NUMI OFF-AXIS ELECTRON NEUTRINO APPEARANCE

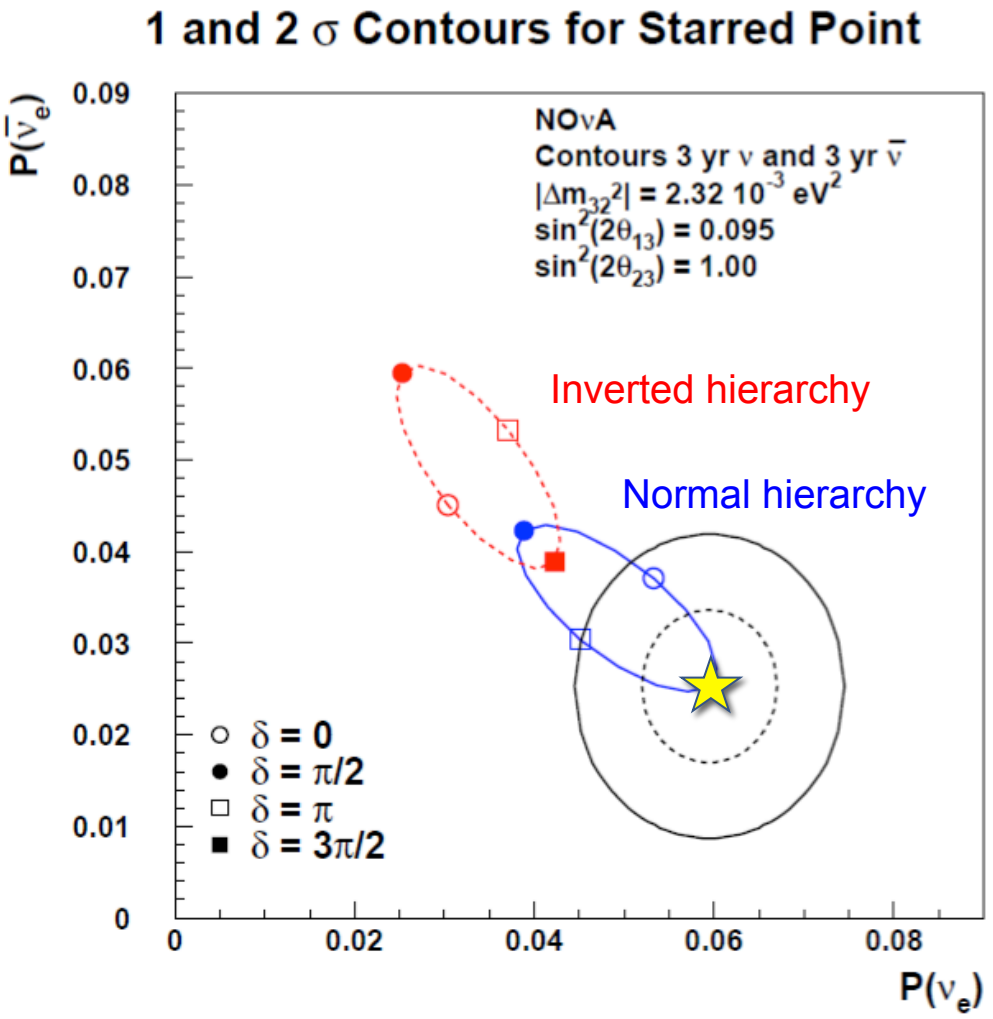
48th Annual Fermilab Users Meeting
June 10th 2015

Louise Suter, Argonne National Laboratory
for the NOvA collaboration

219 collaborators
from
39 institutions and
6 countries

NOvA physics goals

- Designed to measure 4 channels in NuMI beam
  - ν_e appearance ($\nu_\mu \rightarrow \nu_e$)
  - $\bar{\nu}_e$ appearance ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
  - ν_μ disappearance ($\nu_\mu \rightarrow \nu_\mu$)
  - $\bar{\nu}_\mu$ disappearance ($\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$)
- Probability of $\nu_e(\bar{\nu}_e)$ appearance in $\nu_\mu(\bar{\nu}_\mu)$ beam depends on θ_{13}, θ_{23}, δ_{CP}, Δm^2_{31}, Δm^2_{32}
- Results in sensitivity to the neutrino mass hierarchy, CP violation and the θ_{23} octant
- Broad non-oscillation program
  - Neutrino cross-sections
  - Sterile neutrino searches
  - Supernova searches
  - Searches for monopoles and other exotics



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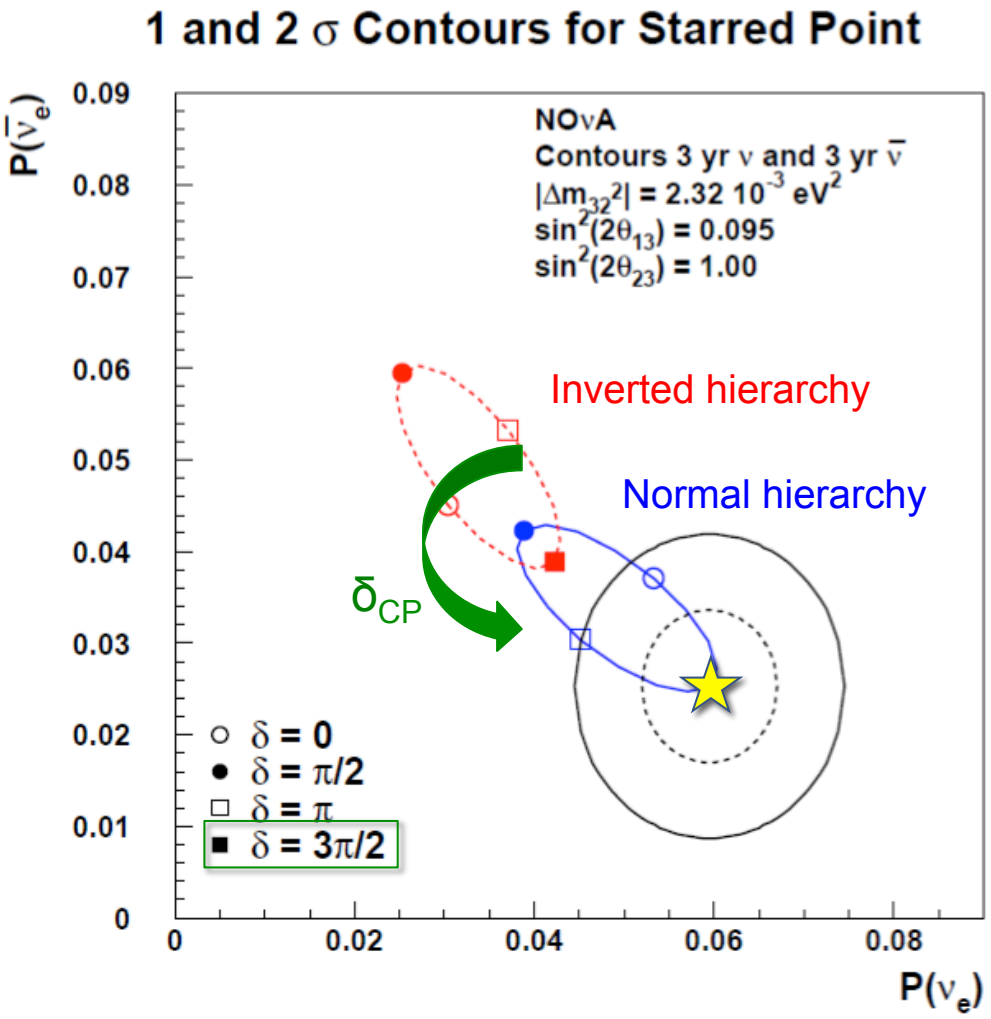

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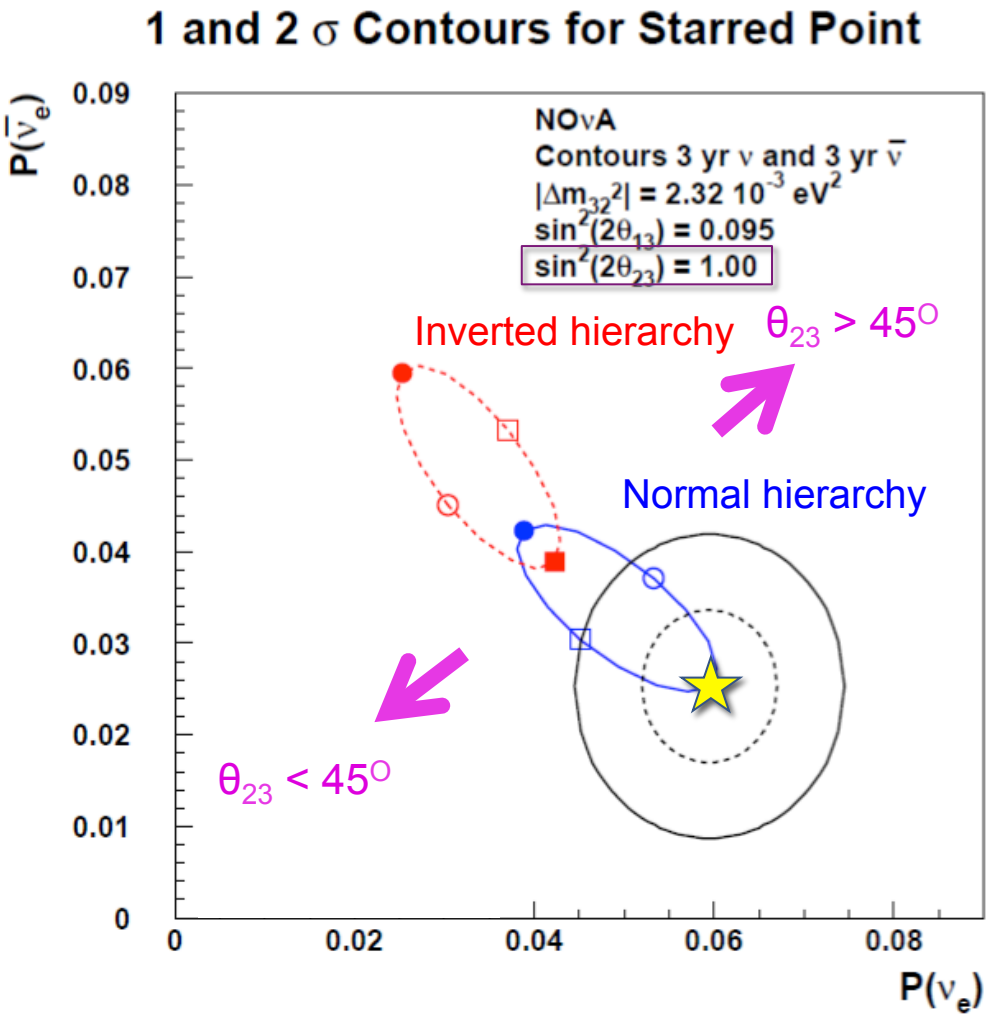

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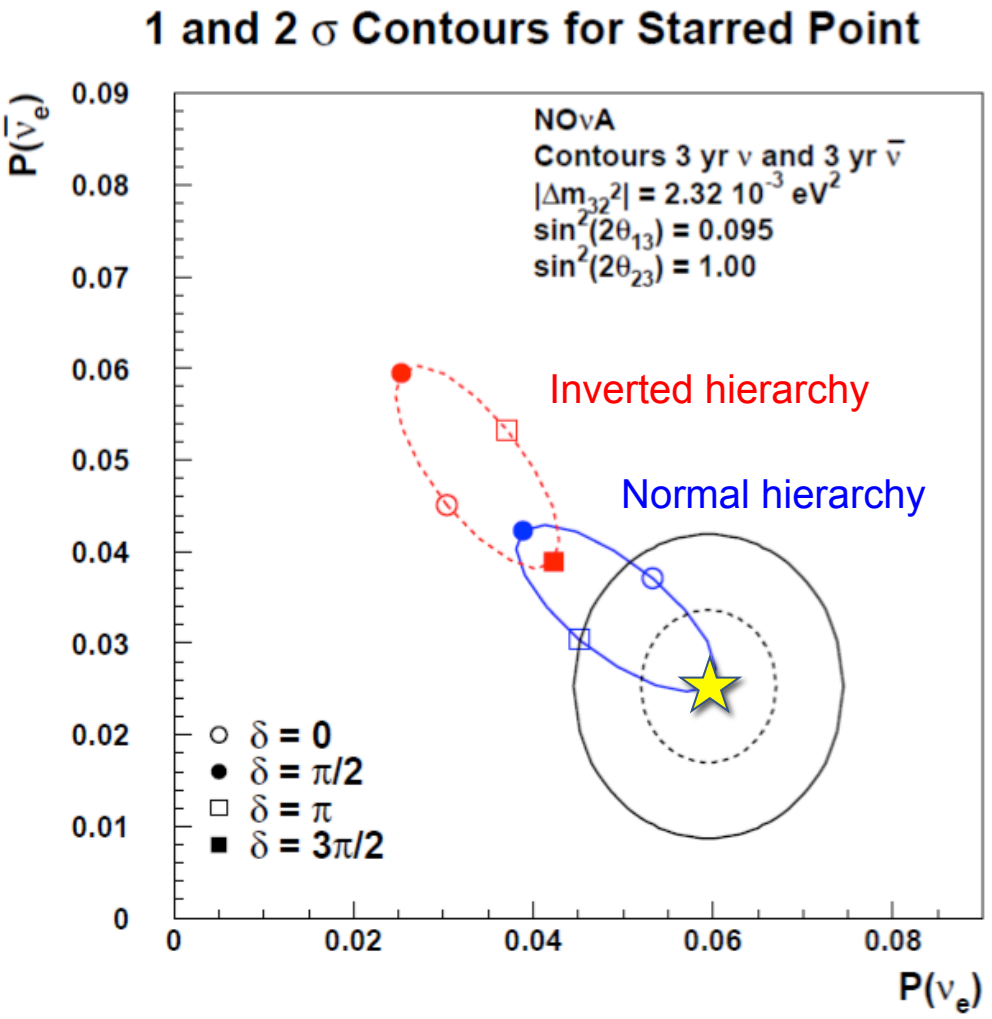
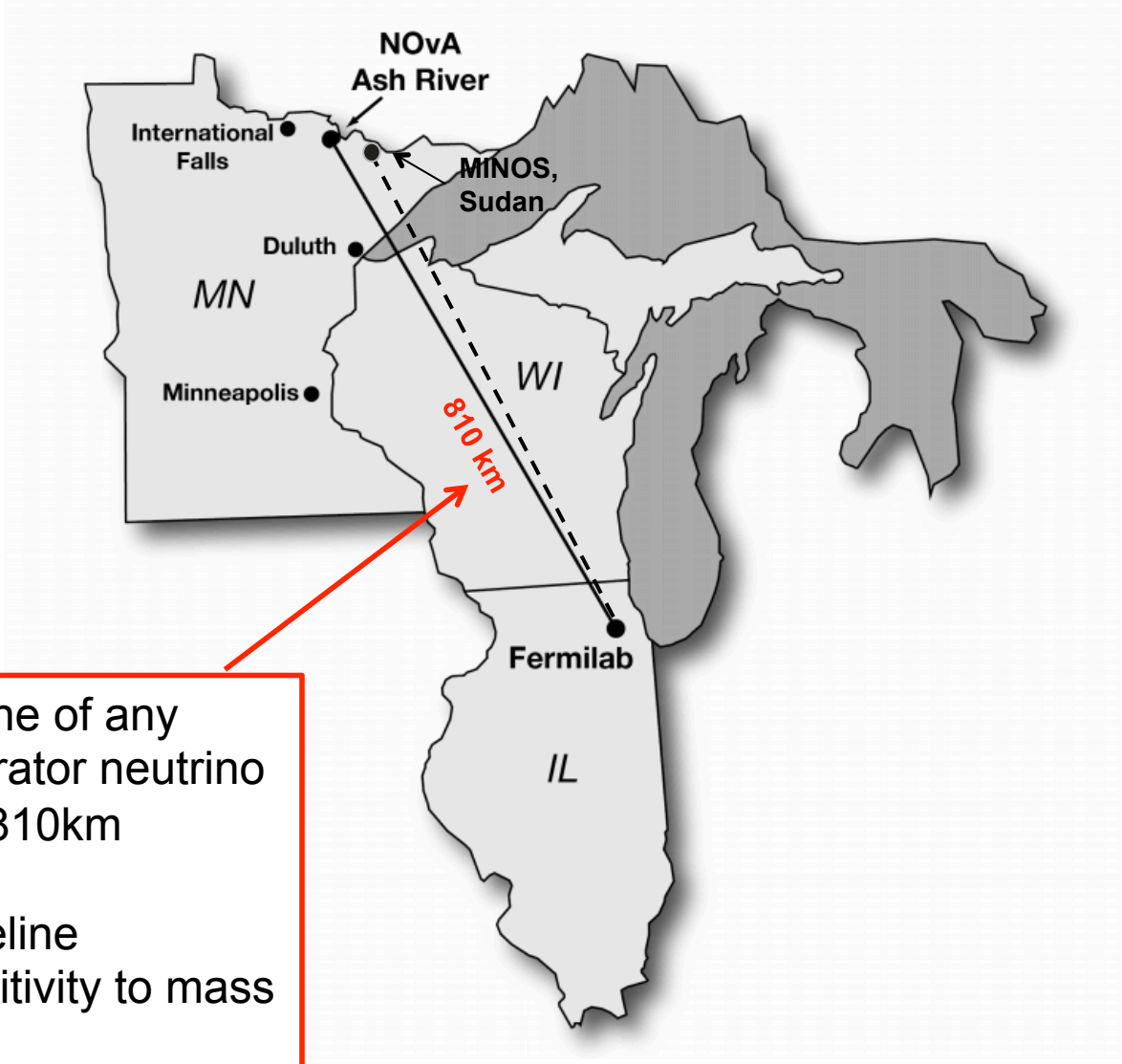


Off-axis long-baseline neutrino oscillation experiment

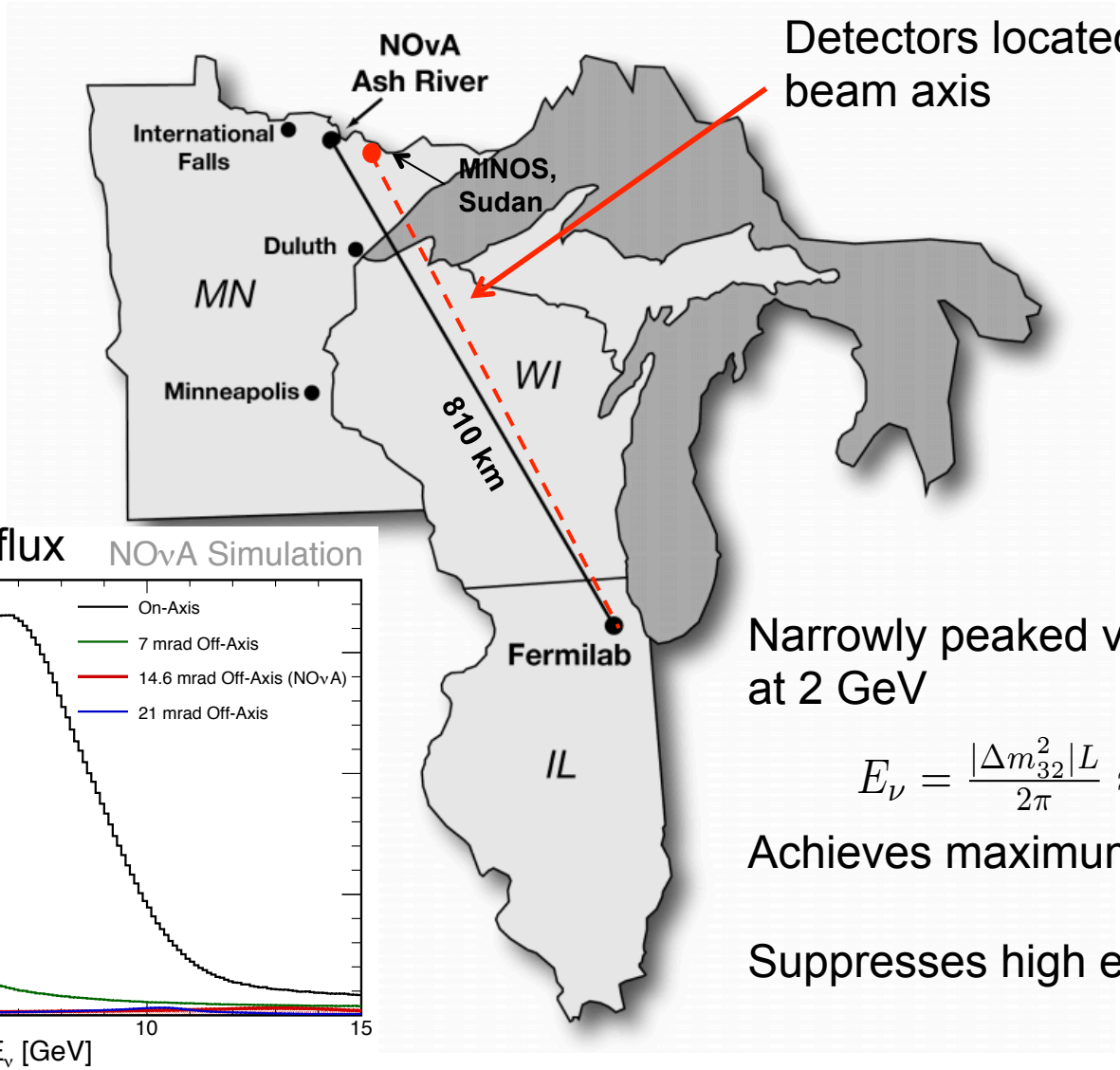
Off-Axis long-baseline neutrino oscillation experiment



Longest baseline of any running accelerator neutrino experiment at 810km

Increased baseline increases sensitivity to mass hierarchy

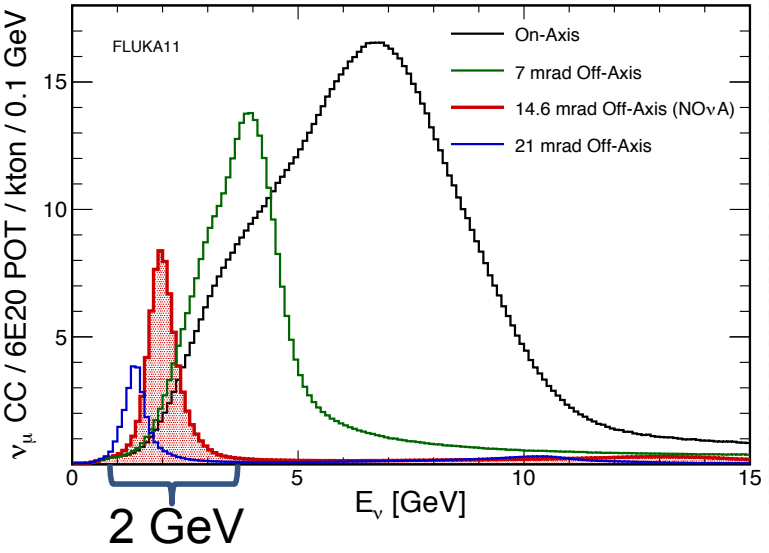
Off-Axis long-baseline neutrino oscillation experiment



Detectors located 0.8° of NuMI beam axis

Far Detector flux

NOνA Simulation



Narrowly peaked ν flux centered at 2 GeV

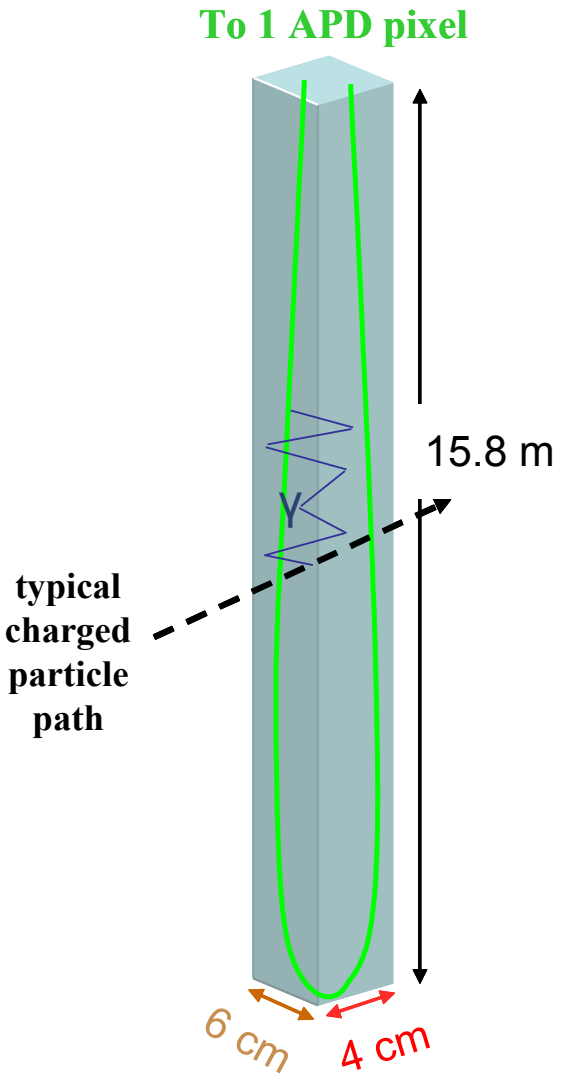
$$E_\nu = \frac{|\Delta m^2_{32}| L}{2\pi} \approx 2 \text{ GeV}$$

Achieves maximum oscillation

Suppresses high energy tail

Need to design a detector with excellent ν_e identification and background rejection

Want a huge, low-Z, totally active, tracking calorimeter



Plastic cell filled with liquid scintillator

Need to design a detector with excellent ν_e identification and background rejection

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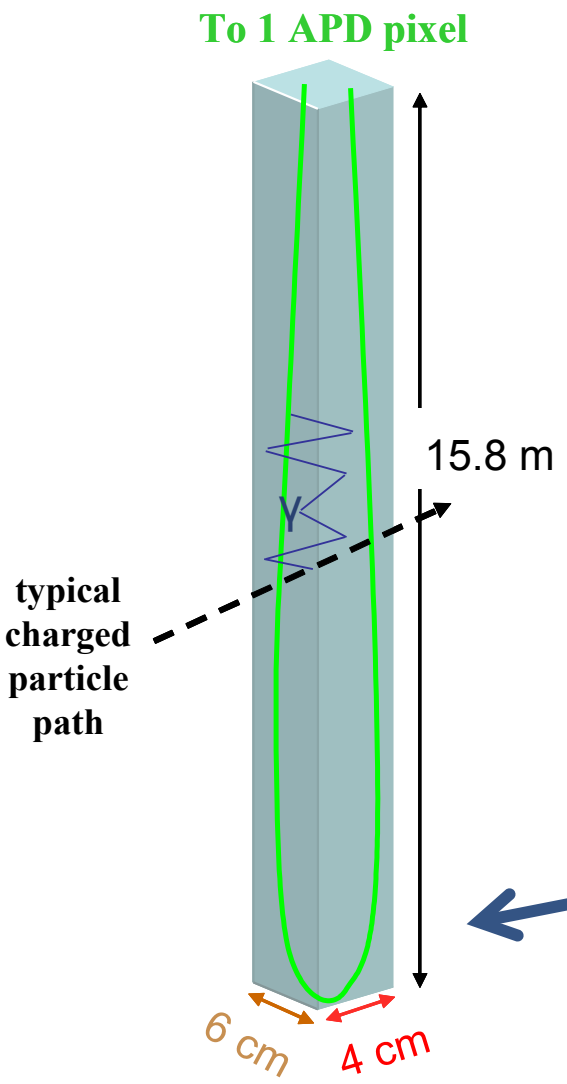
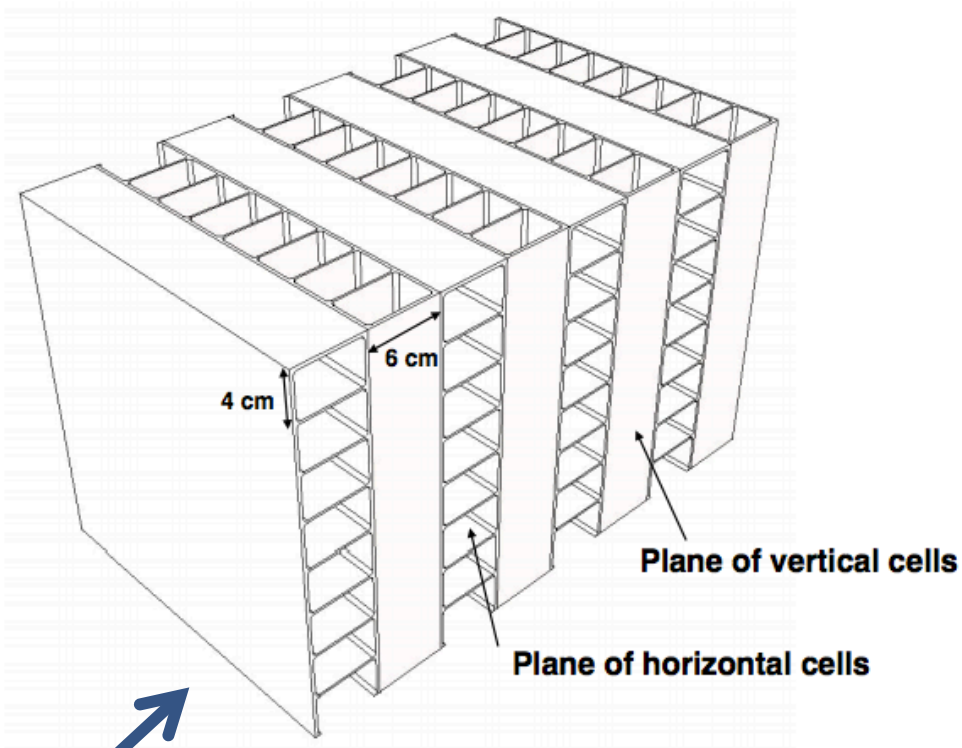


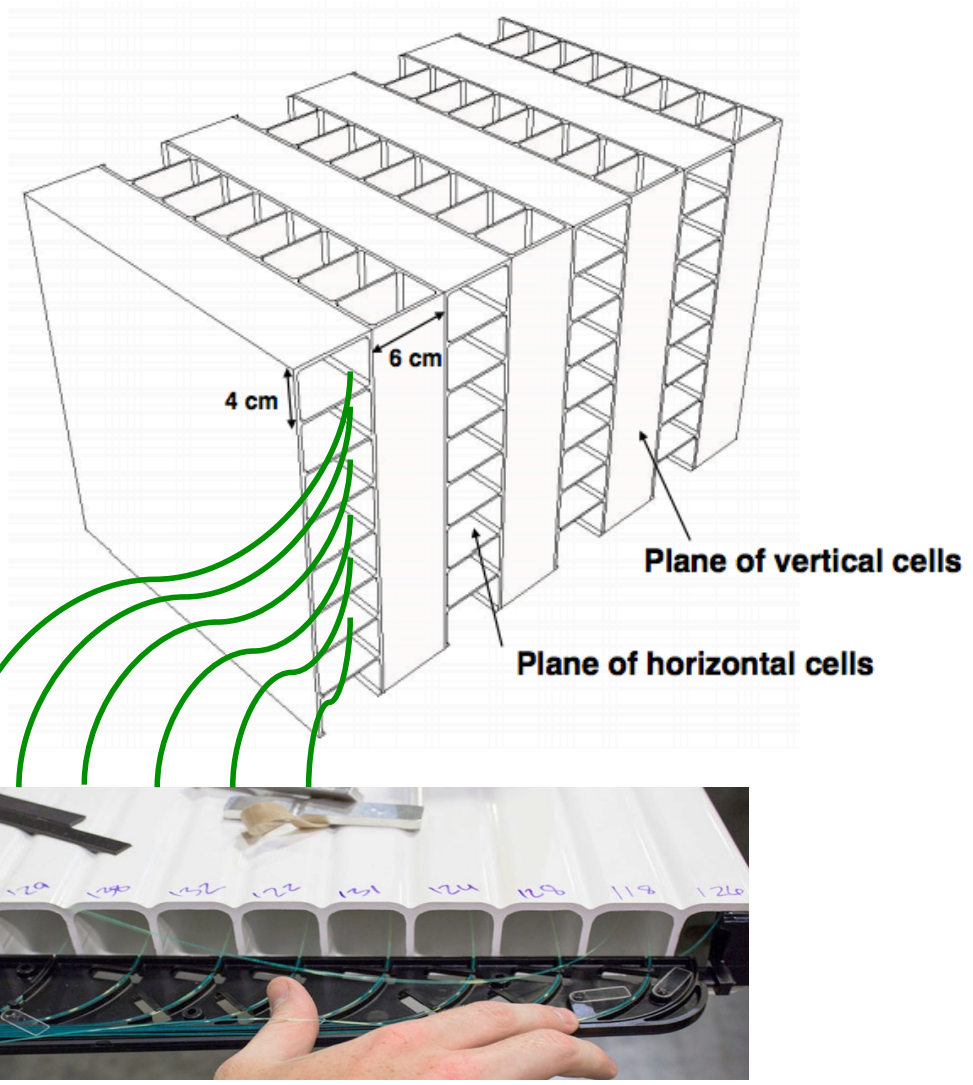


344,064 identical cells constructed into 896 alternating horizontal and vertical planes, each of 384 cells long

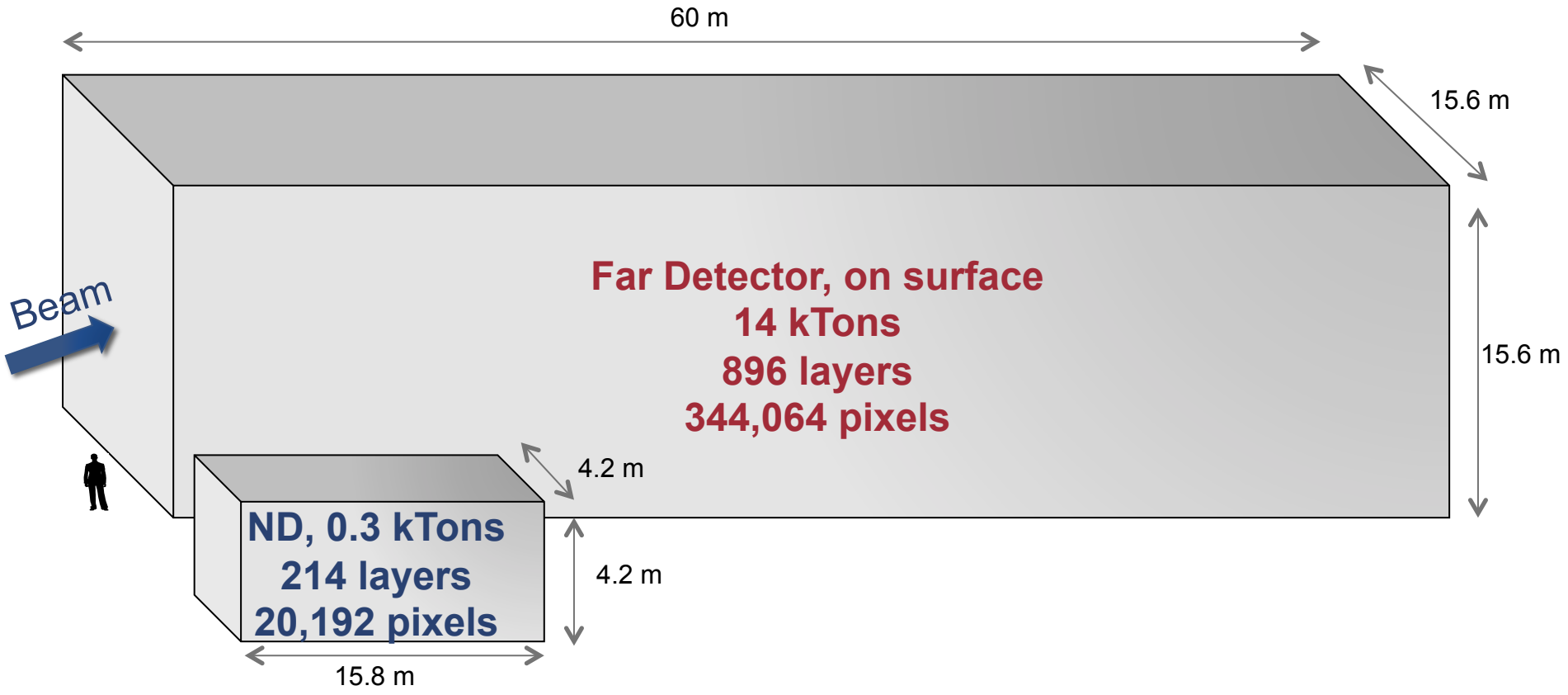
Cells constructed into horizontal and virtual planes for 3D reconstruction

32 pixel APD

32 WSF loops



Each cell has loop of wavelength shifting fiber read out in groups of 32 by a 32 pixel Avalanche Photodiode

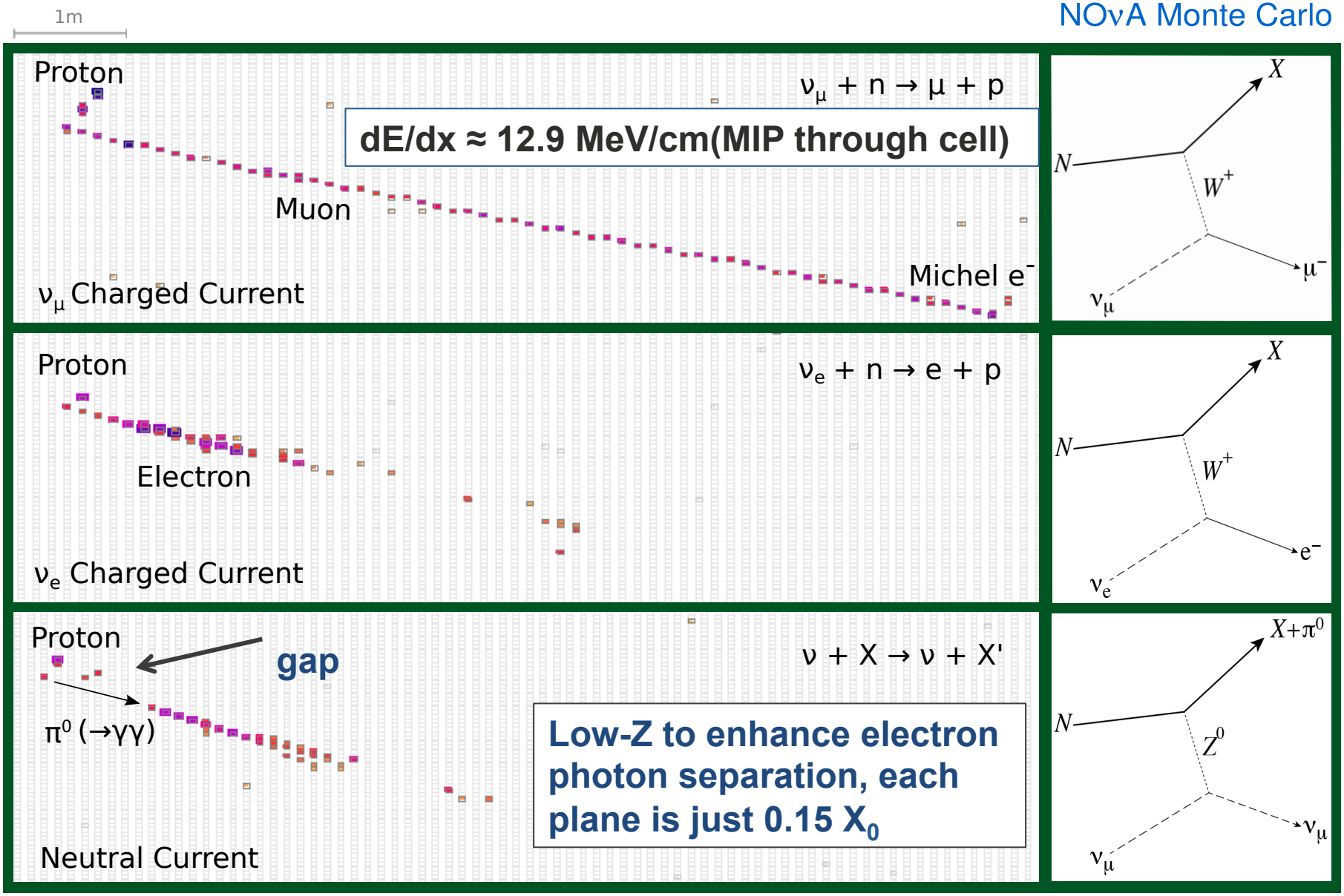


Two identical 65% active low-Z tracking calorimeters

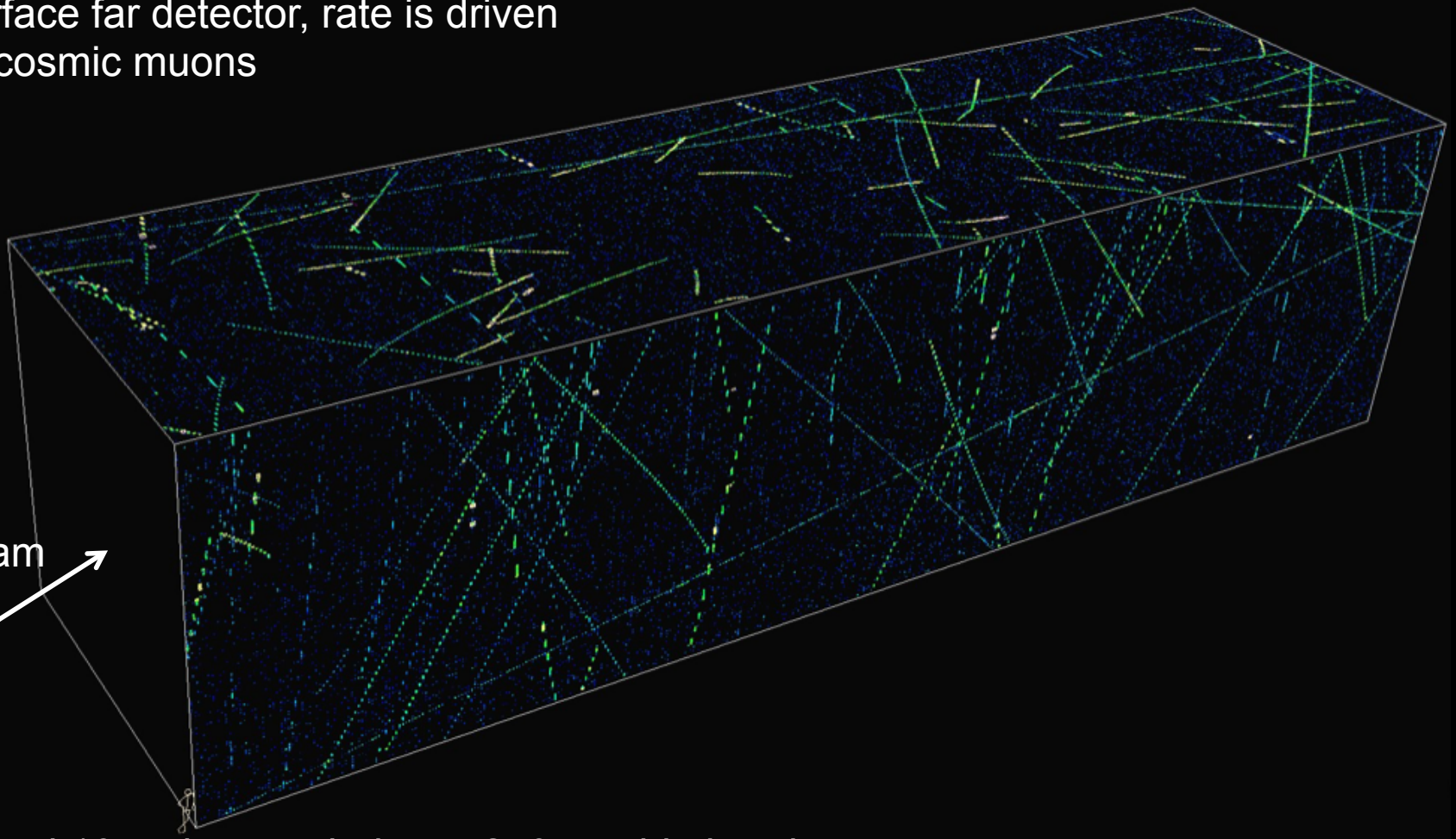
- Measure ν_μ and ν_e rates after oscillation
- Comparison with ND extrapolated data allows for extraction of oscillation parameters
- Use of ratio measurement allows for cancelation of most systematics

- Large flux used to characterize beam of ν_μ before oscillation
- Extrapolate data to predict unoscillated rate at FD

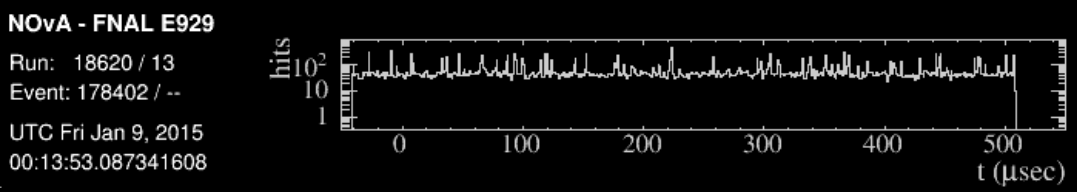
NOνA Monte Carlo

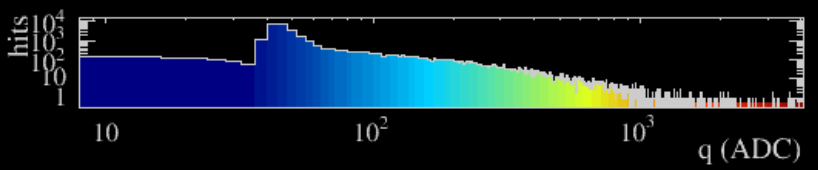


Surface far detector, rate is driven by cosmic muons



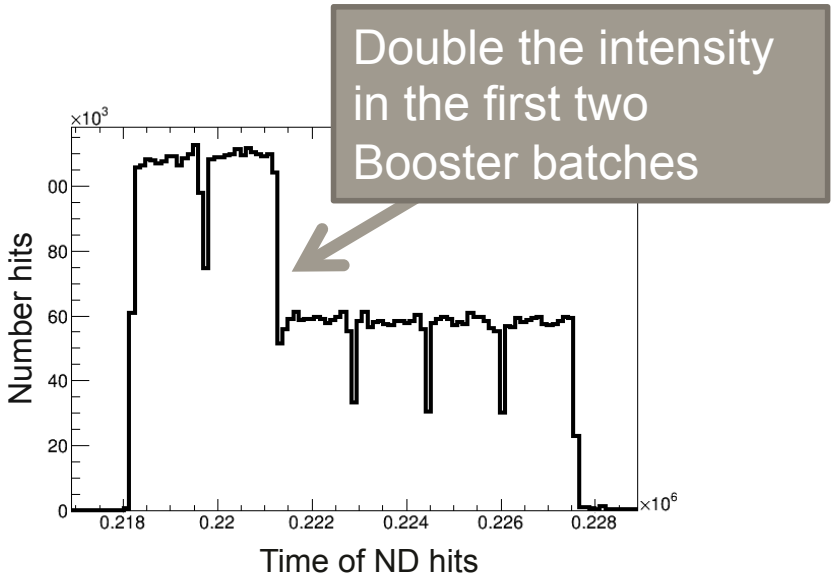
Record 10 μs beam window ± 270 μs side band

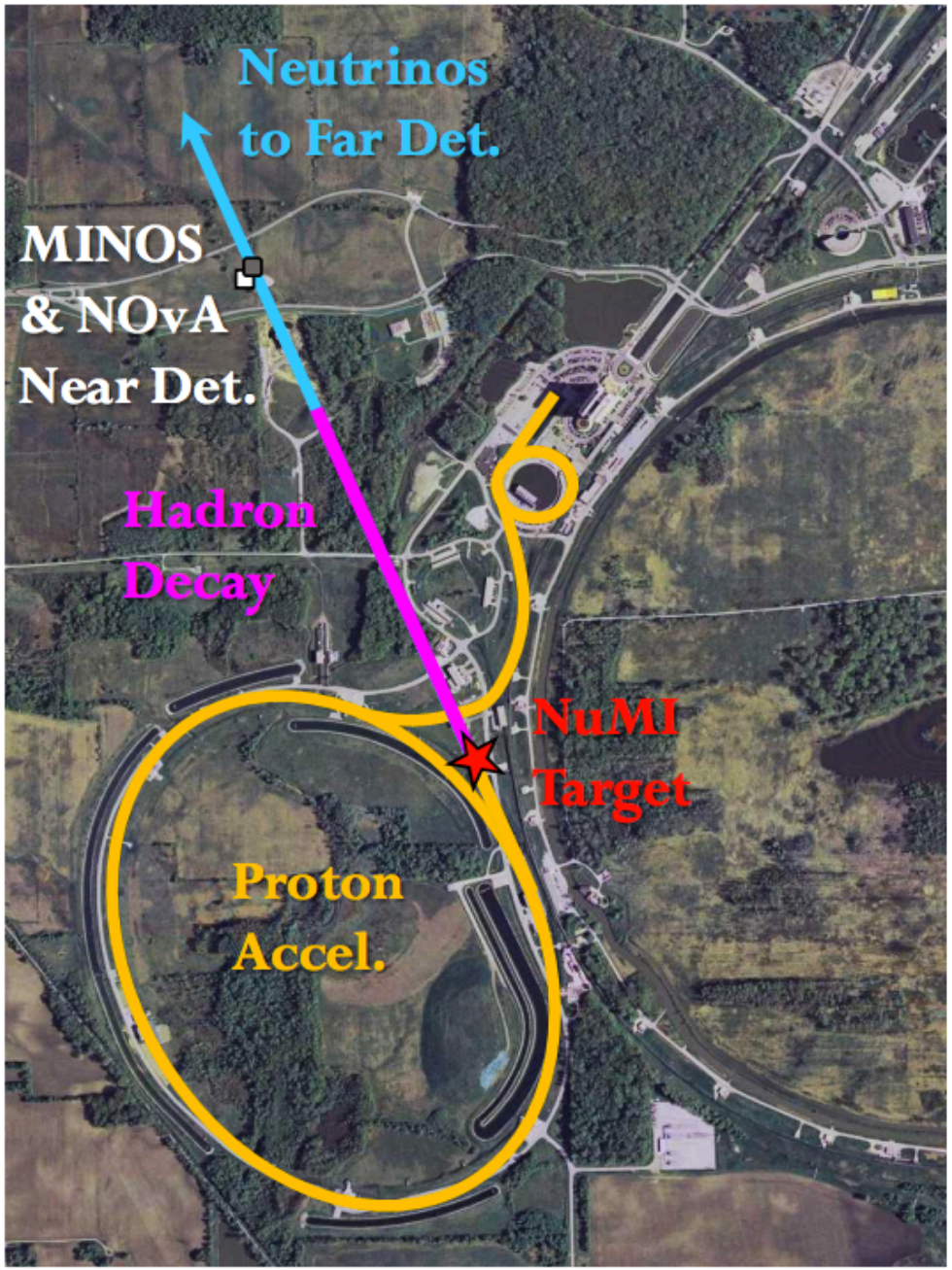




Color denotes charge deposited

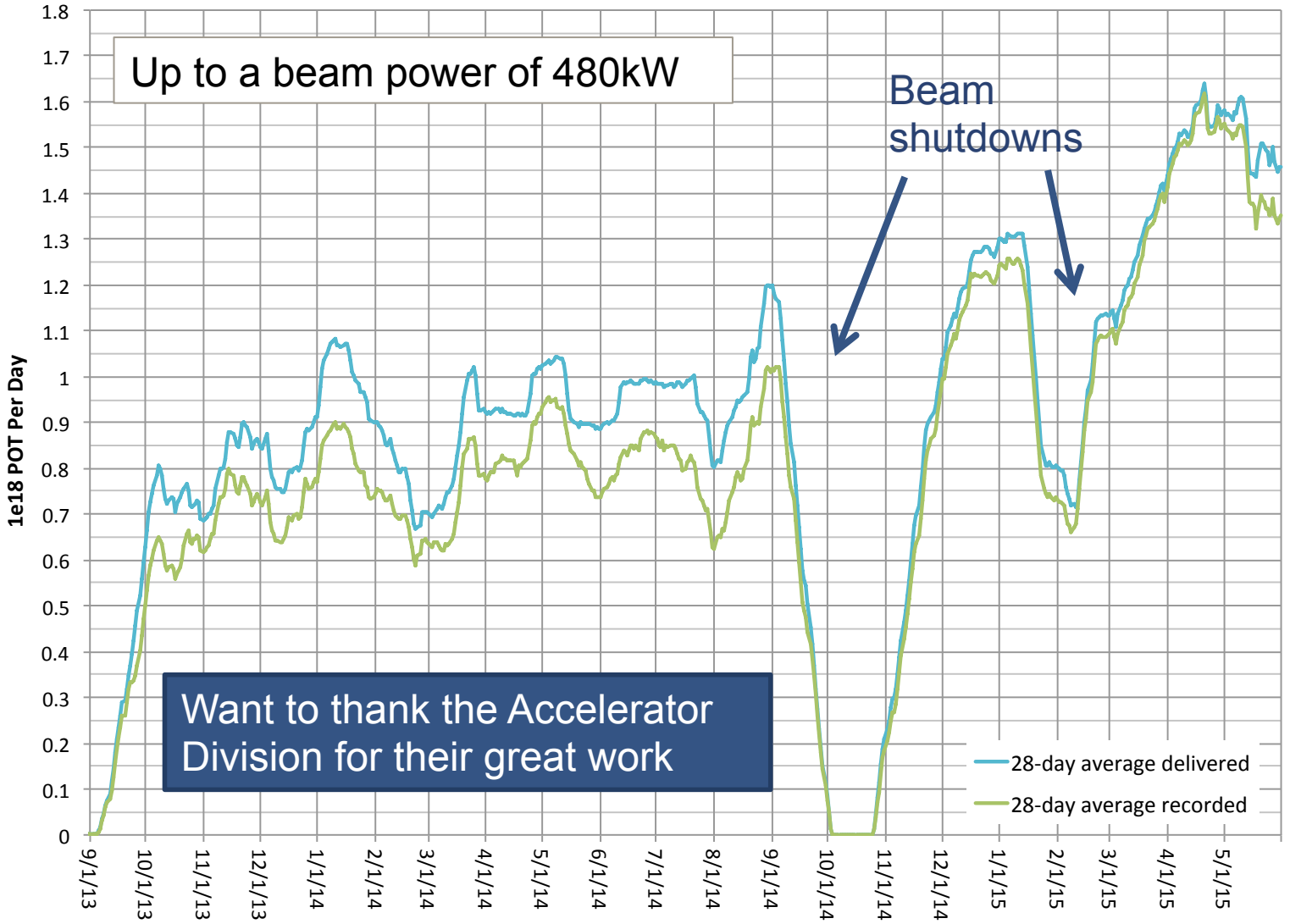
- Far Detector started data taking in March 2013, with both detectors completed August 2014
- NOvA running in medium energy NuMI beam with a beam power from 330-480 kW
- Slip-stacking Booster batches since March 2015
- Upgrade to 700 kW, NOvA design power, dependent on a Booster upgrade and 4+6 slip-stacking





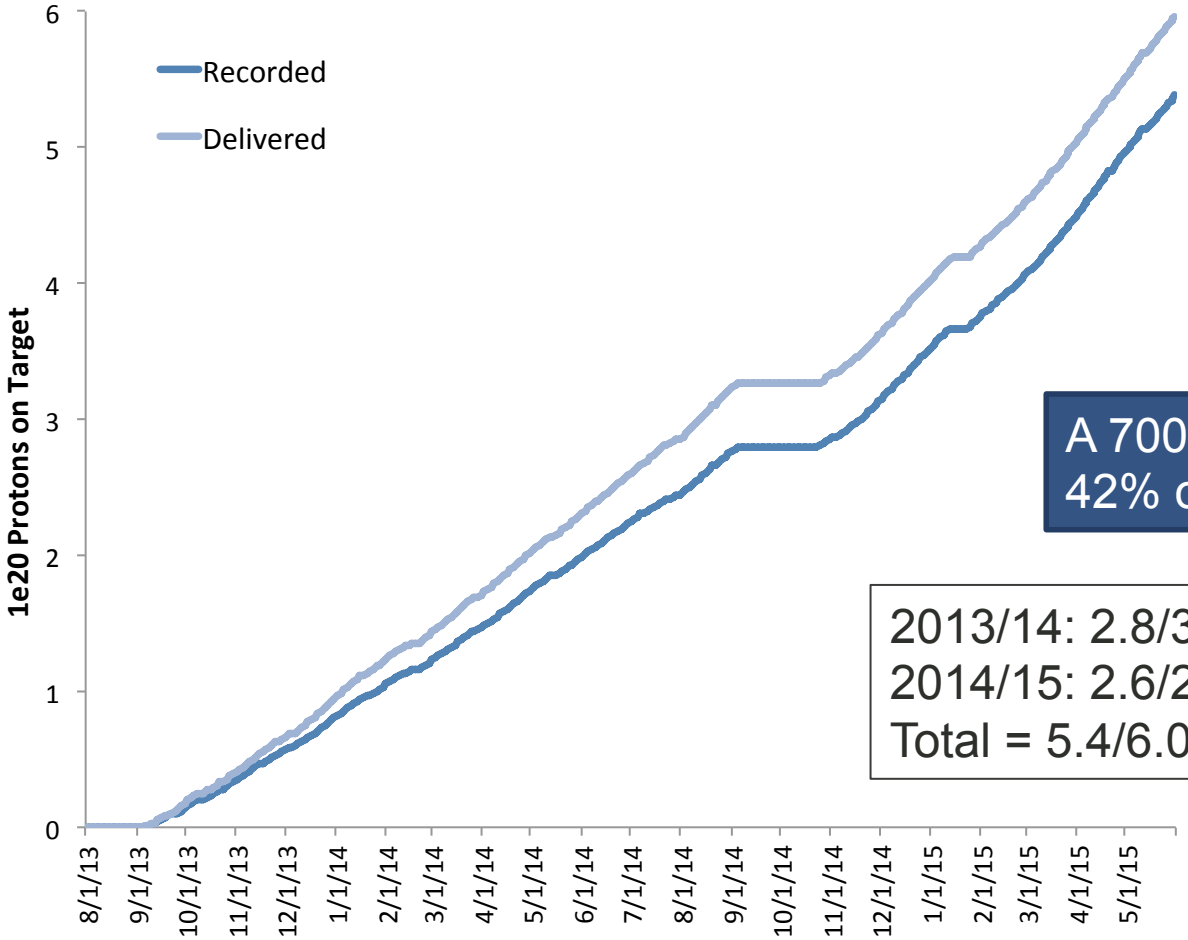
Delivered/Recorded POT

Rapid intensity increase since February



Far Detector Integrated Luminosity

90% of all data delivered has been recorded



A 700 kW NOvA year = 6e20 POT
42% of a year recorded

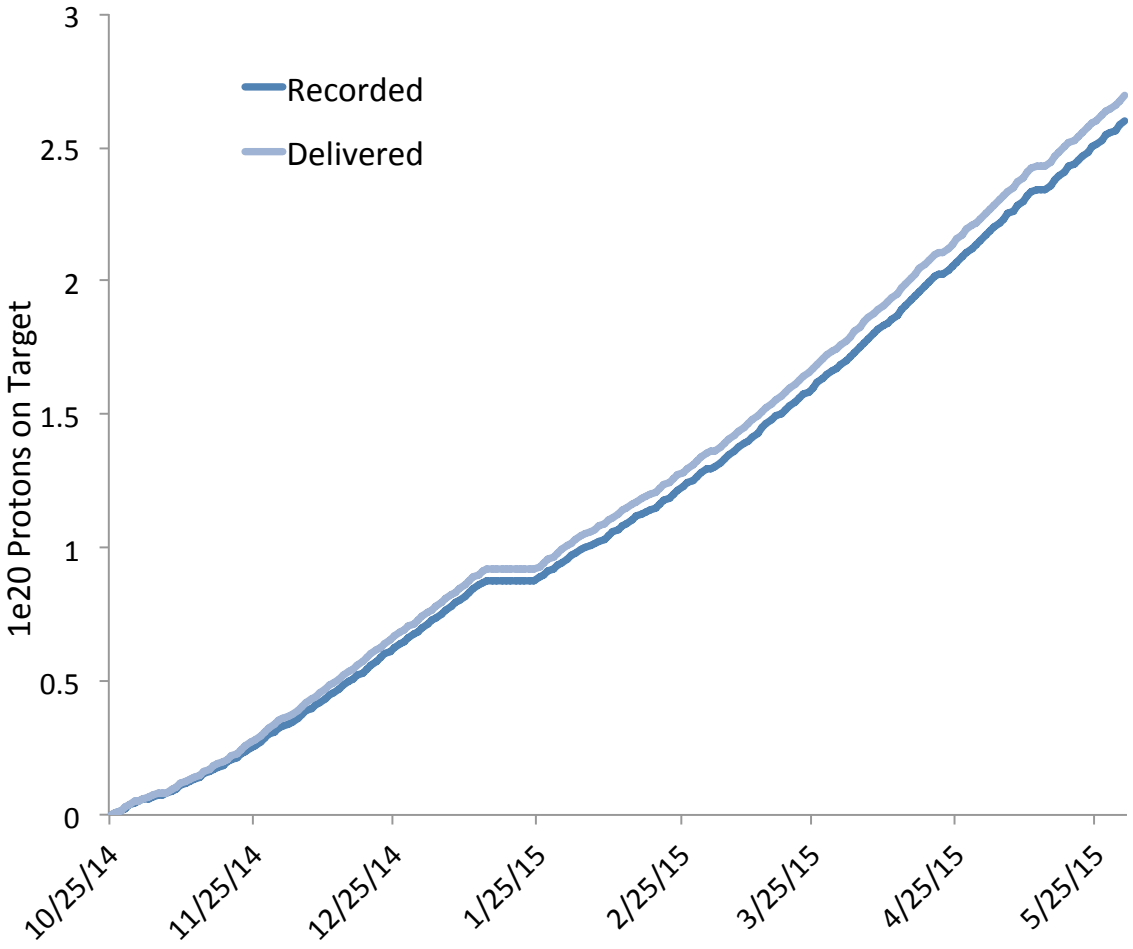
2013/14: 2.8/3.3e20 POT (86%)
2014/15: 2.6/2.7e20 POT (96%) [219 days]
Total = 5.4/6.0e20 (90%) POT

Far Detector was under construction till Aug 2014

Far Detector 14kTon exposure ~ 2.5e20 POT

Near Detector Integrated Luminosity

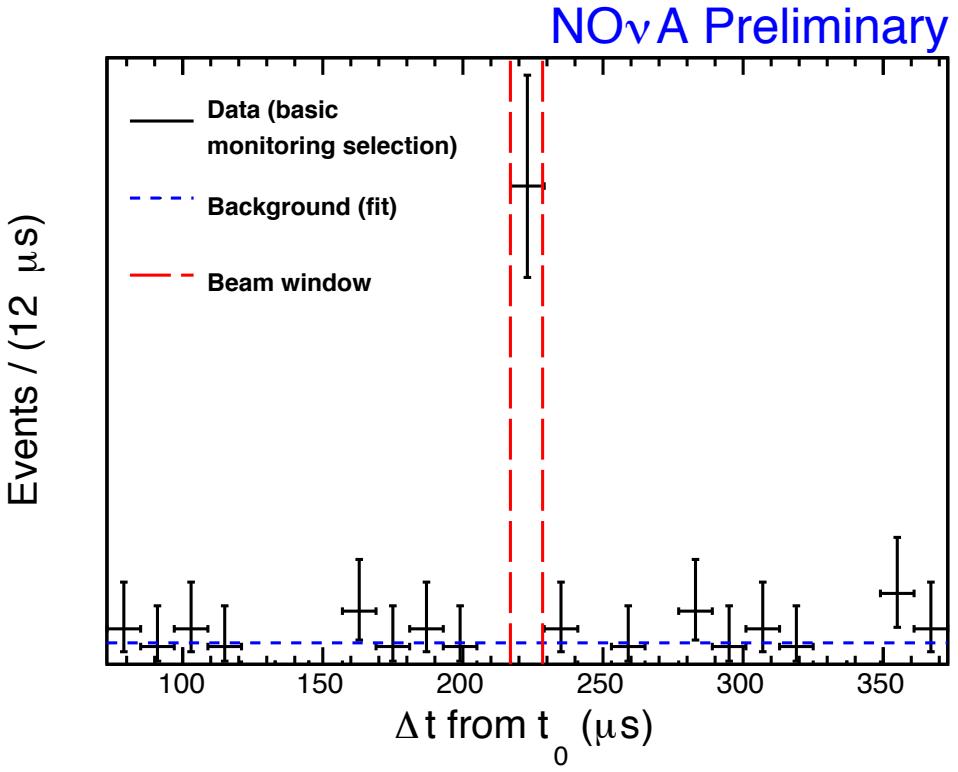
96% of all data delivered has been recorded



2014/15: (97%)
2.6e20 POT recorded
2.69e20 POT delivered

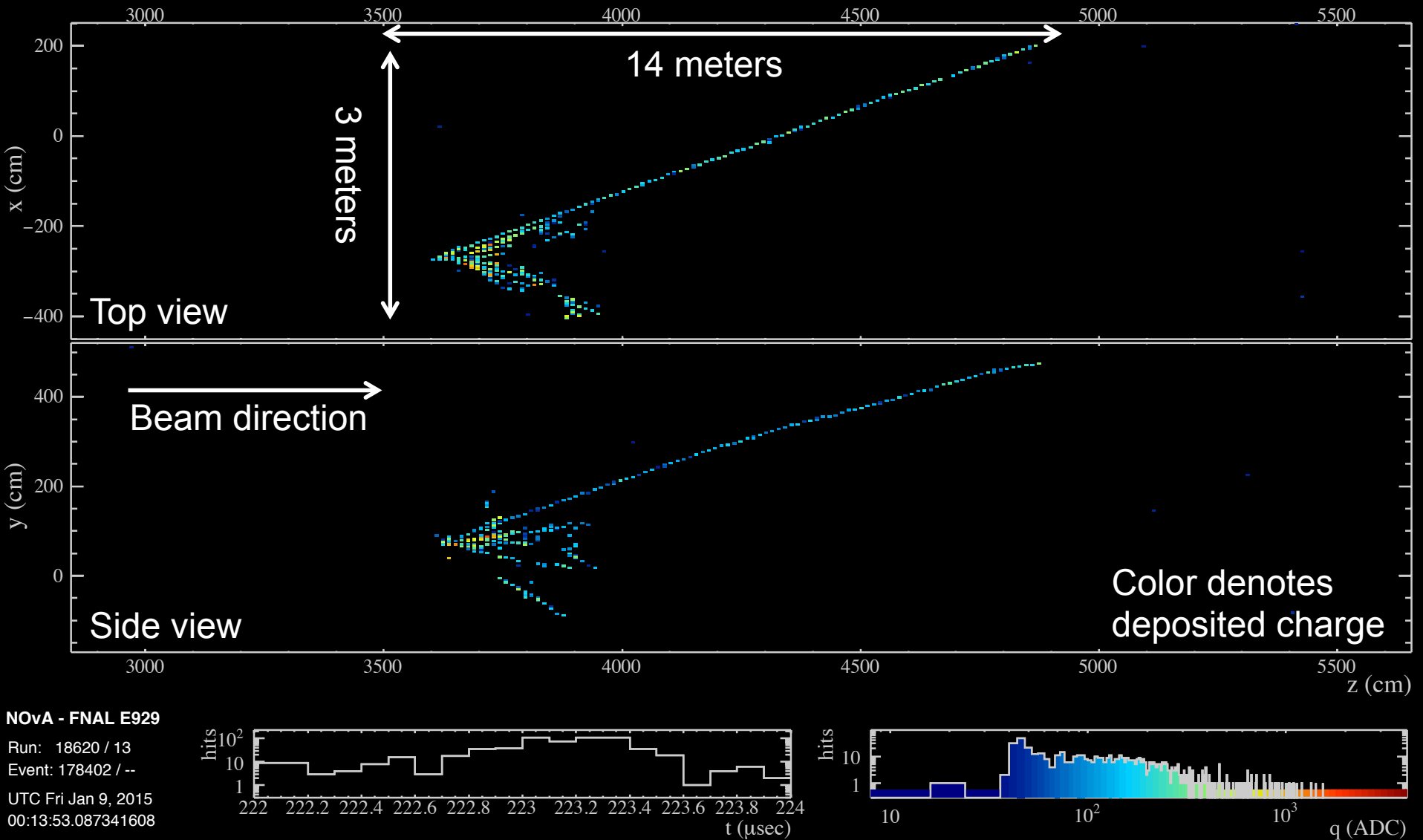
Corresponds to around 40 million ν_μ Charged Current interactions

- NOvA Far Detector neutrino data is blinded
  - Particle identification responses and energy related variables are hidden to remove analysis biases
- NOvA has many handles to validate detector performance
  - Near Detector data, sideband regions and cosmic events
- Perform analysis of Far Detector neutrino rate to monitor our DAQ and timing systems
  - Expect ~0.5 events per day at FD

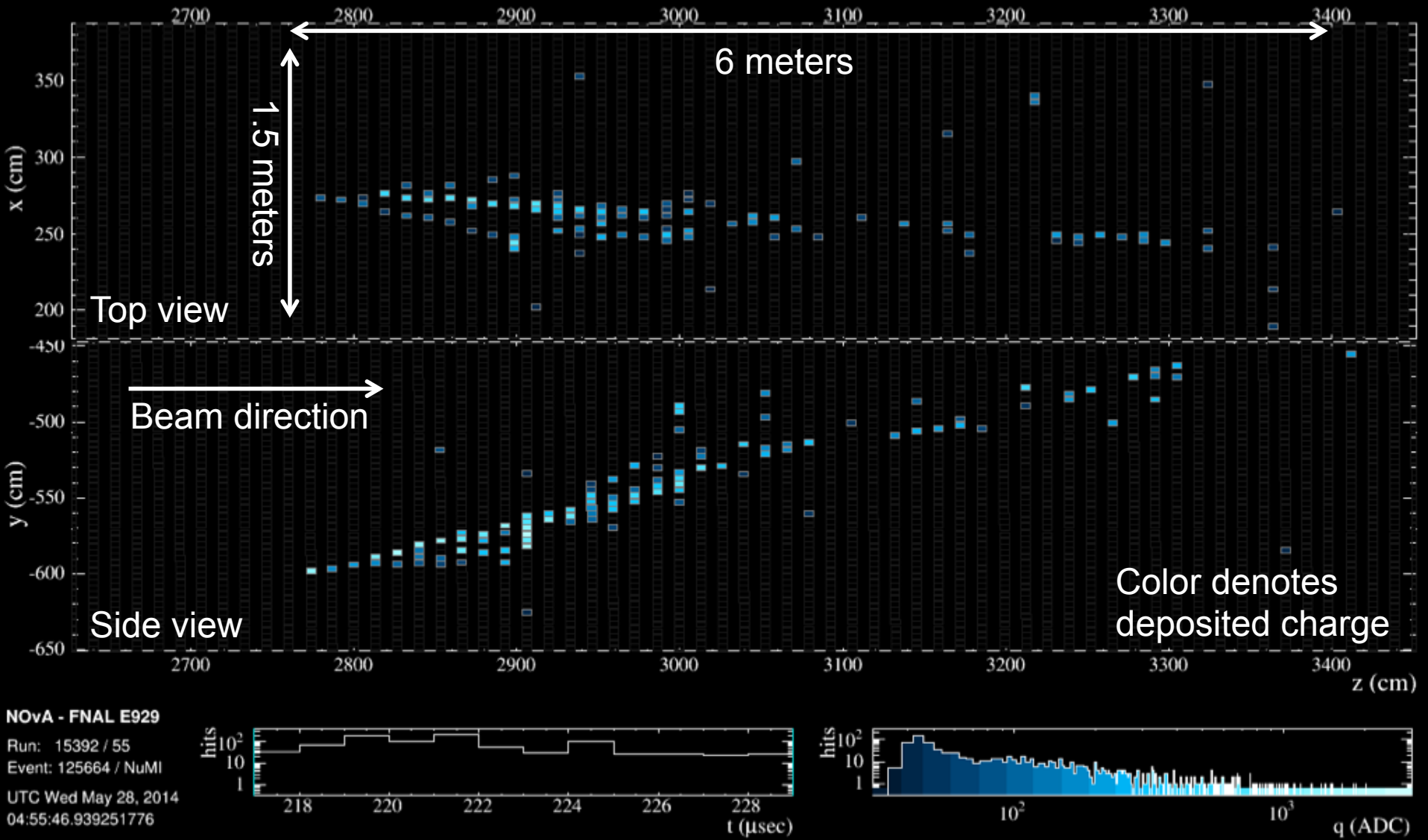


10μs beam peak clearly identified from cosmic backgrounds

Candidate ν_μ event



Candidate ν_e event

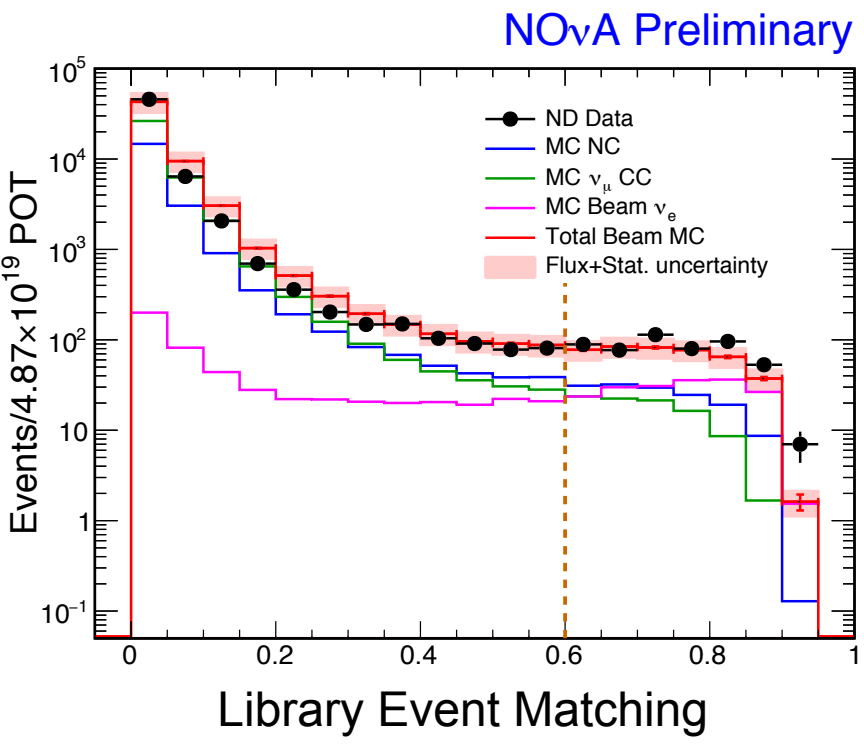


Electron neutrino appearance event selection

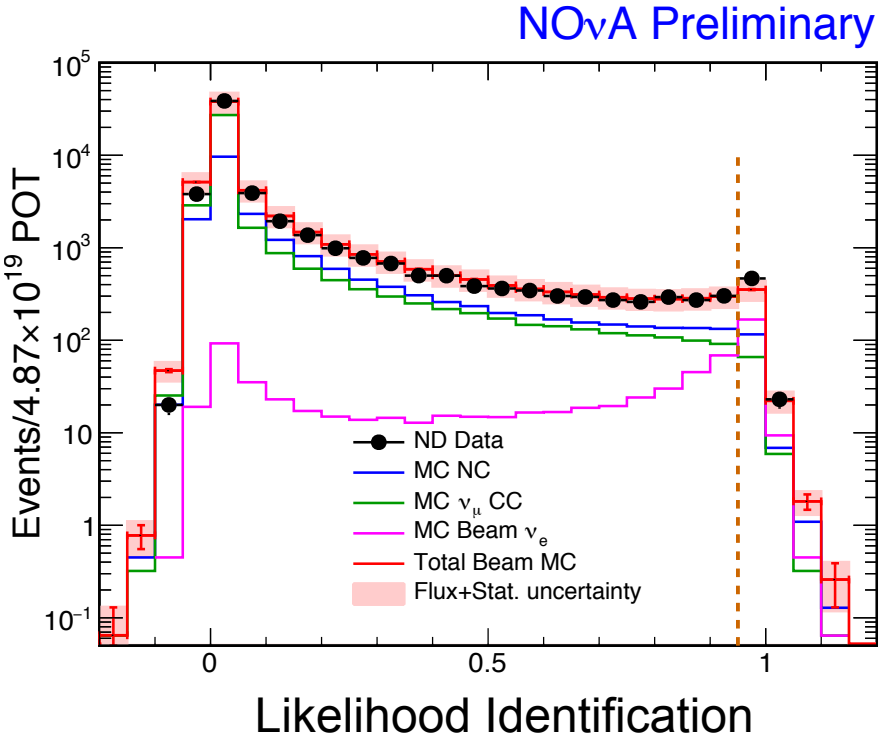
Near Detector

Extrapolate beam intrinsic ν_e's in the ND to predict background ν_e rate at the FD

Two complimentary electron identification algorithms



Matches event topology to library of signal and background events



Neural Net trained on shower shape likelihoods assuming different particle hypothesis

Electron neutrino appearance event selection

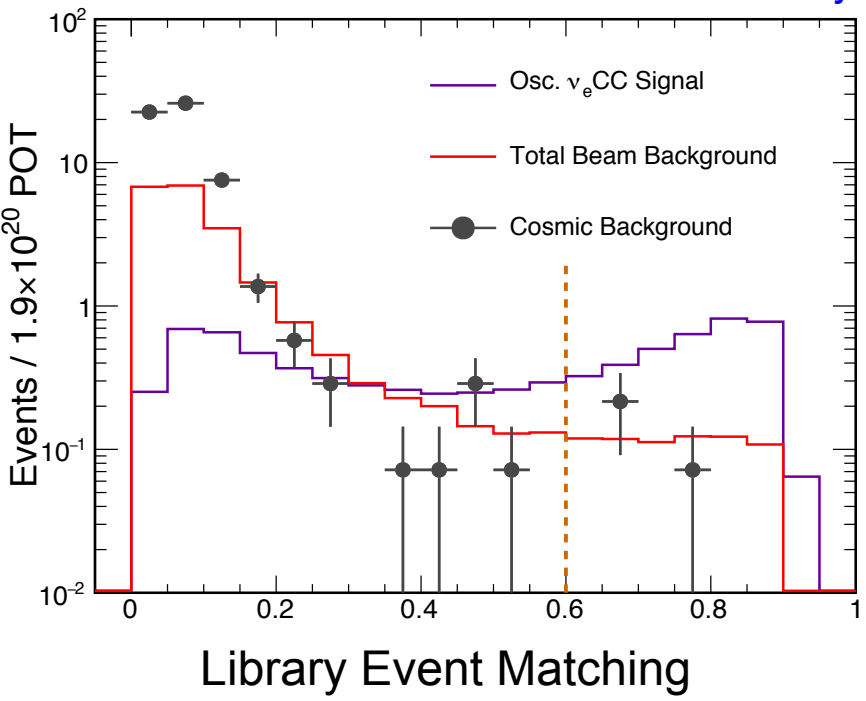
Far Detector

40 million:1 cosmic rejection

Select oscillated ν_e events from the beam and cosmic backgrounds
All backgrounds determined by data driven methods

Two complimentary electron identification algorithms

NOνA Preliminary



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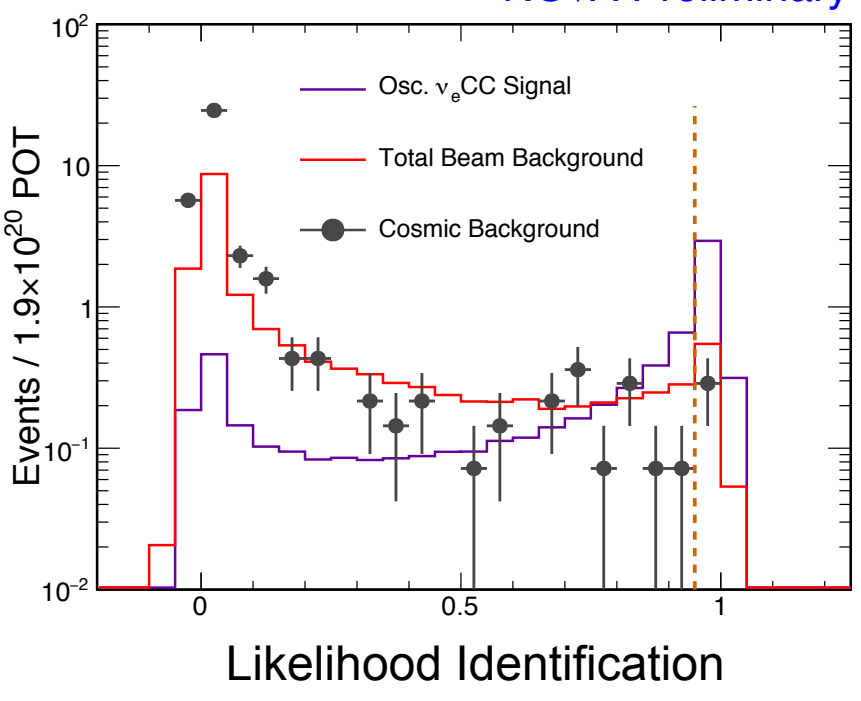
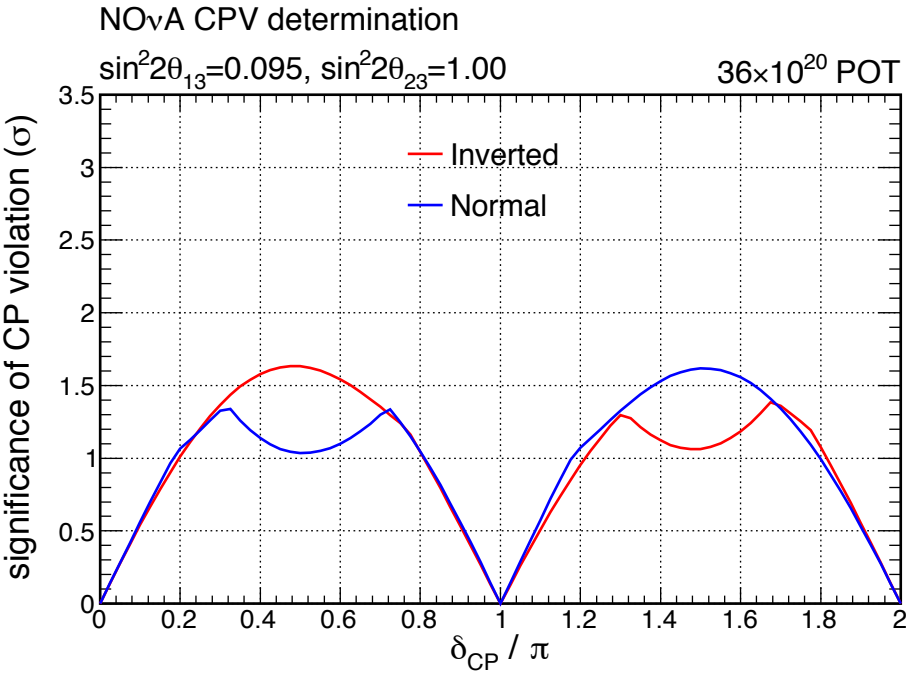


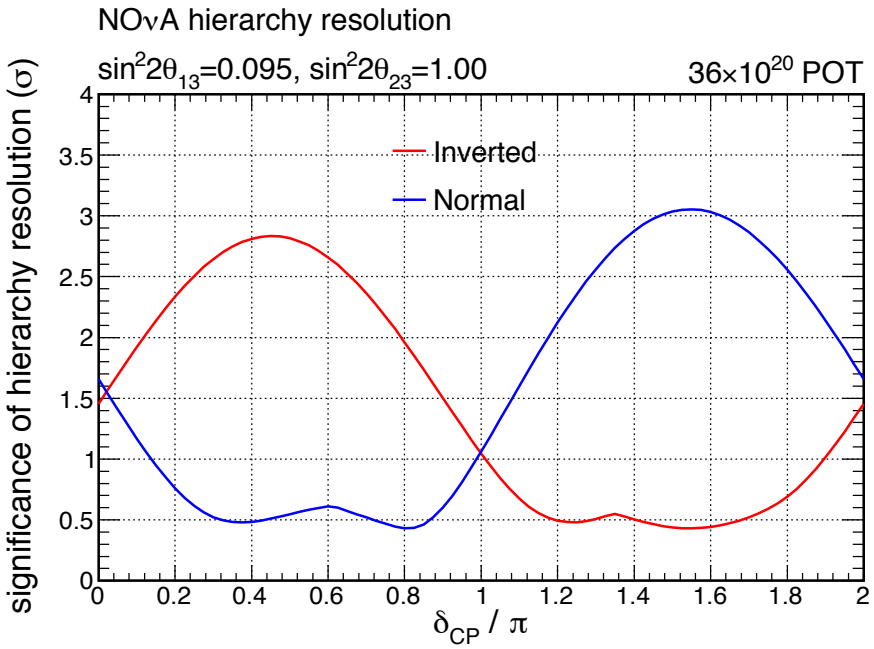
Expect a signal of 3.2 events per background event

ν_e sensitivities after 3+3 years of running

CP violation significance



Mass hierarchy significance



With 3 FHC + 3 RHC years NOvA has a potential neutrino mass hierarchy sensitivity up to 3σ and neutrino sector CP violation up to 1.5σ

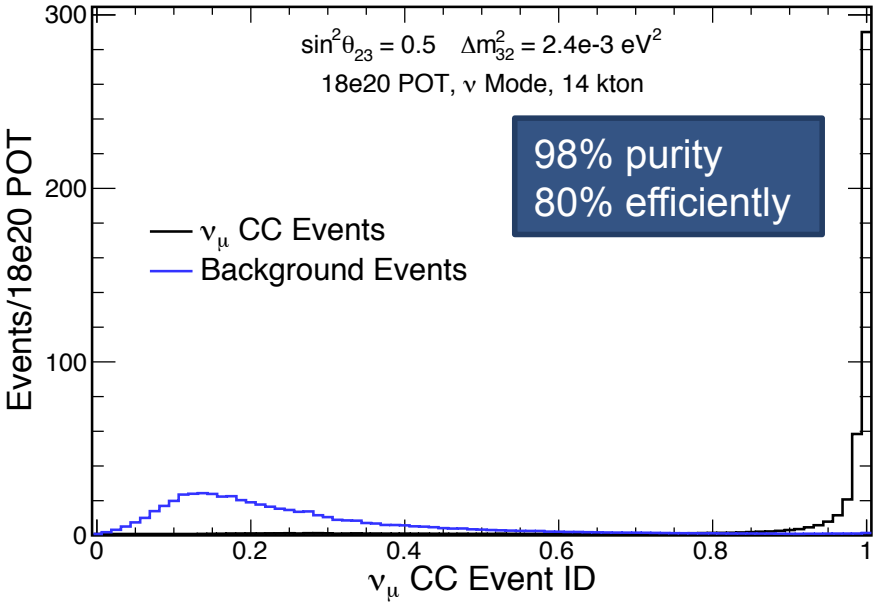
Muon neutrino disappearance event selection

Select charged current ν_μ events from the neutral current and cosmic background

Expect 14 signal events per background event

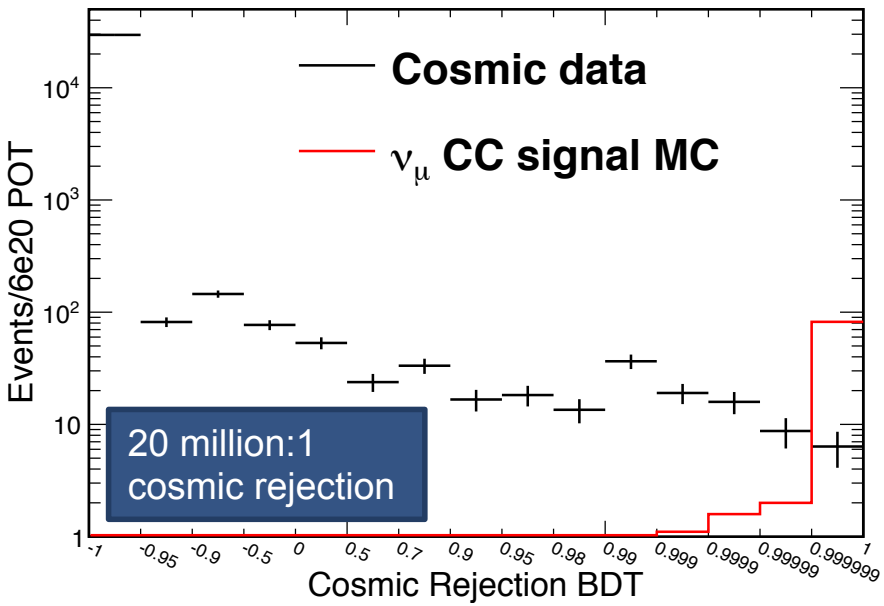
Two complimentary identification algorithms one trained on cosmic muons and one on the NC background

NOνA Simulation



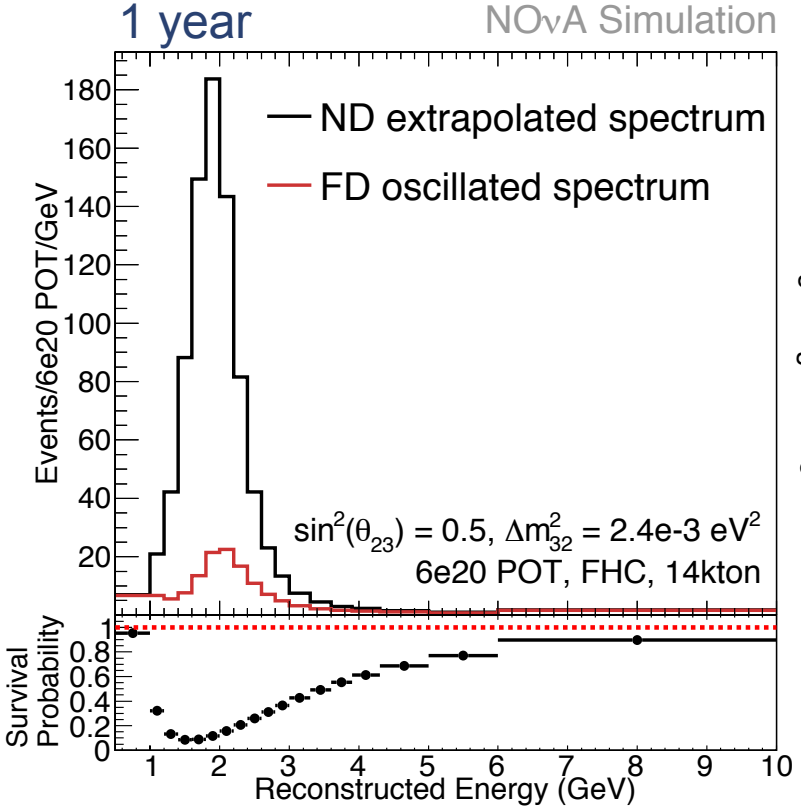
kNN trained on dE/dx likelihoods assuming different particle hypothesis

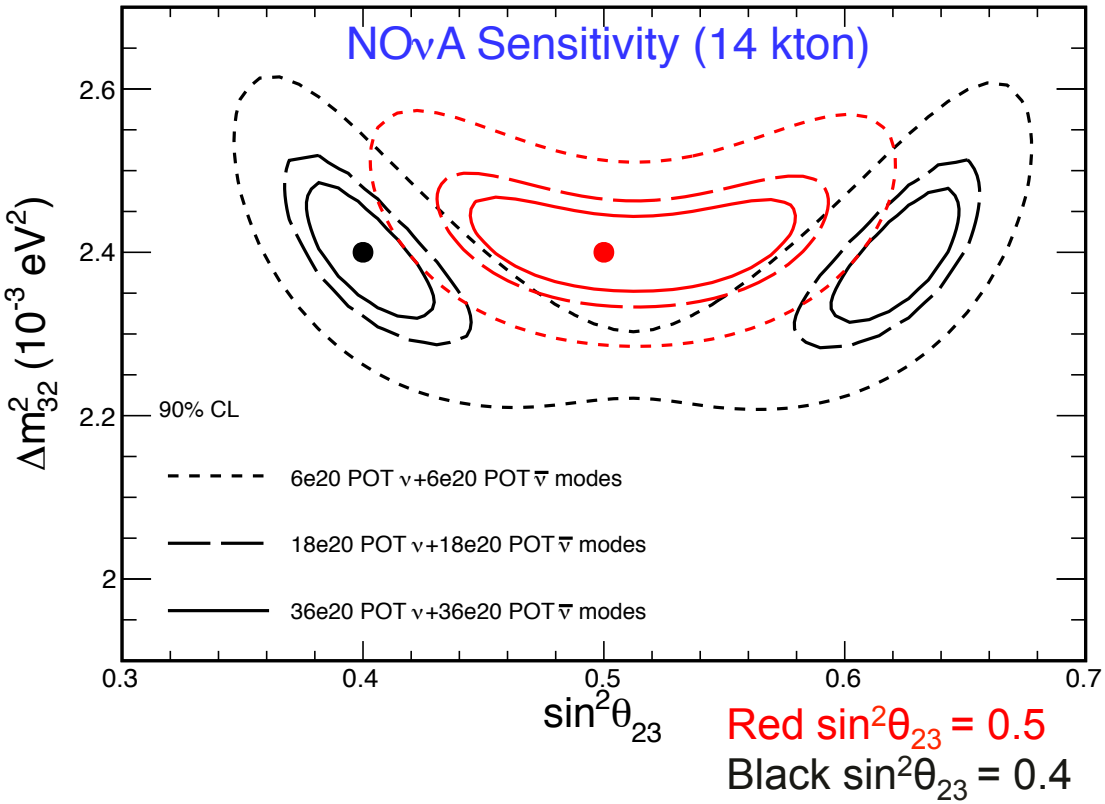
NOνA Preliminary



BDT trained on track direction and position

ν_μ sensitivities

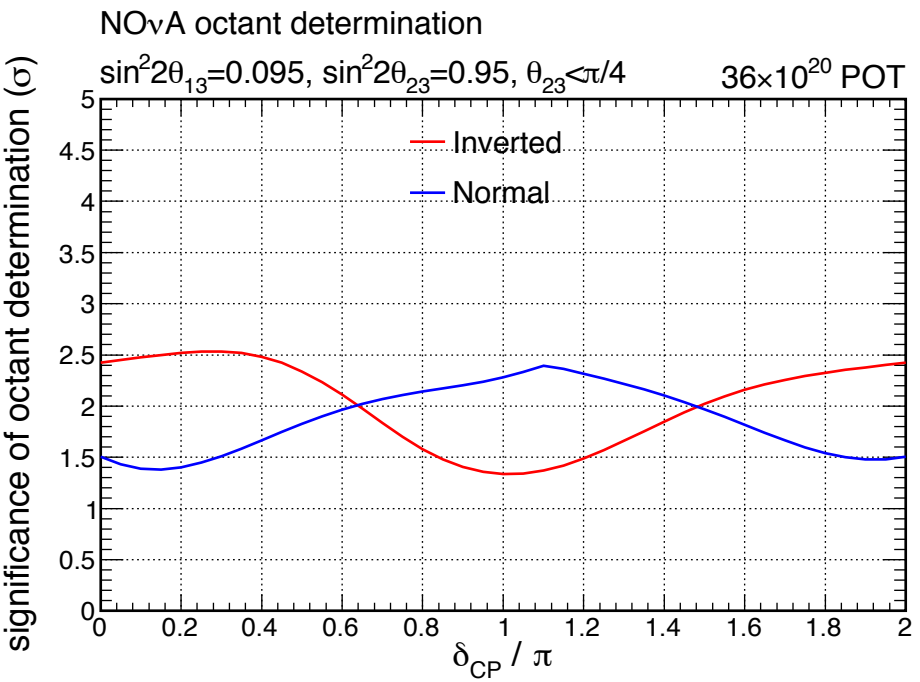




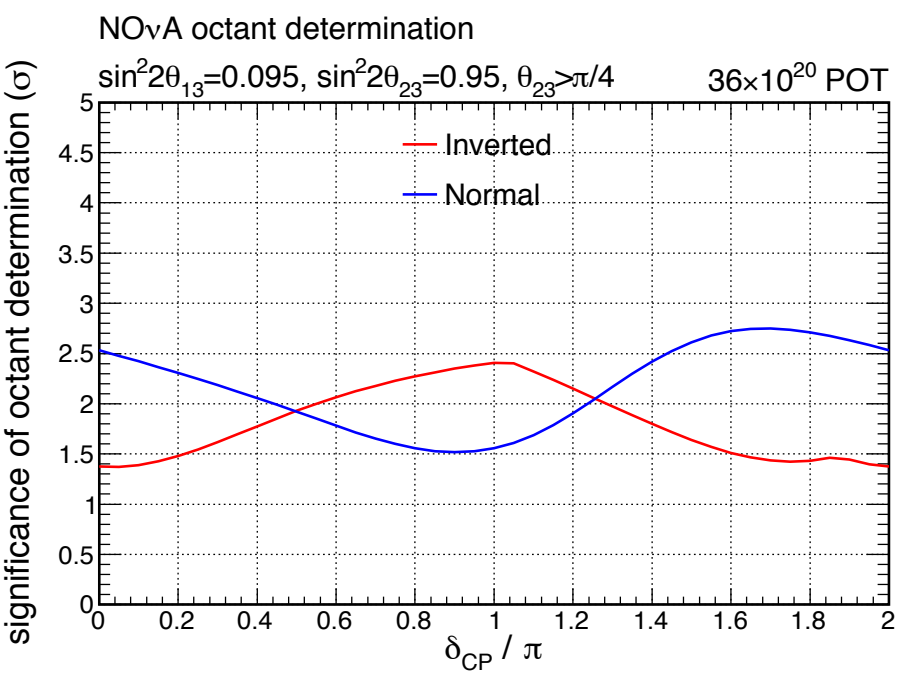
1+1 years of running to exclude maximal mixing at 90% for $\sin^2 2\theta_{23} = 0.95$
3+3 years of running would give percent level uncertainty

Octant determination after 3+3 years of running

Lower Octant



Upper Octant



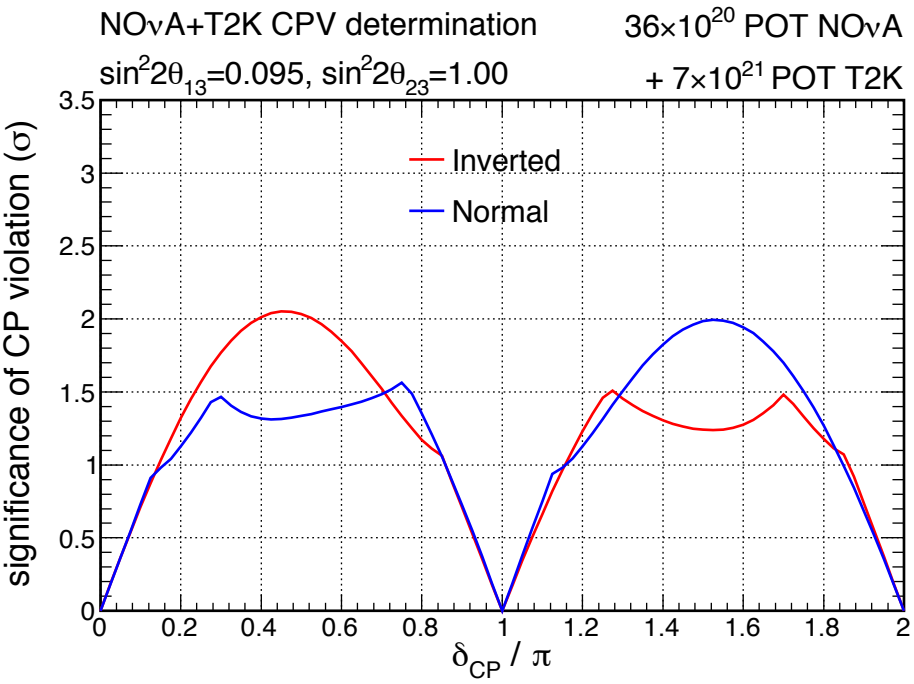
With 3 FHC + 3 RHC years NOvA has a potential sensitivity to the θ_{23} octant up to 2.5σ

Conclusions

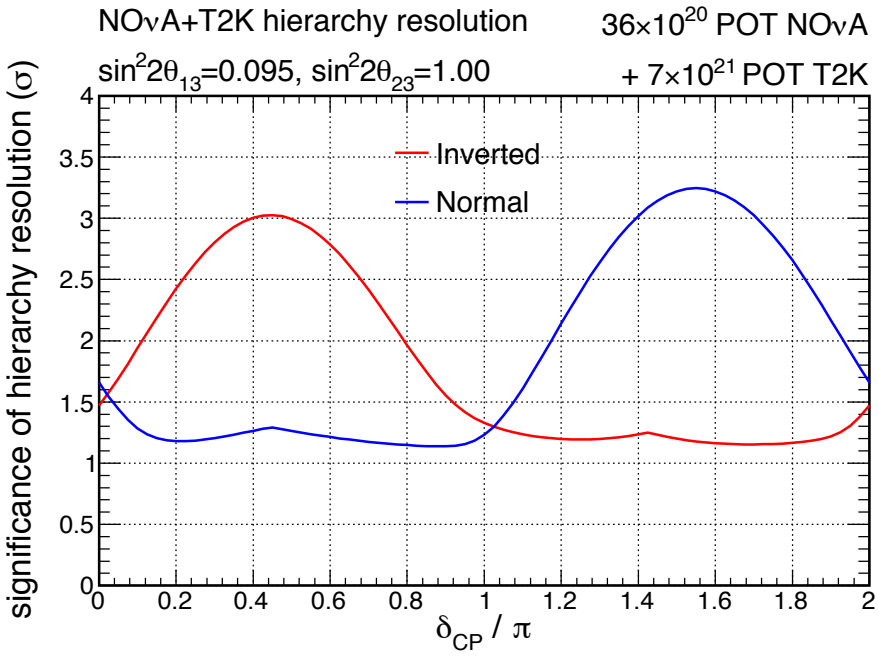
- The NOvA detector showcase a new low-Z large scale detector
- Wide physics reach from oscillation physics, cross sections, to exotics
- Both detectors have been complete and taking data since August 2014
- NOvA will use both appearance and disappearance channels to provide constraints on δ_{CP}, and leading measurements on the mass ordering and the θ_{23} octant
- Expect first analysis results in the coming months, with an expected 14kTon equivalent exposure of 2.5e20 POT (42% of nominal year)

ν_e sensitivities after 3+3 years of running with T2k

CP violation significance



Mass hierarchy significance



With 3 FHC + 3 RHC years NOvA has a potential neutrino mass hierarchy sensitivity up to 3σ and neutrino sector CP violation up to 2σ

Far Detector ν_e Event Predictions

- Predictions of neutrino signal and background event counts come from Near Detector data extrapolated to the Far Detector and are scaled to a full detector equivalent of 2.5×10^{20} POT for the analysis period after preselection and PID cuts have been applied.
- Cosmic background data has been scaled to 96 live-seconds.
- Representative oscillation weight chosen (no matter effect, $\delta_{CP} = 0$, $\sin^2 2\theta_{13} = 0.095$)

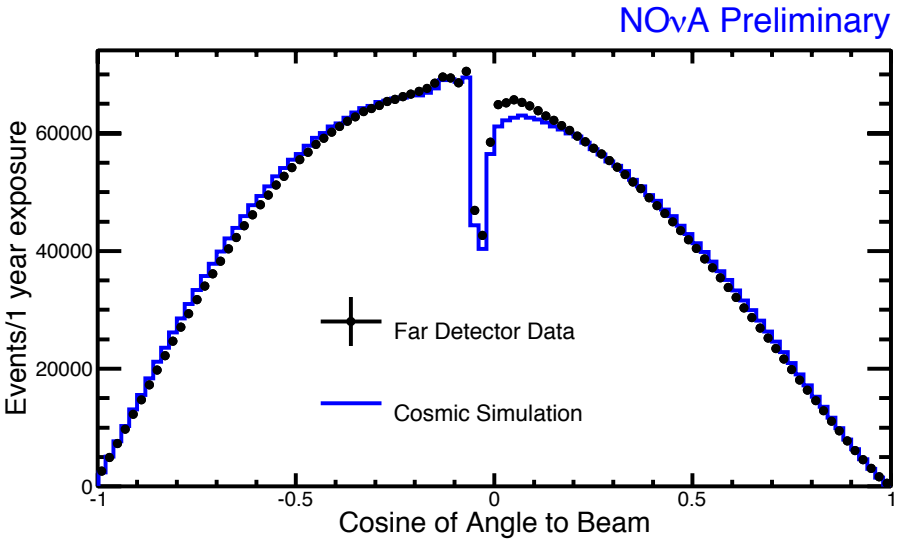
	Osc ν_e	Cosmic bkg.	NC	Osc ν_μ bkg.	Beam ν_e bkg.	Total bkg.
LID	4.4	0.4	0.4	0.07	0.4	1.3
LEM	4.7	0.4	0.5	0.07	0.5	1.5

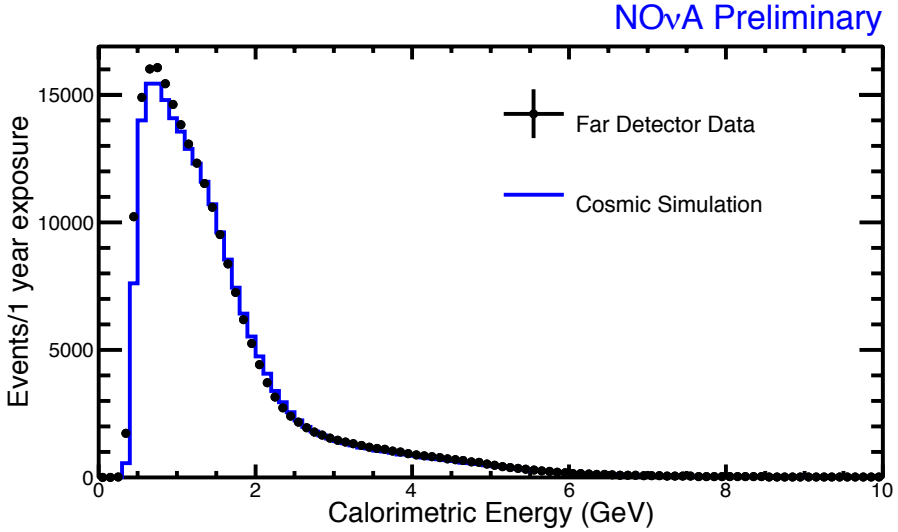
Far Detector ν_μ Event Predictions

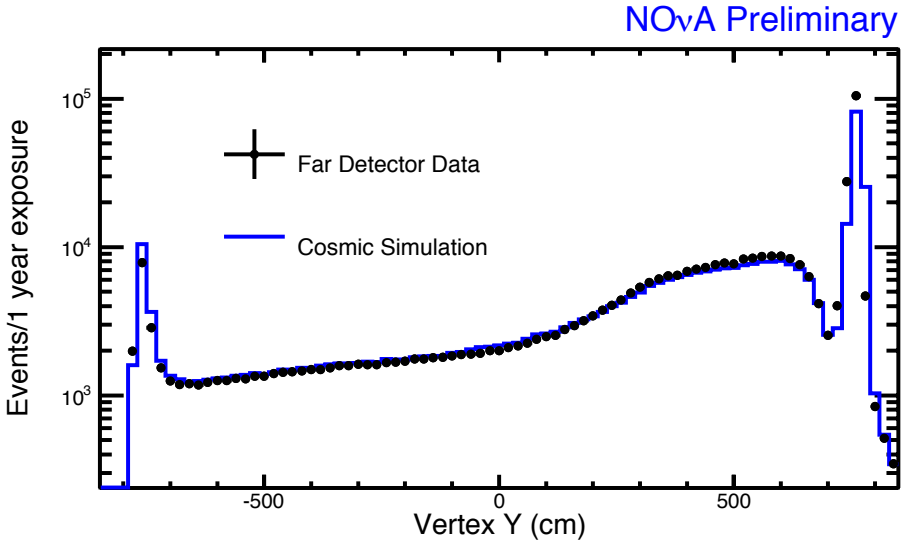
- Predictions of neutrino signal and background event counts come from Near Detector data extrapolated to the Far Detector and are scaled to a full detector equivalent of 2.5×10^{20} POT for the analysis period after preselection and PID cuts have been applied.
- Cosmic background data has been scaled to 96 live-seconds.
- Representative oscillation weight chosen (no matter effect, $\delta_{CP} = 0$, $\sin^2 2\theta_{13} = 0.095$)

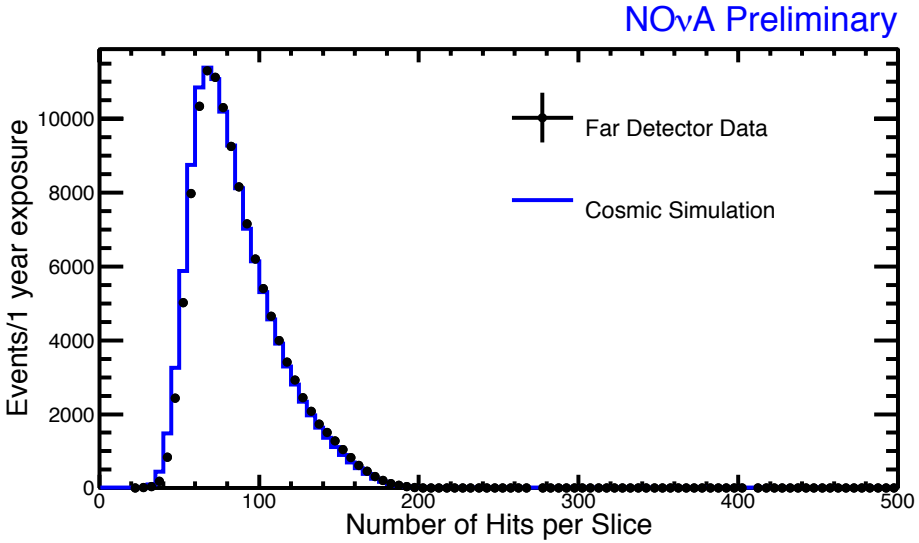
Osc ν_μ	Cosmic bkg.	NC	Osc ν_e bkg.	Beam ν_e bkg.	Total bkg.
32.5	0.4	1.8	0.1	0.04	2.34

Comparison of cosmic data and MC

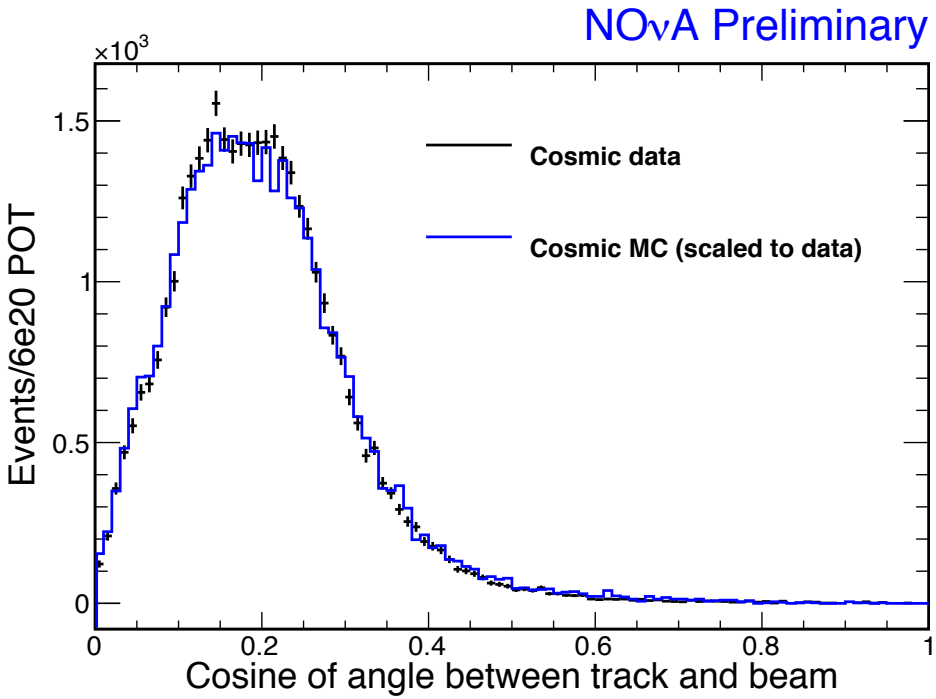


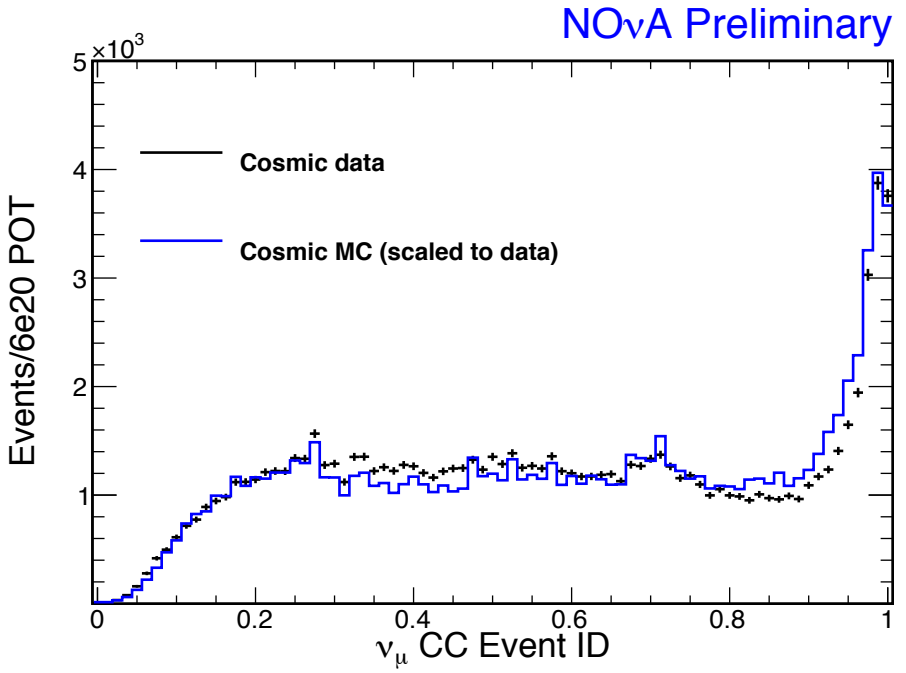




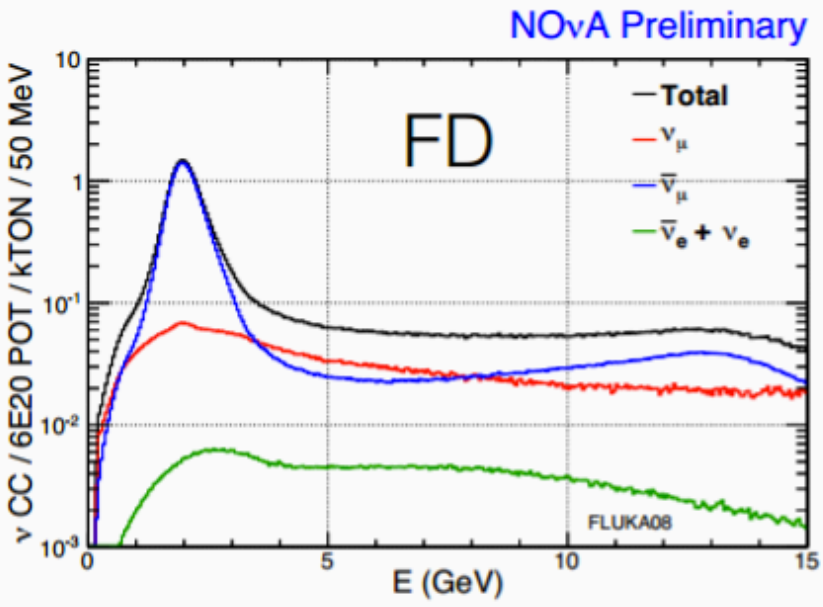


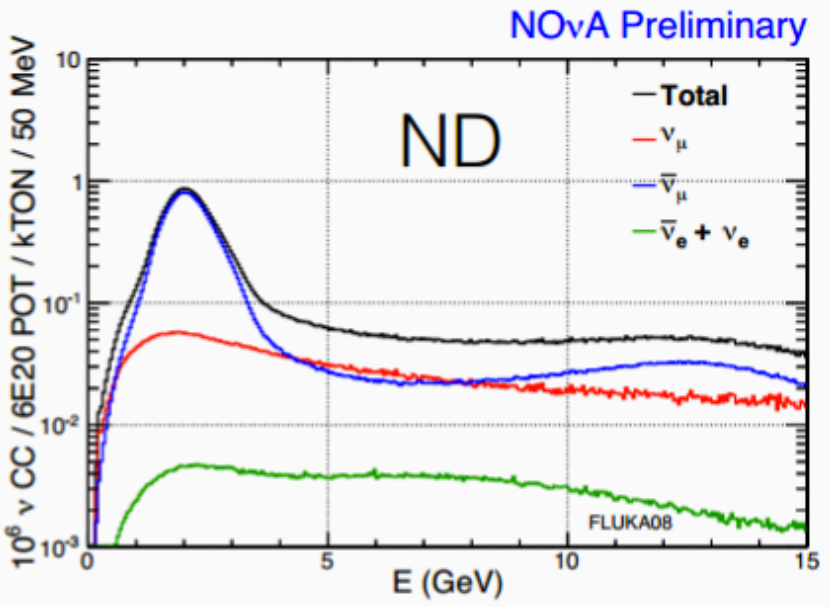
Comparison of cosmic data and MC





Reverse Horn current





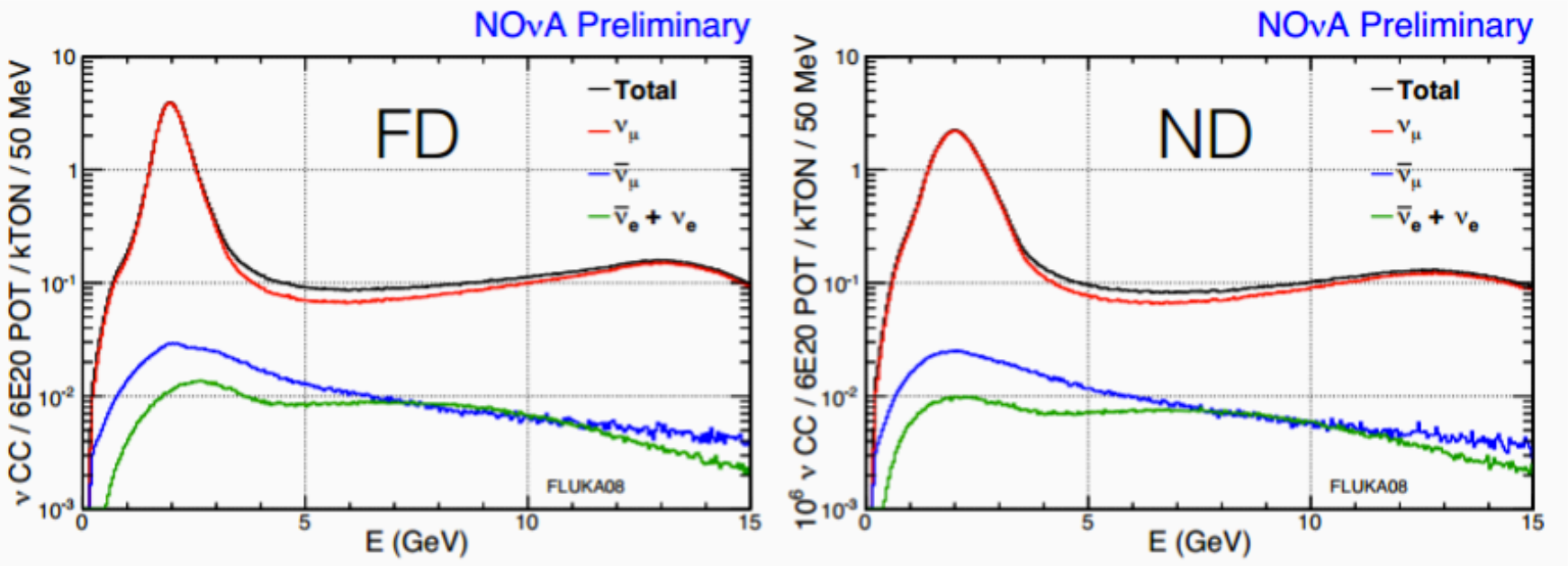
	[1,3]GeV	[0,120]Gev
Total	25.1	46.7
Numu	2.4	13.2
Anti-Numu	22.5	32.2
Nue+Anti-Nue	0.2	1.3

x10⁶	[1,3]GeV	[0,120]Gev
Total	21.4	42.3
Numu	2.1	11.9
Anti-Numu	19.1	29.3
Nue+Anti-Nue	0.2	1.1

[1,3]GeV: $(\nu_e + \bar{\nu}_e)/\nu_\mu = 0.8\%$

[1,3]GeV: $(\nu_e + \bar{\nu}_e)/\nu_\mu = 1.0\%$

Forward Horn current



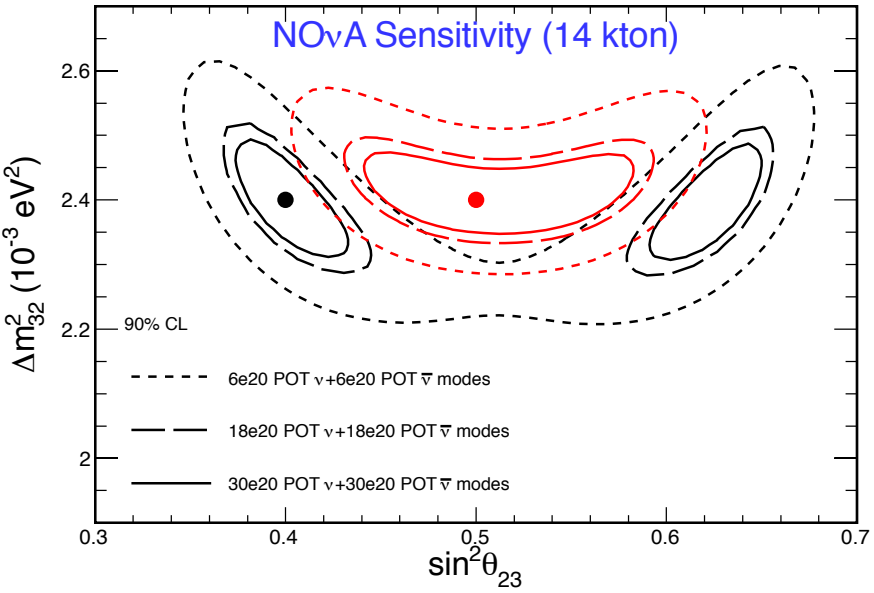
	[1,3]GeV	[0,120]Gev
Total	63.5	103.8
Numu	62.1	97.6
Anti-Numu	1.0	3.9
Nue+Anti-Nue	0.4	2.3

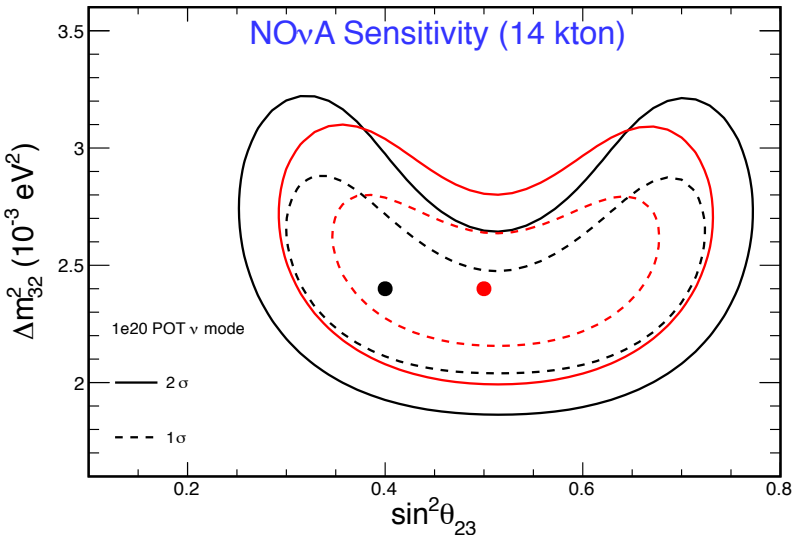
x10^6	[1,3]GeV	[0,120]Gev
Total	53.9	95.0
Numu	52.6	89.5
Anti-Numu	0.9	3.5
Nue+Anti-Nue	0.4	2.0

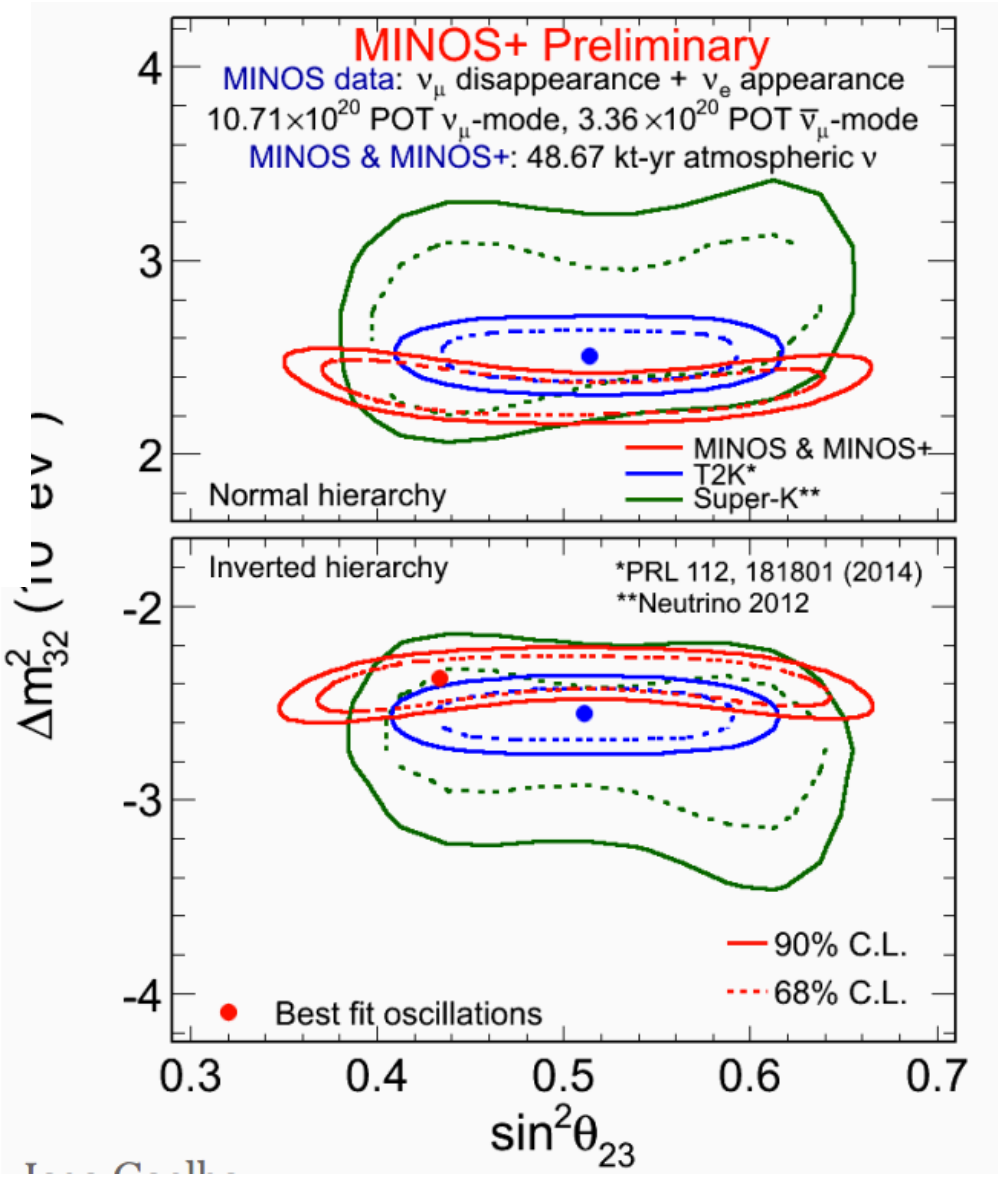
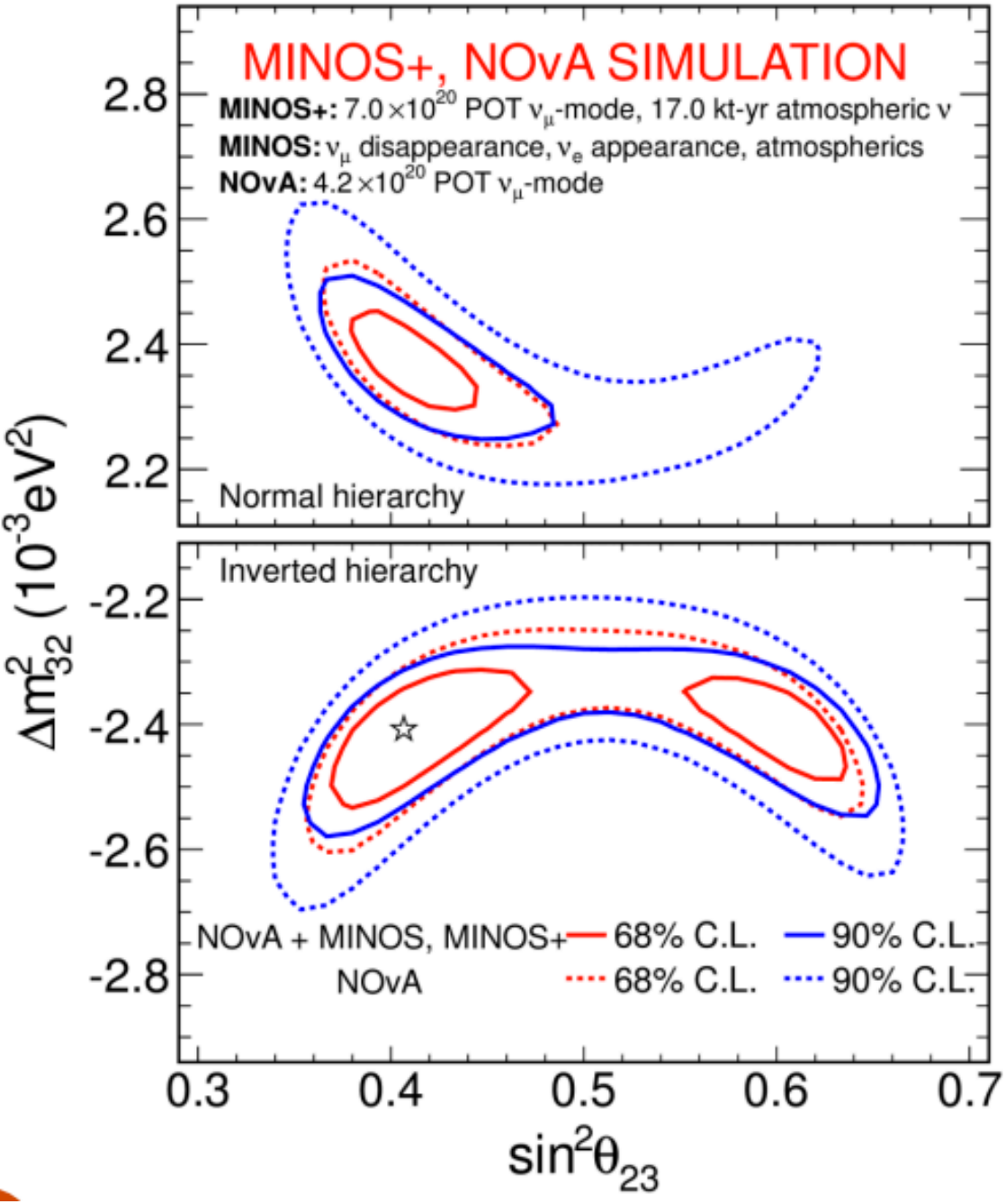
[1,3]GeV: $(\nu_e + \bar{\nu}_e)/\nu_\mu = 0.6\%$

[1,3]GeV: $(\nu_e + \bar{\nu}_e)/\nu_\mu = 0.7\%$

Comparison to MINOS







MINOS and NOvA Combination