The NOνA Experiment

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Fermilab Users' Meeting

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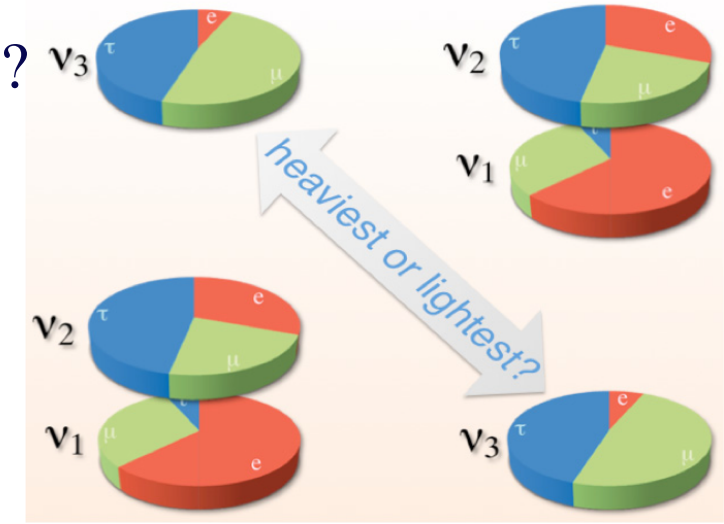
The Current Questions

- The last 15 years have seen tremendous progress
  - $sin^2(2\theta_{23})$, Δm^2_{ATM}, $sin^2(\theta_{12})$, Δm^2_{21}, $sin^2(2\theta_{13})$ now well measured
- Unanswered questions include
  - Leptonic CP violation: $sin(\delta_{CP}) \neq 0$?
  - Mass Hierarchy:

    $m_3 > m_2, m_1$ or $m_3 < m_2, m_1$?
  - θ_{23} : Maximal? $\theta_{23} = 45^o$
  - θ_{23} octant: if not maximal,

    is $\theta_{23} < 45^o$ *or* $\theta_{23} > 45^o$

    (ν_3 more ν_τ or more ν_μ) ?
  - Is the 3 neutrino mixing model a complete description?

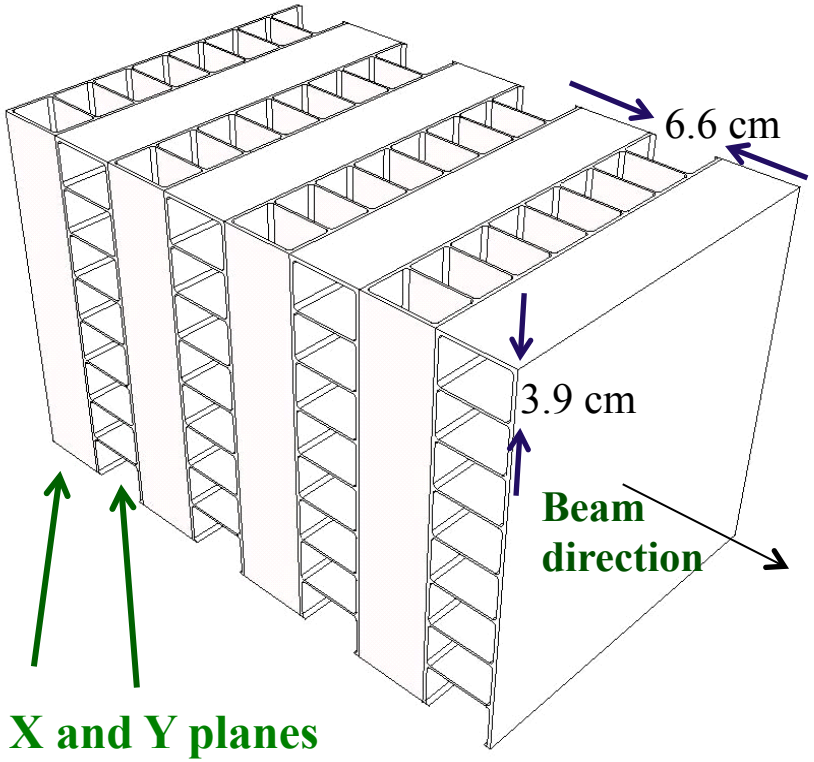


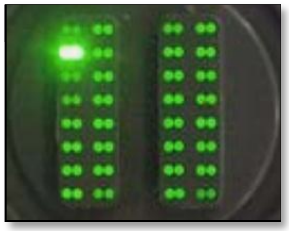
NOνA

- NuMI Off-Axis ν_e Appearance experiment
- Study ν_e and $\bar{\nu}_e$ appearance to address open questions
  - Rich phenomenology of $P(\nu_\mu \rightarrow \nu_e)$, $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ over long-baseline in matter
- Study ν_μ disappearance
- Requirements
  - Excellent ν_e identification and background rejection
  - Optimal matter effect for mass hierarchy (MH)
  - Maximal statistics
- Design
  - High-Power, Narrow-band Beam, with ν and $\bar{\nu}$ modes
  - Huge, Low-Z, totally active, tracking calorimeter Detector

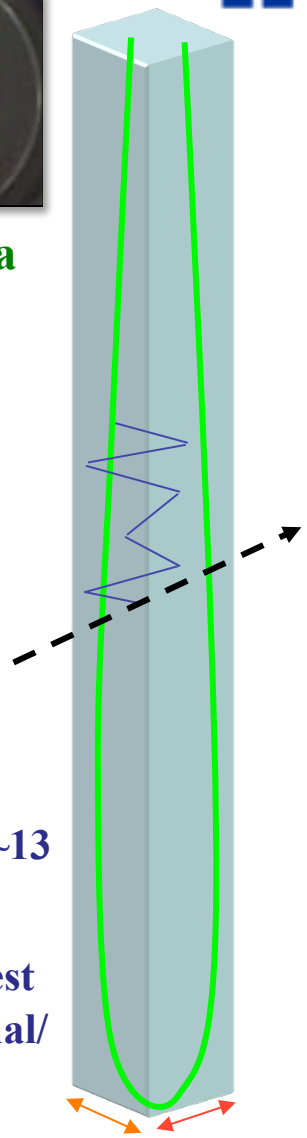
NOvA Detector Technology

Cell structure of reflective PVC extrusions Filled with Liquid Scintillator





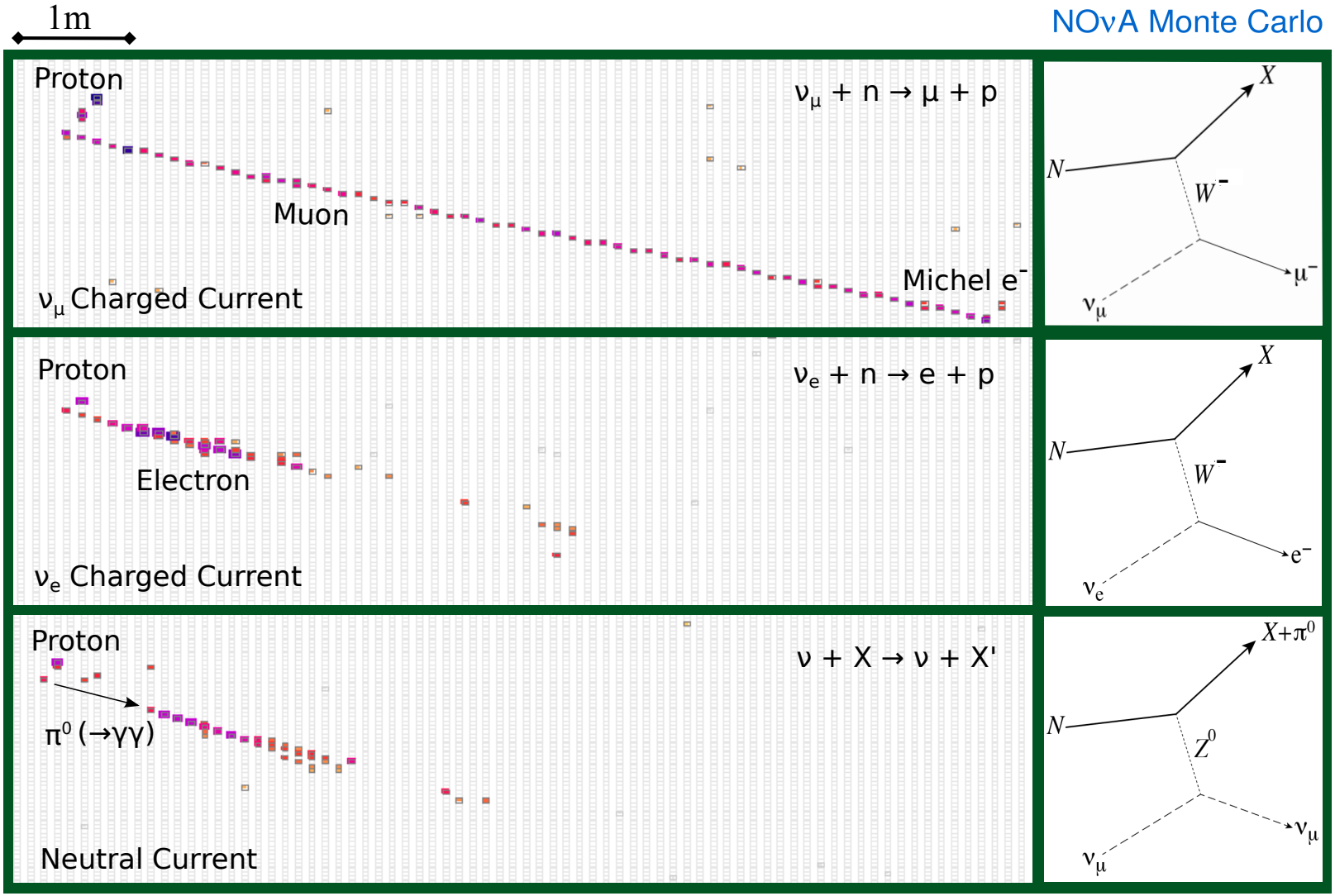
Each cell read out via wavelength-shifting fiber to 1 pixel of 32-channel Avalanche Photo Diode



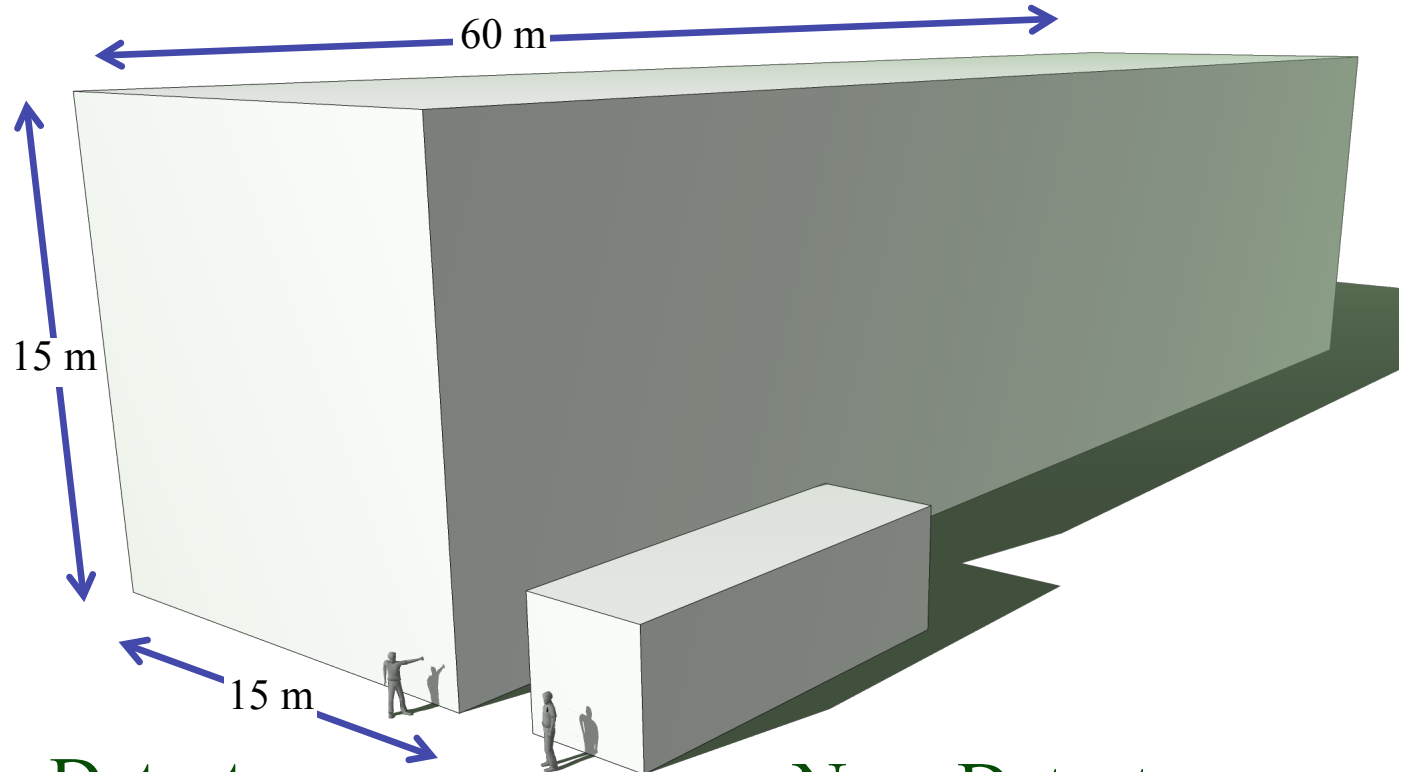
- **0.15 X_0 per plane – excellent EM shower characterization**
- **Normal incidence MIP deposits ~13 MeV per cell**
- **30 photoelectrons for MIP farthest from readout achieves desired Signal/ Noise of 10:1**

Event Topologies

NOνA Monte Carlo

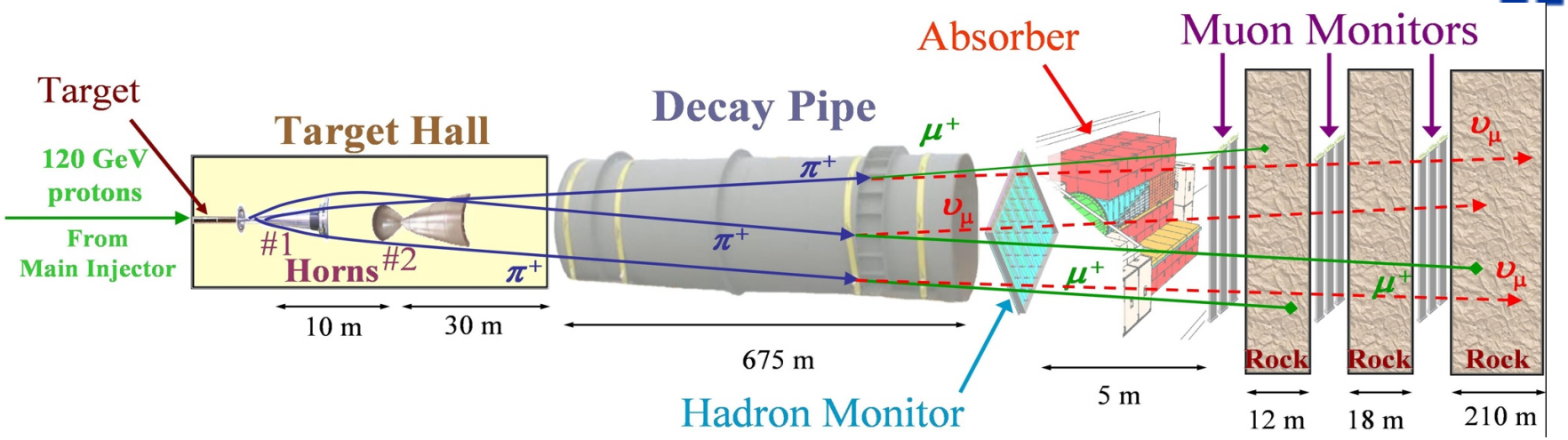


Detectors



- Far Detector
  - 14 kT
  - 896 planes
- Near Detector
  - 192 planes, plus a muon catcher with 10 planes of iron

NuMI Beam

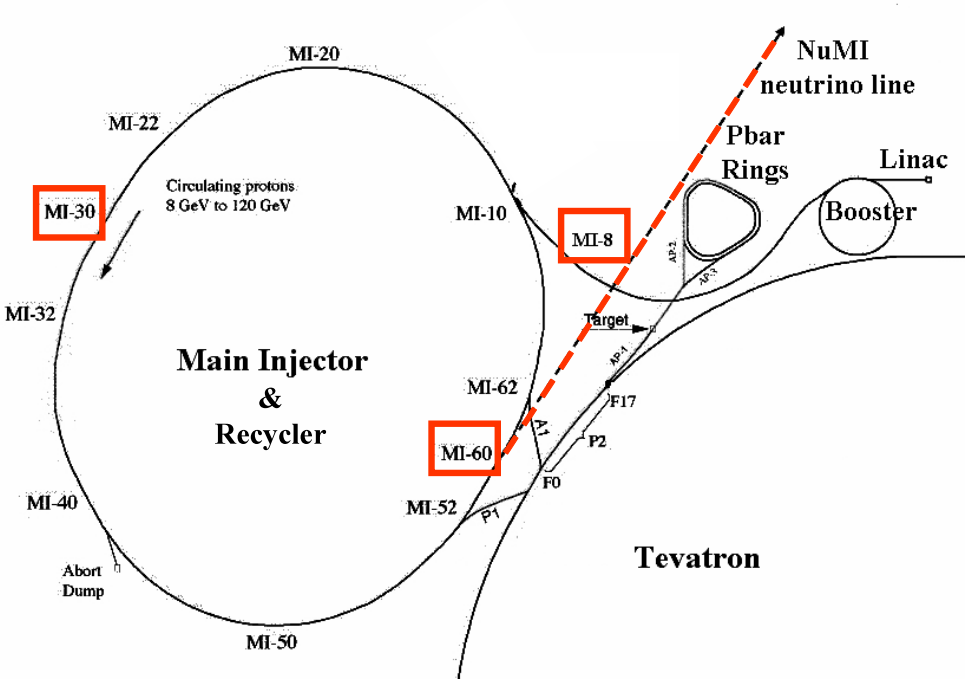


- Neutrinos at the Main Injector
- Beam spectrum tunable by horn currents, relative placement of target and horns
  - ν or $\bar{\nu}$ predominant beam depending on horn current polarity
- 10 μs beam spill

- Pre-NOvA Era
  - Served MINOS, MINERvA, ArgoNEUT
  - 320 kW beam power in 2.2 sec cycle
  - Typically ran in Low Energy configuration

ANU: Accelerator/NuMI Upgrades

- 700 kW power to NuMI using existing accelerator complex
- Reduce cycle time from 2.2 to 1.33 seconds
  - Perform slip-stacking in the Recycler prior to injection to Main Injector
  - Additional MI RF stations
- Increased intensity per cycle
  - E.g, new injection kicker to permit 12 Booster batches (up from 11)
- NuMI upgrades for intensity:
  - Medium Energy Beam Configuration
  - New production target, horn 1
- Also: PIP (1), including refurbished Booster RF Cavities for 15 Hz

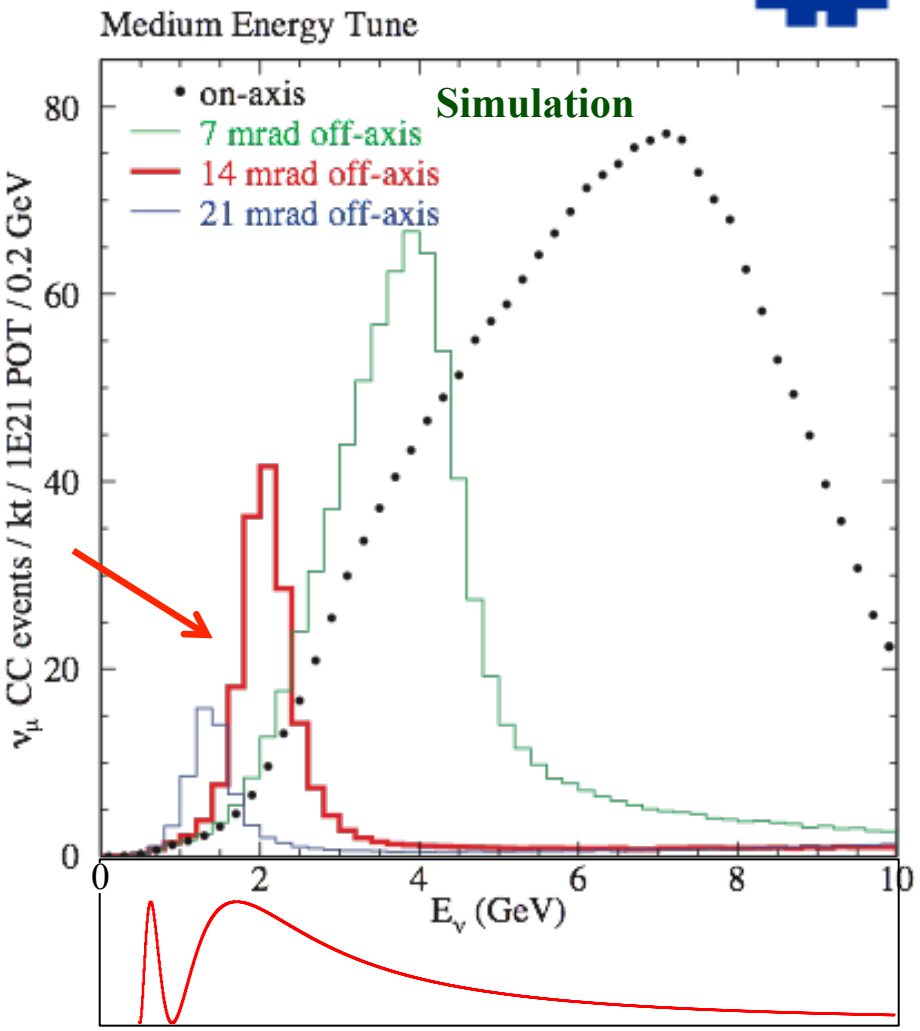


Location

- 14 mrad (11km) off the NuMI beam axis
  - Pion 2-body decay kinematics

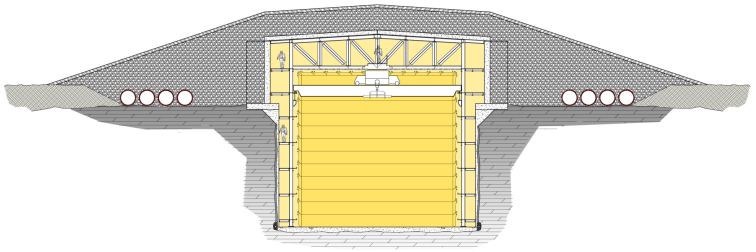
$$E_\nu = \frac{0.43 E_\pi}{1 + \gamma^2 \theta^2}$$

    - Neutrino spectrum peaks around 1st oscillation maximum
    - High energy tail suppressed: reduces Neutral Current π^0 background
- As far as possible from Fermilab for maximum matter effect/Mass Hierarchy
  - 810 km



Far Detector

- Ash River, Minnesota



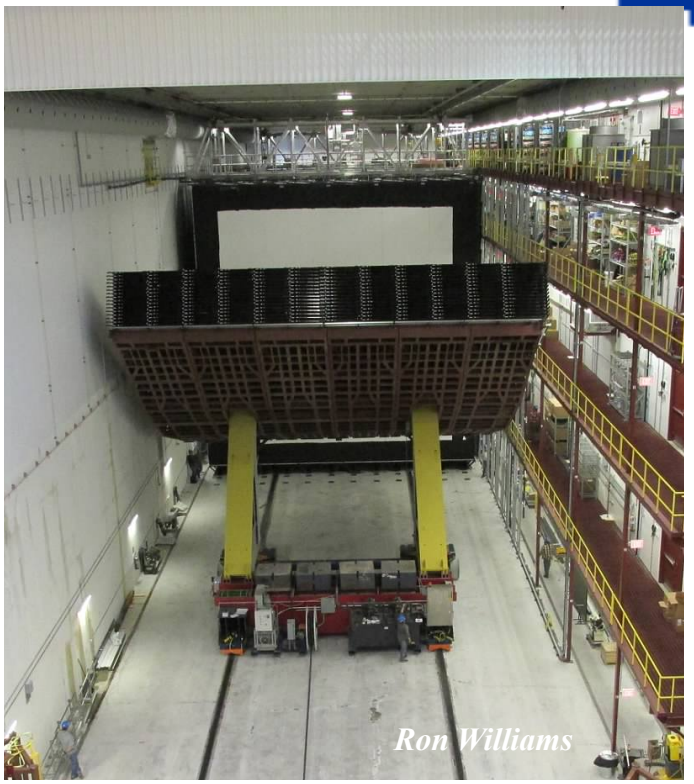
- Detector is mostly below grade
- Overburden: 1.37m concrete + 0.15m Barite ($BaSO_4$) for cosmic background reduction

Far Detector Assembly

32-plane "Blocks" assembled horizontally on Pivoter

Pivoter rolls block into position

Scintillator filled in situ



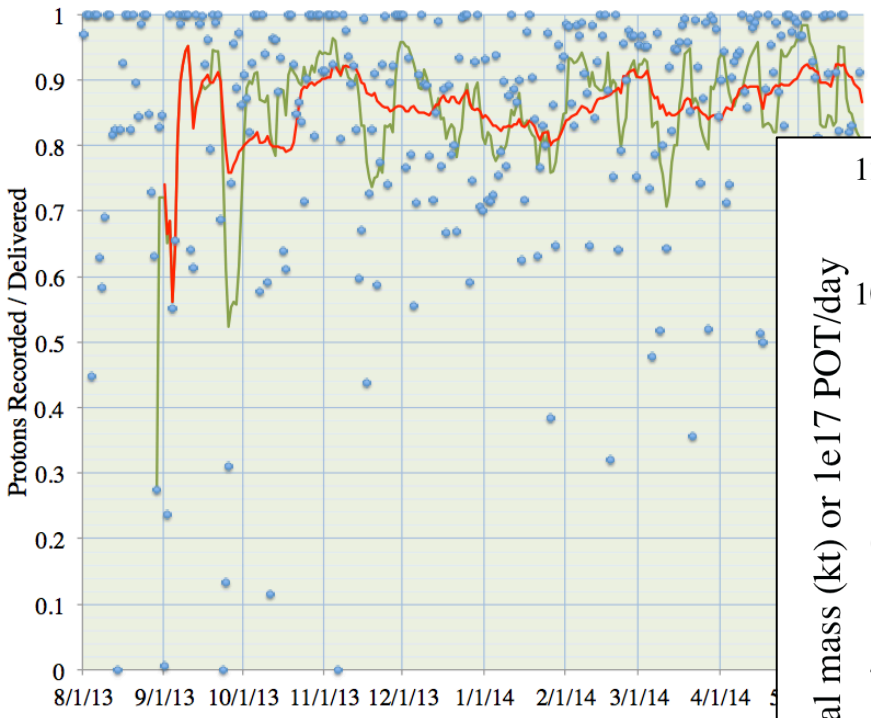
- September 2012 – April 2014
- Along the way, the we needed ~
  - 2.6 million gallons scintillator: mineral oil, 0.15 M gallons pseudocumene, etc.
  - 12,600 km wavelength shifting fiber
  - 21,500 PVC extrusions of 16 cells each
  - 11,000 APDs
  - 112 tons of Glue

Far Detector Assembled

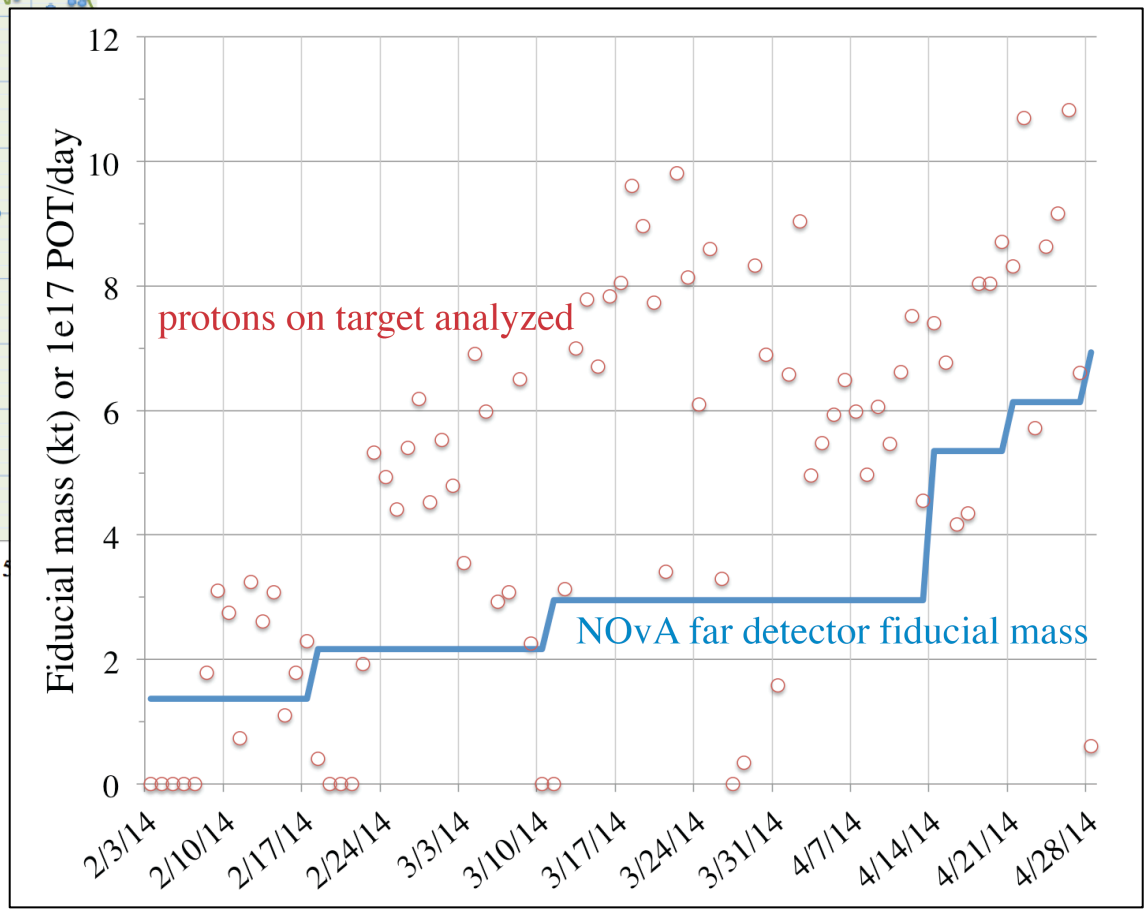
Each small box holds a 32-channel APD, Front End Board

Data Taking

Data taking simultaneous with assembling and commissioning new blocks

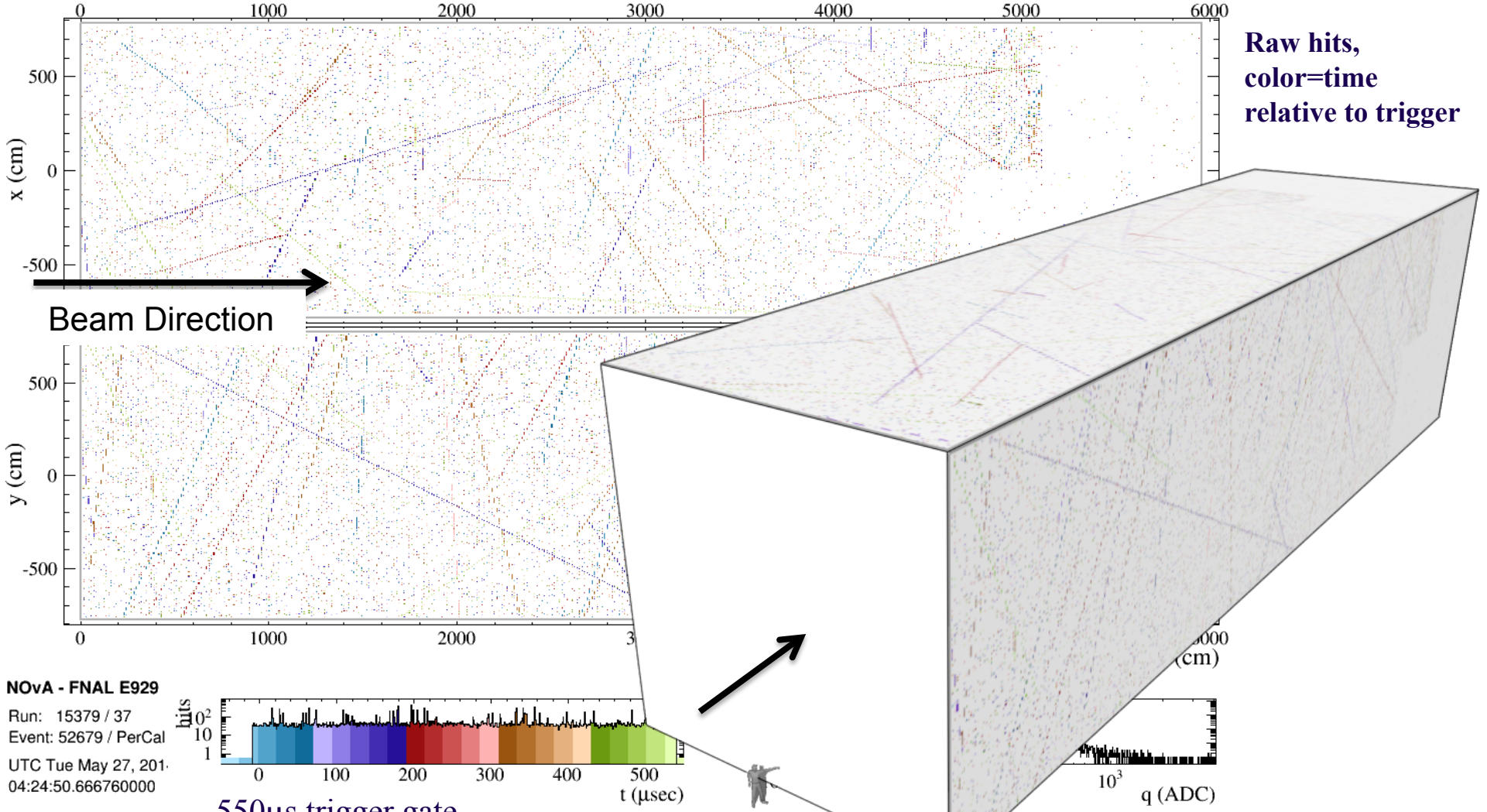


Average beam-on uptime >85%



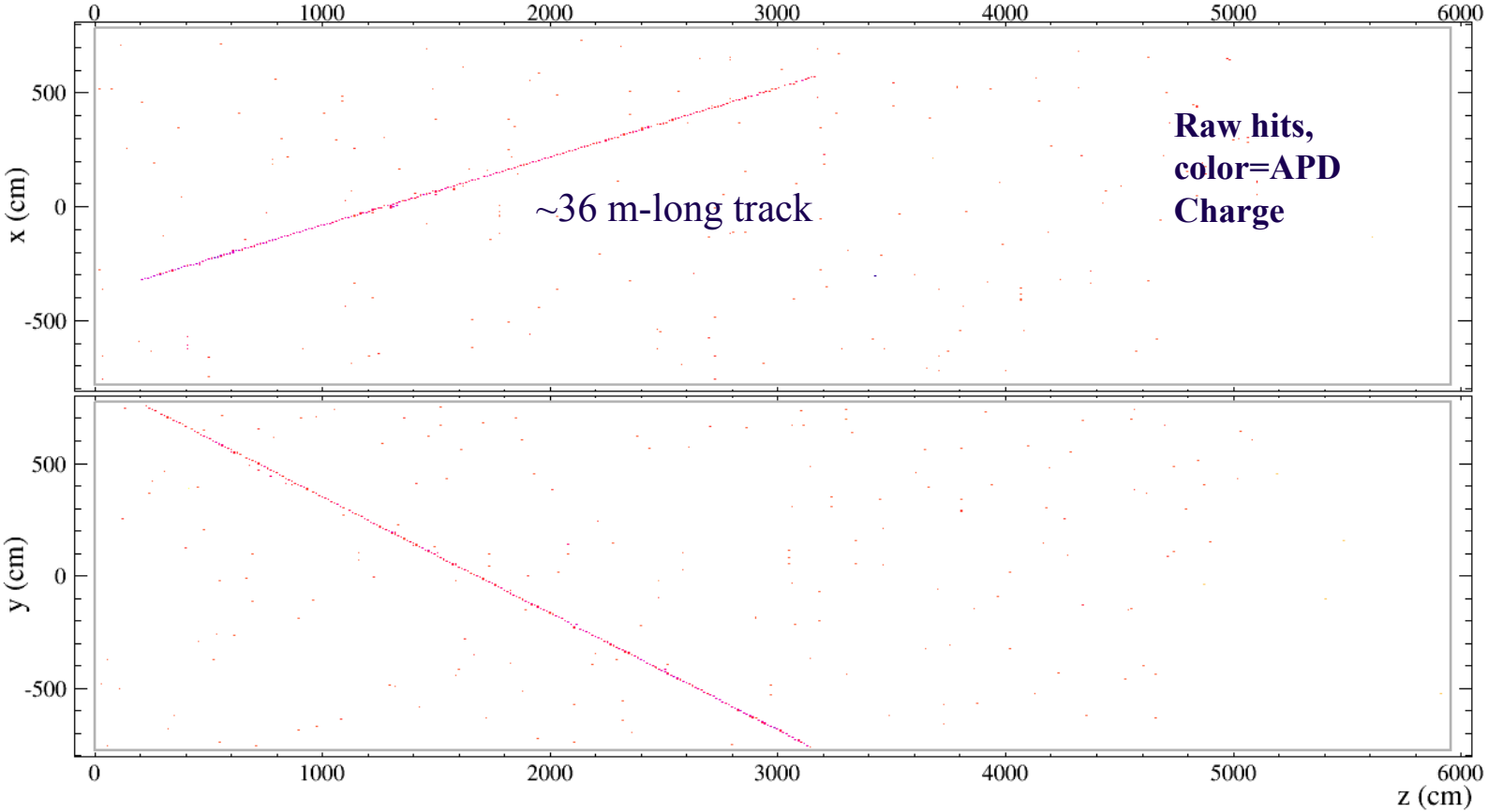
NOvA Data

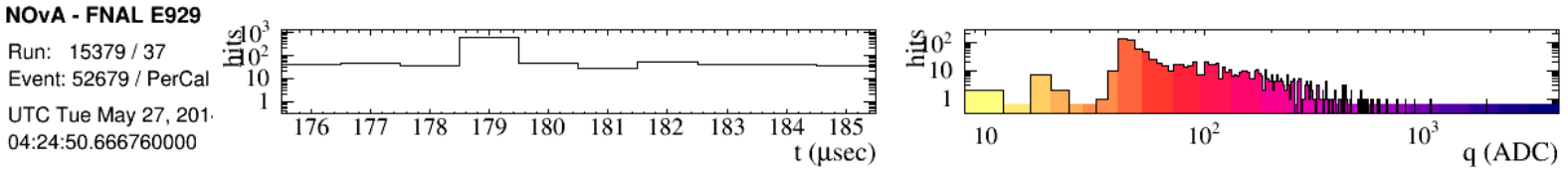
Data with 11.25 kT fully instrumented



Cosmic Muon Track

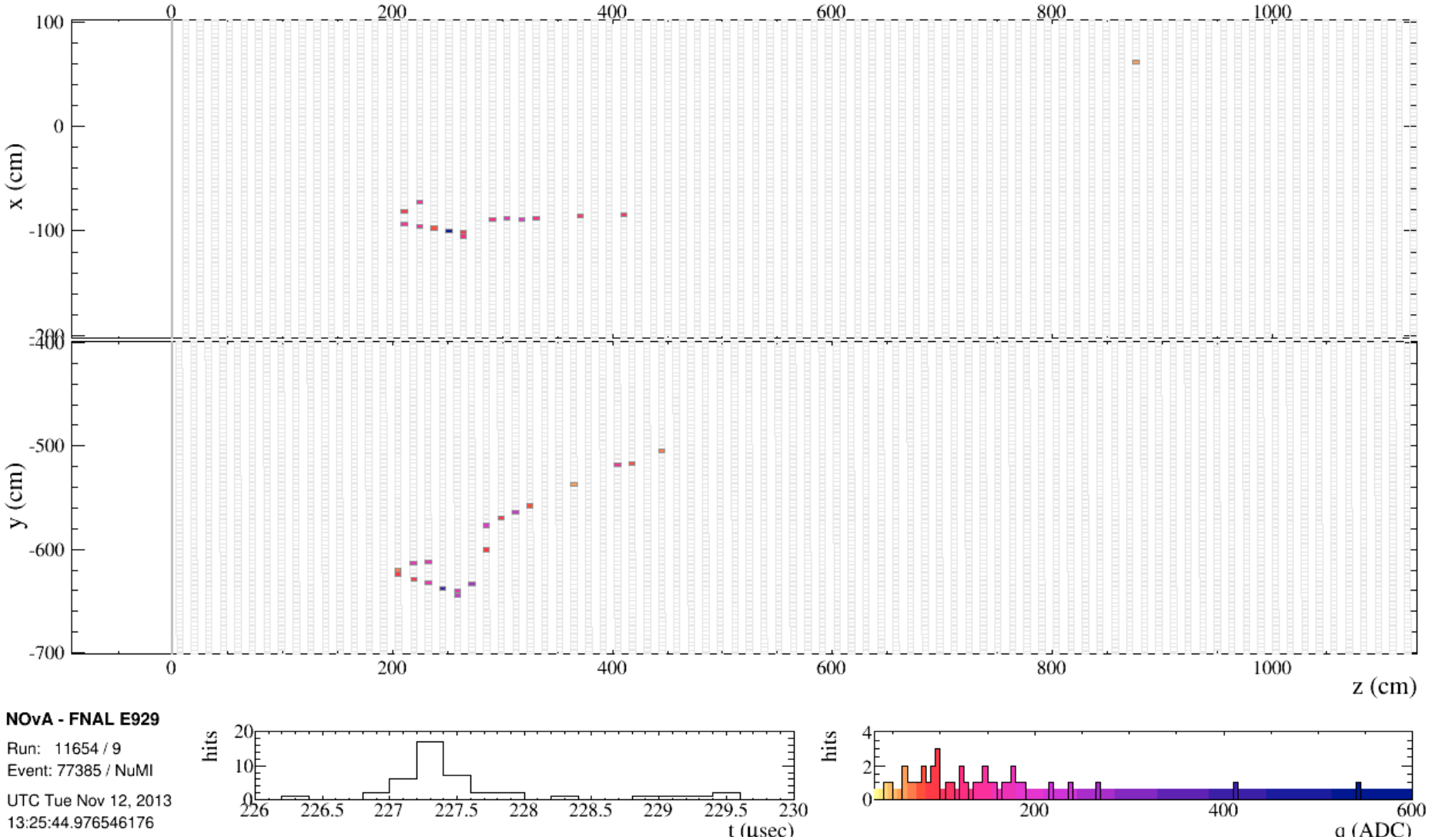
Data with 11.25 kT fully instrumented



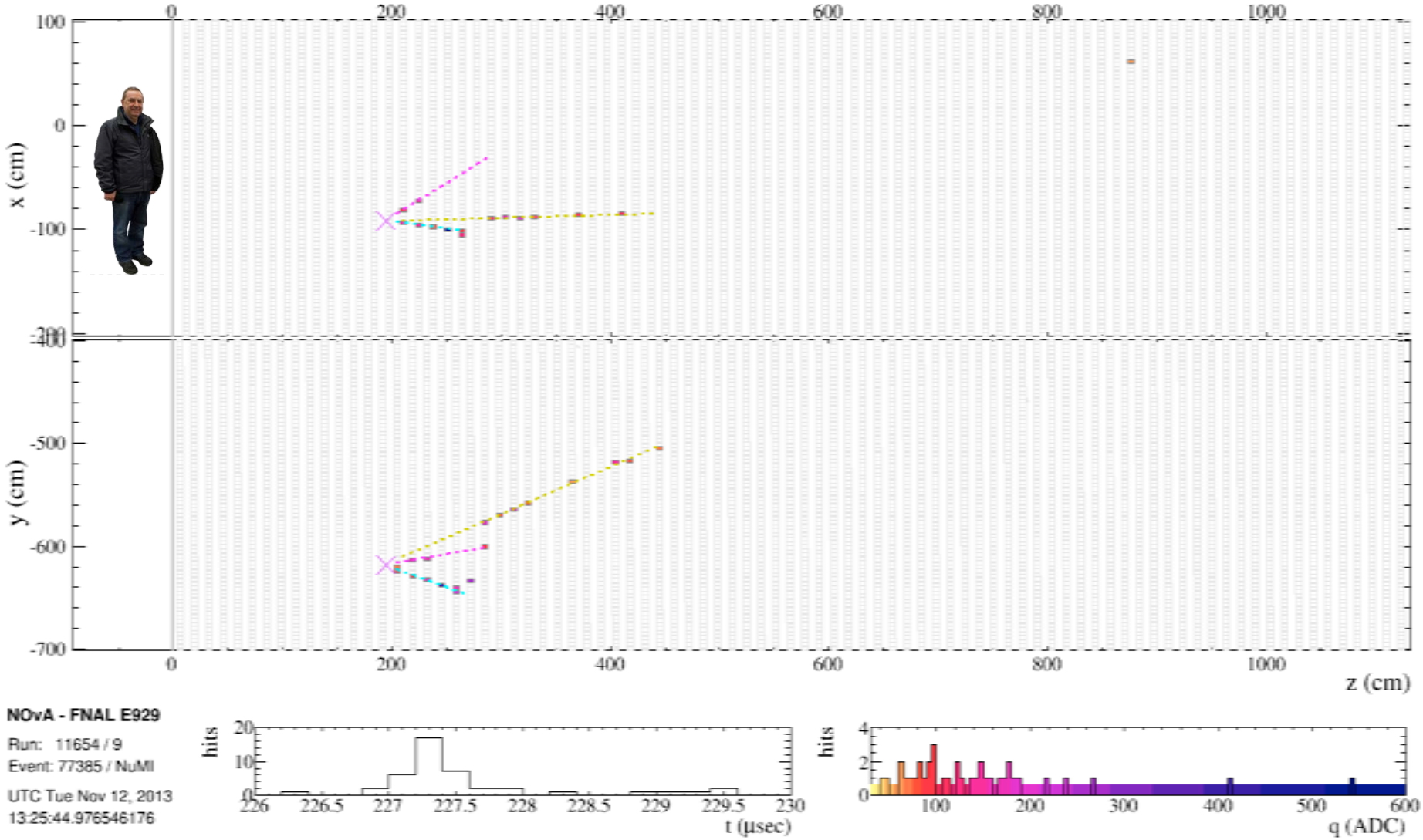


10μs = duration of NuMI spill

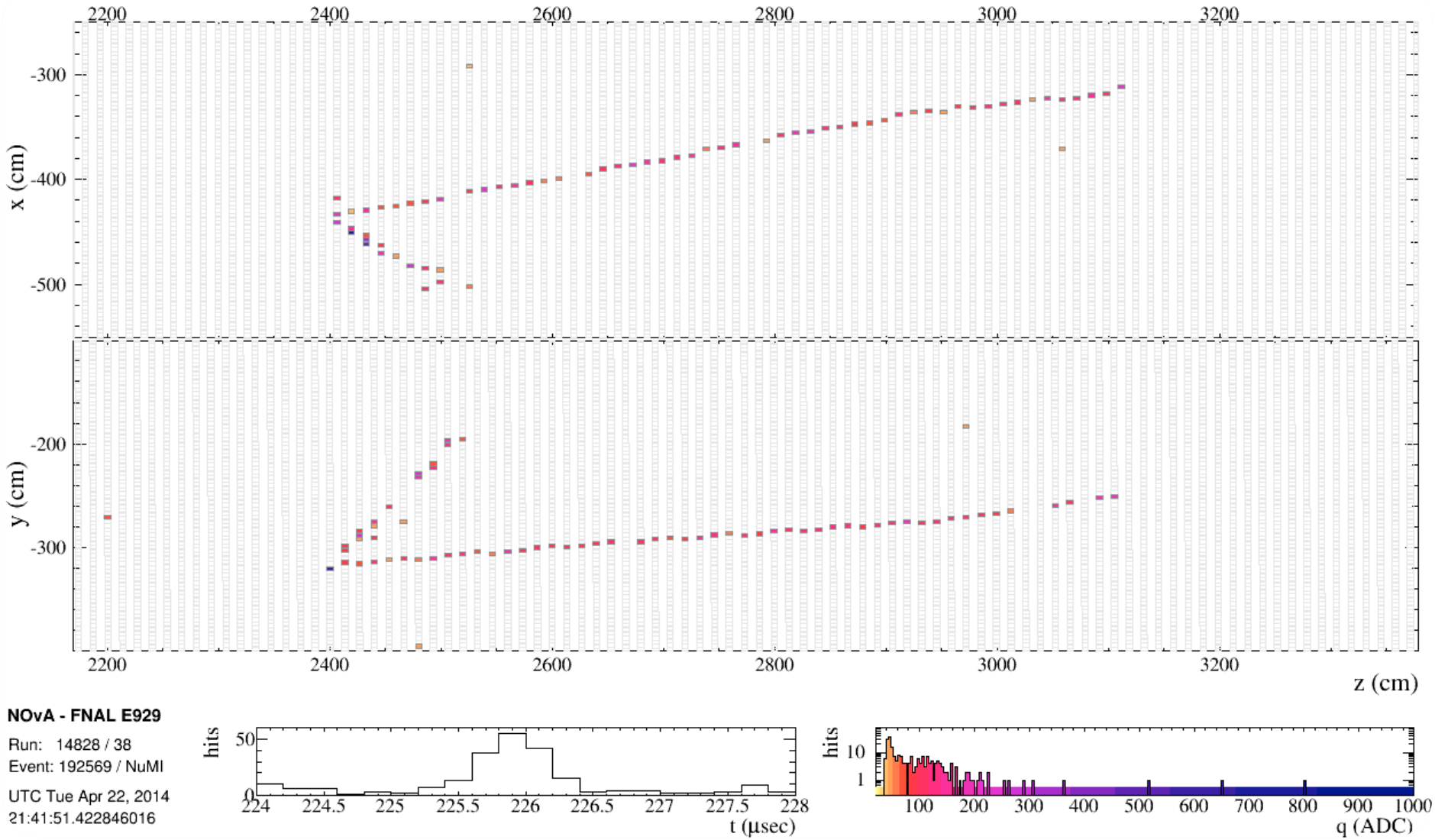
1st Neutrino Candidate



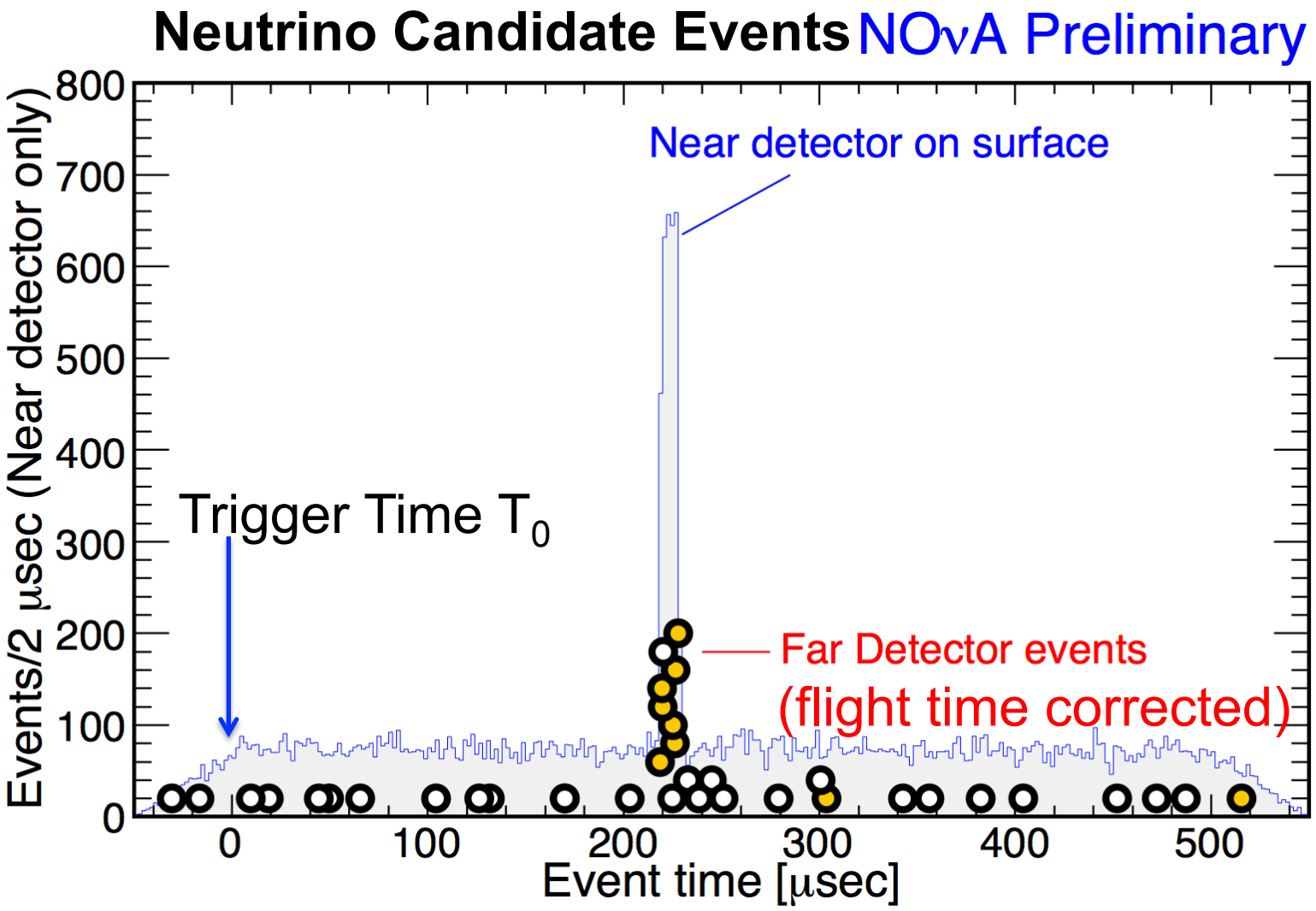
With Reconstruction



ν_μCC Candidate

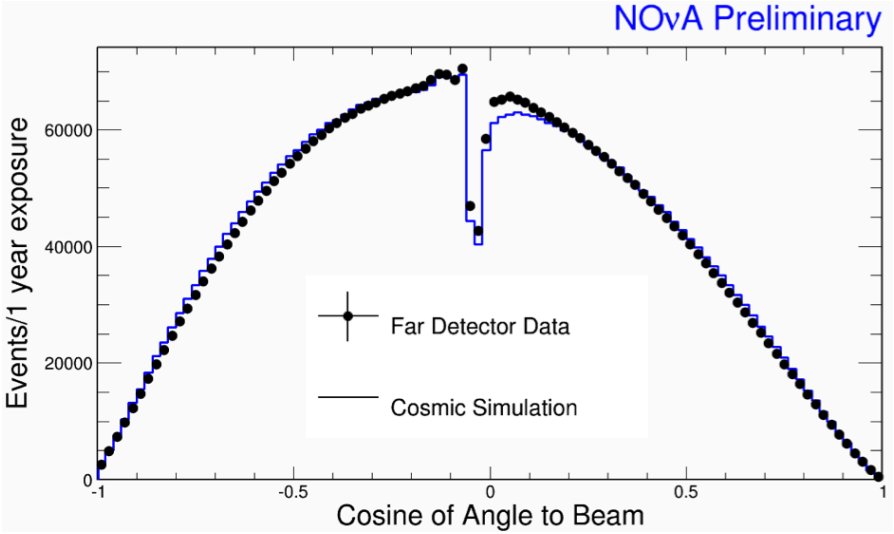


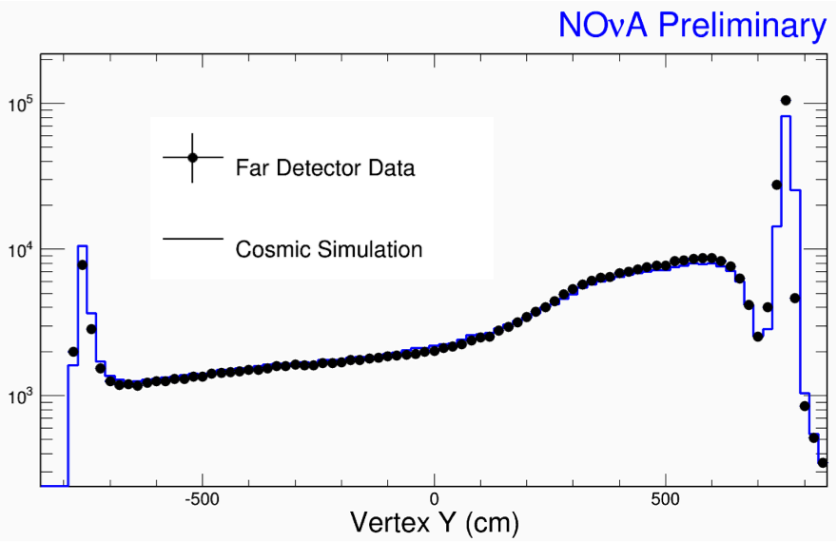
Timing of FarDet ν Events




EXIT

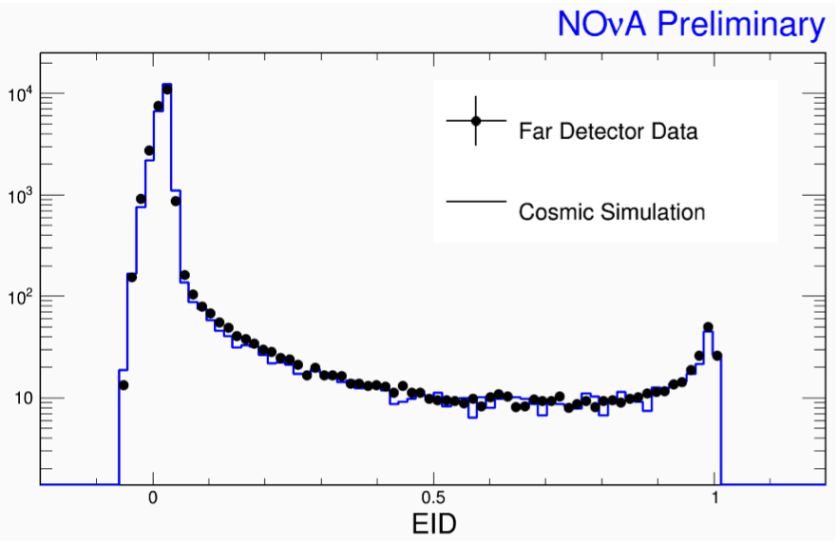
Cosmic Ray Data





Scaled to nominal yearly beam-on exposure of 120 seconds

Good agreement between Data and Monte Carlo Simulations

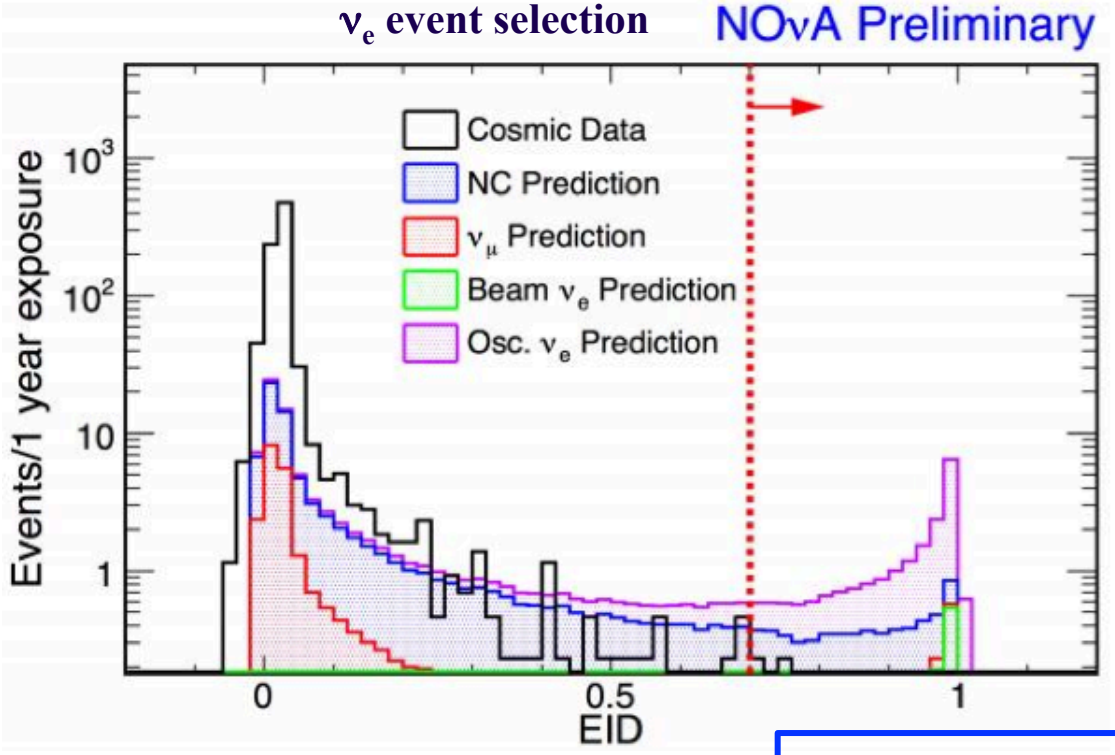


Event ID – ANN based on most energetic shower
+1 = electron-like

Anticipated ν_e Yields

Nominal Design Year:

6×10^{20} Protons-on-Target, 14 kT detector



Leading order oscillation

ν_e: 14 signal / 7 background

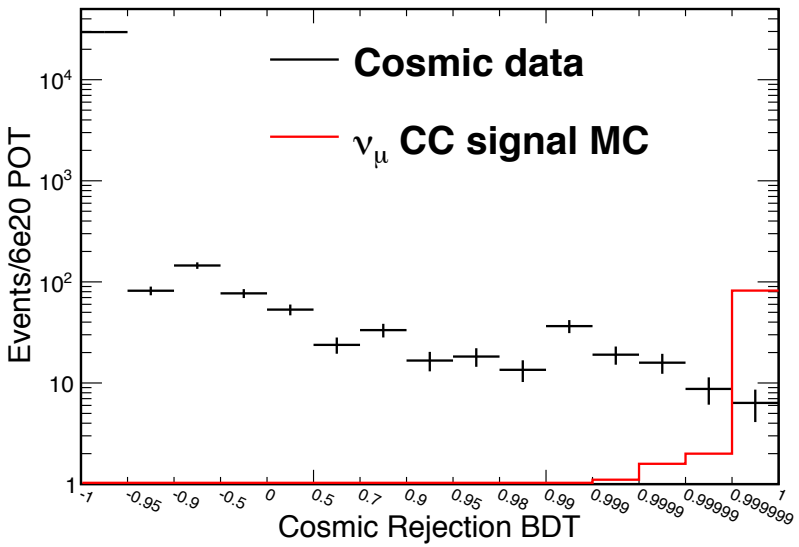
Cosmic background rejection benchmarked to data
40M:1 for ν_e

Anticipated ν_μ Yields

Nominal Design Year:

6×10^{20} Protons-on-Target, 14 kT detector

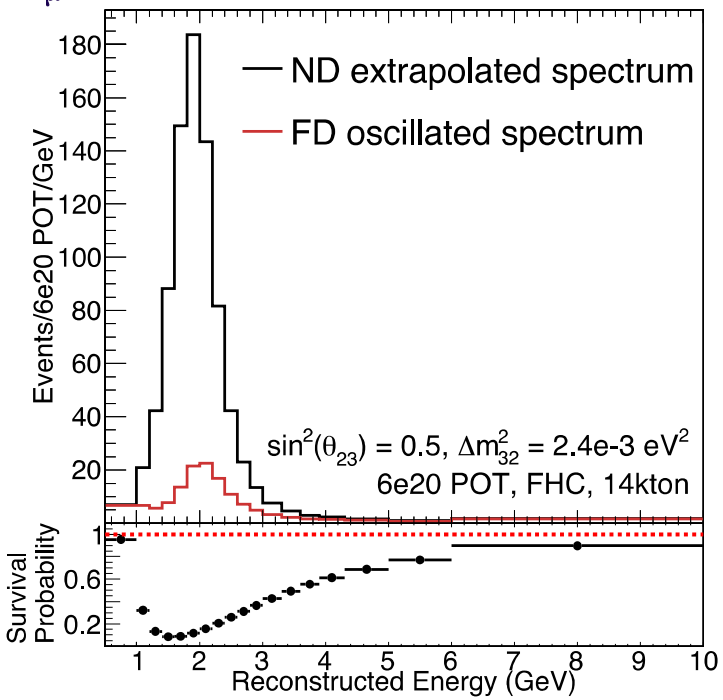
NOνA Preliminary



ν_μ cosmic background rejection BDT

ν_μ event spectrum

NOνA Simulation



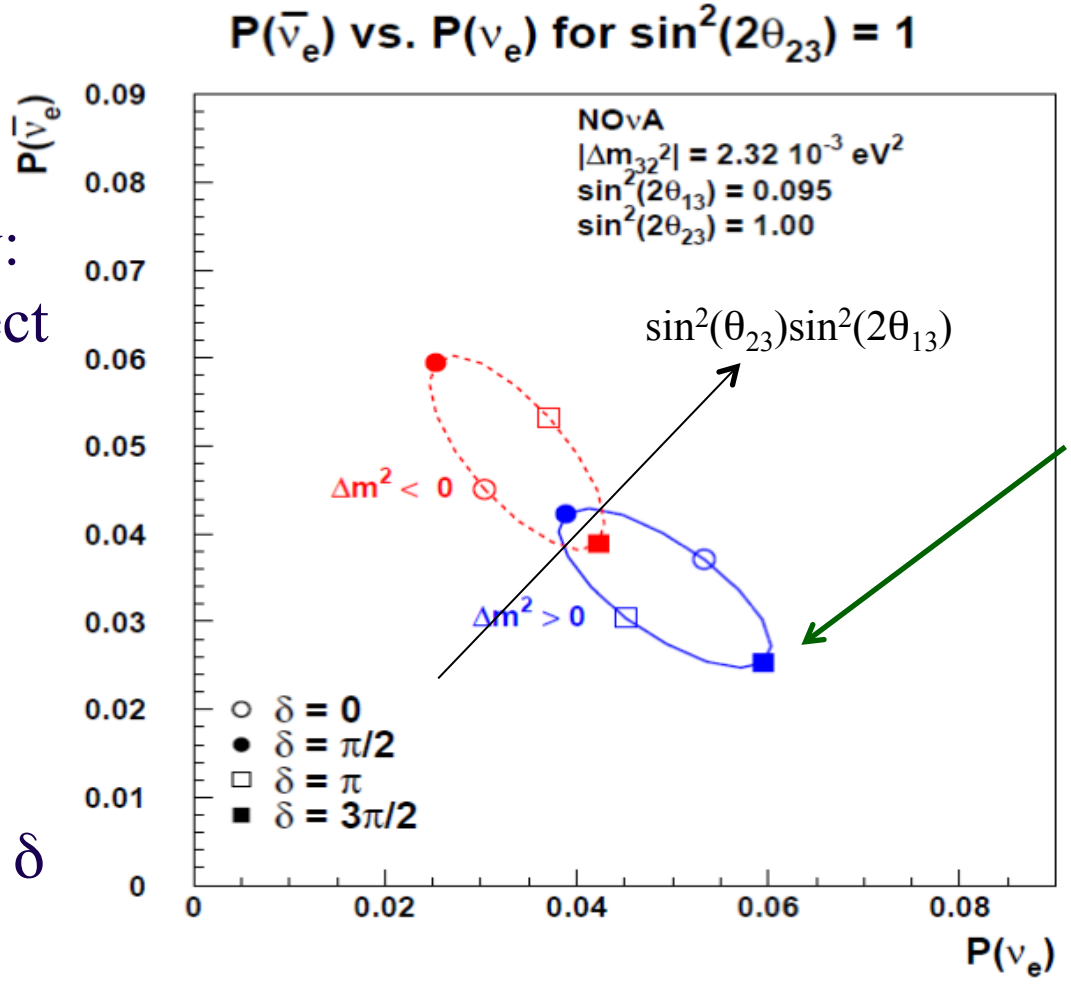
ν_μ: 75 signal / 5.4 background

- 398 signal w/out oscillations

Cosmic background rejection benchmarked to data
20M:1 for ν_μ

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

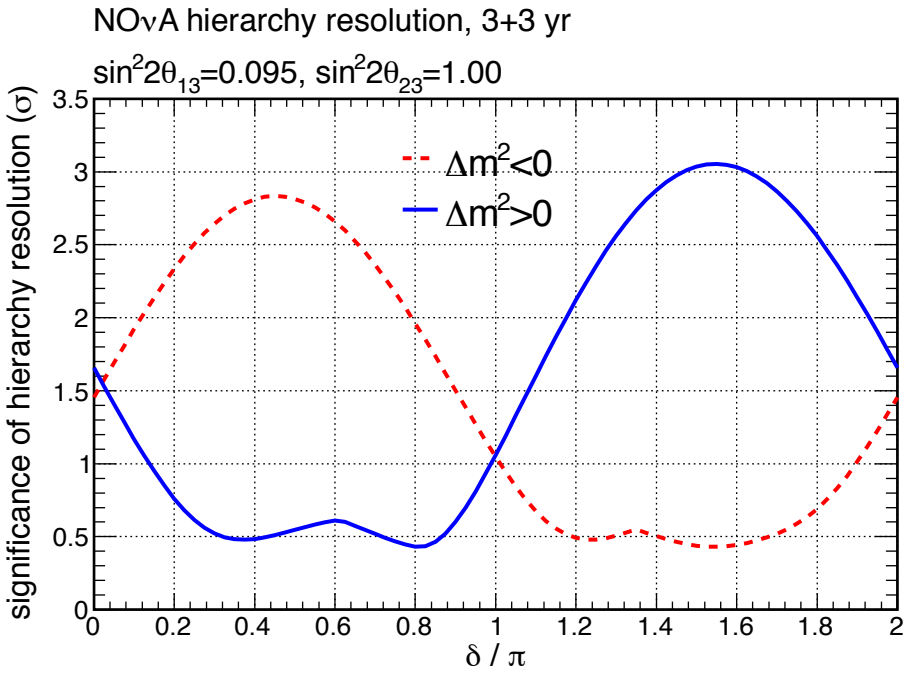
- Mass Hierarchy: Via Matter Effect
- CP Violation: δ
- θ_{23} octant: leading term $\propto sin^2(\theta_{23})$
- sensitivities depend on MH, δ



T2K sees *"slight hint"* in favor of Normal MH, $\delta_{CP}=3\pi/2$ when combined w/ Reactor results
C. Walter, Nu2014

NOνA Reach

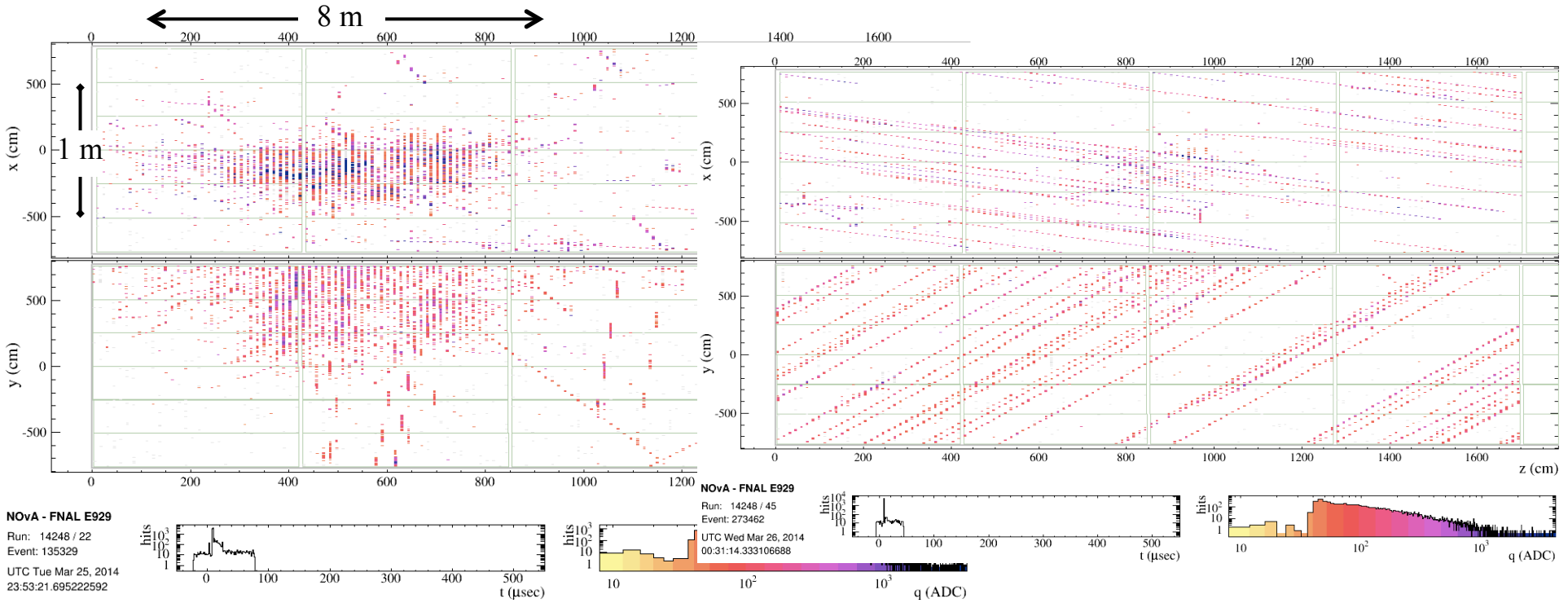
- ν_e Appearance
  - >95% CL determination of Mass Hierarchy over 1/3 of the range of δ
  - >95% CL determination of θ_{23} octant for all δ for $sin^2(2\theta_{23})=0.95$
  - New constraints on allowed range of δ
- ν_μ Disappearance
  - Measure $sin^2(2\theta_{23})$ to ~2% at maximal mixing
- Non-ν/non-oscillation physics



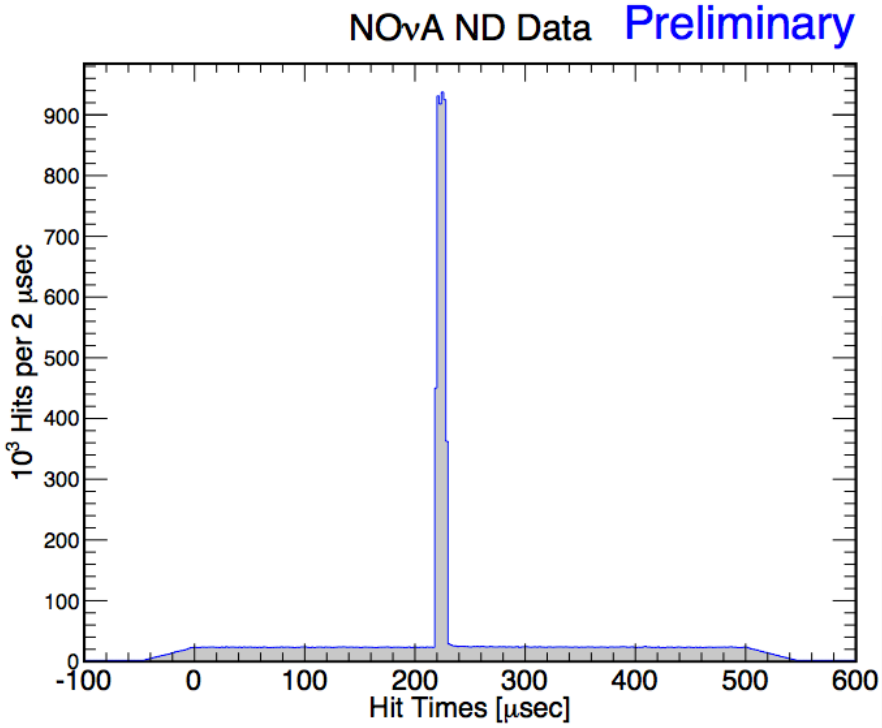
Significance of MH vs δ_{CP}

Not Just ν, Oscillation Physics

- Large, sensitive, finely-segmented detector
  - Supernova neutrinos, Magnetic monopoles …
  - Use Data-driven trigger to select High Energy/High Multiplicity signatures, etc



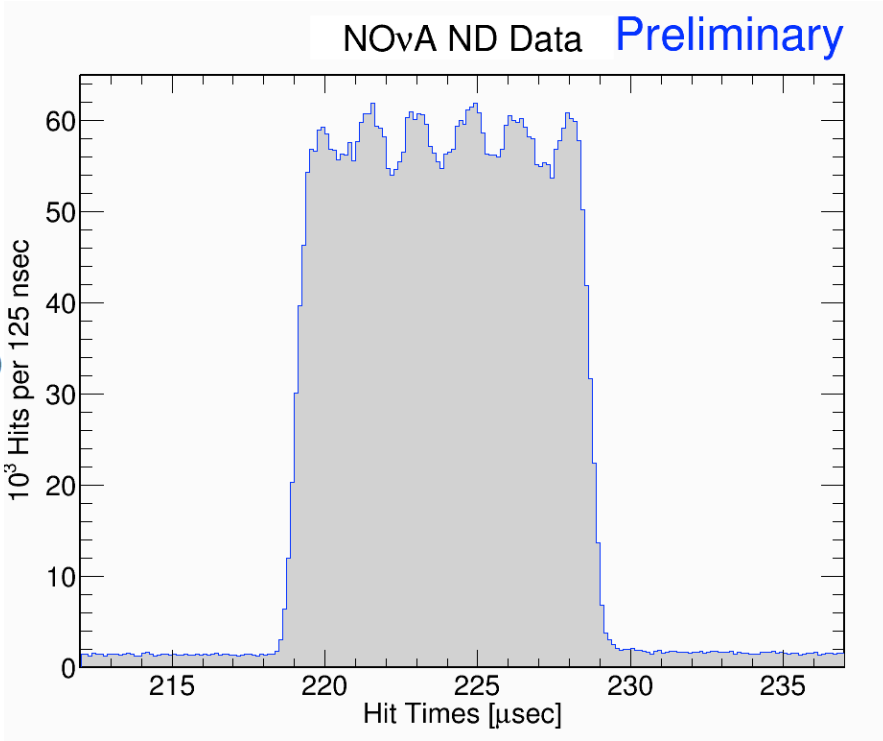
Near Detector



Timing peak from raw hits in the small portion of the detector instrumented on May 23

12 hours of data

Booster batch structure visible



Conclusions

- 10 years after proposal, NOνA is taking data!
- Far Detector and Near Detectors have been assembled
  - Both detectors see NuMI neutrinos
- Cosmic Ray simulations benchmarked to data
  - 40,000,000 : 1 cosmic ray rejection achieved
- Benchmarking neutrino channels will begin with Near Detector Data
- Expect 1st Oscillation Results ~ year's end

Backup Slides

Neutrino Mass Mixing

- Neutrino Flavor Oscillations arise from mixing
  - Flavor eigenstates are mixtures of mass eigenstates

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

$c_{13} \equiv \cos\theta_{13}, etc.$

"Atmospheric"/ Long-baseline ν_μ disappearance

Phase δ not yet measured

"Solar" ν_e disappearance

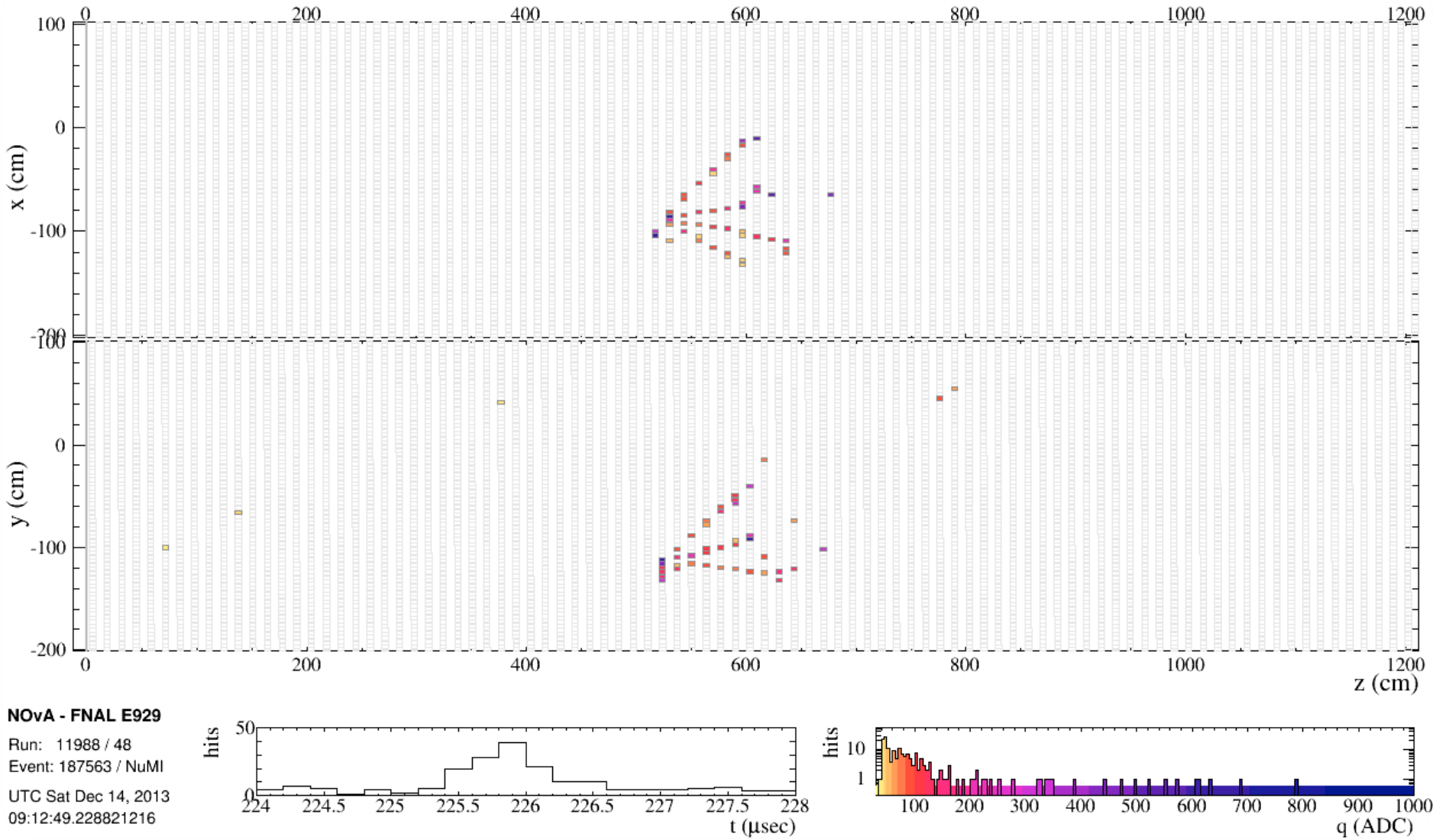
Oscillation probability, in the limit of 2 flavors α and β, mixed by angle θ, mass-squared difference Δm^2:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta M^2 L}{4E}\right)$$

Neutrino energy E
Baseline L


63.00m
15.60m
15.60m
SINGAPORE AIRLINES
3.90m
3.90m
2.60m
3.90m

Candidate 2

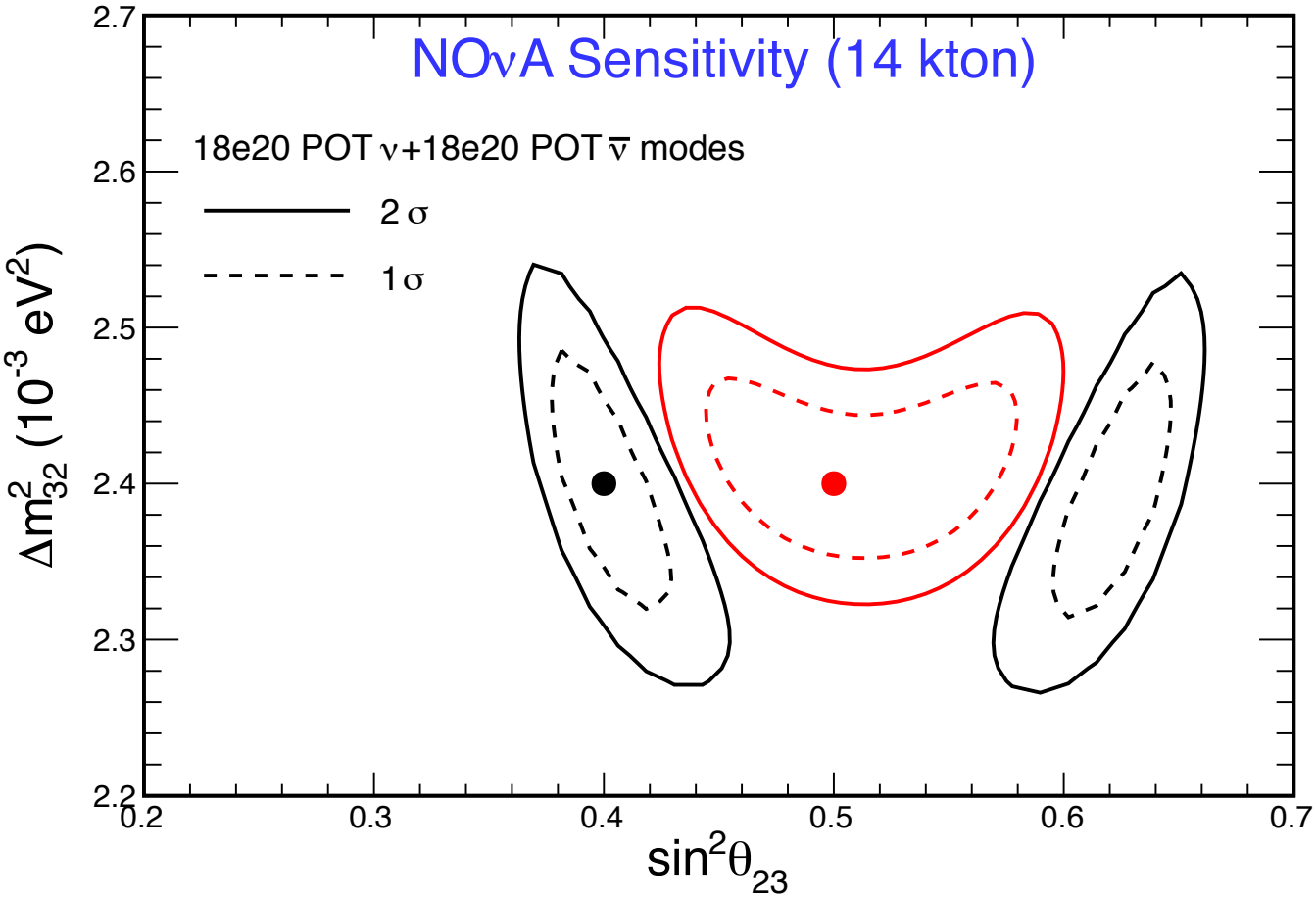

x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 11988 / 48
Event: 187563 / NuMI
UTC Sat Dec 14, 2013
09:12:49.228821216
hits
t (μsec)
hits
q (ADC)

ν_μ Selection

	Simulation					Data	
Cut	Un-Osc. ν_μ	Osc. ν_μ	NC Bkg	Osc. ν_e	Beam ν_e	Cosmic Bkg	Total Bkg
All Events	669	127	380	37	10	19M	19M
Cosmic Veto	660	125	273	36	10.0	6M	6M
Containment	582	109	195	28	7.5	120k	120k
ν_μ CC ID	460	86	5	0.4	0.2	44k	44k
Cosmic Reject	398	**75**	4	0.3	0.1	1	**5.4**

Nominal NOνA Year: 6x1020 POT, 14 kT Detector

ν_μ disappearance



ν_e Selection

Data

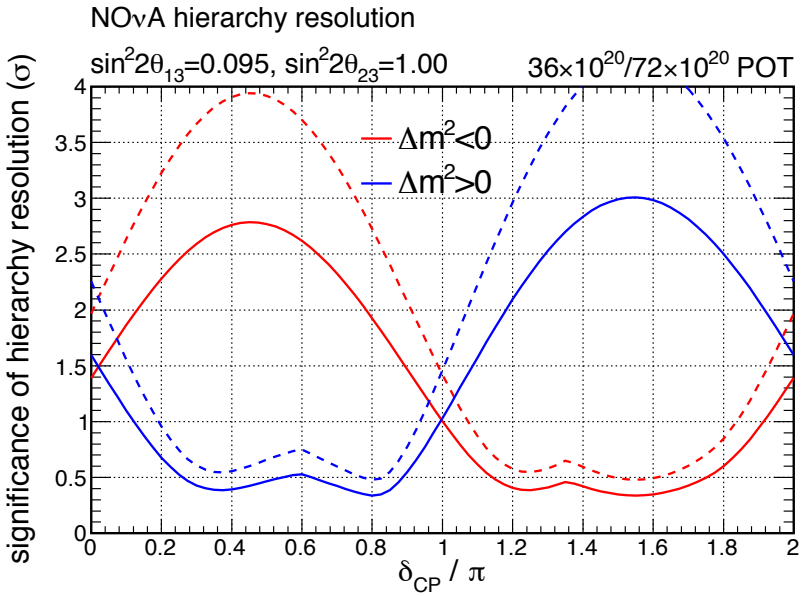
← Simulations →

	Osc. ν_eCC	ν_μCC	NC	Beam ν_eCC	Cosmic	All bkg
No cut	36.7	557.3	379.6	28.1	1.9e+07	1.9e+07
Presel+fid	24.7	30.0	83.5	2.9	56407.3	56523.7
Gap<150 cm	24.6	29.6	81.8	2.9	55055.1	55169.5
$P^T/P < 0.6$	22.0	24.3	59.6	2.6	1247.5	1334.0
Max Y < 700 cm	21.2	23.0	57.4	2.5	834.1	917.0
EID>0.7	13.9	0.7	3.9	1.5	0.5(2)	6.5
Eff.	37.8%	0.1%	1.0%	5.2%	2.4e-08	3.4e-07
LEM>0.37	14.0	1.1	3.5	1.5	0.9(4)	7.0
Eff.	38.1%	0.2%	0.9%	5.2%	4.8e-08	3.6e-07

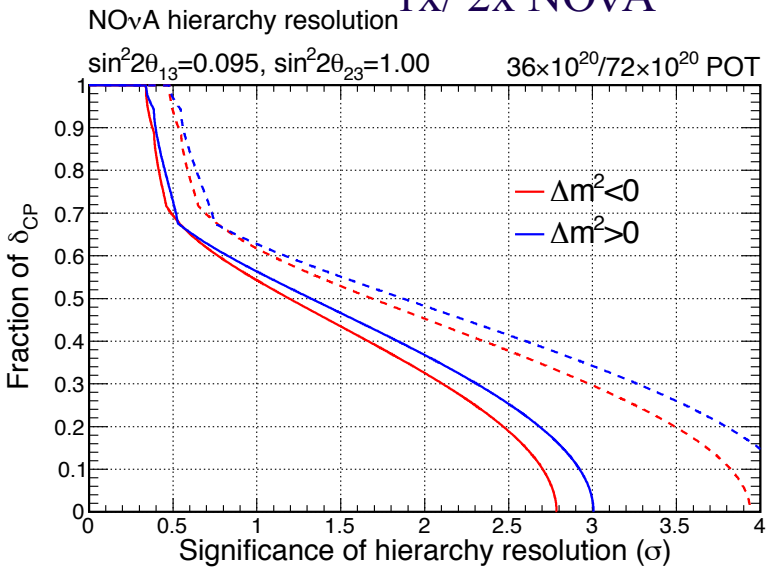
Nominal NOνA Year: 6x1020 POT, 14 kT Detector

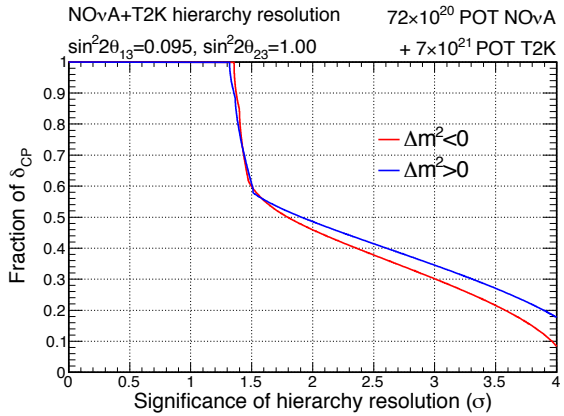
Mass Hierarchy – Extended Run

Significance of HM determination vs δ_{CP}
1x / 2x NOνA



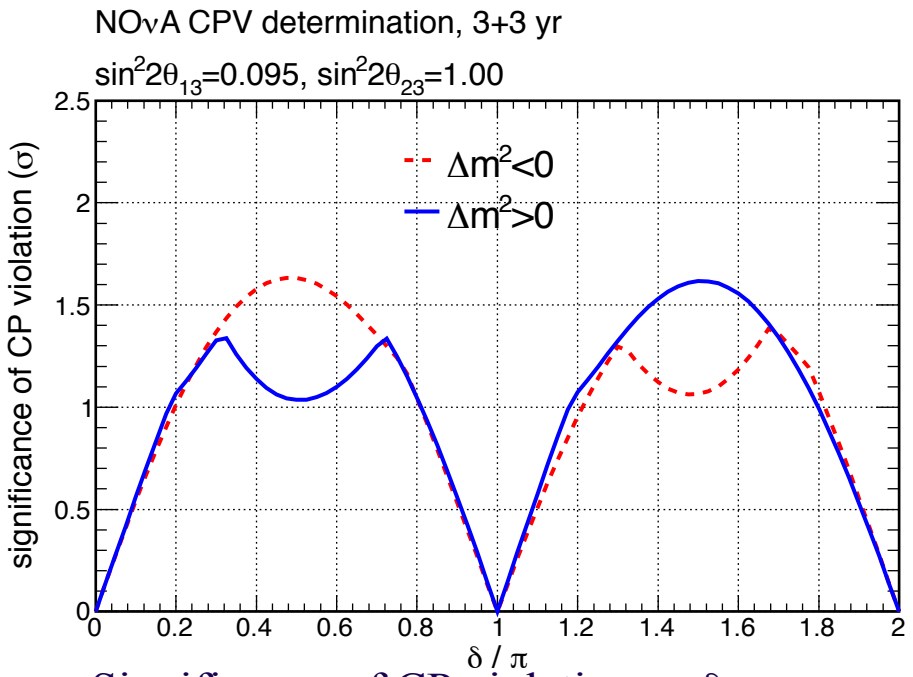
Fraction of δ_{CP} values vs. Significance of HM determination
1x/ 2x NOνA



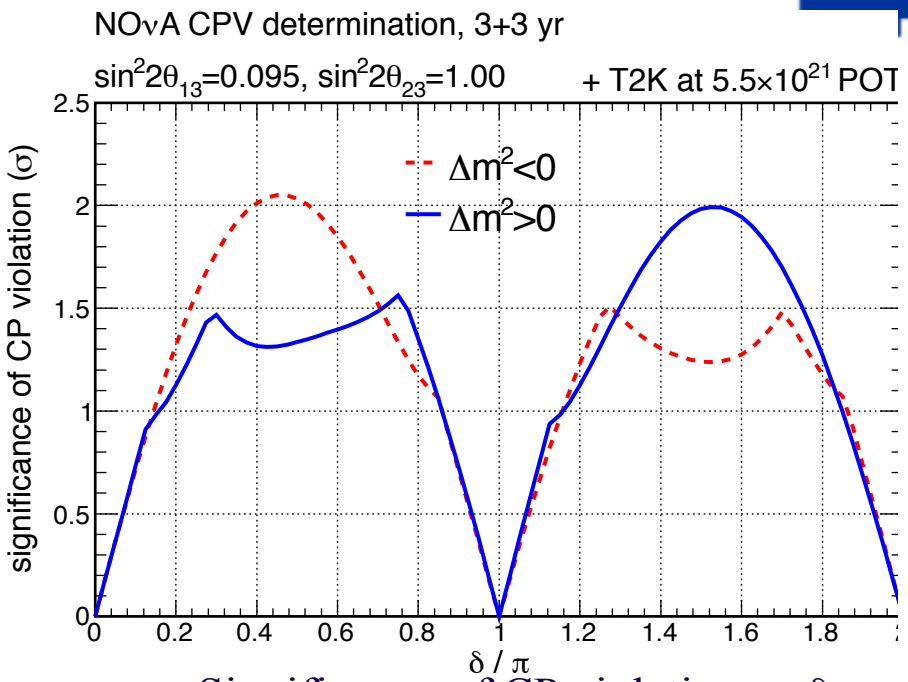


Fraction of δ_{CP} values vs. Significance of HM determination
2x NOνA + scaled T2K

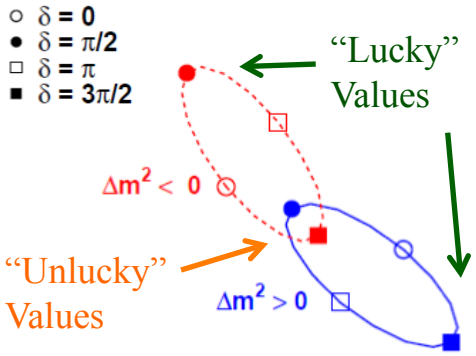
CP Violation

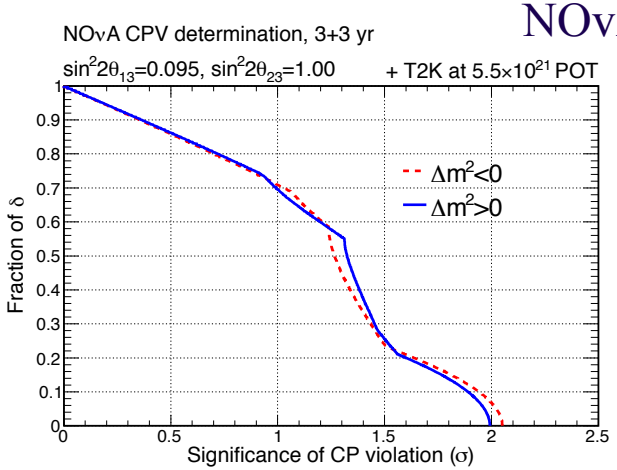


Significance of CP violation vs δ_{CP}
NOvA Only



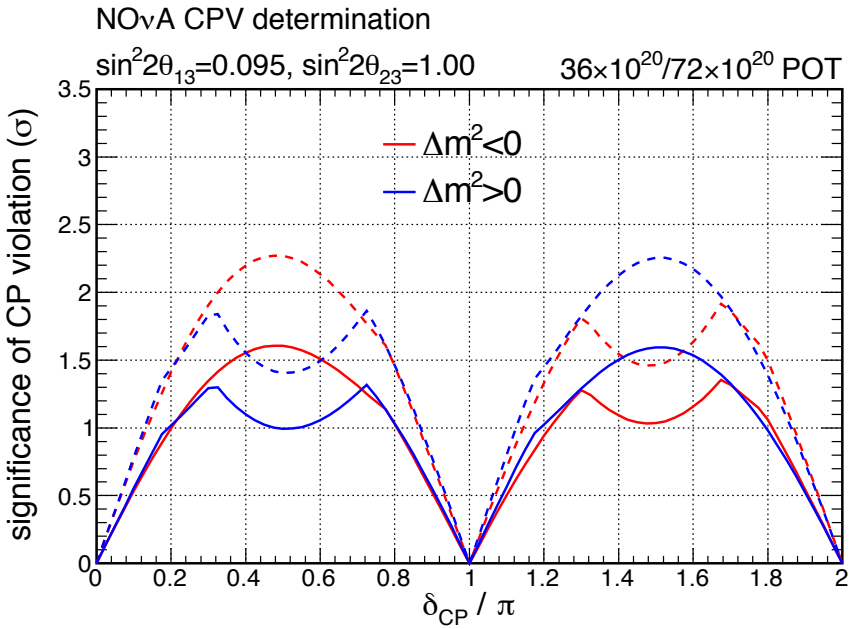
Significance of CP violation vs δ_{CP}
NOvA + T2K



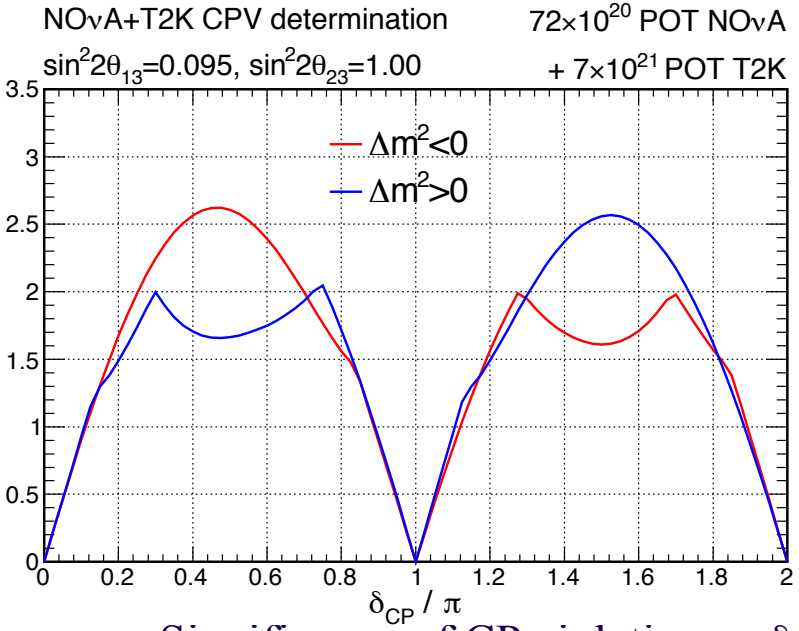


NOvA + T2K

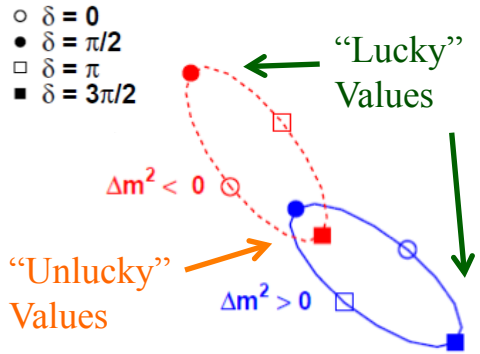
CP Violation – Extended Run

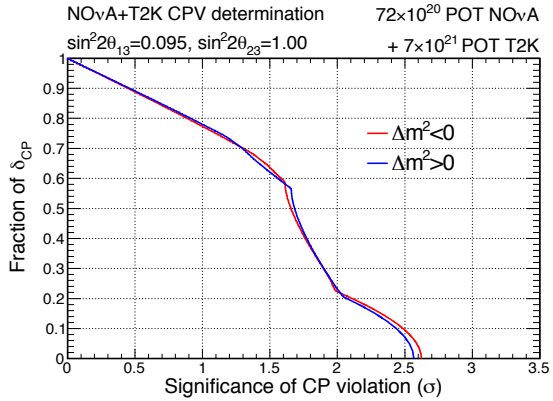


Significance of CP violation vs δ_{CP}
NOvA Only, nominal & 2x nominal



Significance of CP violation vs δ_{CP}
2x NOvA + scaled T2K

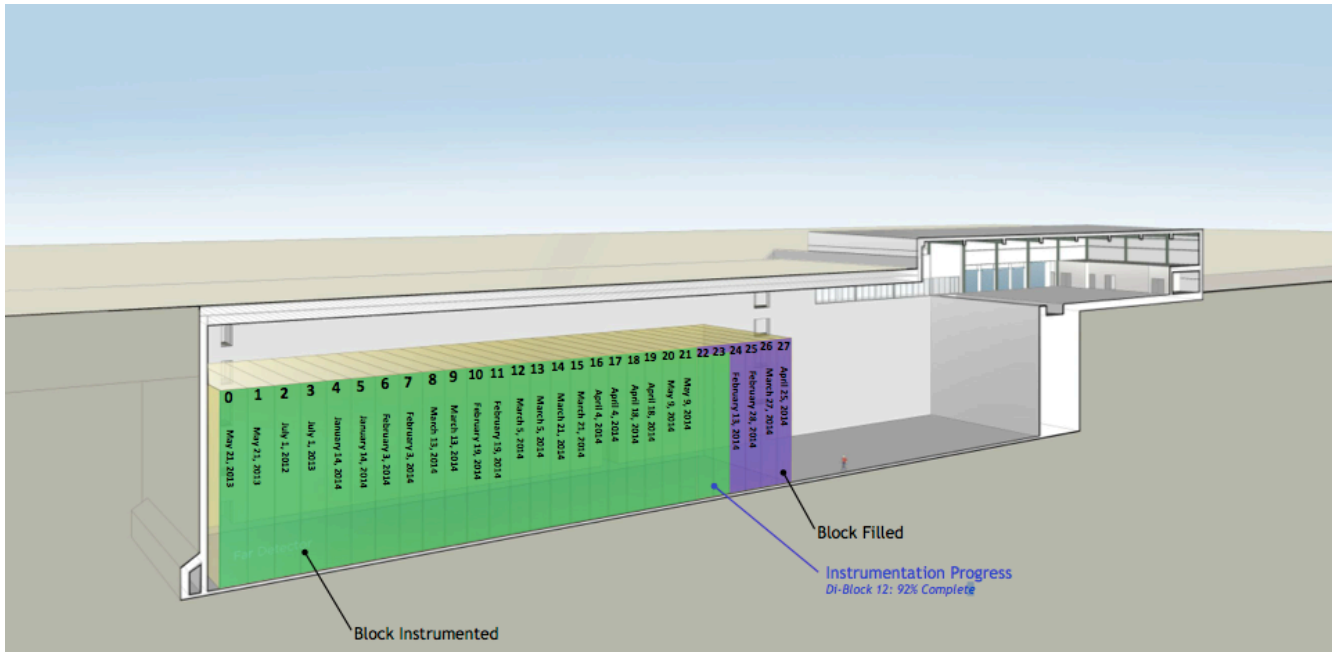




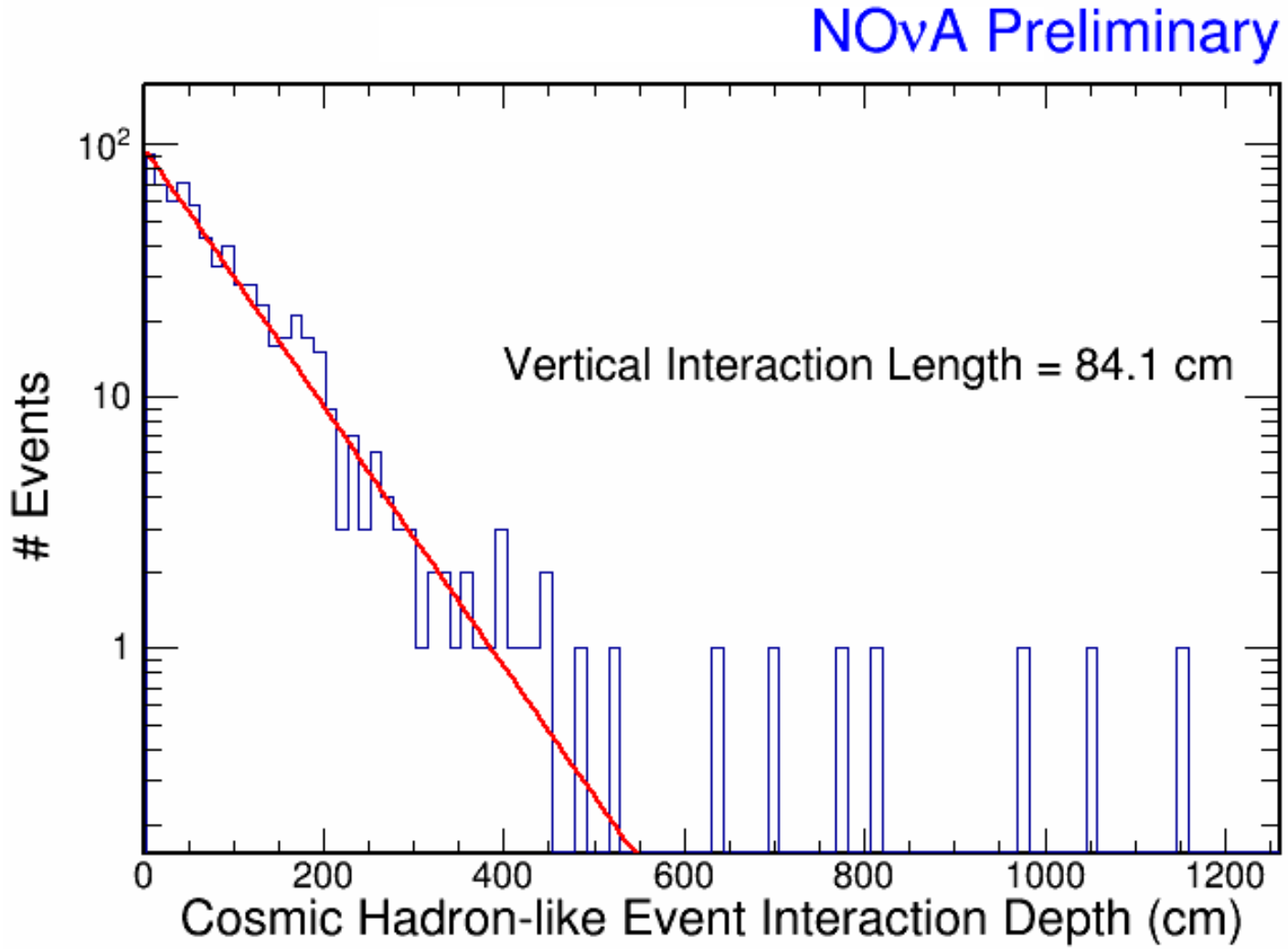
2x NOvA + scaled T2K

Some History

- Formal NOνA Proposal: 2004
- NOνA Project: CD-1: 2006, CD-2: 2008
- Far Detector Building construction: 7/2009-7/2011
- Far Detector assembly and filling: 9/2012 – 4/2014
- APDs and commissioning: 2/2013 – 8/2014



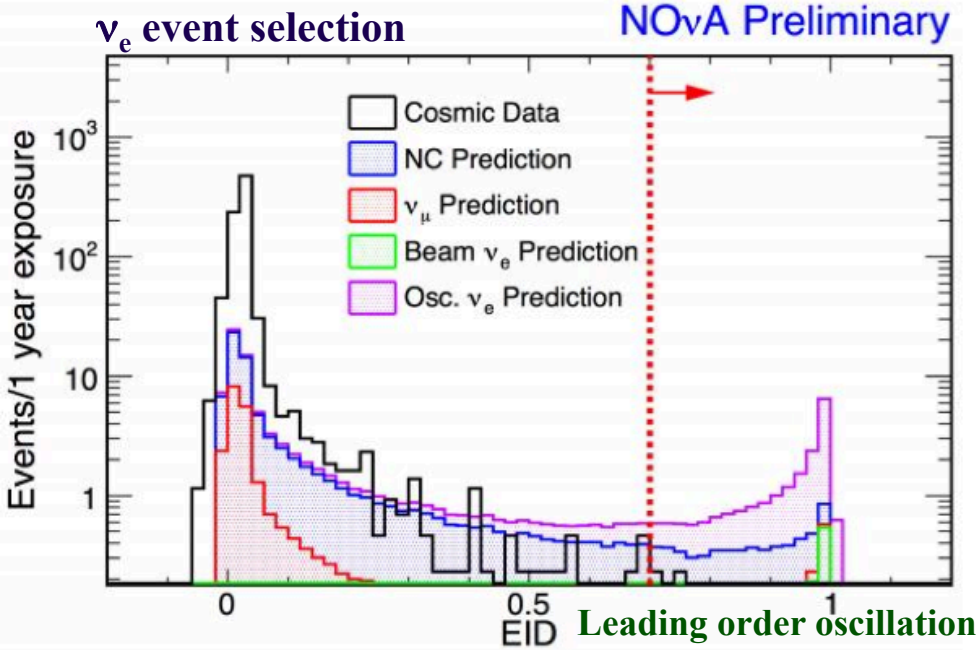
Neutron Candidates vs. Y



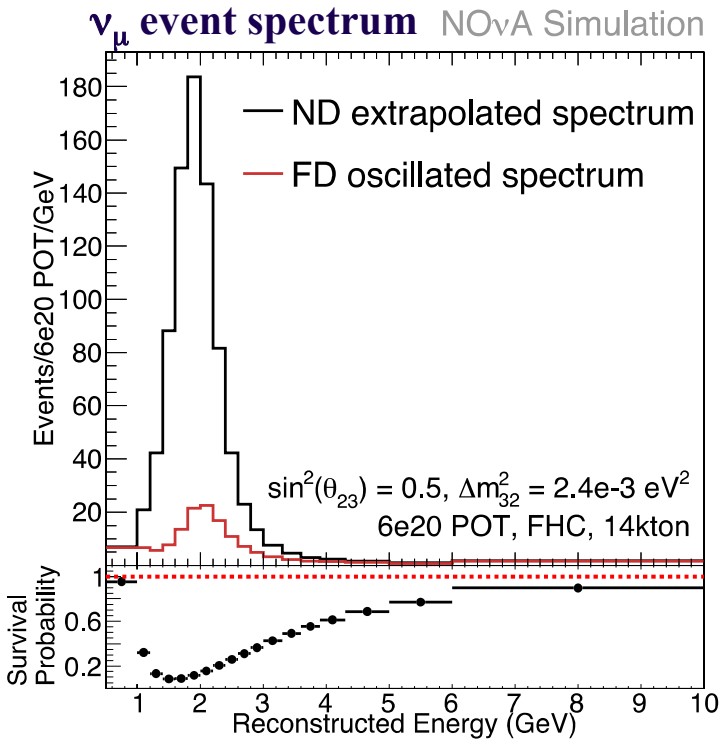
Anticipated Event Yields

Nominal Design Year:

6×10^{20} Protons-on-Target, 14 kT detector



ν_e: 14 signal / 7 background



ν_μ: 75 signal / 5.4 background

- 398 signal w/out oscillations

Cosmic background rejection benchmarked to data
40M:1 for ν_e
20M:1 for ν_μ