NOvA

Thomas Coan

- Intro
- Detector technology
- Physics reach
- Conclude

SMU, April 2014

Clarification

Neutrinos, NOT Nutria !!

Clarification

Neutrinos, NOT Nutria !!

Fred: Can you check at Peggy Sue's ??

Neutrinos Mix

Solar vs

Homestake, Gallex, SAGE, Super-K, SNO, Borexino

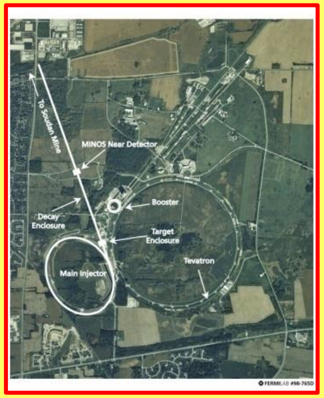
Reactor vs

KamLAND, CHOOZ, …

Atmospheric vs

Kamiokande, Super-K

Accelerator vs



K2K, MINOS, MiniBOONE

Neutrinos change flavor

$\Rightarrow$ Neutrinos have mass and mix

flavor eigenstates

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

mass eigenstates

PMNS Leptonic Mixing Matrix

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$$

$U_{\alpha i}$ can be written w/ 3 mixing angles and 1 phase

and w/ $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

atmospheric — cross-mixing — solar

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

- Mixing angle θ_{13} large ($\sin^2 2\theta_{13} = 0.090 \pm 0.009$).
- CP violating phase δ unknown.

Vacuum Oscillations

Neutrinos propagate as mass eigenstates
Interact as different (i.e., weak) eigenstates

➢ Oscillations result

In absence of matter (key caveat) & to lowest order:

$$P_{vac}(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{atm}$$

$$\Delta_{atm} \simeq 1.27\left(\frac{\Delta m^2_{32}(\mathrm{eV}^2)L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

Additional sub-dominant terms, sensitive to CPV phase δ:

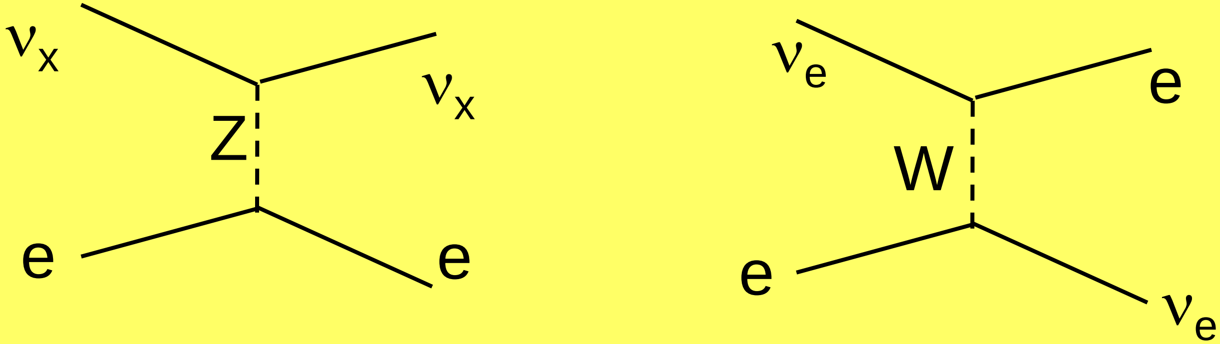
$$\Delta P_\delta(\nu_\mu \rightarrow \nu_e) = J\sin\Delta_{sol}\sin\Delta_{atm}(\cos\delta\cos\Delta_{atm} \mp \sin\delta\sin\Delta_{atm})$$

$$J = \sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}$$

ν (upper sign), $\bar{\nu}$ (lower sign)

… but NOνA's neutrinos travel though Earth ...

"Matter Effects"



ν_e – e scattering Hamiltonian modified

Effective mass eigenstates & mixing angles altered

$$P_{mat}(\nu_\mu \to \nu_e) \simeq (1 \pm 2\frac{E}{E_R})P_{vac}(\nu_\mu \to \nu_e)$$

$E_R \cong 12$ GeV (earth's mantle)

$E(\nu) \cong 2$ GeV $\Rightarrow$ 30% enhancement/suppression

NOνA's long baseline key

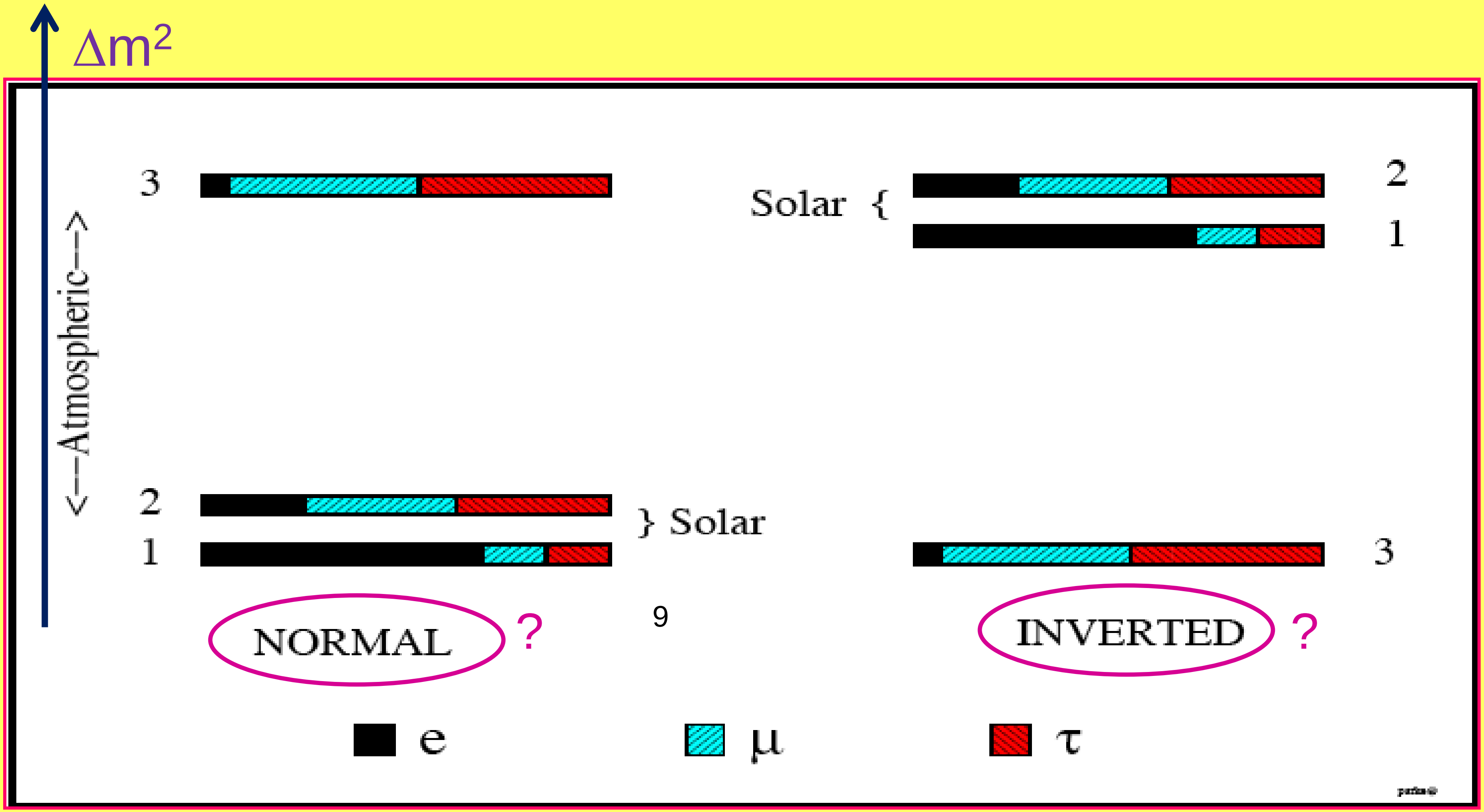
Key NOνA Physics Goals

L/E ~ 400 km/GeV regime:

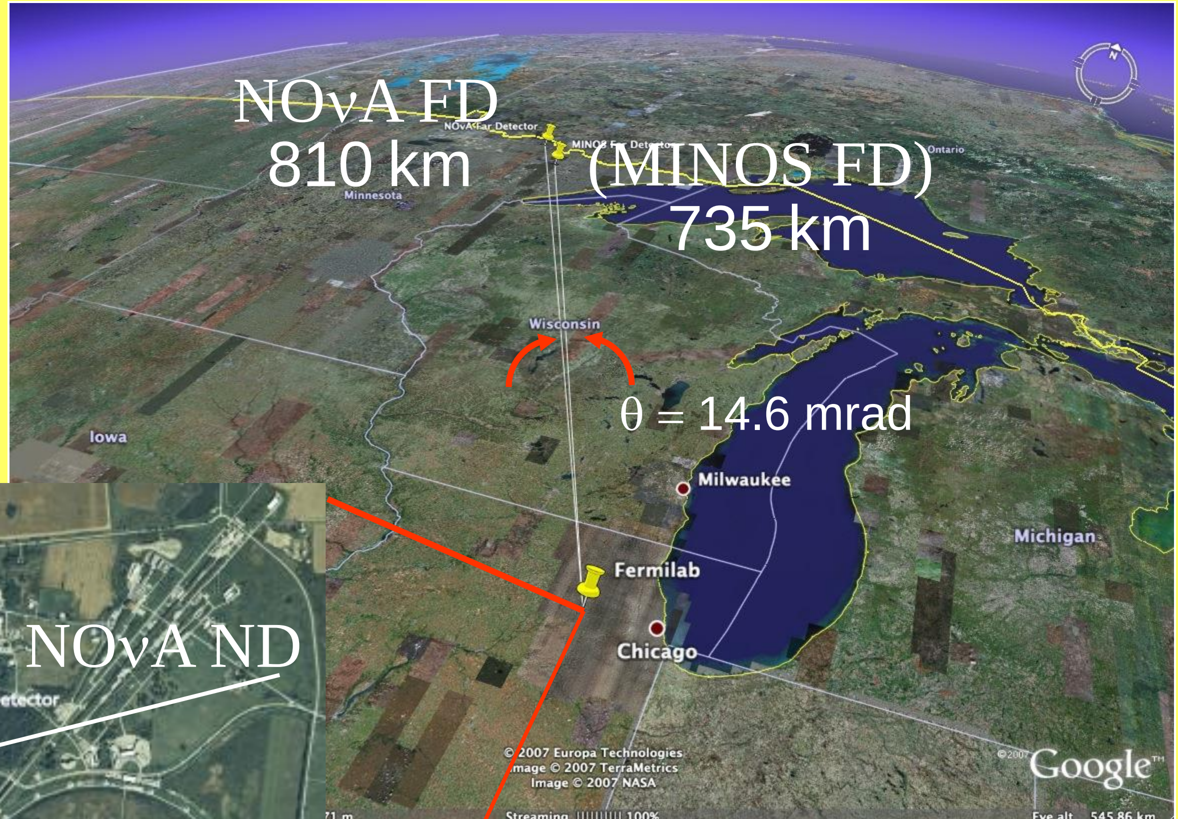
- Measure $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions
- Measure $\nu_\mu \to \nu_\mu$ & $\bar{\nu}_\mu \to \bar{\nu}_\mu$ survival probability

- Search for CP violation in neutrino sector
  i.e., measure/constrain δ_CP
- Resolve neutrino mass hierarchy.
- Measure $\sin^2(2\theta_{23})$ with high precision.
- Determine octant of θ_{23}
- Measure PMNS mixing angle θ_{13}
- Other (monoples, supernovae, NSI…)

Neutrino Ignorance…



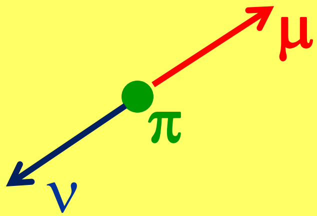
2-Detector Configuration



- Near detector measures un-osc ν flux & bkg rates.
- Far detector measures osc ν flux.

Off-Axis Beam Technique

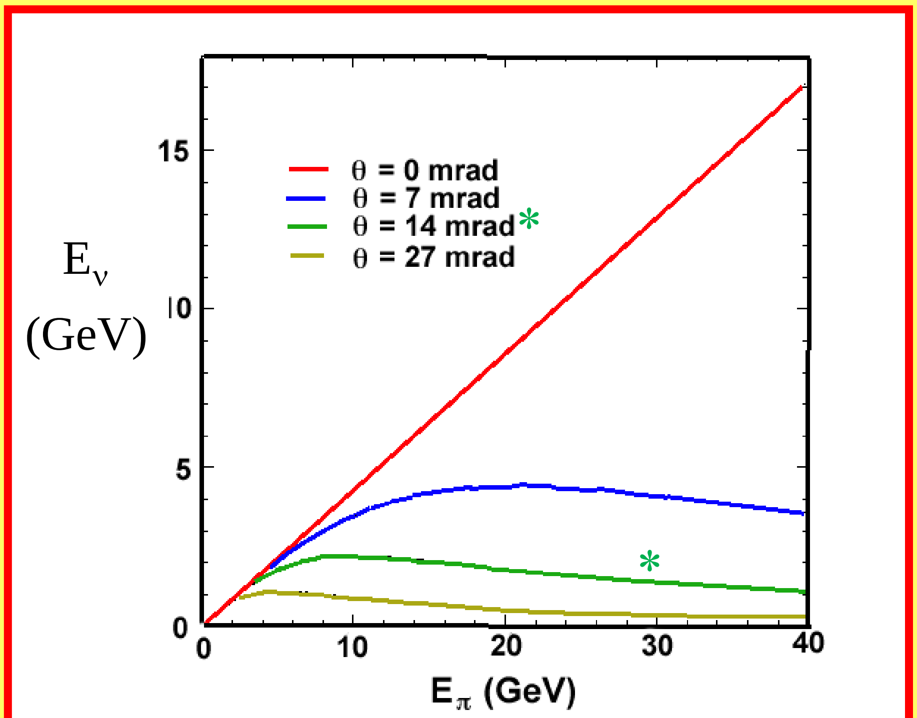
CoM:

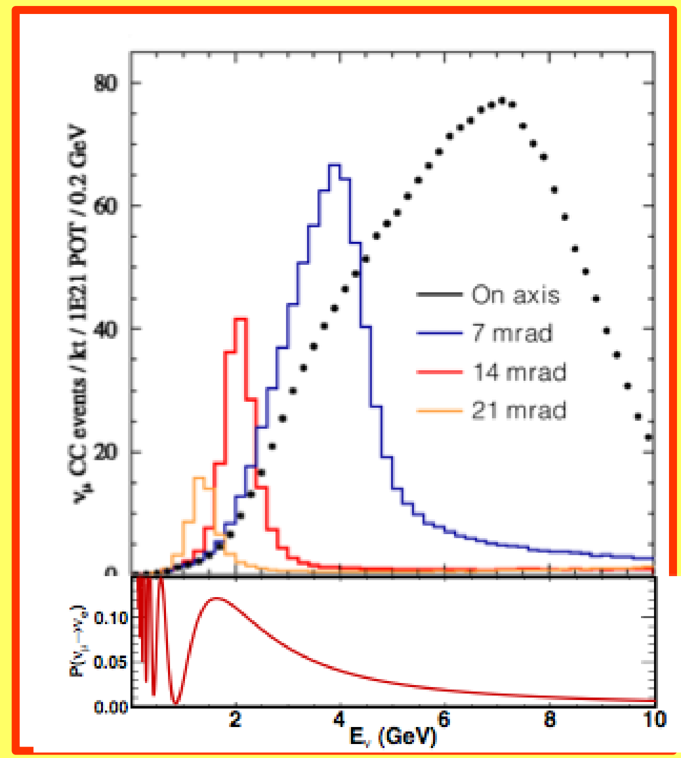


Lab Frame:

$$E_\nu \propto \frac{E_\pi}{1 + (E_\pi/m_\pi)^2\theta^2}$$

∴ E(ν) ~independent of parent hadron E



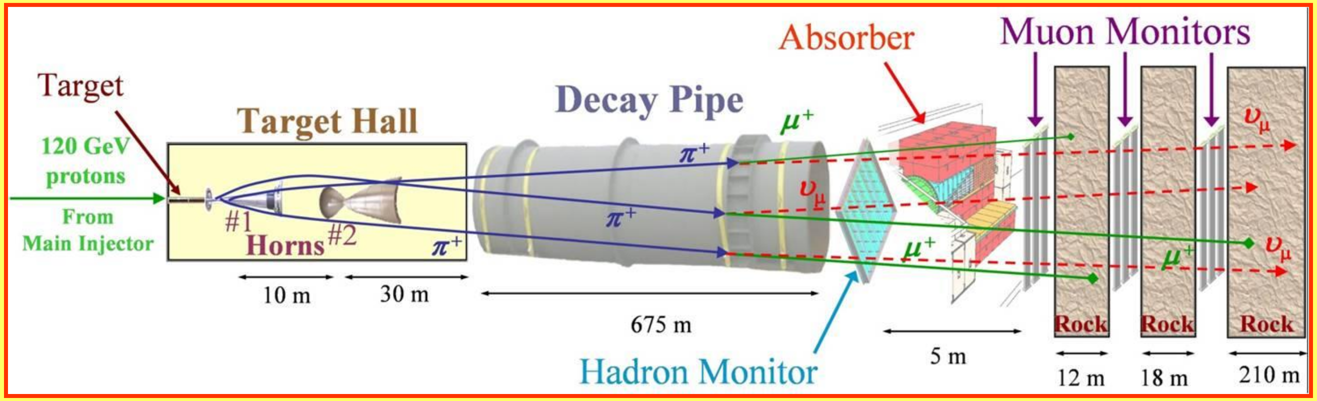


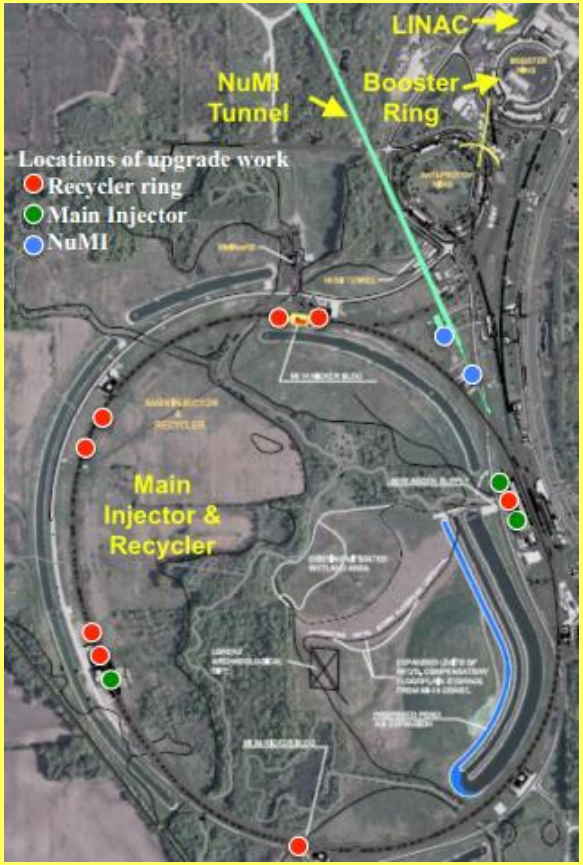
NuMI Beam Upgrade

Booster → Recycler → MI → target

p: 8 GeV → 120 GeV

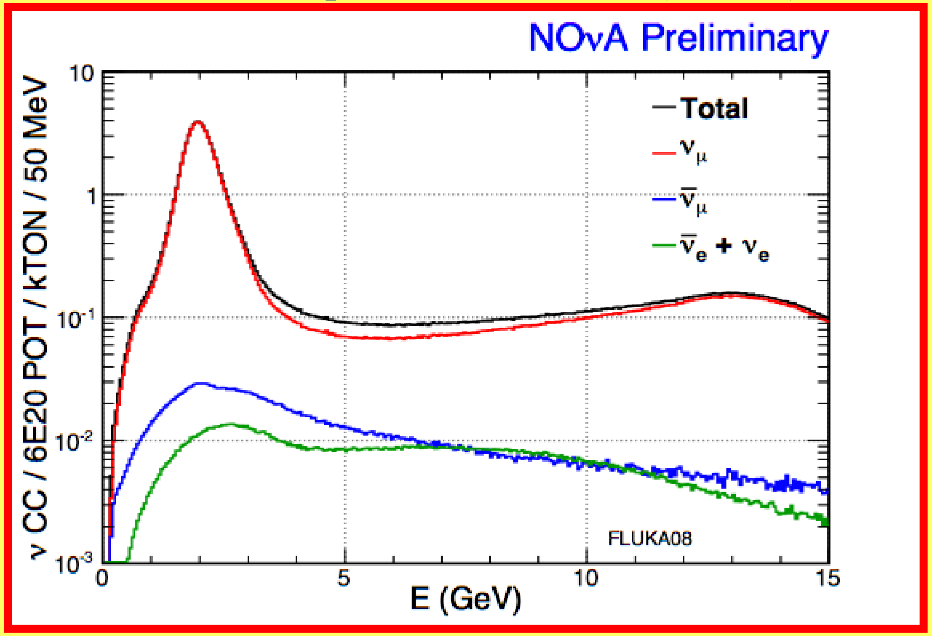
- Recycler: $\overline{p}$ → p storage ring
  - slip-stack batches in Recycler
  - single turn extraction into MI
  - 53 MHz RF added
- 10 μsec spill every 1.3 sec
- 4.9 × 10^{13} p/pulse @120 GeV/p
- 700 kW beam power
- 6 × 10^{20} POT/yr



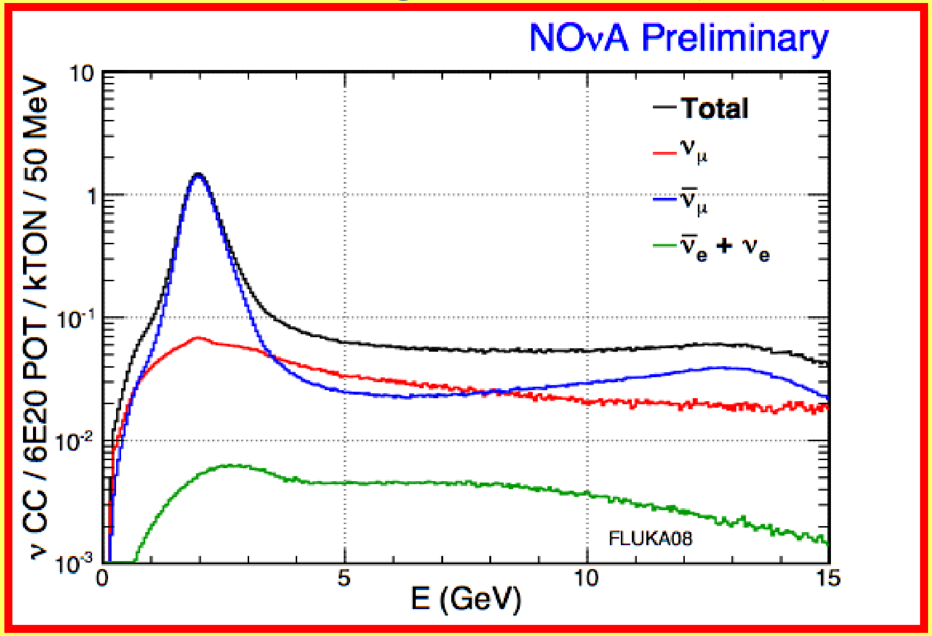


NuMI Beam Composition

Horn focuses positive hadrons (ν runs)

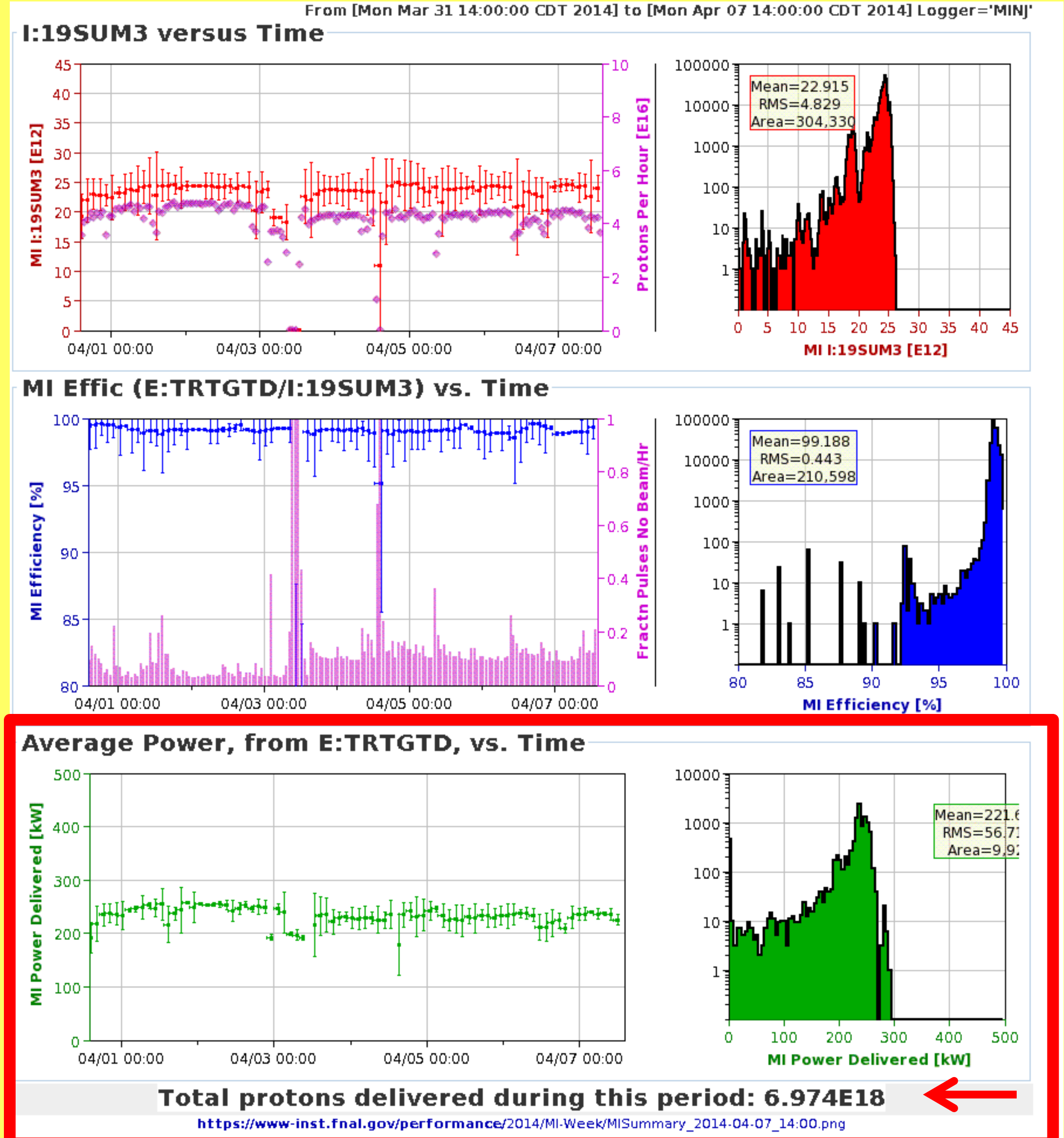


Horn focuses negative hadrons ($\bar{\nu}$ runs)



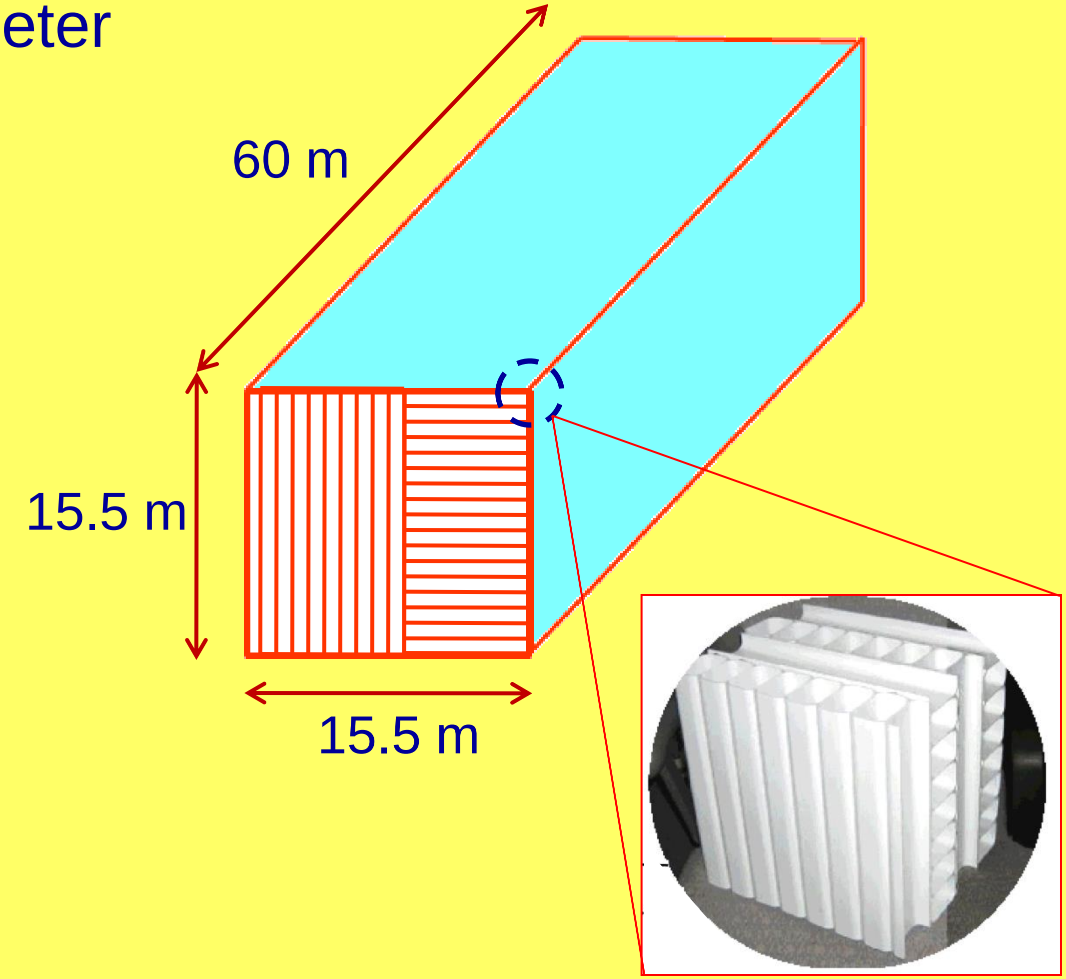
NuMI Beam Performance

- **Beam Power < 500 kW pending booster upgrade**

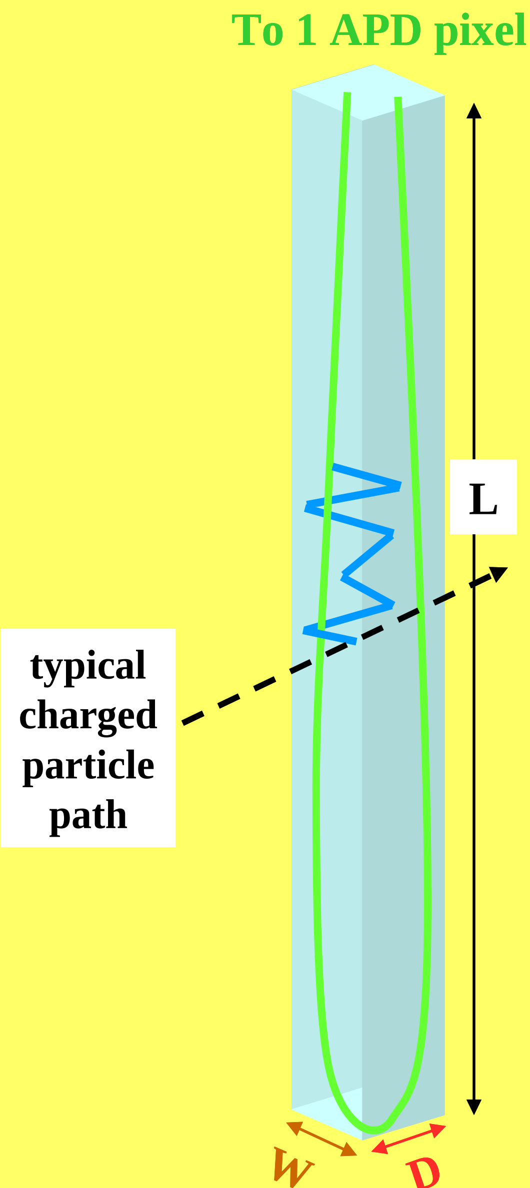


NOνA Far Detector Overview

- Low-Z tracking calorimeter
  65% active
- Surface location
- 14 kT total mass
- 896 Detector planes
  Alternate x-y layers
  0.15 X_0/layer
  R_M = 9.8 cm (2.5 cells)
- Liquid scintillator cells
  32 PEs from far end
- 1-sided readout/plane
  via avalanche photodiodes (APDs)



NOνA Detector "Atom"



Liquid Scintillator

- Mineral oil solvent: 94.6 % (BW)
- Primary scintillator: 5.2% (BW) pseudocumene
- Waveshifters: PPO + bis-MSB

Hollow PVC cells provide granularity

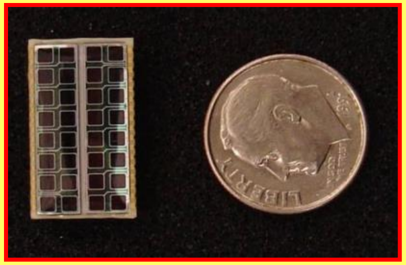
- 15% (BW) TiO_2: high reflectivity walls
- Each cell: 3.6 cm x 5.7 cm x 15.5 m long

Looped Wavelength Shifting Fiber

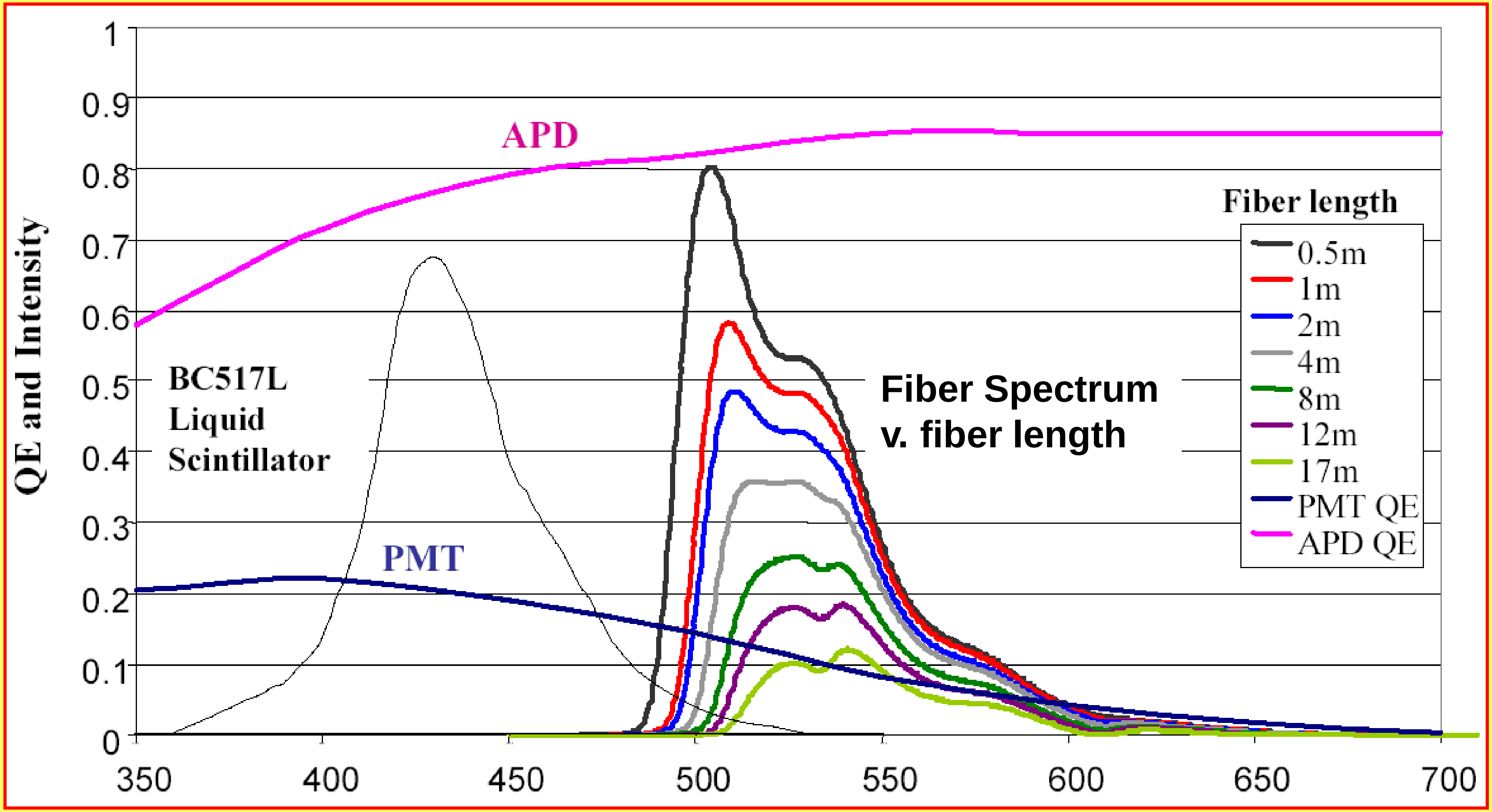
- Maximizes light collection: no mirrors
- Diameter = 0.7mm, K-27 dye @ 300ppm

Avalanche Photodiode

- QE = 85%
- Gain = 100
- T_run = -15 C



Why APDs

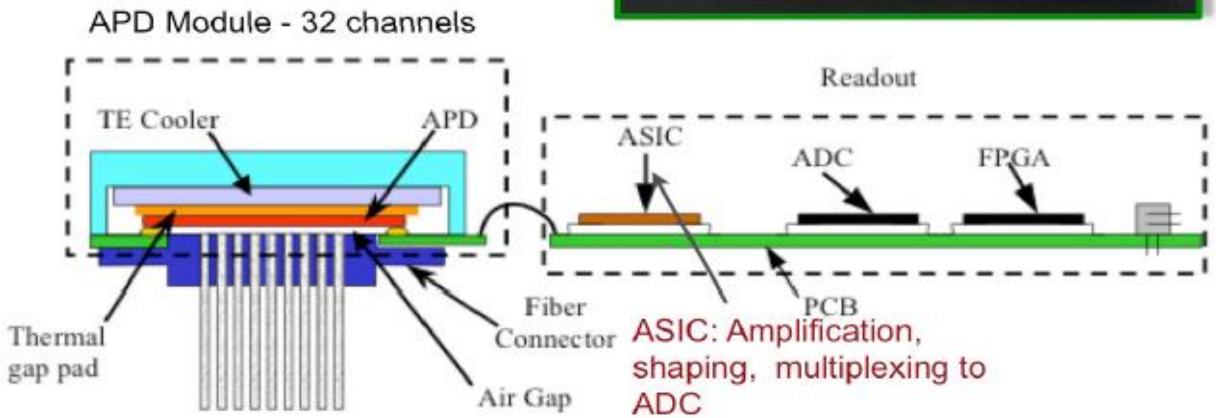


QE and Intensity
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
APD
PMT
BC517L
Liquid
Scintillator
Fiber Spectrum
v. fiber length
Fiber length
0.5m
1m
2m
4m
8m
12m
17m
PMT QE
APD QE
350
400
450
500
550
600
650
700

λ (nm)

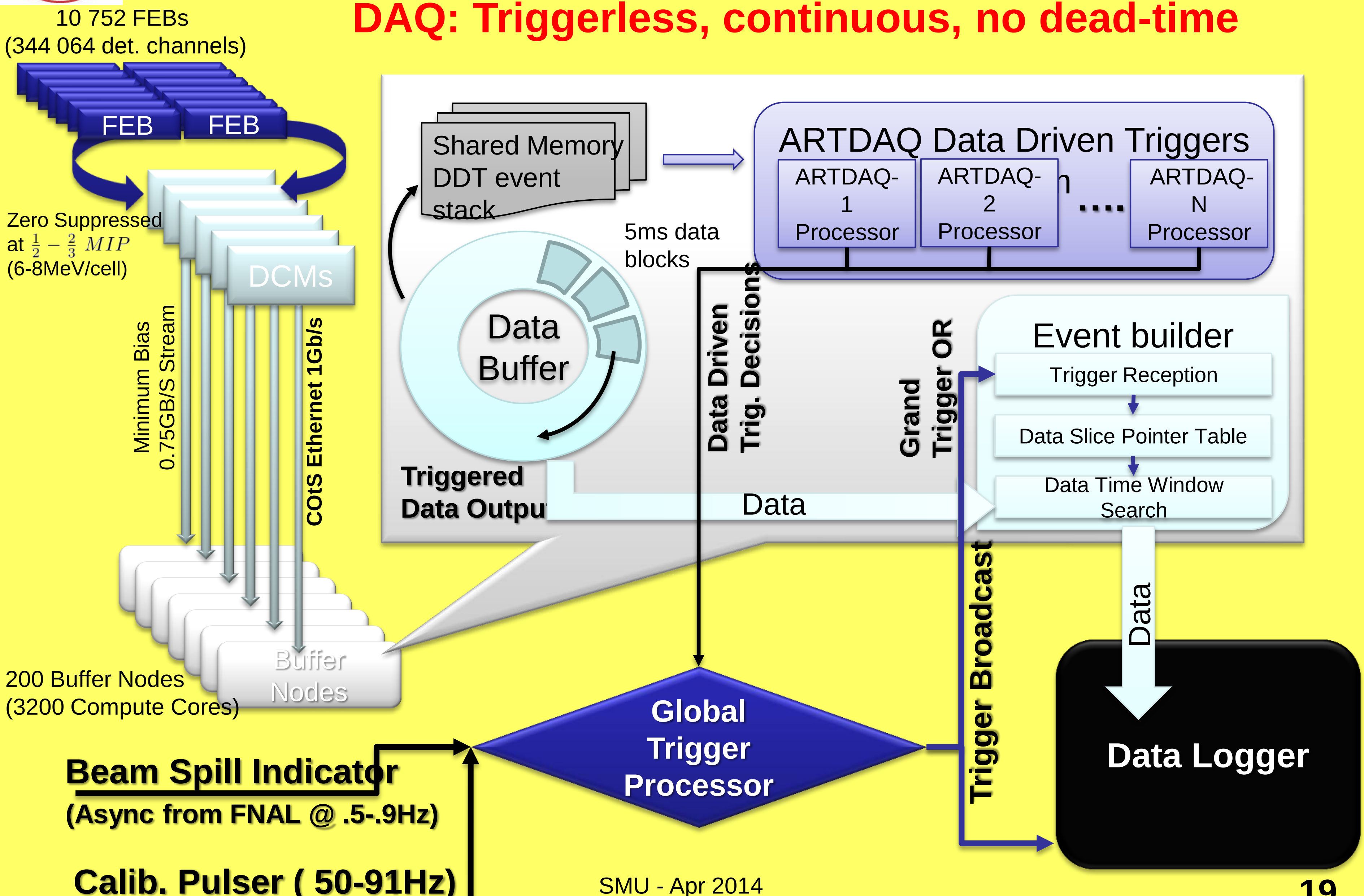
Front-end Electronics

APD

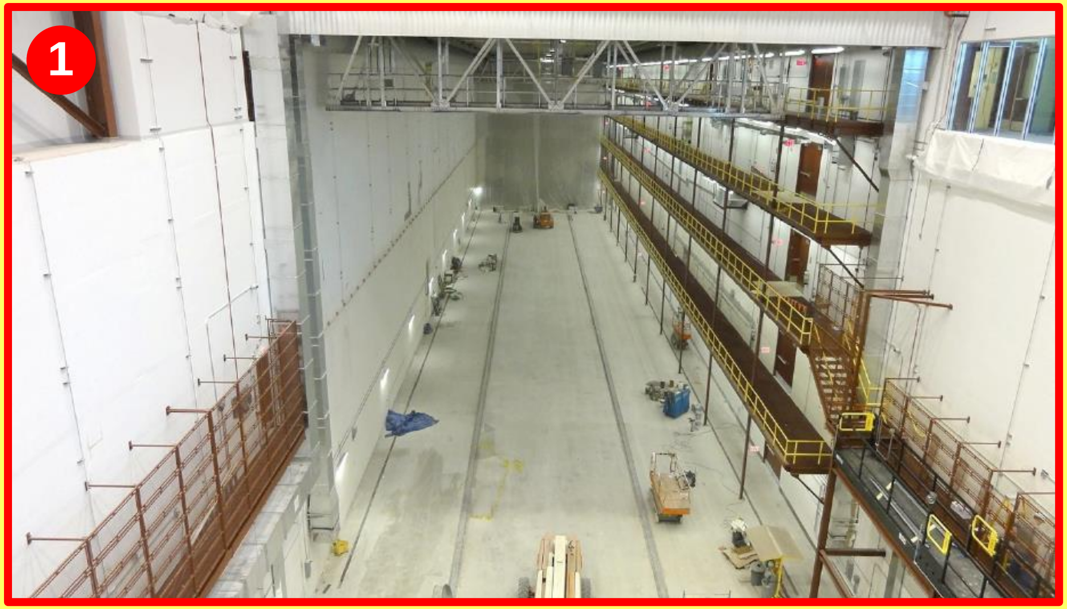


DAQ Architceture

DAQ: Triggerless, continuous, no dead-time

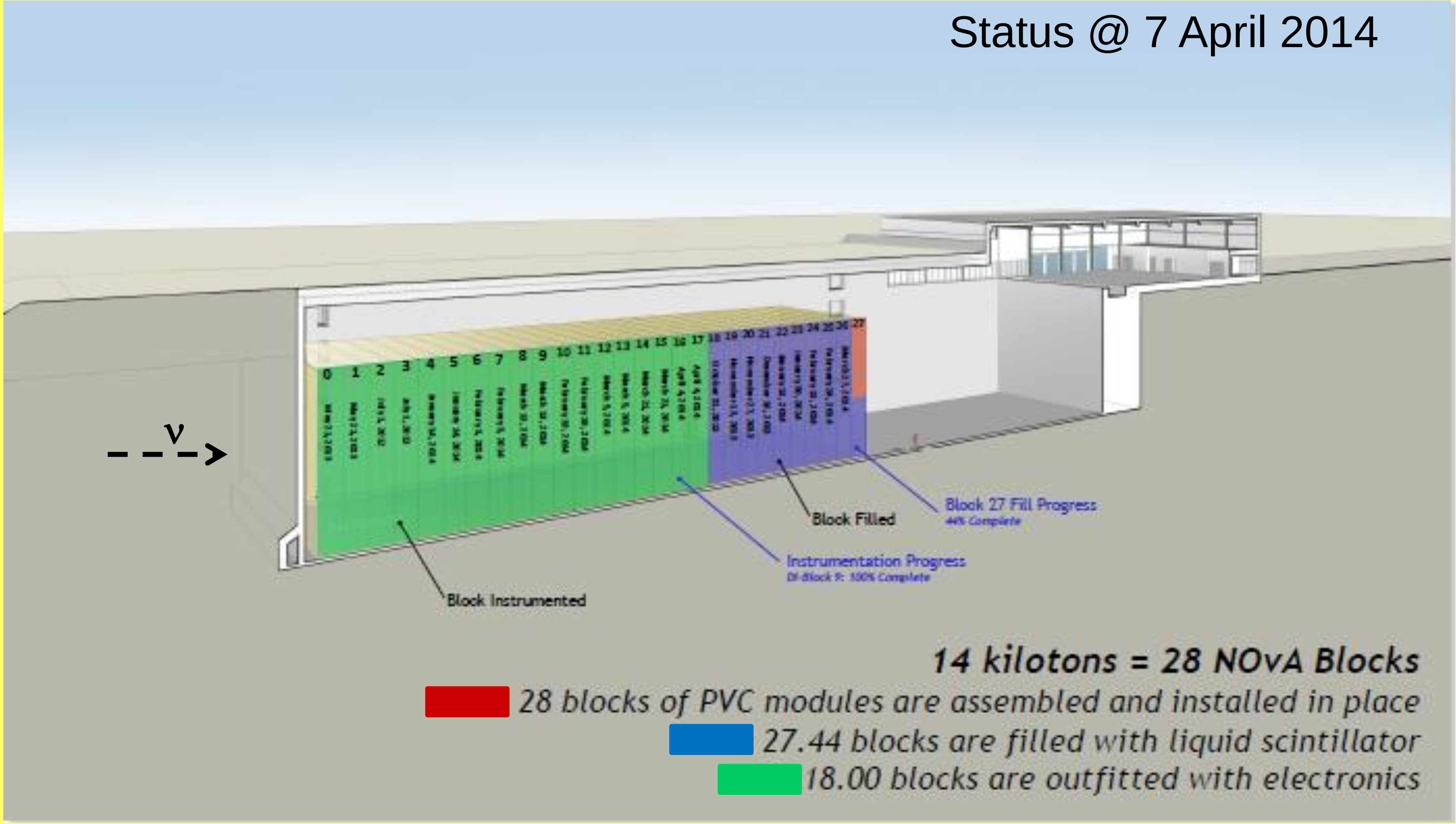


Far Detector Construction



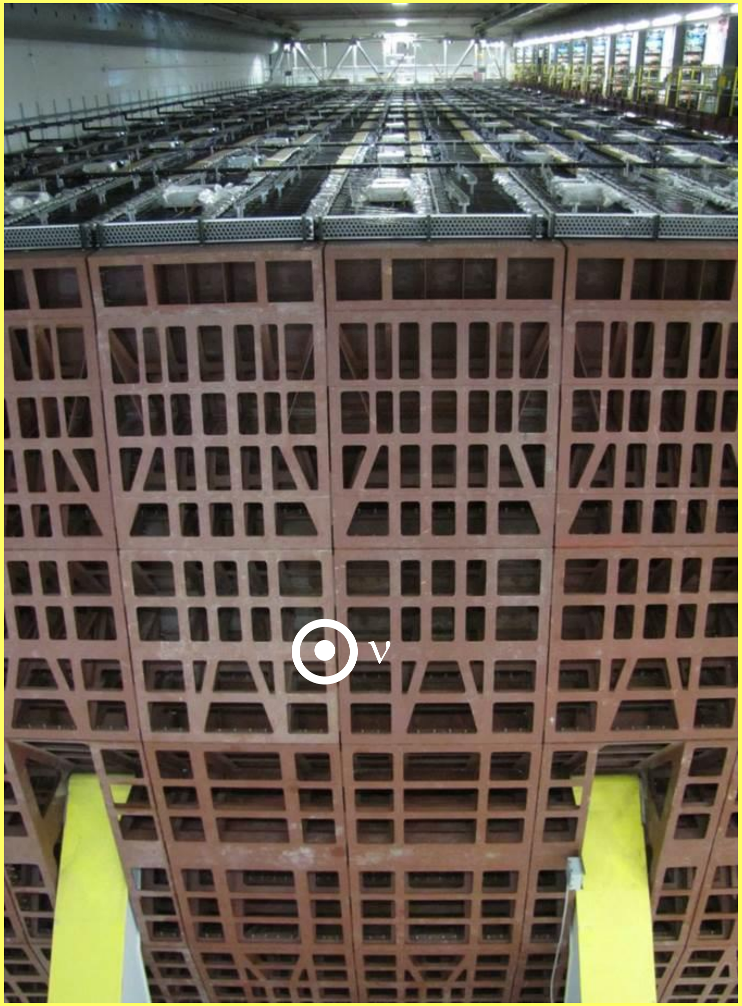
Far Detector Status

Completion date - July 2014



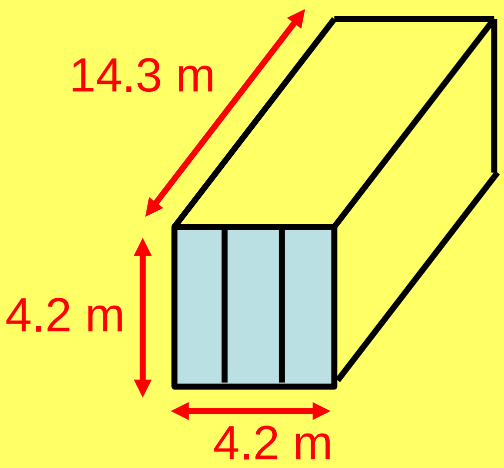
Far Detector Status (2)

Last block installed 25 Feb 2014

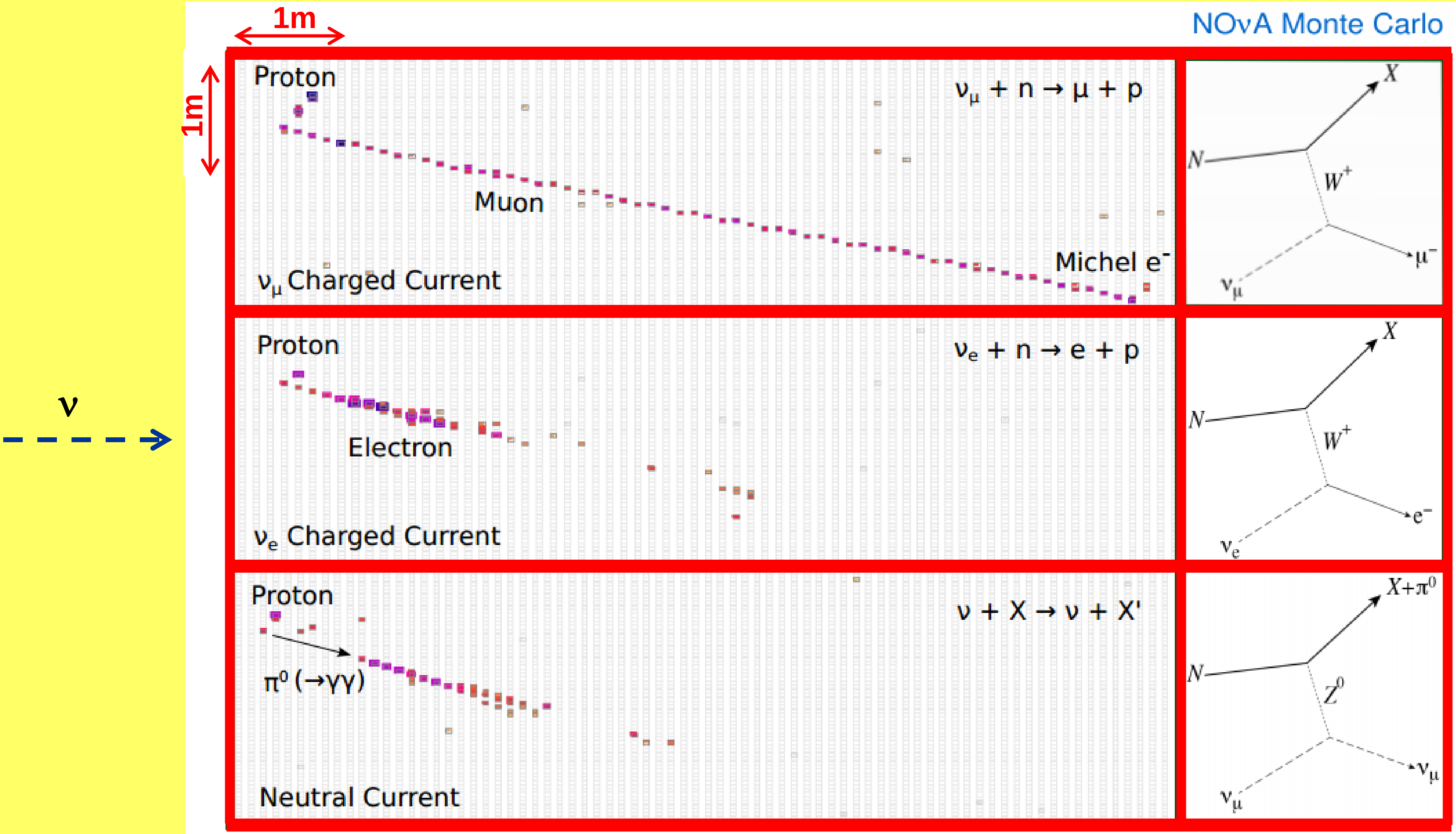


Near Detector Construction

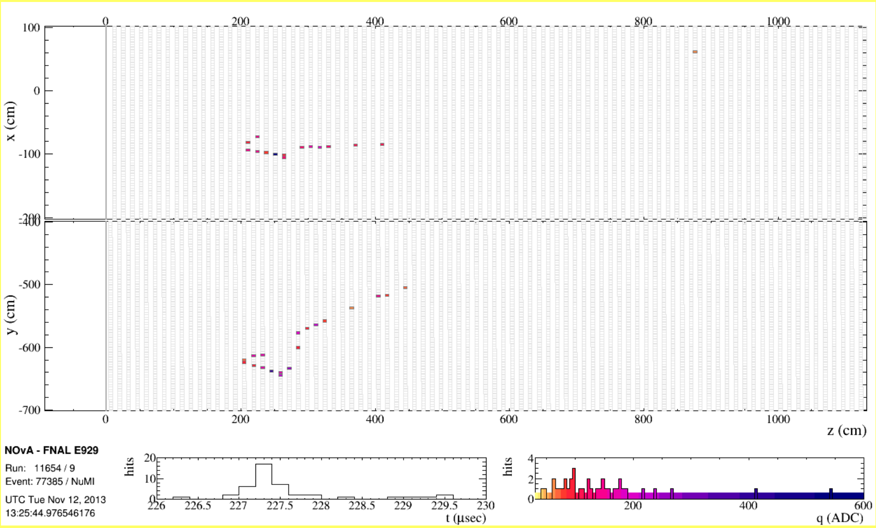
- 0.3 kT mass
- 20k channels
- 1 km from target & 100 m underground
- Cell structure similar to far detector
- Front end & DAQ identical to far detector
- Completion ~May 2014

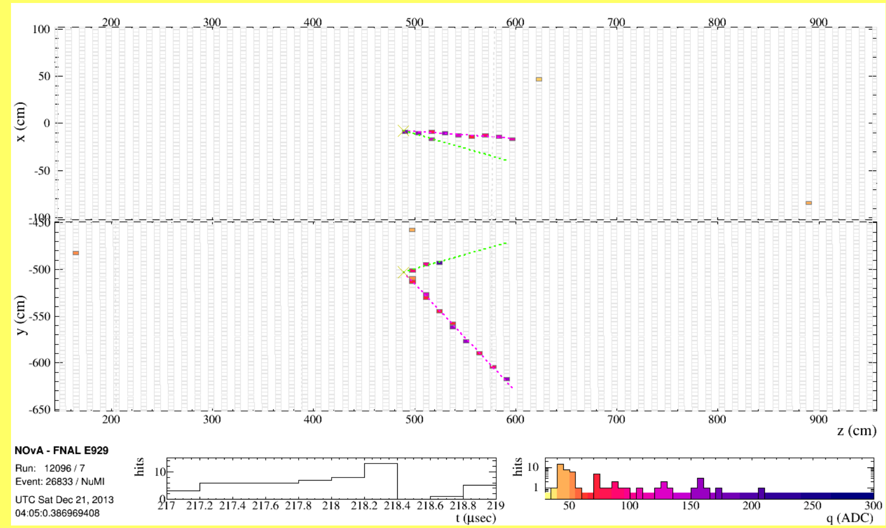


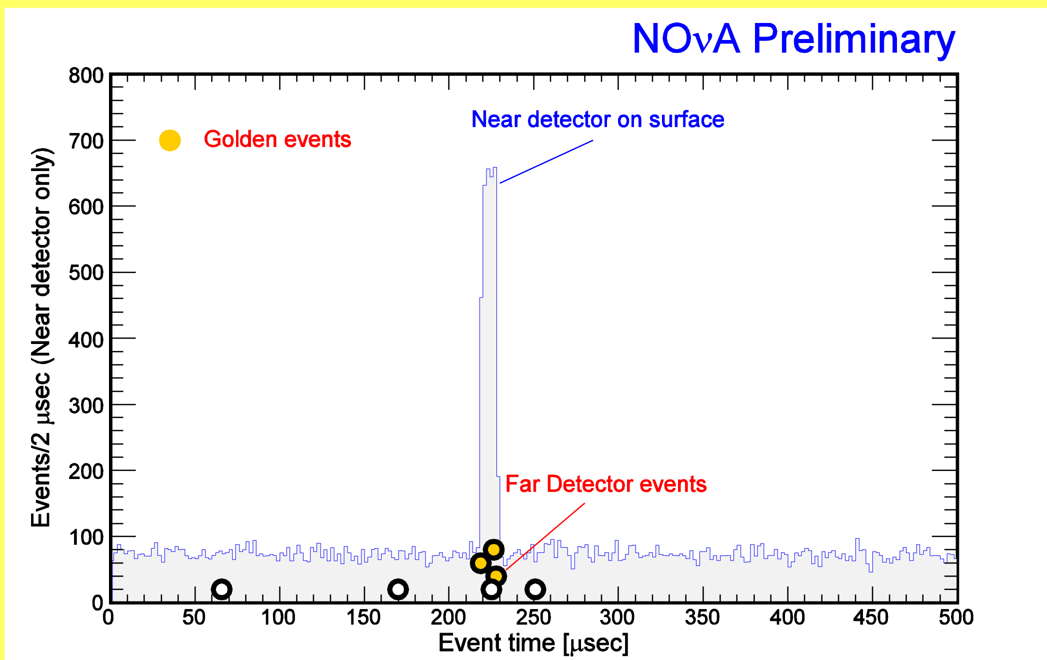
Final State Topologies



Neutrinos !!

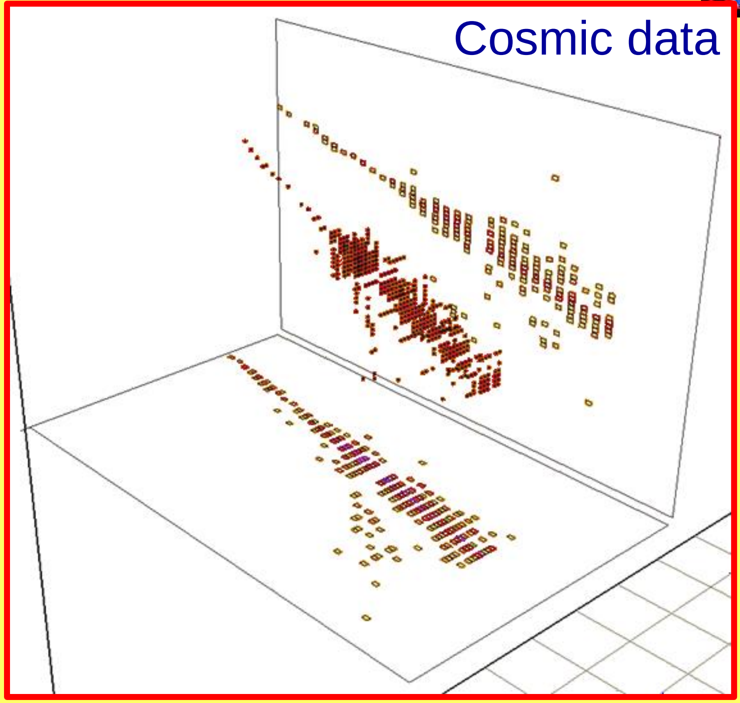

NOvA - FNAL E929
Run: 11654 / 9
Event: 77385 / NuMI
UTC Tue Nov 12, 2013
13:25:44.976546176
x (cm)
y (cm)
z (cm)
hits
t (μsec)
q (ADC)

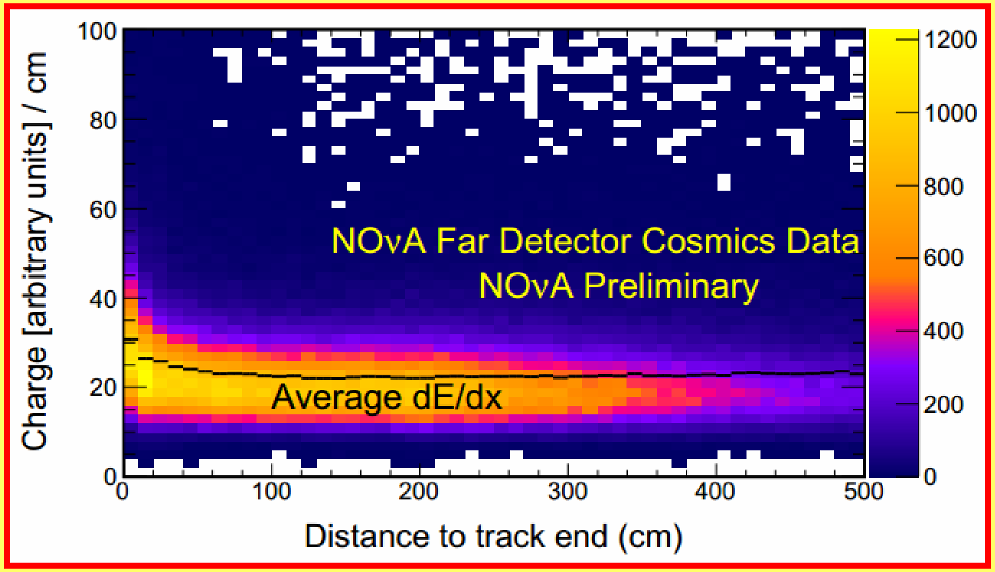

NOvA - FNAL E929
Run: 12096 / 7
Event: 26833 / NuMI
UTC Sat Dec 21, 2013
04:05:0.386969408
x (cm)
y (cm)
z (cm)
hits
t (μsec)
q (ADC)


NOνA Preliminary
Golden events
Near detector on surface
Far Detector events
Events/2 μsec (Near detector only)
Event time [μsec]

Performance w/ Cosmics

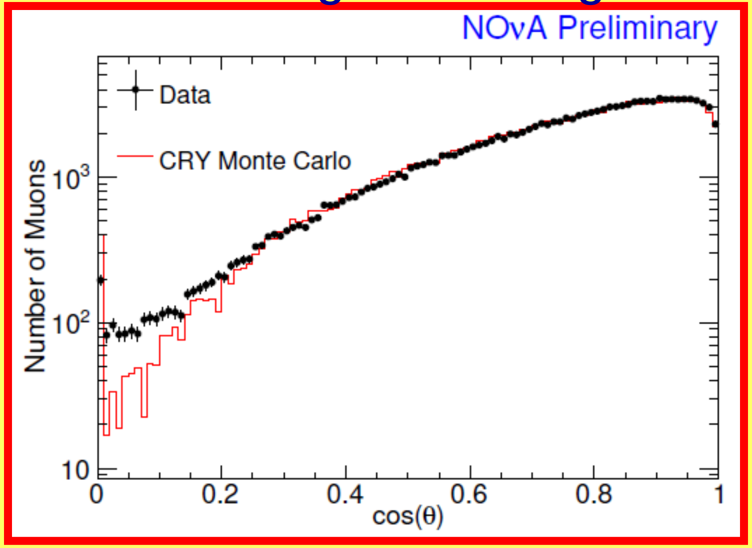
- 9.0 kT/14 kT instrumented.
- Lots of cosmics observed.
- Reconstruction & calibration algorithms tested on cosmics



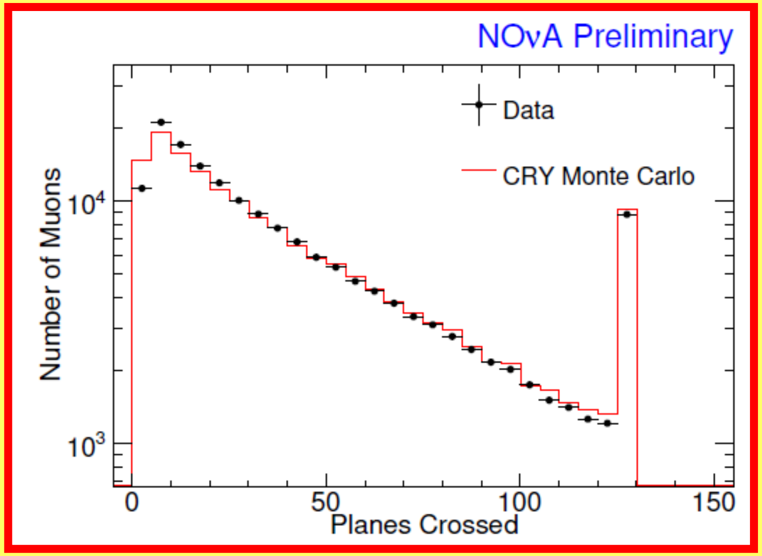


Performance w/ Cosmics (2)

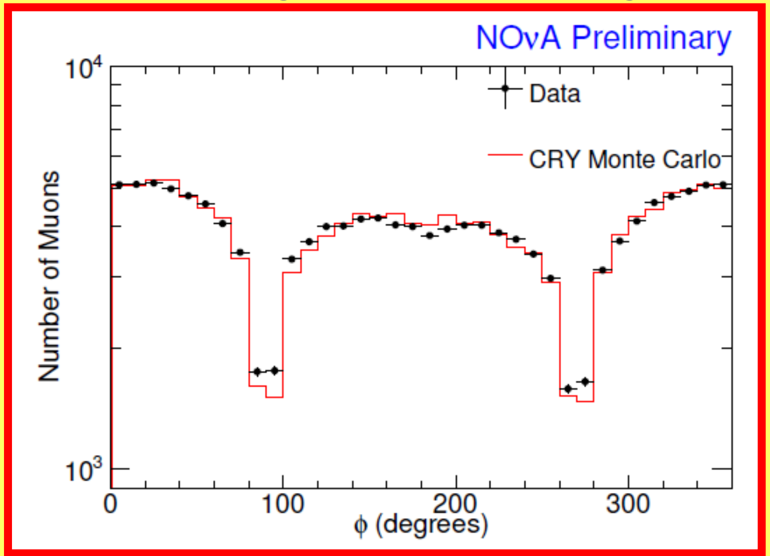
Incoming zenith angle



Planes crossed

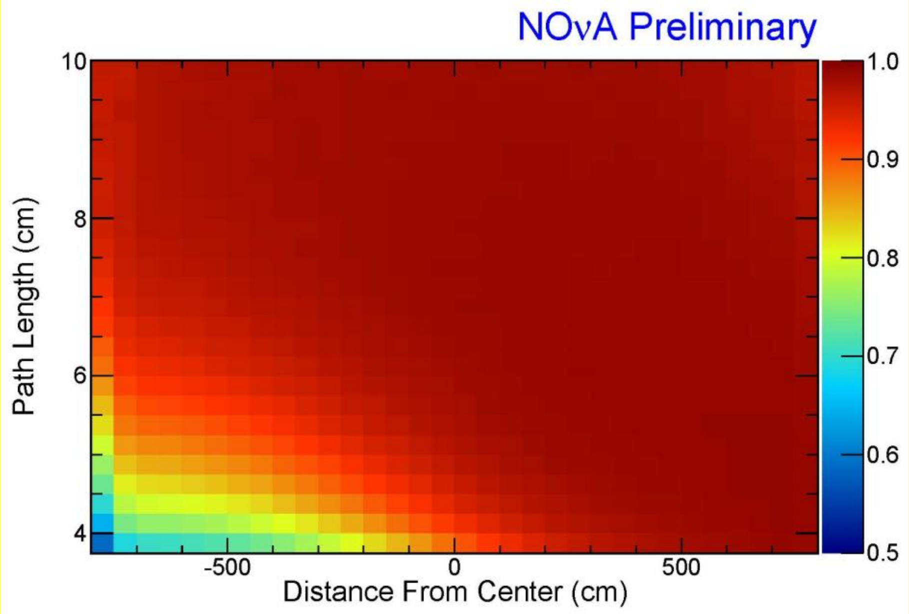


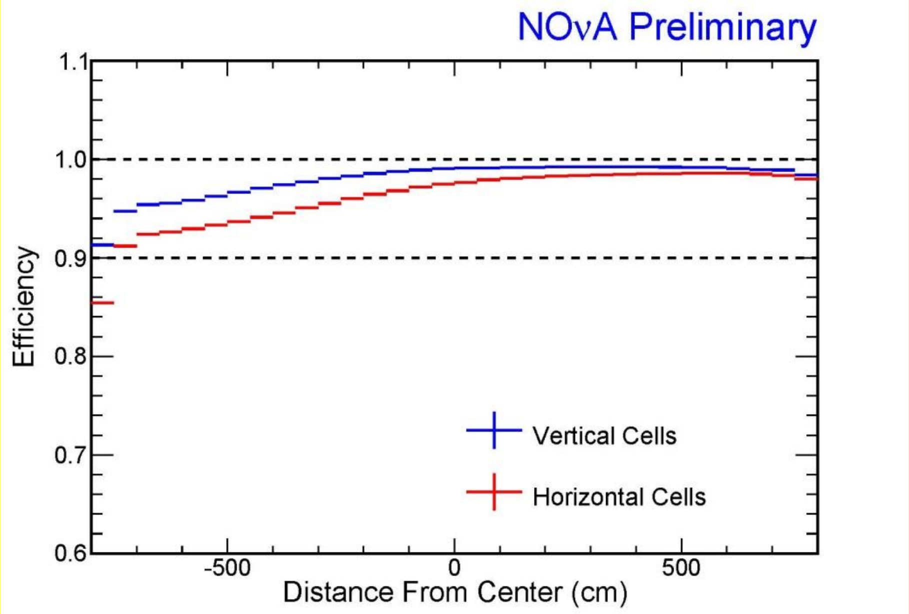
Incoming azimuthal angle



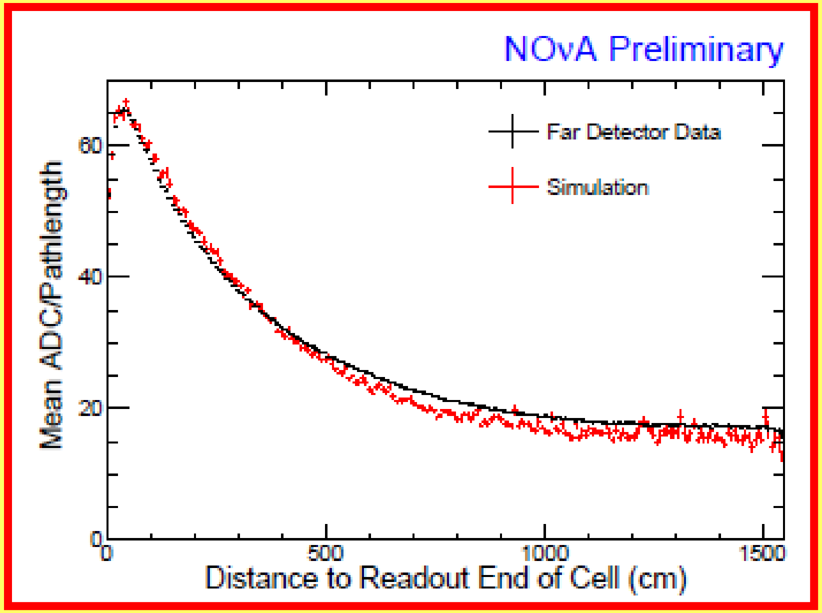
- 1/7 detector only.
- 14k data triggers.
- Tracks must pass > 7 planes.
- MC/data agreement good.

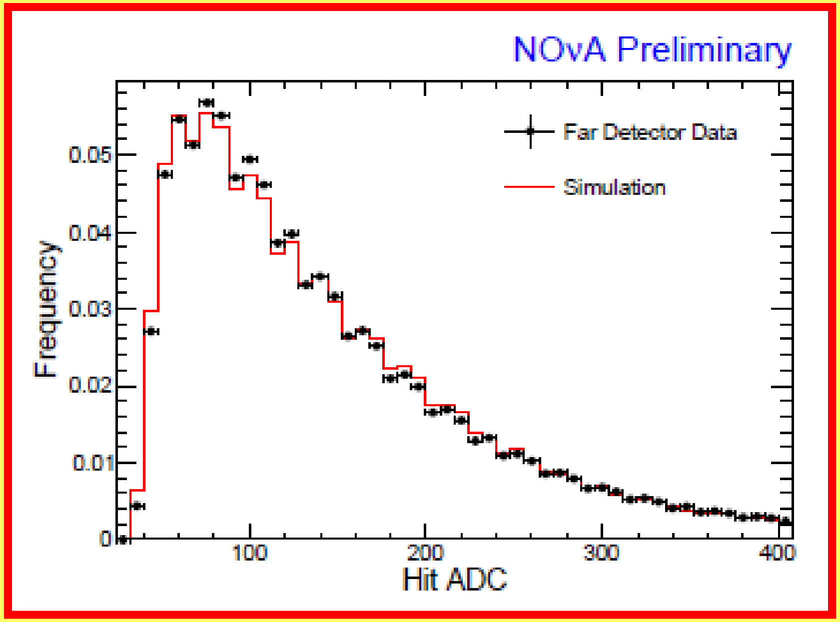
Hit Efficiency w/ Cosmics





Far Detector: MC v Data





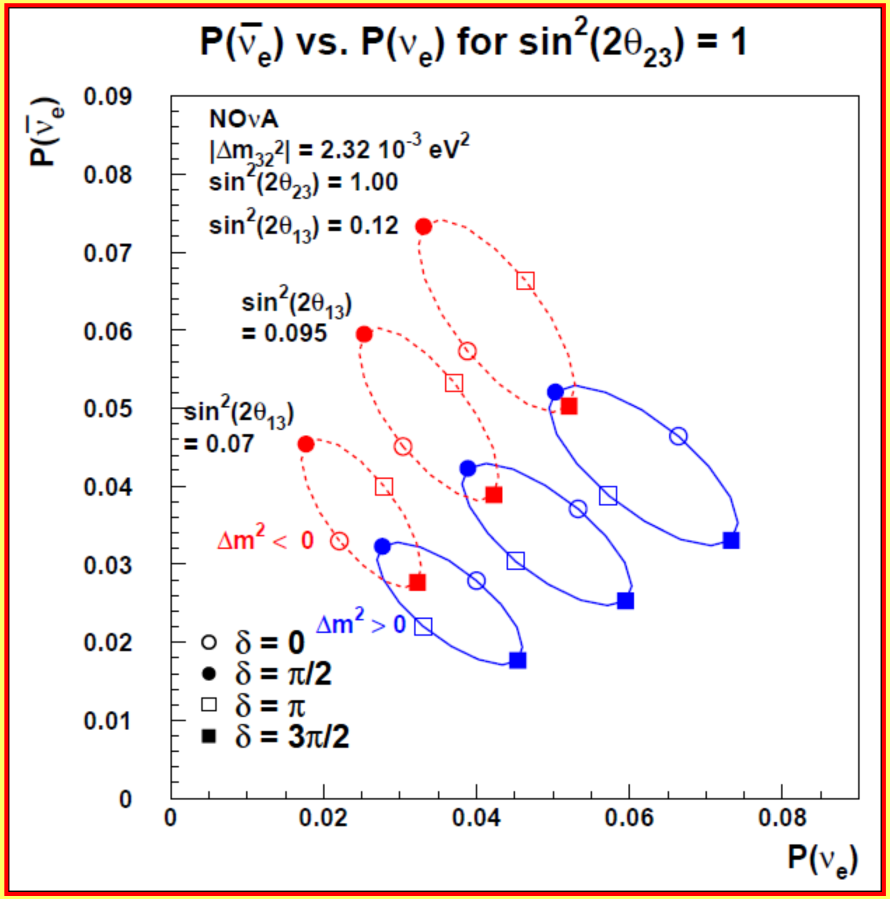
- Decent MC/data agreement.
- Expected to improve.

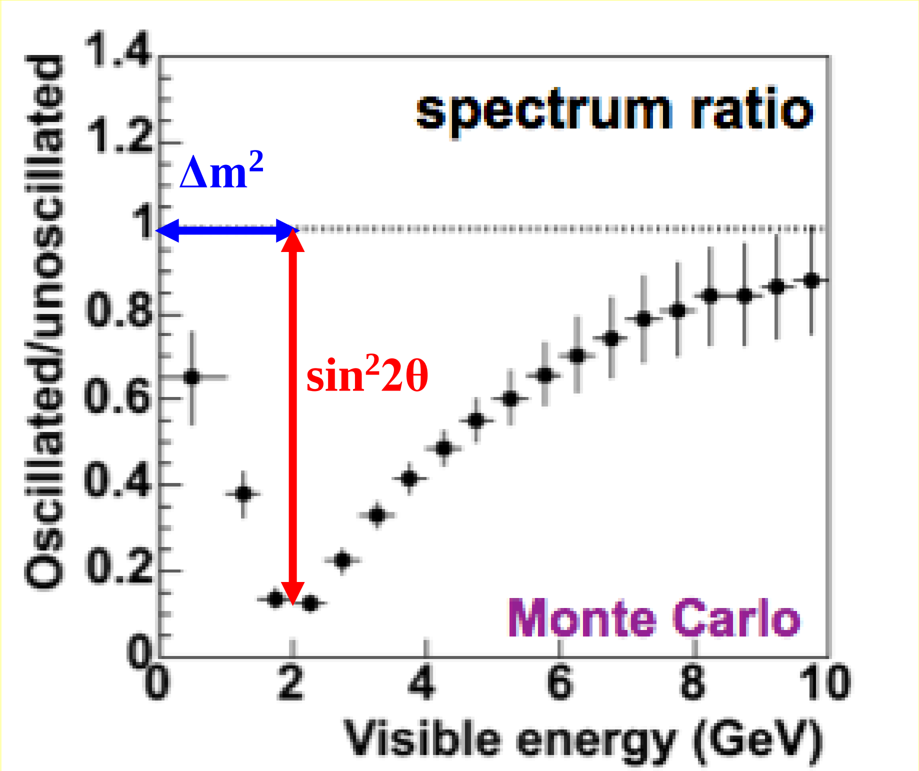
Physics Measurement Scheme

NOνA measures probability of 4 reactions:

$\nu_\mu \rightarrow \nu_e$ $\quad$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\quad$ "appearance" measurements

$\nu_\mu \rightarrow \nu_\mu$ $\quad$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ $\quad$ "disappearance" measurements





Anticipated Event Yields

- 6×10^{20} POT/yr ν's & 6×10^{20} POT/yr anti-ν's
- 3 yrs ν's + 3 yrs anti-ν's

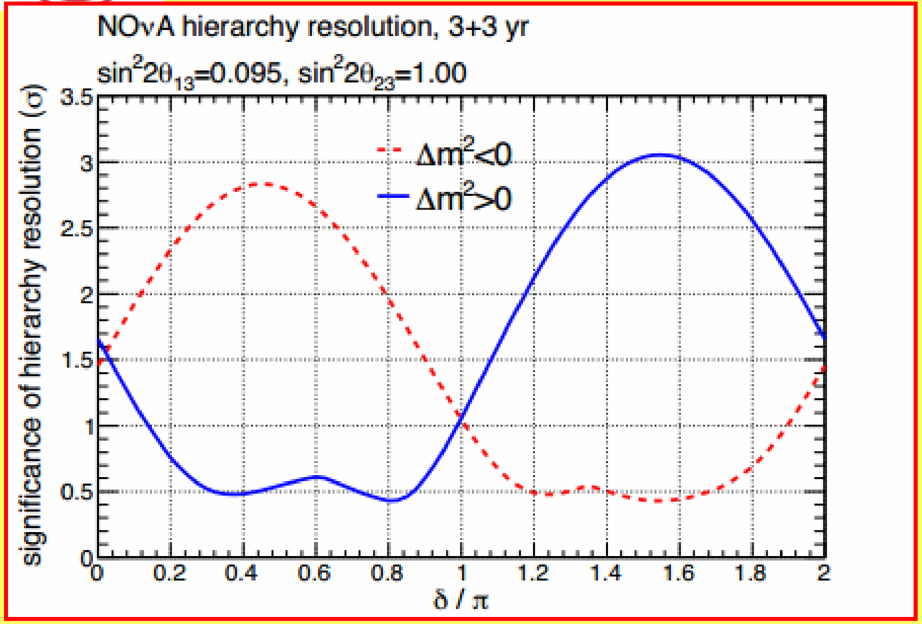
- $\sin^2 2\theta_{13} = 0.095$, $\sin^2 2\theta_{23} = 0.95$ or 1.0
- $\Delta m^2_{32} = 2.35 \times 10^{-3}\ eV^2$

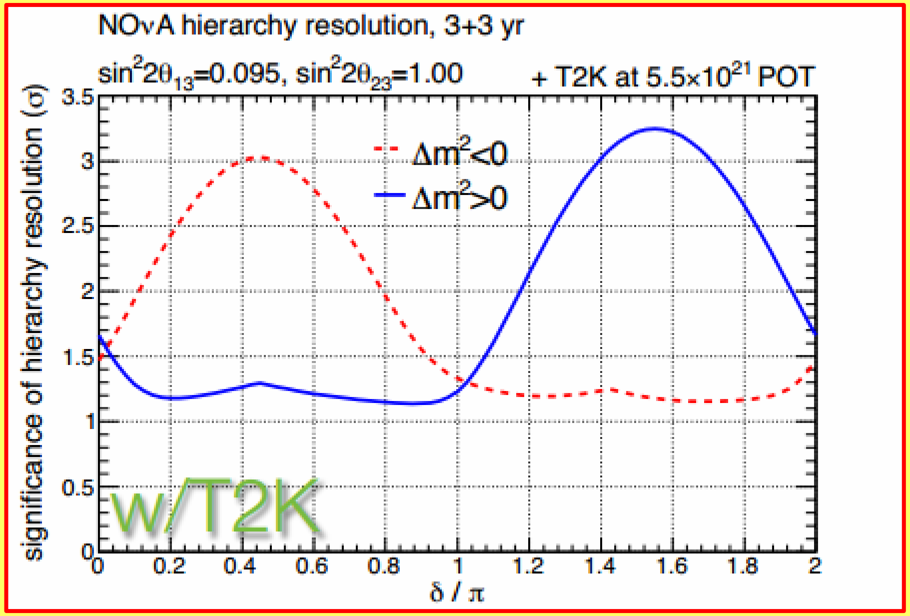
ν_e selected	ν	anti-ν
NC	19	10
ν_μ CC	5	<1
Beam ν_e	8	5
Total bkg	32	15
Signal	68	32

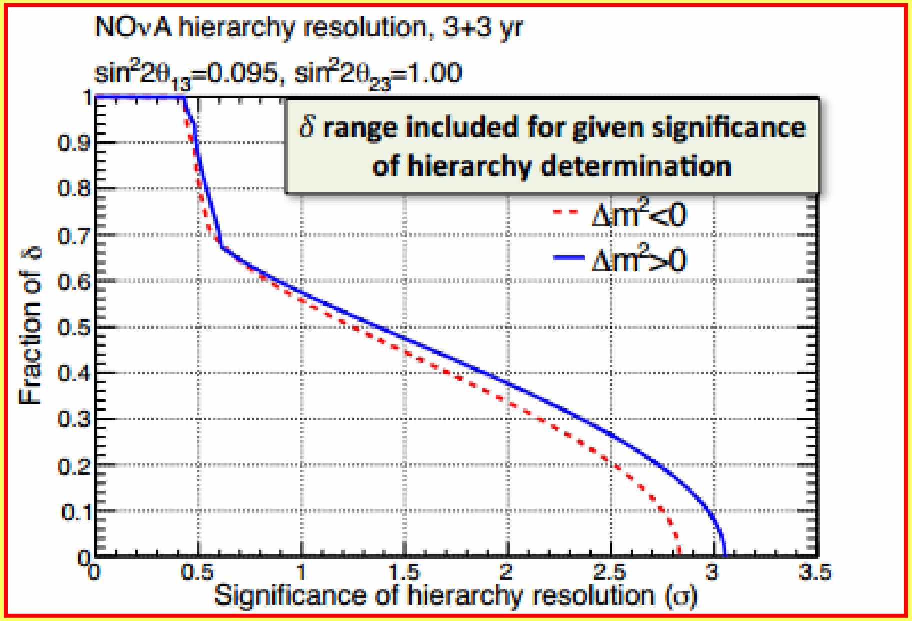
ν_μ selected	ν	anti-ν
QE signal	82	49
NC bkg	< 1	< 1
Non-QE signal	168	78
NC bkg	14	6
Uncont. signal	233	134
NC bkg	6	3

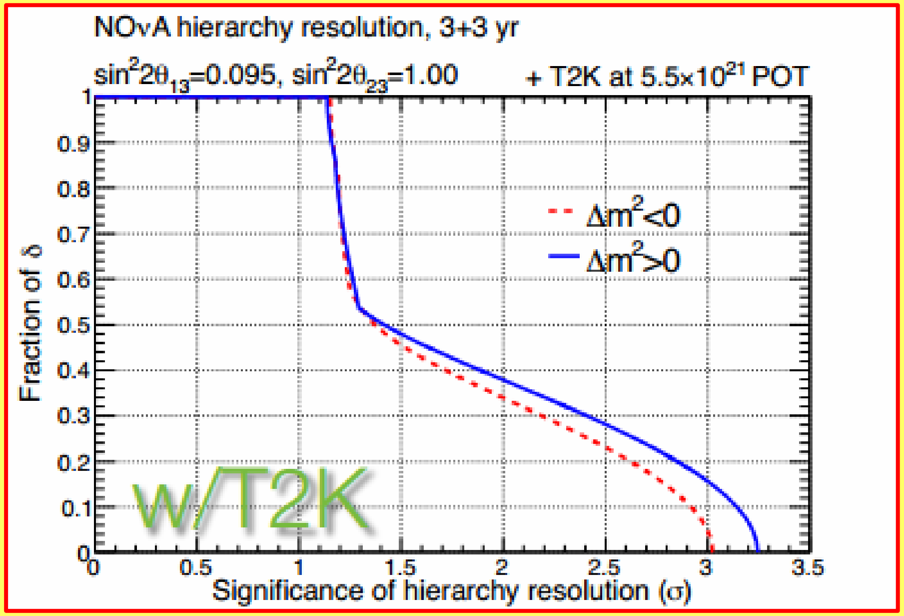
Need to be patient !!

Mass Hierarchy Sensitivity

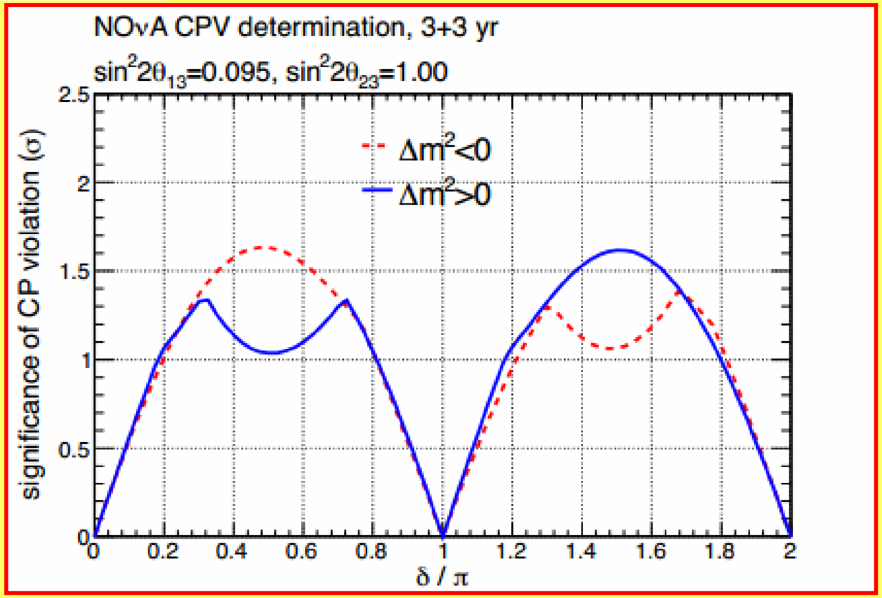


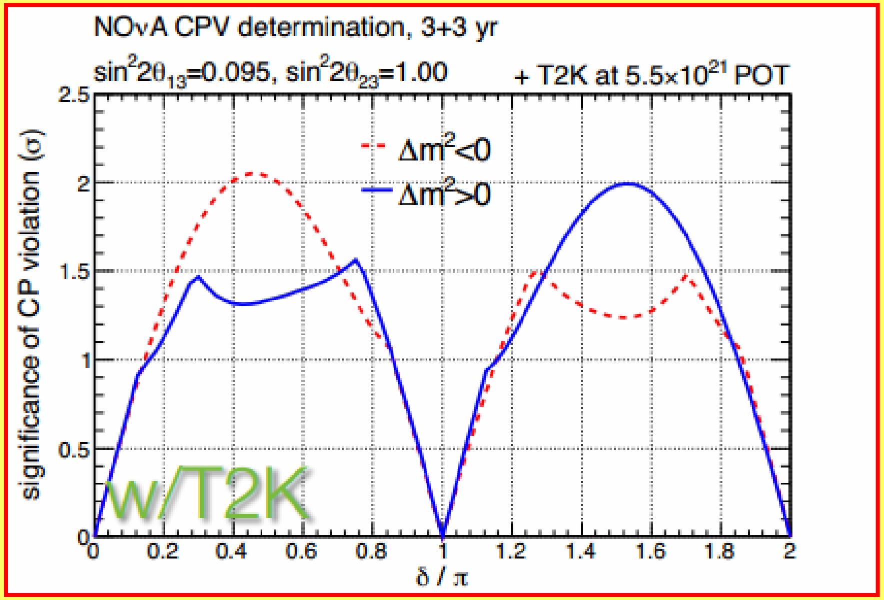


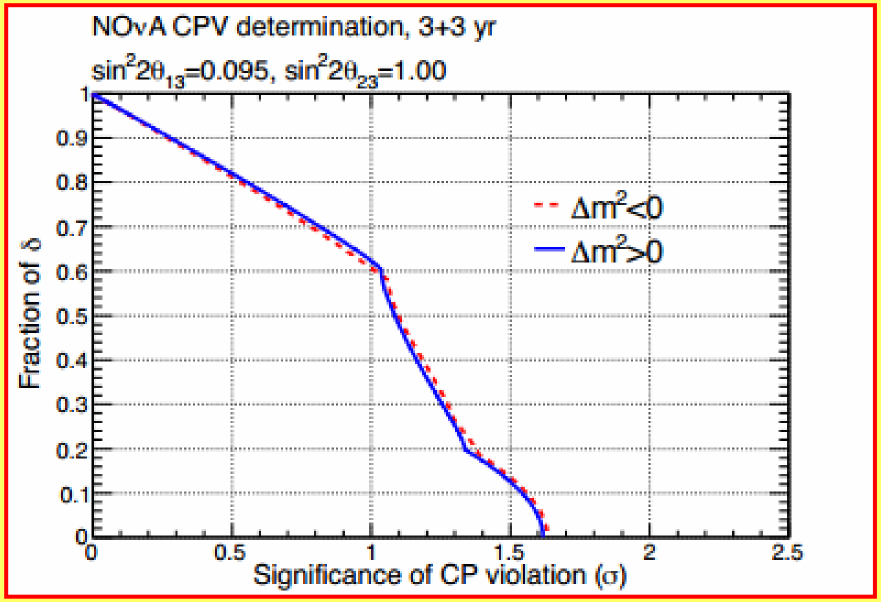


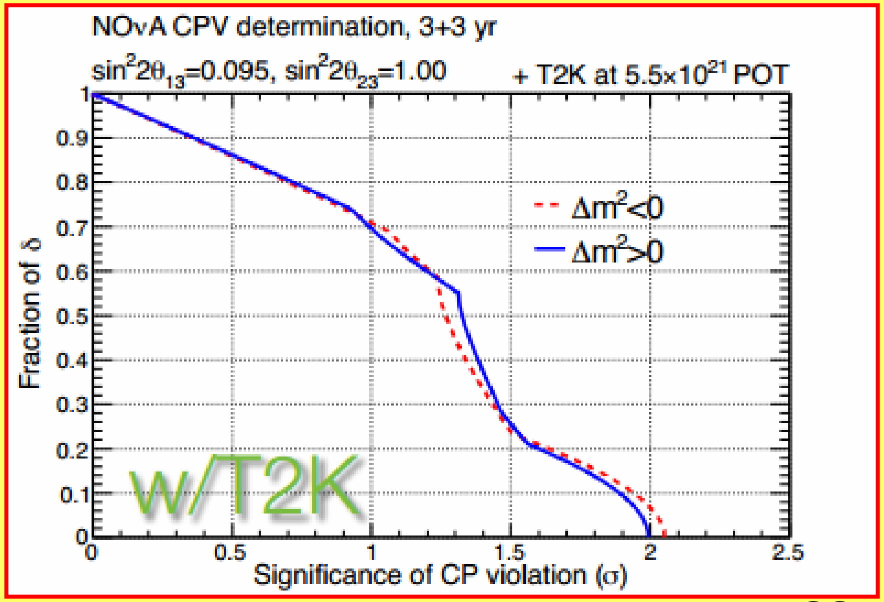


δ_CP Sensitivity

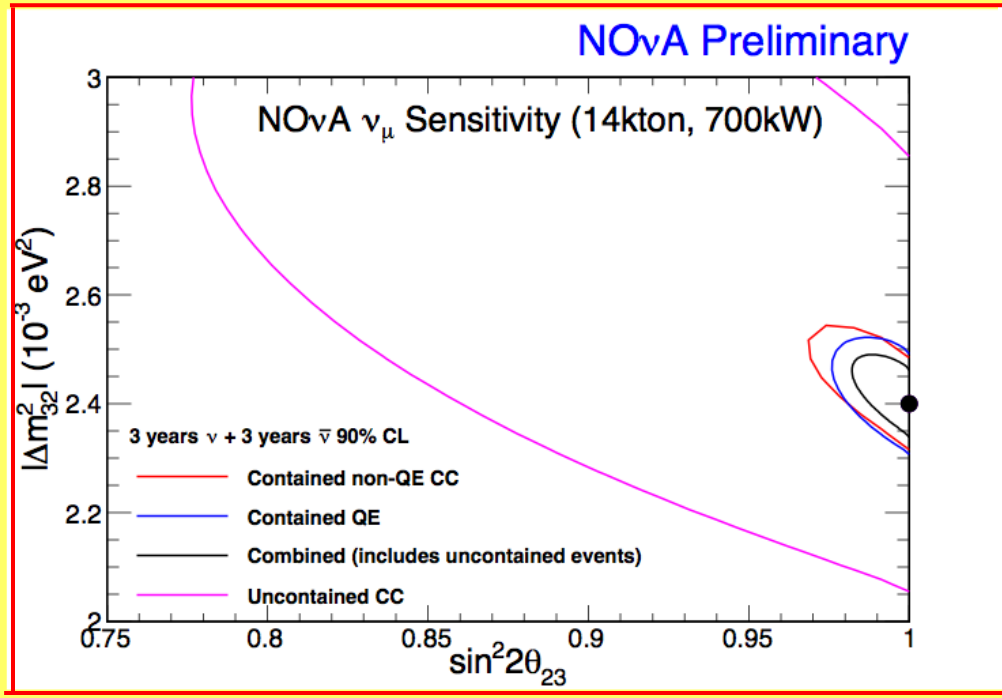


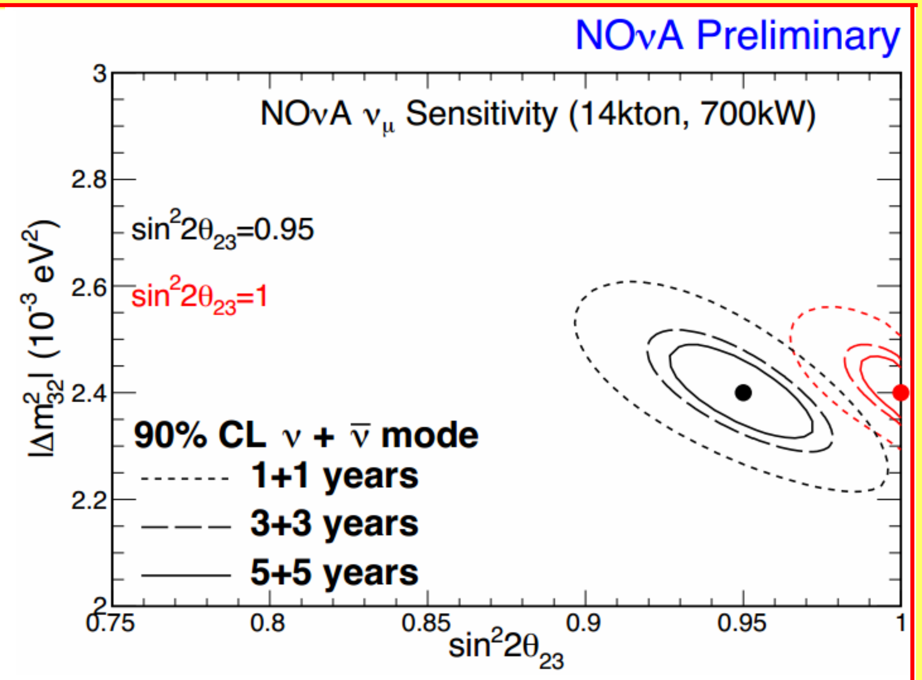






ν_μ Disappearance Measurements





NOνA Summary

- Both detectors rapidly being completed.
- Far detector performing well.
- Precise measurement of $\sin^2(2\theta_{23})$ & Δm^2_{23}.
- Constrain θ_{23} octant.
- Constrain CP violating angle δ_CP.
- Information on neutrino mass hierarchy.
- Measure θ_{13}.
- NOνA detector finished summer 2014
- Expect first publication late 2014.

Backup

ν Transition Probablity

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

$$\overset{(+)}{-}\ 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

$$+\ 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ $\Delta = \Delta m^2_{31} L/(4E)$ $A = \overset{(-)}{+} G_f n_e L/(\sqrt{2}\Delta)$