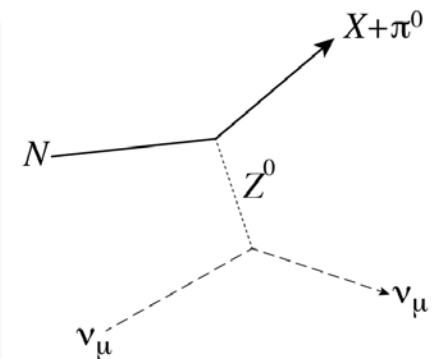
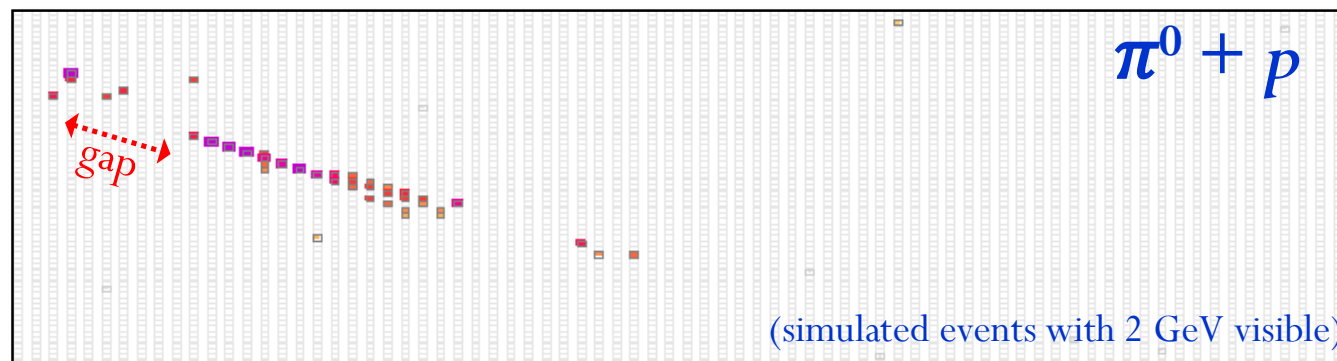
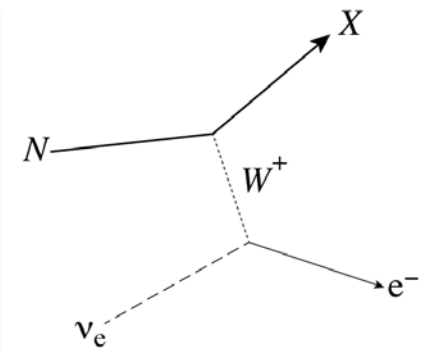
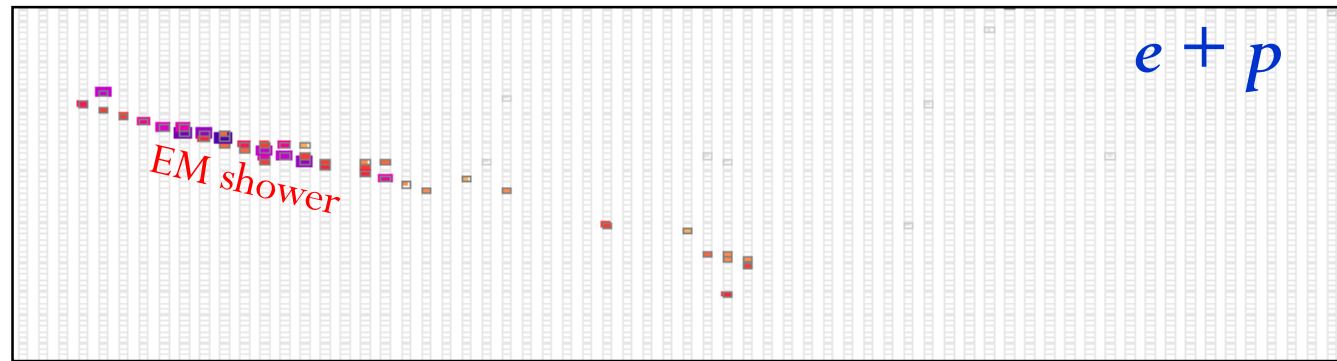
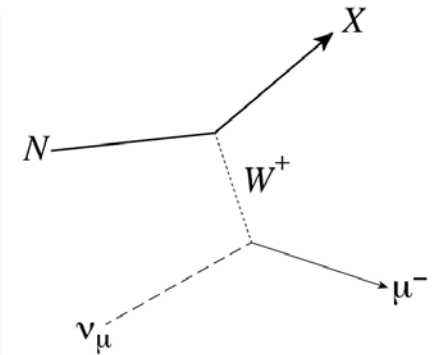
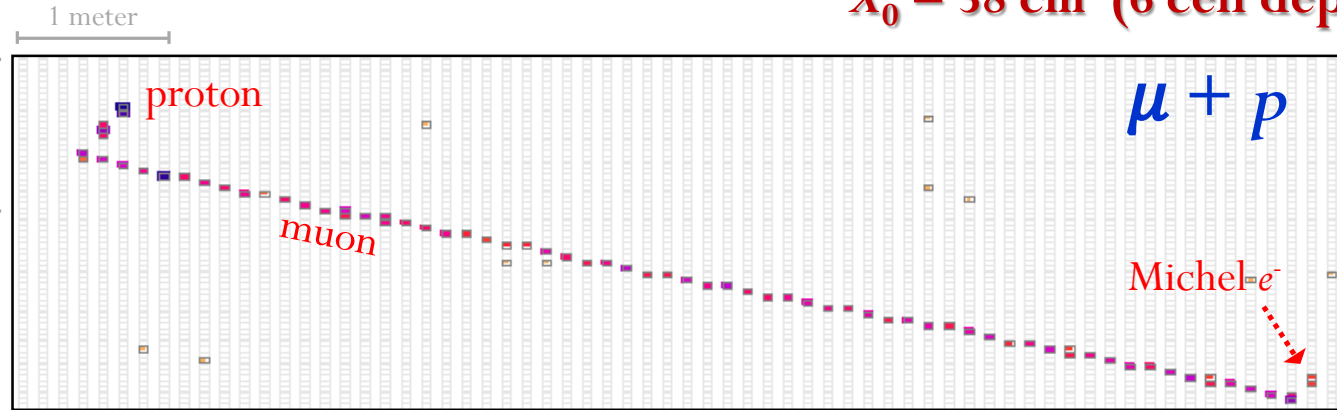




# Events in NOvA

## Superb spatial granularity for a detector of this scale

$X_0 = 38 \text{ cm}$  (6 cell depths, 10 cell widths)



(simulated events with 2 GeV visible)

# Summary Aug 18, 2014

## FarDet:

- Far detector completed and running 14-diblock with final configuration over 3 days.
- Now we have started a new phase: the retrofitting.
- We have closed the book of the Far detector assembly and are just opening the doors to retrofitting which should eliminate water leaks in future.

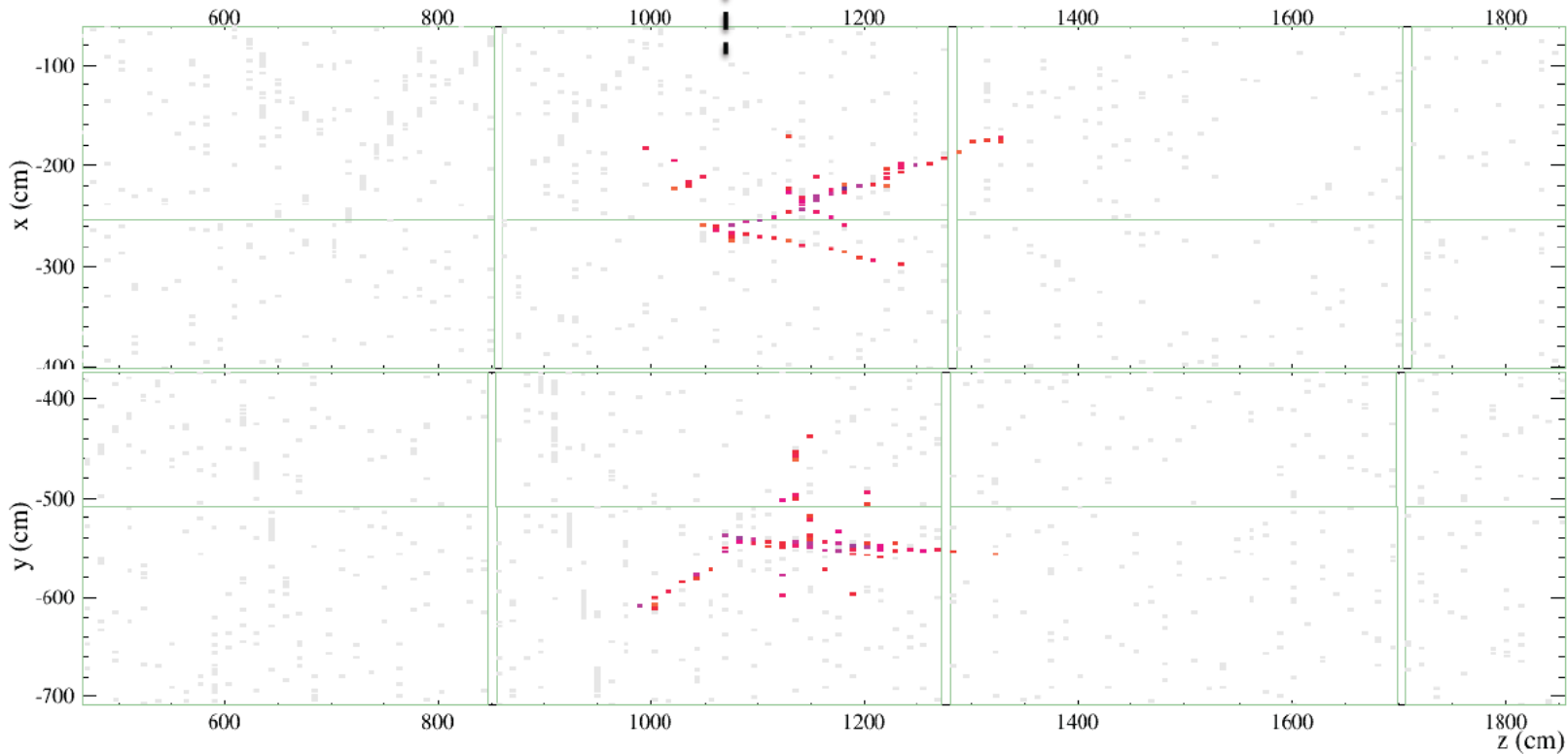
## NearDet:

- Near detector completed and running 3-diblock (+MC) with final configuration over 3 days.
- Waiting for evaluation of its performance and perhaps some repair works will be done this week.

# FD: Golden neutrino candidate #1/R3

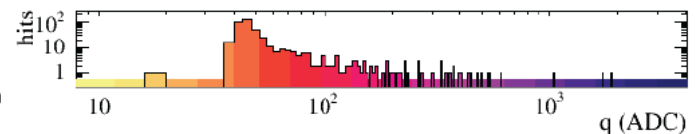
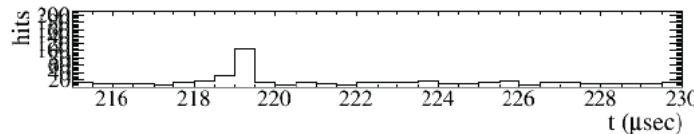
Event Displays:

1<sup>st</sup> Super-Block (SB 0)    2<sup>nd</sup> Super-Block (SB 1)



NOvA - FNAL E929

Run: 14737 / 6  
 Event: 62508 / NuMI  
 UTC Thu Apr 17, 2014  
 21:23:10.091535768



14737    6    62508    (6/0/0)    12

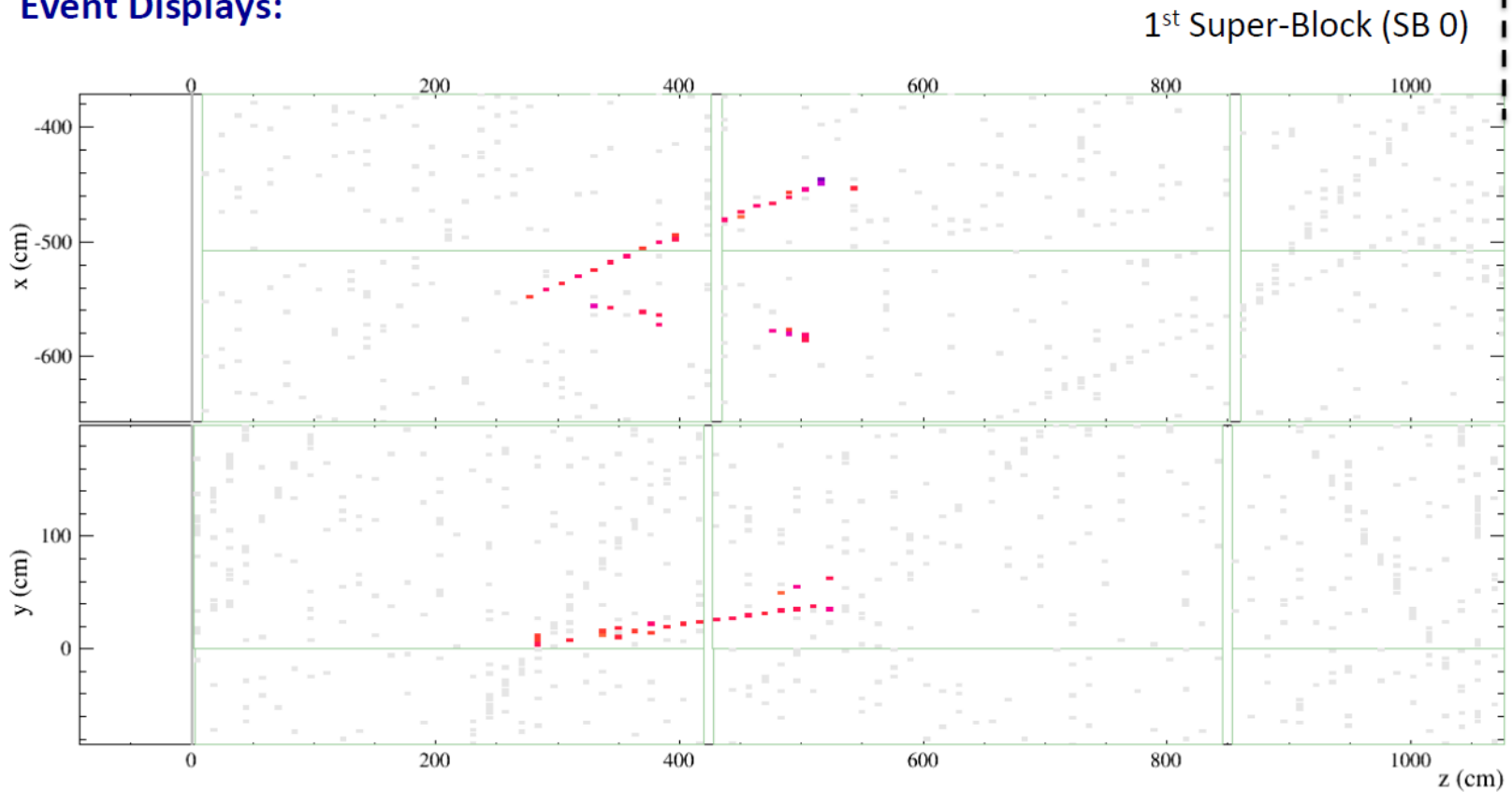
IN Beam Window

NuMI Scan Results - Round 3

16

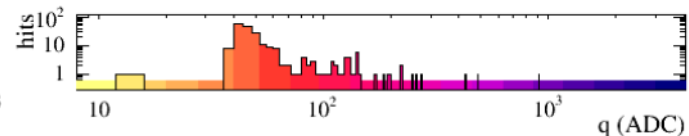
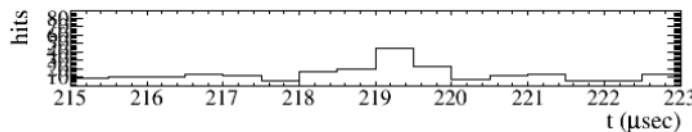
# FD: Golden neutrino candidate #2/R3

## Event Displays:



NOvA - FNAL E929

Run: 14737 / 31  
 Event: 291483 / NuMI  
 UTC Thu Apr 17, 2014  
 22:33:39.130709640



14737    31    291483    (5/1/0)    11

IN Beam Window

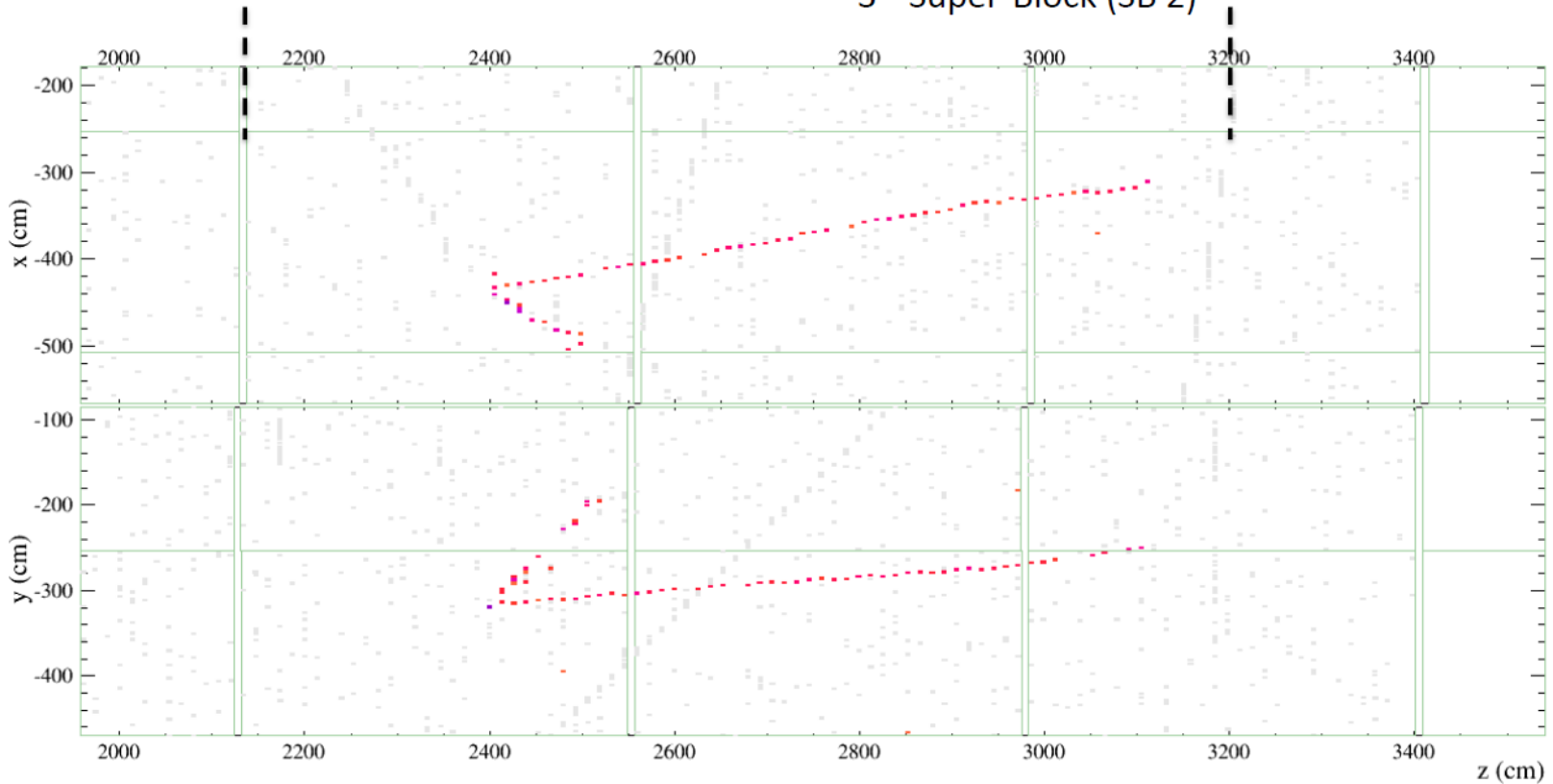
NuMI Scan Results - Round 3

17

# FD: Golden neutrino candidate #3/R3

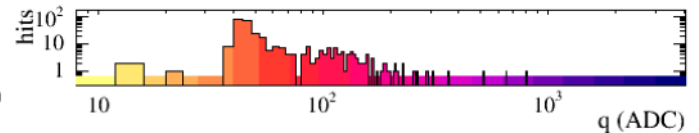
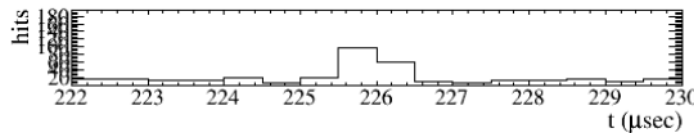
## Event Displays:

3<sup>rd</sup> Super-Block (SB 2)



NOvA - FNAL E929

Run: 14828 / 38  
 Event: 192569 / NuMI  
 UTC Tue Apr 22, 2014  
 21:41:51.422846016



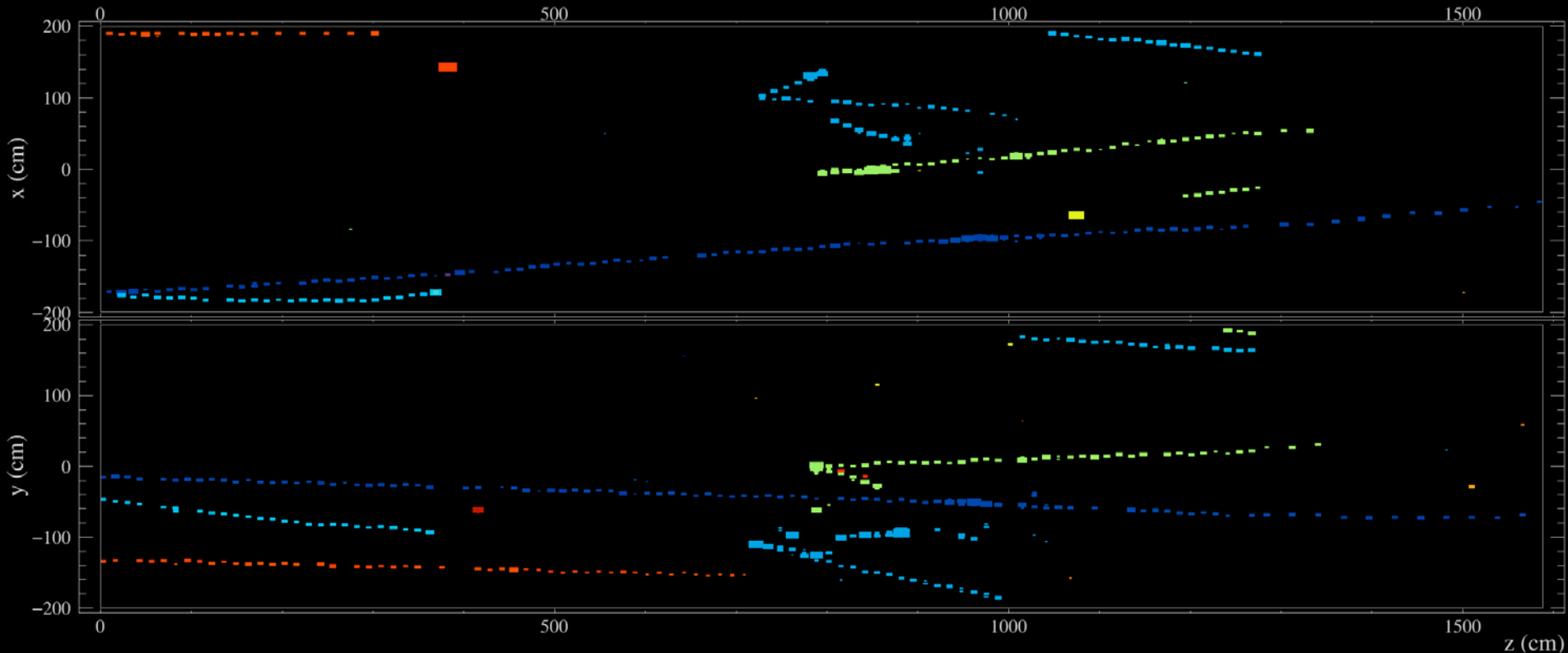
14828    38    192569    (5/0/0)    10

IN Beam Window

NuMI Scan Results - Round 3

18

# Near Detector Event Display



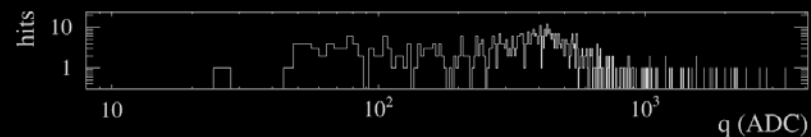
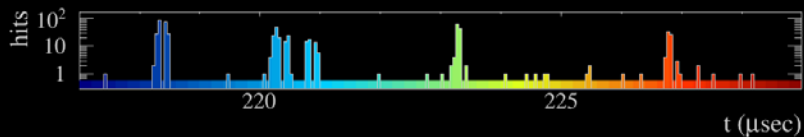
NOvA - FNAL E929

Run: 10407 / 1

Event: 27950 / --

UTC Thu Sep 4, 2014

05:28:44.034495968



# Possible schedule assuming \$10M/yr

	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27
MI ps/RF 1.2s cycle	Yellow									
NuMI target station 1 MW	Dark Grey	Dark Grey								
Proton Source ppp	Olive	Olive	Olive	Olive						
20 Hz					Brown	Brown	Brown			
Booster D-mag (20 Hz, ppp)							Grey	Grey	Grey	Grey
Infrastructure	Dark Red	Dark Red	Dark Red	Dark Red	Dark Red					
PIP excl Booster cavities	Olive									
PIP Booster cavities			Push off this task from current PIP schedule to allow NuMI target work							
Power (kW)	700	700	800	900	900	900	900	1000	1000	1000

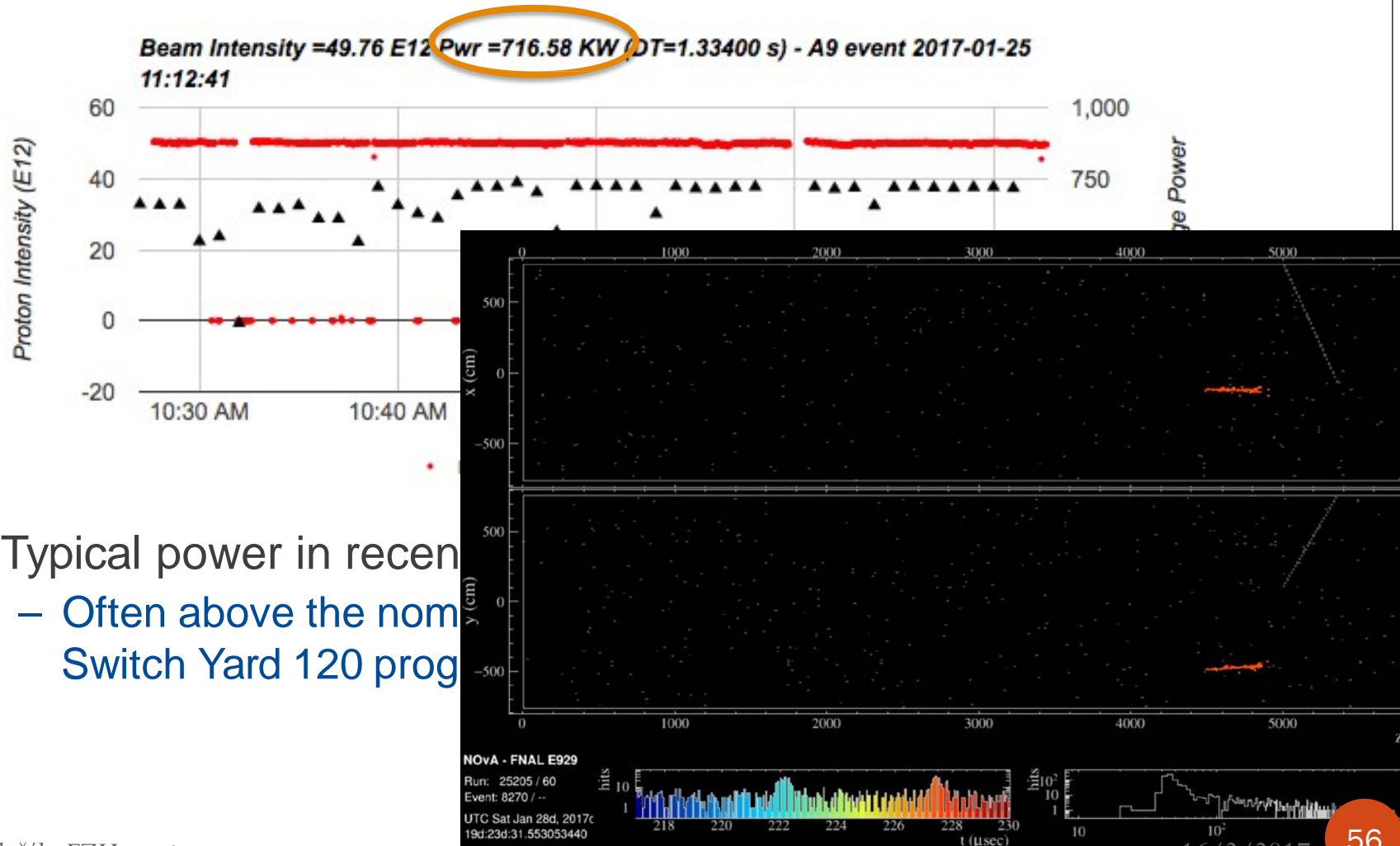
1.2s cycle in between g-2 and Mu2e

Gains from ppp

20 Hz capable on timescale of LBNF (PIP-II?)

# Beam Power

- 700+ kW sustained for first time on January 25, 2017!



- Typical power in recent  
– Often above the nominal  
Switch Yard 120 program



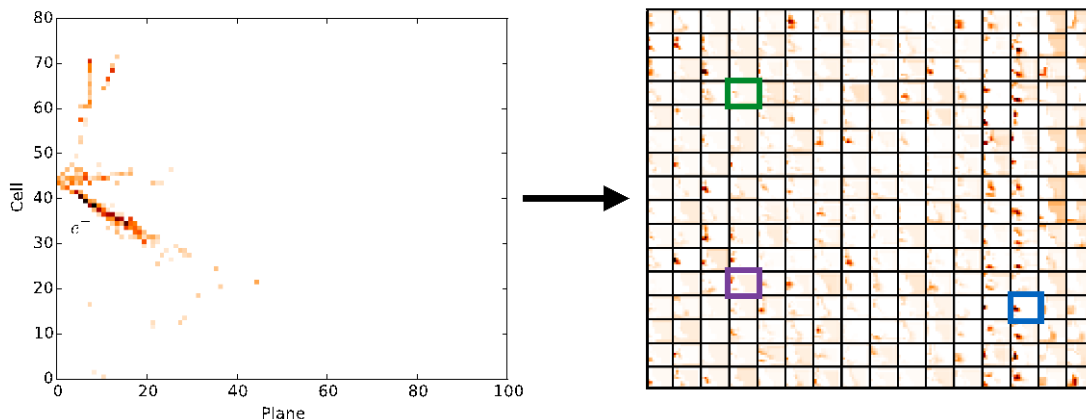
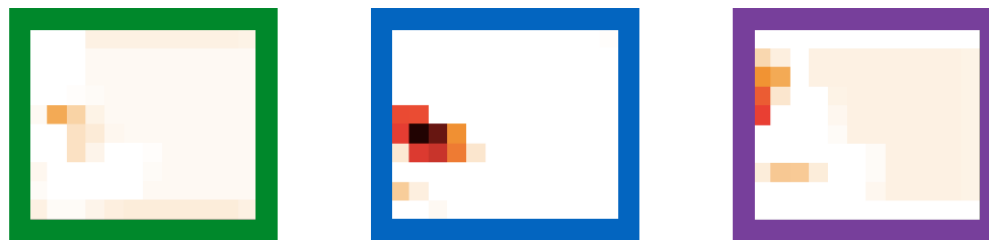
# Beyond 700 kW – PIP-1+

- PIP (Proton Improvement Plan) is nearly completed
  - campaign to get to 700 kW, with additional equipment improvements
- PIP-II – longer term project for 1.2+ MW beam for LBNF, etc.
- In between, PIP-1+
  - Director has asked for a study to explore impact and possibility of ~1MW in the Fermilab accelerator complex on a shorter timescale.
  - If achieved early enough, it could have a significant impact on competitiveness with T2K
- Mary Convery will tell us more in this session

# Improved Event Selection

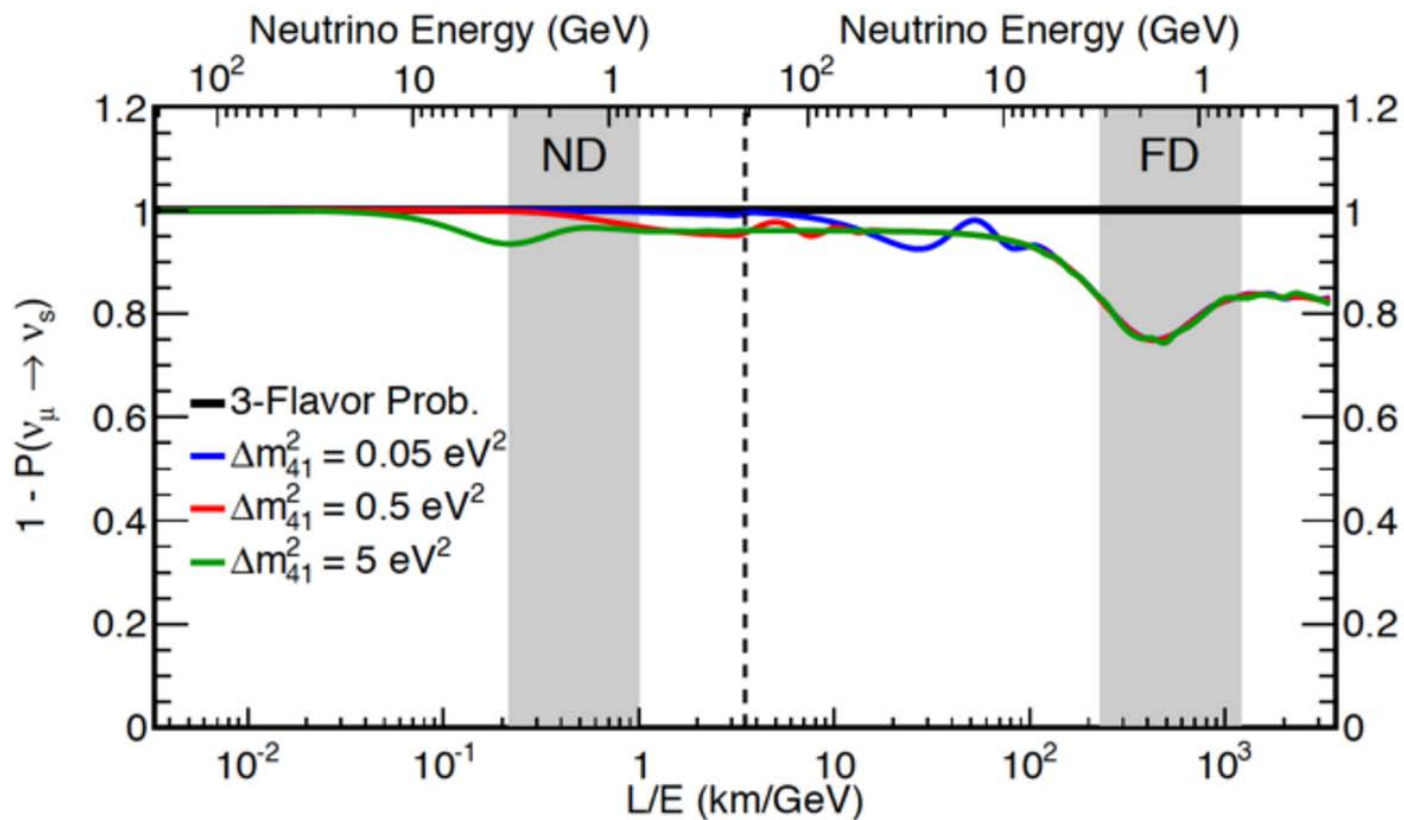
- This analysis features a new event selection technique based on ideas from computer vision and deep learning

- 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

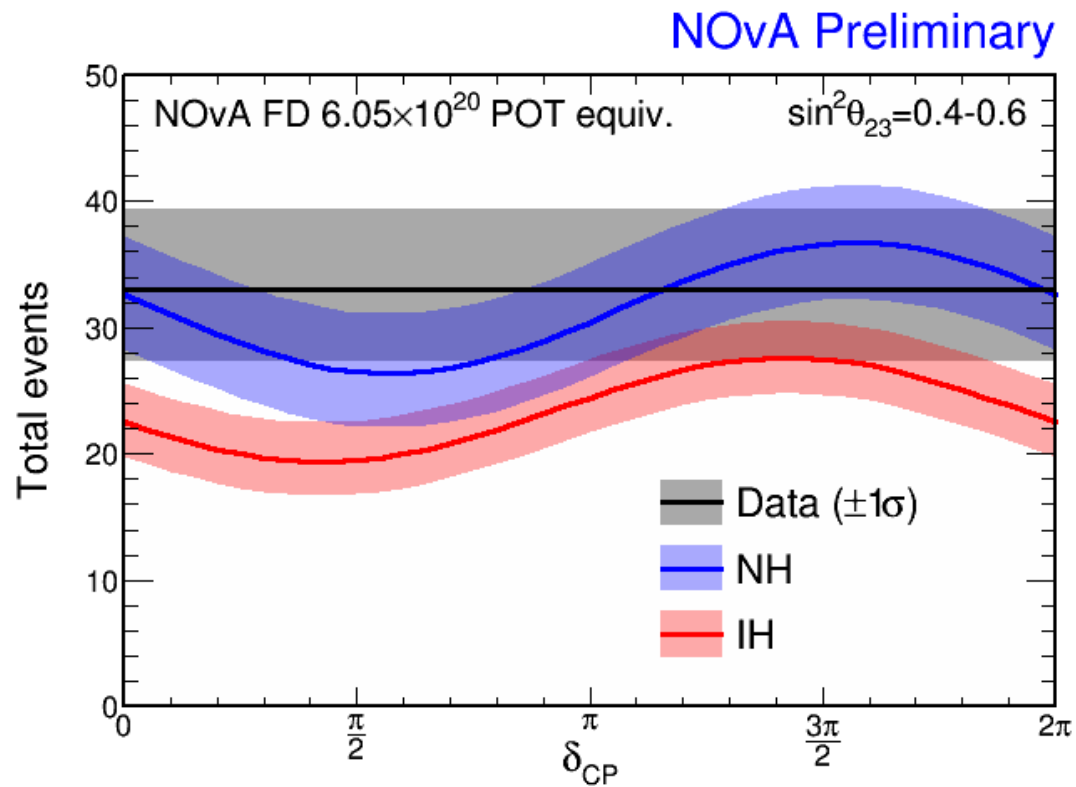


Improvement in sensitivity from CVN  
equivalent to 30% more exposure

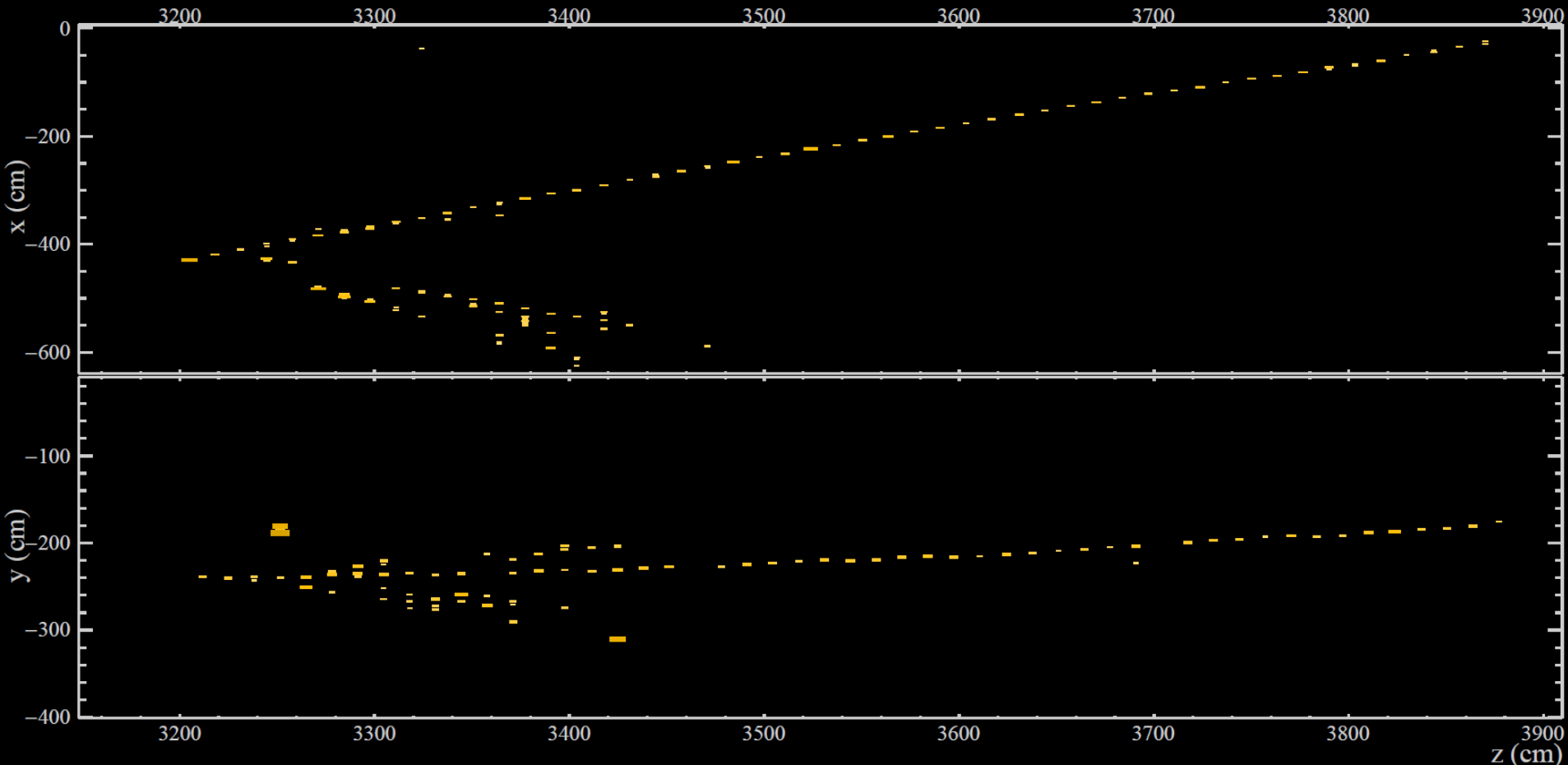
# Sterile Oscillations



# Electron Neutrino FD Data



# NOvA Far Detector Selected $\nu_\mu$ CC Candidate



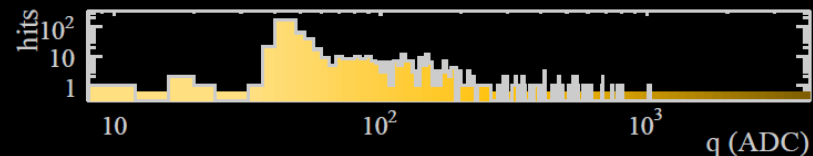
NOvA - FNAL E929

Run: 19084 / 62

Event: 908450 / --

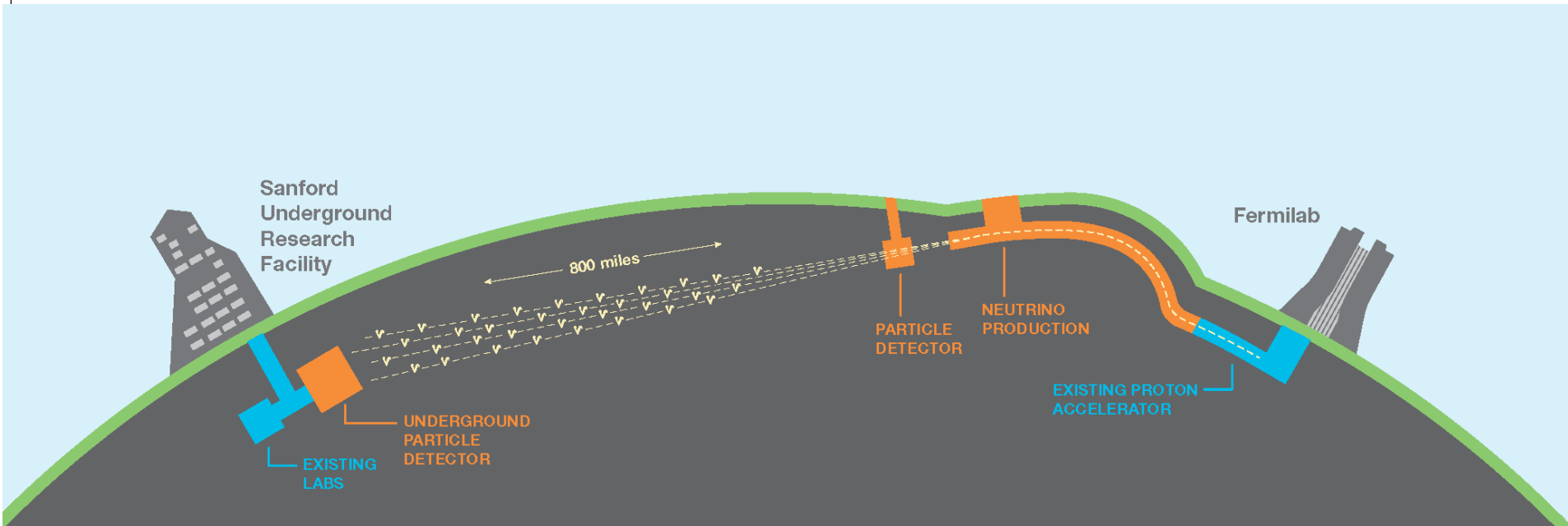
UTC Thu Mar 12, 2015

04:16:51.818581248



OLD

# DUNE



The **Deep Underground Neutrino Experiment** will be:

- a 40 kton fiducial liquid argon neutrino detector...
- located 1.5 km underground...
- 1300 km from Fermilab, which will host a 1.2 MW at 120 GeV neutrino beam...
- and a highly-capable near detector.

# DUNE Experimental Scope

## Physics Goals Driving Design

Make precise measurements of neutrino oscillations, including determining the **mass hierarchy** and the potential discovery of leptonic ***CP violation***.



Requires...

- Large detector mass
- Long baseline
- Good energy resolution
- Efficient electron neutrino identification

...liquid argon

Search for **nucleon decay**.



Requires...

- Low cosmic ray backgrounds
- Timing for non-beam events

...deep underground

...photon detection

Measure the spectrum and flavor composition of a **supernova burst** in our galaxy.



Requires...

- Several MeV energy threshold

...good signal/noise

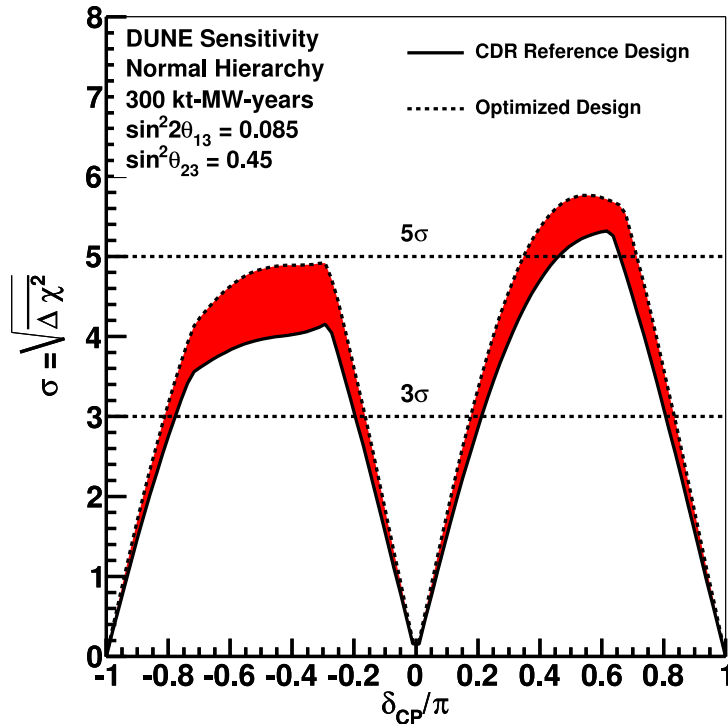


# DUNE Physics Landscape:

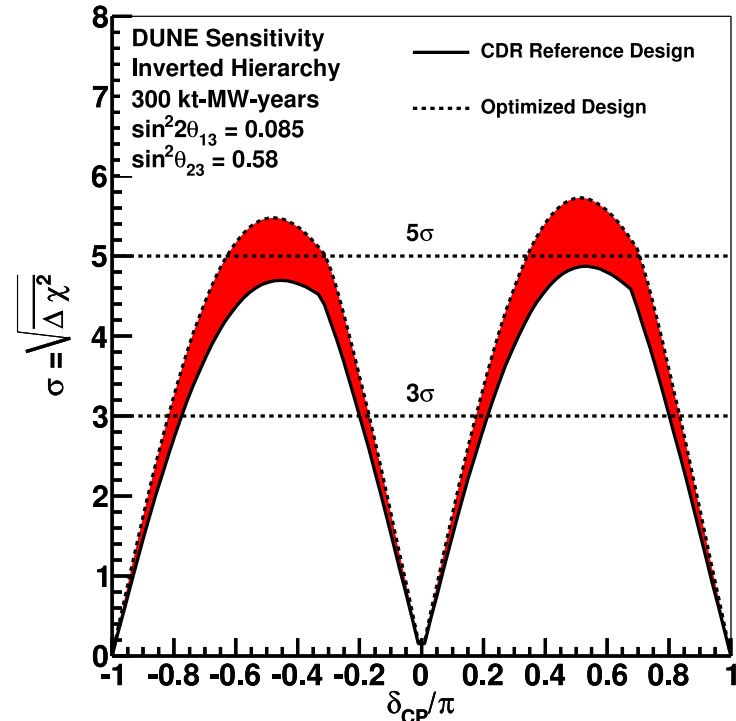
## CP Violation Sensitivity as a function of $\delta_{cp} / \text{MH}$

Sensitivity to CP Violation, after 300 kt-MW-yrs  
(3.5+3.5 yrs x 40kt @ 1.07 MW)

CP Violation Sensitivity



CP Violation Sensitivity



# DUNE Strategy / Implementation Plan

## Selected milestones:

- Selection of DUNE Name & Election of Spokespersons, ~March 2015
- Inaugural Collaboration Meeting, April 2015
- Conceptual Design Report, June 2015
- Passed Technical, Cost/Schedule Reviews (CD-1), Summer 2015
- Successful US DOE review of plan for excavation at SURF (CD-3a), Dec 2015

## Key Steps/Milestones:

- Two ProtoDUNE Detectors** (SP & DP) operational at CERN in 2018  
Provides key risk mitigation opportunity for Far Detector modules
- DUNE Technical Design Report** to be reviewed in 2019  
Done in context of both US DOE process and international organizations
  - Set up of Far Detector fabrication facilities in Q1 2020
  - Start of FD installation: 1<sup>st</sup> module in Q4 2021, 2<sup>nd</sup> module in 2023
  - 20 kt operational in 2024
  - Beam operations at 1.2 MW beginning 2026

# Česká účast



# The NOvA Collaboration



[www-nova.fnal.gov](http://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



# Příspěvek ČR k projektu NOvA

- ❑ Naši technici a fyzici se podíleli na stavbě Blízkého detektoru v podzemí ve Fermilab.
- ❑ Od roku 2013 jsme se podíleli
  - ❑ na přípravě testování APD v Ash River pomocí tzv. temného boxu,
  - ❑ **dodávkou výpočetních kapacit na počítačových prostředcích v Praze,**
  - ❑ **přispíváme do vývoje a testování systému pro sběr dat a dalších softwarových úkolů**
  - ❑ **a do přípravy fyzikálního programu.**
- ❑ Jaroslav Zálešák získal od Fermilab pozice – (tzv. International Fellowship, později **Application Physicist**) a od října 2012 do září **2016** pracoval ve Fermilab. Je to pro nás velký úspěch i ocenění našeho příspěvku do experimentu.
  - ❑ **koordinace našich (CZ) aktivit vůči experimentu.**
- ❑ Důležitým cílem je stát se autory experimentu. Experiment pro autorství vyžaduje podstatný příspěvek k experimentu.
  - ❑ V roce 2013 získali autorství F. Jediný, M. Lokajíček, J. Smolík, K. Soustružník, P. Tas, T. Vrba a J. Zálešák, **v roce 2016 se stal autorem i T. Nosek.**
- ❑ Podílíme se též na řízení kolaborace – M. Lokajíček a K. Soustružník zastupují všechna naše pracoviště v řídicí radě institucí.
- ❑ **Experiment NOvA vydal v srpnu 2016 tiskovou zprávu (viz seznam publikací) o pozorování nemaximálního mixování neutrin a postupně publikuje základní experimentální výsledky.**

## Spolupráce na DAQ

- ❑ Dlouhodobý pobyt ve Fermilab umožnil J. Zálešákovi zapojit se do prací na vývoji systému pro sběr dat z detektoru (DAQ), jeho testování a implementaci.
  - ❑ příprava, kompletace a vydávání nových verzí softwaru,
  - ❑ analýza zefektivnění běhu softwaru na nabírání dat pro analýzu šumu a extrakci hodnot k potlačení tohoto šumu a následné vložení hodnot databází.

## Vývoj softwaru

- ❑ Karel Soustružník v roce 2016 dokončil práci na tzv. "Downtime Logger" aplikaci, softwarovém nástroji, který ukládá informace o problémech se systémem sběru dat (DAQ), což umožní jejich efektivnější odstranění.
  - ❑ Aplikace je součástí DAQ a nyní již dochází pouze k úpravám konfigurace.
  - ❑ Vyvinul rovněž aplikaci na grafické zobrazení rozdělení výskytu a délky období s problémy se sběrem dat (tzv. downtimes).
- ❑ V tomto roce navrhl a začal vyvíjet tzv. "DAQ Dashboard" aplikaci
  - ❑ zvýšení efektivity monitoringu detektorů.
  - ❑ shromáždění informací o stavu jednotlivých částí detektoru na jednom místě.
  - ❑ grafické rozhraní pro online zobrazení je hotové a probíhá jeho testování.
  - ❑ Petr Tas pro tuto aplikaci vyvíjí webové rozhraní, které zpřístupní informace o stavu detektoru z libovolného místa.
  - ❑ Tomáš Nosek vyvíjí část aplikace, která zajistí sběr relevantních informací z DAQ systému a jejich uložení do souboru.

## *Spolupráce na DCS*

- ❑ DCS (Detector Control Systems) je skupina systémů zajišťujících bezproblémový a bezpečný chod detektorů experimentu NOvA.
  - ❑ F. Jediný navrhnul nový systém DCS - sjednotil dva subsystémy monitoringu prostředí a monitoringu relay racků a implementoval odečet signálů pomocí PLC z chladicího systému. Vedle toho dále instaloval podzemní kamerový systém.
  - ❑ Jako **DCS expert pokračuje v roce 2016 s občasou potřebnou údržbou kamer.**

## *Spolupráce na DDT*

- ❑ Po návratu z USA se J. Zálešák zapojil do **skupiny DDT (Data Driven Trigger)**.
  - ❑ Příprava rámce na validaci dat v oblasti speciálních trigrů (data nepocházející ze svazků urychlovače, sloužící k analýze exotických jevů, neutrin ze supernov apod.).
  - ❑ **Nastavení softwarového prostředí, v němž se validace bude provádět.**

## *Run koordinátor*

- ❑ V březnu 2014 se stal J. Zálešák run koordinátorem celého experimentu NOvA. Tuto funkci **vykonával téměř nepřetržitě do září 2016, kdy se po 4 letech strávených v laboratoři Fermilab vrátil zpět na FZU.**
  - ❑ V rámci této funkce **koordinoval běh obou detektorů a činil důležitá rozhodnutí ohledně směru, jakým se ubíralo nabírání dat.**
  - ❑ Z titulu funkce byl automaticky **součástí, s hlasovacím právem, obou rozhodovacích komisí experimentu, „Institutional board“ a „Executive Committee“.**

## *Příprava na dlouhodobé studium vlastností APD*

- ❑ V předchozích letech jsme v pražské laboratoři vybudovali pracoviště pro dlouhodobé studium vlastností APD.
  - ❑ Pracoviště je vybaveno potřebnými přístroji pro daná měření (řiditelný zdroj vysokého napětí, přesný a citlivý voltmetr a ampérmetr, klimatická komora). Byl postaven **chladicí okruh pro dosažení pracovního bodu APD při  $-15^{\circ}\text{C}$ , který umožňuje udržovat zadanou teplotu s přesností lepší než  $0,01^{\circ}\text{C}$ .**
  - ❑ Byl navržen a vyzkoušen prototyp měřicí desky pro odzkoušení dvou různých metod sekvenčního měření VA charakteristik osmi kanálů APD. Měření probíhala v temném boxu, kam byl vháněn dusík pro zamezení vzdušné vlhkosti na vychlazeném APD. **Na základě získaných zkušeností jsou v současnosti připravovány nový temný box a měřicí deska pro současné měření všech 32 kanálů APD matice.**
  - ❑ Na vývoji a stavbě celé aparatury se podíleli inženýři J. Zuklín, I. Polák a J. Kvasnička a technici V. Zamazal, Vl. Zamazal a J. Weichert. Na měřeních se dále podílí J. Smolík a V. Linhart.

## *Temný box pro testování APD*

- ❑ Z. Kotek a J. Palacký vyvinuli a vyrobili testovací zařízení, které umožňuje měřit sumární temný proud ze všech 32 kanálů APD současně bez rušení okolním světlem.
  - ❑ První zařízení bylo dodáno do Fermilab koncem roku 2012, druhé pak pro instalaci Blízkého detektoru bylo dodáno v polovině roku 2013.
  - ❑ V roce 2015 jsme oba boxy zdokonalili doplněním optické závory na vypínání vysokého napětí pro zvýšení bezpečnosti.



## Počítačové simulace

- ❑ Fyzikální ústav provozuje Regionální výpočetní centrum pro fyziku částic a dlouhodobě dodává potřebný výpočetní výkon pro experimenty DØ a NOvA a další experimenty.
  - ❑ V roce 2013 jsme pořídili diskový prostor 14 TB a integrovali do prostředí počítačové farmy ve FZÚ, v roce 2014 byla navýšena i výpočetní kapacita.
  - ❑ Petr Vokáč s využitím OSG (Open Science Grid) middleware připravil automatické zpřístupnění našich výpočetních kapacit pro zpracování dat úlohami NOvA, které začalo v srpnu 2014 a **úspěšně pokračuje**. Prováděl dále i **servisní práce a měl na starosti zpracování OSG gridových úloh** (DZero, NOvA, v přípravě DUNE) na výpočetním clusteru umístěném ve Fyzikálním ústavu Akademie věd.
  - ❑ Jan Švec zodpovídá za funkčnost výpočetních prostředků pro NOvA, Lukáš Fiala za webové a další služby. **Příspěvek českého projektu je dokumentován na obr.**
  - ❑ M. Lokajíček je kontaktní osobou pro gridové aplikace a pro využití moderních síťových spojení.
    - ❑ **V roce 2016 se podařilo ve spolupráci s CESNET, GEANT a ESNET převést počítačové spojení mezi Fermilab a FZÚ do sítě LHCONe, která umožňuje vyšší rychlosti přenosů a dlouhodobě zajišťuje nárůst rychlosti podle potřeb uživatelů.**

Wall Hours by Facility (Sum: 15,512,112 Hours)  
62 Weeks from Week 39 of 2015 to Week 48 of 2016

