Neutrino as a tool to investigate the origin of mass and the universe: The Hunt Begins

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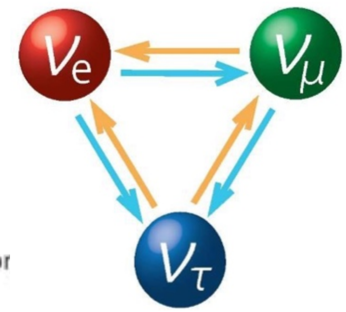
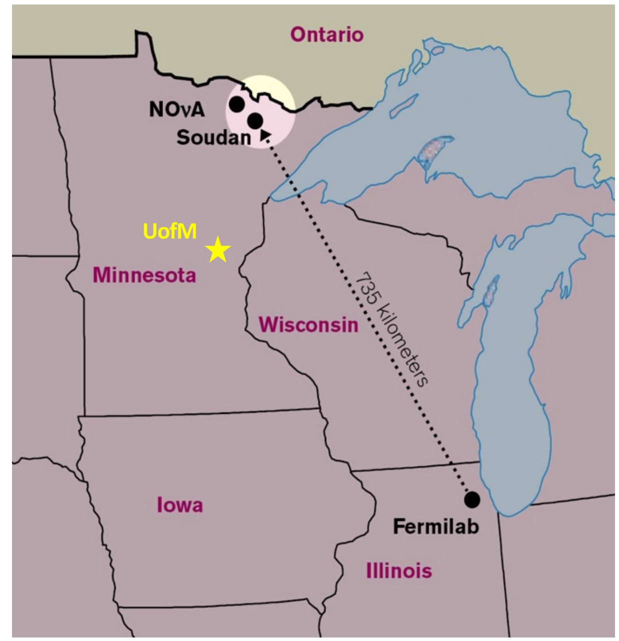
T2K

295 km
.6 GeV

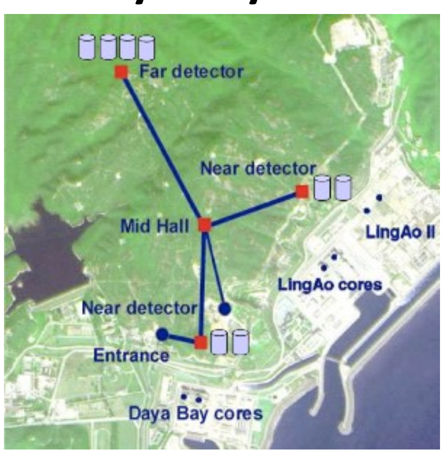


NOνA



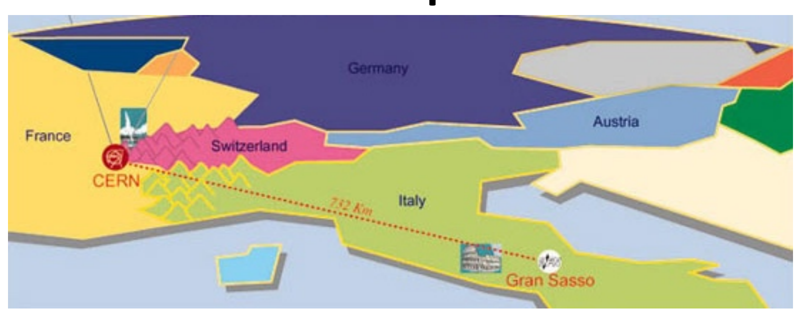
810 km
2 GeV

Daya Bay



2 km
3 MeV

Opera

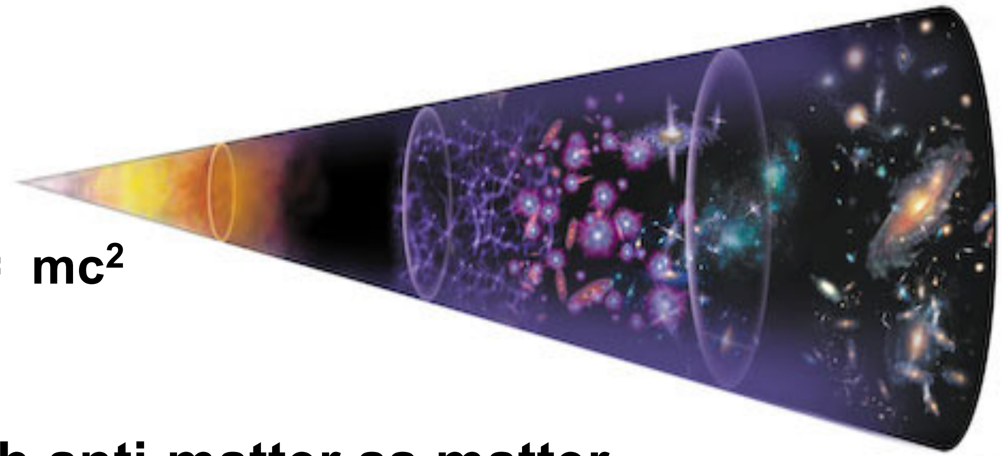


730 km
17 GeV

The Problem With the Universe

We don't know why it exists.

$E = mc^2$



Initial energy makes as much anti-matter as matter

Matter and anti-matter annihilate leaving no matter

No galaxies, stars, planets, us

Solution – matter and anti-matter interact or decay at different rates to leave 1 part in a billion of matter left over

This asymmetry seen in quarks but too small

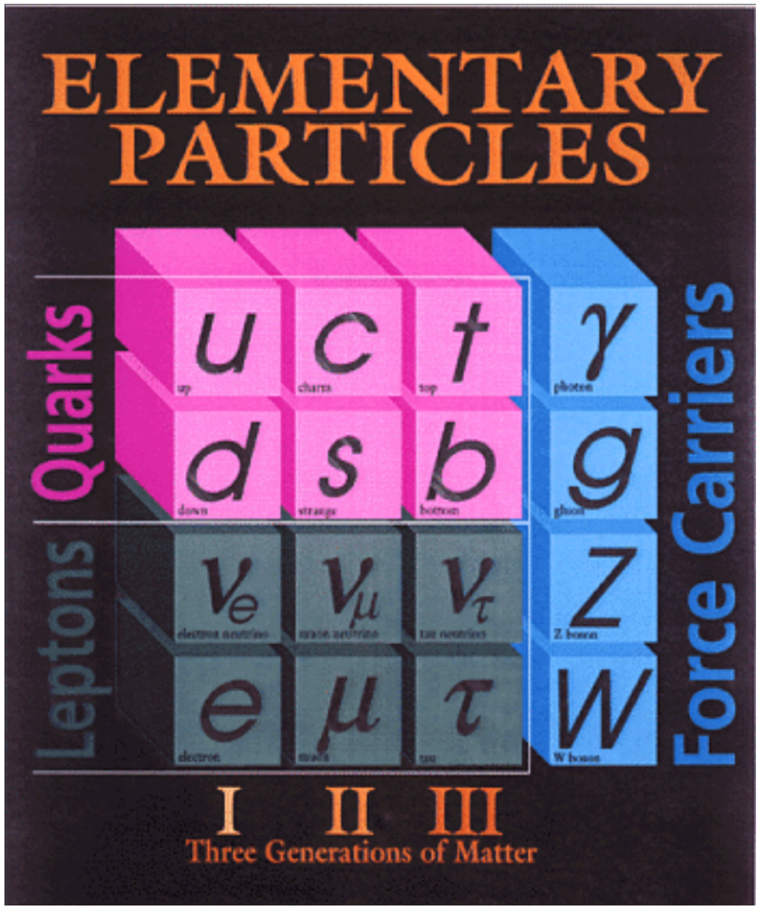
Only place for big asymmetry in known physics - neutrinos

Shows up in a certain type of neutrino oscillation

Why the Mass Sequence of the Elementary Particles?

The Standard Model

Spin 1/2

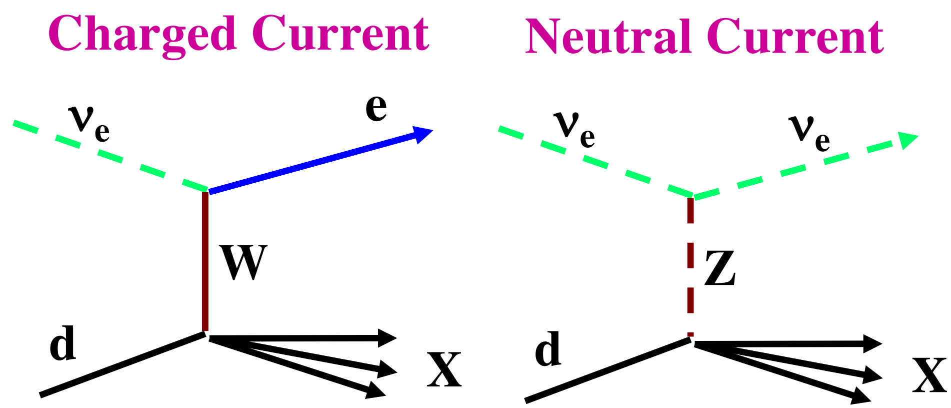


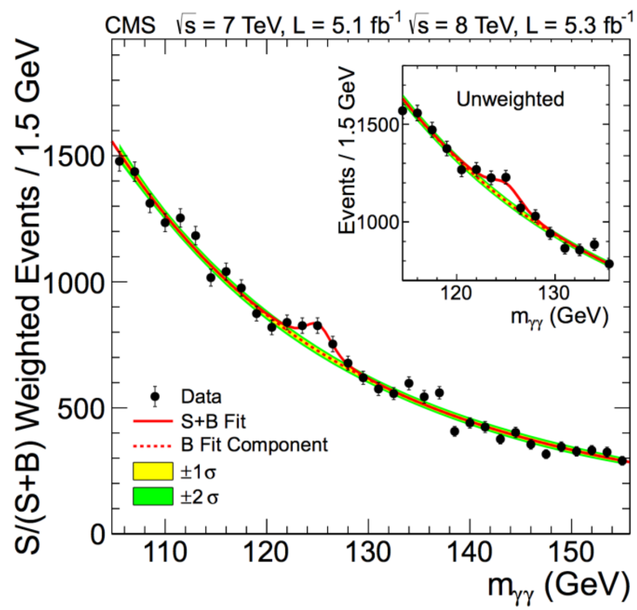
Spin 1

Mass ⟶ $(\sim 10^4)$

Surprise! Neutrinos Have Mass

Interactions are the Exchange of a Particle





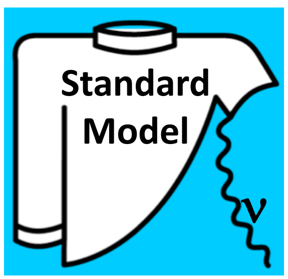
Mass is the Exchange of a Particle - Higgs

Neutrino Oscillation Experiments

Could Help Answer The Big Questions

Neutrino / Anti-neutrino Asymmetry
Could Generate the Matter Dominated Universe

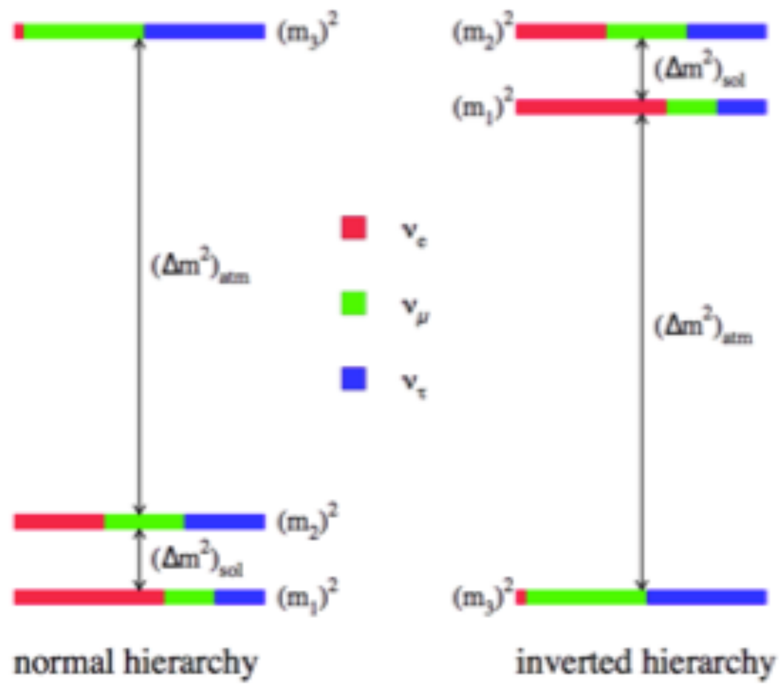
Neutrinos Open a Window Beyond the Standard Model



Neutrinos are not massless.

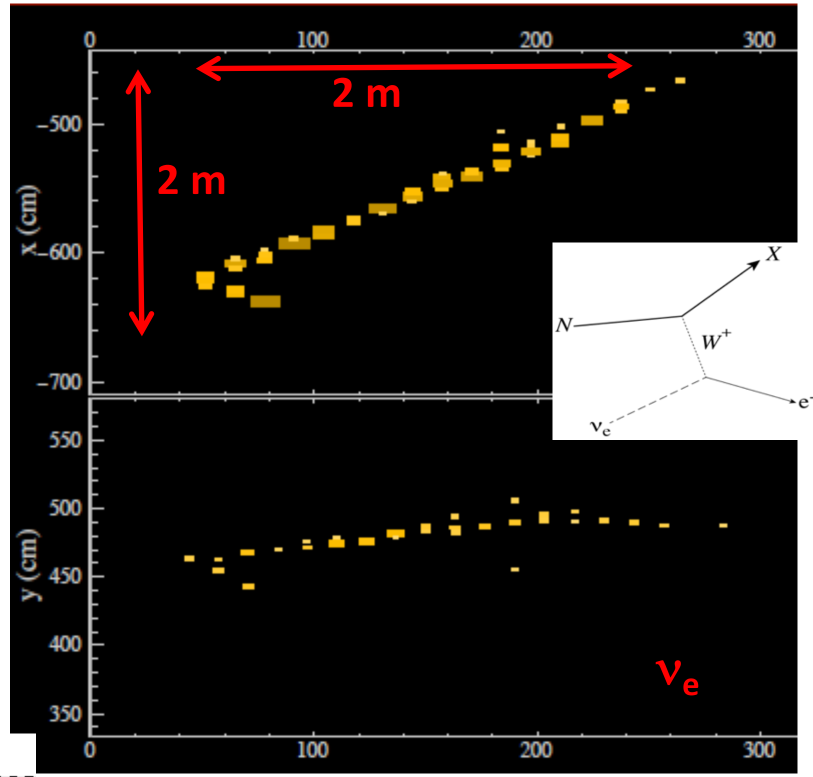
Neutrinos are mixed states.

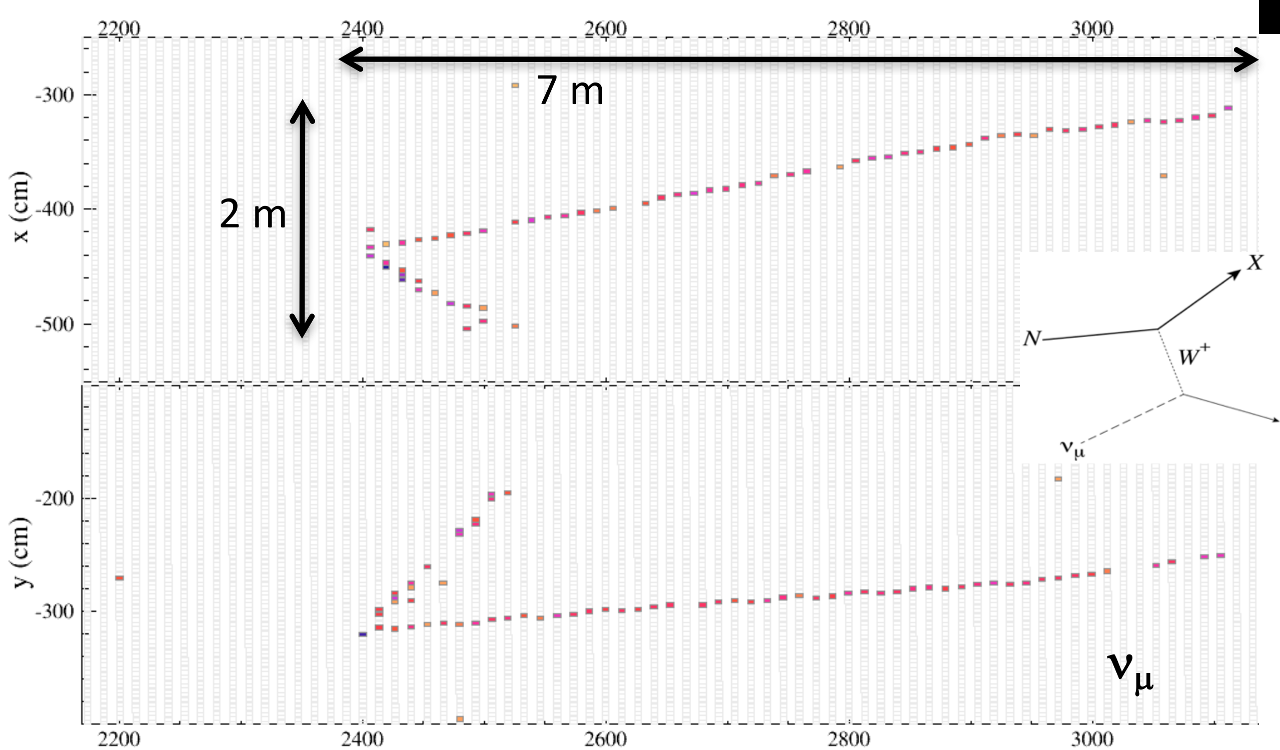
What is the Mass Hierarchy?



NOνA: The Newest Experiment

- The physics.
- The apparatus
- Latest results
- Expected final results.
- Other physics measured





First measurement of electron neutrino appearance in NOvA

PRL, Feb.2016

First measurement of muon-neutrino disappearance in NOvA

PRD Rapid Communications, Feb. 2016

Last Year's Data From Start-up

Now more than twice as much data

Mixed States

Identify neutrinos by their interaction:

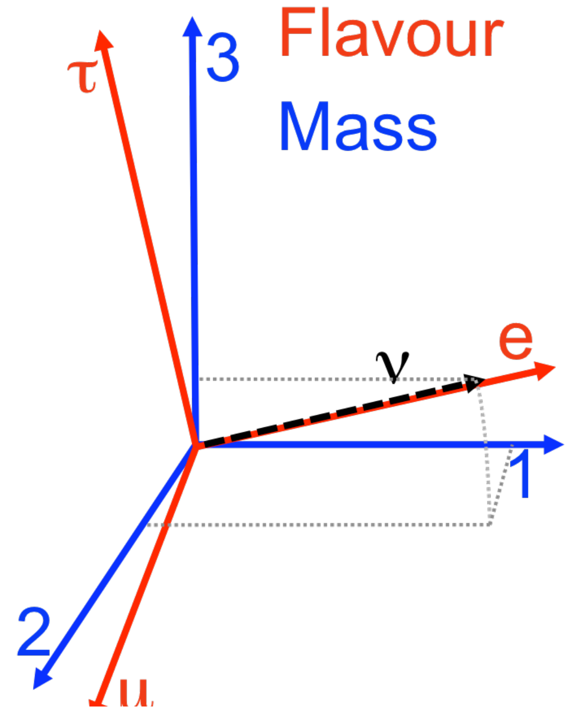
electron neutrino, muon neutrino, tau neutrino (flavor eigenstates)

Neutrinos travel:

neutrino 1, neutrino 2, neutrino 3 (mass eigenstates)

A neutrino identified with a certain flavor is a mixture of neutrino mass states.

A neutrino traveling with a certain mass is a mixture of neutrino flavor states.



$$R_X R_Y R_Z = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos A & -\sin A \\ 0 & \sin A & \cos A \end{pmatrix} \begin{pmatrix} \cos B & 0 & \sin B \\ 0 & 1 & 0 \\ -\sin B & 0 & \cos B \end{pmatrix} \begin{pmatrix} \cos C & -\sin C & 0 \\ \sin C & \cos C & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

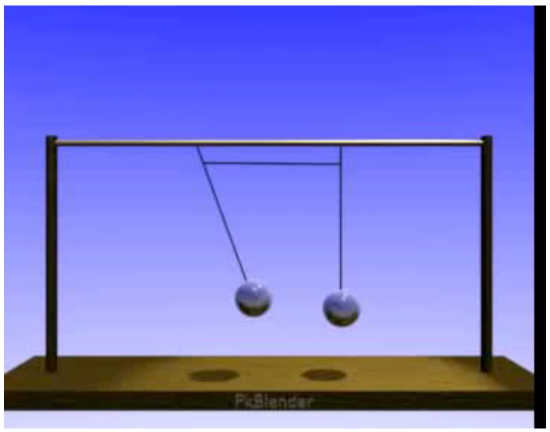
Euler rotations

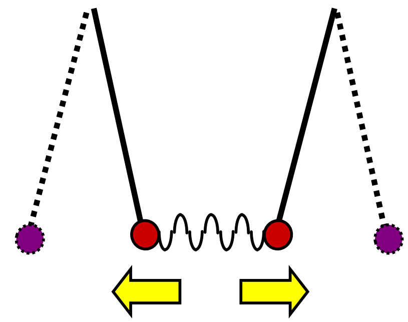
3 mixing angles (A, B, C)

Oscillations & Mixed States

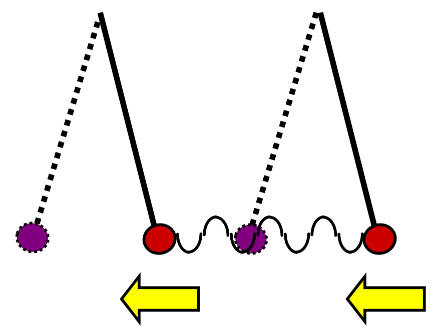
- **Two coupled pendulums have two stable modes of oscillation**

The "breathing" mode

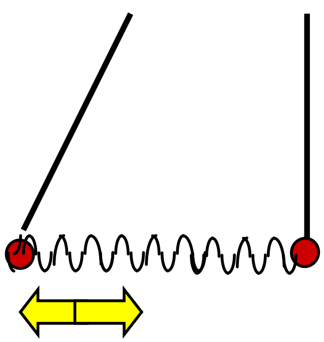




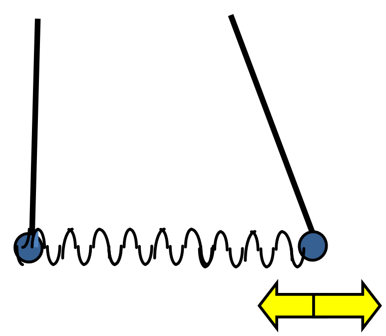
The "swaying" mode



Start only one pendulum swinging



Energy "moves" from one pendulum to the other



Mixed state gives oscillations

Mixing

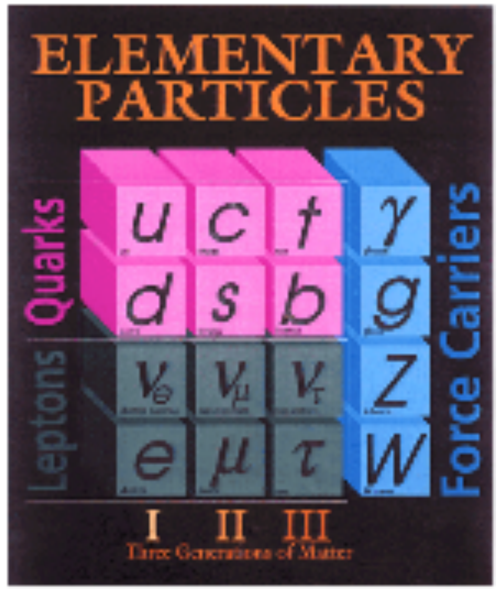
Interaction states (flavor) are not the same as propagation states (mass)

CKM Quark Mixing Matrix

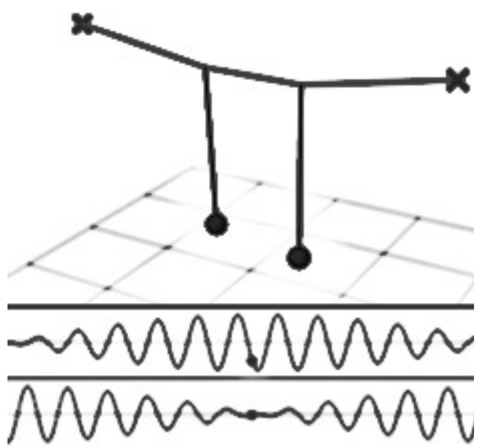
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} U_{ud} & U_{us} & U_{ub} \\ U_{cd} & U_{cs} & U_{cb} \\ U_{td} & U_{ts} & U_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} 0.97 & 0.23 & 0.003e^{i\delta} \\ -0.23 & 0.97 & 0.041 \\ -0.008e^{i\delta} & -0.04 & 1.00 \end{pmatrix}$$

Small off-diagonal



δ gives
CP violation



PMNS Lepton Mixing Matrix

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

$$\begin{pmatrix} 0.8 & 0.5 & 0.1e^{i\delta} \\ -0.5 & 0.6 & 0.6 \\ -0.3e^{i\delta} & -0.6 & 0.8 \end{pmatrix}$$

Big off-diagonal

https://en.wikipedia.org/wiki/Oscillation

Neutrino Oscillation Measurements

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

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


$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$

MINOS, SuperK/CR

$\theta_{23} \sim 45^o$

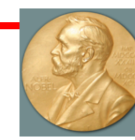
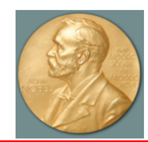
NOνA, T2K, Daya Bay, RENO

$\theta_{13} \sim 9^o$

KAMLAND, SNO

Solar/Reactor

$\theta_{12} \sim 32^o$

Ignoring the Majorana phases

$$\begin{bmatrix} e^{ia_1/2} & 0 & 0 \\ 0 & e^{ia_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Need to measure: CP phase δ , Mass hierarchy

Oscillation Formalism – Quantum Mechanics

$$H(t)|\psi(t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle$$

The probability that one mixed state (e.g. Ψ_1) will evolve to the other mixed state (e.g. Ψ_2) is

$P(1\rightarrow2) = \sin^2 2\theta\ \sin^2(1.27\ \Delta m^2\ L/E)$

Experimental Parameters

L (distance from source to detector in km)

E (neutrino energy in GeV)

Oscillation (Physics) Parameters

2θ (mixing angle)

$\Delta m^2 = m_\alpha^2 - m_\beta^2$ (mass squared difference, eV^2)

The results are slightly more complicated for 3 state mixing

Rate of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ gives δ and sign of Δm^2

$$P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\ \Delta m_{23}^2\ L/E)$$

$$P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\ \Delta m_{12}^2\ L/E)$$

$$P_3 = \mp J \sin(\delta) \sin(1.27\ \Delta m_{23}^2\ L/E)$$

$$P_4 = J \cos(\delta) \cos(1.27\ \Delta m_{23}^2\ L/E)$$

$$J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23}) \sin(1.27\ \Delta m_{23}^2\ L/E) \sin(1.27\ \Delta m_{12}^2\ L/E)$$

Matter Effect

P_1 x $(1 \pm 2E/E_R)$

P_3, P_4 x $(1 \pm E/E_R)$

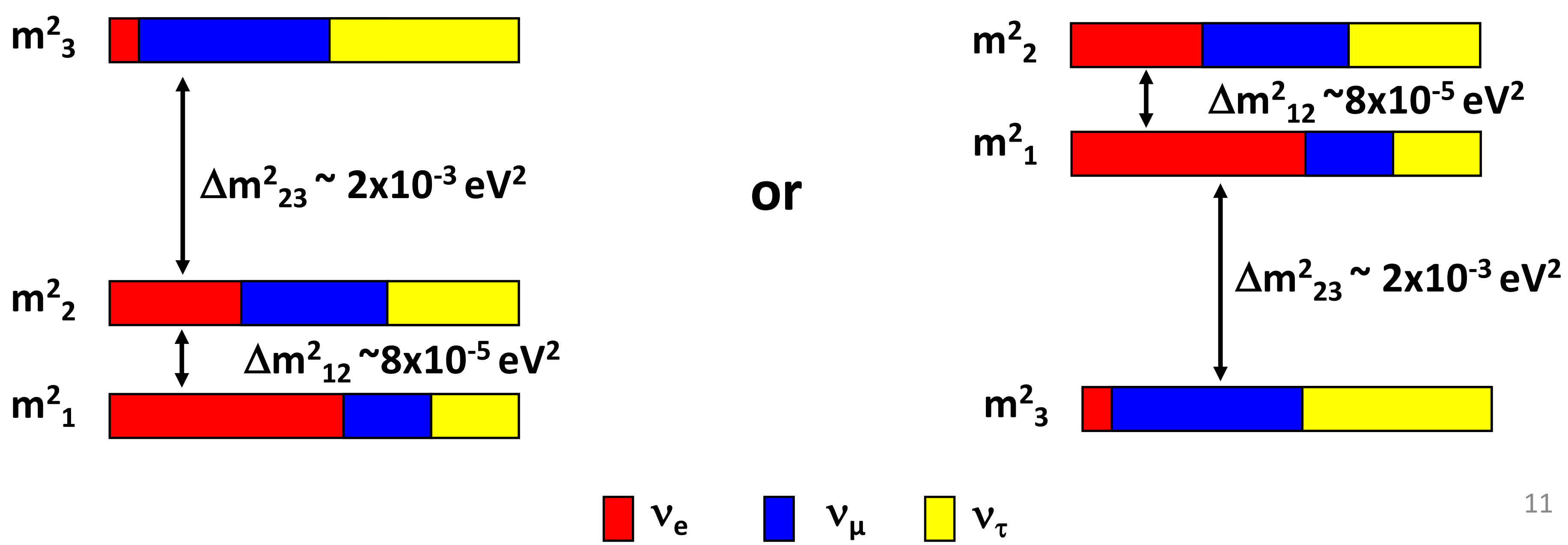
E_R = 11 GeV (Earth)

23% effect (10% T2K)

Enhancement for $\Delta m^2 > 0$

Suppression for $\Delta m^2 < 0$

Which Mass Hierarchy?



Signal Size

Ignore matter effects, CP violation

$$P(\nu_\mu \rightarrow \nu_e) \approx P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\, \Delta m_{23}^2\, L/E)$$

Peak of oscillation at $E = 1.7\,\mathrm{GeV}\left(\frac{\Delta m_{32}^2}{2.5\times10^{-3}\,\mathrm{eV}^2}\right)\left(\frac{L}{820\,\mathrm{km}}\right)$

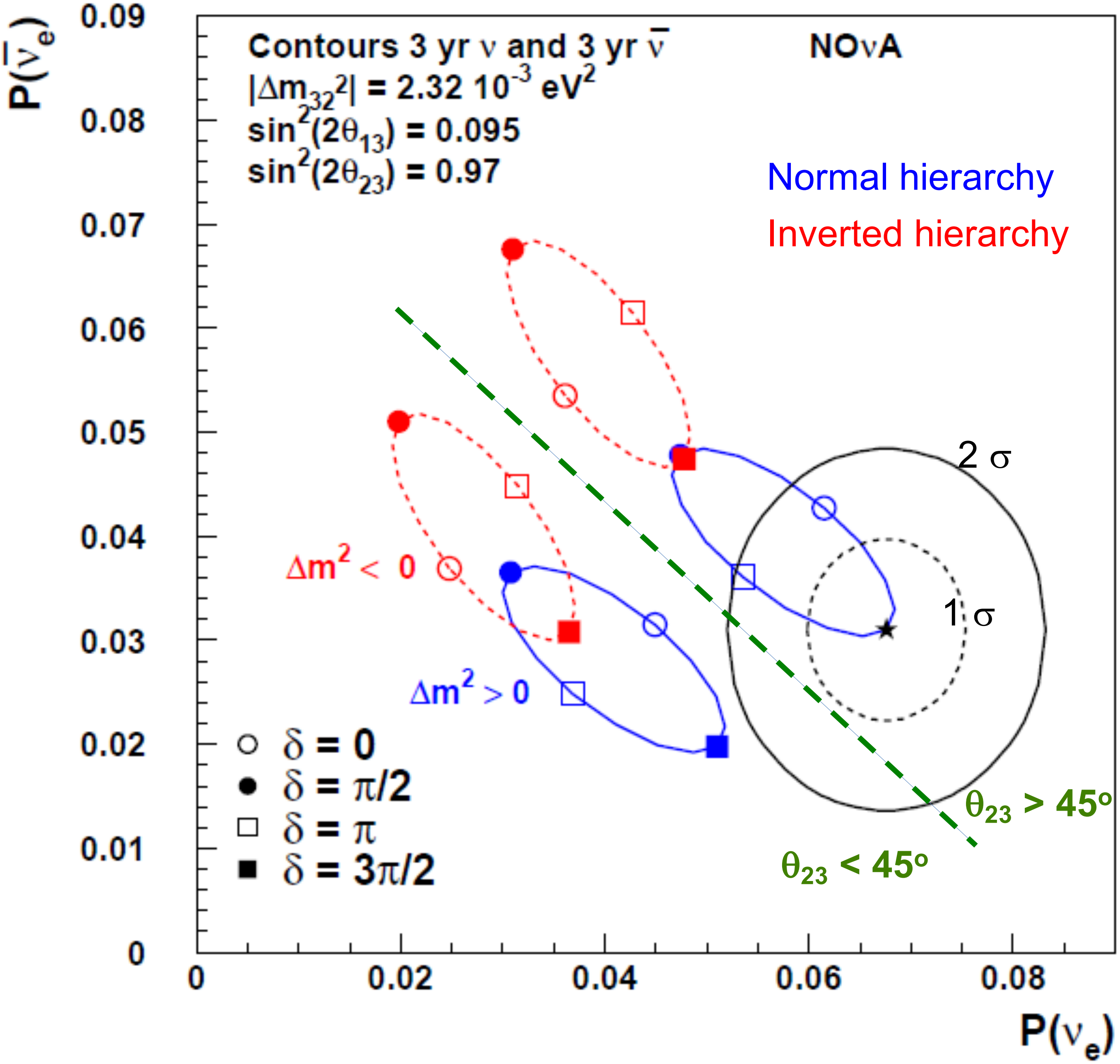
$$P(\nu_\mu \rightarrow \nu_e) \approx ½\ \sin^2(2\theta_{13})$$

Measurement from Daya Bay and RENO:

For NOνA

$$P(\nu_\mu \rightarrow \nu_e) \sim 5\%$$

ν_e Physics



Contours 3 yr ν and 3 yr ν̄
NOνA
|Δm$_{32}^2$| = 2.32 10^{-3} eV^2
sin^2(2θ$_{13}$) = 0.095
sin^2(2θ$_{23}$) = 0.97
Normal hierarchy
Inverted hierarchy
2 σ
1 σ
Δm^2 < 0
Δm^2 > 0
δ = 0
δ = π/2
δ = π
δ = 3π/2
θ$_{23}$ > 45°
θ$_{23}$ < 45°
P(ν̄$_e$)
P(ν$_e$)
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.02
0.04
0.06
0.08

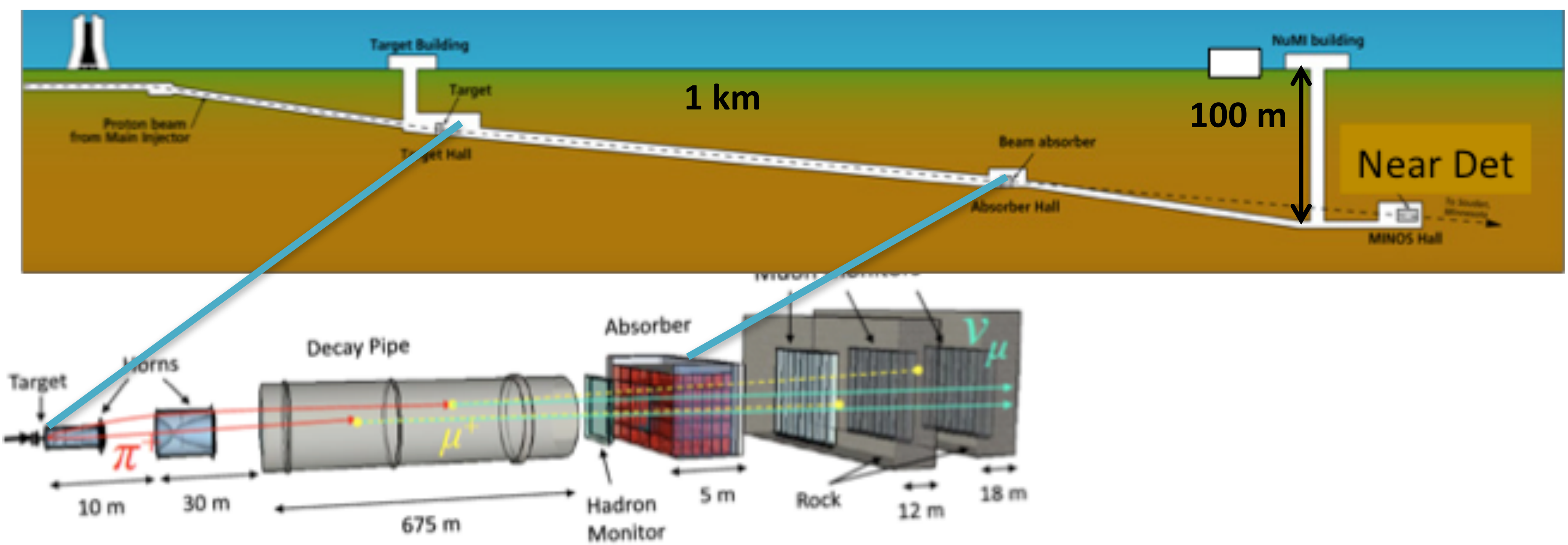
First collaboration meeting at International Falls

Argonne • Atlantico • Athens • Banaras Hindu • Caltech • Charles • Cincinnati • Cochin • Colorado St • Czech AS • Czech Tech • Delhi • Dubna • Fermilab • Golas • Guwahati • Harvard • Hyderabad • Hyderabad IIT • Indiana • Iowa State • Jammu • Lebedev • Michigan St • Minnesota -Crookston • Minnesota-Duluth • Minnesota-TC • INR Moscow• Panjab • S Carolina • SMU • S Dakota School of Mines • Stanford •Sussex • Tennessee • Texas • Tufts • U. College London • Virginia • Wichita State • William & Mary • Winona St

Recent collaboration meeting

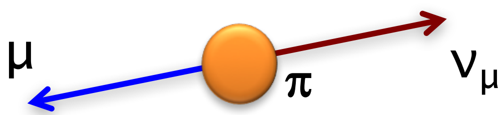
Beam :

- 120 GeV protons from the Main Injector
- 1.3 second cycle time
- Single turn extraction (10μs)
- Now 520 kW increasing to 700 kW (Spring, 2016)
    - 5×10^{13} protons/pulse on target

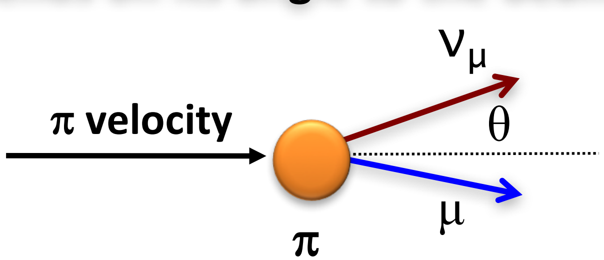


Off-Axis Beam Kinematics

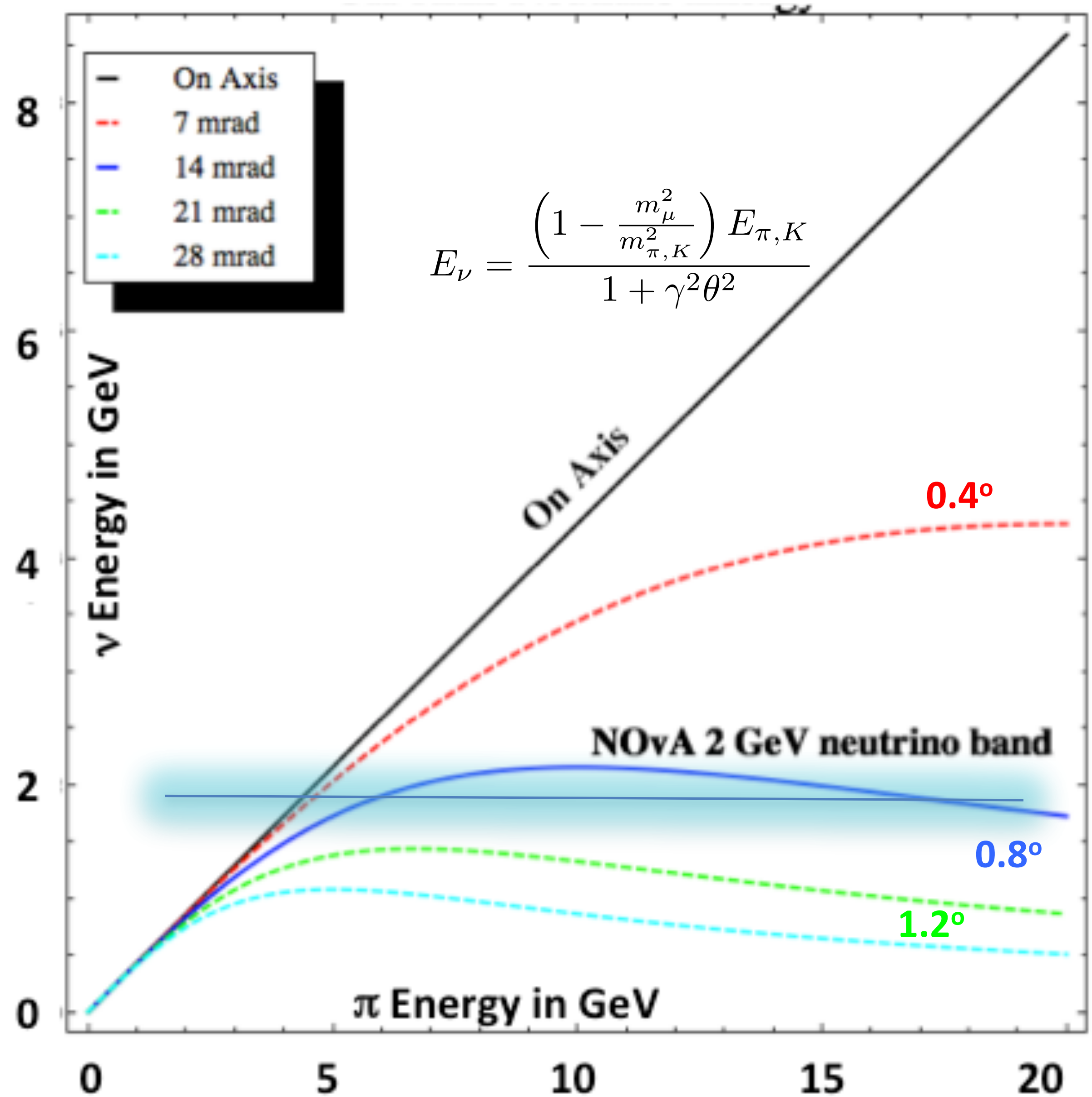
In pion rest frame the ν kinematics are completely determined for the decay



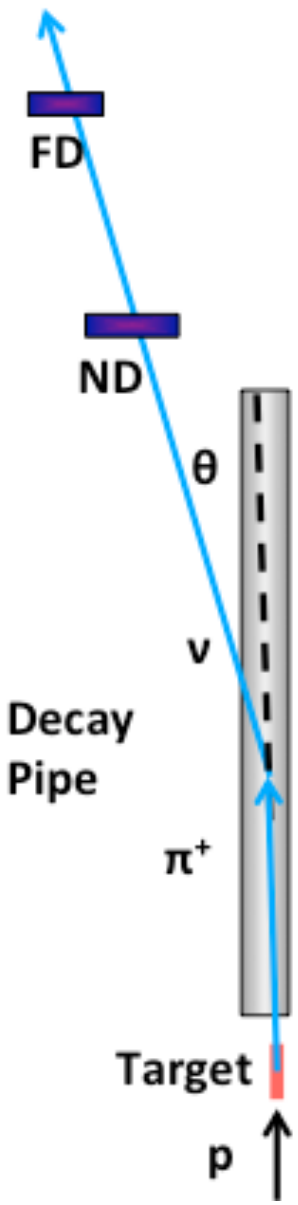
In lab frame neutrino's energy depends on its angle to the beam.

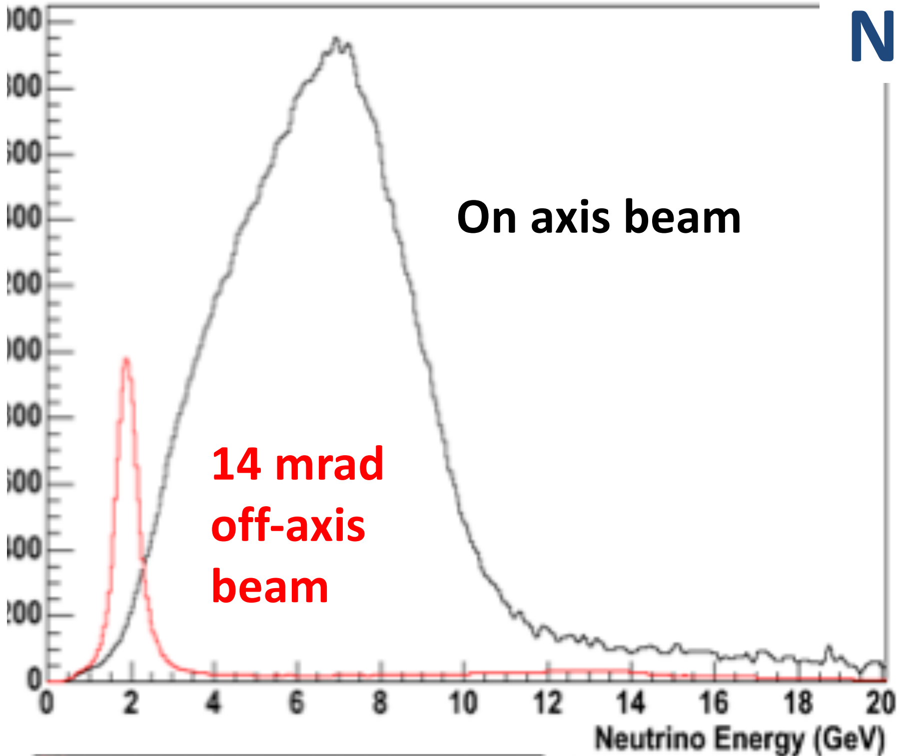


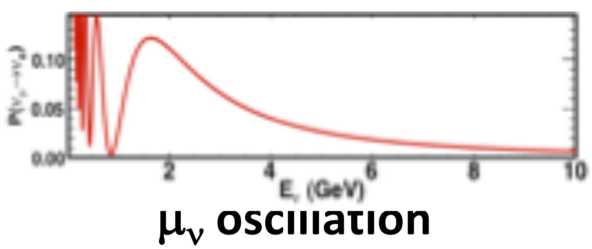
Using relativistic kinematics, the neutrino energy is almost constant at angles off the original beam direction.

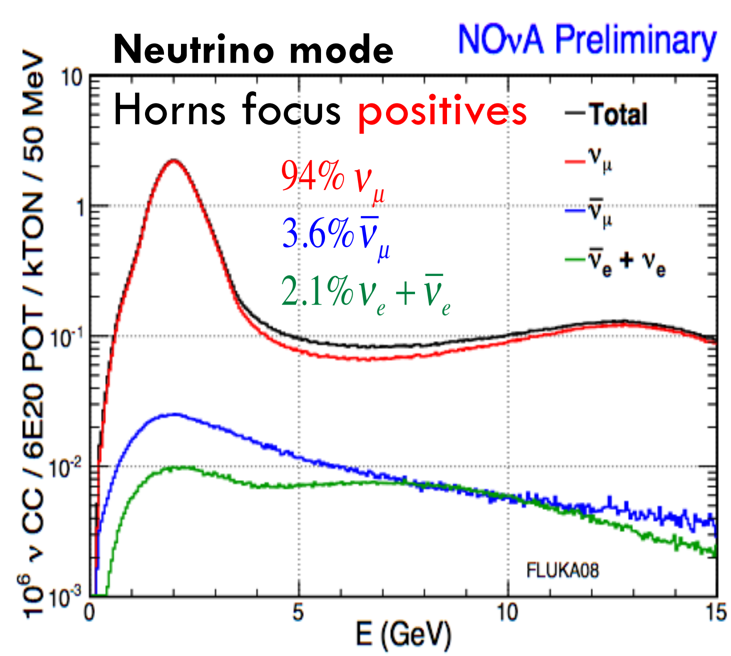


Neutrino Beam 14 mrad



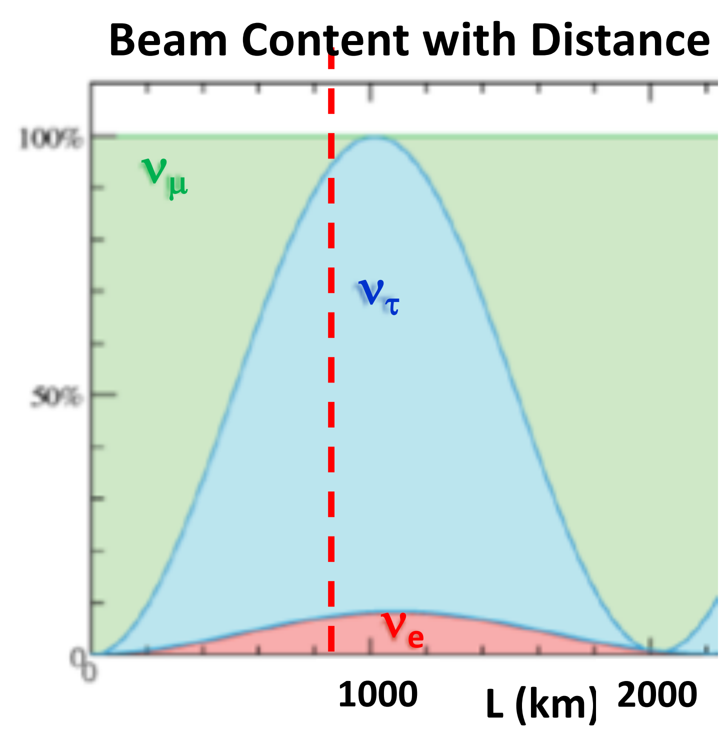


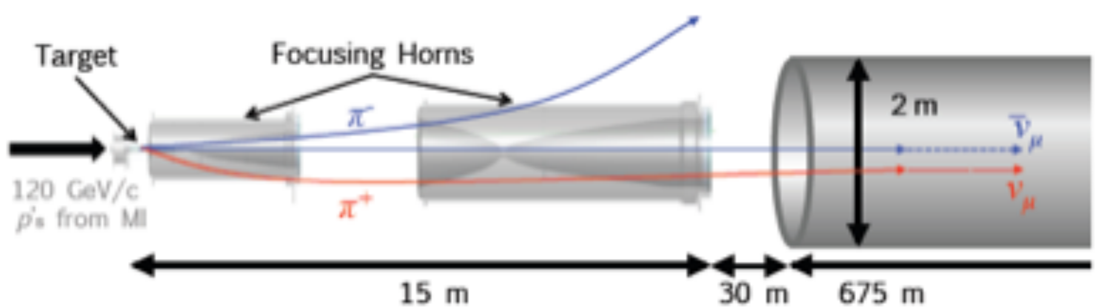




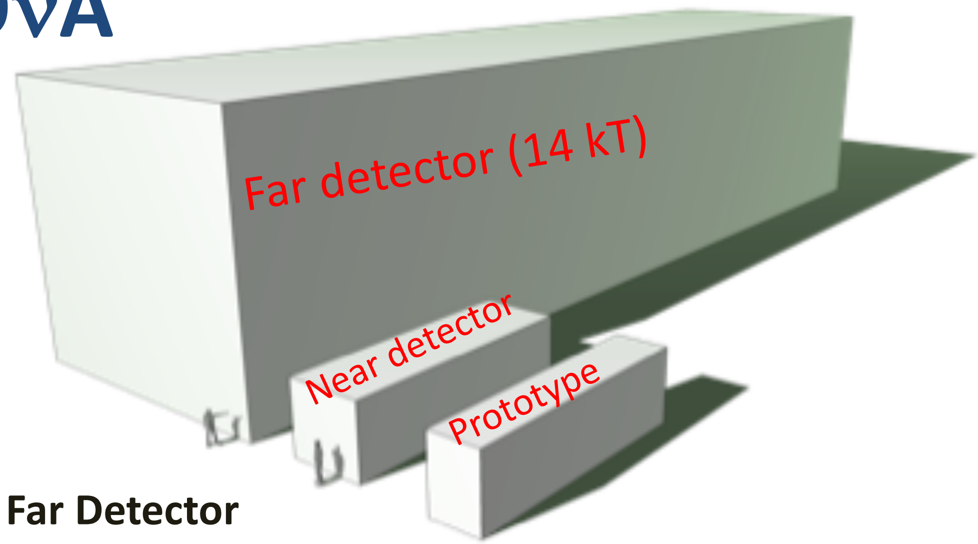
100 %

50 %

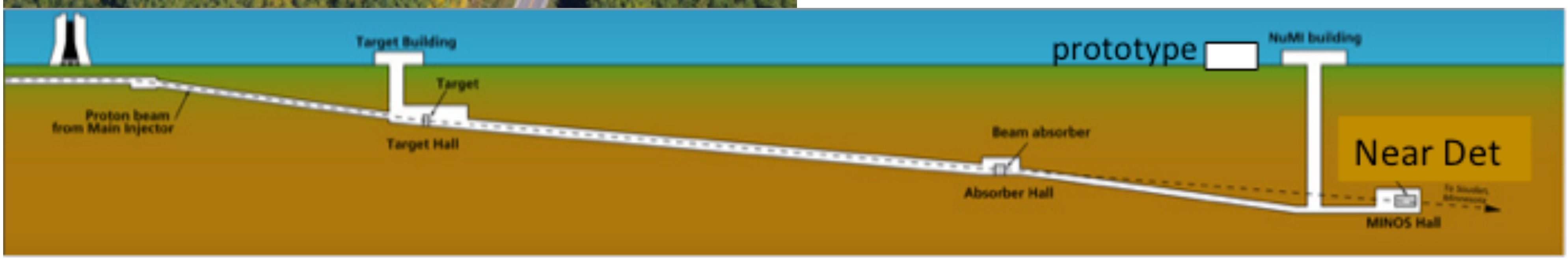




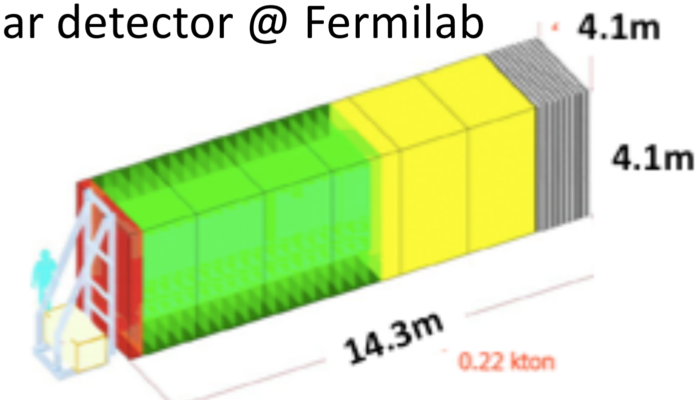
NOνA



Far Detector
- 896 Planes (16m x 16m)
- 14 kTons
- 344000 cells
- Cosmic Ray Muon Rate: ~200 kHz
- 2 neutrino events/wk



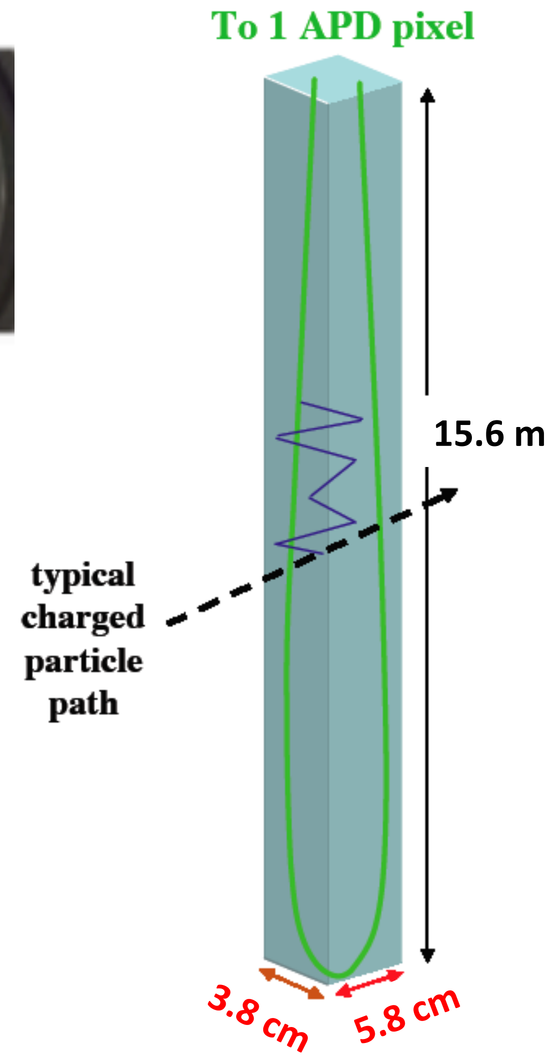
Near detector @ Fermilab

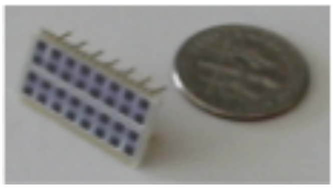


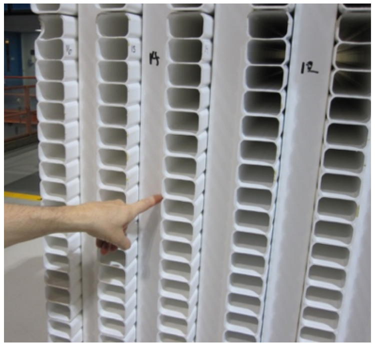
Near Detector
- 230 Planes (4m x 4m)
  + 10 Steel Planes
- 220 Tons
- 22000 cells
- Cosmic Ray Muon Rate: ~50 Hz
- 3 neutrino events/spill (10 μs)

NOνA Detector Technology

- Good electron ID
  - Low atomic number (0.15 rad length/plane
  - Tracking & calorimetry
- Good energy resolution
  - Mostly active (64%)
- Cheap parts
  - Extruded plastic (PVC)
  - Liquid scintillator (mineral oil)
  - Wavelength shifting fiber optics (0.7mm diameter)
  - Avalanche photodiodes (350,000 channels)
- Cheap to build
  - Modular (32 cell self-contained objects)
  - 11, 000 modules built by undergrads at University of Minnesota
- Fit in a truck
- Easy installation
- Remote operation



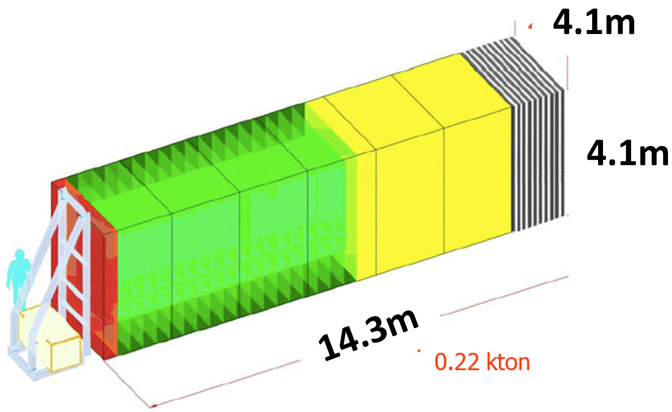


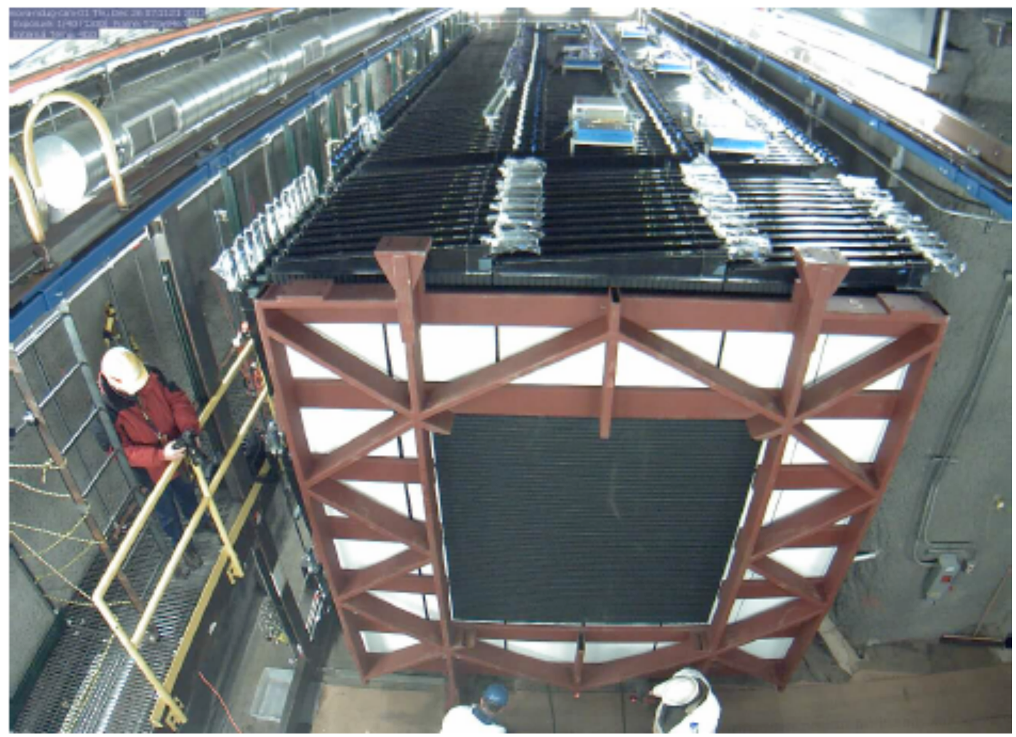


Near Detector @ Fermilab

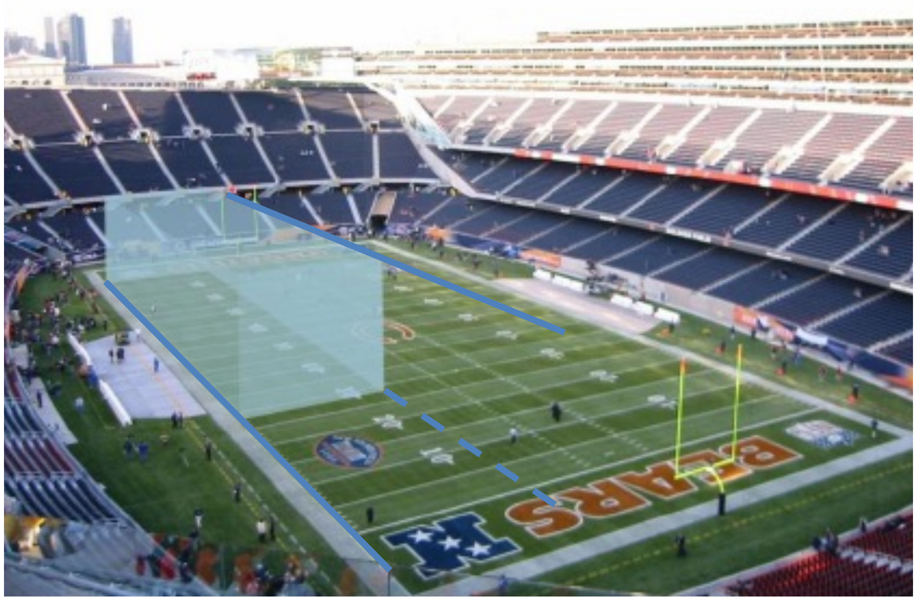
Next to MINOS near detector

- 14 mrad (0.8°) off beam axis
- 300 ft underground

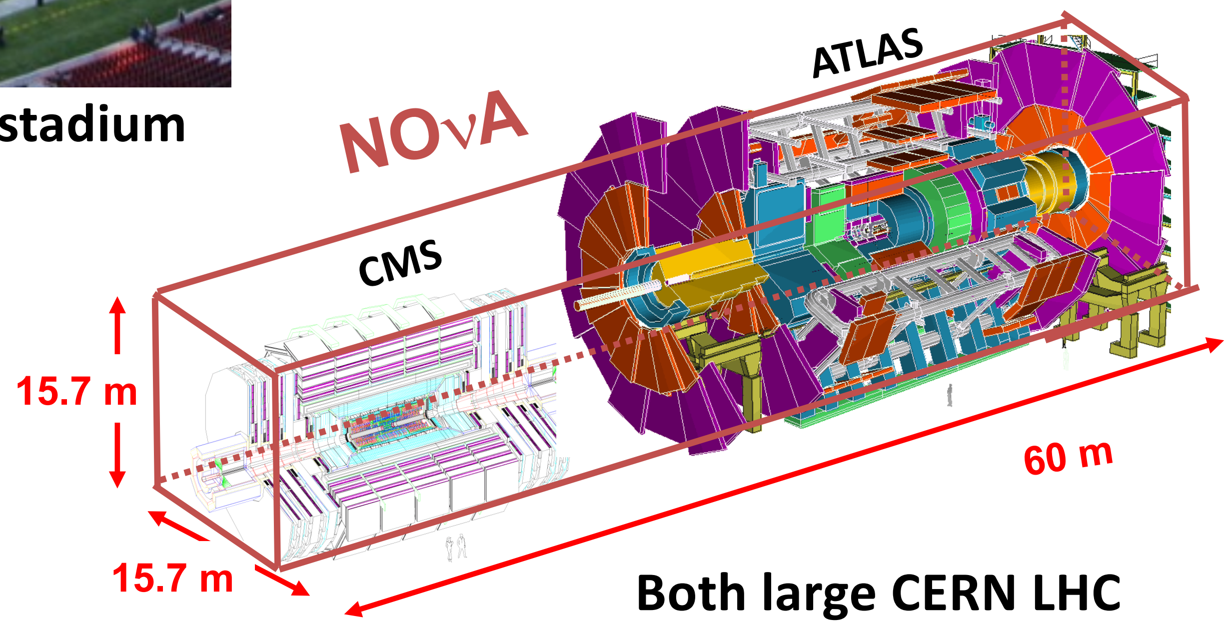




NOνA Far Detector is Big

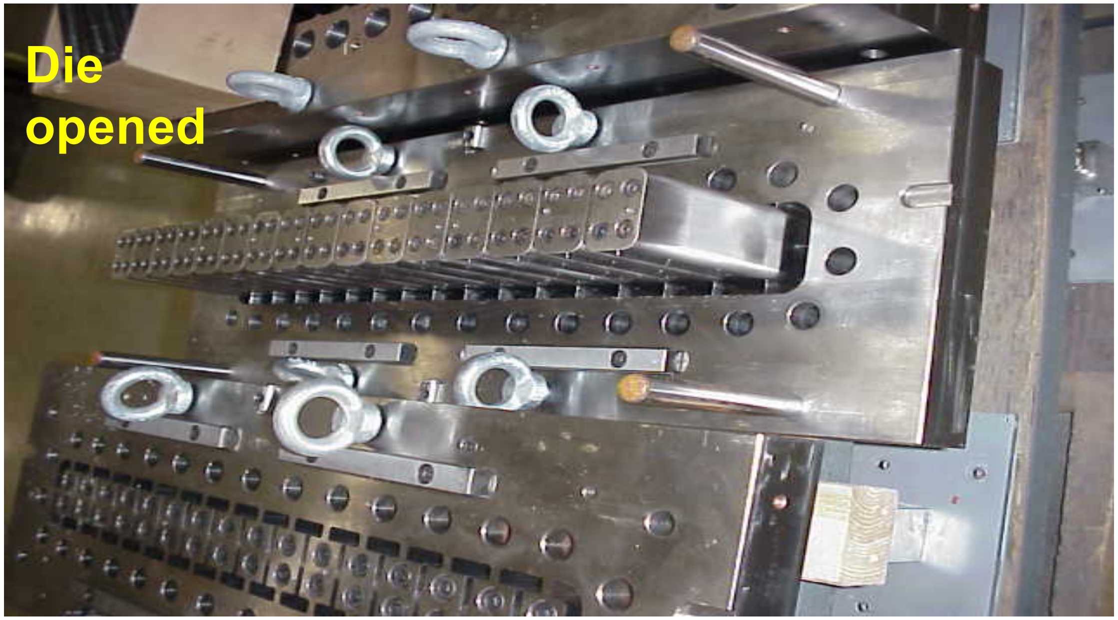


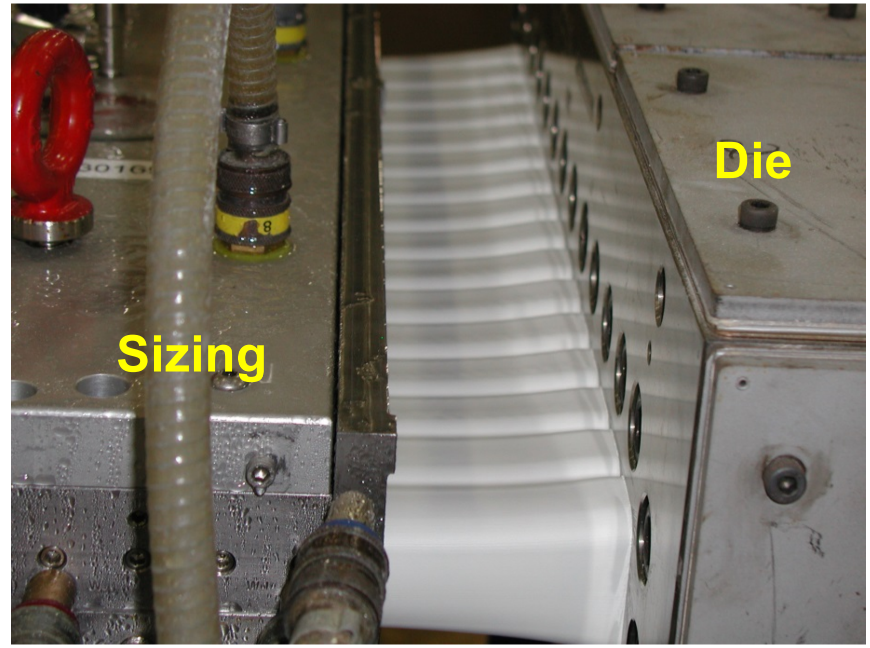
NOνA fits nicely in a football stadium

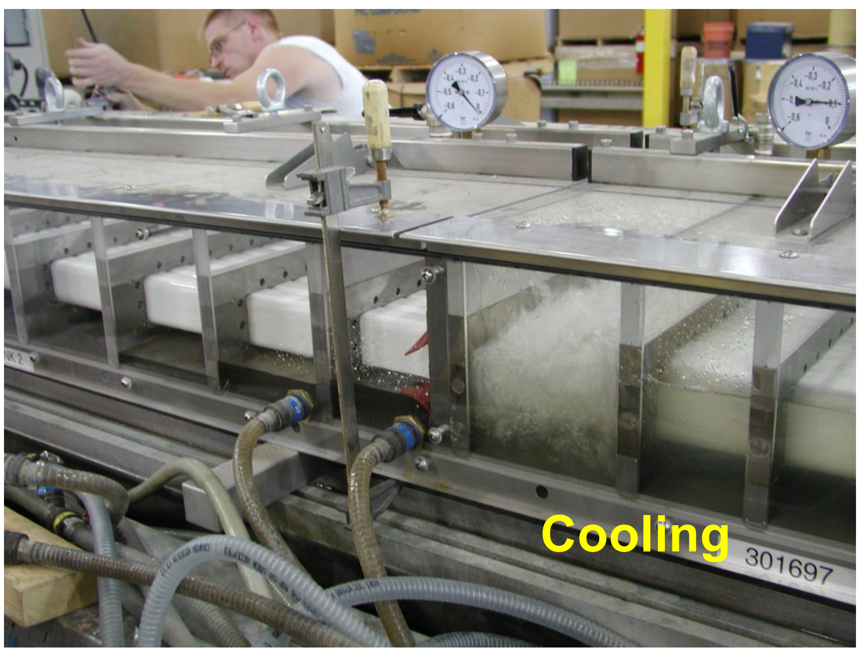


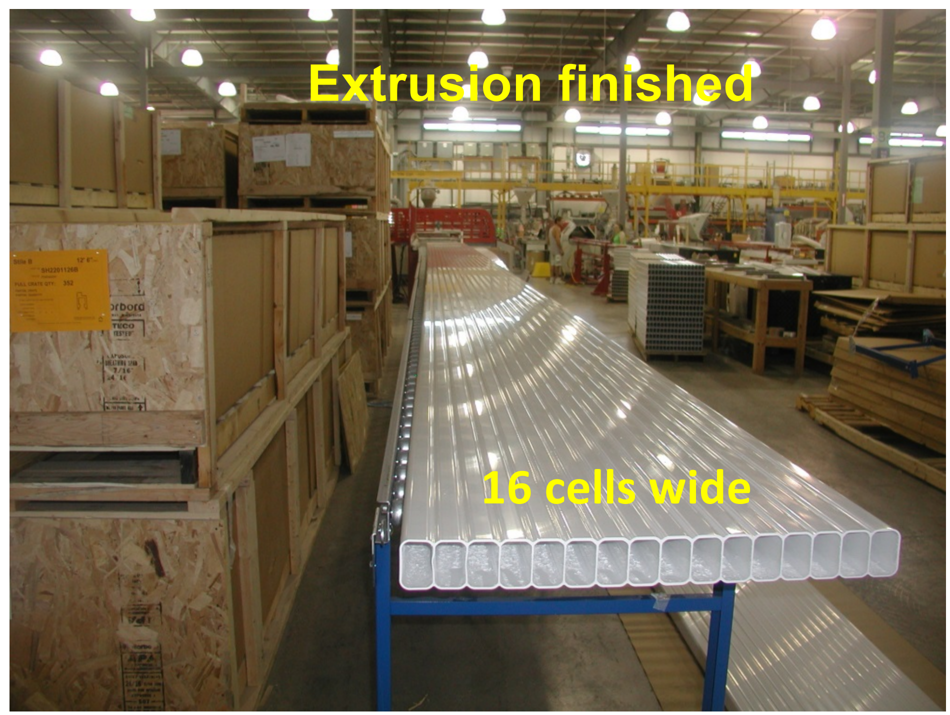
Both large CERN LHC detectors fit into NOνA

Making the PVC Shell: Extrusion





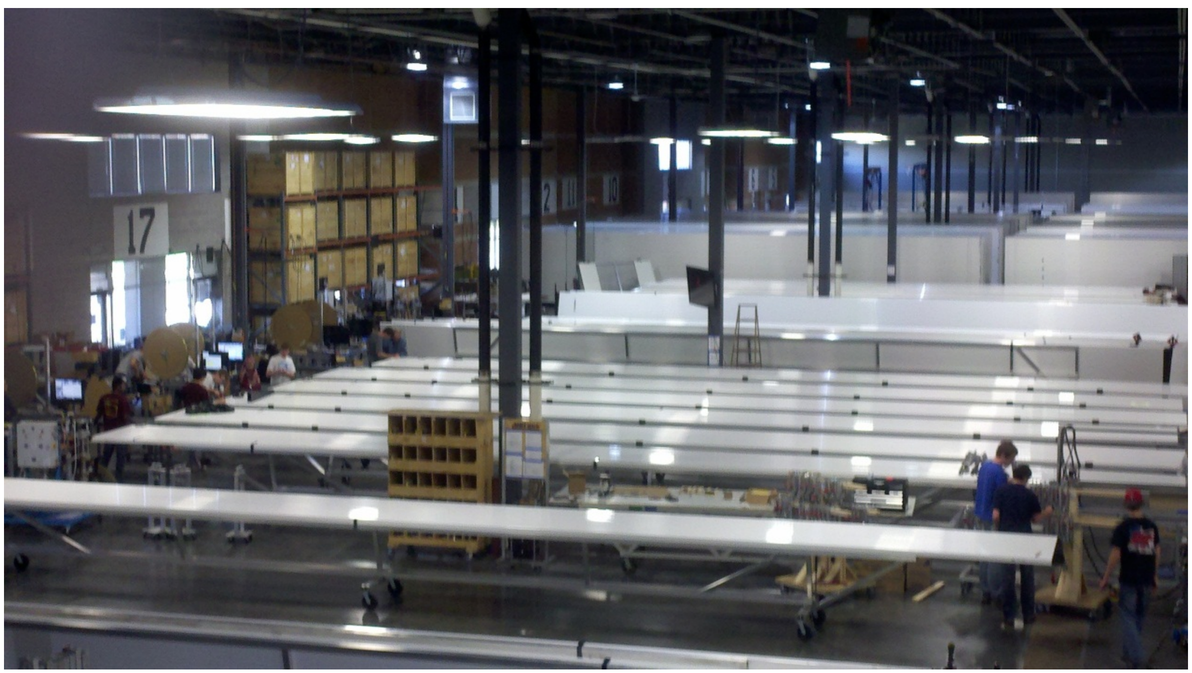




Building Modules @ University of Minnesota

~700 undergrads build 11,000 modules

The Assembly Line in a 125,000 sq ft warehouse



- **Glue 2 extrusions together**
- **Cut to size**
- **String fiber**
- **Glue on top and bottom**
- **Test for leaks**
- **QA/QC at every step**

See the Utube video

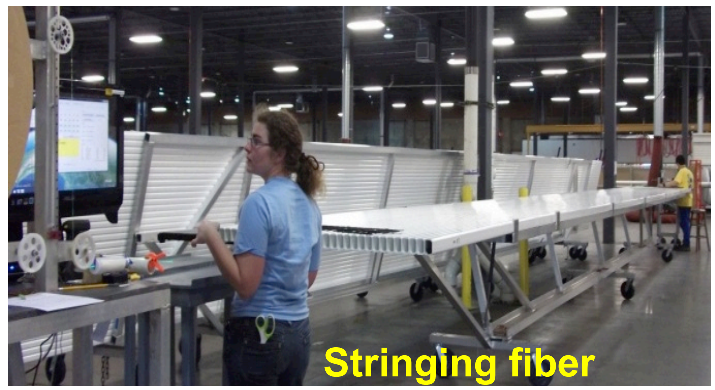
Google:
Building nova neutrino utube

Sample of assembly steps


Unloading extrusions


Craning extrusions to glue together


Gluing 2 extrusions together


Stringing fiber


Threading fiber

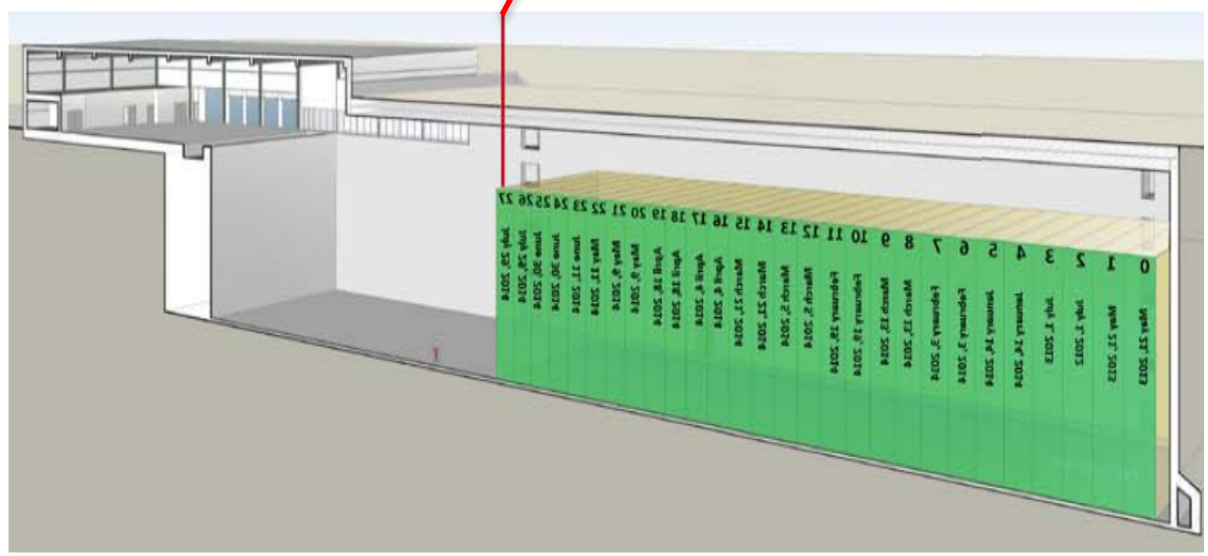

Glue endplate


Waiting for shipping

Far Detector Lab

Owned & operated by University of Minnesota

Funded by DOE



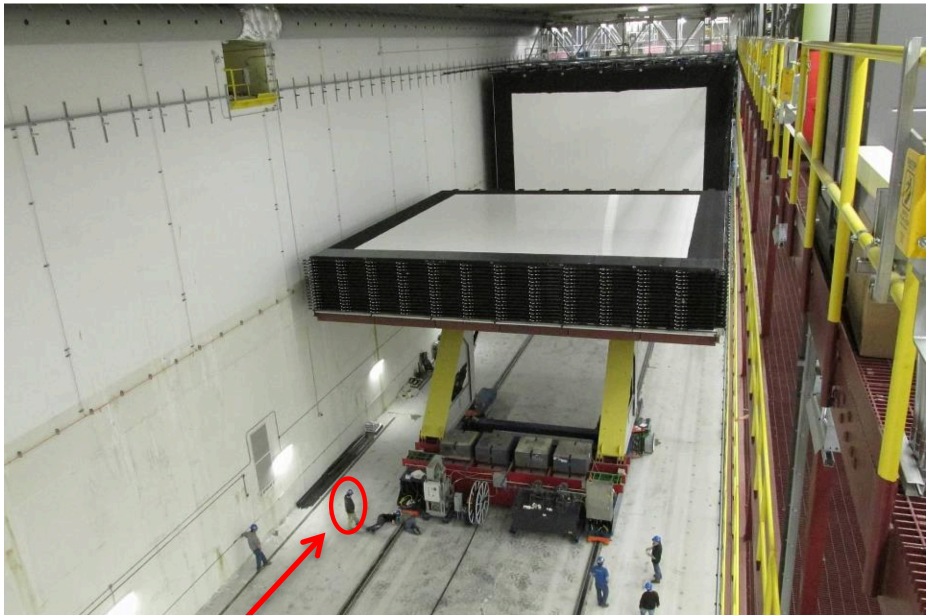
Gluing Modules Together to Make a Block

1 block = 384 modules

1 block weighs 200 Tons empty (300 Tons of scintillator added later)

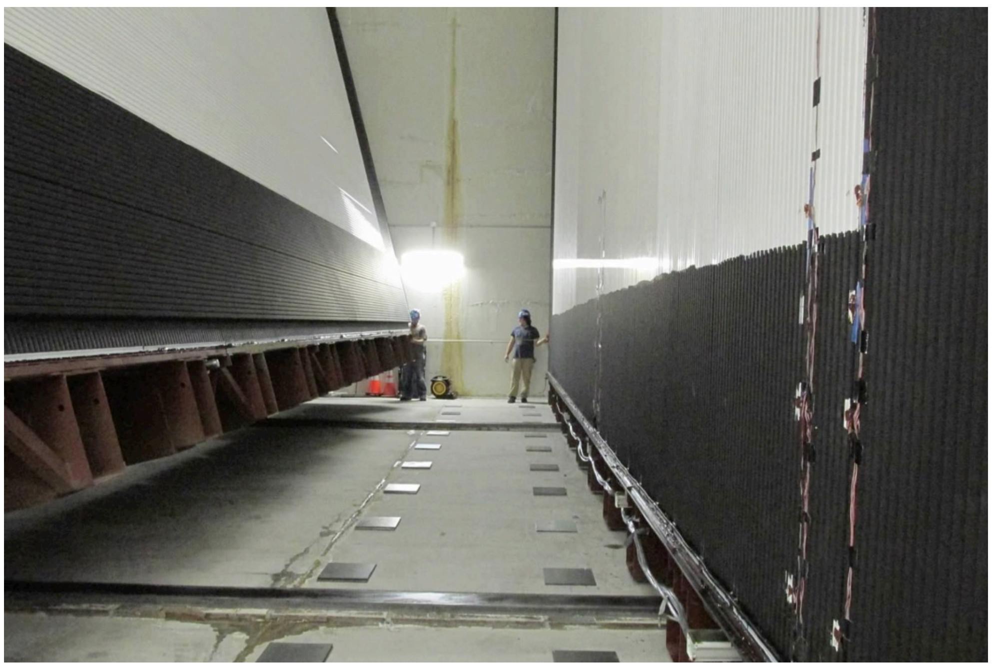
1 block mass = 1/2 KTon when filled with scintillator

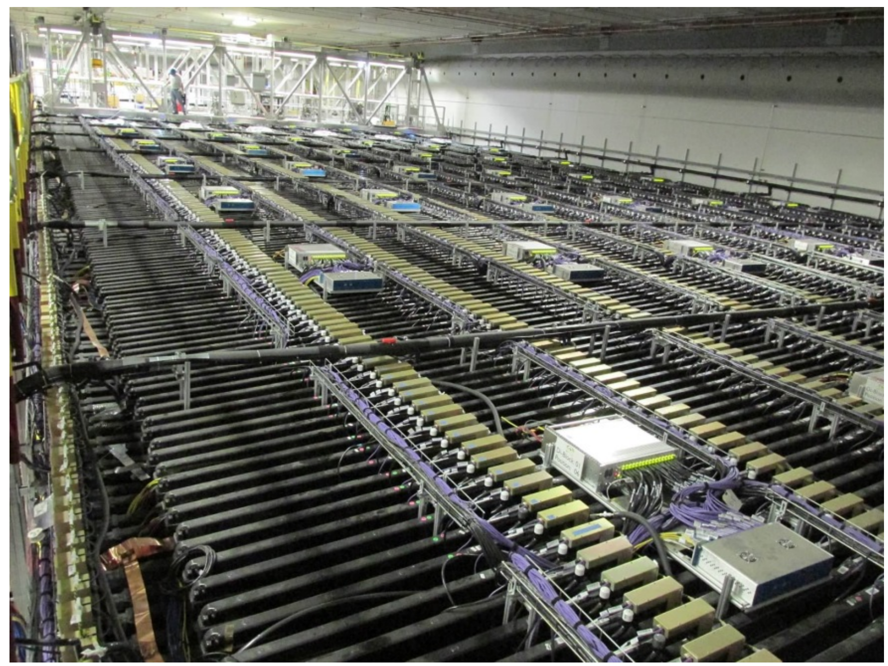
person



person

Moving a Block (200 Tons: 16m x 16m x 2 m) Into Place





Far Detector Activity: 550 microseconds

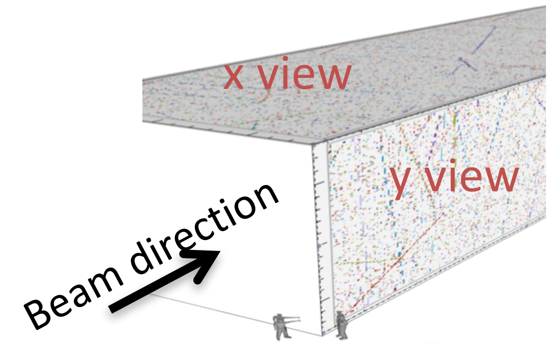
Beam spill: 10 μs

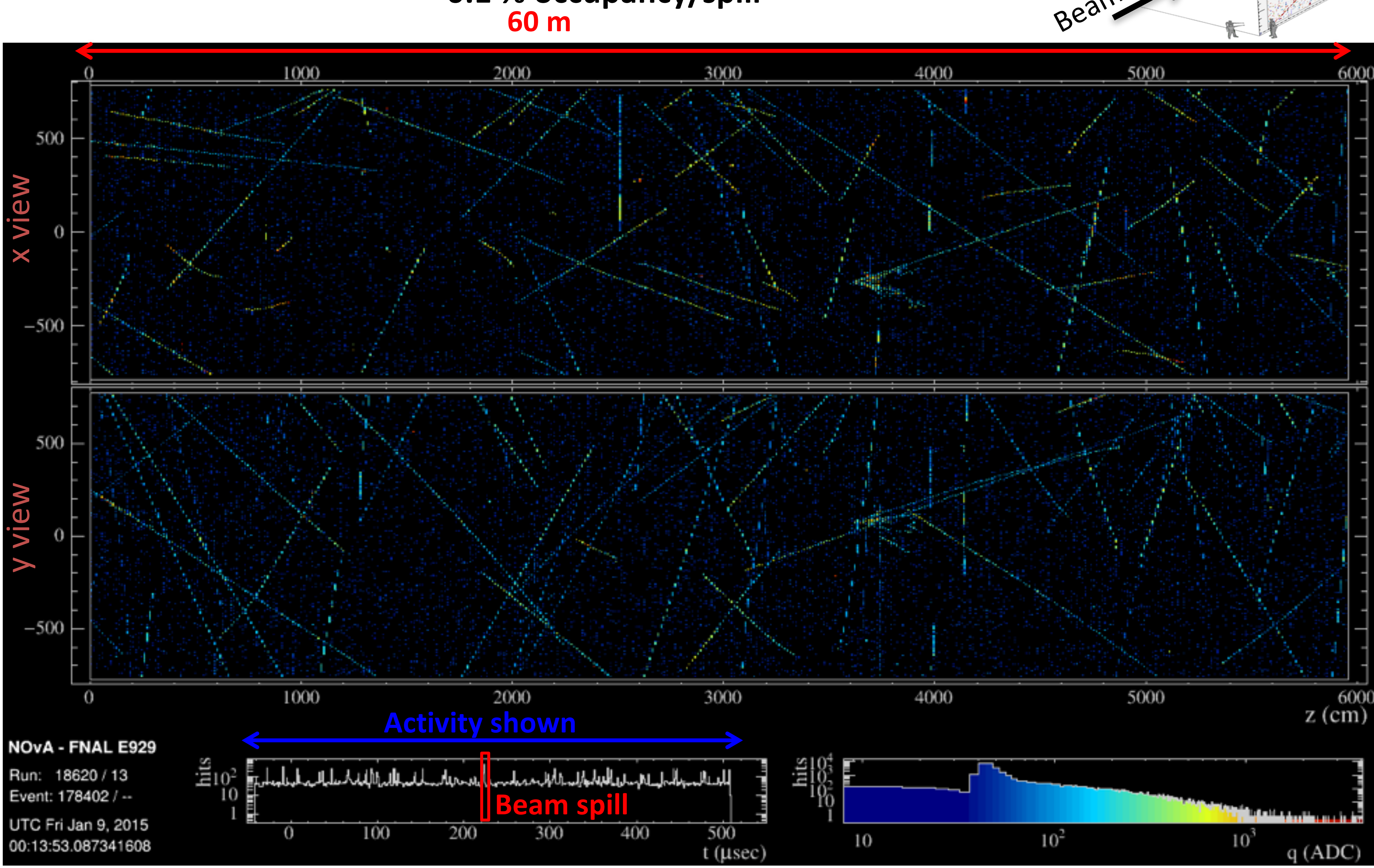
Timing: 50 ns

200,000 cosmic rays/second

2 cosmic rays/spill (10 μs)

0.1 % occupancy/spill





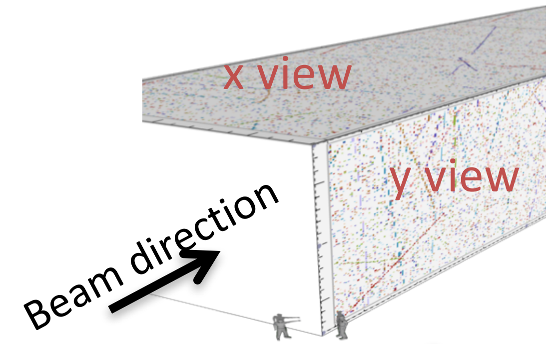
Far Detector Activity: 10 microseconds

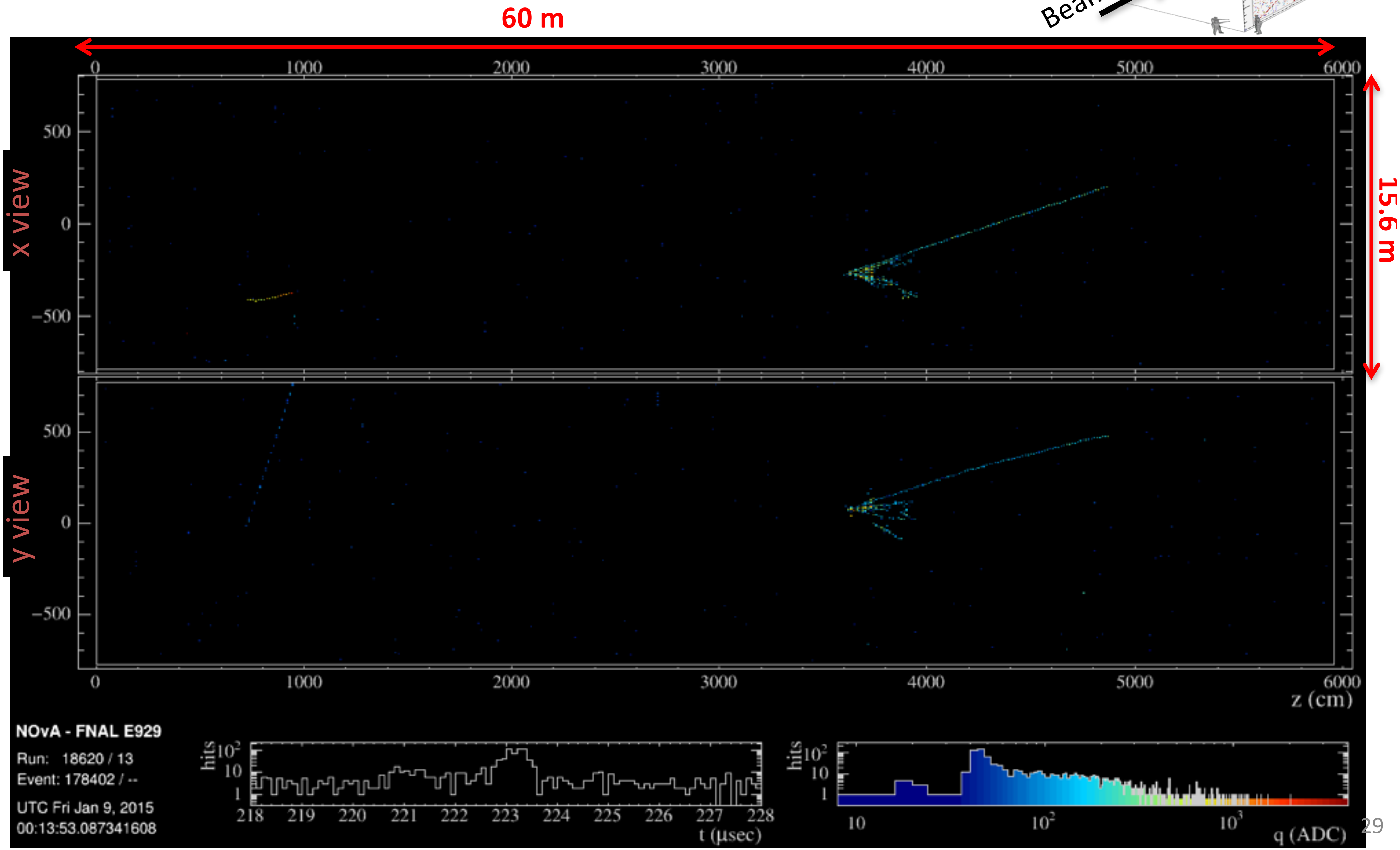
Beam spill: 10 μs

Timing: 50 ns

Cosmic ray rejection

19 million → 1



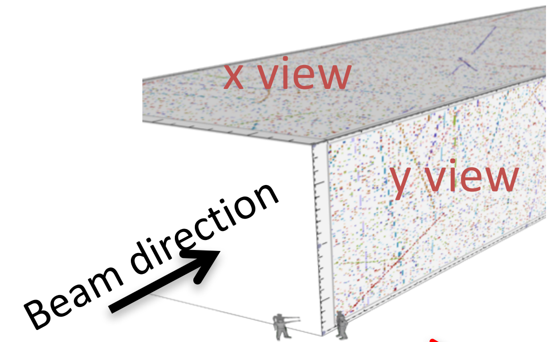


Far Detector Activity: 2 microseconds

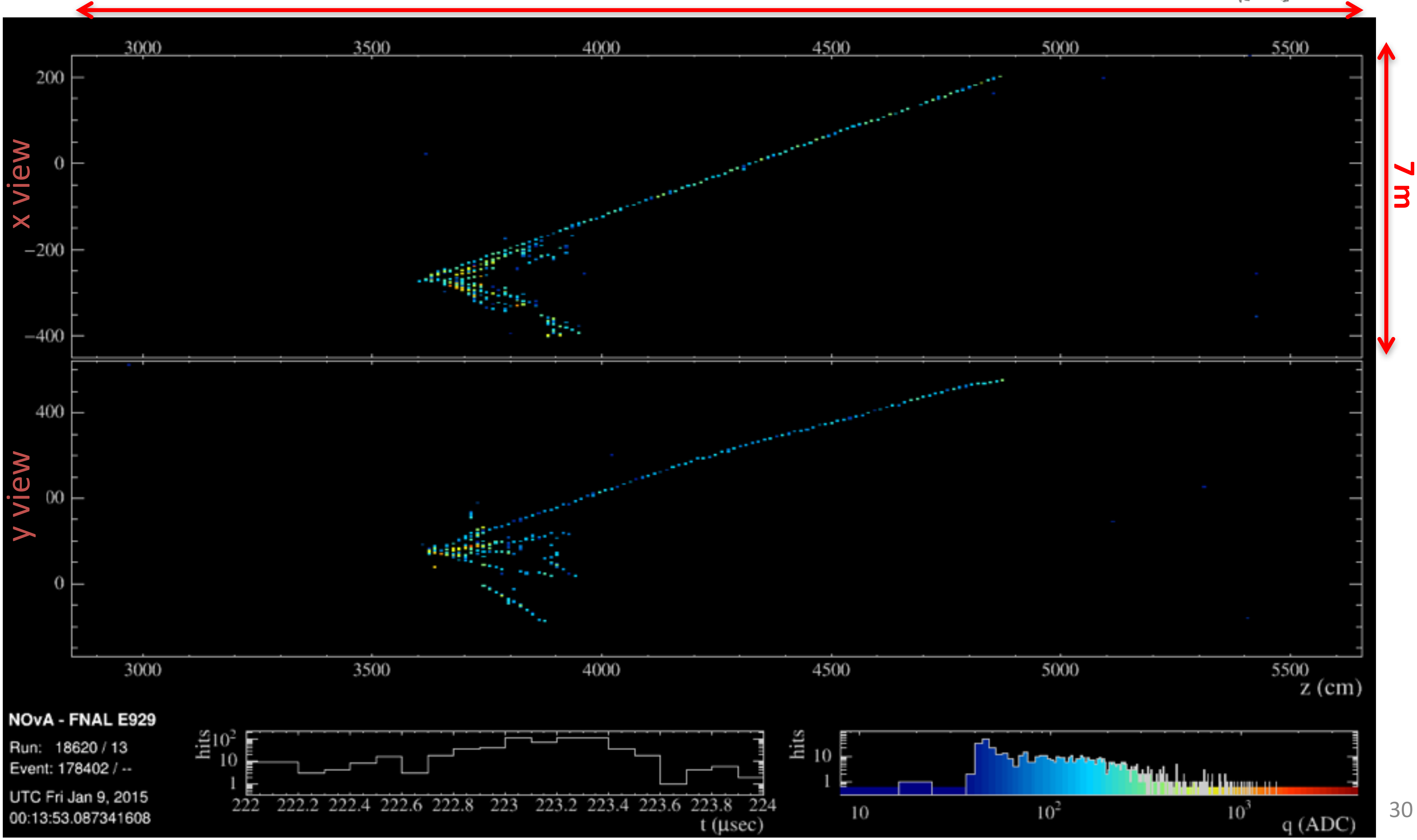
Beam spill: 10 μs

Timing: 50 ns

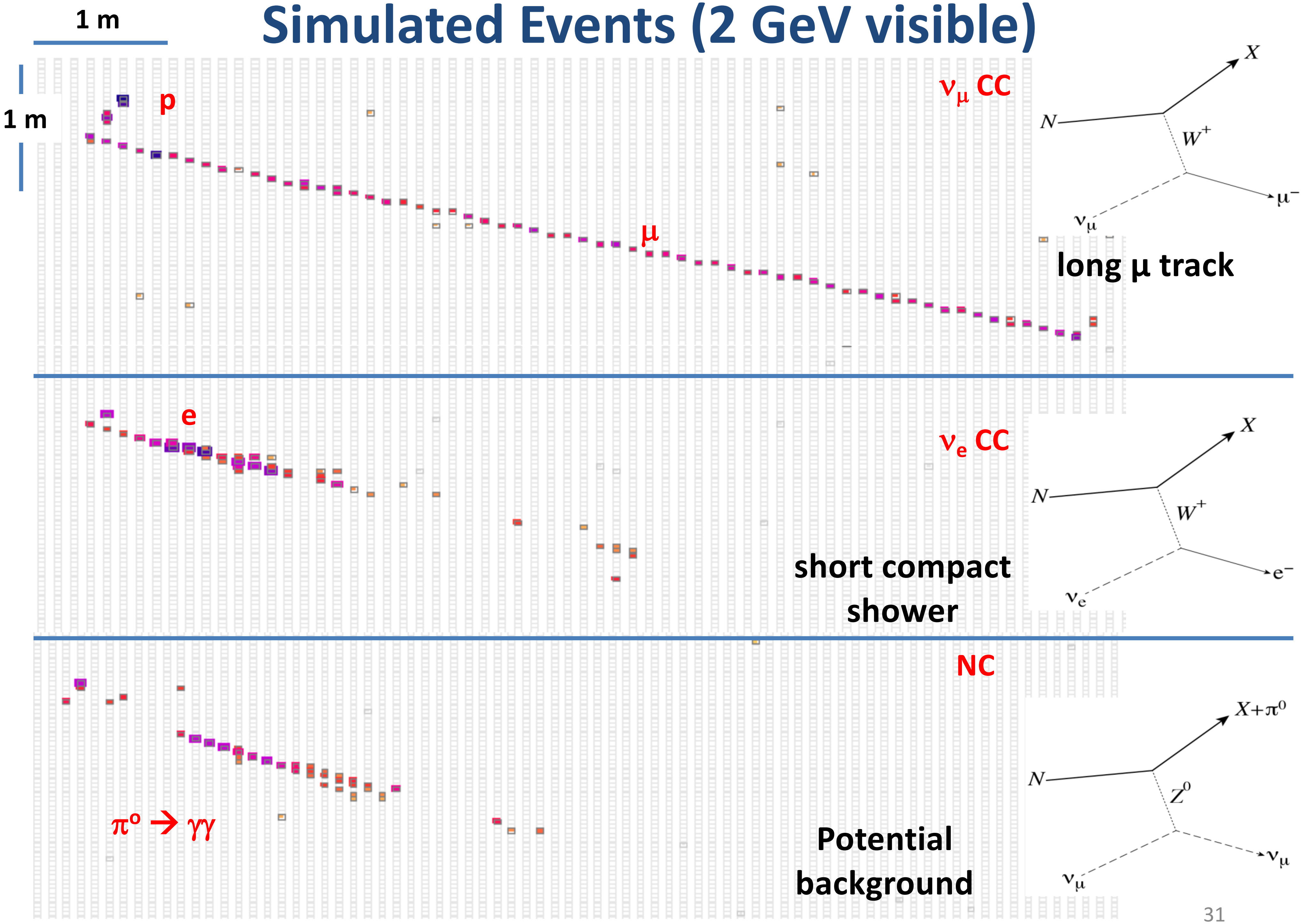
cell 4 cm 6 cm



20 m

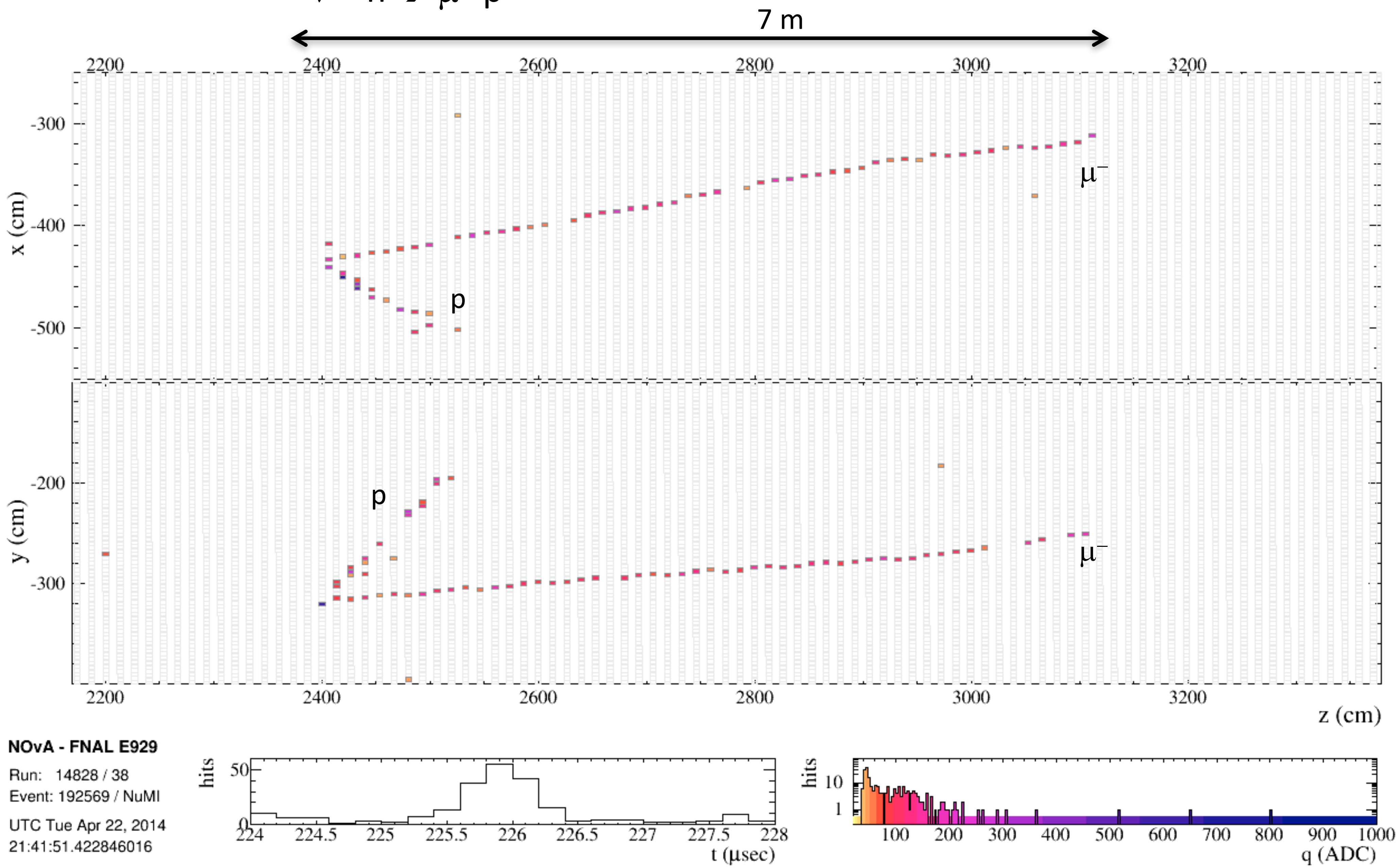


Simulated Events (2 GeV visible)



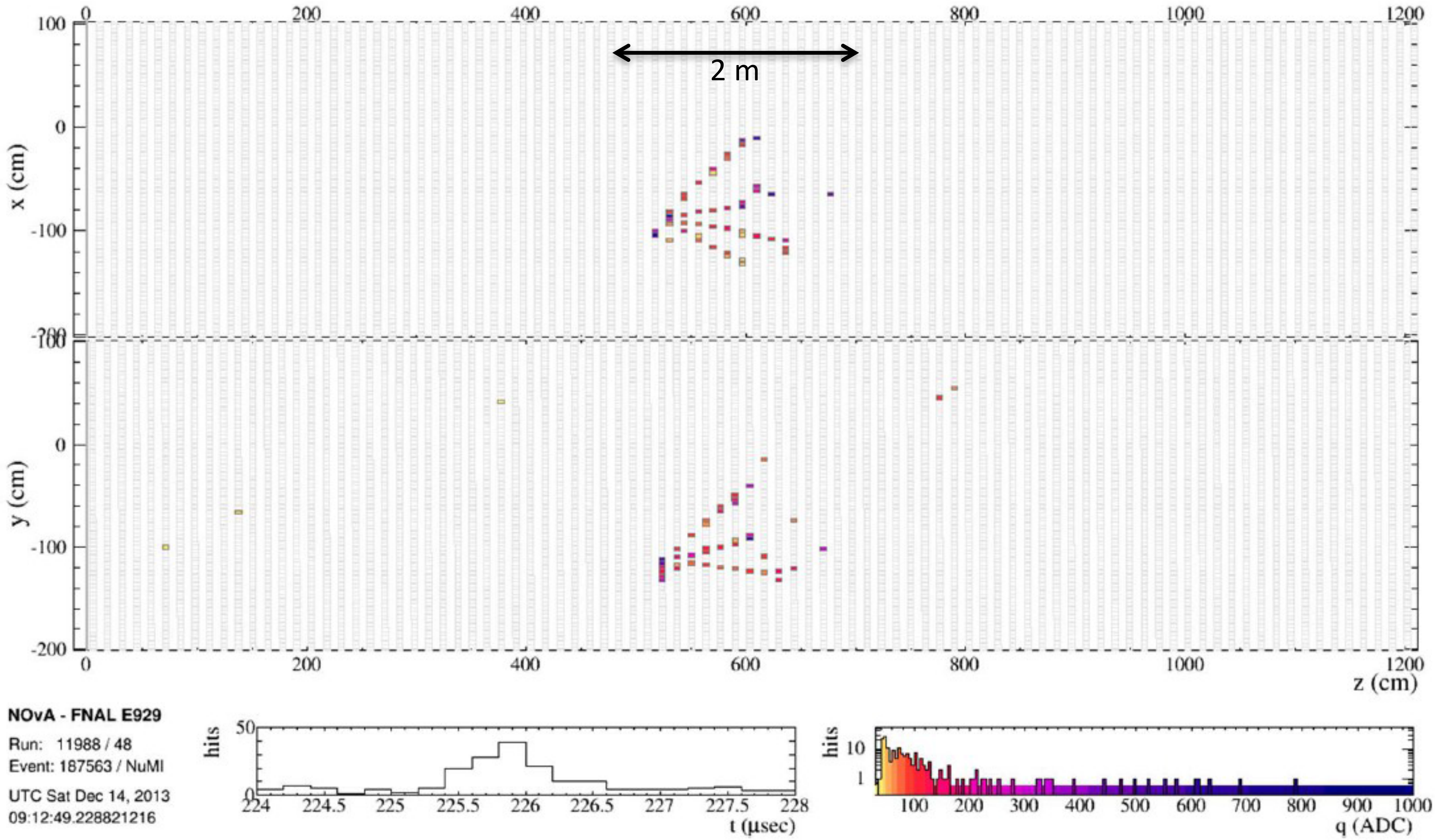
Muon Neutrino Charged Current Candidate in Far Detector

$\nu + n \rightarrow \mu^- p$



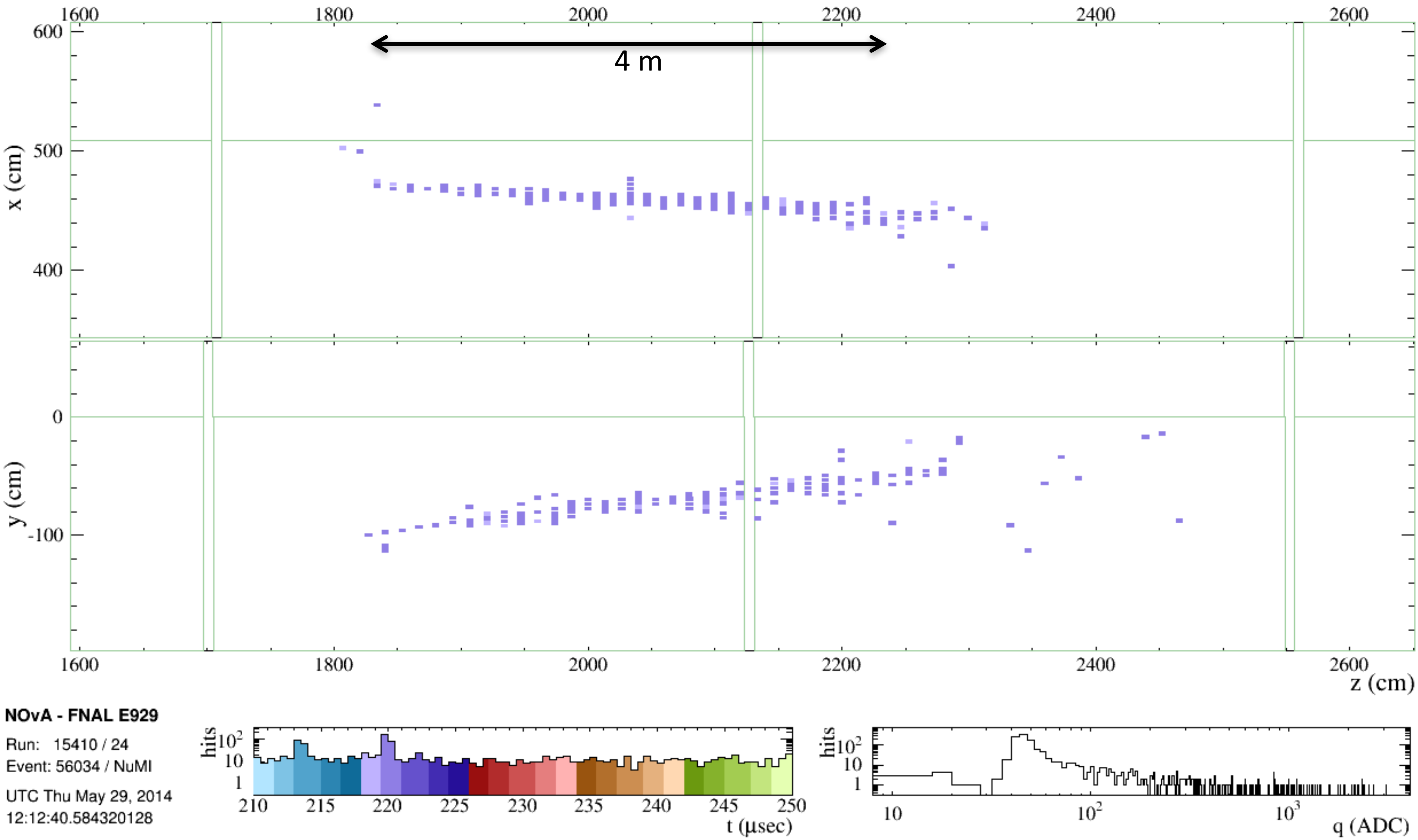
Neutrino Neutral Current Candidate in Far Detector

$\nu + N \rightarrow \nu X$

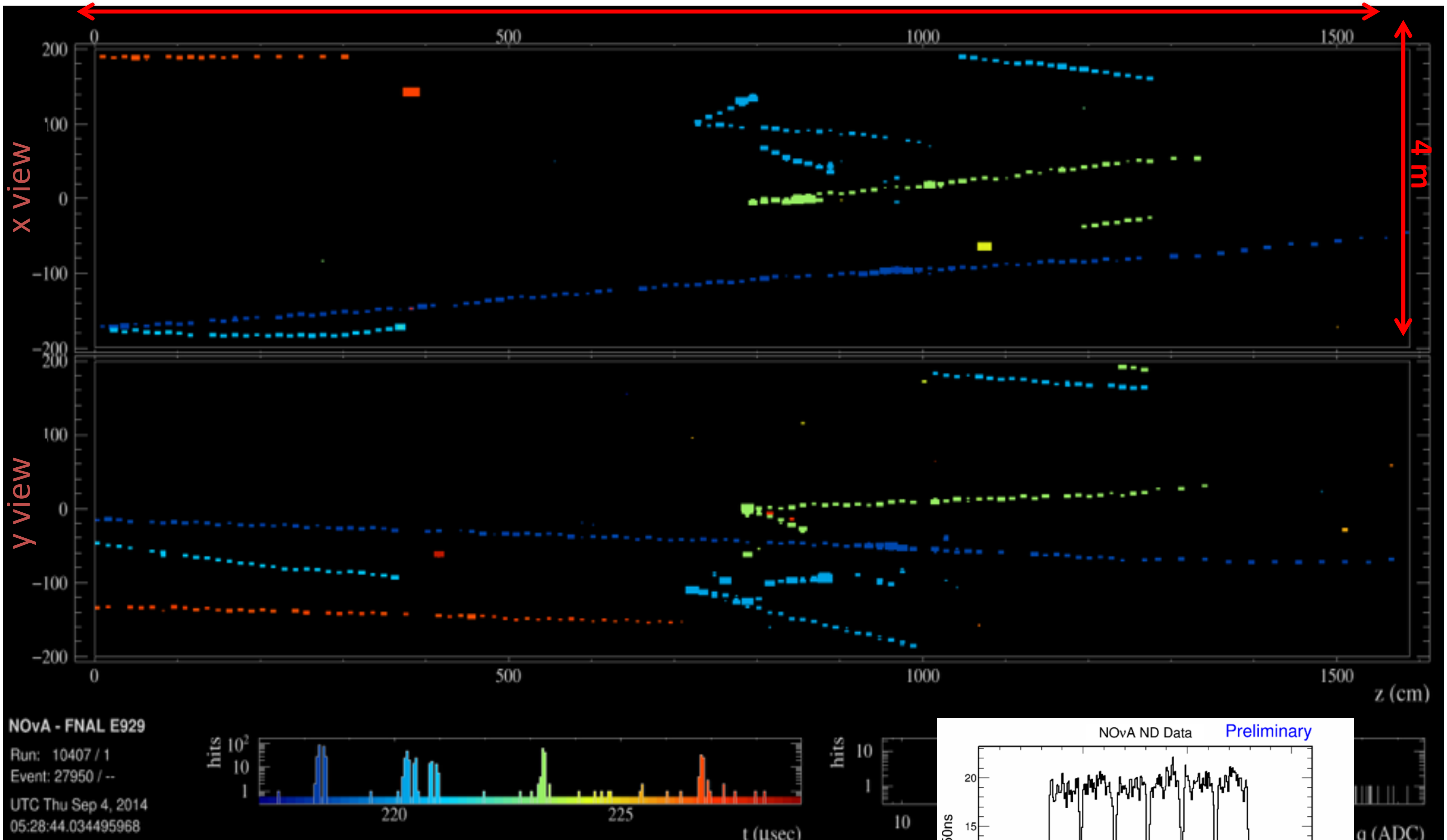


Electron Neutrino Charged Current Candidate in Far Detector

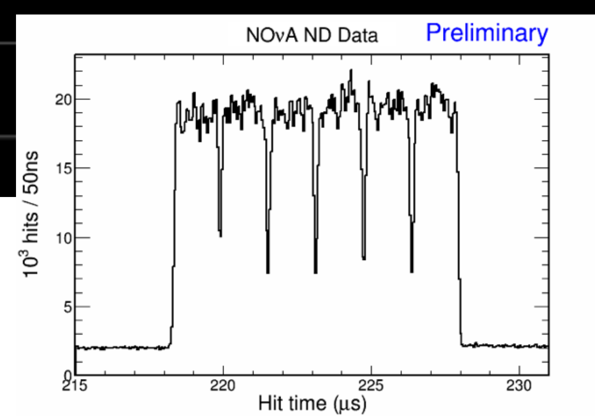
$\nu + n \rightarrow e\ X$



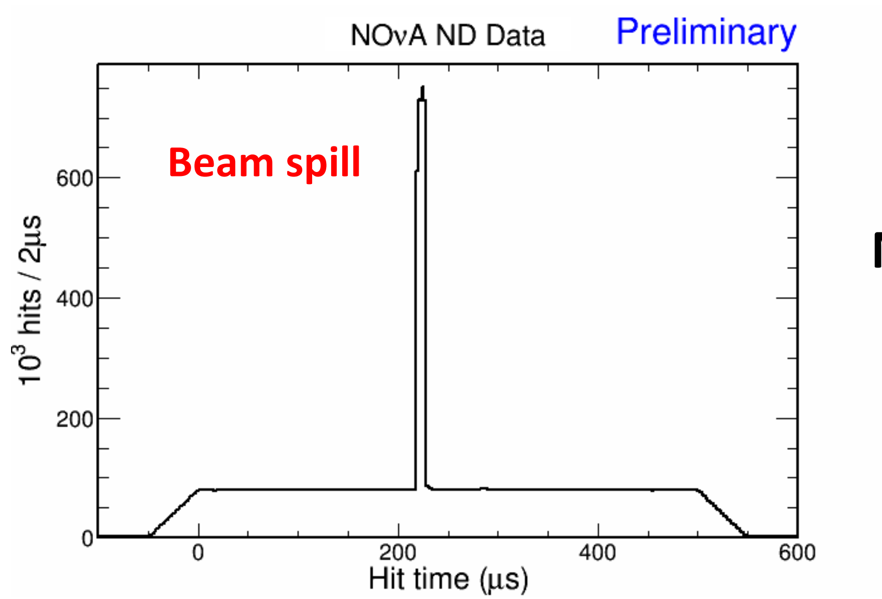
Near Detector Activity: 10 μs



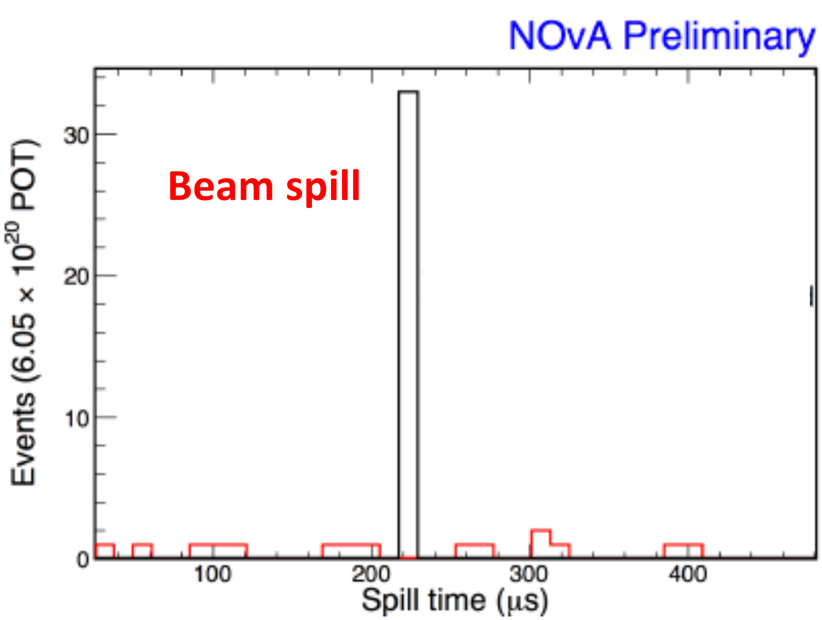
Beam structure



Both Detectors See the Beam (10 μsec) every 1.3 sec

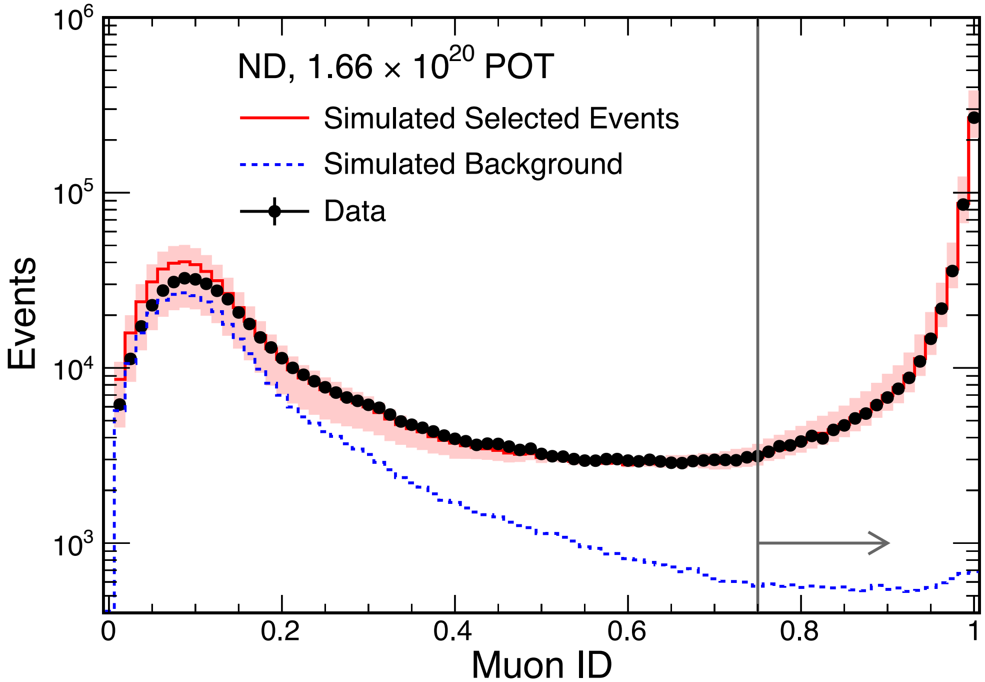


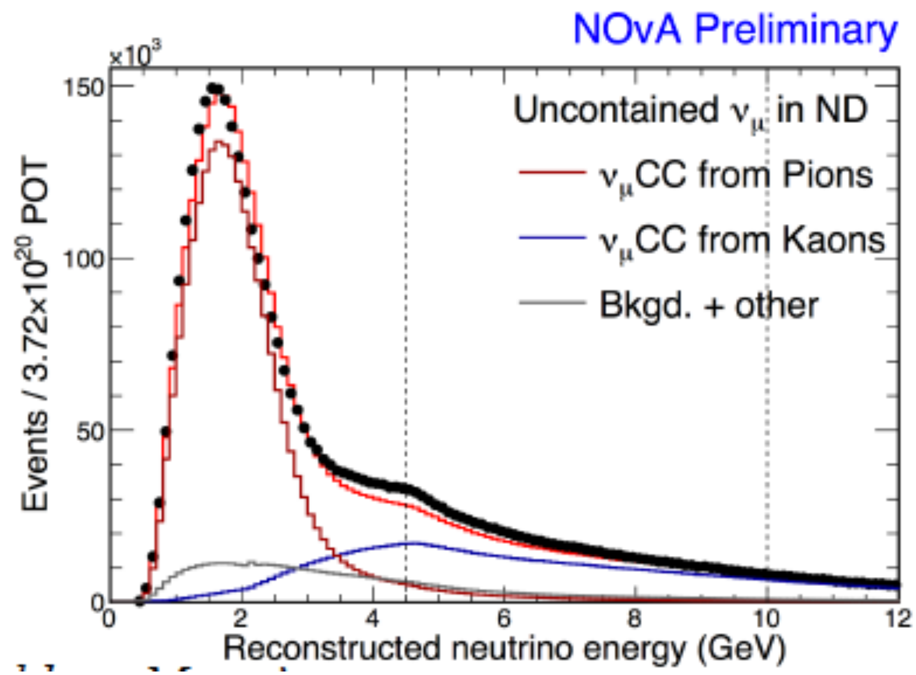
Near Detector Timing Peak Using ν Events



Far Detector Timing Peak Using e Events

Near Detector ν_μ events to get neutrino energy





Select ν_μ from likelihood based on:

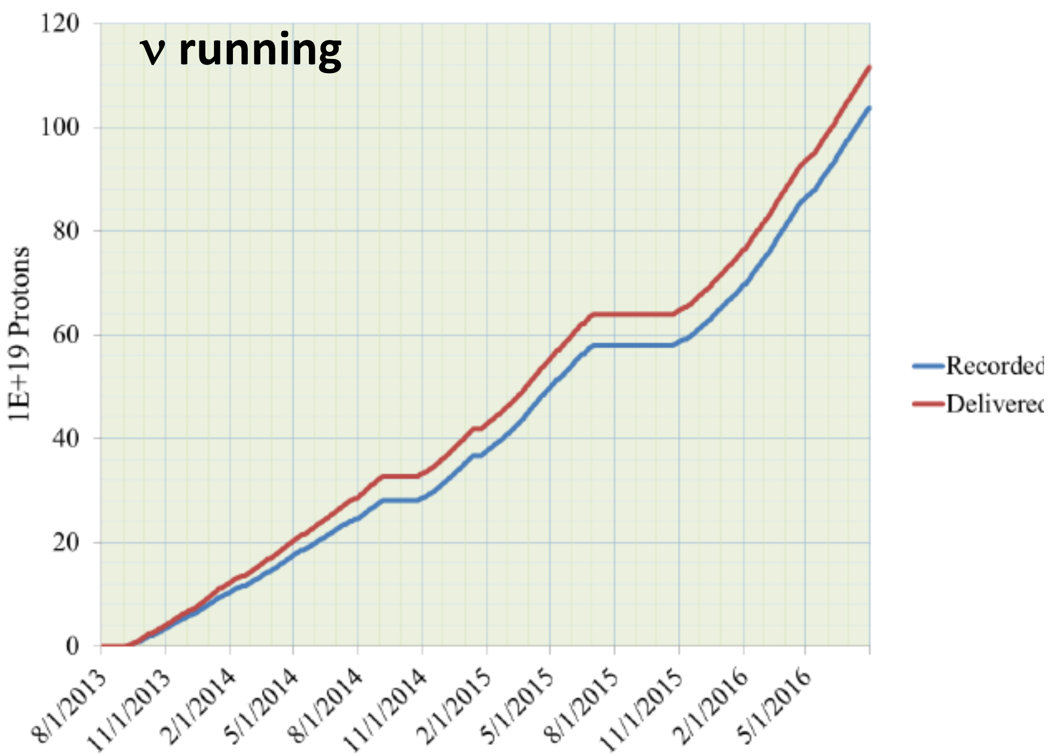
- **Contained, in beam spill**
- **Beam direction**
- **Planes with only muon activity**
- **Muon-like**
  - **Track length**
  - **Track straightness**
  - **Energy deposition/length (dE/dx)**

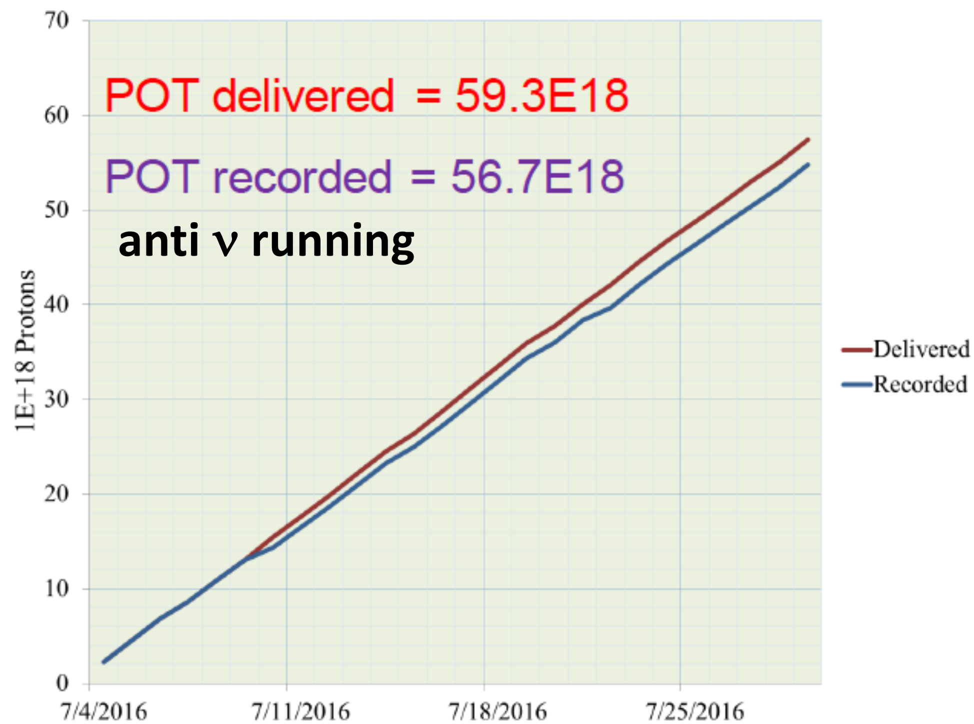
Extrapolate to get unoscillated spectrum in the Far Detector

Data Collection Status

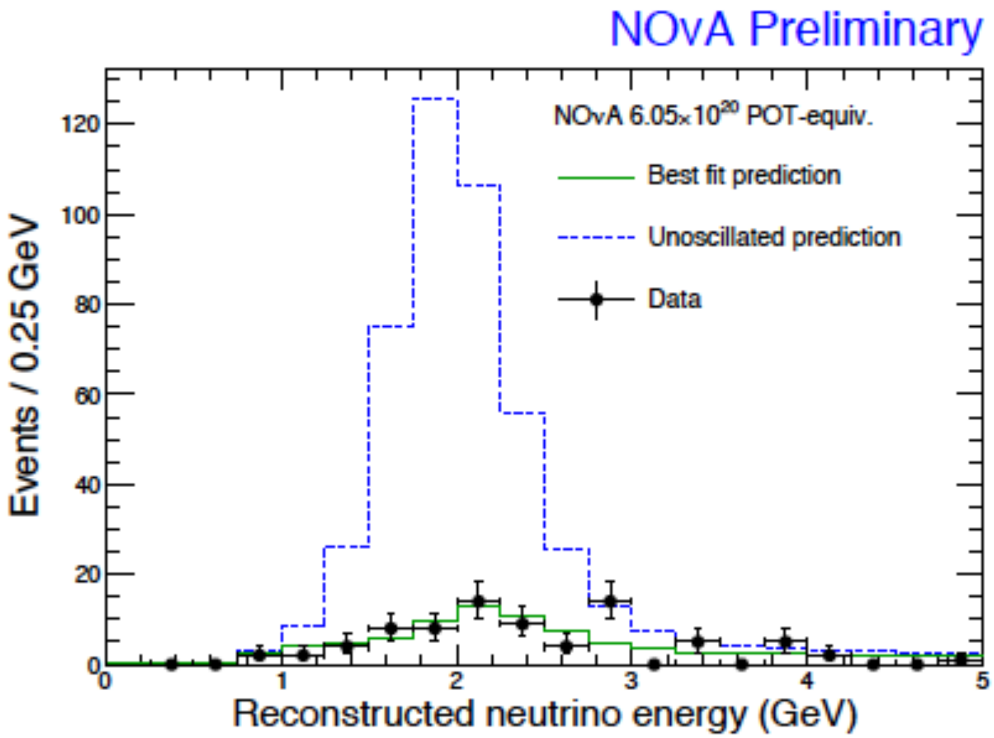
- Beam now at 550 KW tested to 700 KW
- Far Detector Active Channels > 99%
- Far Detector Up Time 98%
- Near Detector Up Time 92%
- Recorded 8.4 x 10^{18} POT/wk (overall 95% efficient)
- So far 6 x 10^{20} POT with full detector

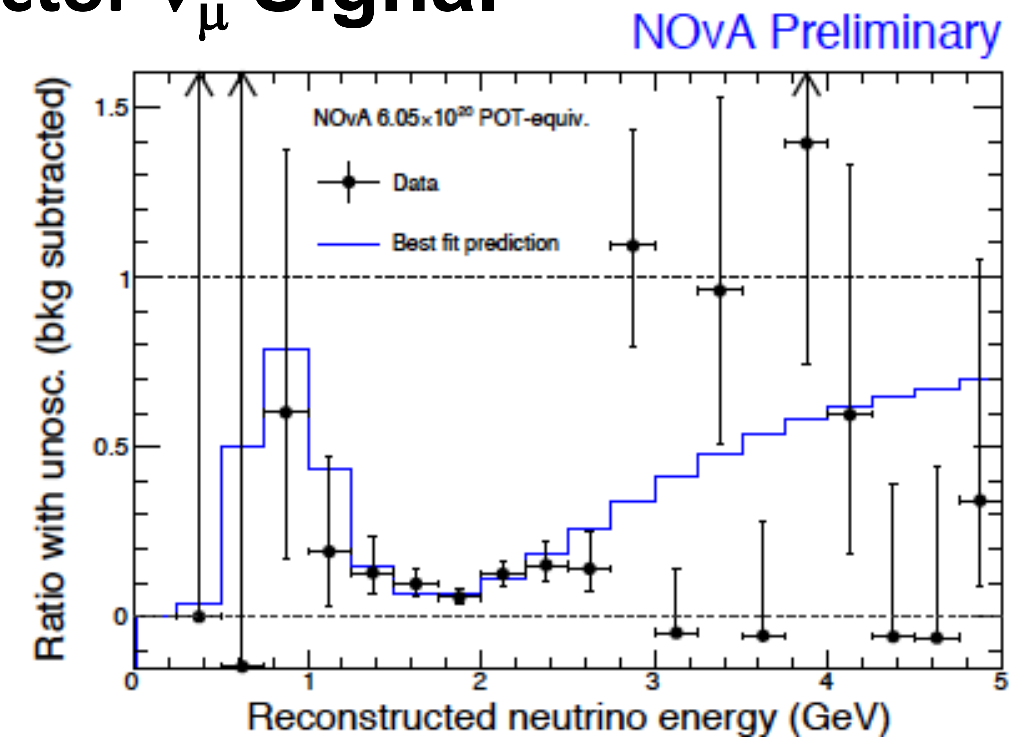
POT = protons on target





Far Detector ν_μ Signal

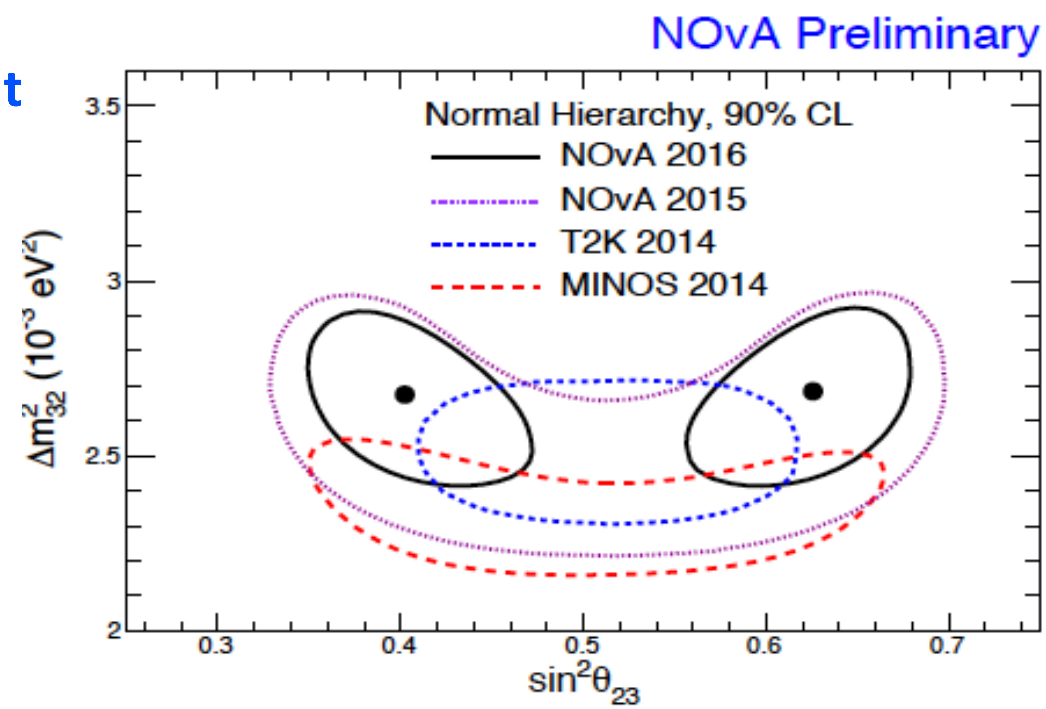




If no oscillation: Expect 473 ν_μ event

Observe 78 events

Background 6 events

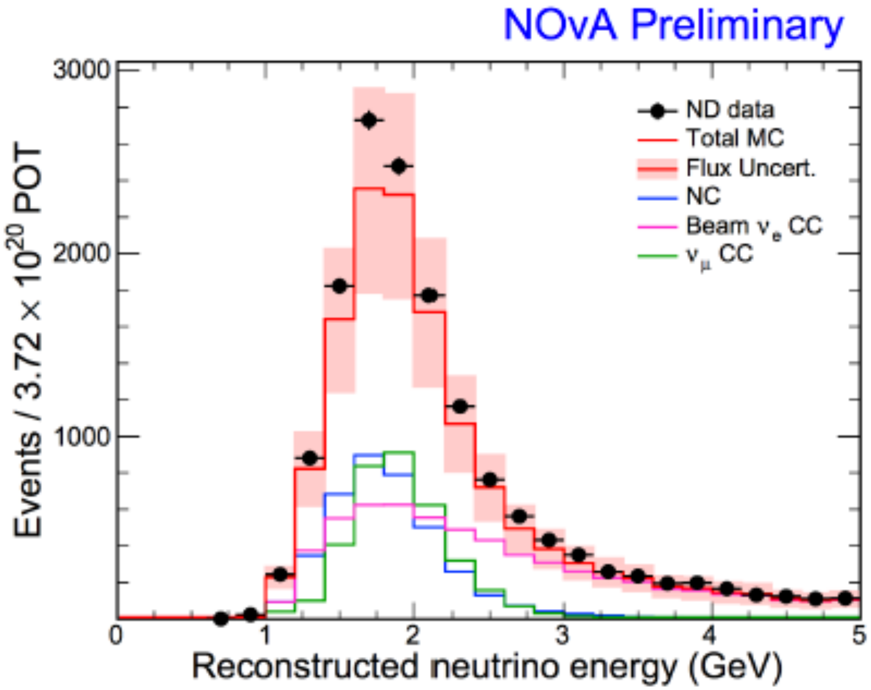


Δm^2_{32} = 2.7 ± 0.1 X 10^{-3}(eV^2)

$Sin^2\,\theta_{23}$ = 0.40 or 0.63 ± 0.03

Fit to oscillation predicts 82 events

ν_e Signal in Near Detector



Extrapolate to Far Detector

Predict Background

8.2 ± 0.8 events

3.1 beam ν_e

3.7 neutral current

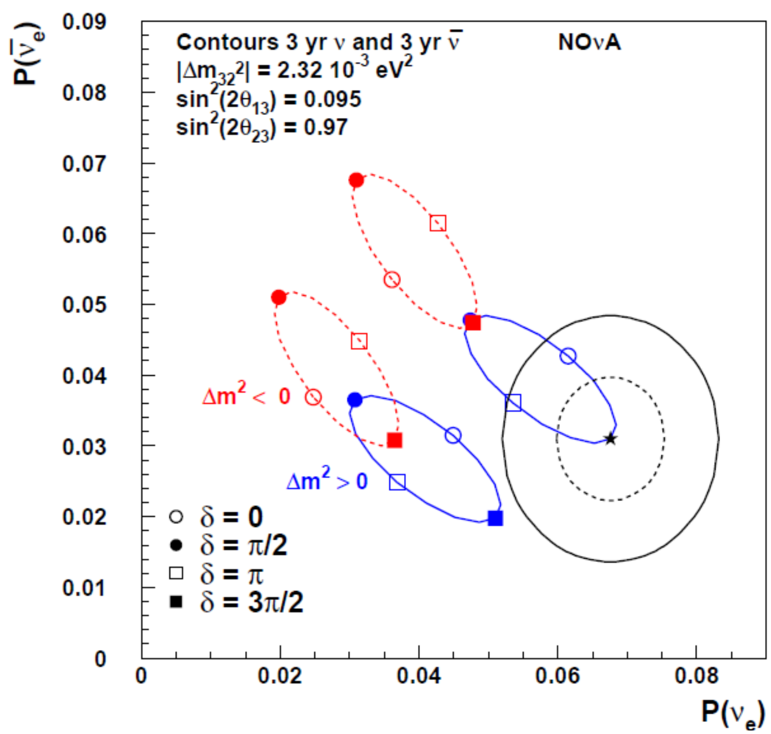
0.7 ν_μ charged current

0.5 cosmic ray

Select ν_e from likelihood based on:

- **Contained, in beam spill**
- **Beam direction**
- **Electron-like**
  - **Shower shape**
  - **Shower energy**
  - **Vertex gap**

Chose analysis technique and parameters before looking at far detector data – blind analysis



Predict Signal

Maximum

Normal, $\delta = 3\pi/2$

36.4 events

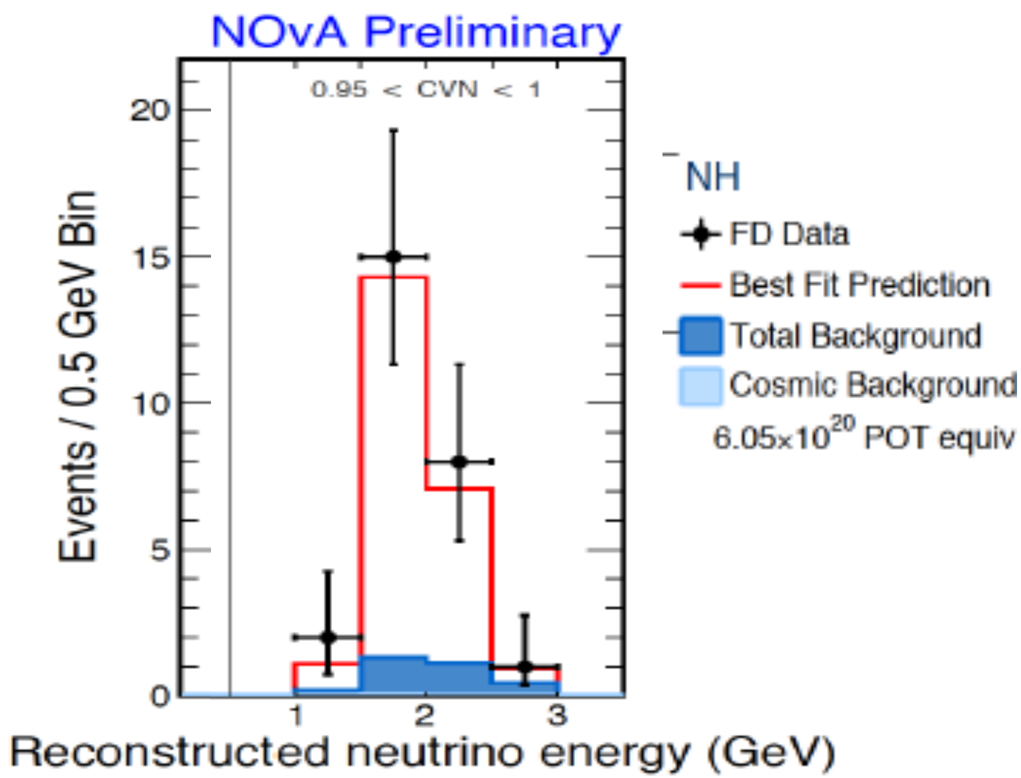
Minimum

Inverted, $\delta = \pi/2$

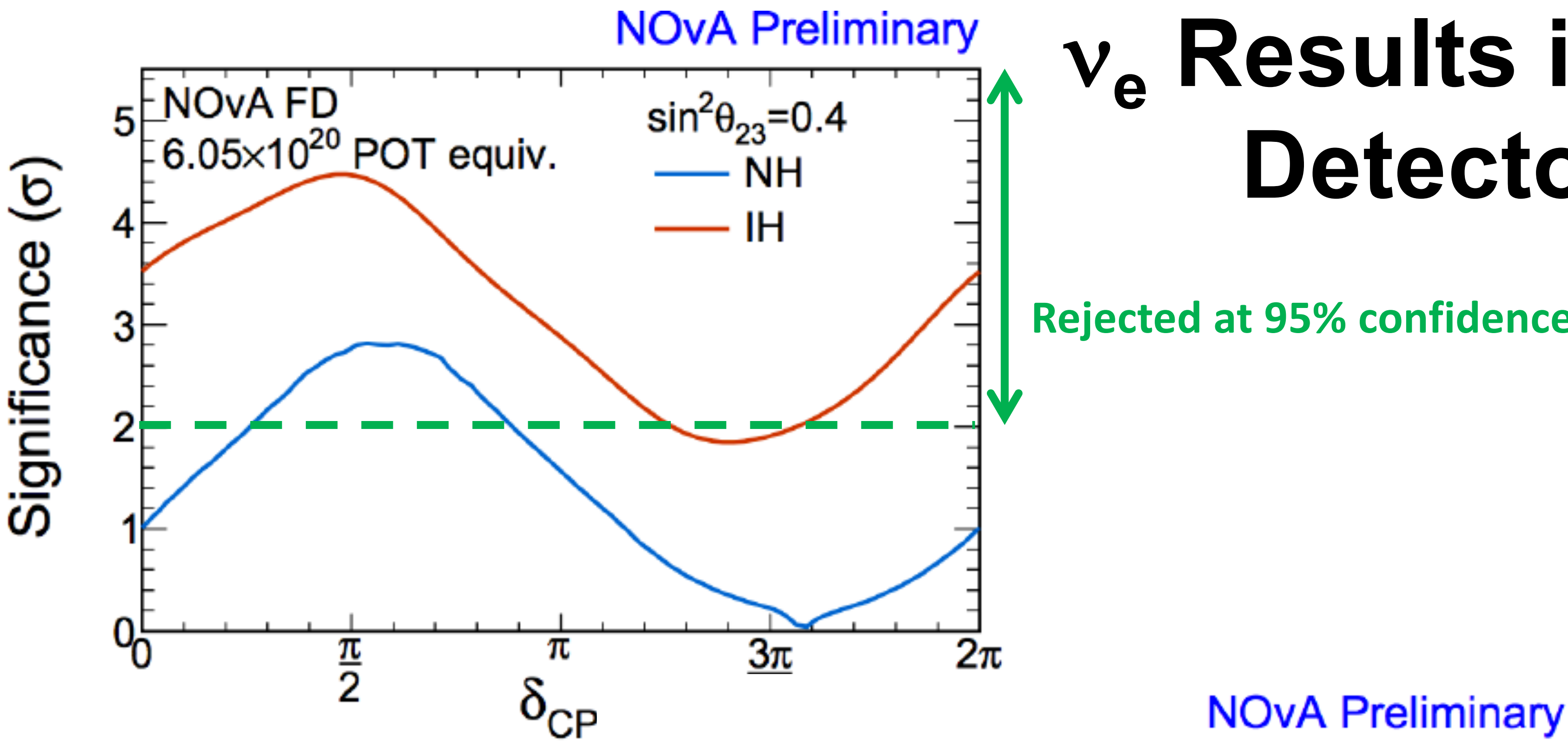
19.4 events

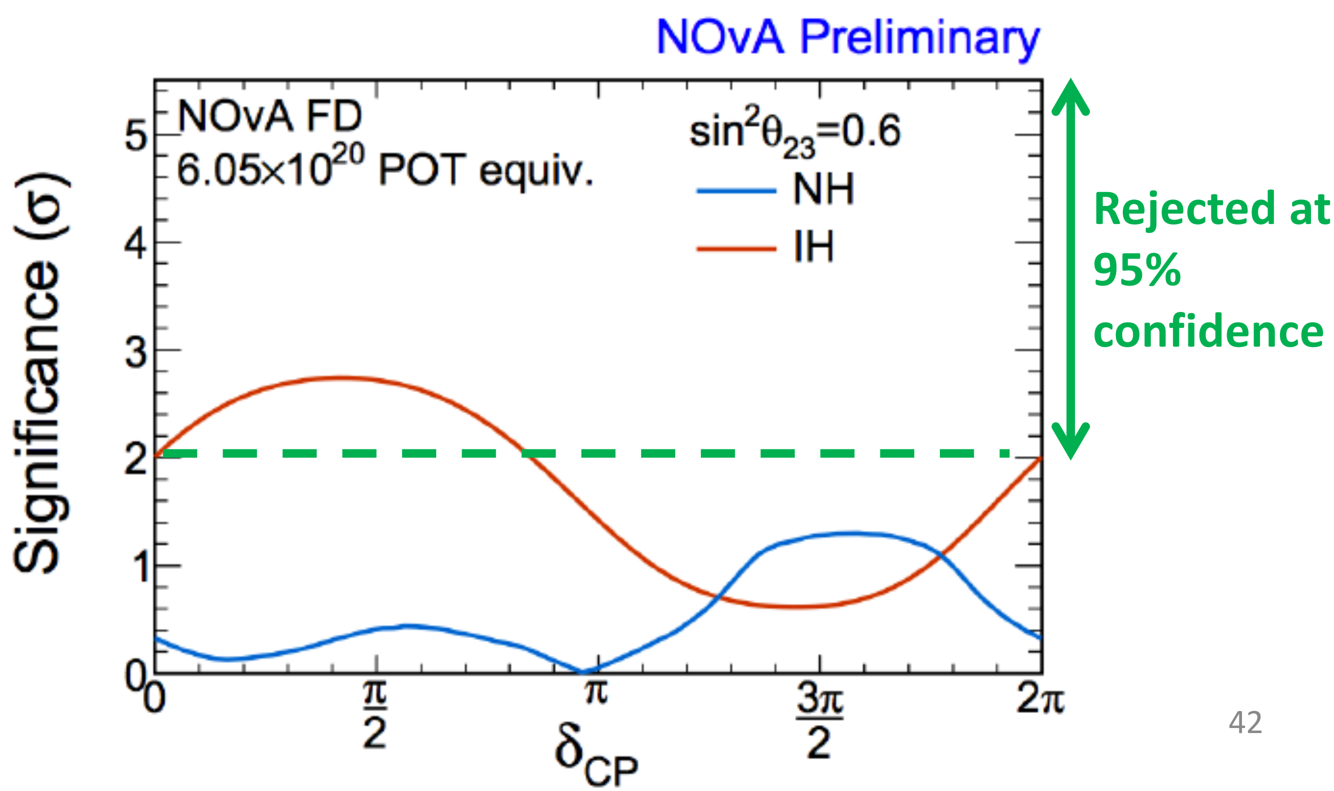
ν_e Signal in Far Detector

Observe 33 events with expected background of 8

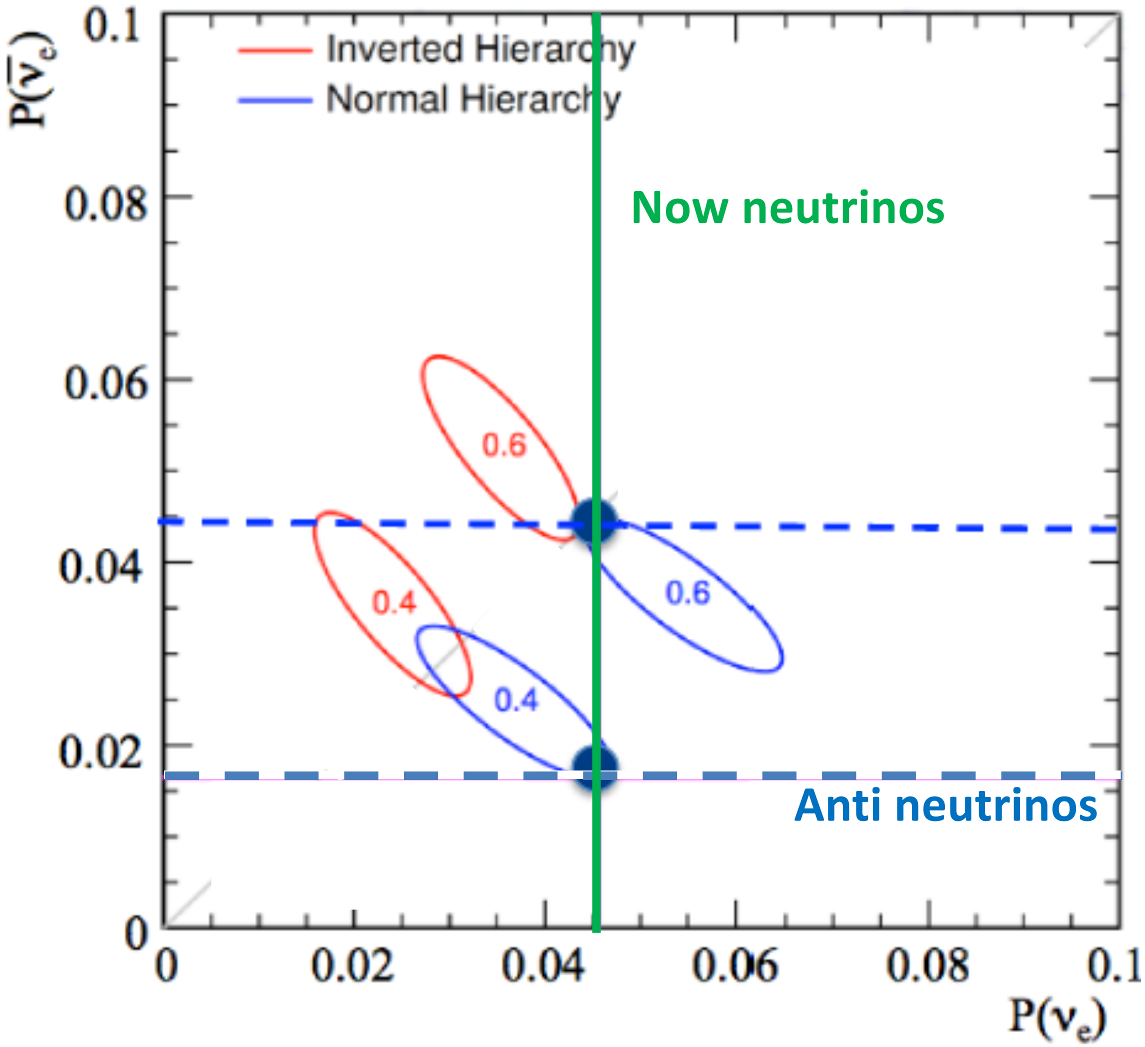


ν_e Results in Far Detector





Anti neutrino data can resolve the ambiguity – Start in October



Examples of Other Physics

Near Detector

- Neutrino cross-sections (0.5 – 5 GeV)

  Quasi-elastic

  Resonance Hadronization

  Deep inelastic

- Neutrino – electron scattering
- Neutrino magnetic moment
- Magnetic monopoles
- WIMPs

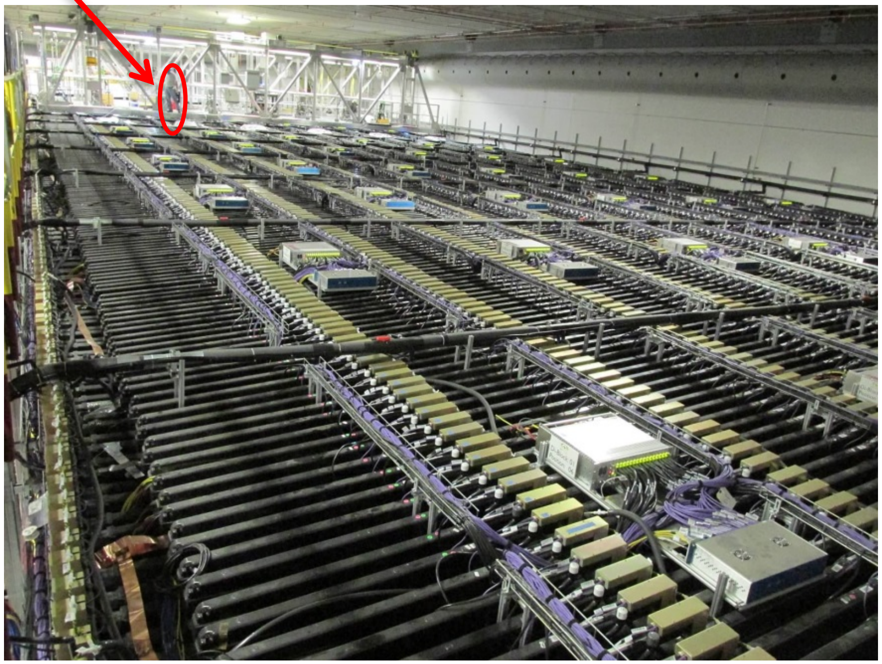
Far detector

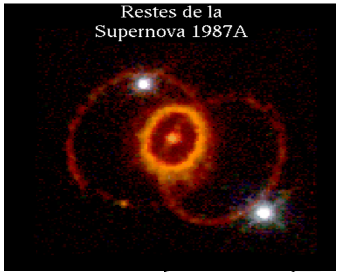
- Supernova neutrinos
- Cosmic ray neutrinos
- Cosmic ray physics

Near detector

person

Far detector

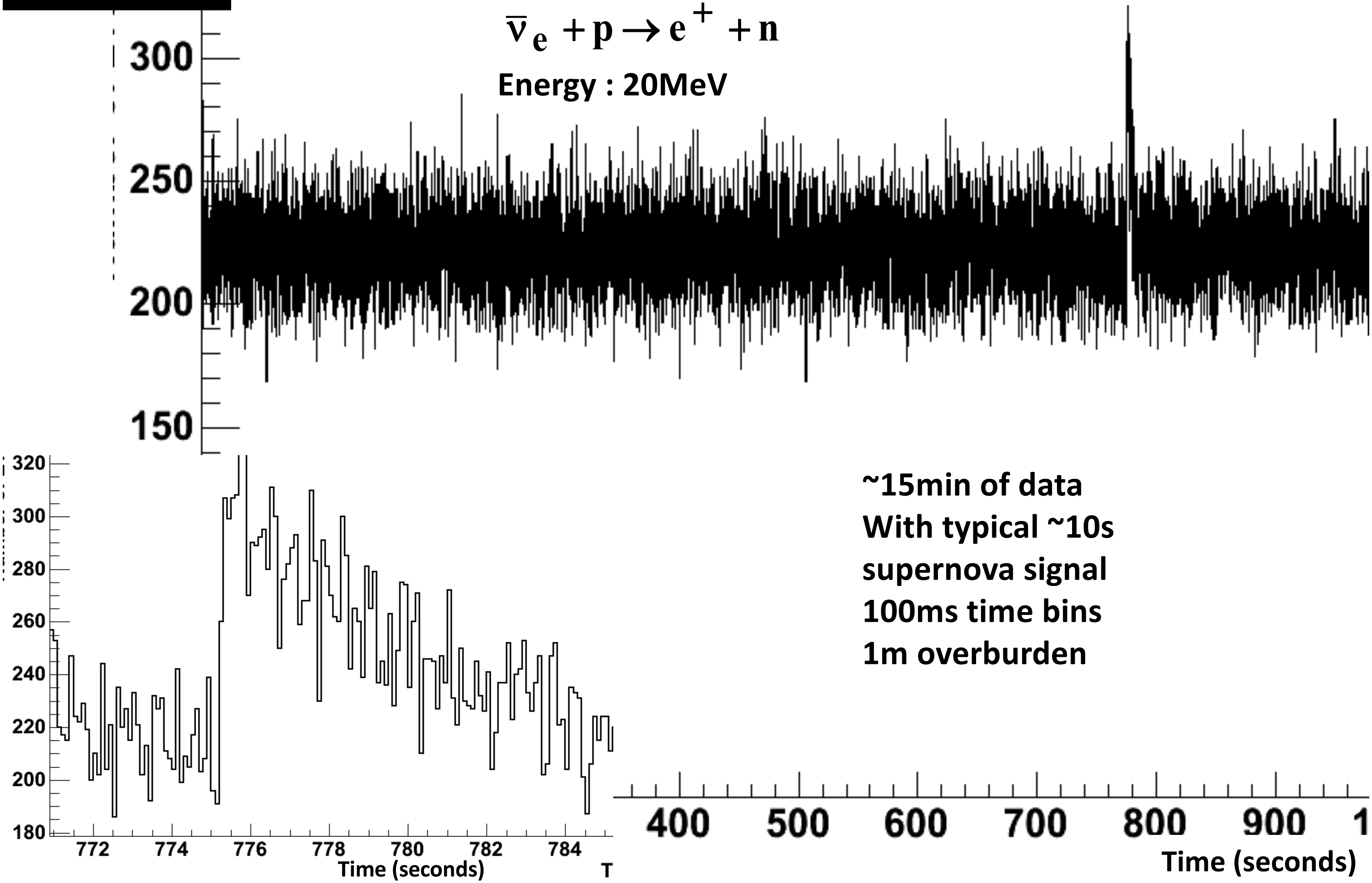




Supernova Neutrinos

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

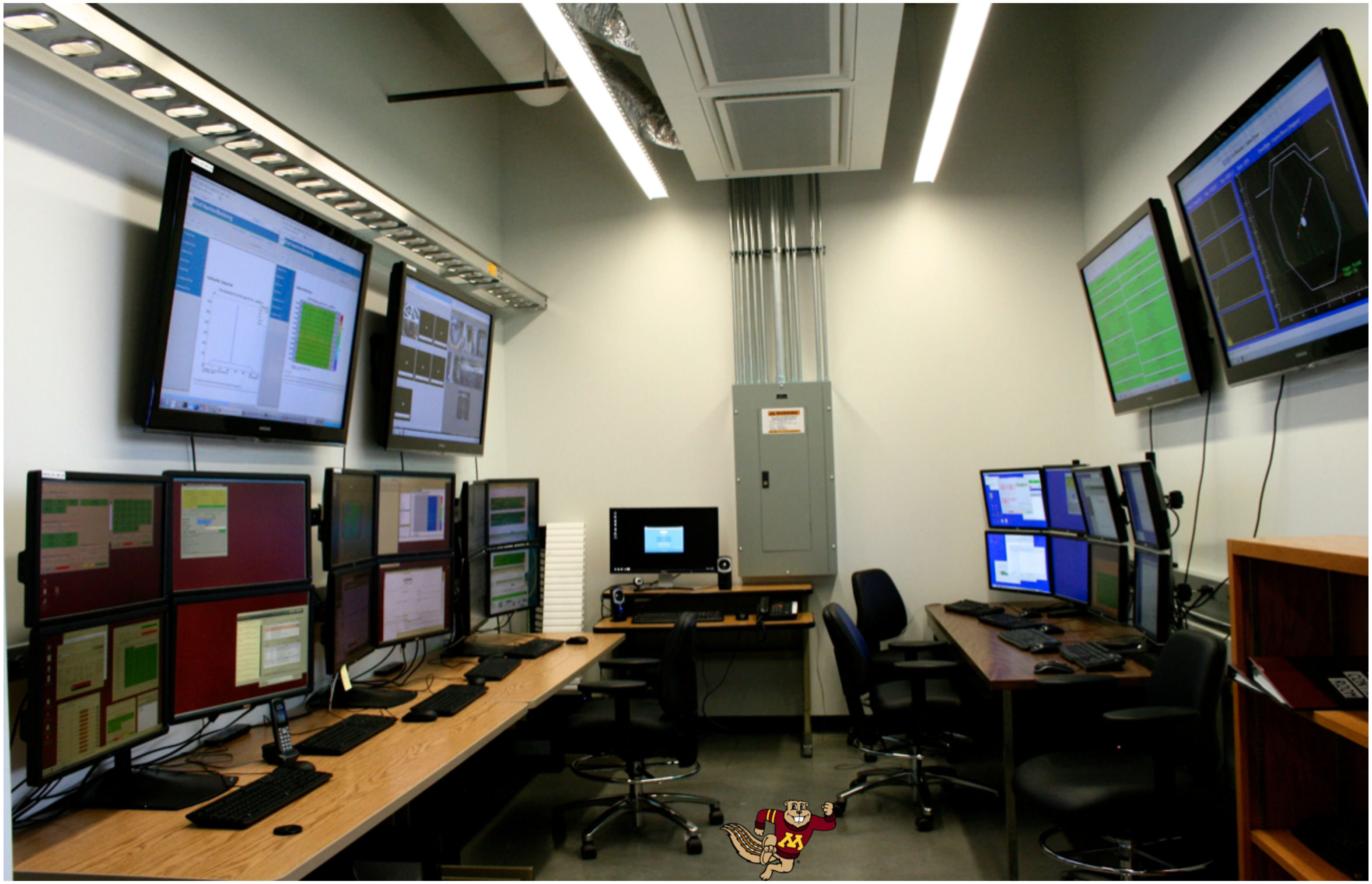
Energy : 20MeV



~15min of data
With typical ~10s supernova signal
100ms time bins
1m overburden

NOνA is operated from all over the world.

Remote Control Room at University of Minnesota



Thanks to All Our 200 Collaborators From 40 Institutions

With Major Support From

University of Minnesota Fermilab

P. Adamson, C. Ader, M. Andrews, N. Anmov, I. Anghel,, K. Arms, E. Arrieta-Diaz, A. Aurisano, D. Ayres, C. Backhouse, M. Baird, B. A. Bambah, K. Bays, R. Bernstein, M. Betancourt,V. Bhatnagar, B. Bhuyan, J. Bian, K. Biery, T. Blackburn, V. Bocean, D. Bogert, A. Bolshakova,M. Bowden, C. Bower, D. Broemmelsiek, C. Bromberg, G. Brunetti, X. Bu, A. Butkevich,D. Capista, E. Catano-Mur, T. R. Chase, S. Childress, B. C. Choudhary, B. Chowdhury, T. E. Coan,J. A. B. Coelho, M. Colo, J. Cooper, L. Corwin, D. Cronin-Hennessy, A. Cunningham, G. S. Davies,J. P. Davies, M. Del Tutto, P. F. Derwent, K. N. Deepthi, D. Demuth, S. Desai, G. Deuerling,A. Devan, J. Dey, R. Dharmapalan, P. Ding, S. Dixon, Z. Djurcic, E. C. Dukes, H. Duyang,R. Ehrlich, G. J. Feldman, N. Felt, E. J. Fenyves,, E. Flumerfelt, S. Foulkes, M. J. Frank,W. Freeman, M. Gabrielyan, H. R. Gallagher, M. Gebhard, T. Ghosh, W. Gilbert, A. Giri, S. Goadhouse, R. A. Gomes, L. Goodenough, M. C. Goodman, V. Grichine, N. Grossman, R. Group,J. Grudzinski, V. Guarino, B. Guo, A. Habig, T. Handler, J. Hartnell, R. Hatcher, A. Hatzikoutelis,K. Heller, C. Howcroft, J. Huang, X. Huang, J. Hylen, M. Ishitsuka, F. Jediny, C. Jensen, D. Jensen,C. Johnson, H. Jostlein, G. K. Kafka, Y. Kamyshkov, S. M. S. Kasahara, S. Kasetti, K. Kephart,G. Koizumi, S. Kotelnikov, I. Kourbanis, Z. Krahn, V. Kravtsov, A. Kreymer, Ch. Kulenberg,A. Kumar, T. Kutnink, R. Kwarciancy, J. Kwong, K. Lang, A. Lee, W. M. Lee, K. Lee, S. Lein,J. Liu, M. Lokajicek, J. Lozier, Q. Lu, P. Lucas, S. Luchuk, P. Lukens, G. Lukhanin, S. Magill,K. Maan, W. A. Mann, M. L. Marshak, M. Martens, J. Martincik, P. Mason, K. Matera, M. Mathis,V. Matveev, N. Mayer, E. McCluskey, R. Mehdiyev, H. Merritt, M. D. Messier, H. Meyer, T. Miao,D. Michael,, S. P. Mikheyev,, W. H. Miller, S. R. Mishra, R. Mohanta, A. Moren, L. Mualem,M. Muether, S. Mufson, J. Musser, H. B. Newman, J. K. Nelson, E. Niner, A. Norman, J. Nowak,Y. Oksuzian, A. Olshevskiy, J. Oliver, T. Olson, J. Paley, P. Pandey, A. Para, R. B. Patterson,G. Pawloski, N. Pearson, D. Perevalov, D. Pershey, E. Peterson, R. Petti, S. Phan-Budd, L. Piccoli, A. Pla-Dalmau, R. K. Plunkett, R. Poling, B. Potukuchi, F. Psihas, D. Pushka,X. Qiu, N. Raddatz, A. Radovic, R. A. Rameika, R. Ray, B. Rebel, R. Rechenmacher, B. Reed,R. Reilly, D. Rocco, D. Rodkin, K. Ruddick, R. Rusack, V. Ryabov, K. Sachdev, S. Sahijpal, H. Sahoo, O. Samoylov, M. C. Sanchez,, N. Saoulidou, P. Schlabach, J. Schneps, R. Schroeter,J. Sepulveda-Quiroz,, P. Shanahan, B. Sherwood, A. Sheshukov, J. Singh, V. Singh, A. Smith,D. Smith, J. Smolik, N. Solomey, A. Sotnikov, A. Sousa, K. Soustruznik, Y. Stenkin, M. Strait,L. Suter, R. L. Talaga, M. C. Tamsett, S. Tariq, P. Tas, R. J. Tesarek, R. B. Thayyullathil, K. Thomsen,X. Tian, S. C. Tognini, R. Toner, J. Trevor, G. Tzanakos,, J. Urheim, P. Vahle, L. Valerio,L. Vinton, T. Vrba, A. V. Waldron, B. Wang, Z. Wang, A. Weber,, A. Wehmann, D. Whittington,N. Wilcer, R. Wildberger, D. Wildman,, K. Williams, S. G. Wojcicki, K. Wood, M. Xiao, T. Xin,N. Yadav, S. Yang, S. Zadorozhnyy, J. Zalesak, B. Zamorano, A. Zhao, J. Zirnstein, and R. Zwaska

University of Minnesota Neutrino Group

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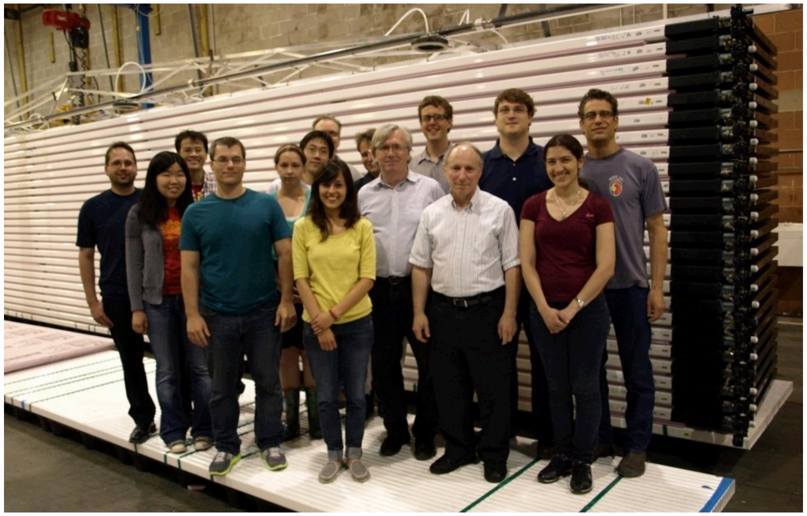
5 professors
5 post docs
6 graduate students



13 technicians
700 undergraduate students