The NOvA Experiment

Mark Messier
Indiana University / Caltech
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Implications of Neutrino Flaver Oscillations (INFO) 2011
Sante Fe, New Mexico

NOvA Collaboration

24 Institutions
110 physicists

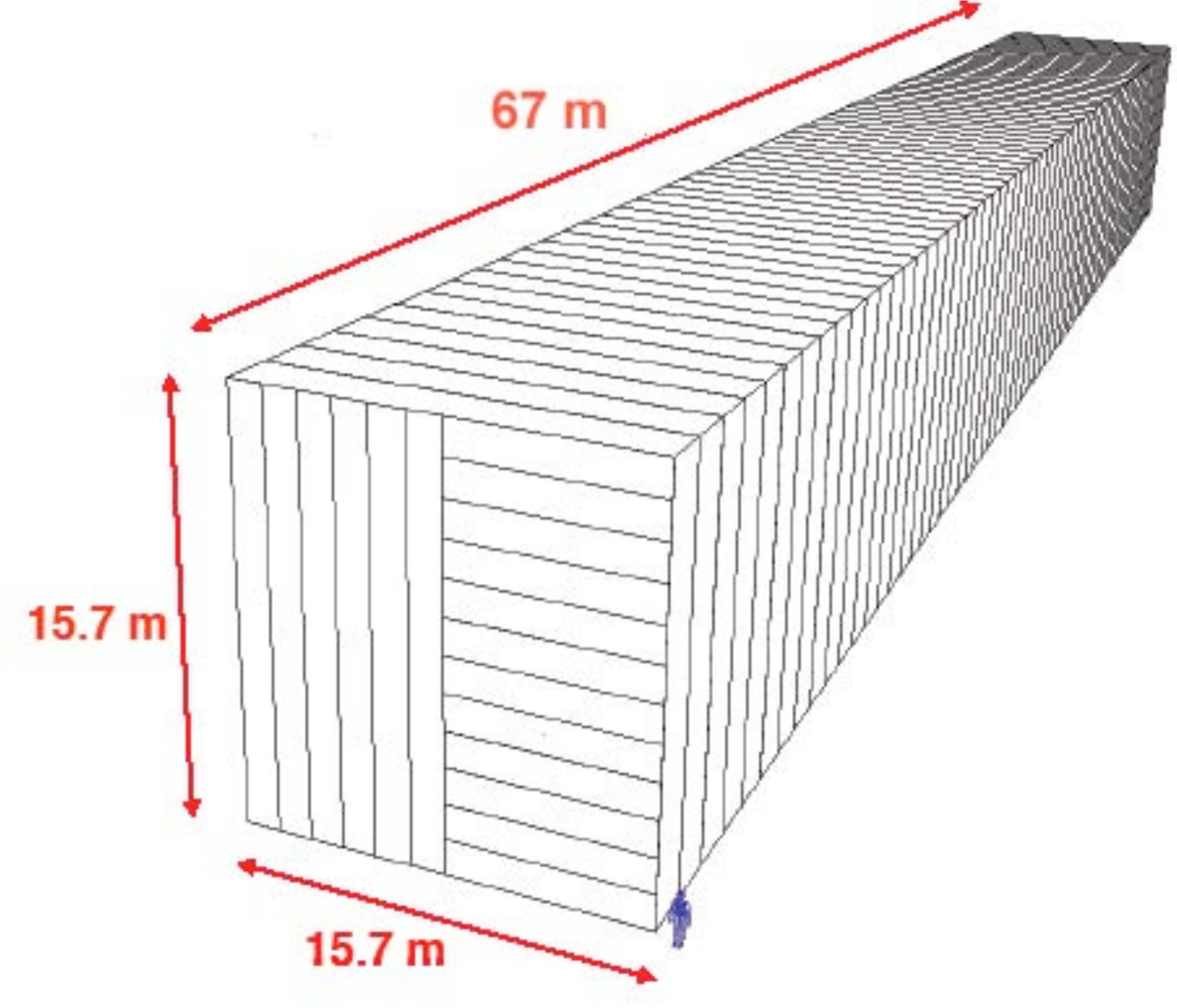
The NOvA Experiment

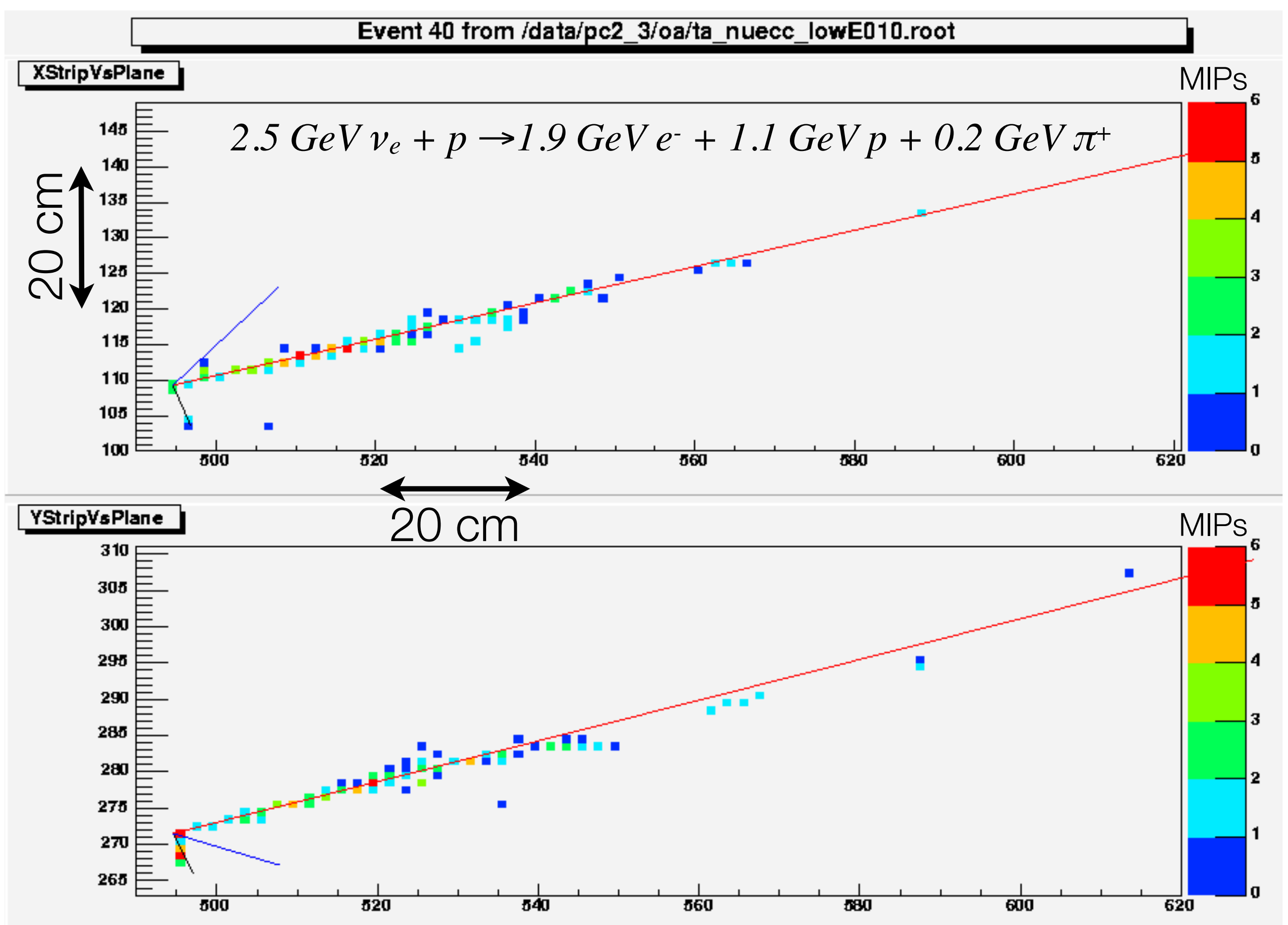
- "Executive summary" of the experiment
  - Experimental setup
  - Overview of physics program
- NOvA Physics
  - Neutrino oscillations and NOvA
  - $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ channels
  - $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ channels
- The NOvA detectors
  - Detector design
  - Construction progress and schedule
  - NOvA prototype detector
- Future ideas for NOvA

The NOvA Experiment

- NOvA is a second generation experiment on the NuMI beamline which is optimized for the detection of $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations

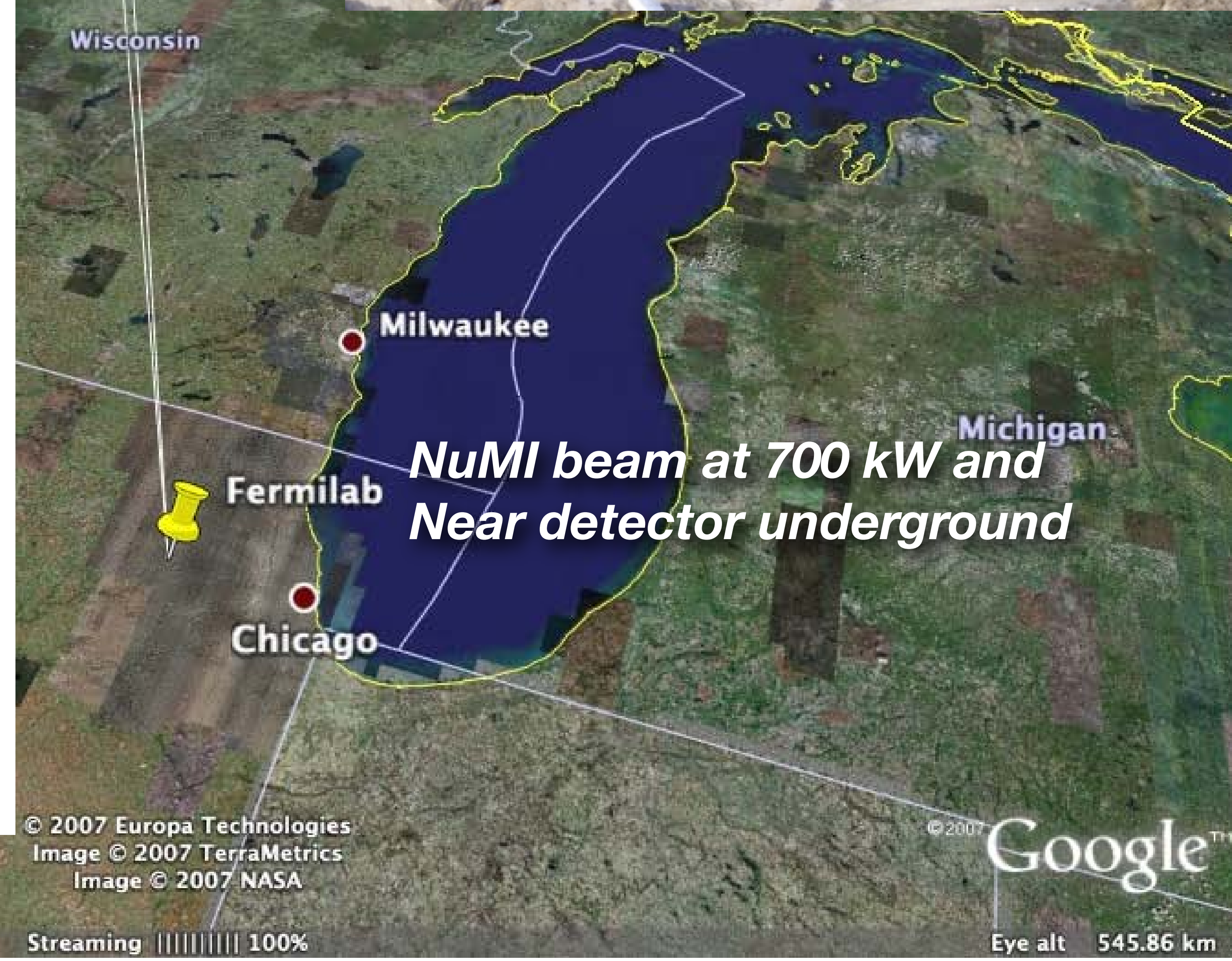
- NOvA is:
  - An upgrade of the NuMI beam intensity from 400 kW to 700 kW
  - A 15 kt "totally active" tracking liquid scintillator calorimeter sited 14 mrad off the NuMI beam axis at a distance of 810 km
  - A 220 ton near detector identical to the far detector sited 14 mrad off the NuMI beam axis at a distance of 1 km

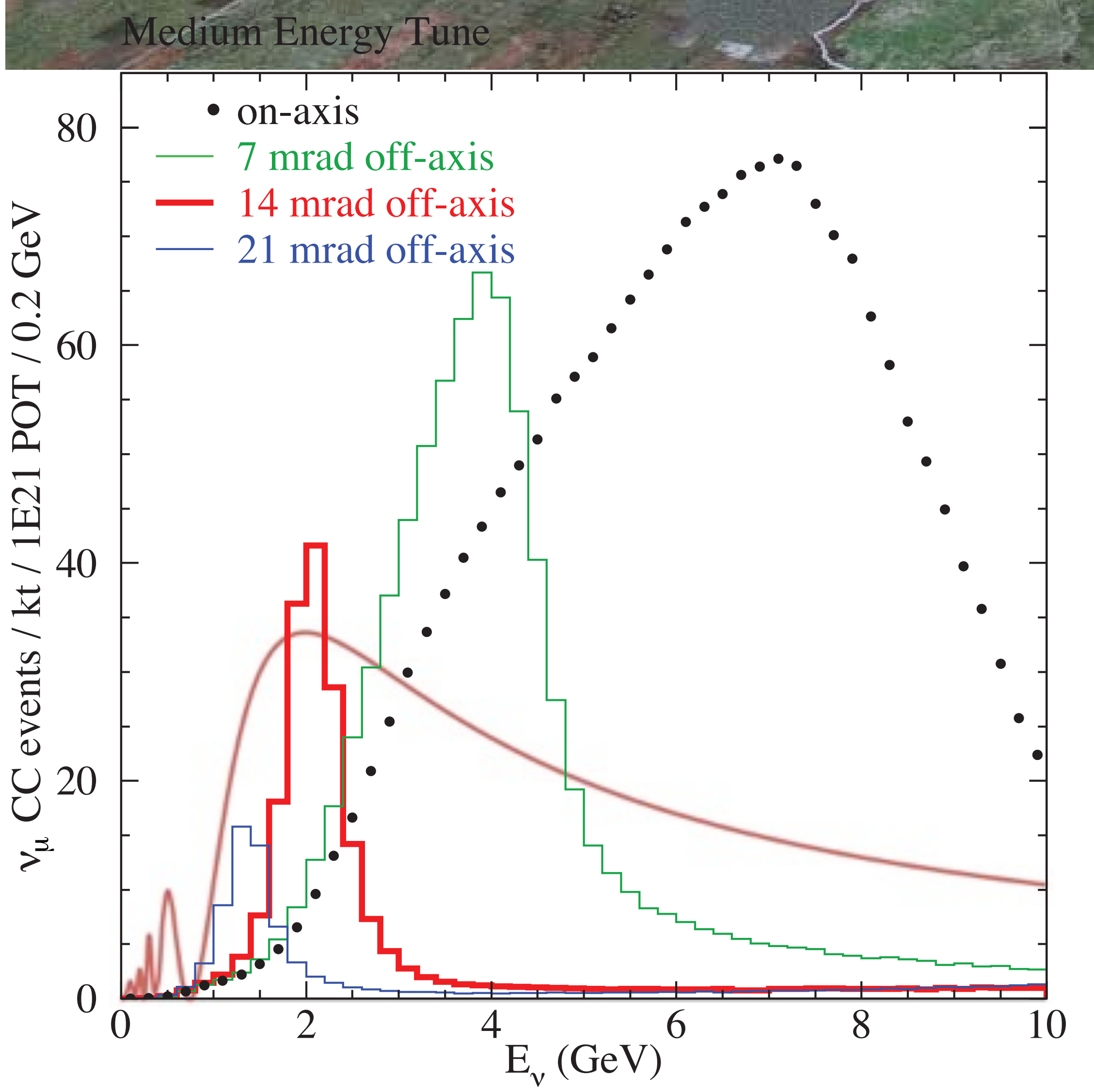




NOvA Far Detector Location

Ash River, MN
810 km from Fermilab





NuMI beam at 700 kW and
Near detector underground

Event quality

Topologies of basic interaction channels shown at right. Each "pixel" is a single 4 cm x 6 cm x 15 m cell of liquid scintillator

Top: ν_μ *charged-current*

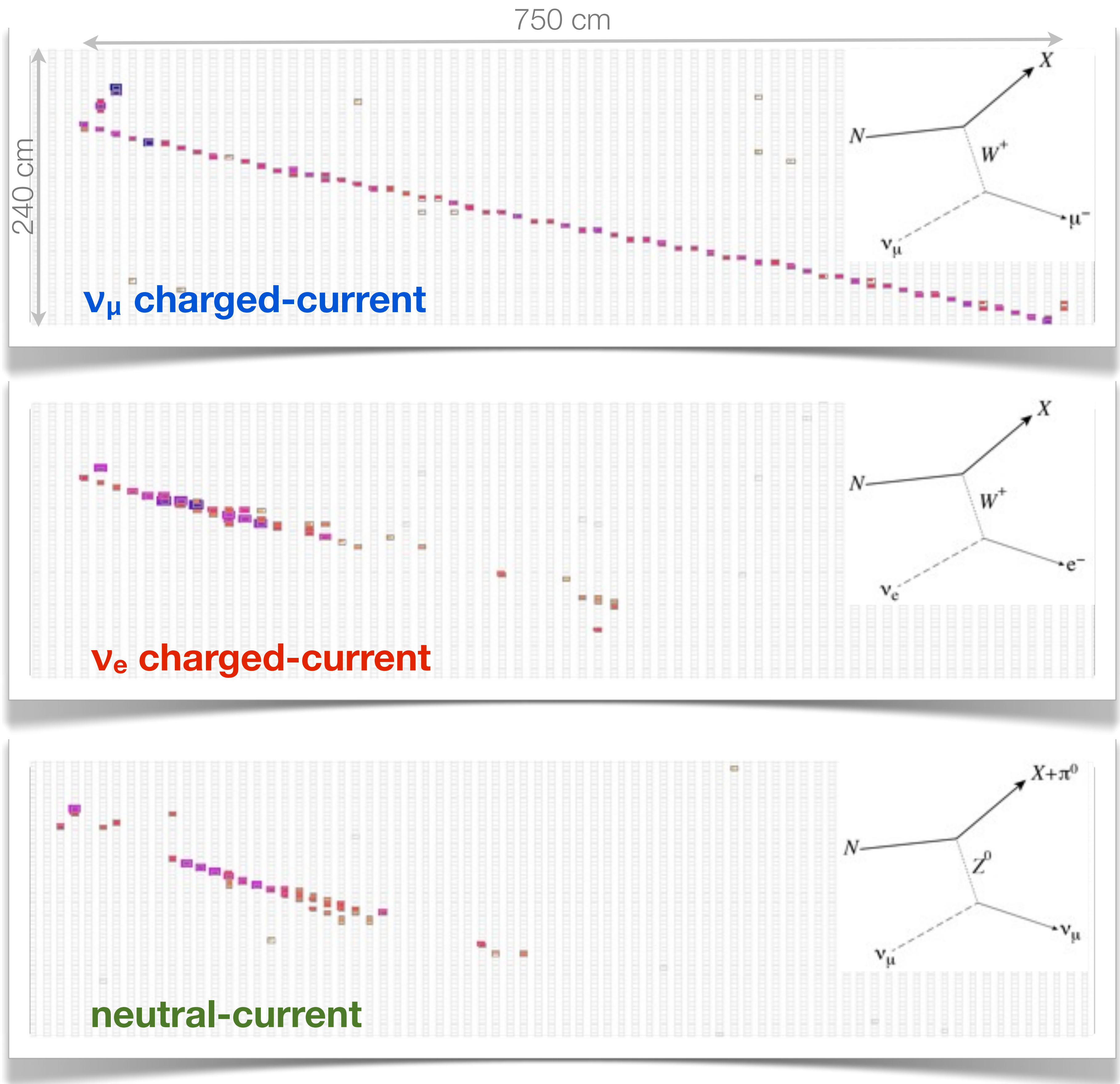
Center: ν_e *charged-current*

Bottom: *neutral-current*

Need >100:1 rejection against background

Detector challenge: Achieve large target mass (10's+ kilotons) while maintaining high granularity to avoid confusing the detection channels

NOvA achieves 35% efficiency for ν_e CC while limiting NC→ν_e CC fake rate to 0.1%



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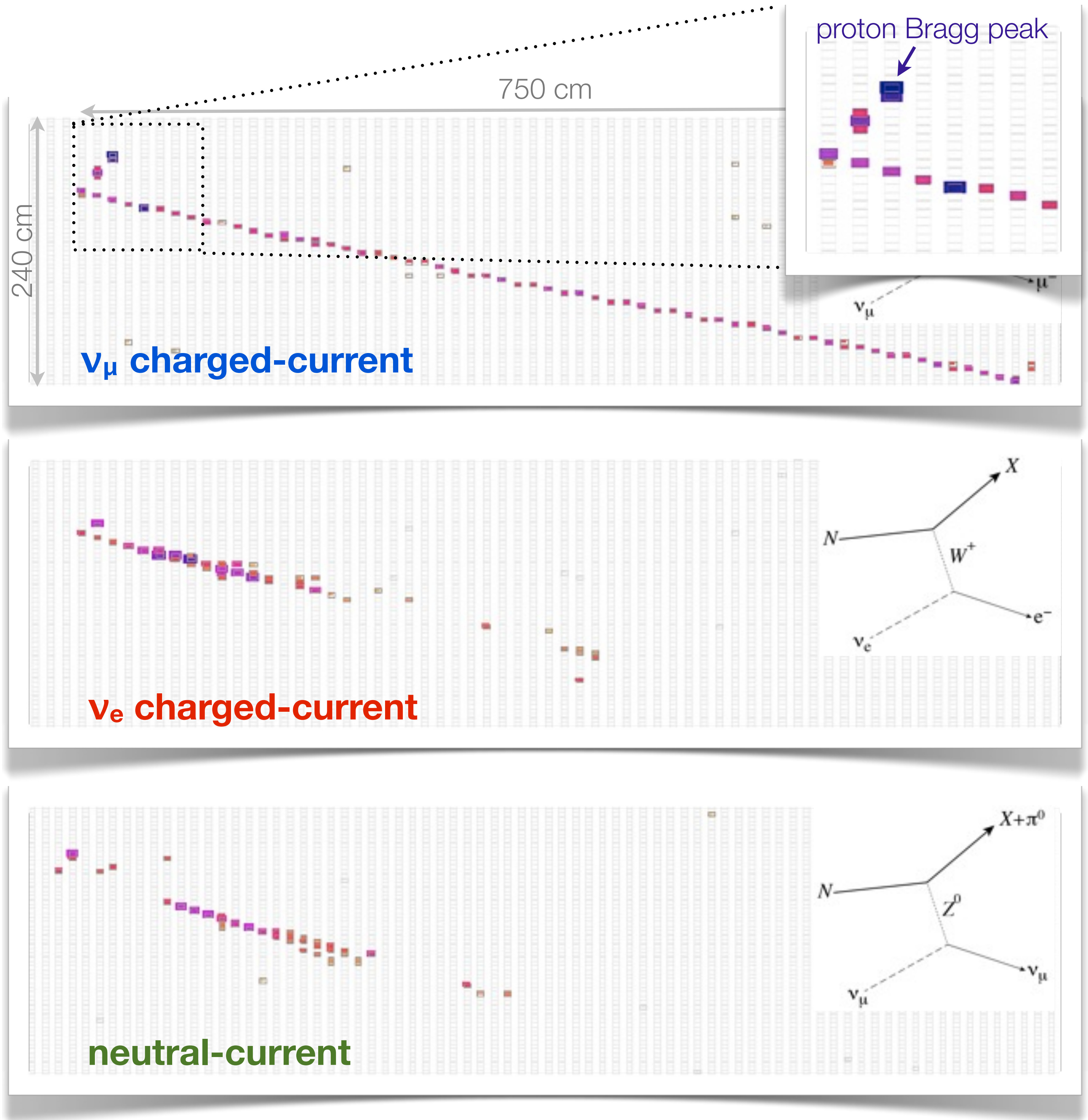

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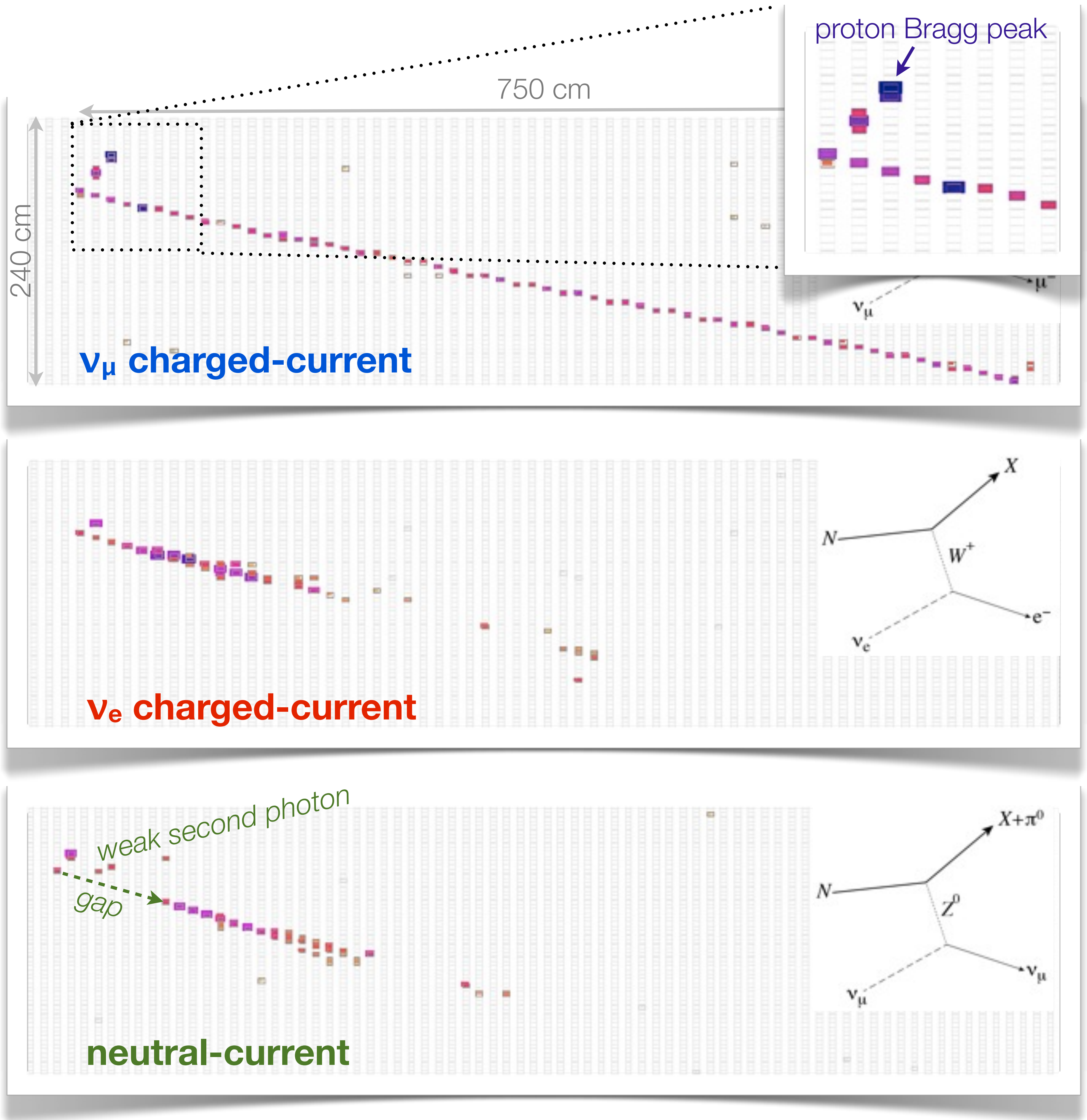

Questions for the future

As the first chapter in the study of neutrino oscillations comes to an end, a new chapter begins. The great progress in neutrino physics over the last few decades raises new questions and provides opportunities for major discoveries. Among the compelling issues today:

1) What is the value of θ_{13}, the mixing angle between first- and third-generation neutrinos for which, so far, experiments have only established limits? Determining the size of θ_{13} has critical importance not only because it is a fundamental parameter, but because its value will determine the tactics to best address many other questions in neutrino physics.

2) Do neutrino oscillations violate CP? If so, how can neutrino CP violation drive a matter-antimatter asymmetry among leptons in the early universe (leptogenesis)? What is the value of the CP violating phase, which is so far completely unknown? Is CP violation among neutrinos related to CP violation in the quark sector?

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4) Is θ_{23} maximal (45 degrees)? if so, why? Will the pattern of neutrino mixing provide insights regarding unification of the fundamental forces? Will it indicate new symmetries or new selection rules?

5) Are neutrinos their own antiparticles? Do they give rise to lepton number violation, or leptogenesis, in the early universe? Do they have observable laboratory consequences such as the sought-after neutrinoless double beta decay in nuclei?

6) What can we learn from observation of the intense flux of neutrinos from a supernova within our galaxy? Can we observe the neutrino remnants of all supernovae that have occurred since the beginning of time?

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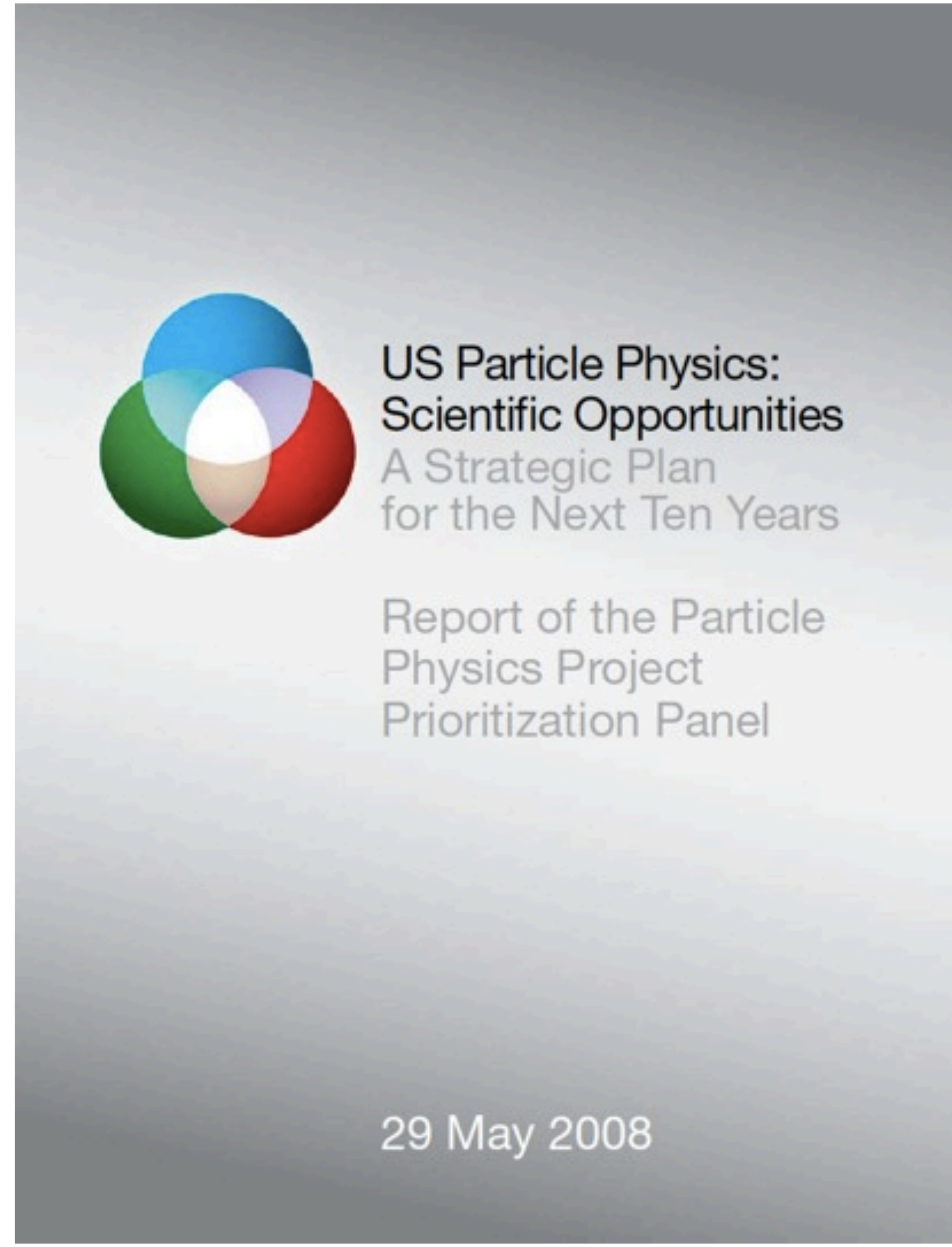

excerpted from US Particle Physics: Scientific Opportunities. A Strategic Plan for the Next Ten Years. Report of the Particle Physics Project Prioritization Panel, May 2008

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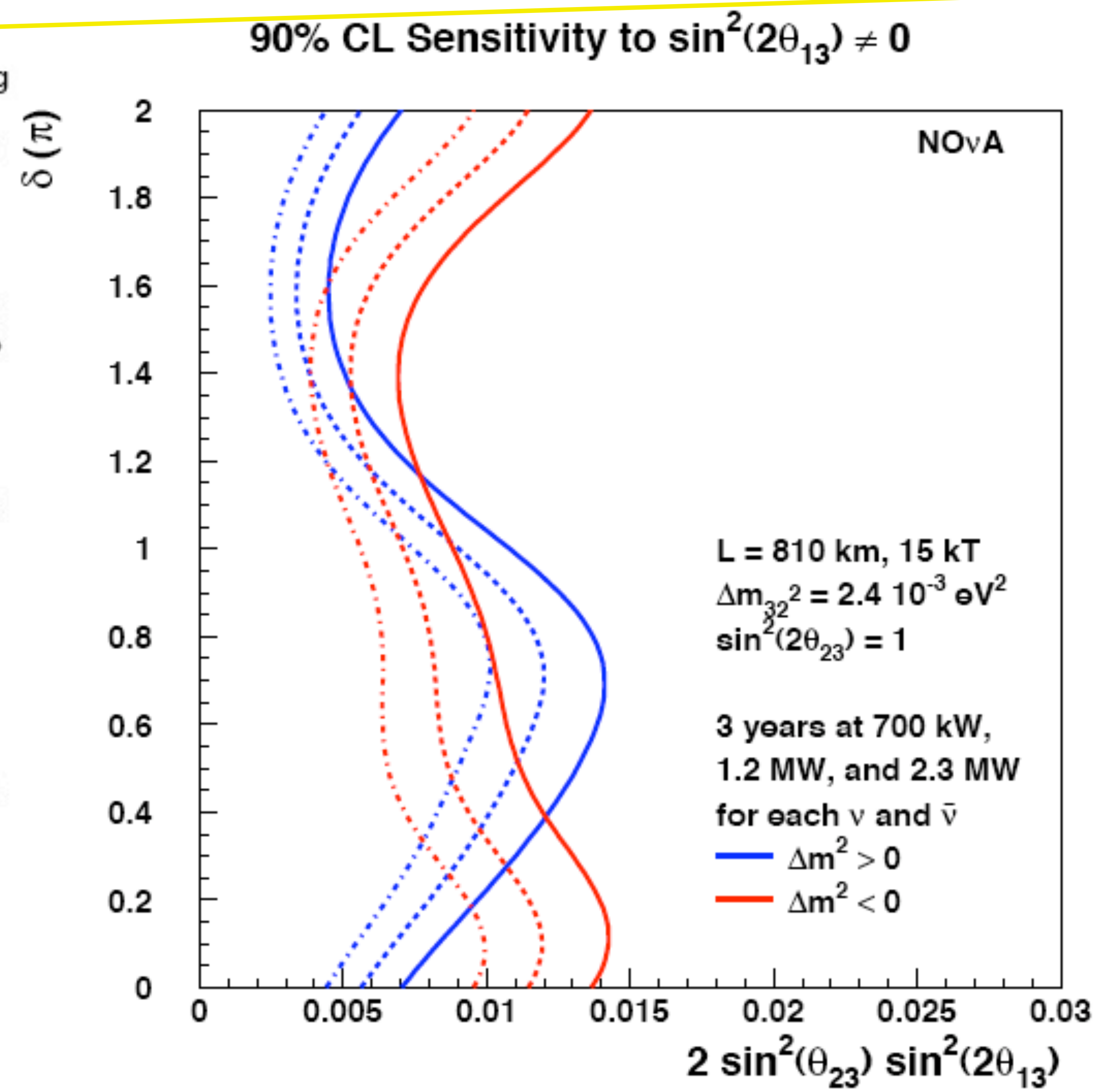

NOvA searches for electron neutrino appearance down to ~0.01 at 90% CL

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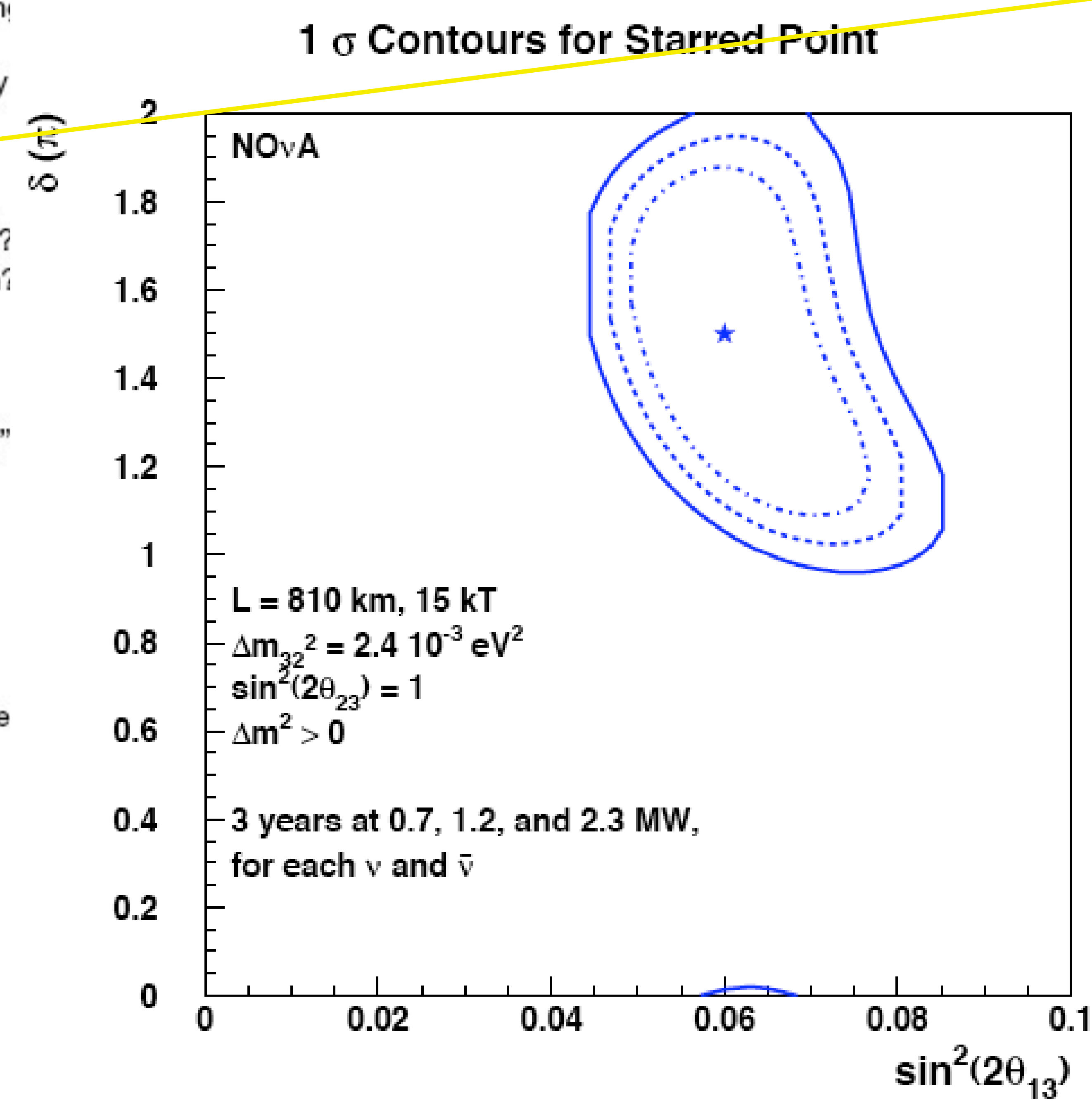

NOvA provides the first look into the CPV parameter space

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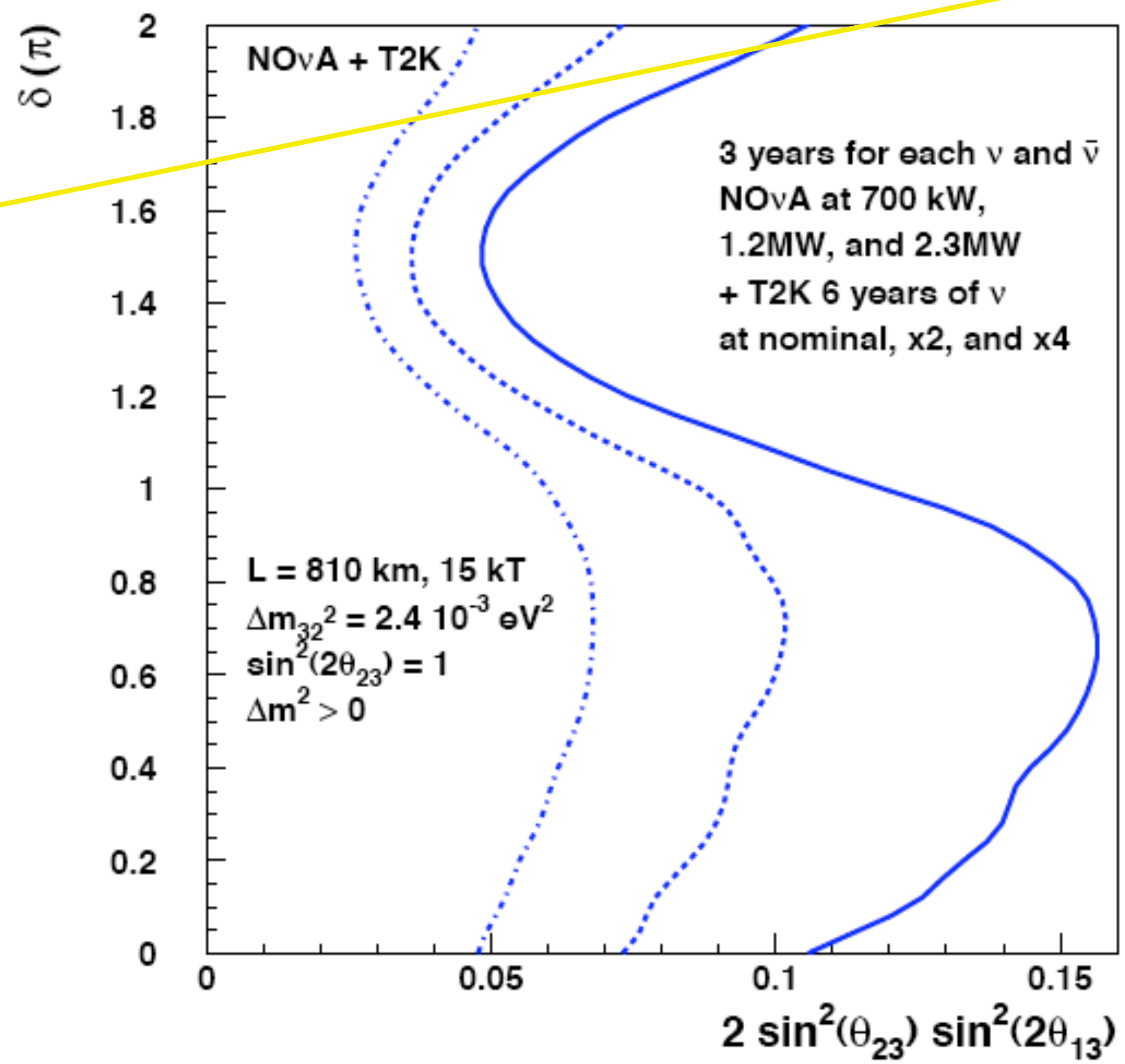

NOvA's long baseline makes it sensitive to the mass ordering

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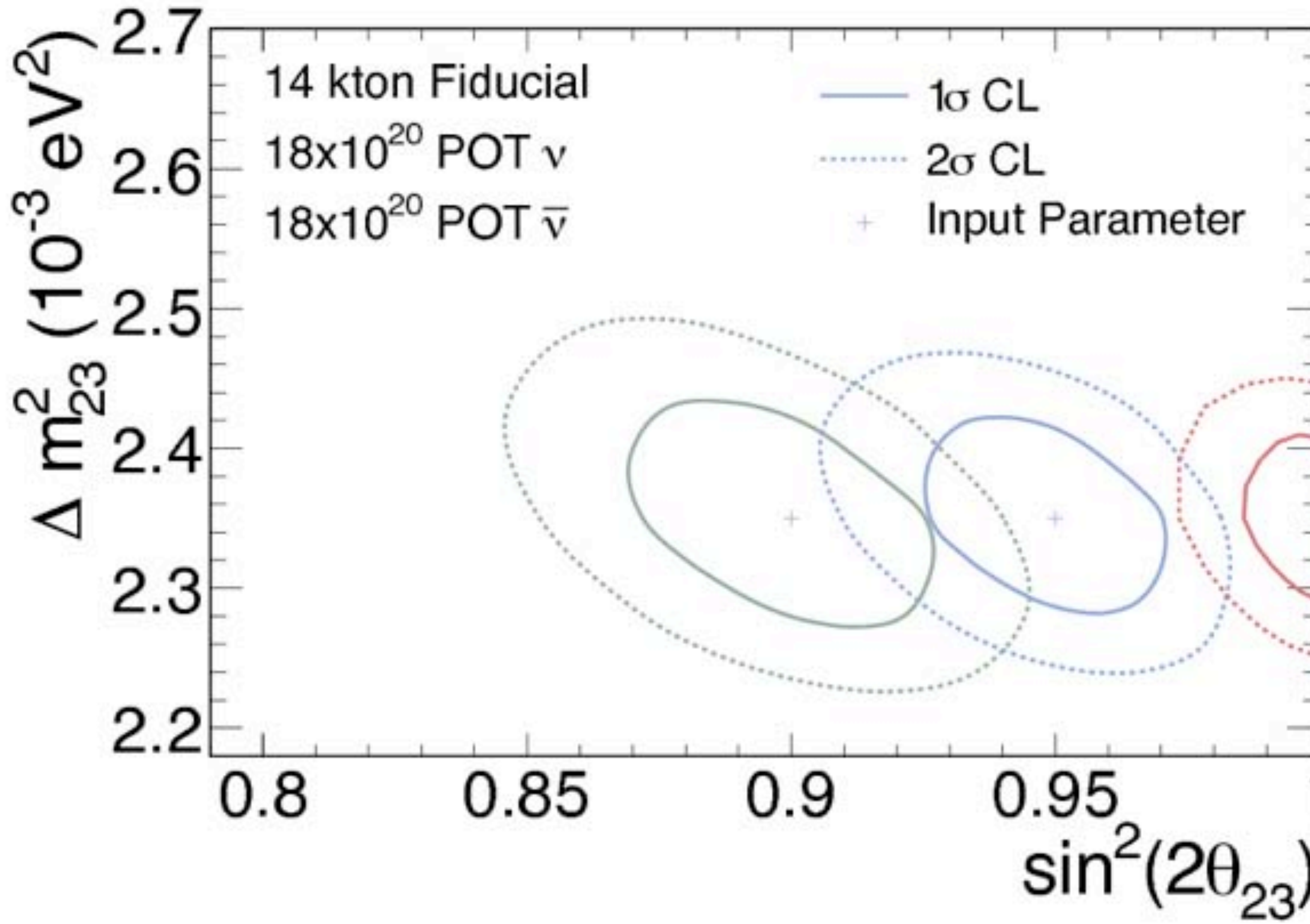

4) Is θ_{23} maximal?

Because of its excellent energy resolution NOvA can make ~1% measurements of muon neutrino disappearance using quasi-elastic channel

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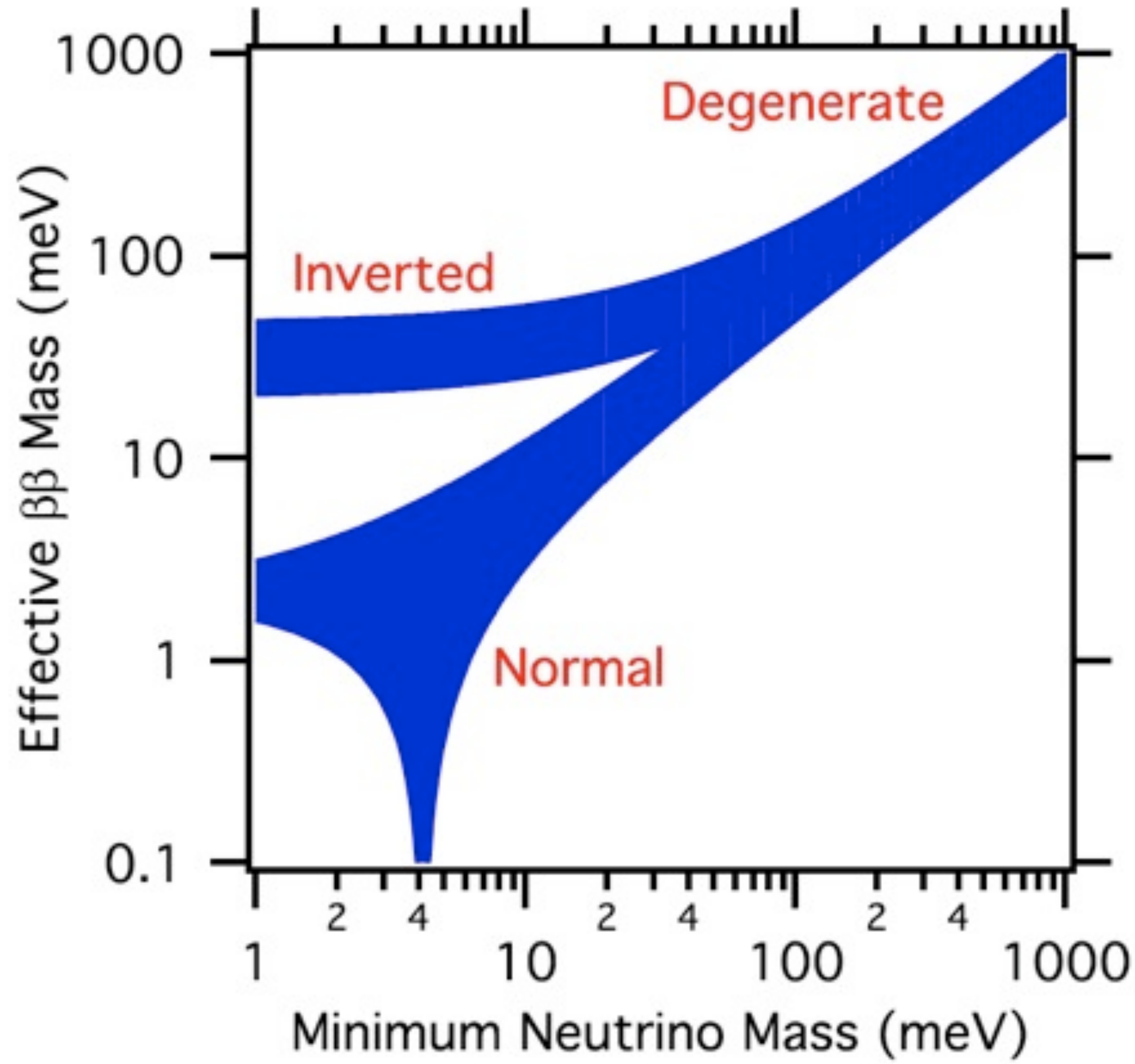

If NOvA establishes inverted hierarchy and next generation of $0\nu\beta\beta$ experiments see nothing, then it is very likely that neutrinos are Dirac particles

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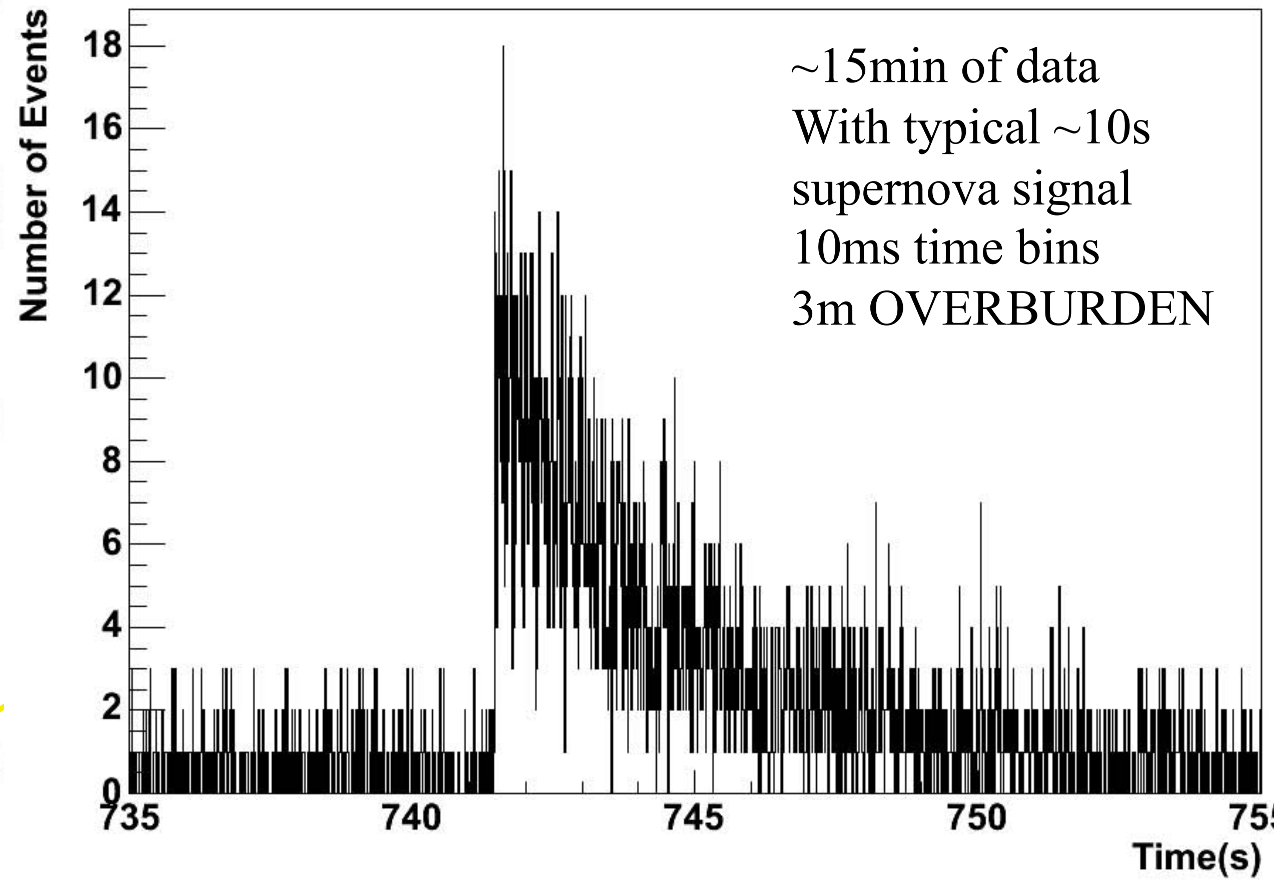
6) ...supernova within our galaxy?



NOvA would see burst of 5000 events for a supernova at the center of the galaxy

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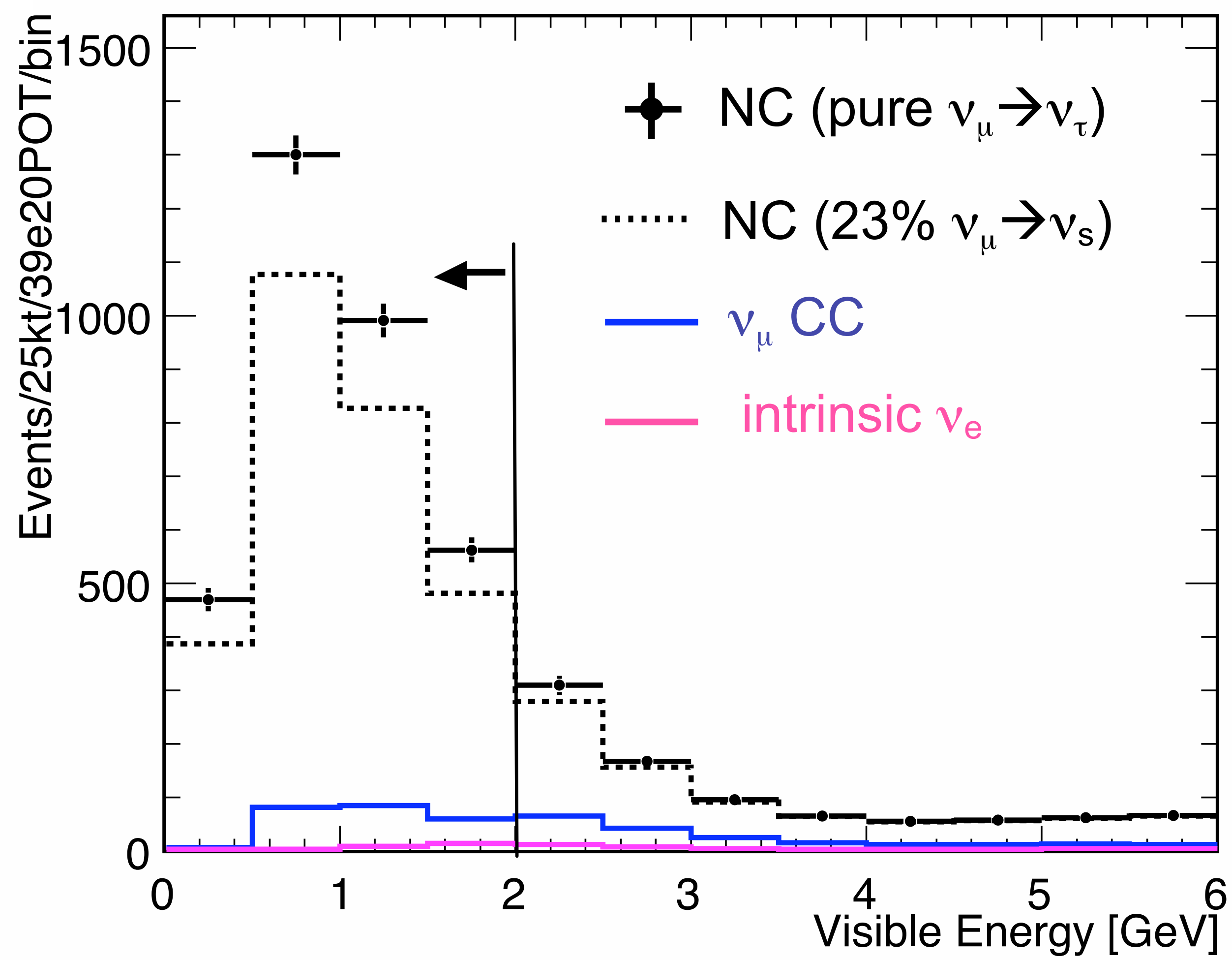
8) ...beyond the Standard Model...Do sterile neutrinos exist?

Reconstructed visible energy for NC sample



NOvA's granularity allows for clean neutral-current measurements facilitating searches for sterile neutrinos

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Neutrino oscillations

Following presentation by Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402. arXiv:0710.0554 [hep-ph]

In vacuum:

$$P(\nu_\mu \to \nu_e) = |2U^*_{\mu 3}U_{e3}\sin\Delta_{31}e^{-i\Delta_{32}} + 2U^*_{\mu 2}U_{e2}\sin\Delta_{21}|^2$$

$$\Delta_{32} \equiv \frac{1.27\Delta m^2_{32}[\mathrm{eV}^2]L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]} = \frac{1.27 \cdot 2.32 \times 10^{-3} \cdot 810}{2.1} \simeq 1.1$$

For NOvA: $$\Delta_{31} \equiv \frac{1.27\Delta m^2_{31}[\mathrm{eV}^2]L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]} \simeq \Delta_{32}$$

$$\Delta_{21} \equiv \frac{1.27\Delta m^2_{21}[\mathrm{eV}^2]L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]} = \frac{1.27 \cdot 7.58 \times 10^{-5} \cdot 810}{2.1} \simeq 0.04$$

$$\begin{aligned} P(\nu_\mu \to \nu_e) &\simeq |\sqrt{P_{\mathrm{atm}}}e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{\mathrm{sol}}}|^2 \\ &= P_{\mathrm{atm}} + P_{\mathrm{sol}} + 2\sqrt{P_{\mathrm{atm}}P_{\mathrm{sol}}}\,(\cos\Delta_{32}\cos\delta \mp \sin\Delta_{32}\sin\delta) \end{aligned}$$

$$P_{\mathrm{atm}} \equiv \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$

$$P_{\mathrm{sol}} \equiv \cos^2\theta_{23}\cos^2\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

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$$P_{\mathrm{atm}} \equiv \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\Delta_{31}$$

long baseline experiments measure this combination

$$P_{\mathrm{sol}} \equiv \cos^2\theta_{23} \cos^2\theta_{13} \sin^2 2\theta_{12} \sin^2\Delta_{21}$$

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In vacuum:

$$P(\nu_\mu \to \nu_e) = |2U^*_{\mu 3} U_{e3} \sin \Delta_{31} e^{-i\Delta_{32}} + 2U^*_{\mu 2} U_{e2} \sin \Delta_{21}|^2$$

$$\Delta_{32} \equiv \frac{1.27 \Delta m^2_{32} [\mathrm{eV}^2] L \ [\mathrm{km}]}{E \ [\mathrm{GeV}]} = \frac{1.27 \cdot 2.32 \times 10^{-3} \cdot 810}{2.1} \simeq 1.1$$

For NOvA: $$\Delta_{31} \equiv \frac{1.27 \Delta m^2_{31} [\mathrm{eV}^2] L \ [\mathrm{km}]}{E \ [\mathrm{GeV}]} \simeq \Delta_{32}$$

$$\Delta_{21} \equiv \frac{1.27 \Delta m^2_{21} [\mathrm{eV}^2] L \ [\mathrm{km}]}{E \ [\mathrm{GeV}]} = \frac{1.27 \cdot 7.58 \times 10^{-5} \cdot 810}{2.1} \simeq 0.04$$

$$P(\nu_\mu \to \nu_e) \simeq |\sqrt{P_{\mathrm{atm}}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{\mathrm{sol}}}|^2$$
$$= P_{\mathrm{atm}} + P_{\mathrm{sol}} + 2\sqrt{P_{\mathrm{atm}} P_{\mathrm{sol}}} \, (\cos \Delta_{32} \cos \delta \mp \sin \Delta_{32} \sin \delta)$$

$$P_{\mathrm{atm}} \equiv \sin^2 \theta_{23} \sin^2 2\theta_{13} \cancel{\sin^2 \Delta_{31}}$$

long baseline experiments measure this combination

"$-$" : ν

"$+$" : $\bar{\nu}$

$$P_{\mathrm{sol}} \equiv \cos^2 \theta_{23} \cos^2 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

Neutrino oscillations

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$$\sqrt{P_{\rm atm}} = \sin\theta_{23}\sin 2\theta_{13}\frac{\sin(\Delta_{31}-aL)}{\Delta_{31}-aL}\Delta_{31}$$

$$\sqrt{P_{\rm sol}} = \cos\theta_{23}\sin 2\theta_{12}\frac{\sin(aL)}{(aL)}\Delta_{21}$$

$$a = G_F N_e/\sqrt{2} \simeq \frac{1}{3500\ \rm km}$$

$$aL = 0.08\ \text{for}\ L = 295\ \rm km$$
$$aL = 0.23\ \text{for}\ L = 810\ \rm km$$

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dependence on relative sign of ***Δ_{31}*** *and* ***a***

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*dependence on relative sign of **Δ_{31}** and **a***

$$\sqrt{P_{\rm atm}} = \sin\theta_{23}\sin 2\theta_{13}\frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL}\Delta_{31}$$

*"fake" CP violation as **a** changes sign for antineutrinos*

$$\sqrt{P_{\rm sol}} = \cos\theta_{23}\sin 2\theta_{12}\frac{\sin(aL)}{(aL)}\Delta_{21}$$

$$a = G_F N_e/\sqrt{2} \simeq \frac{1}{3500 \text{ km}}$$

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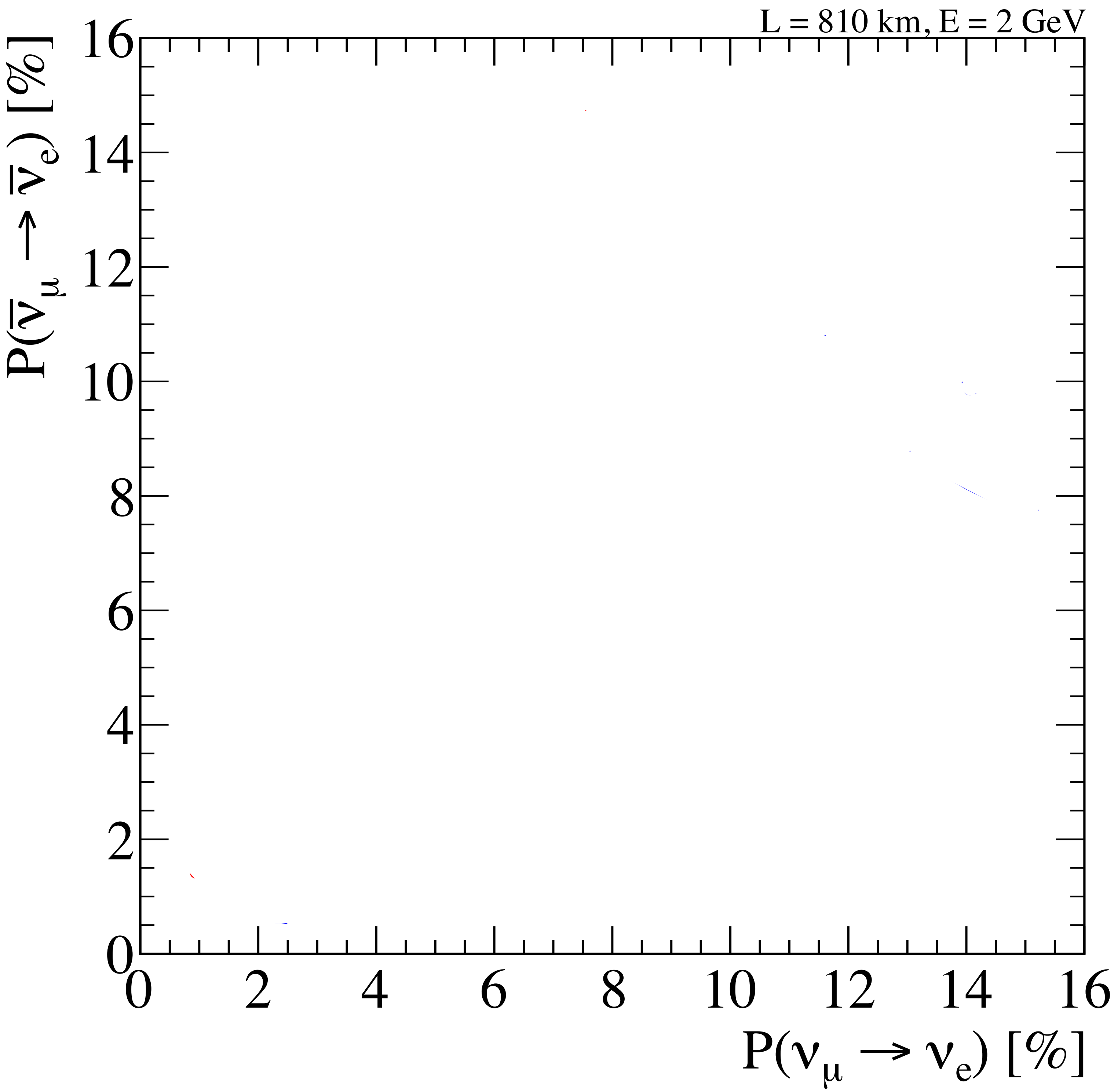
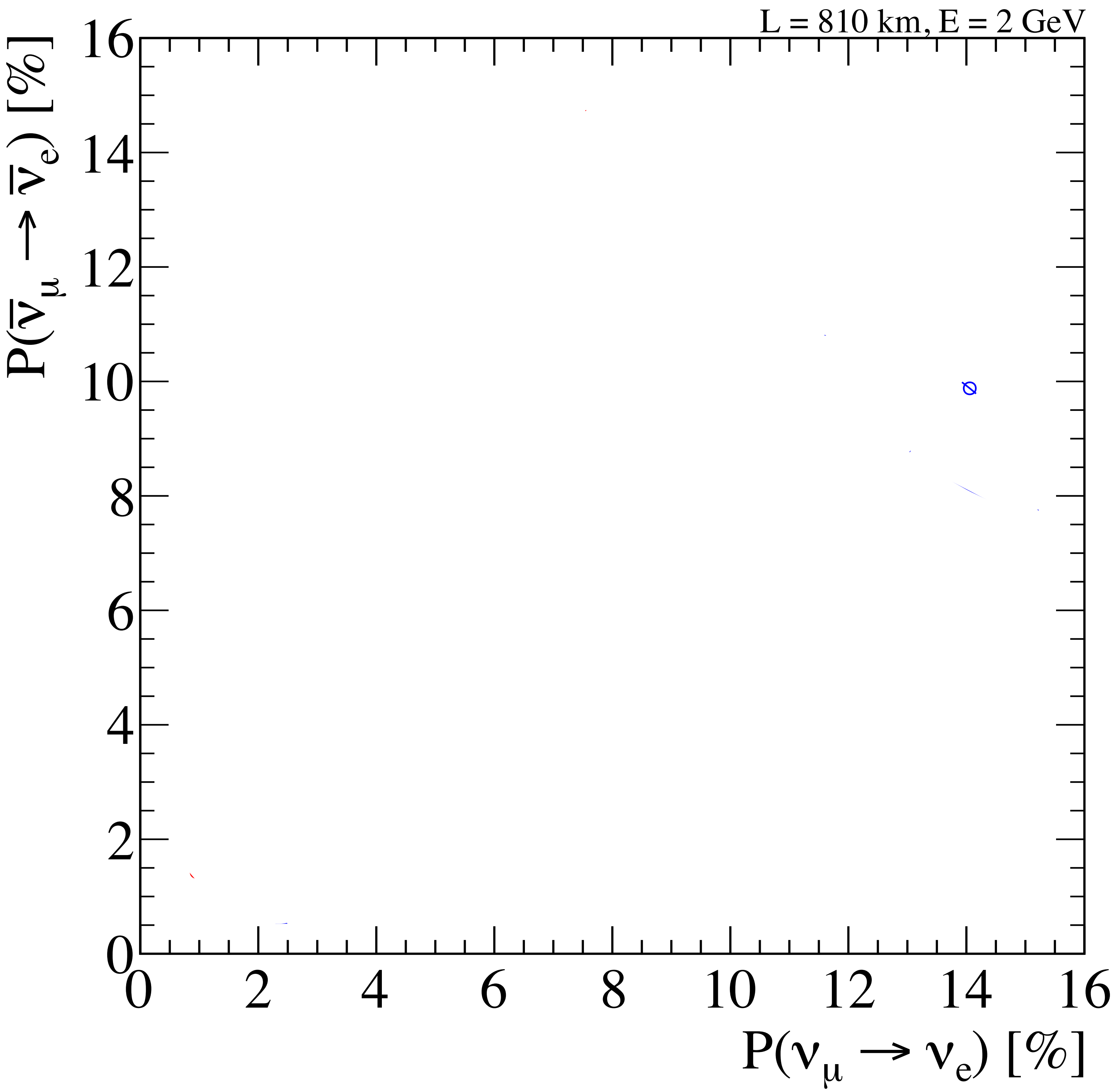


Using a muon neutrino beam, we have two basic observables

1. $P(\nu_\mu \rightarrow \nu_e)$ for neutrinos
2. $P(\nu_\mu \rightarrow \nu_e)$ for anti-neutrinos

We can plot these two observables as a function of the remaining unknowns θ_{13}, δ_{CP}, and mass hierarchy.

Principle of the NOvA Experiment



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$\delta_{CP} = 0$

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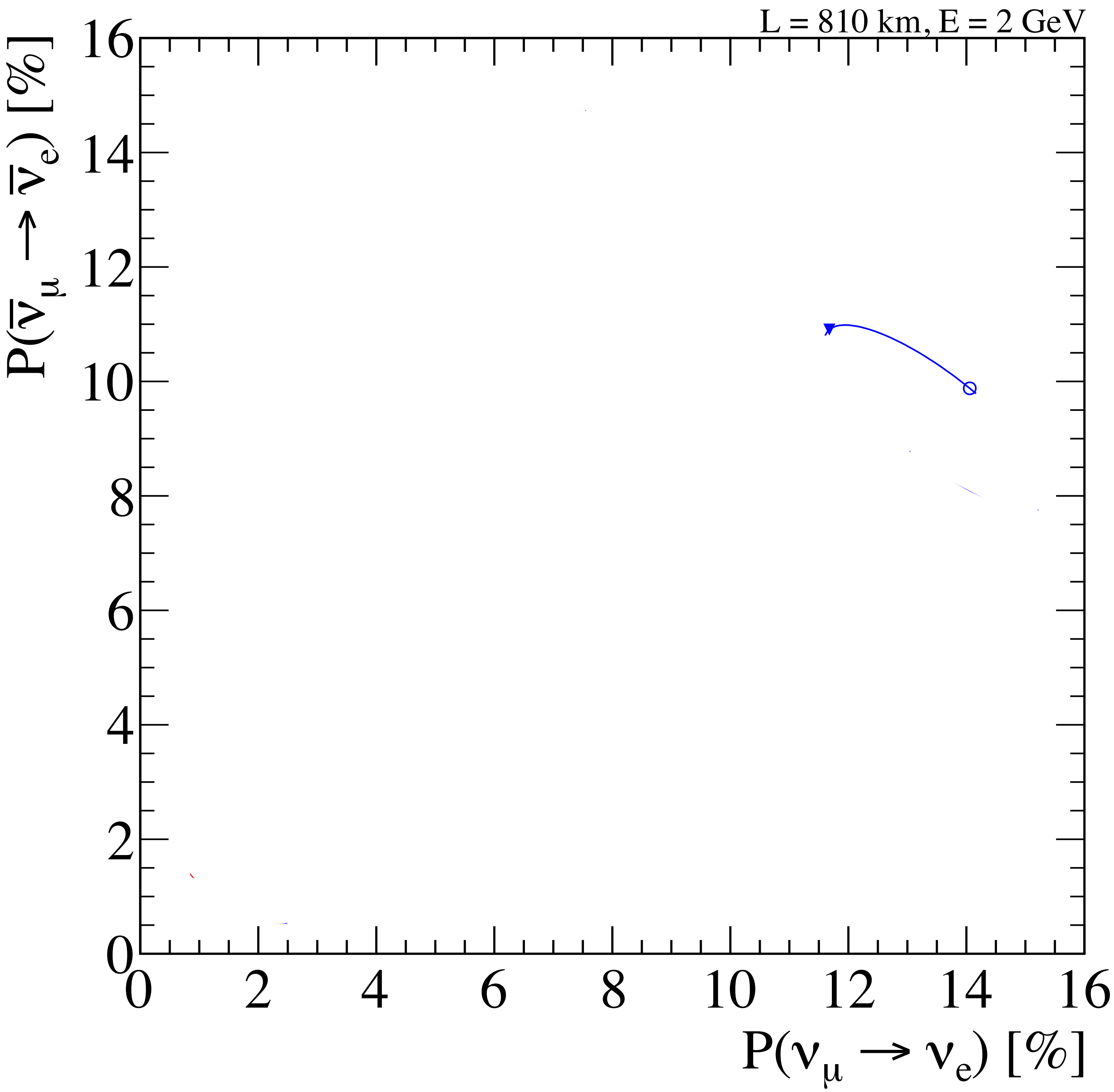

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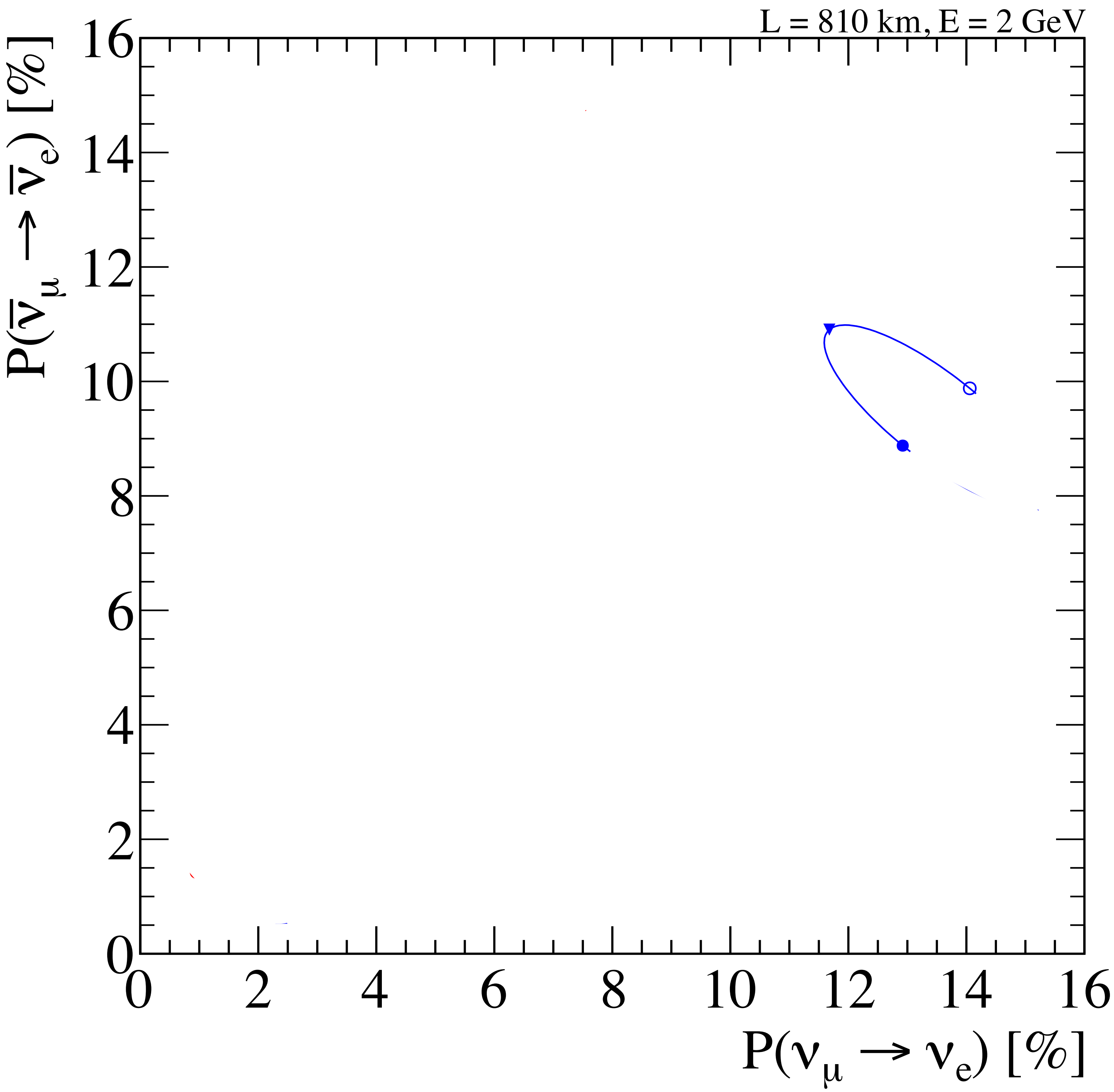

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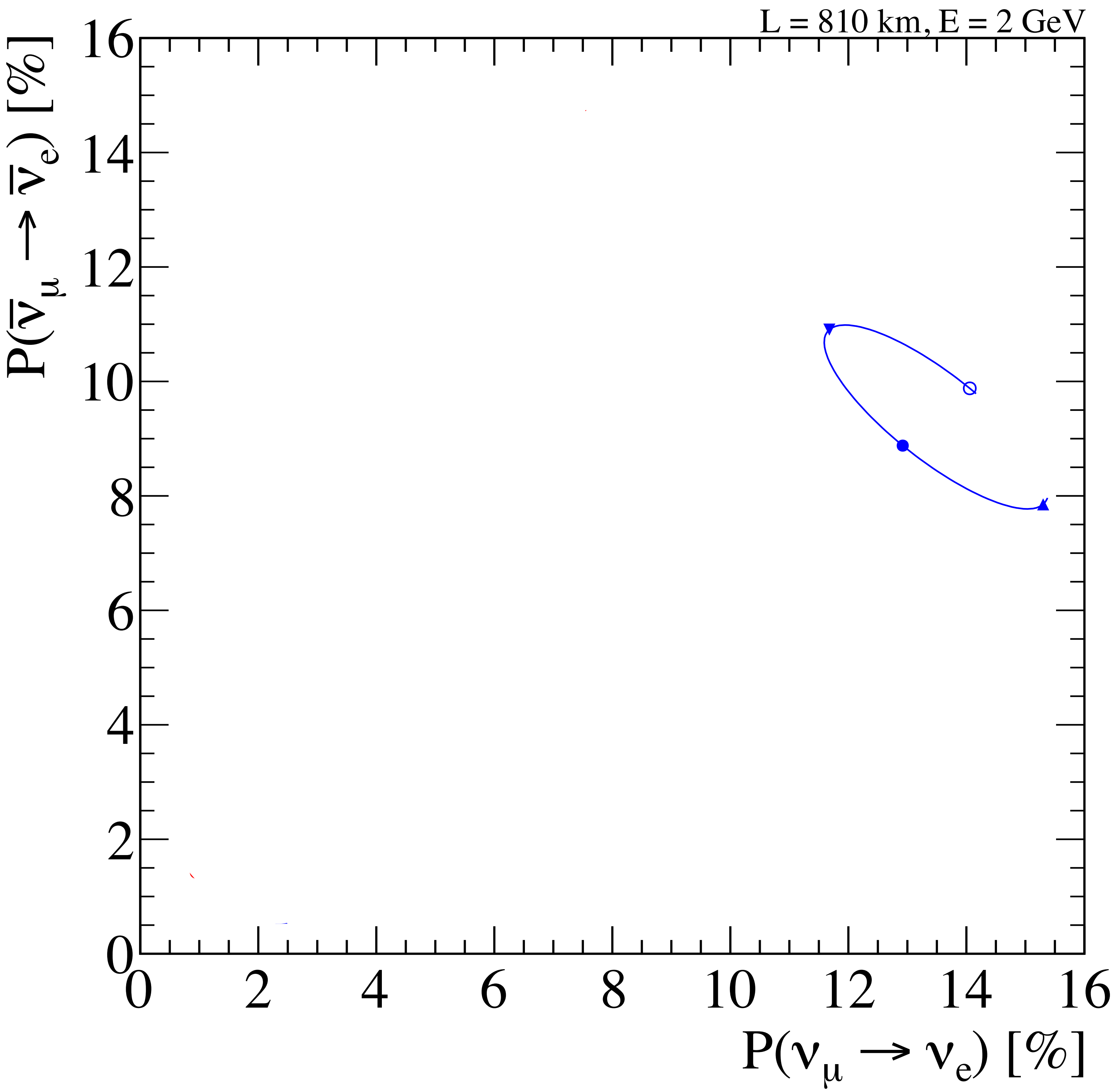

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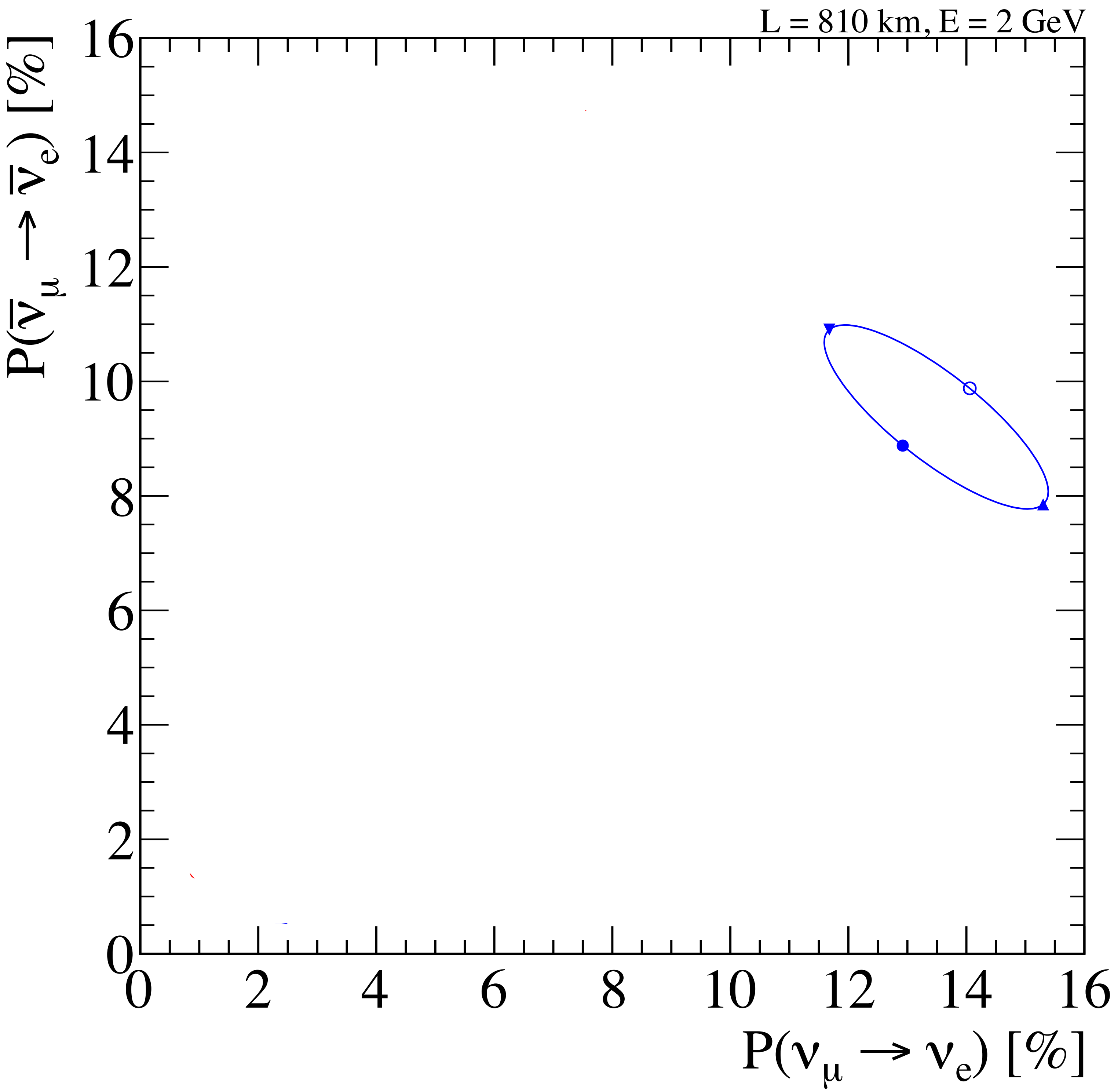

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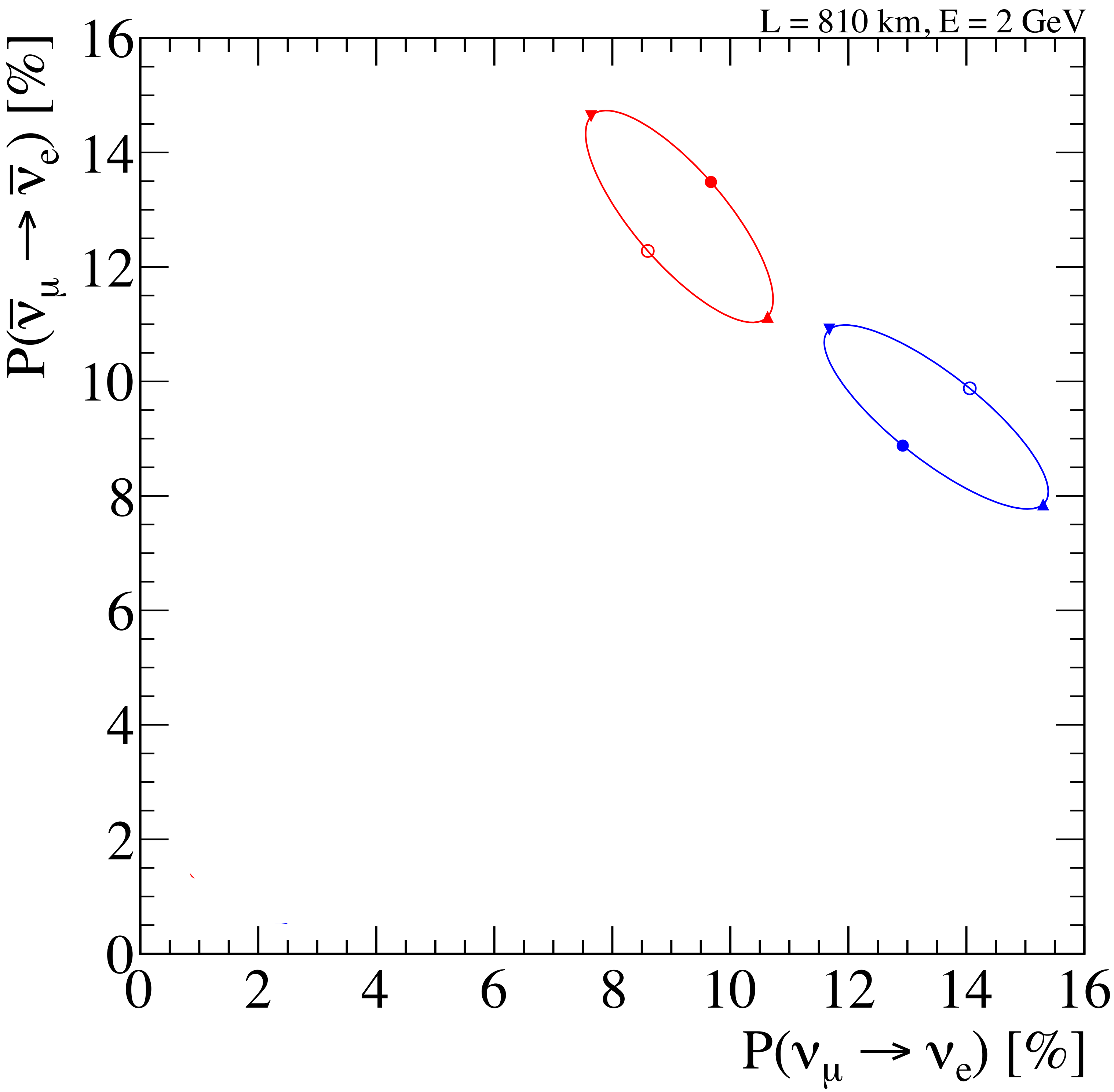

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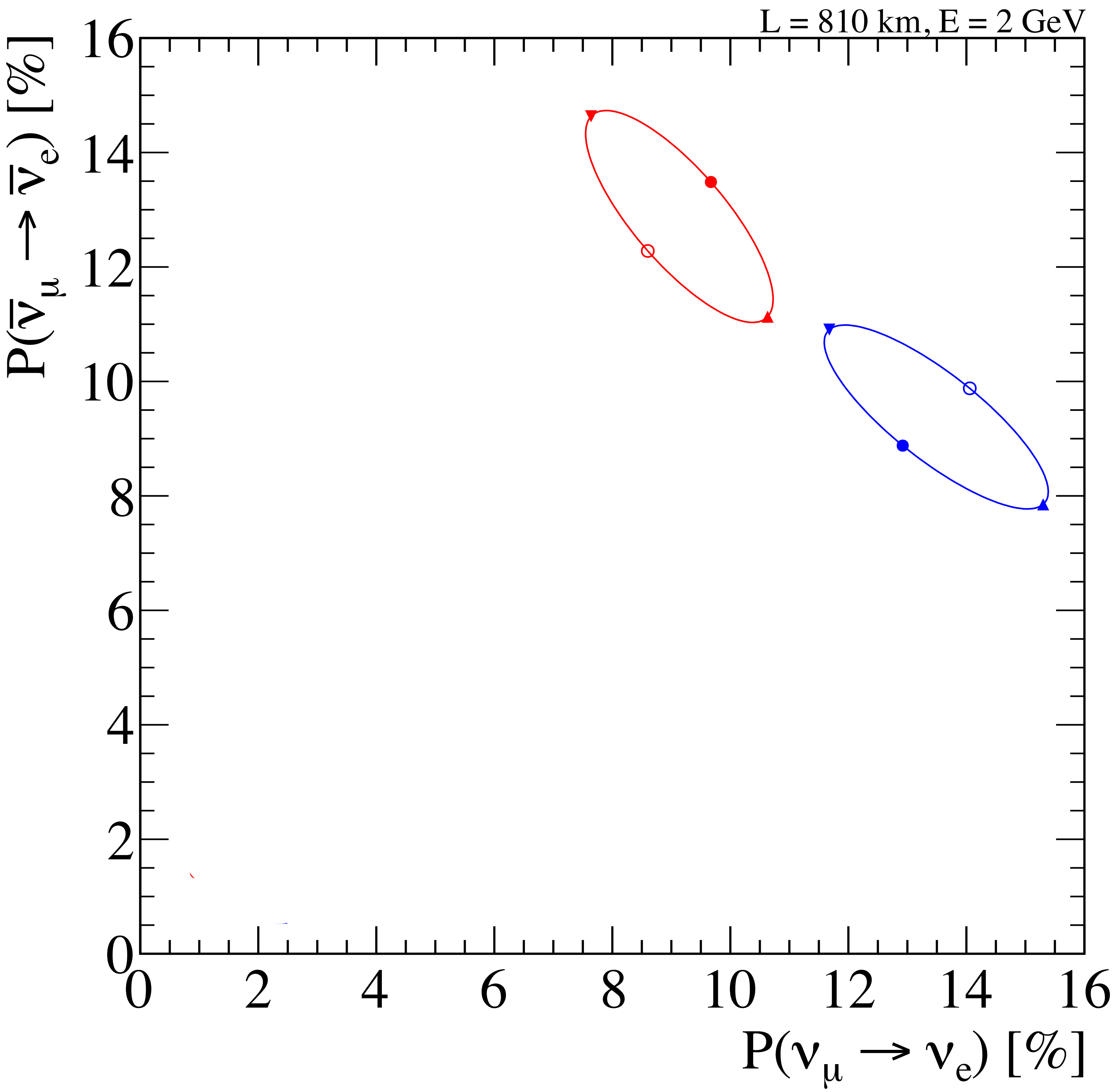

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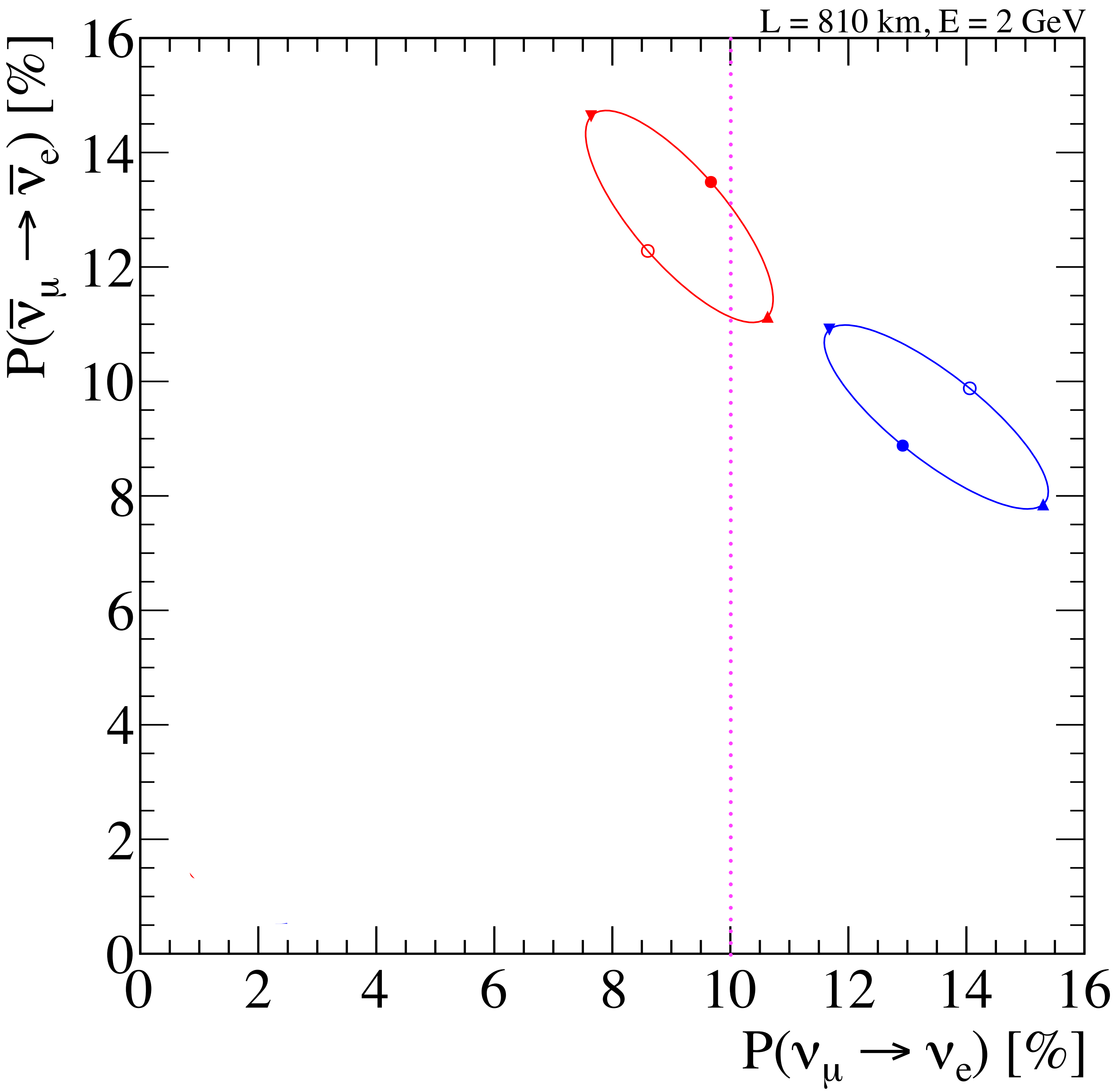

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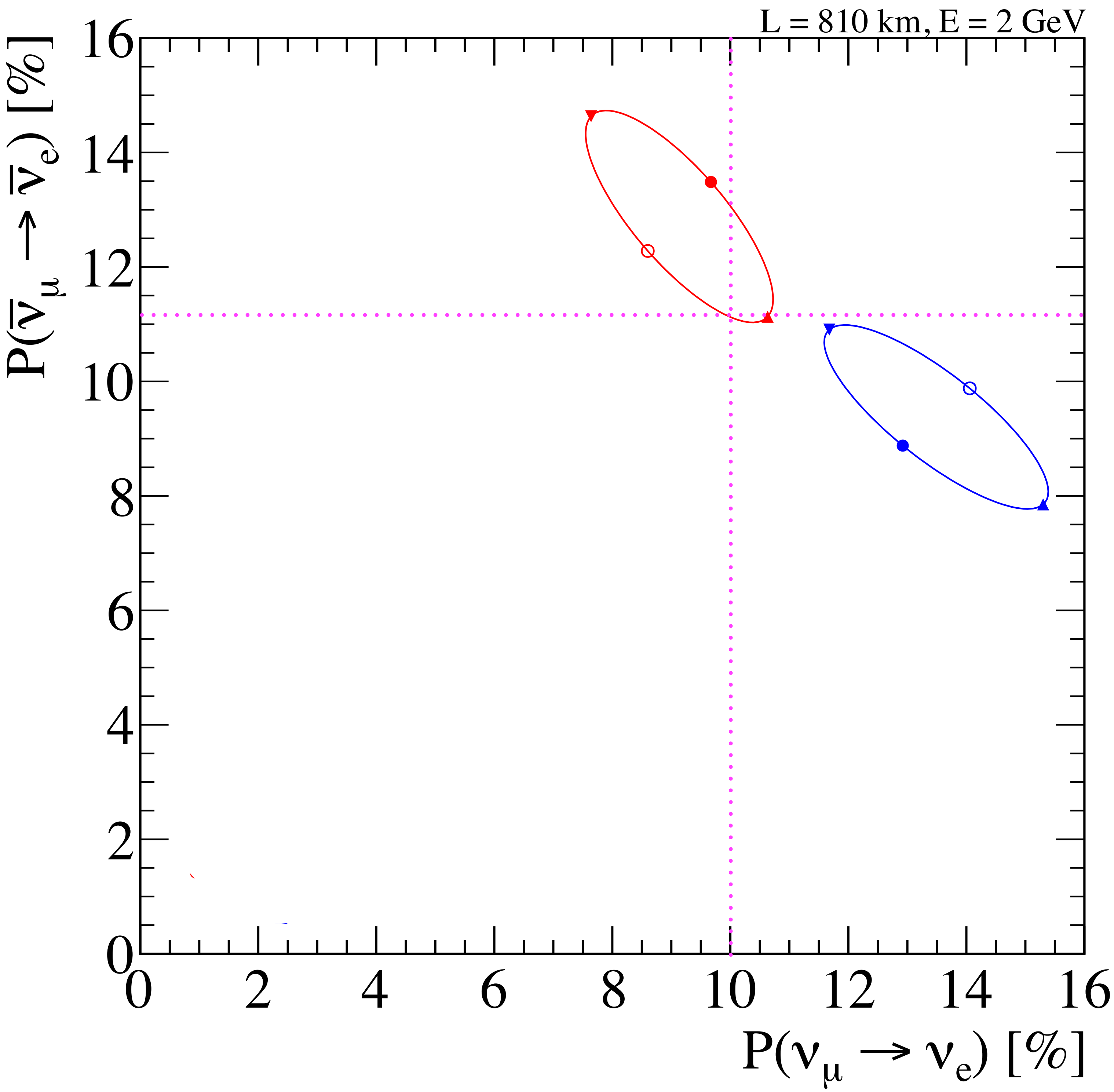

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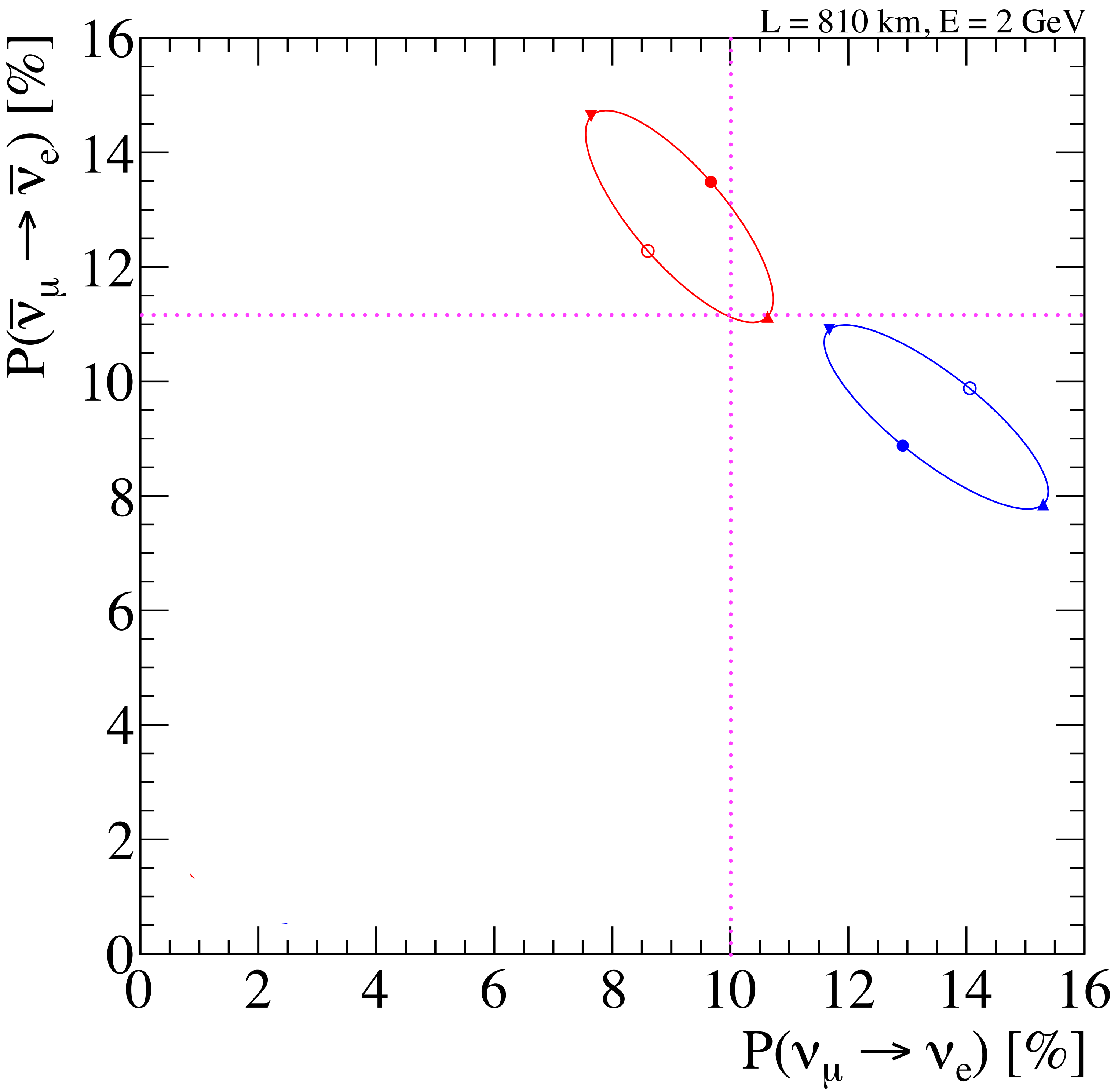

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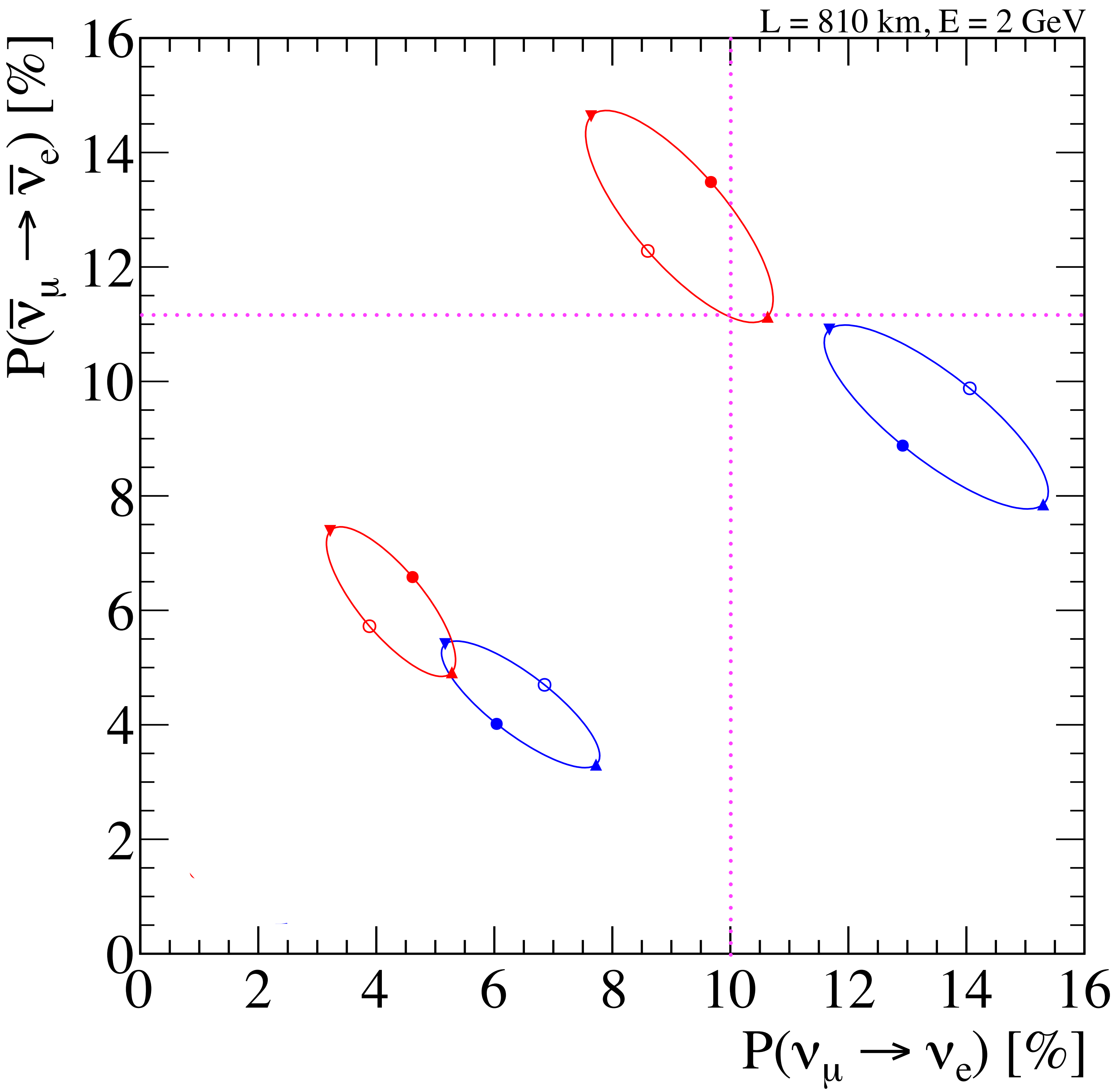
For small θ_{13} there are inherent ambiguities between hierarchy choice and δ_{CP}. However, even in these cases we learn something about δ_{CP}.

Principle of the NOvA Experiment



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$\theta_{13} = 15^o, 10^o$

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δ_{CP} = 0, ▼π/2, ● π, ▲3π/2, 2π

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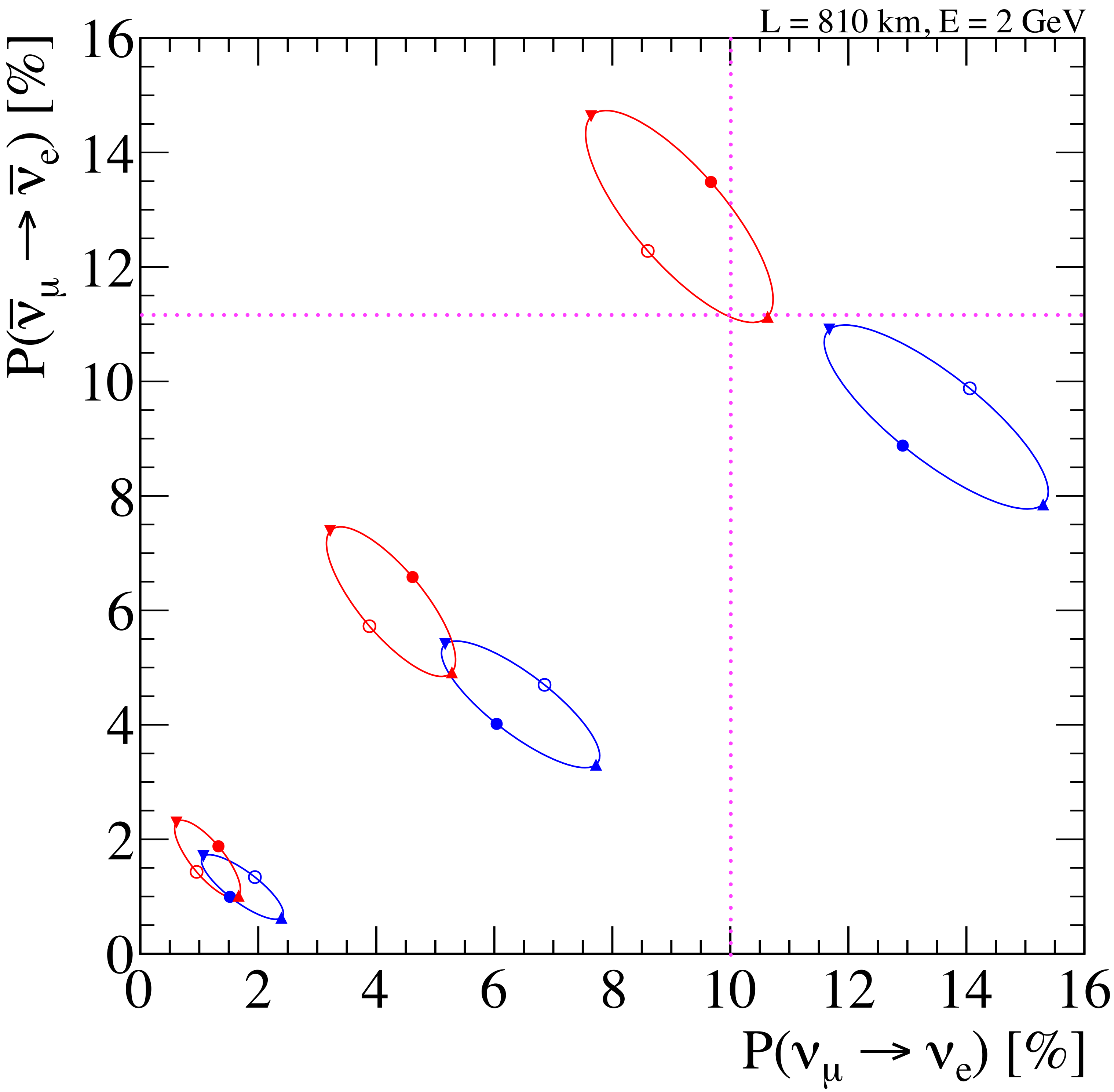

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We can plot these two observables as a function of the remaining unknowns θ_{13}, δ_{CP} , and mass hierarchy.

θ_{13} = 15°, 10°, 5°

$\Delta m^2_{31}>0$ ("Normal hierarchy")

$\Delta m^2_{31}<0$ ("Inverted hierarchy")

δ_{CP} = 0, ▼π/2, ● π, ▲3π/2, 2π

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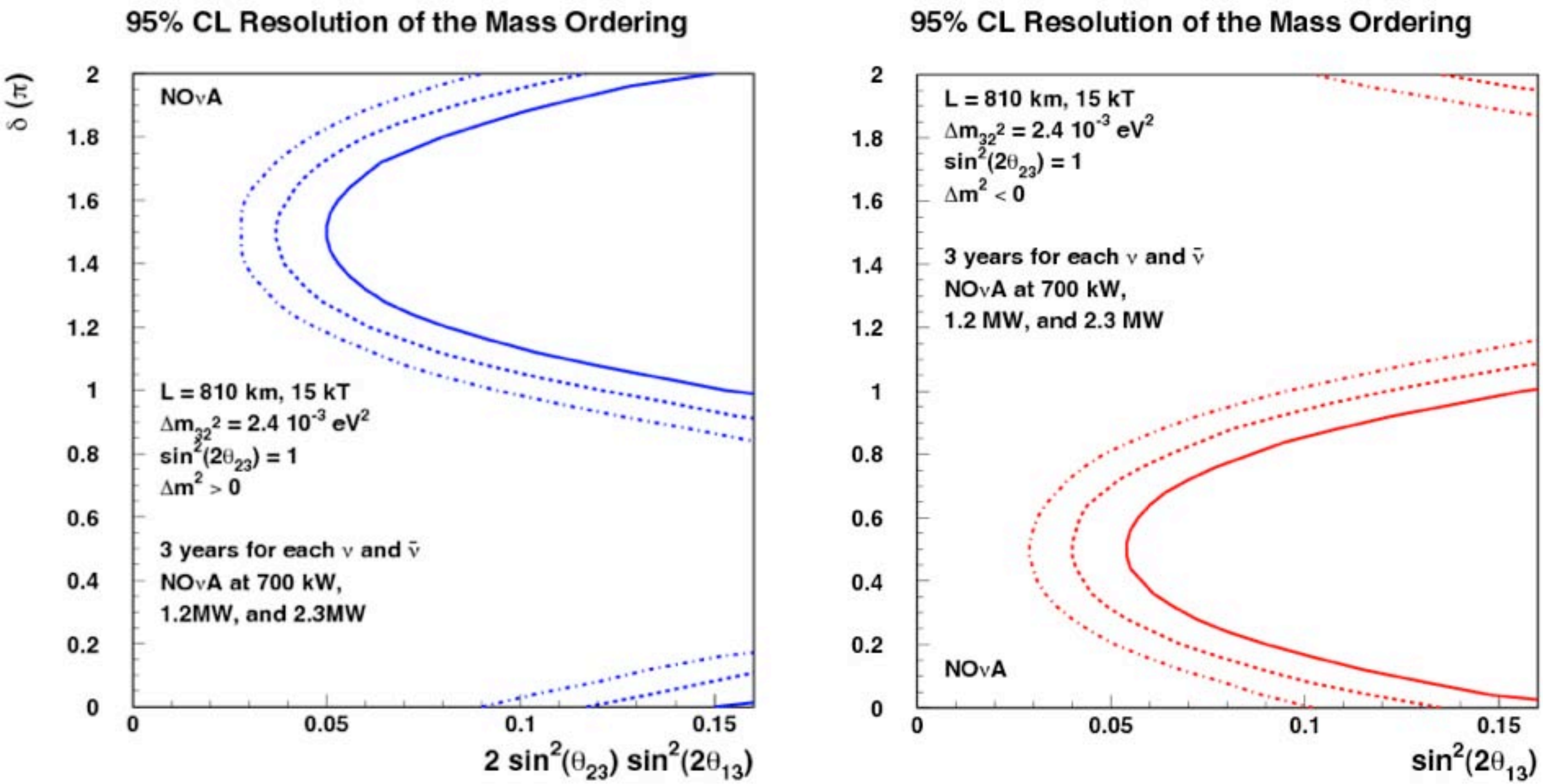
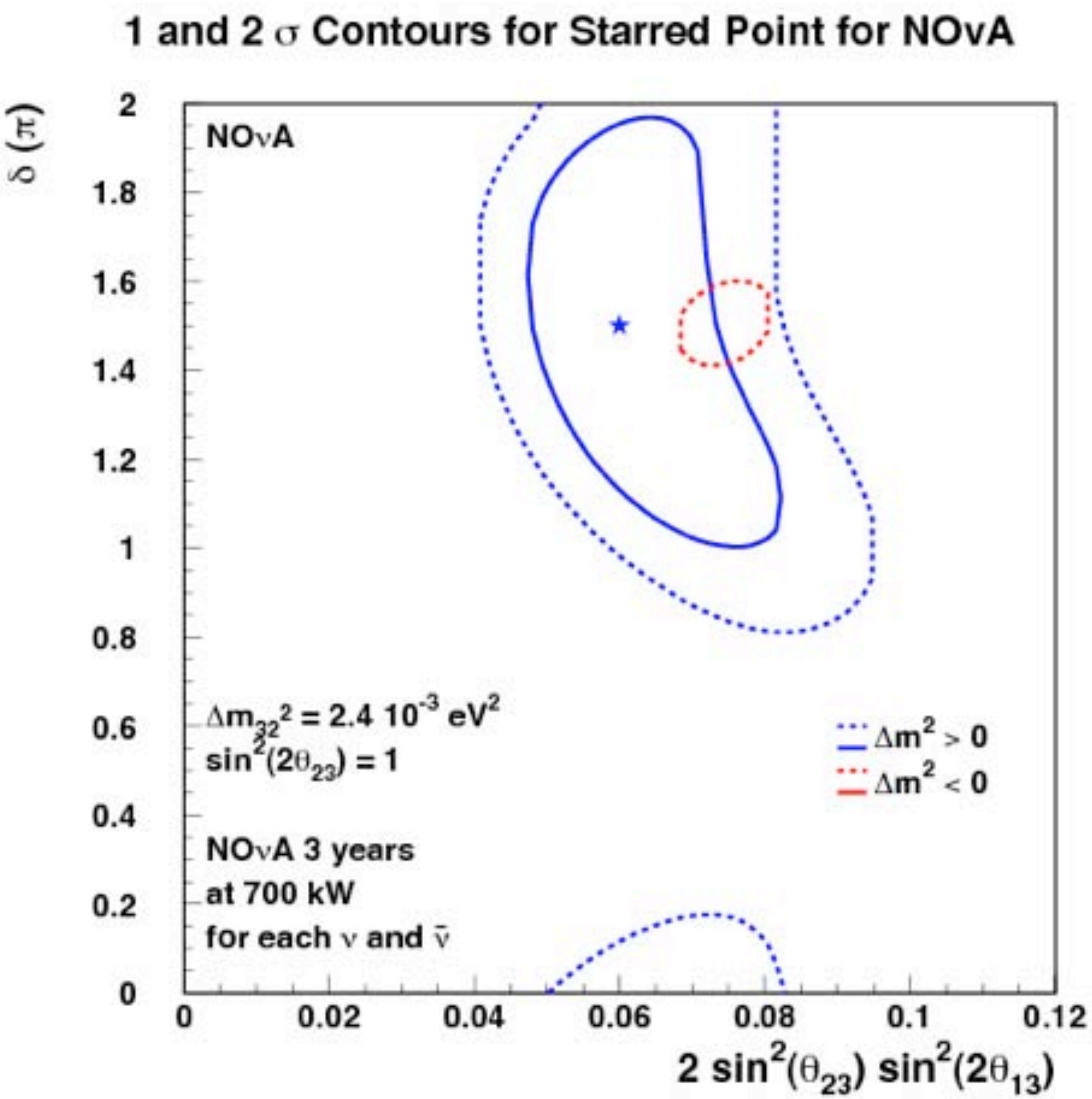
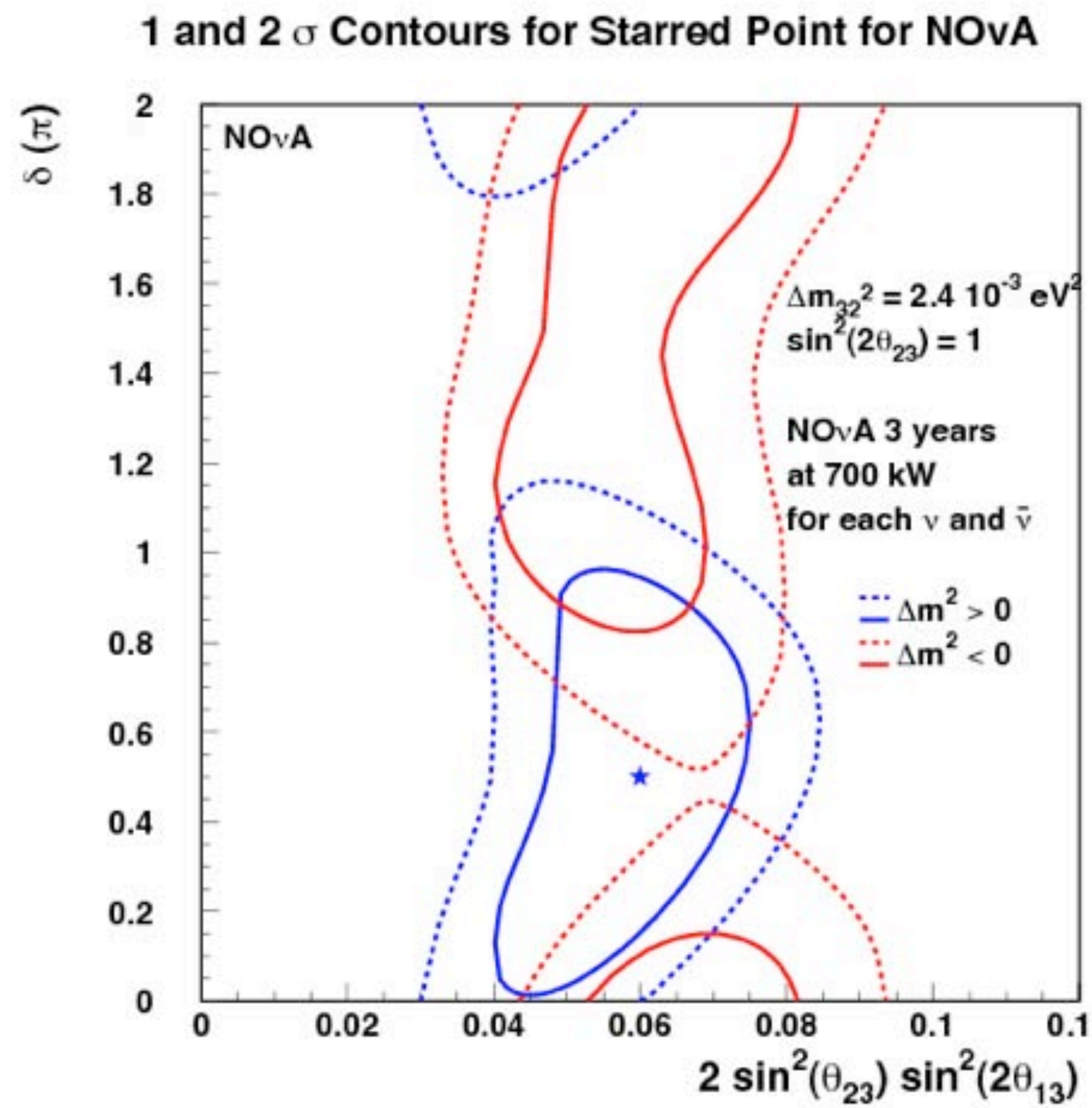


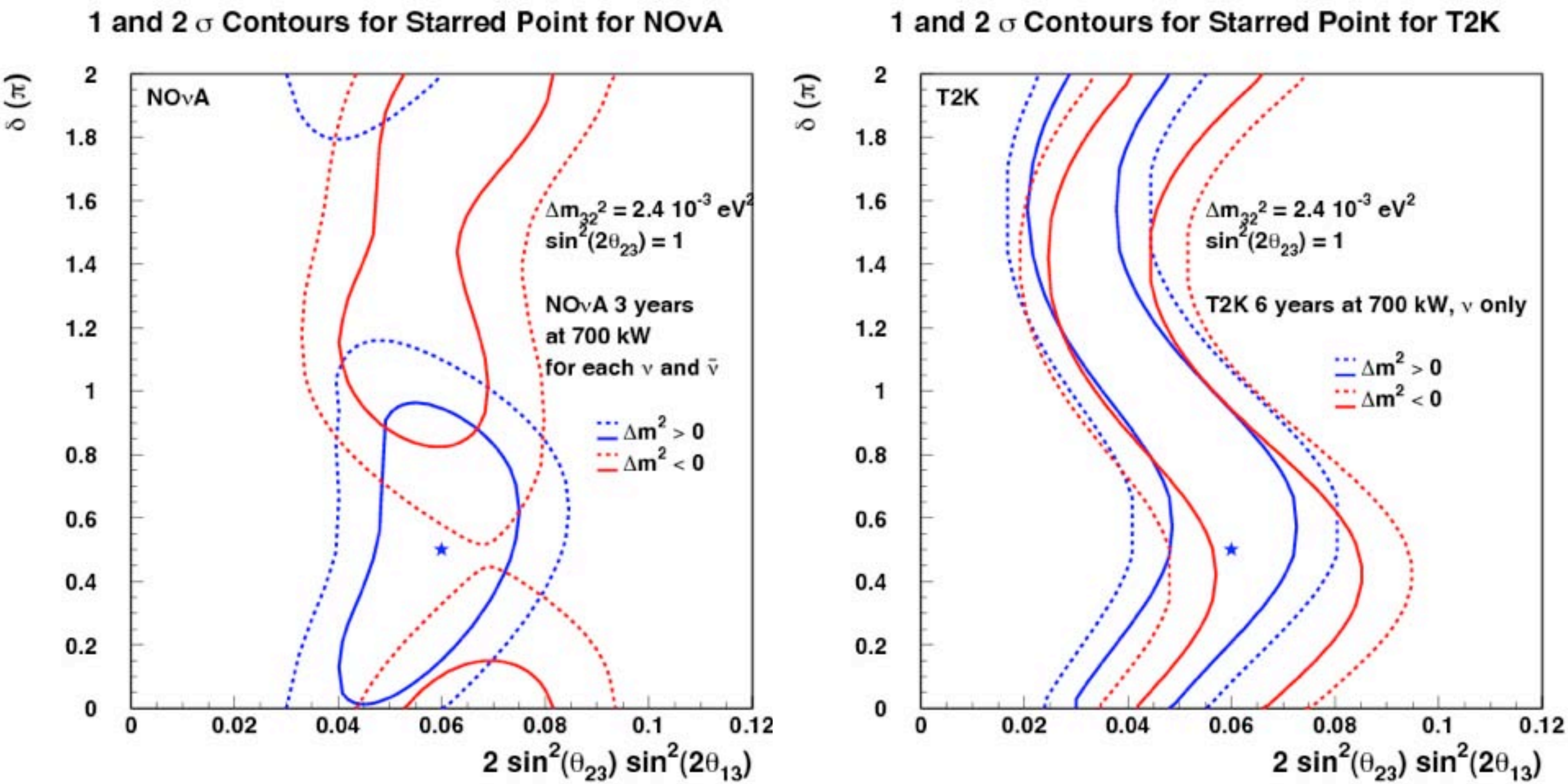
Resolution of the mass hierarchy





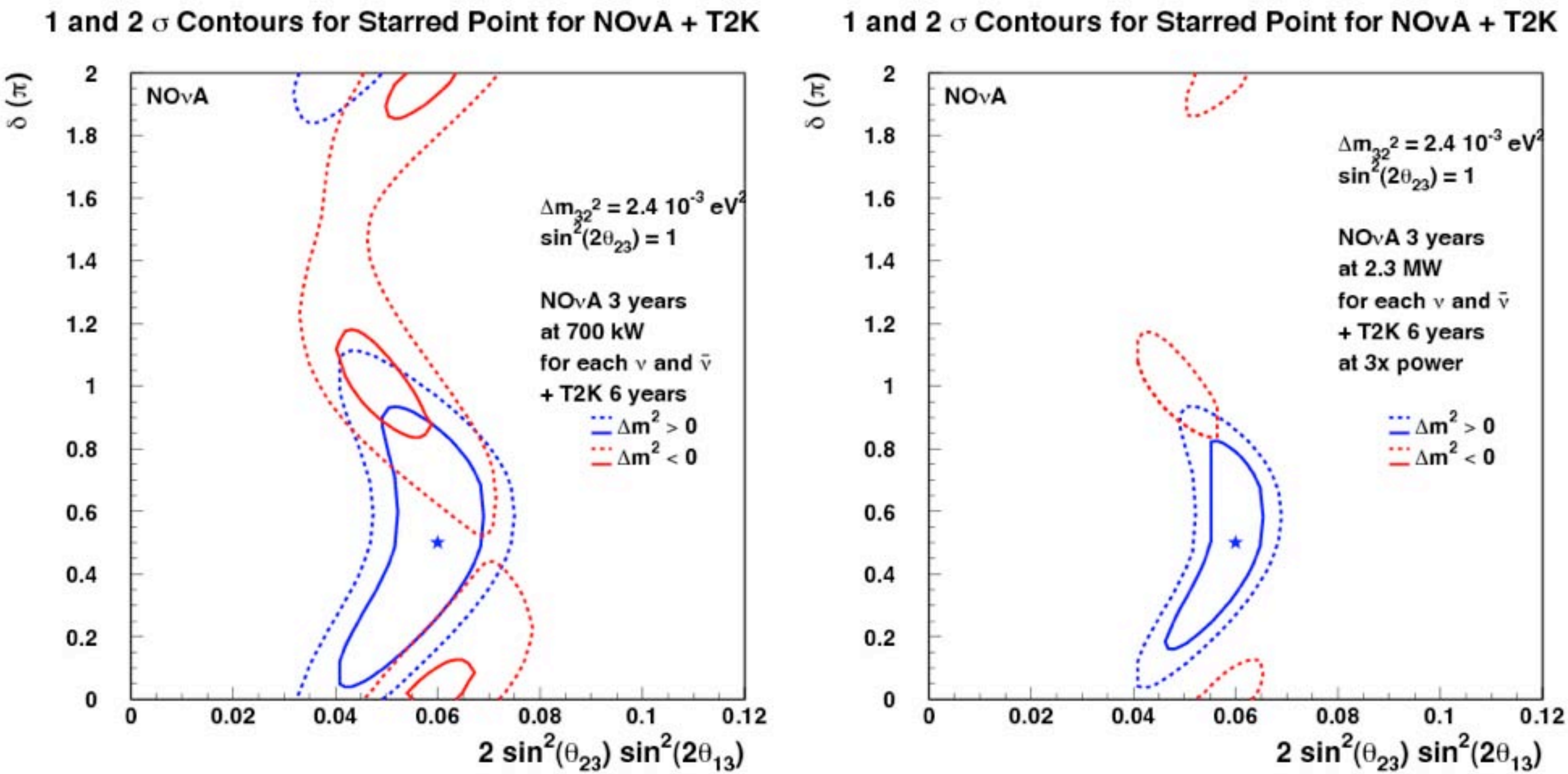
Begin study of δ_{CP}

We will learn if affects of CP phase and mass hierarchy go in same direction (upper half plane for normal hierarchy case) or in opposite directions.



Combining NOvA with T2K in worst case

As NOvA runs both neutrinos and antineutrinos its contours are relatively straight. T2K's contours trace an "S" which intersects NOvA's contours in the lower part of the plot.

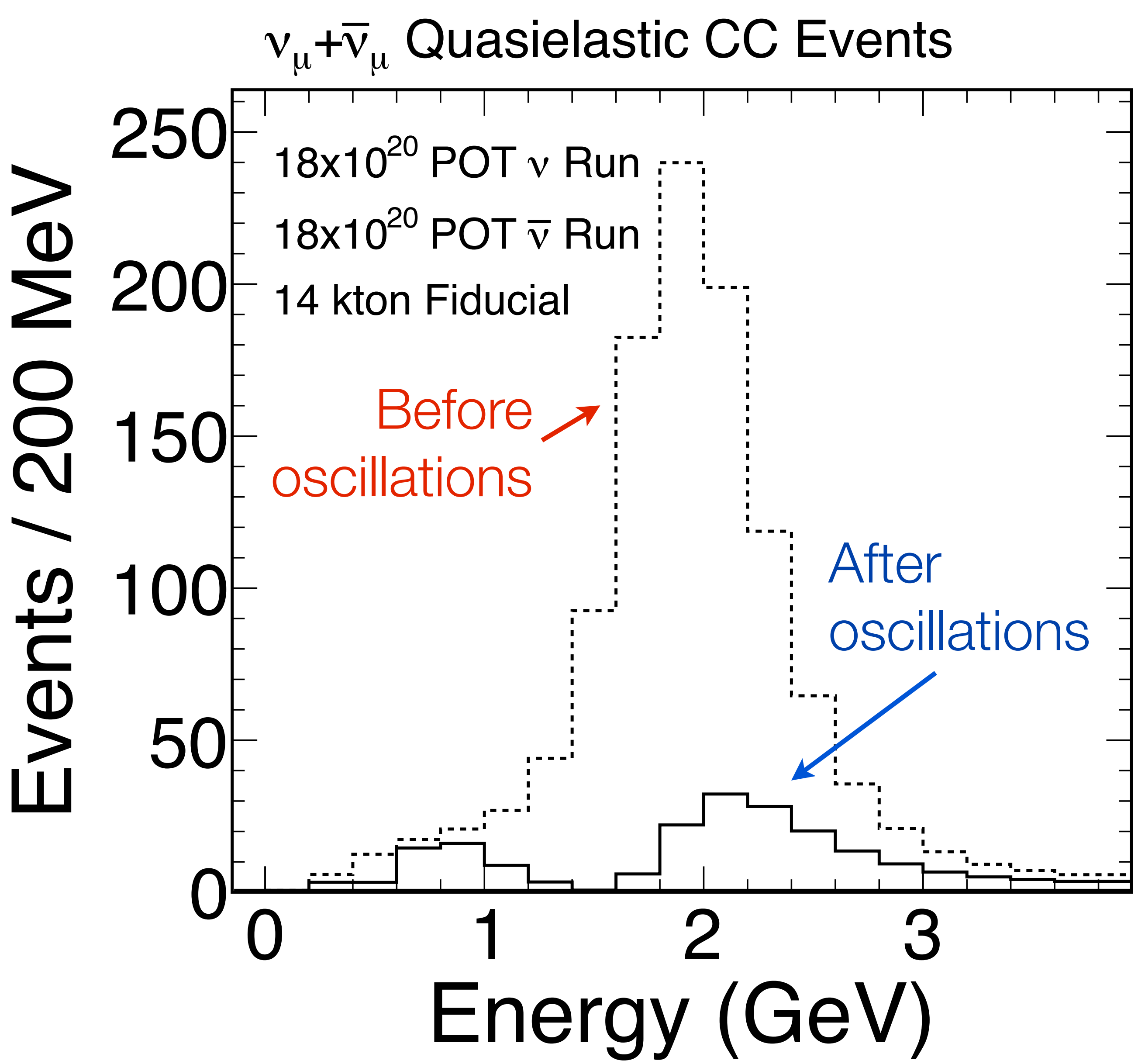


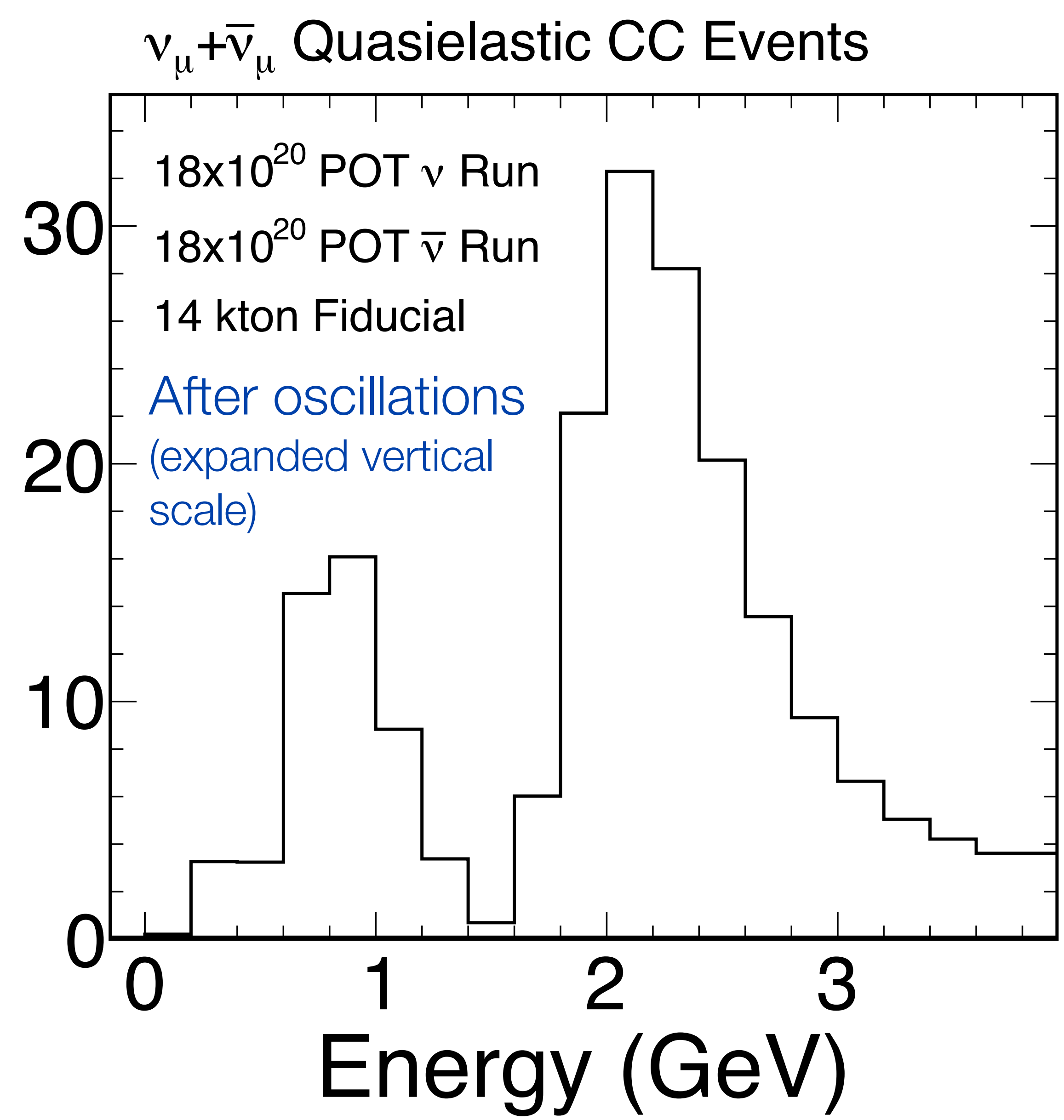
Combining NOvA with T2K

On the left we assume nominal T2K and NOvA runs. This constrains the CP phase to the lower half plane (1 sigma), but leaves the hierarchy unresolved. Increasing the statistics to each experiment by 3x resolves the hierarchy.

$\nu_\mu \rightarrow \nu_\mu$ Channel

Precision θ_{23} and Δm^2_{32} measurements

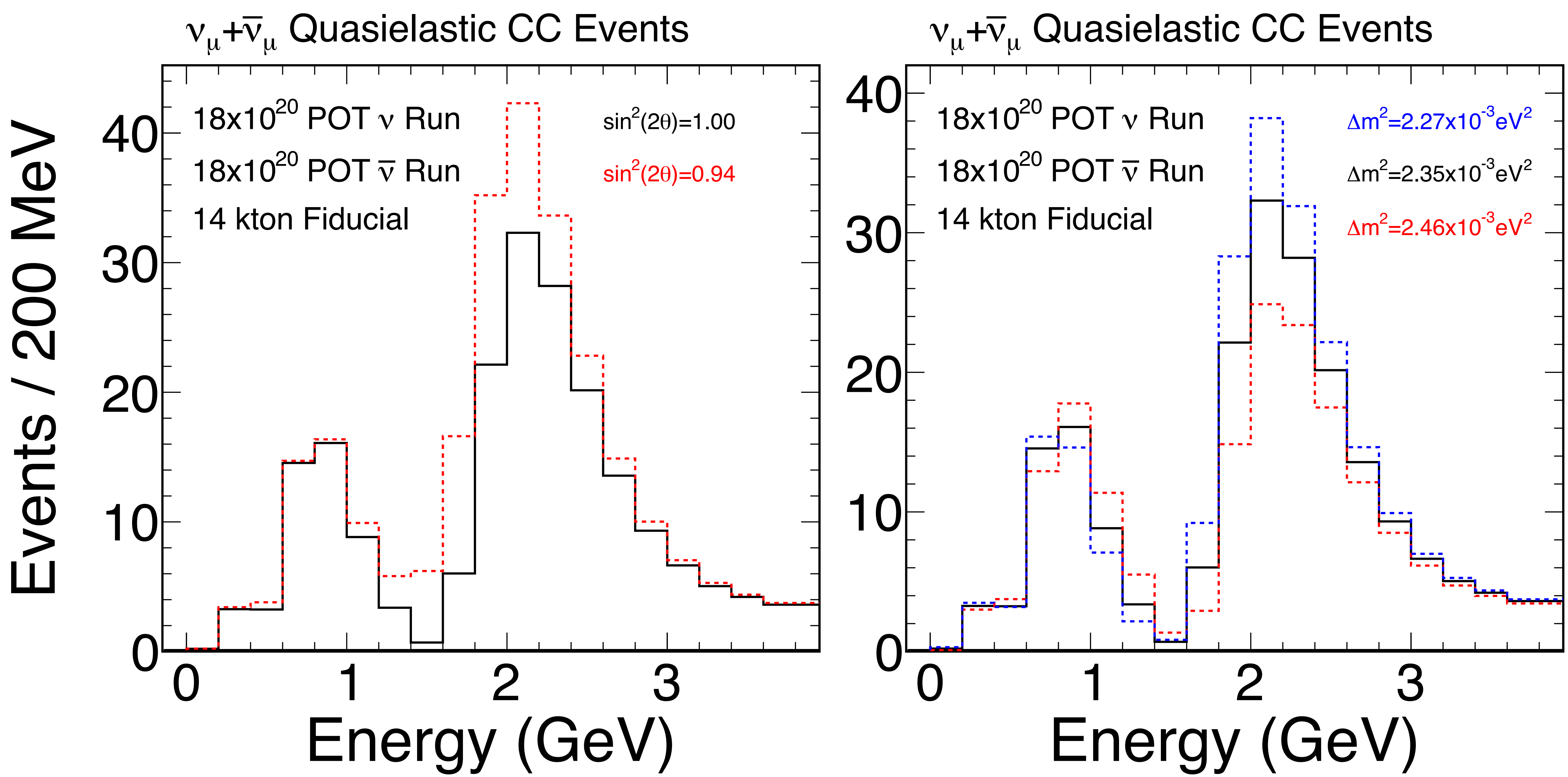




Oscillations applied using $\Delta m^2_{32} = 2.35 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1.0$

$\nu_\mu \rightarrow \nu_\mu$ Channel

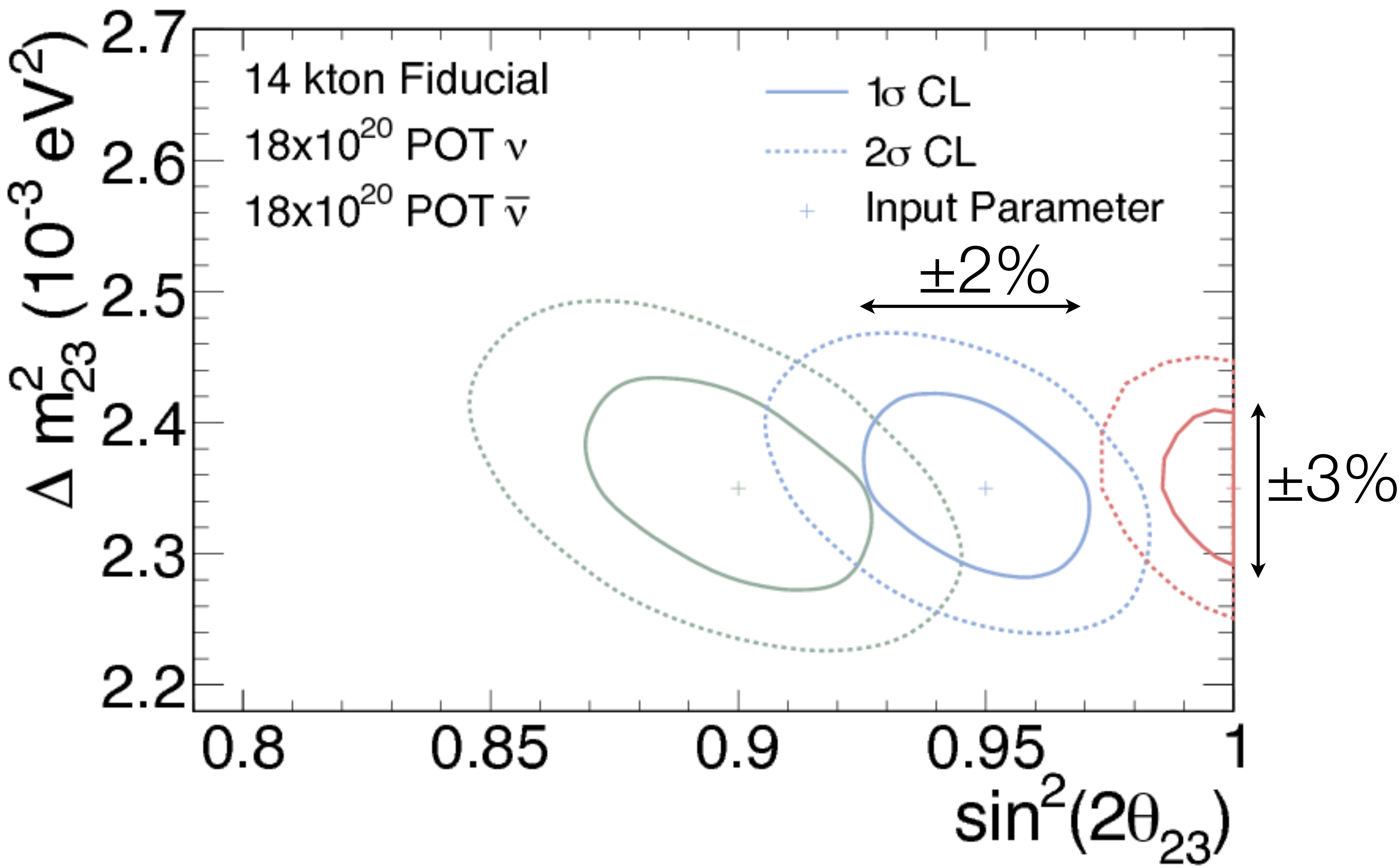
Precision θ_{23} and Δm^2_{32} measurements



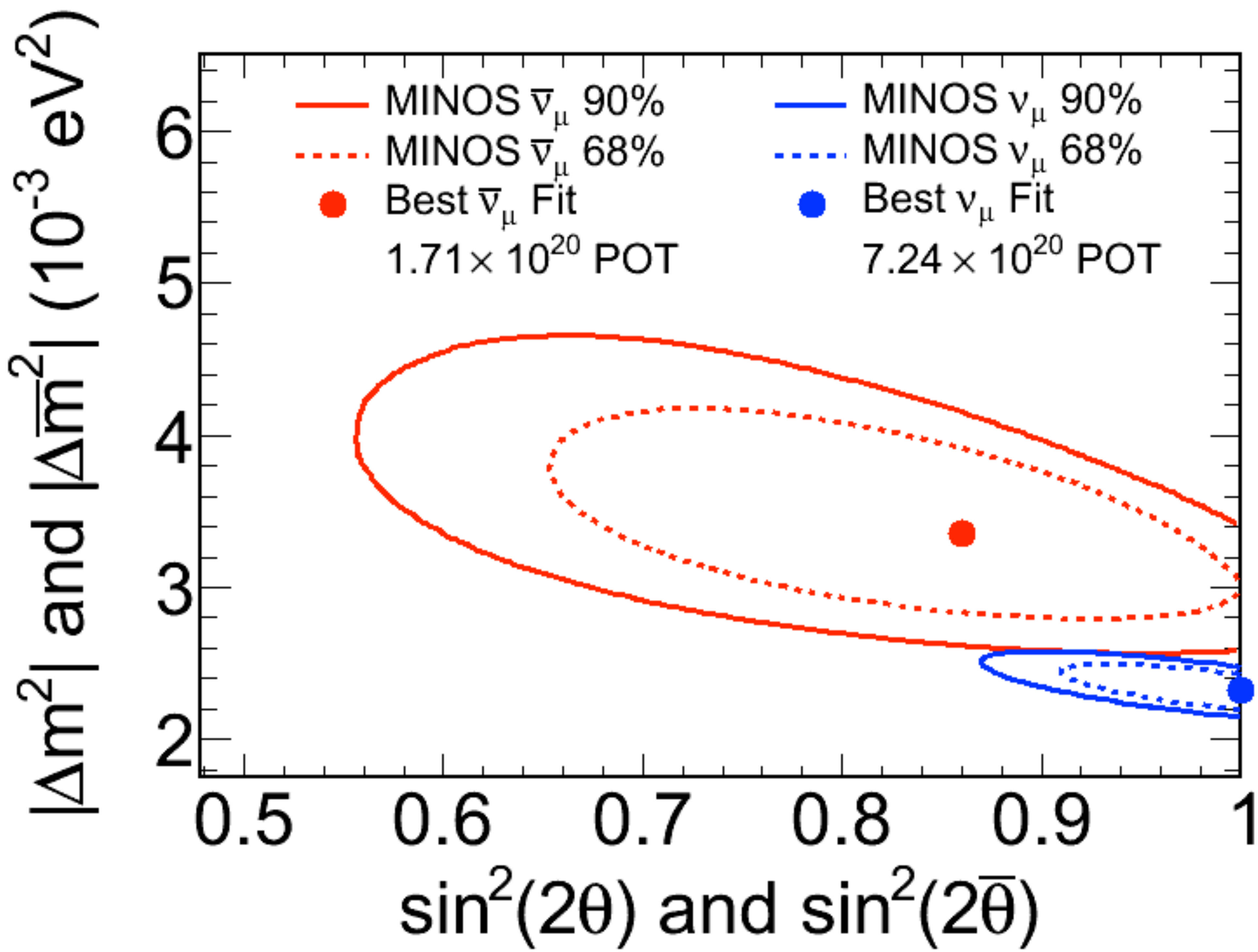
- Energy resolution (determined from simulations) is 4% for ν_μ-CC quasi-elastic events
- 10% absolute energy scale uncertainty fitted as nuisance parameter; constrained by narrow-band beam
- ~0 backgrounds due to detector performance and narrow-band beam

$\nu_\mu \rightarrow \nu_\mu$ Channel

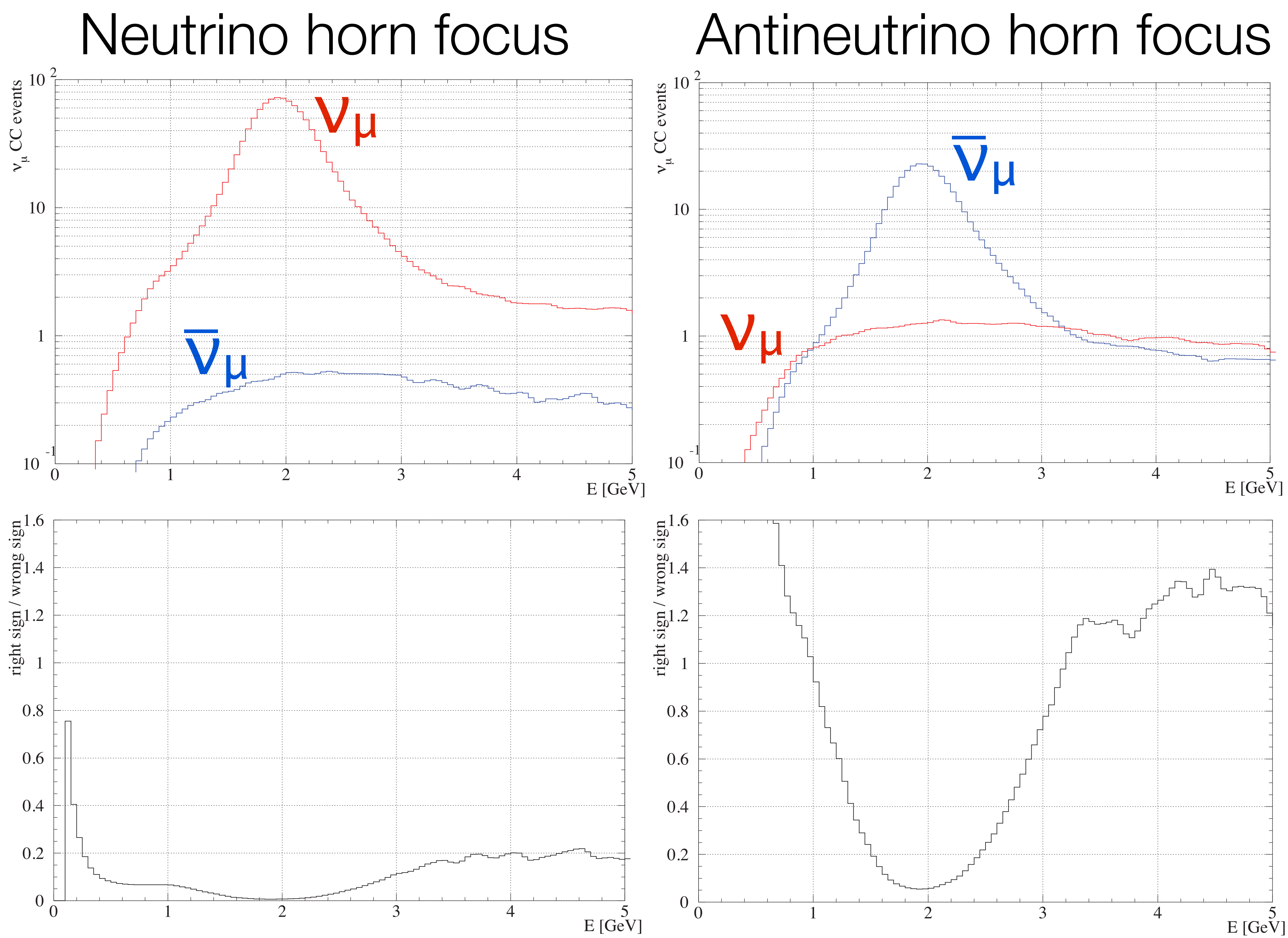
Precision θ_{23} and Δm^2_{32} measurements



$\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ MINOS Results



2% probability these are compatible

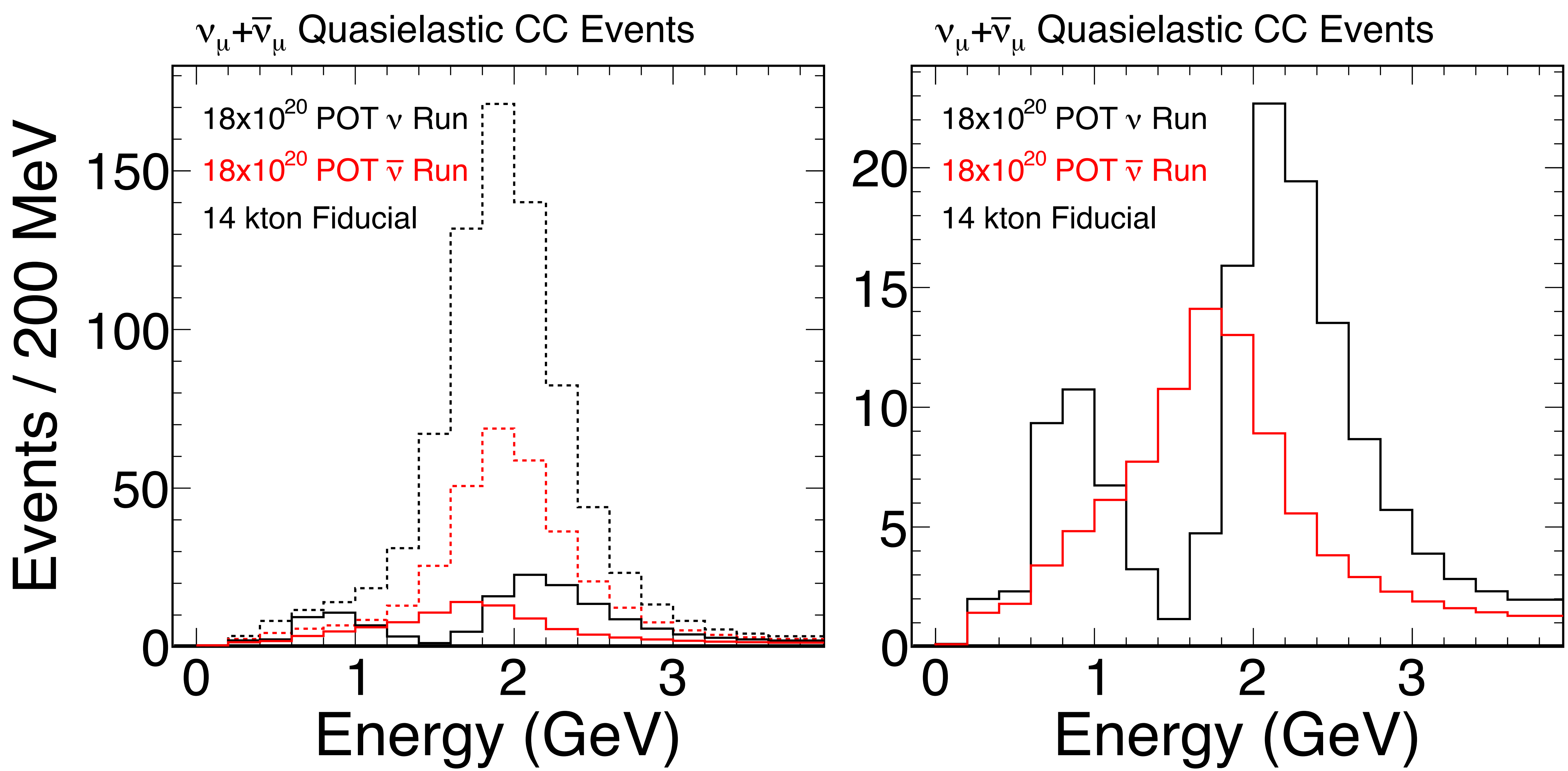


Neutrino and antineutrino rates

The combination of the NuMI medium horn position and off-axis kinematics gives a relatively pure antineutrino beam

$\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ Channels

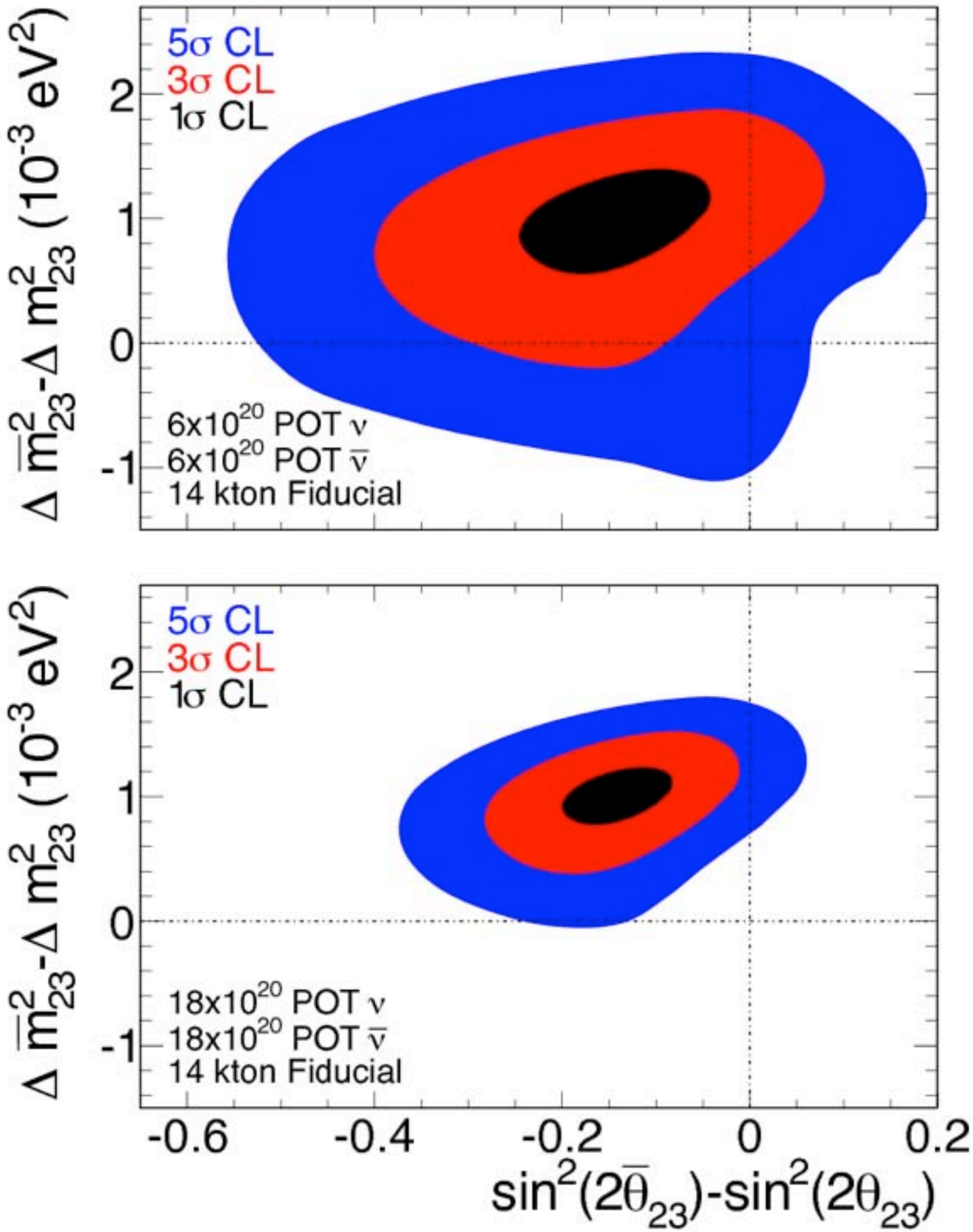
Do ν_μ and $\bar{\nu}_\mu$ oscillate the same way?



Left: ν_μ-CC and ν_μ-CC spectra before and after oscillations.
Right: Zoom of the oscillated ν_μ-CC and ν_μ-CC spectra.
ν_μ oscillations use $(\Delta m^2, \sin^2 2\theta) = (2.35\ \text{meV}^2, 1.00)$
ν_μ oscillations use $(\Delta m^2, \sin^2 2\theta) = (3.36\ \text{meV}^2, 0.86)$

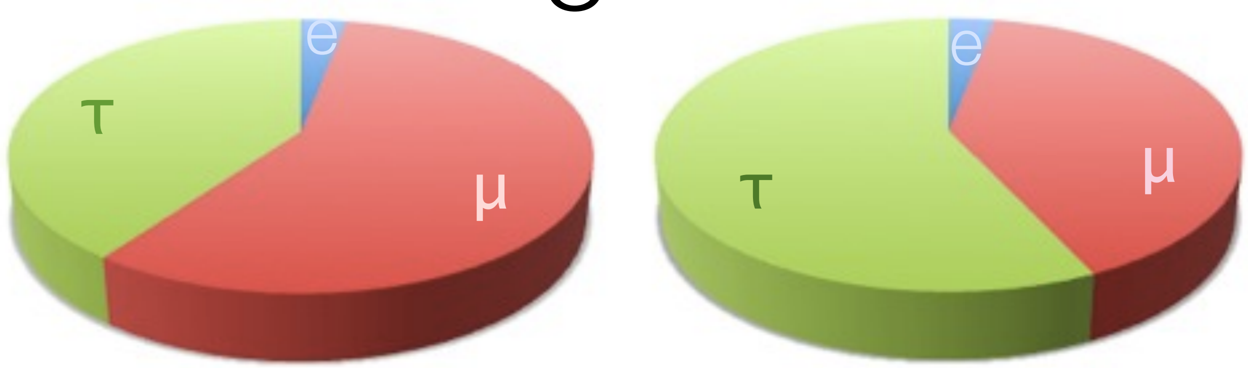
$\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$

- Top: NOvA result after two years (one year in neutrinos, one year in antineutrinos)
- Bottom: Full 6 year run, 3+3 years in neutrinos + antineutrinos.
- If MINOS central values are correct, NOvA will establish the difference with 3 σ significance in 2 years, 5 σ in 6 years



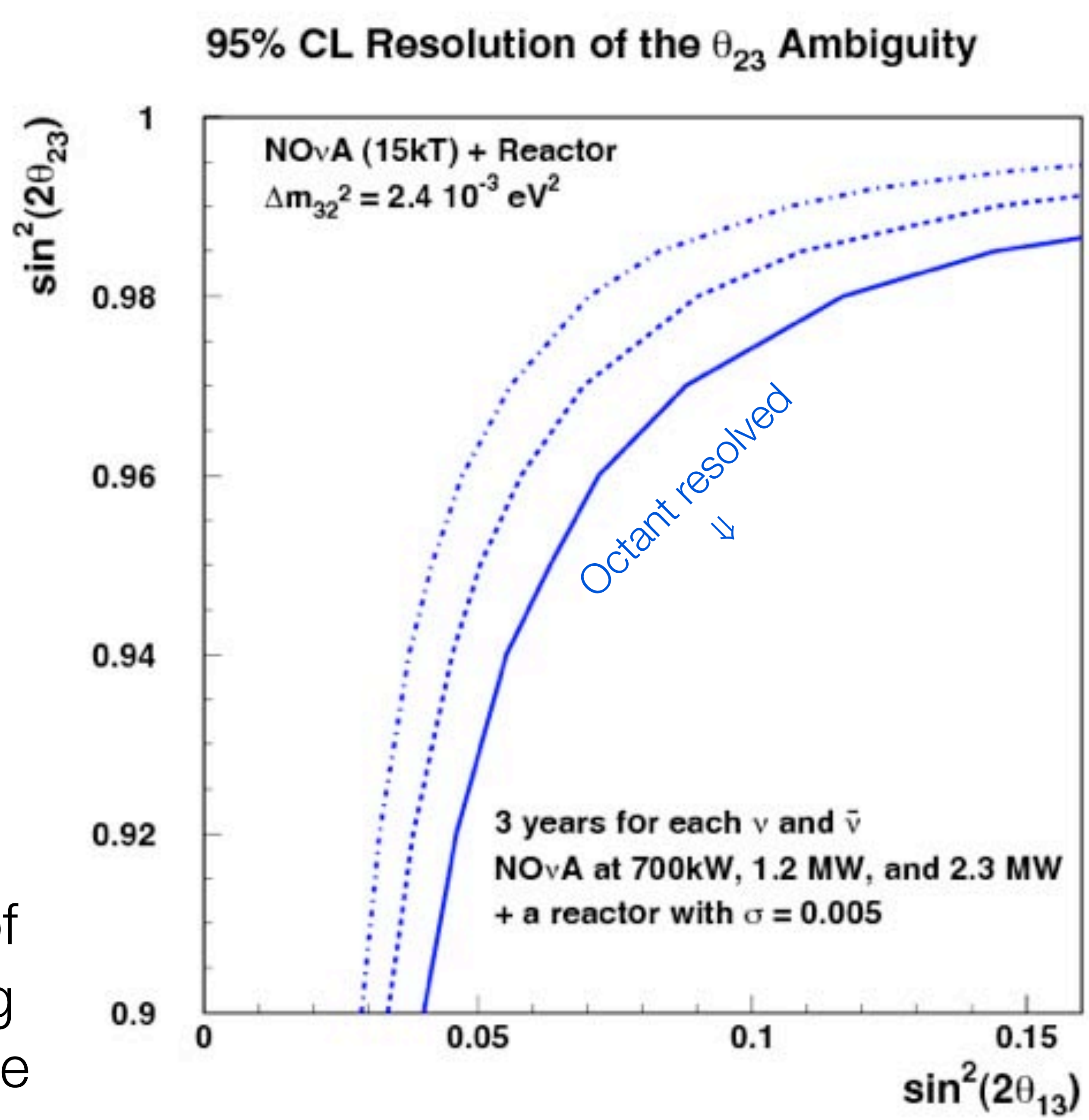
θ_{23} Quadrant: NOvA + Reactor

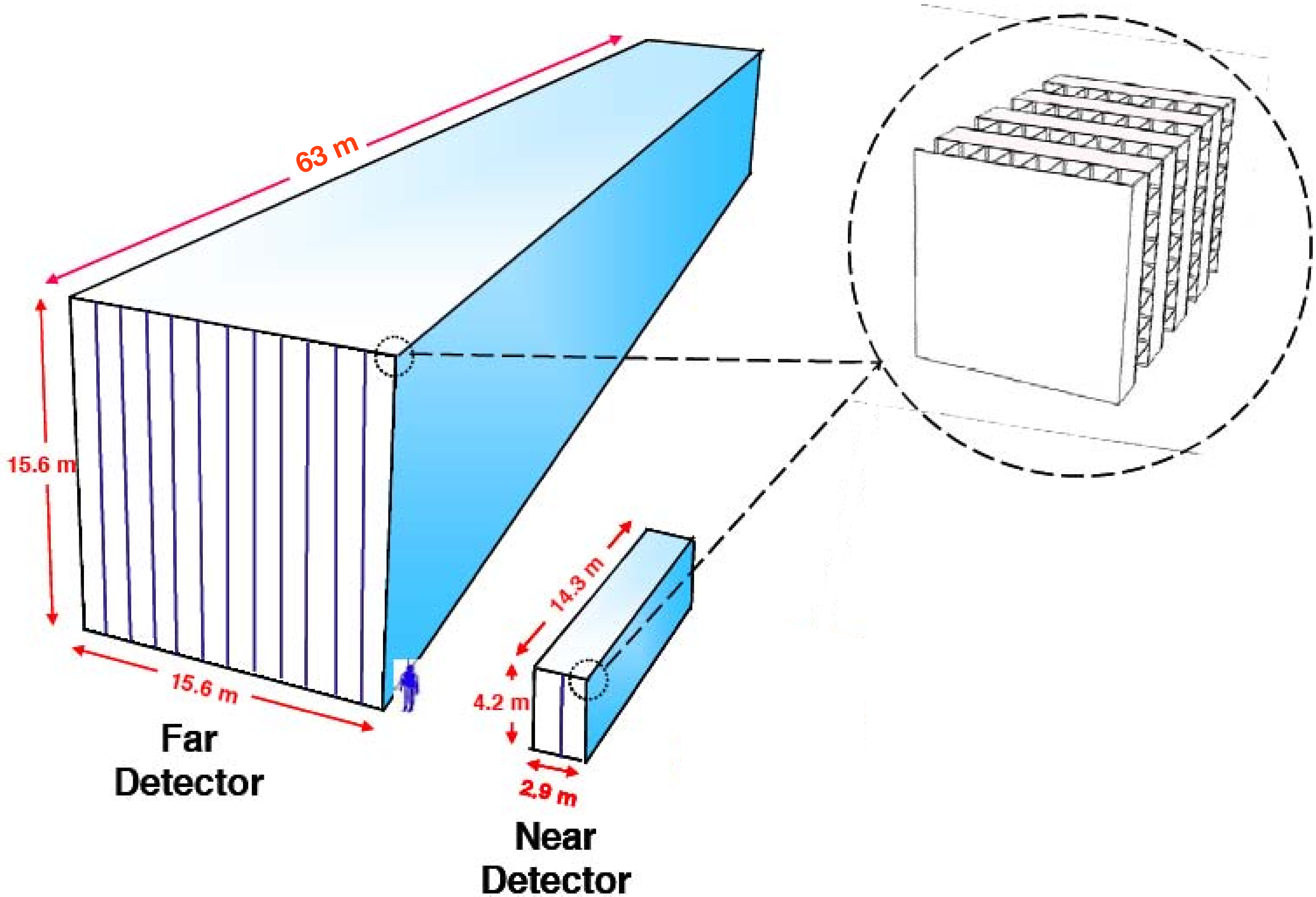
$\nu_3 = ?$



$\theta_{23} = 40^\circ$ $\theta_{23} = 50^\circ$

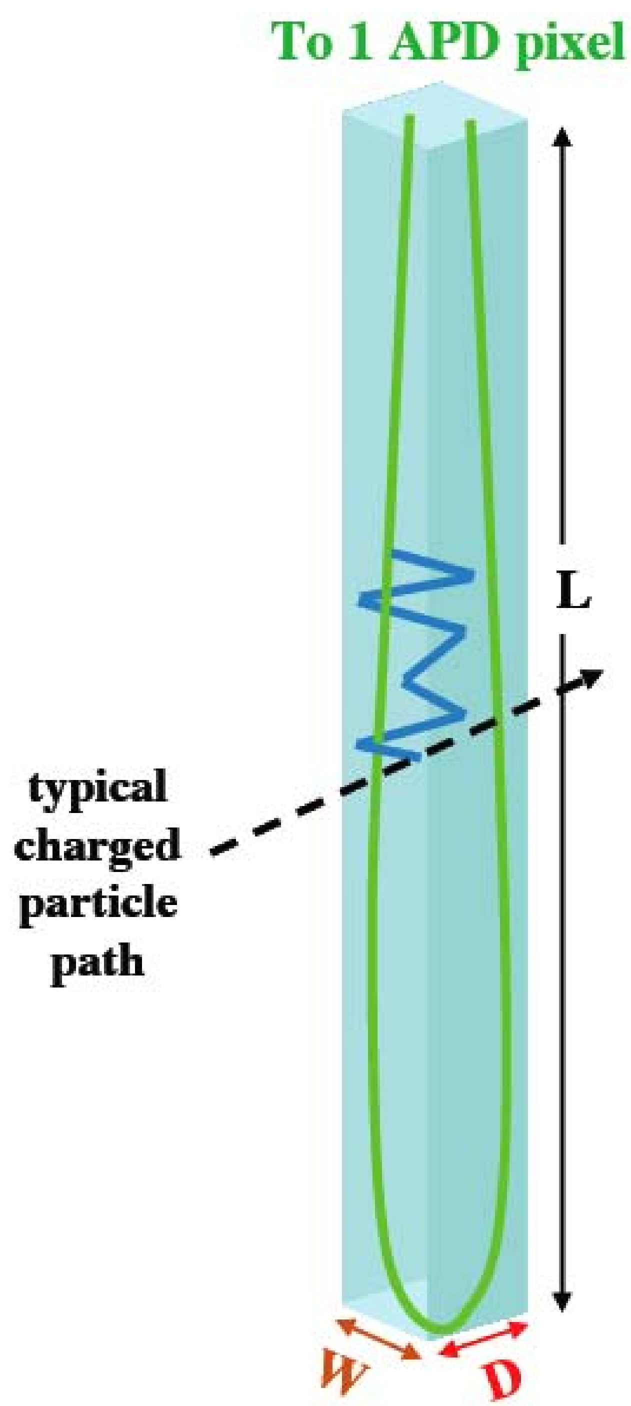
- Long baseline experiments measure $\sin^2 2\theta_{23}$ using the $\nu_\mu \rightarrow \nu_\mu$ channel and $2\sin^2\theta_{23}\sin^2 2\theta_{13}$ using $\nu_\mu \rightarrow \nu_e$
- Reactor experiments measure $\sin^2 2\theta_{13}$ using $\nu_e \rightarrow \nu_e$
- The combination allows measurement of $\sin^2\theta_{23}$ and $\sin^2 2\theta_{23}$ separately resolving the octant of the angle θ_{23} answering the question of whether ν_3 has more muon or tau content

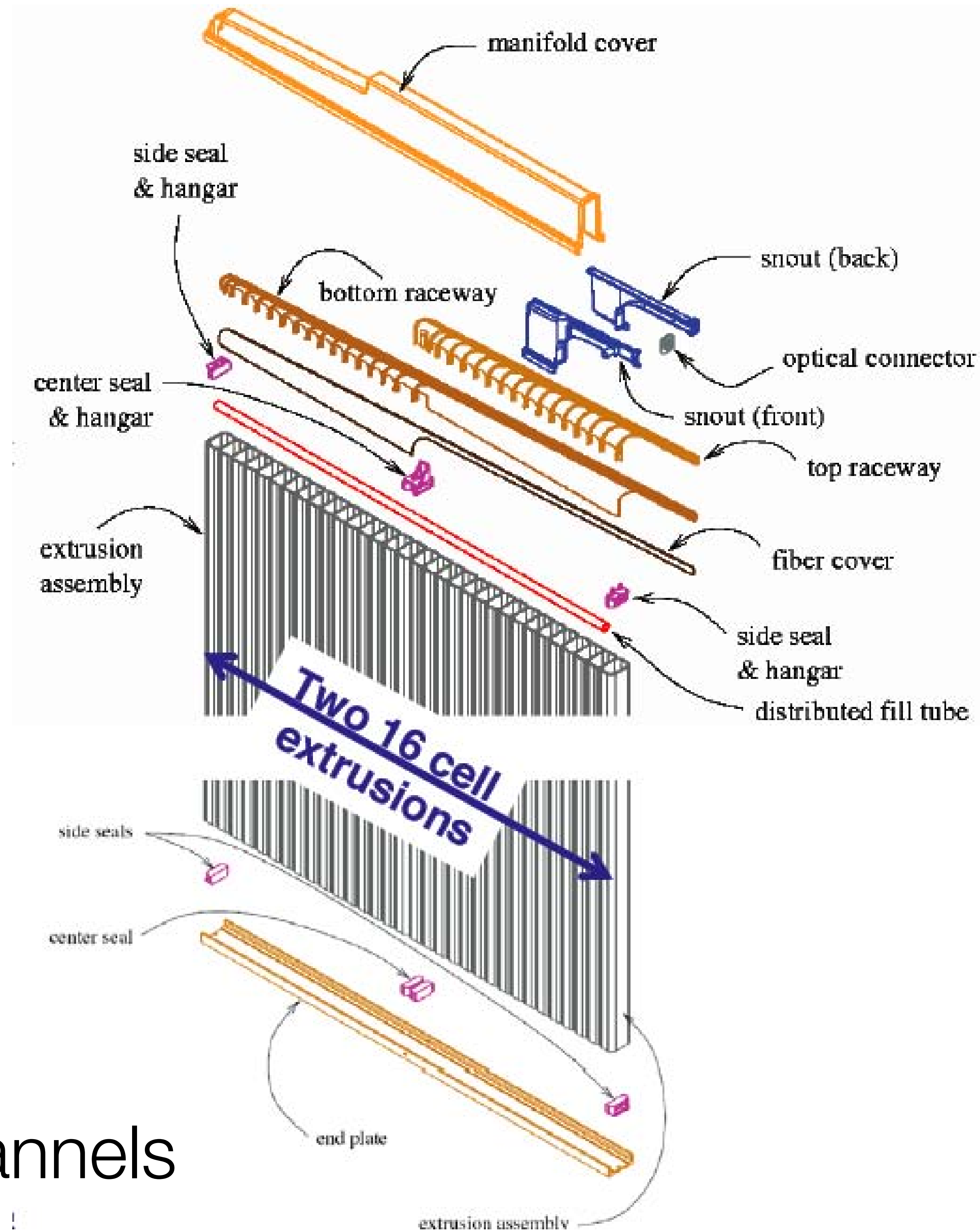




The NOvA Detectors

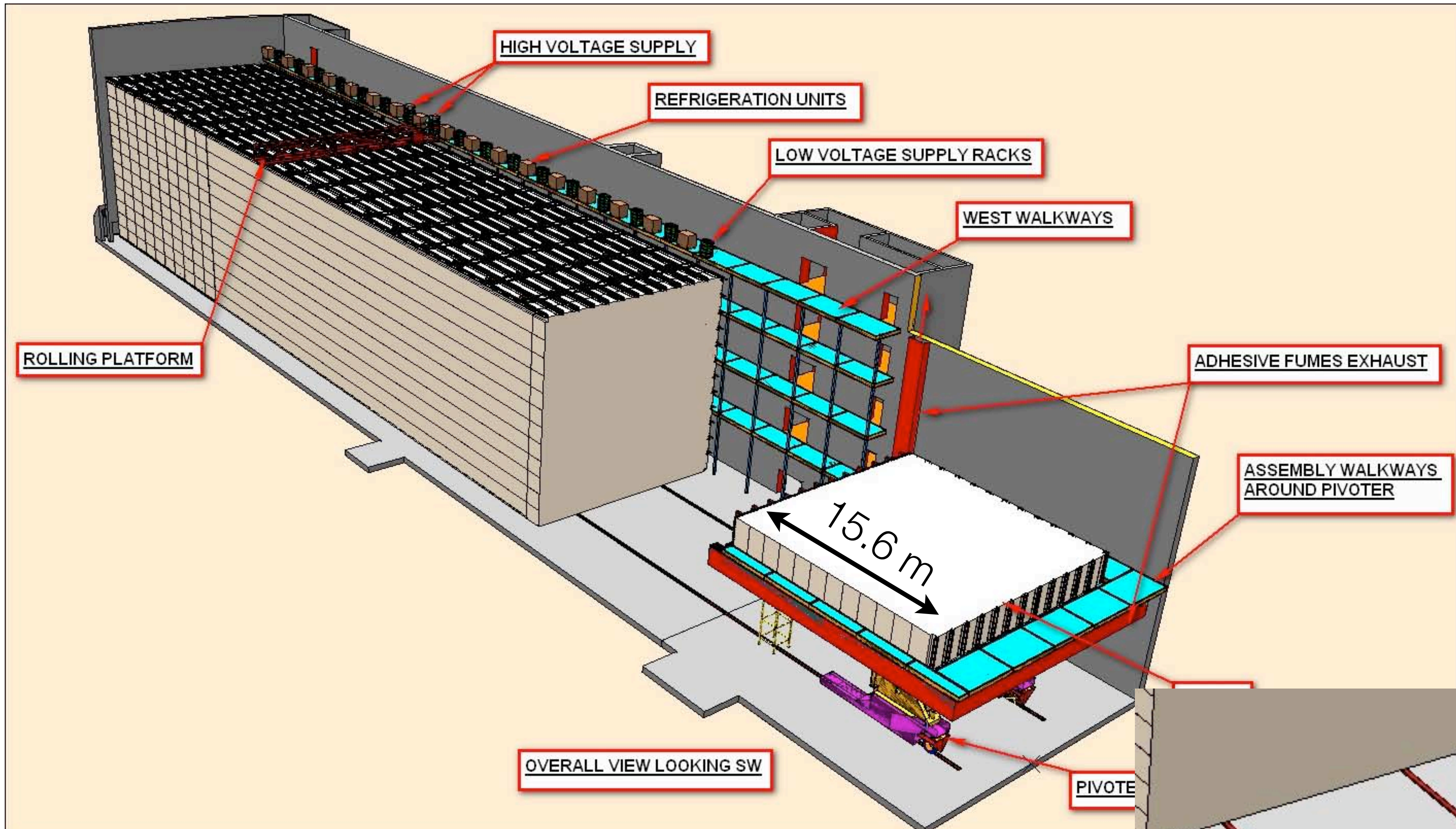
- 14-18 kton far detector
- 220 ton near detector



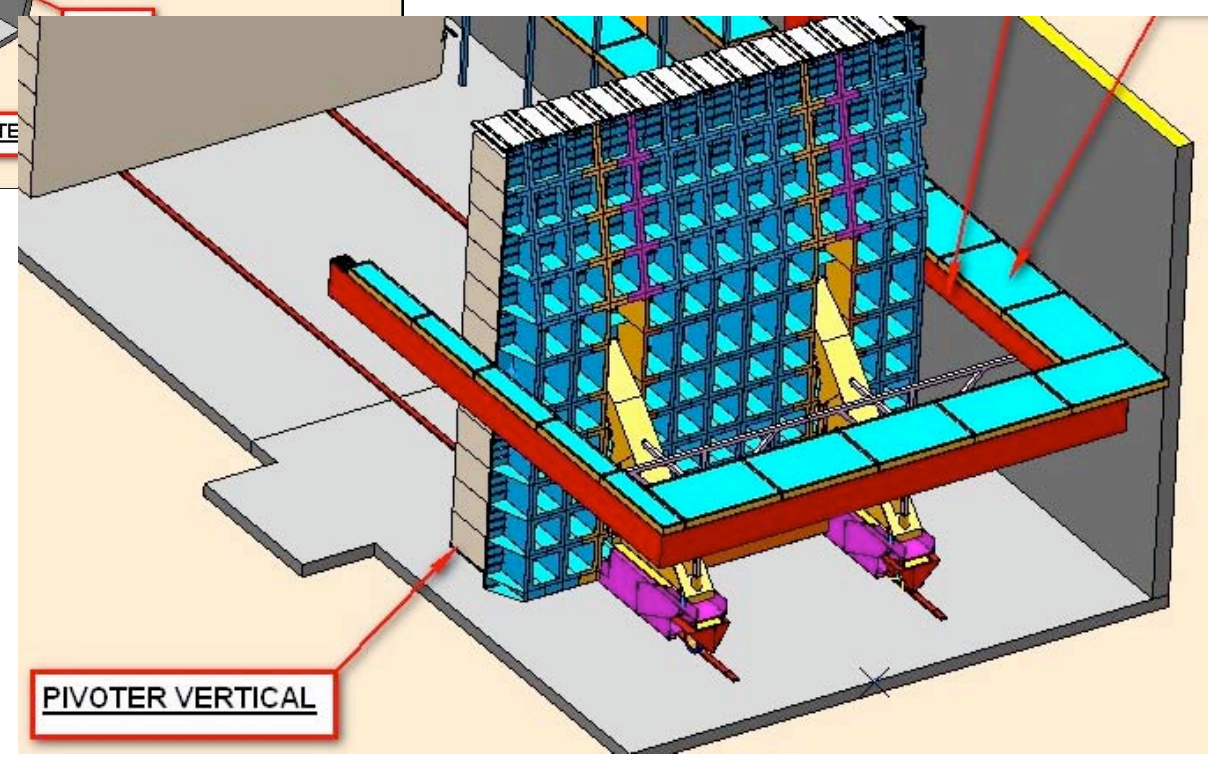


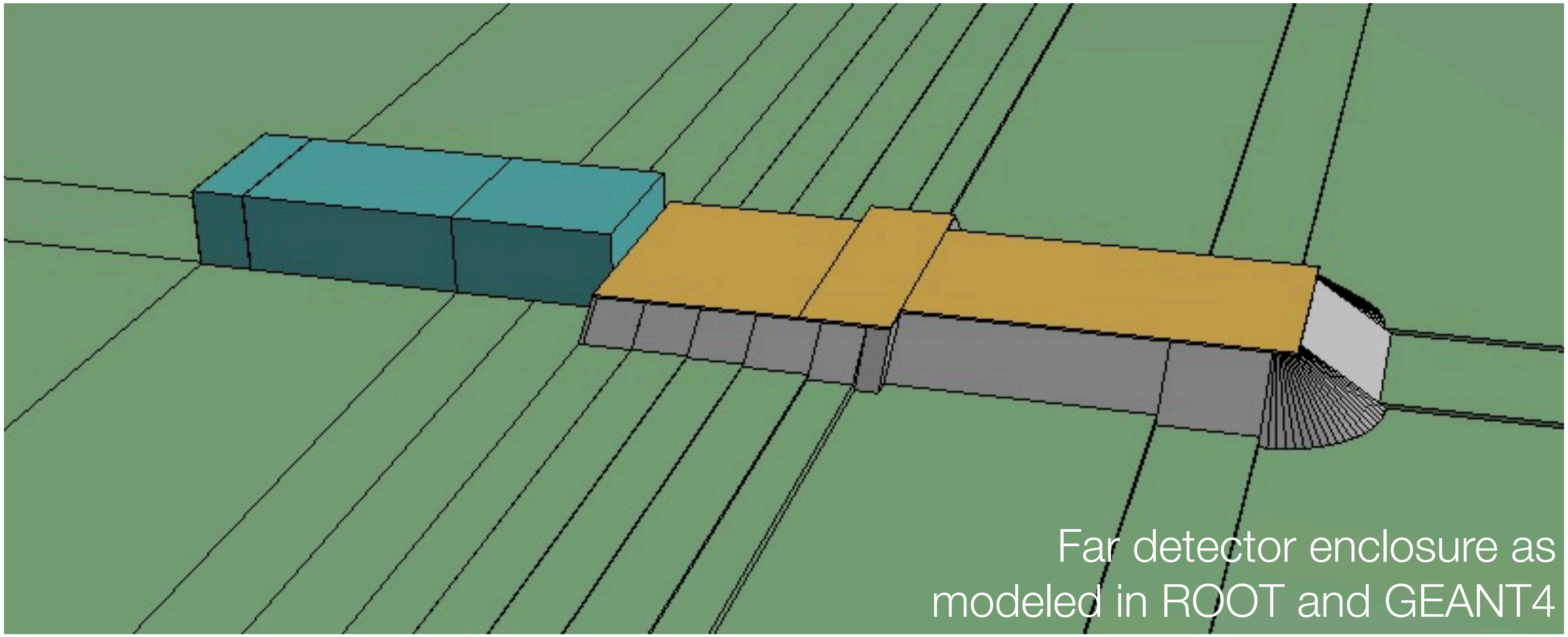
357,120 total channels

Block Pivoter



work platform





Experiment progress:

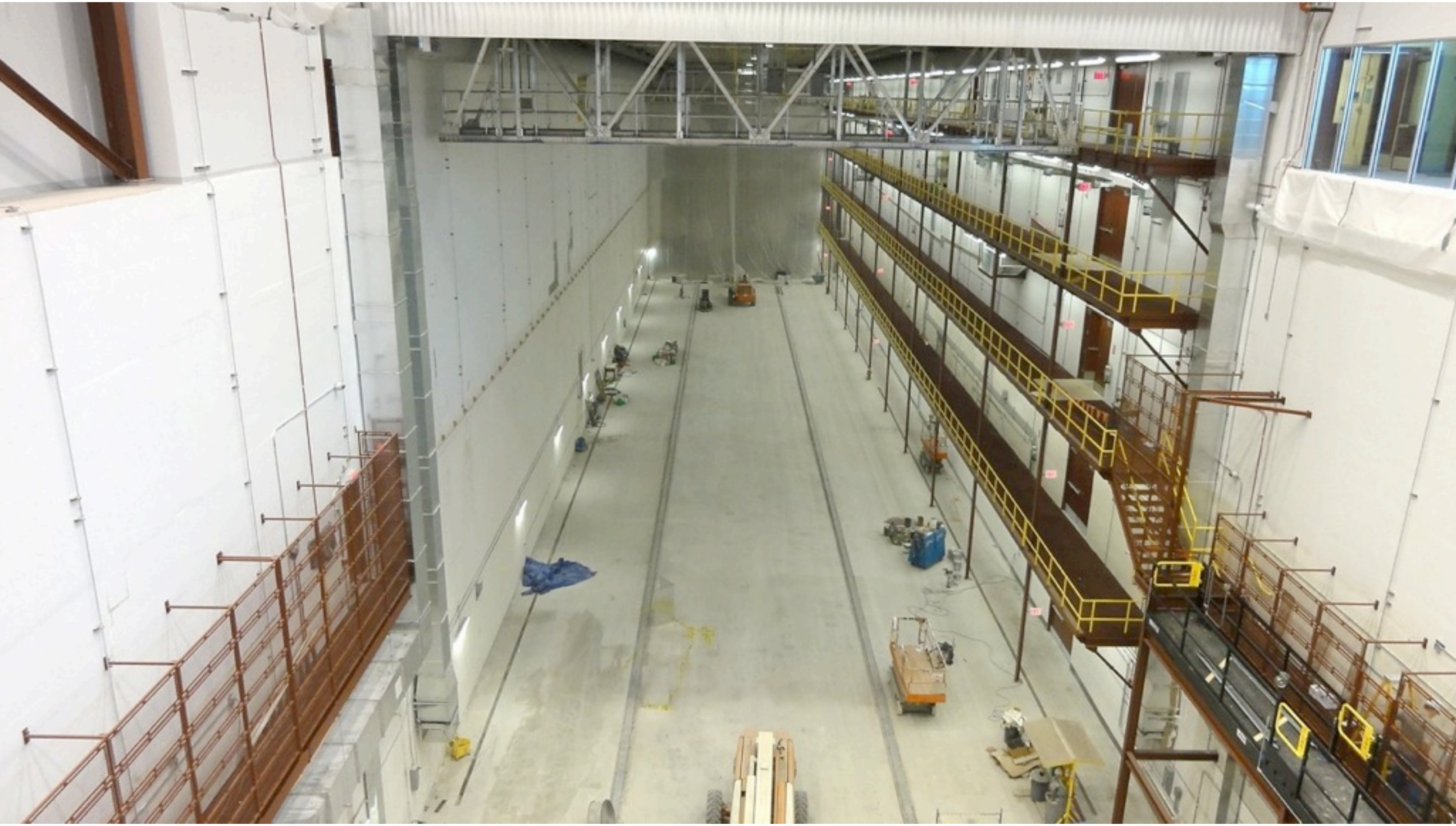
Far detector laboratory complete

After many years of looking at this. We can now look at this...

Experiment progress:

Far detector laboratory complete

Beneficial occupancy of Ash River laboratory on April 13, 2011



Experiment progress:

Far detector laboratory complete

Inside the detector enclosure looking south

Experiment progress:

Far detector assembly area

Block assembly area

Experiment progress:

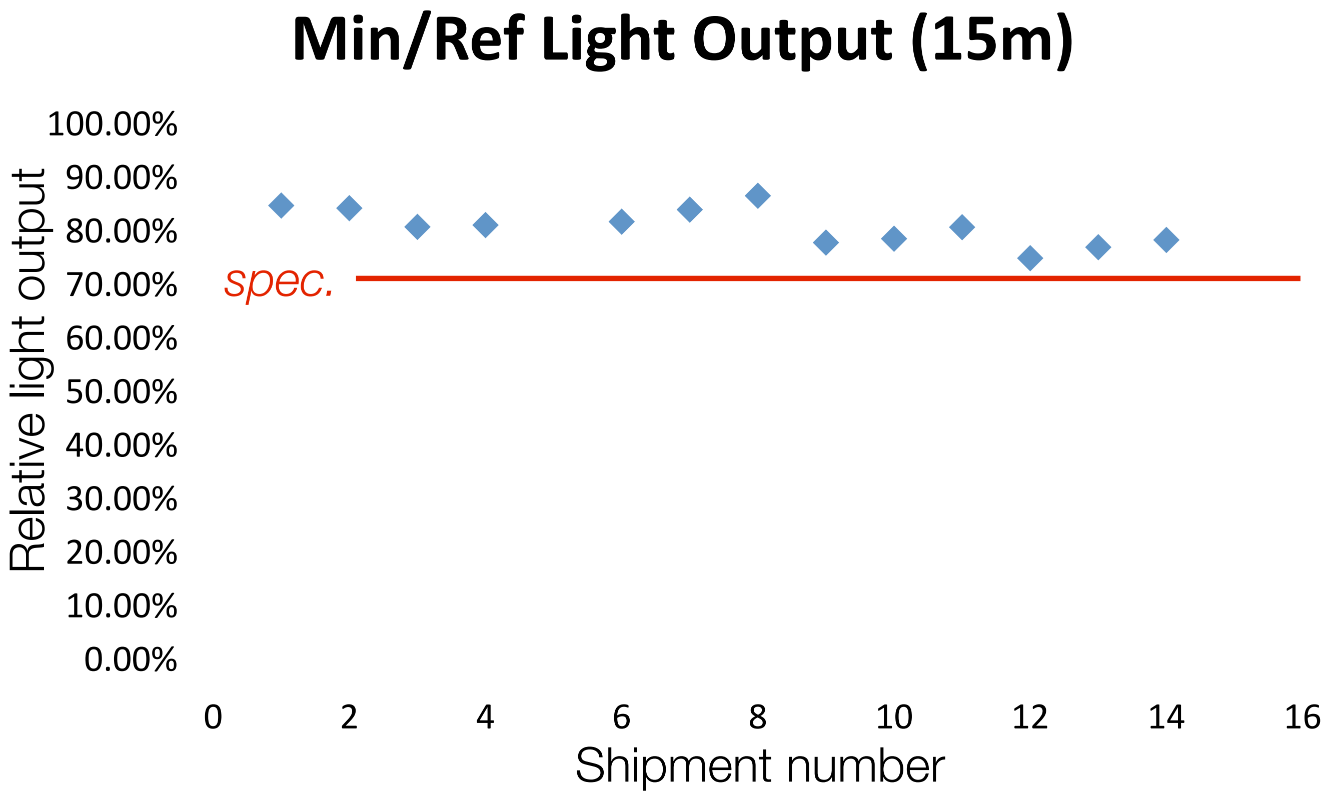
Scintillator and fiber

Scintillator

- **Mineral oil contract in place**
  - Have contract for fixed price for crude oil in range $60-$110 bbl, indexed outside this range. At $111 bbl price would be 22% higher than the fixed price; we continue to have 30% assigned contingency.
  - Taken delivery of first 164,000 gal of 3.2 million gallons required
- **Pseudocumene contract in place**
  - Price indexed to Asian naptha (crude oil)
  - 155,000 gallons required (22 ISO tanks)
- **Wave shifters in hand**
- **Blending PO has been issued**
  - Fixed price of $0.67/gal + $600K of setup
  - Test batch of 30,000 gallons blended and in use by near detector prototype

WLS fibers

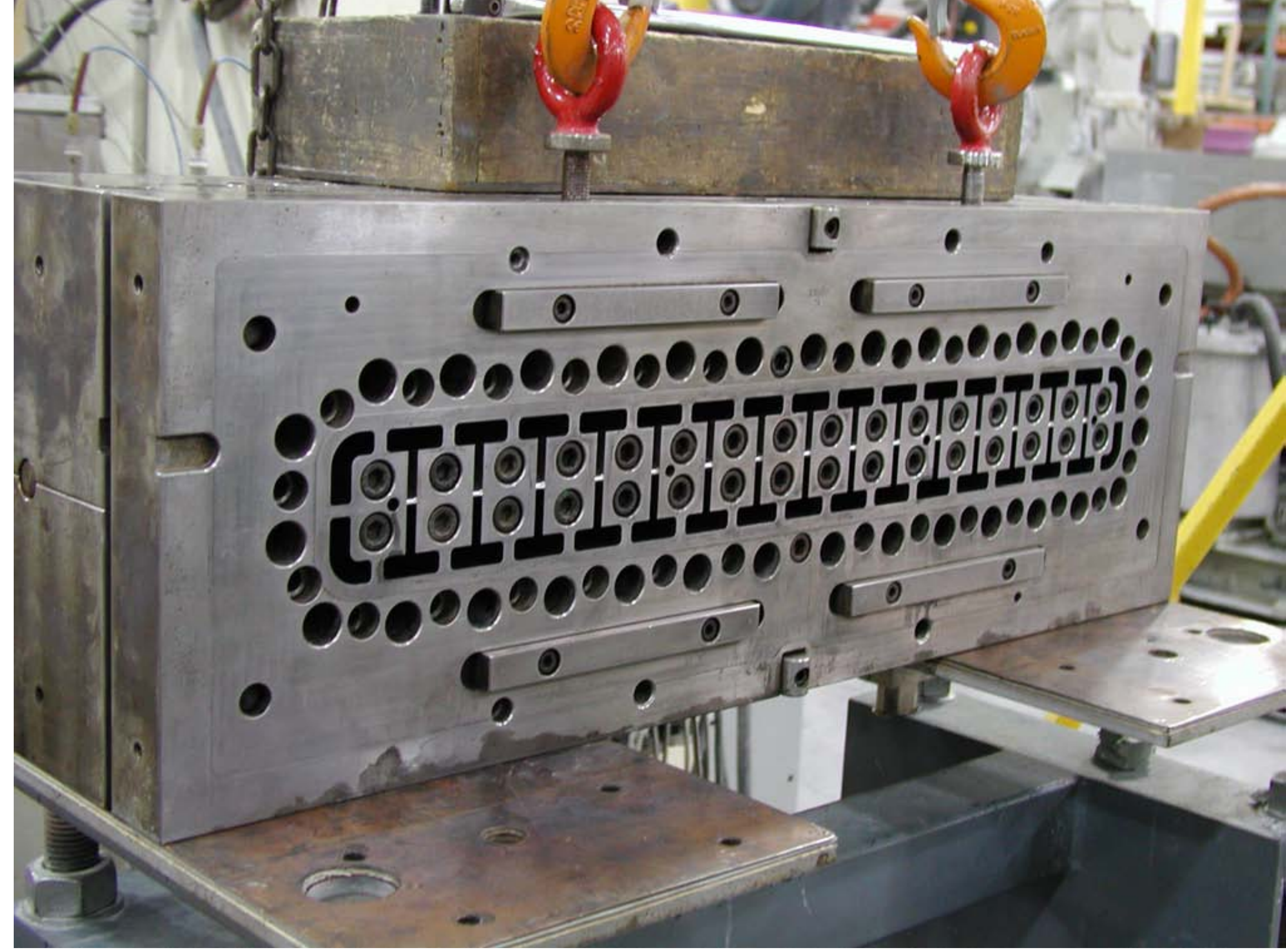
- **5,400 km delivered and tested**; 12,000 km required
- Kuraray continues to deliver on schedule despite earthquake and tsunami



Experiment progress:

PVC extrusions

- **Contracts in place for**
  - **PVC resin** for fixed price of $1 / lb
  - **Extruding** for fixed price of $0.96 / lb
- **Produced 1184 extrusions** for far detector which meet spec's; 23,000 required
- **Production currently running at 50%** full rate. Study time used to improve:
  - **Knitting**: There are ~70 points in the extrusion where two streams of melted resin merge and must "knit" together. Adjustments to die, flow rate, mixing, and melt temperature are likely to improve these joints.
  - **Reflectivity**: Vendor has sent several batches with unacceptably high fractions of rutile TiO_2; we require anatase which has better reflectivity. Working with vendor to ensure <2% rutile on all future shipments.
- **Plan to use thick walled extrusions only**
  - Original plan was to use thick for vertical planes and thin for horizontal
  - Having only thick simplifies construction, strengthens the detector, and expedites filling
  - Active fraction reduced from 71% to 66%



Experiment progress:

PVC modules

- Two 16-cell extrusions are assembled into 1 32-cell module at U. Minnesota factory. Fibers installed and routed, ends sealed.

- Two 16-cell extrusions are assembled into 1 32-cell module at U. Minnesota factory. Fibers installed and routed, ends sealed.
- Factory moved to large warehouse for far detector production.
- Much work has gone into understanding and redesigning the manifold cover which developed cracks on the prototype. New design is stronger and eliminates all stress concentrators. First parts expected in July.

Experiment status:

Assembly

- Prototype pivoter is completed and tested (pictured at right)
- Ash River pivoter is under construction.
- 5 outfitting workshops held in past 6 months to refine plans in light of experience with prototype detector
- Detector structure modified to be simpler and stronger by opting to use only a single style of PVC extrusion. Safety factor increased from 1.3 to 3.1 which allows for immediate filling of blocks with scintillator.
- Planning to have first block in place and filled prior to March 2012 shutdown

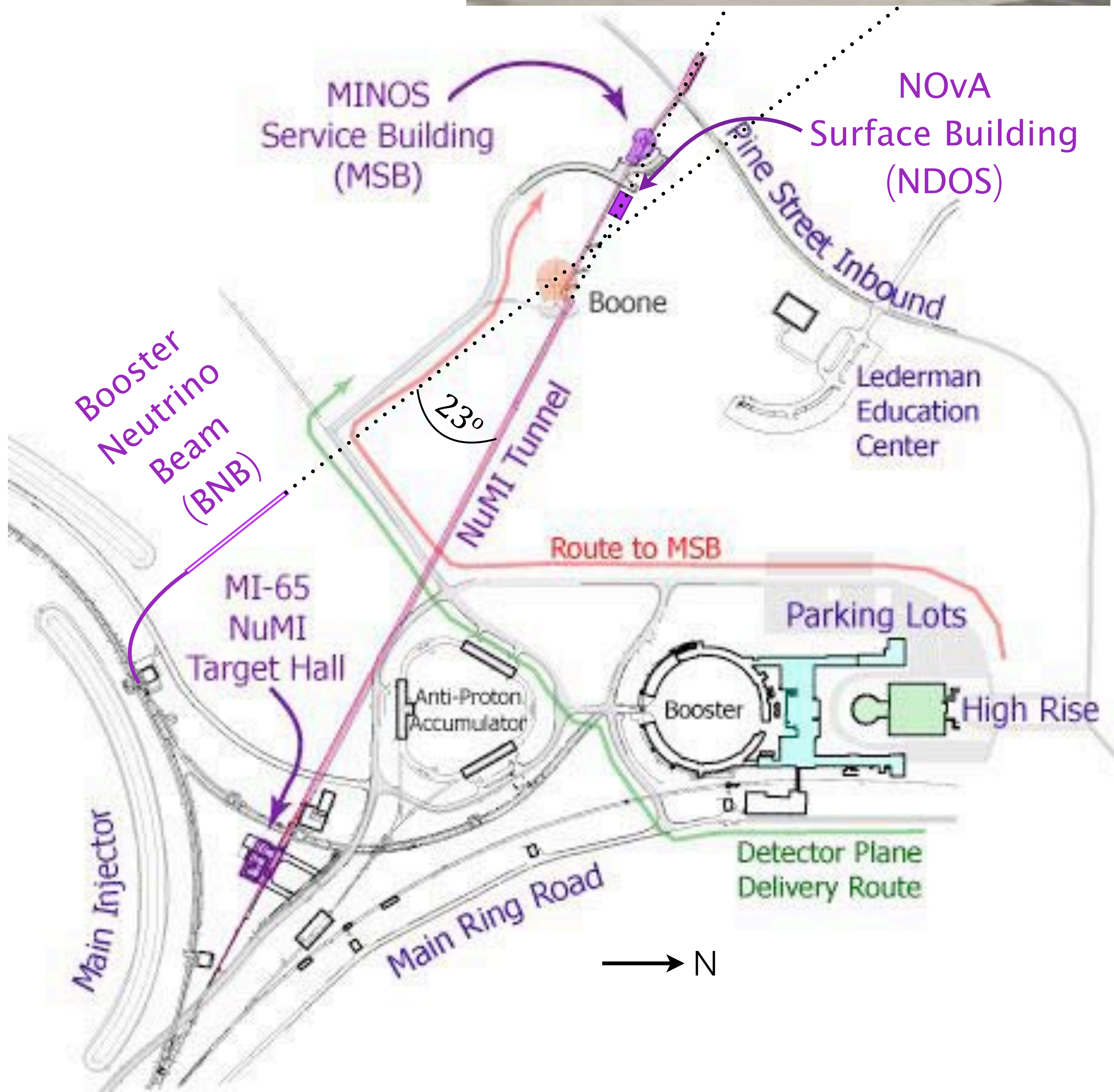
Block pivoter prototype at CDF

Near Detector On Surface (NDOS)

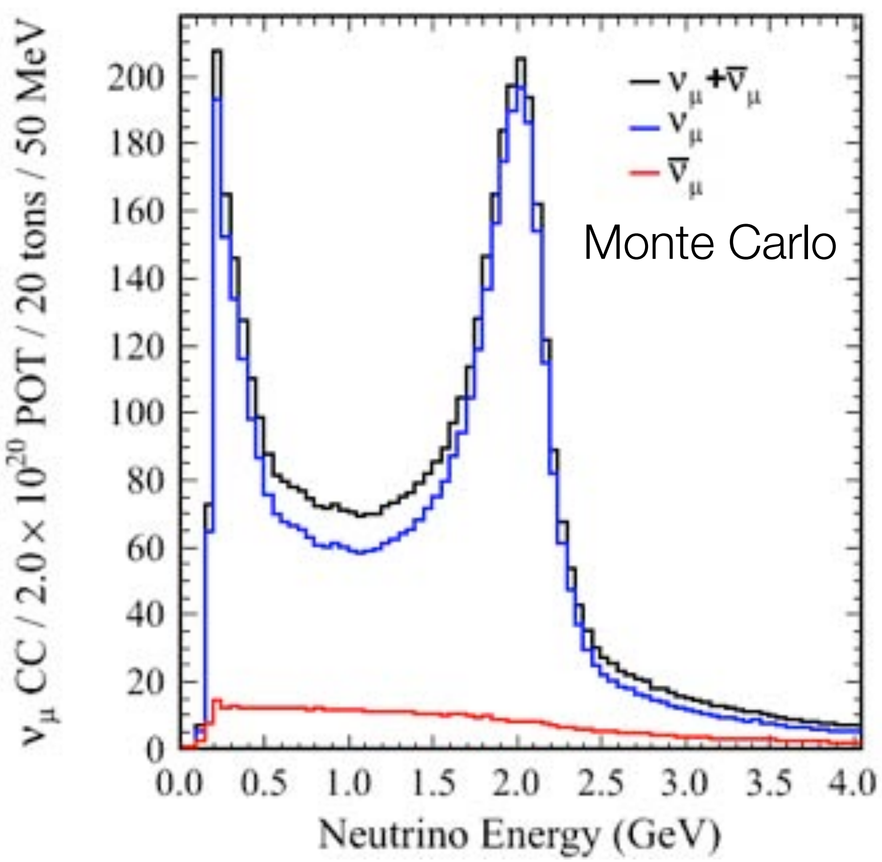
- Designed to prototype all detector systems prior to installation at Ash River as a full end-to-end test of systems integration and installation
- 2 modules wide by 3 modules high by 6 blocks long. Far detector is 12×12×30. NDOS mocks up upper corner of far detector ~exactly.
- Installation completed May 9, 2011.
- Commissioning and data collection on going 11/2010 - present

NDOS location

- Located in two neutrino beams providing an early look at data and a chance to tune up DAQ, calibration, reconstruction, and analysis prior to first data from Ash River
- NDOS is located directly above the NuMI neutrino beam line and is oriented parallel to the NuMI beamline. It sees neutrinos at an off-axis angle of 110 mrad.
- NDOS is located ~on the Booster Neutrino Beam (BNB) line, but the detector axis is rotated 23^{o} with respect to the BNB beamline

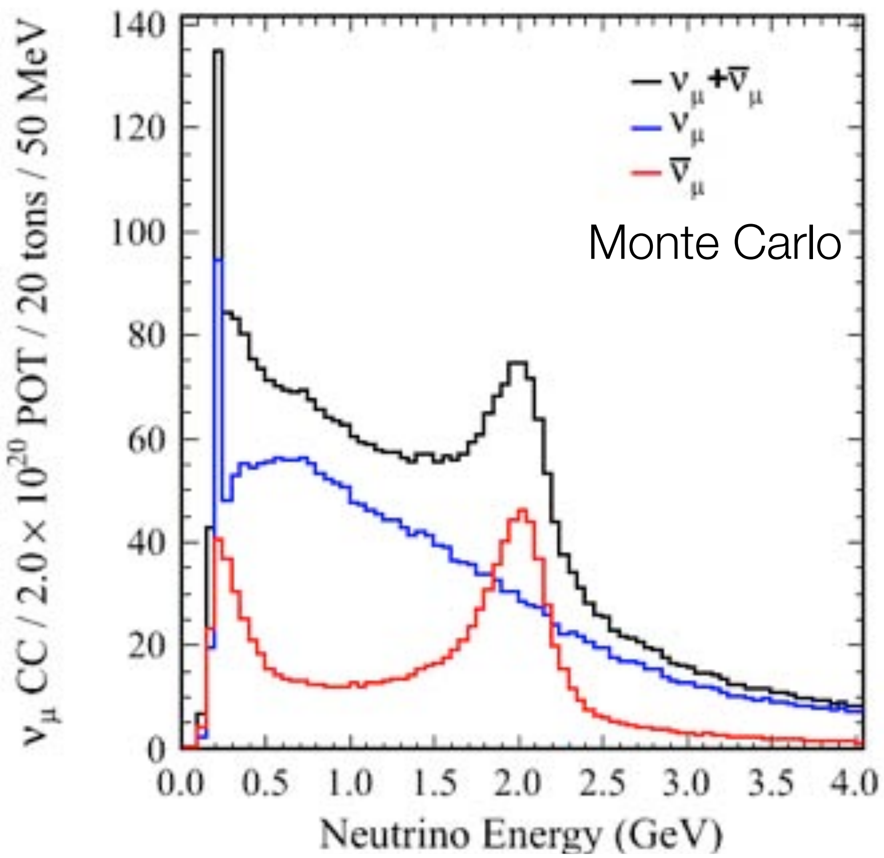


NuMI Neutrino Beam



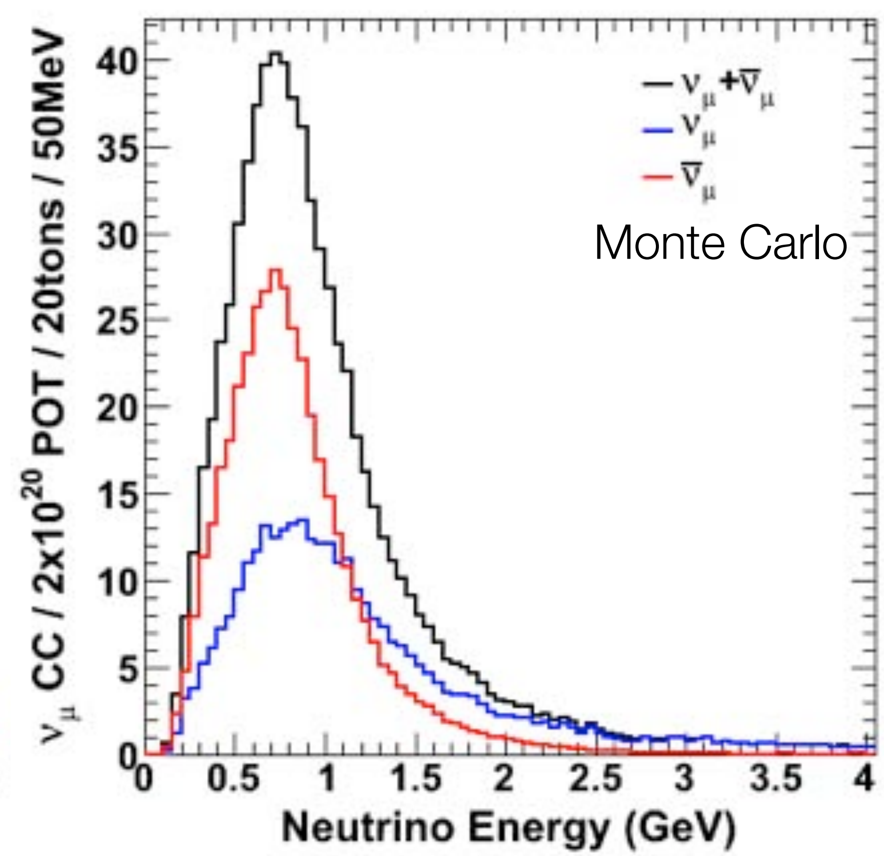
4500 events / 20 tons / 2E20 POT

NuMI Antineutrino Beam



3300 events / 20 tons / 2E20 POT

Booster Antineutrino Beam



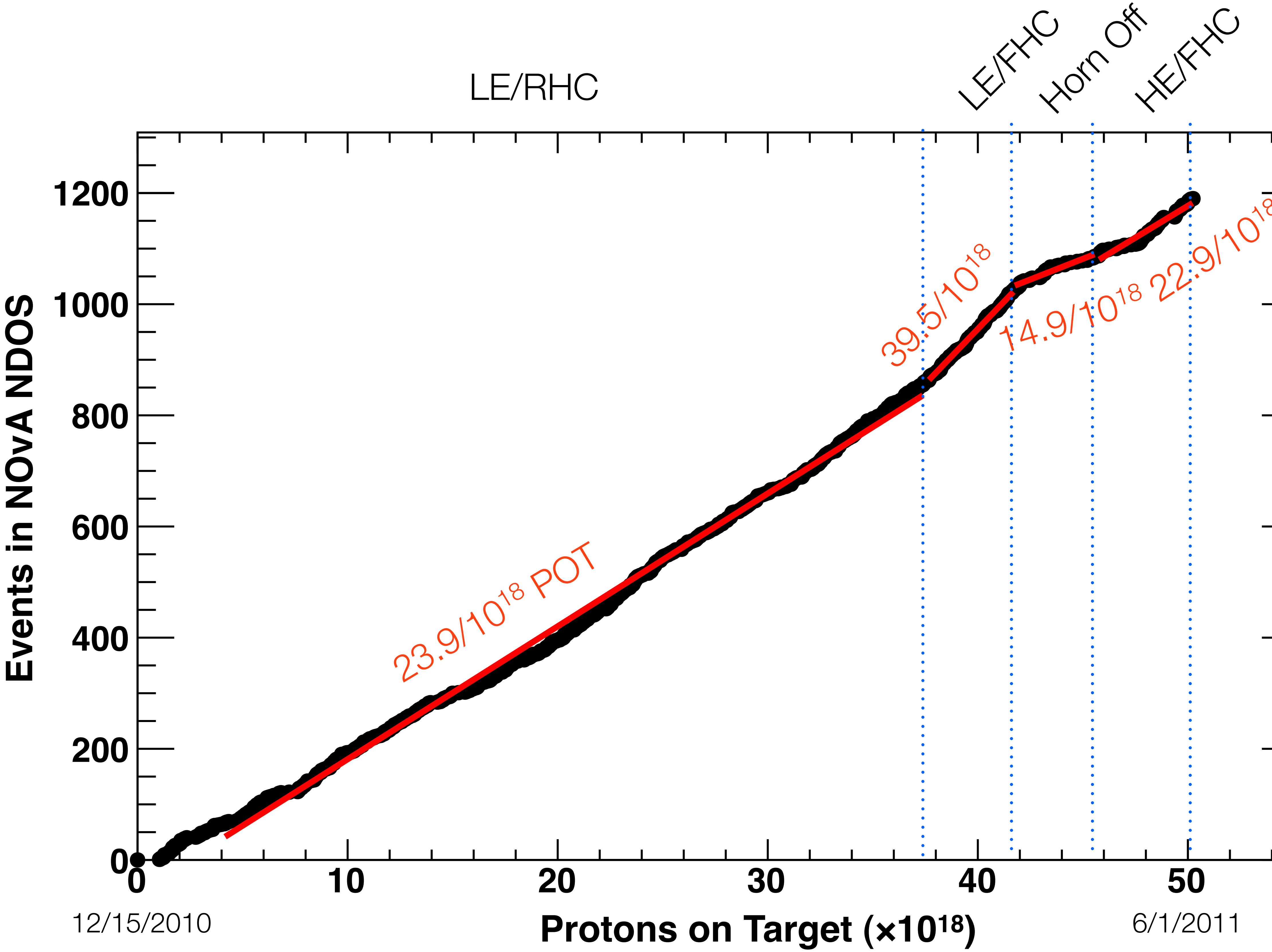
735 events / 20 tons / 2E20 POT

NuMI Beam

- In neutrino running kaon decays produce a peak at 2 GeV - a good match to the 2 GeV peak from pion decay at 14 mrad to be used in experiment.
- In antineutrino beam, the wrong-sign contamination washes the 2 GeV peak out.
- We've taken 5.6E19 POT in antineutrino mode and 8.4E18 POT in neutrino mode.

BNB Beam

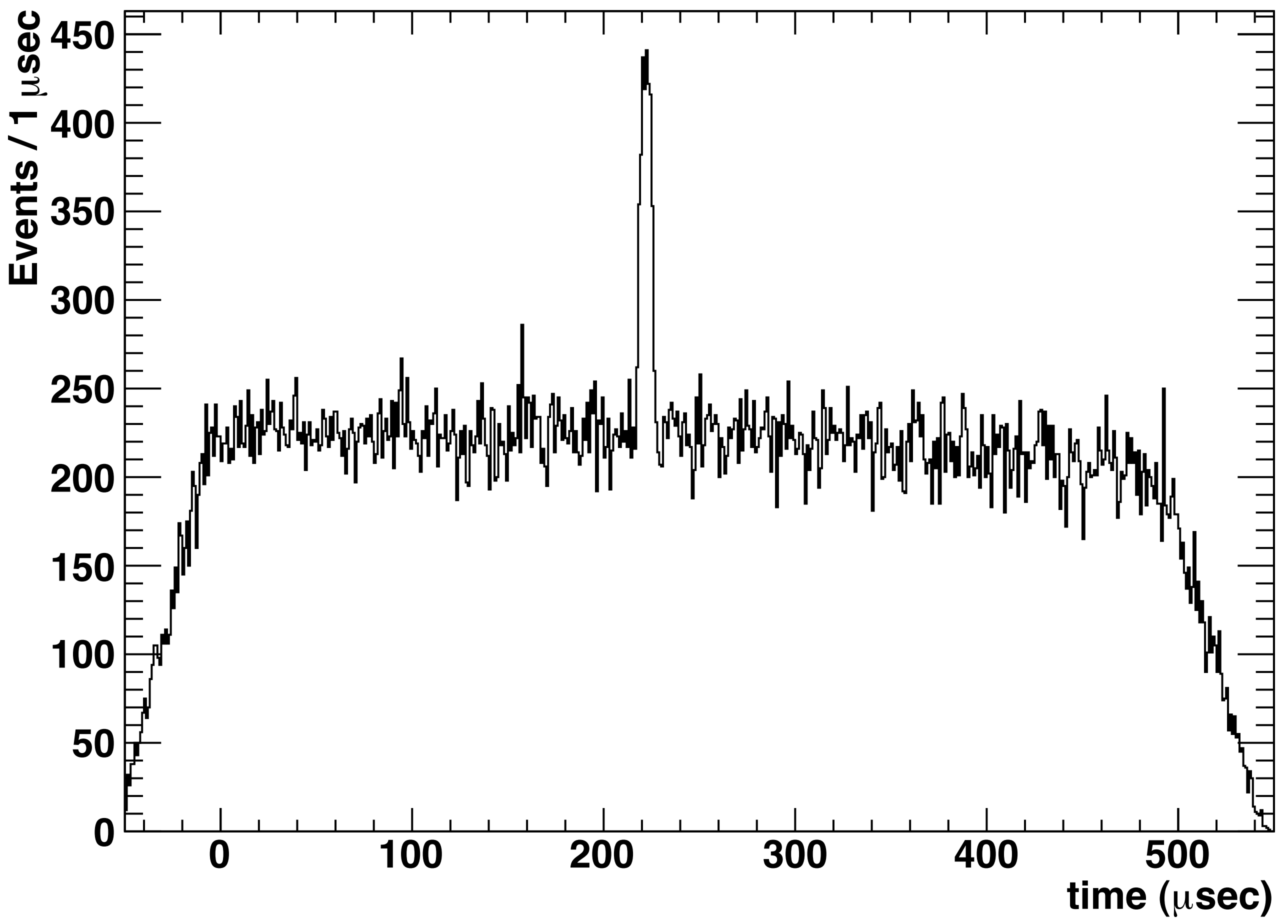
- Peaks at 700 MeV
- We've taken 2.7E19 POT in antineutrino mode

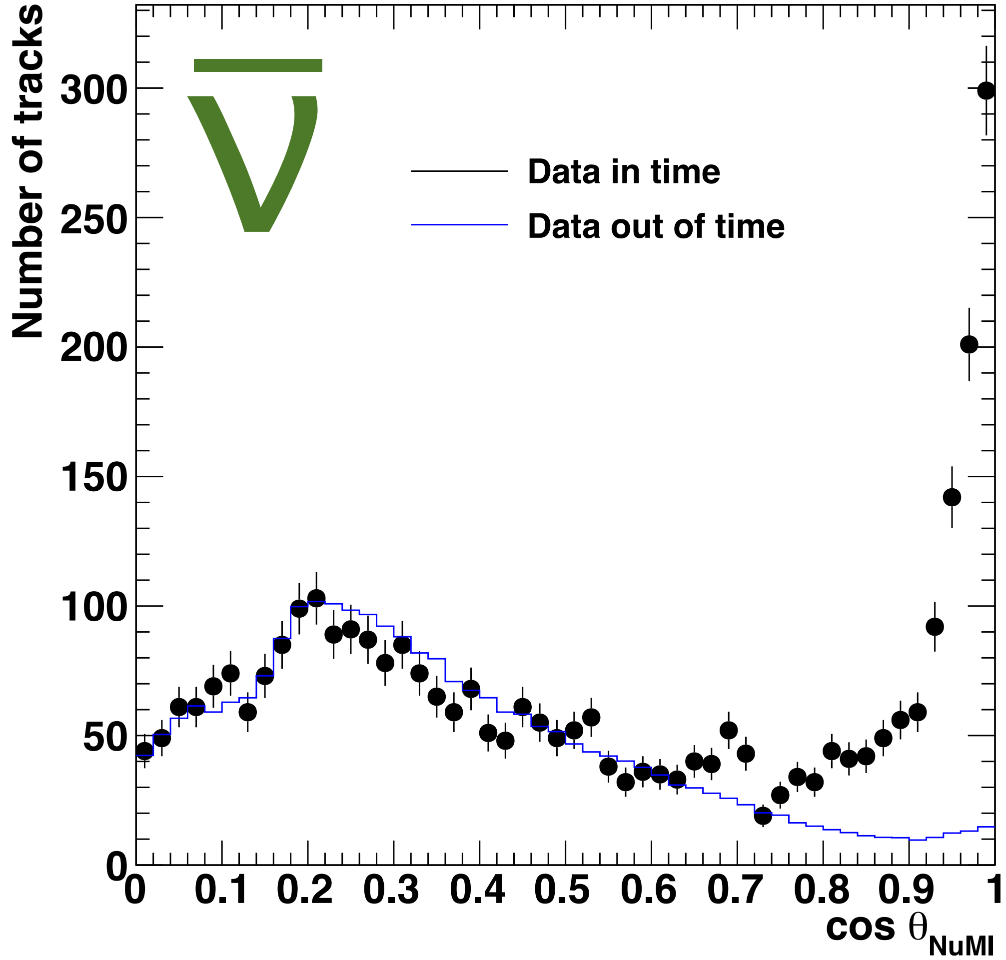


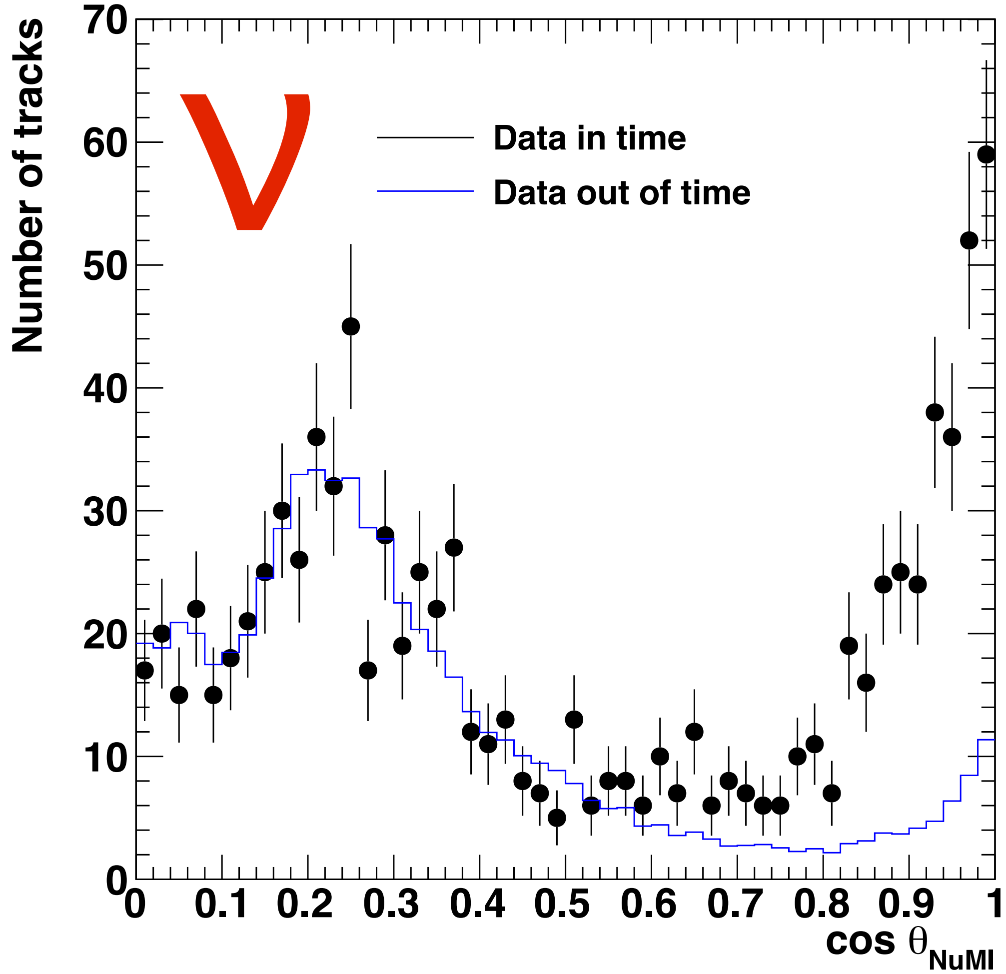
NuMI Events In NDOS

LE = Low Energy target position
HE = High Energy target position
RHC = Reverse horn current (antineutrinos)
FHC = Forward horn current (neutrinos)

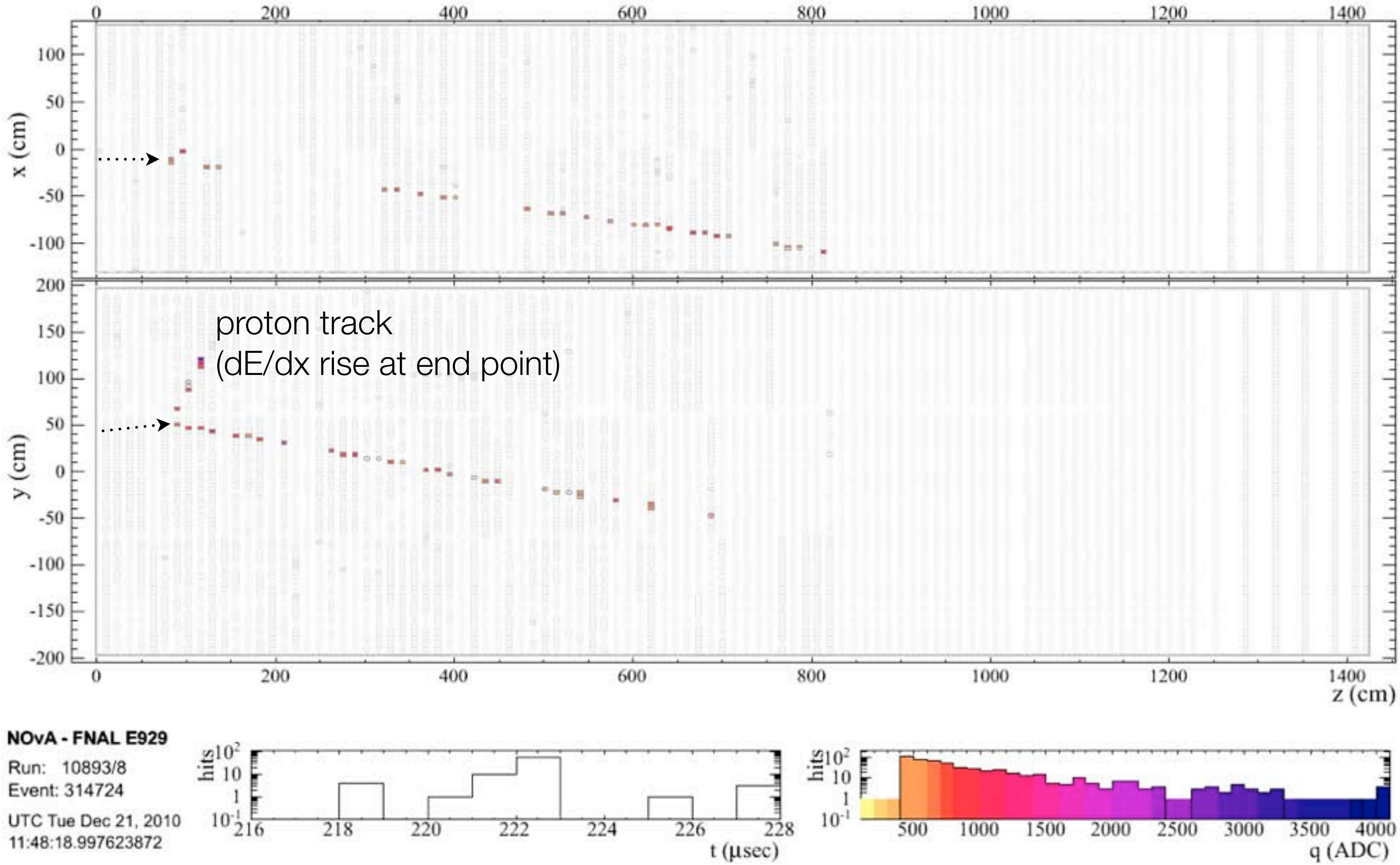
NuMI events





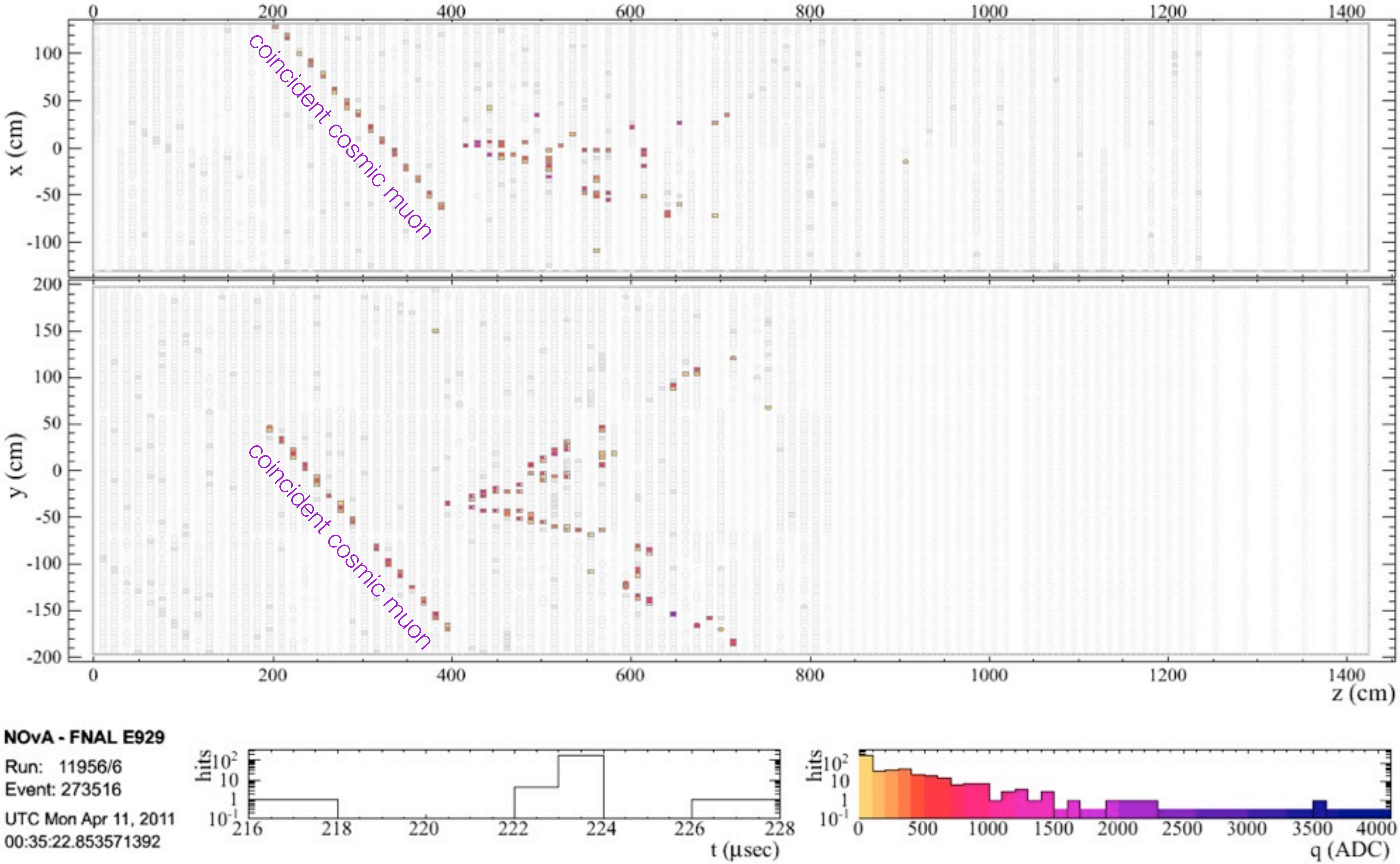


- See NuMI beam at off-axis angle of 110 mrad
- Recorded 1001 events in antineutrino mode (69 cosmic background)
- Recorded 253 events in neutrino mode (39 cosmic background)



NOvA NDOS NuMI Data

ν_μ quasi-elastic candidate

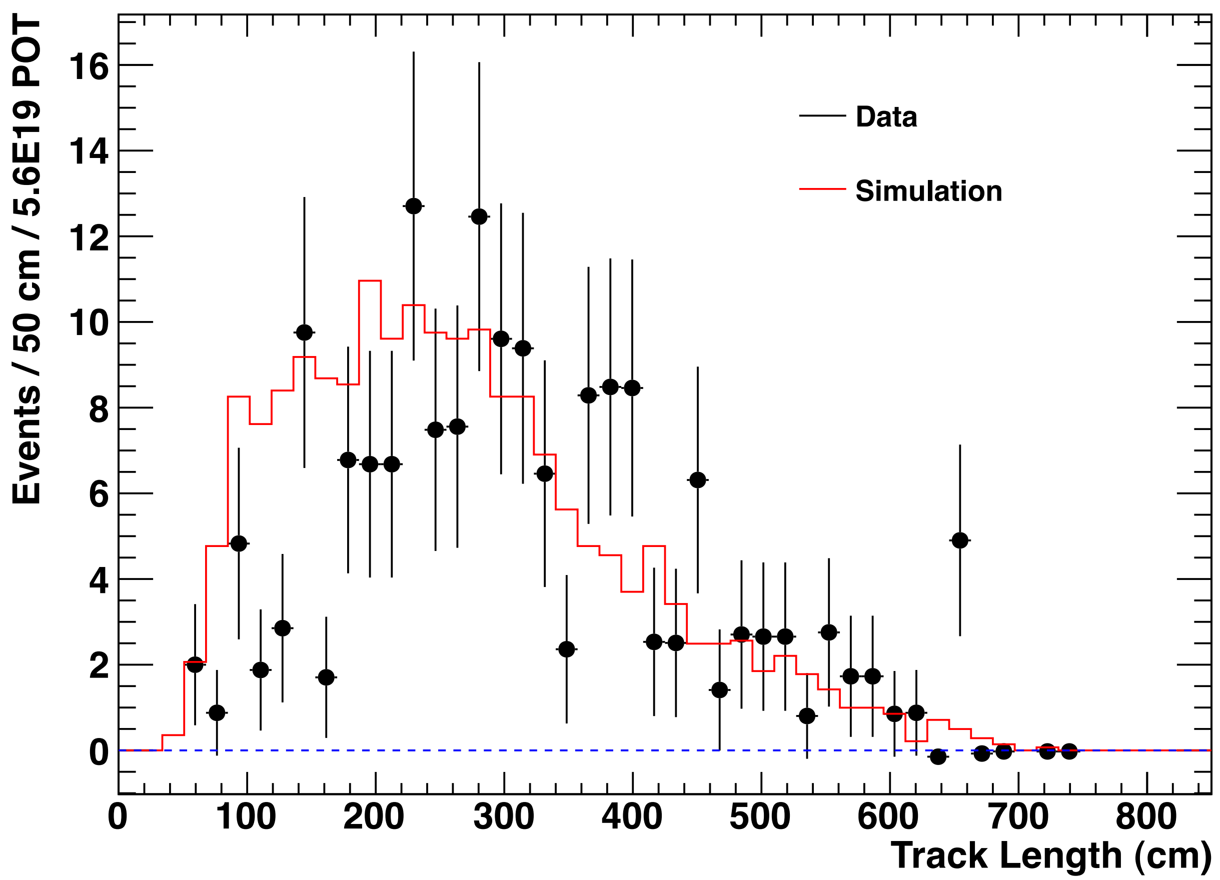


NOvA NDOS NuMI Data

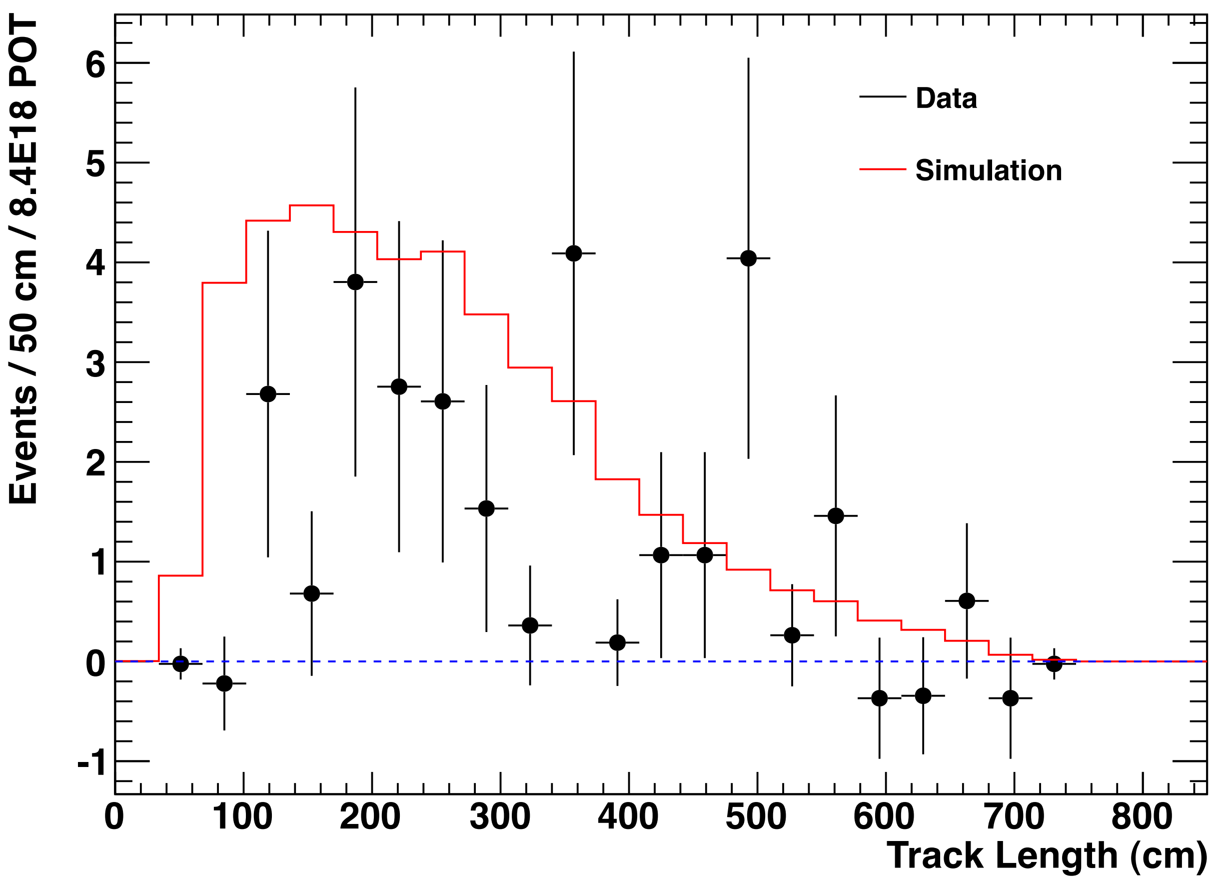
$\nu_\mu + N \rightarrow N' + \nu_\mu + \pi^0 + \pi^0$ candidate

NuMI neutrinos
Track length comparisons

antineutrino beam

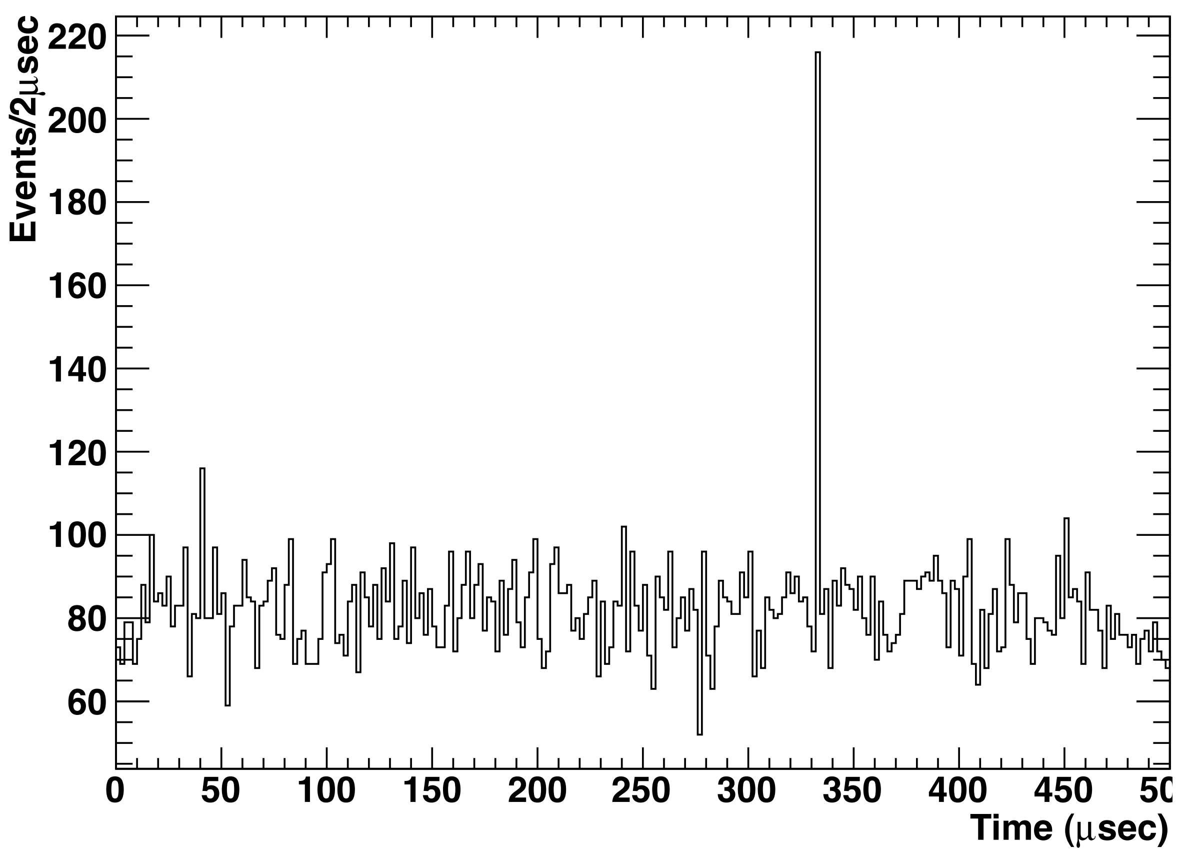


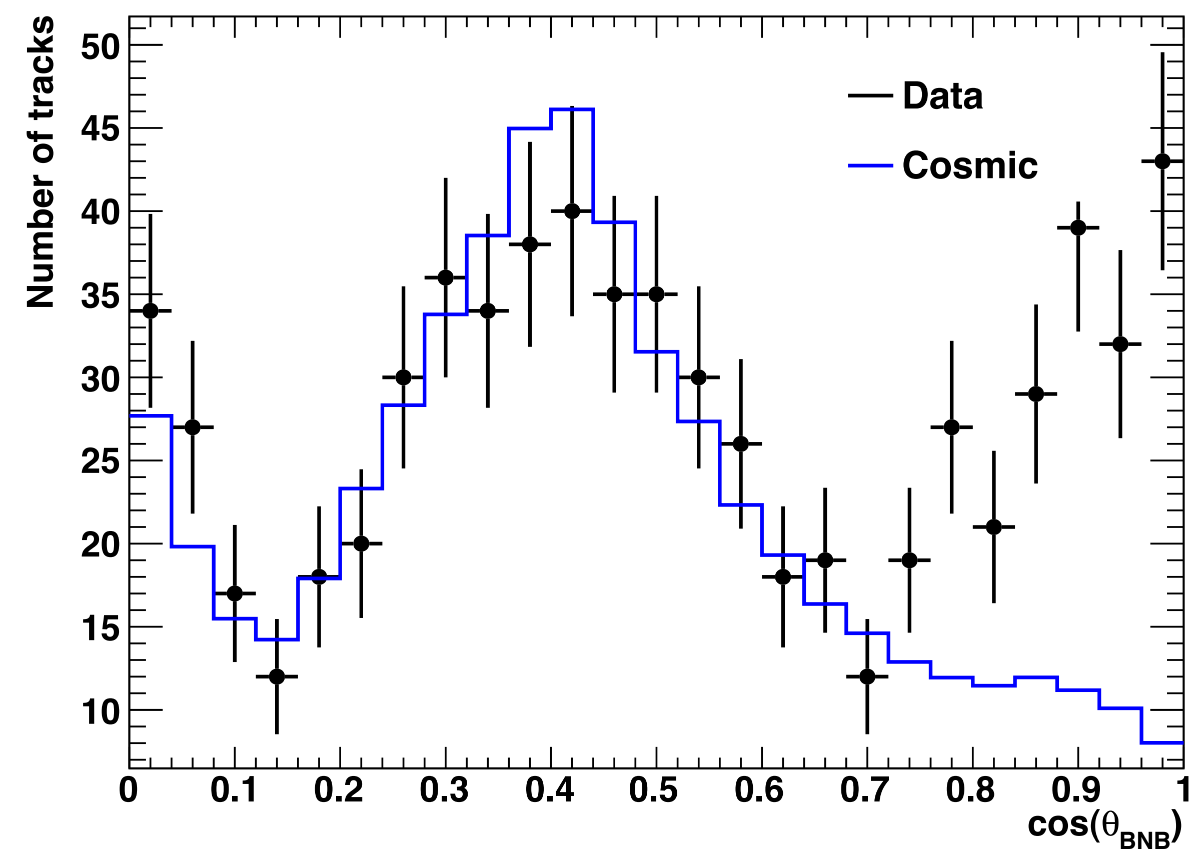
neutrino beam



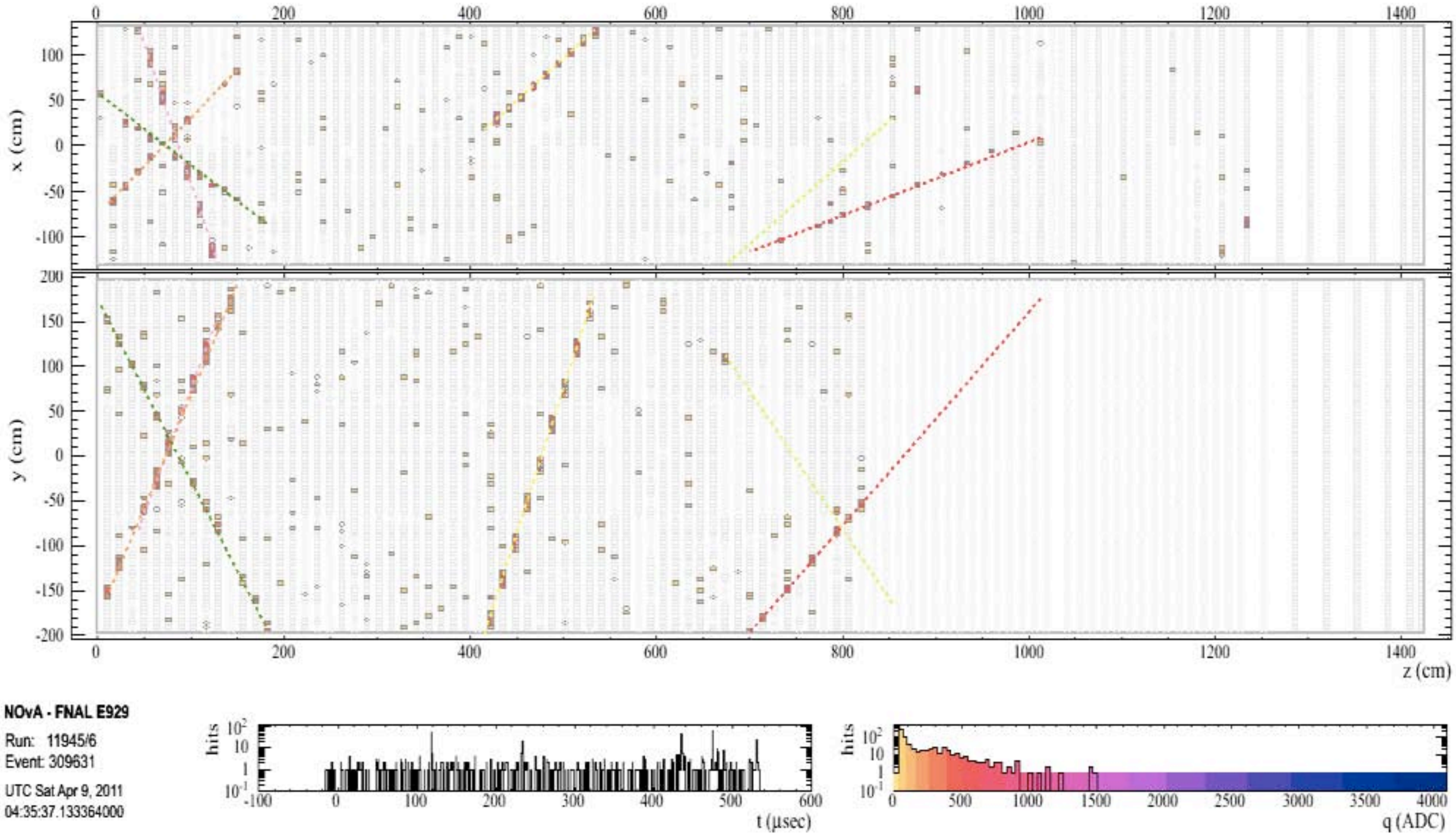
Comparisons of the track length distributions for fully-contained events in antineutrino (left) and neutrino (right) NuMI beam. Data and simulation are normalized to protons on target.

Booster Neutrino Beam



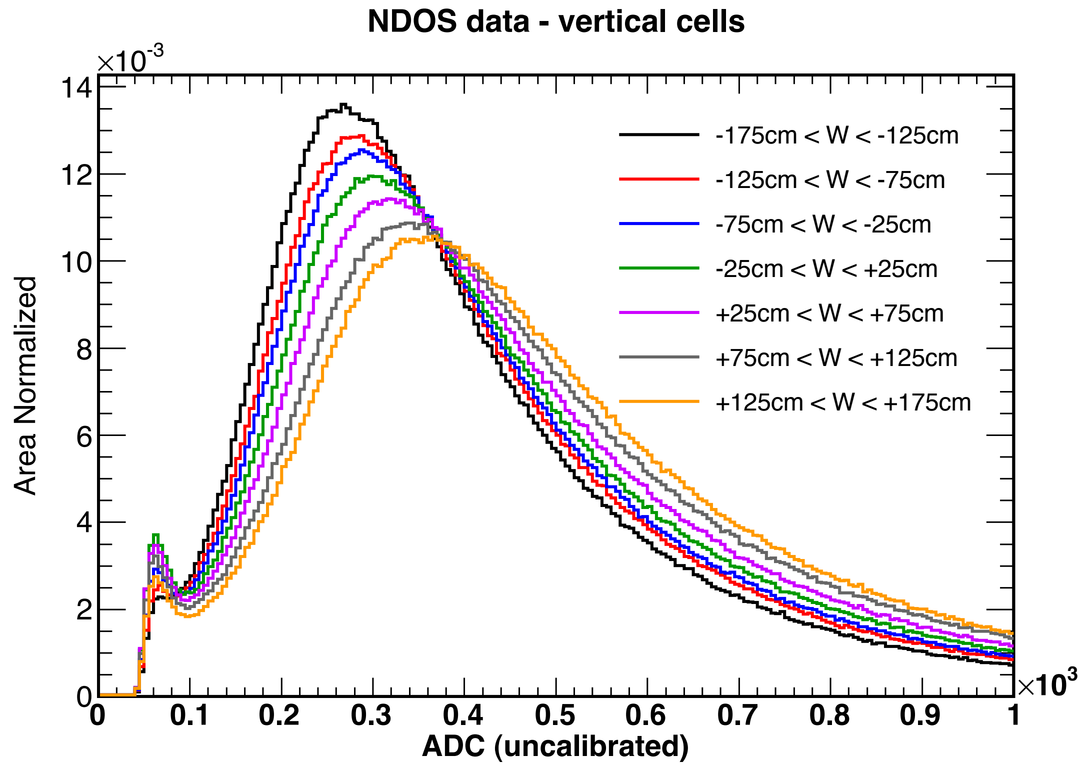


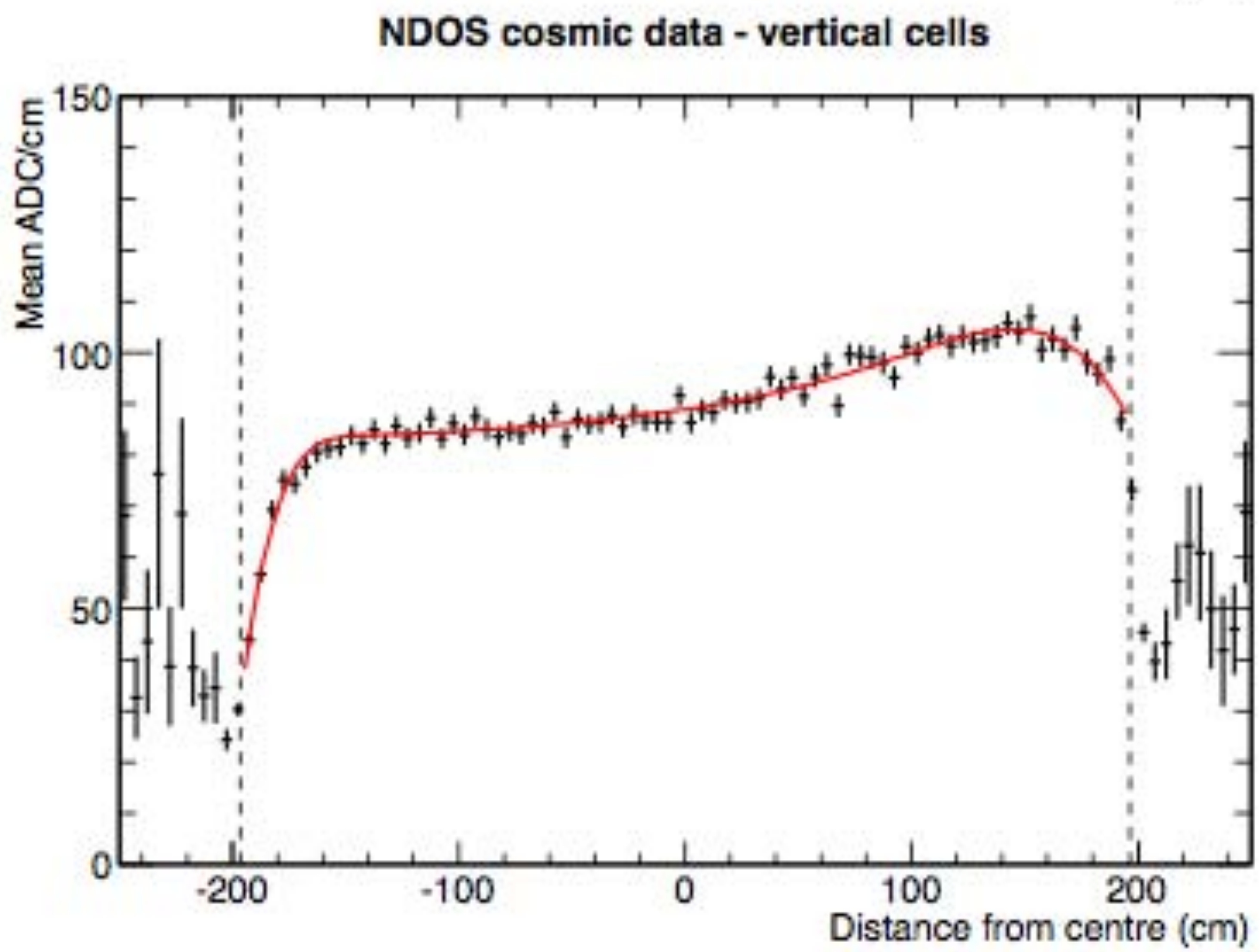
- NDOS is located on Booster Neutrino Beam (BNB) axis, rotated with respect to the beam by 23^{o}
- Recorded 2.7×10^{19} protons on target. First event recorded on 12/24/2010. Last event in this sample recorded on 5/22/2010.
- 222 events on a background of 92 cosmic ray backgrounds. 5 ν's / 10^{18} POT.

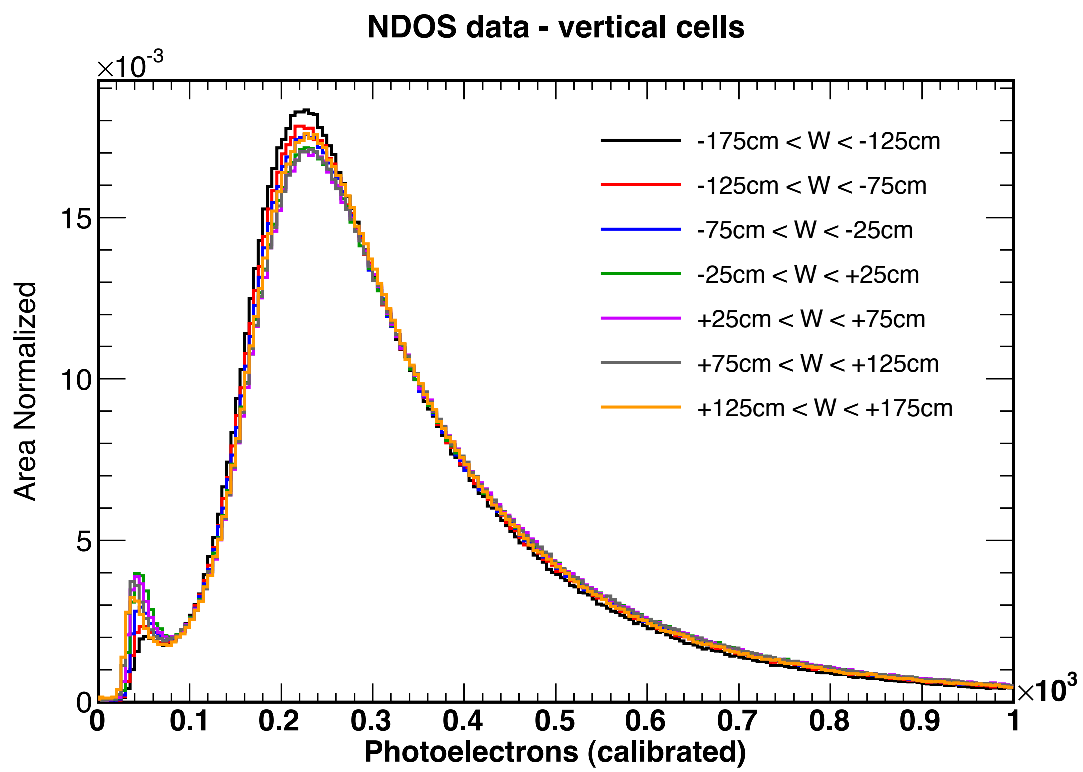


Cosmic rays in NDOS

Using cosmic rays:
Cell-by-cell calibration

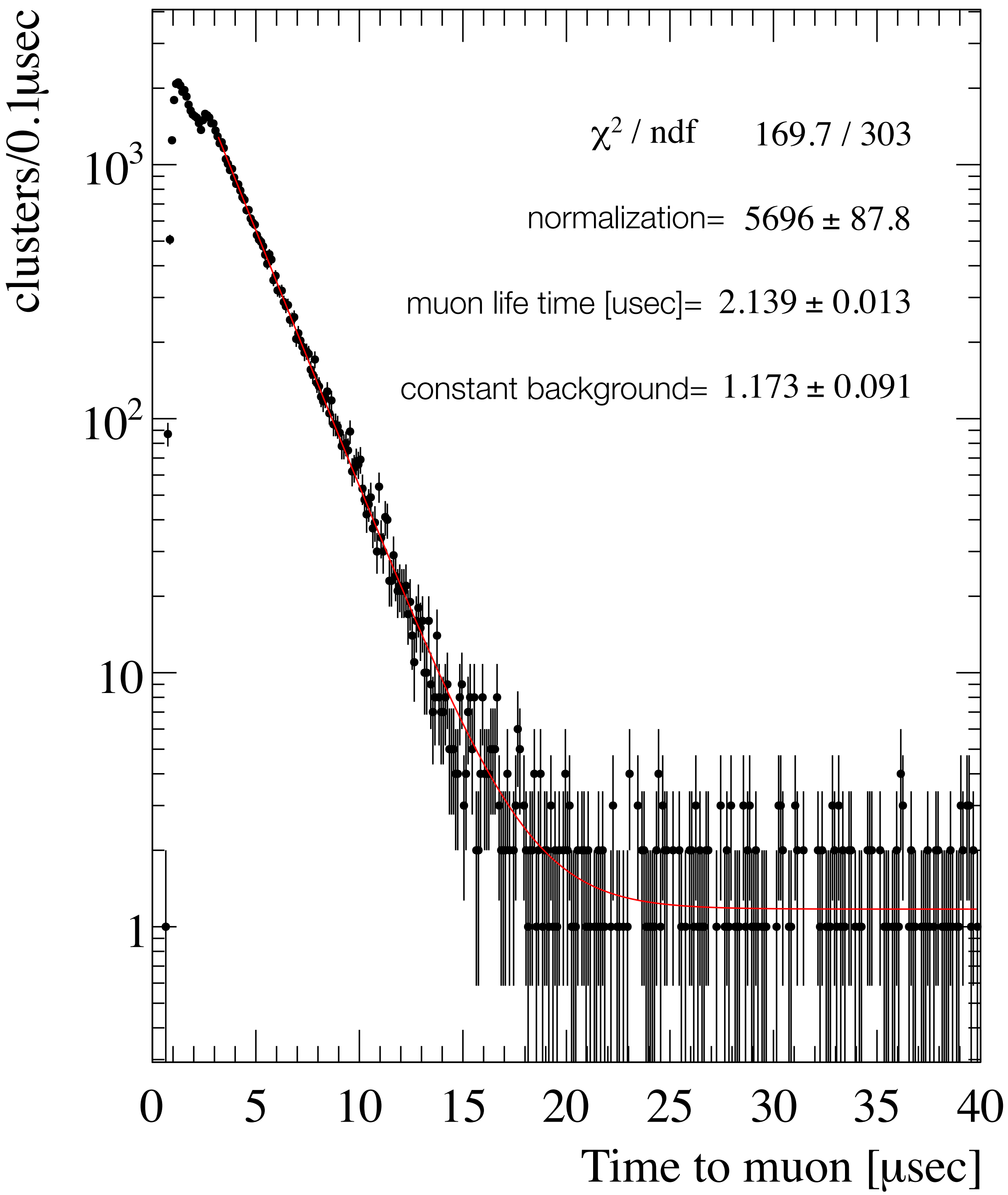


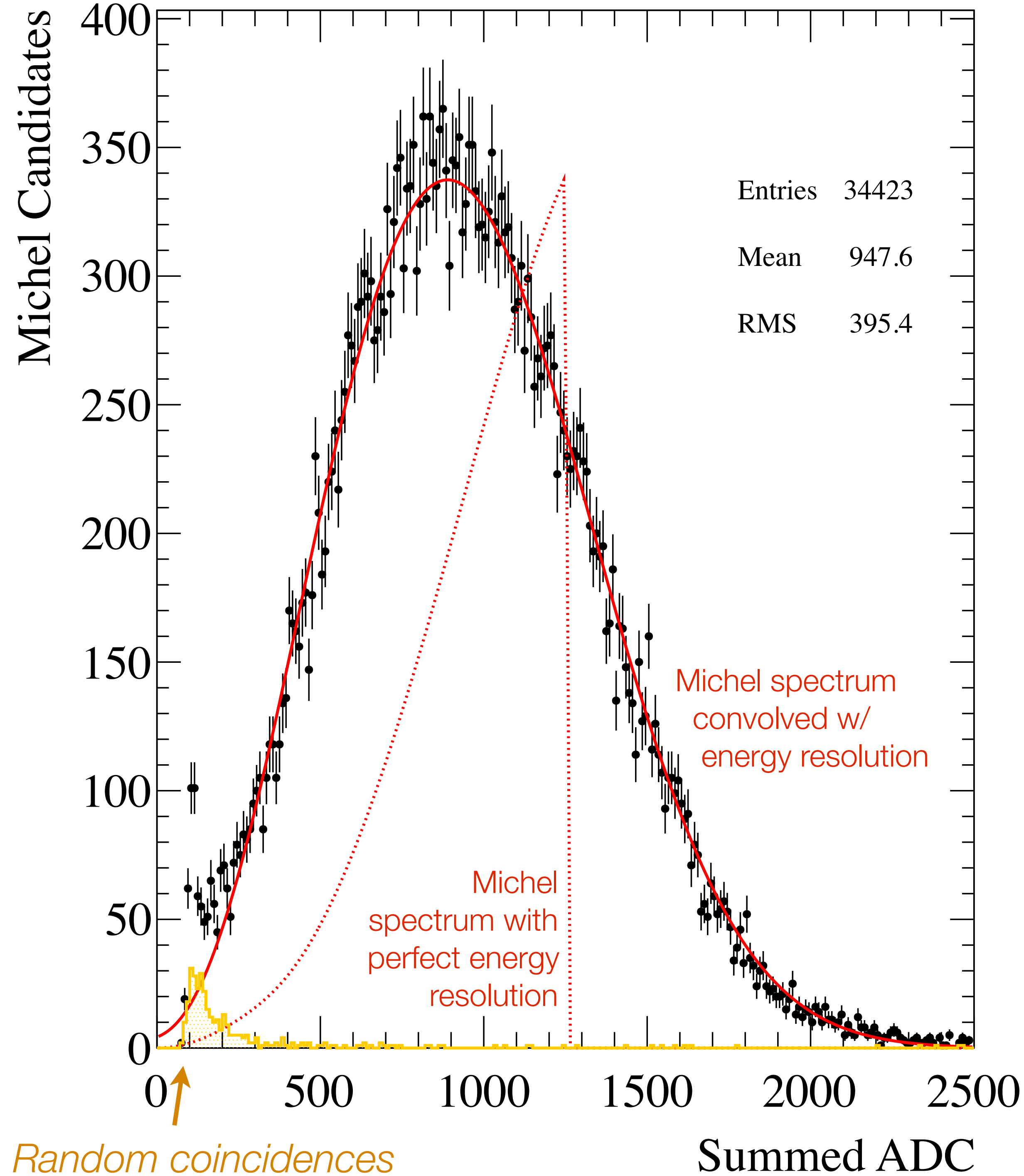




- Top left: Path length-corrected muon response for different distances from fiber end for a single example cell
- Above: Measured and fitted fiber attenuation for the example cell
- Bottom left: Muon response after attenuation corrections

Using cosmic rays:
Michel electron calibration



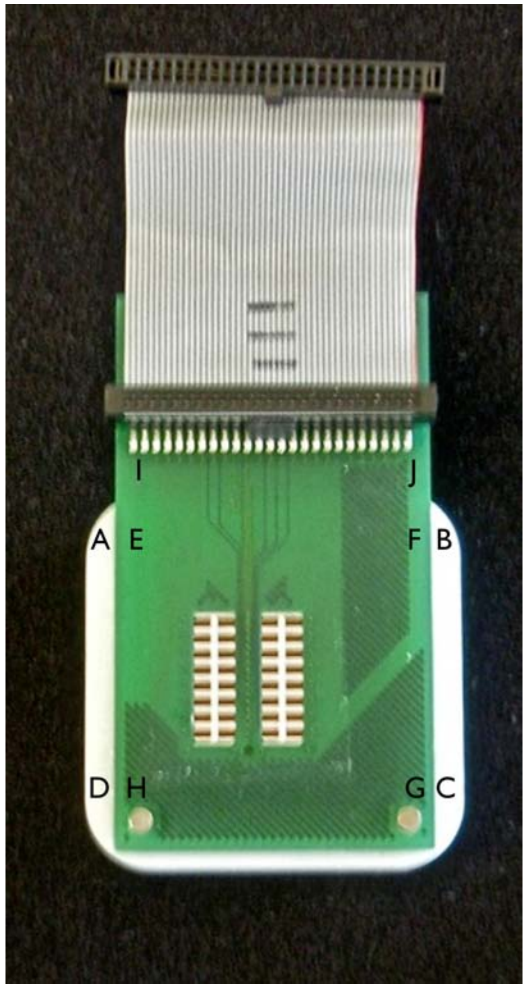


Random coincidences

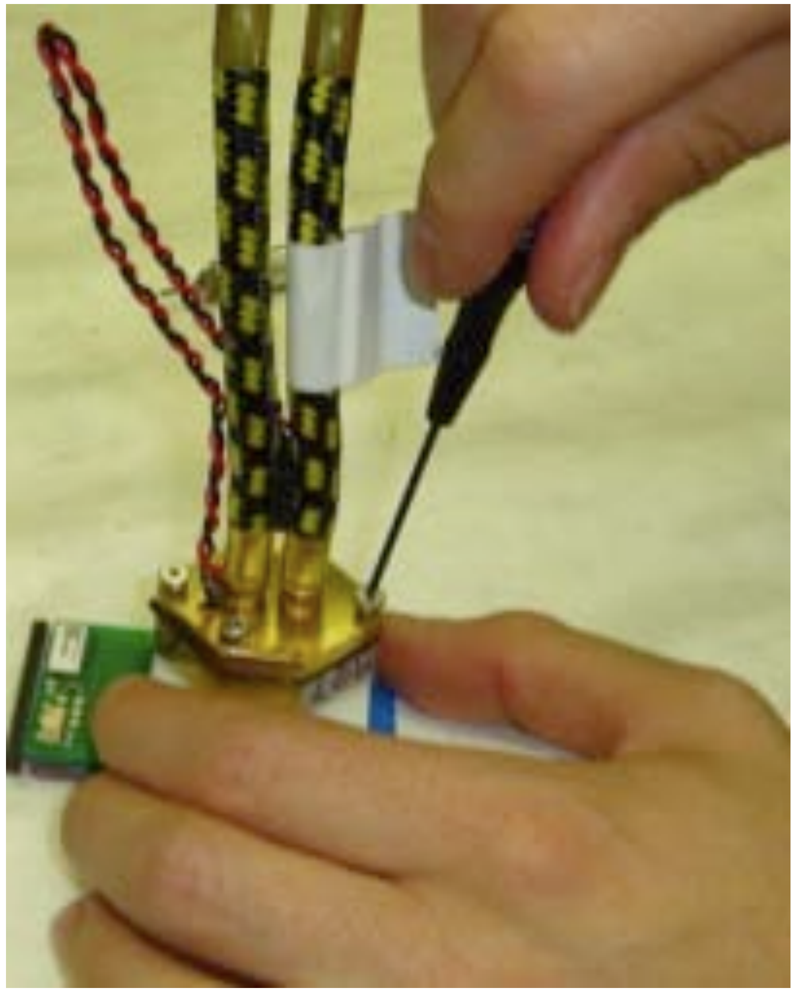
These are clusters that are matched to muons recorded 20 seconds prior to event

NDOS lessons learned

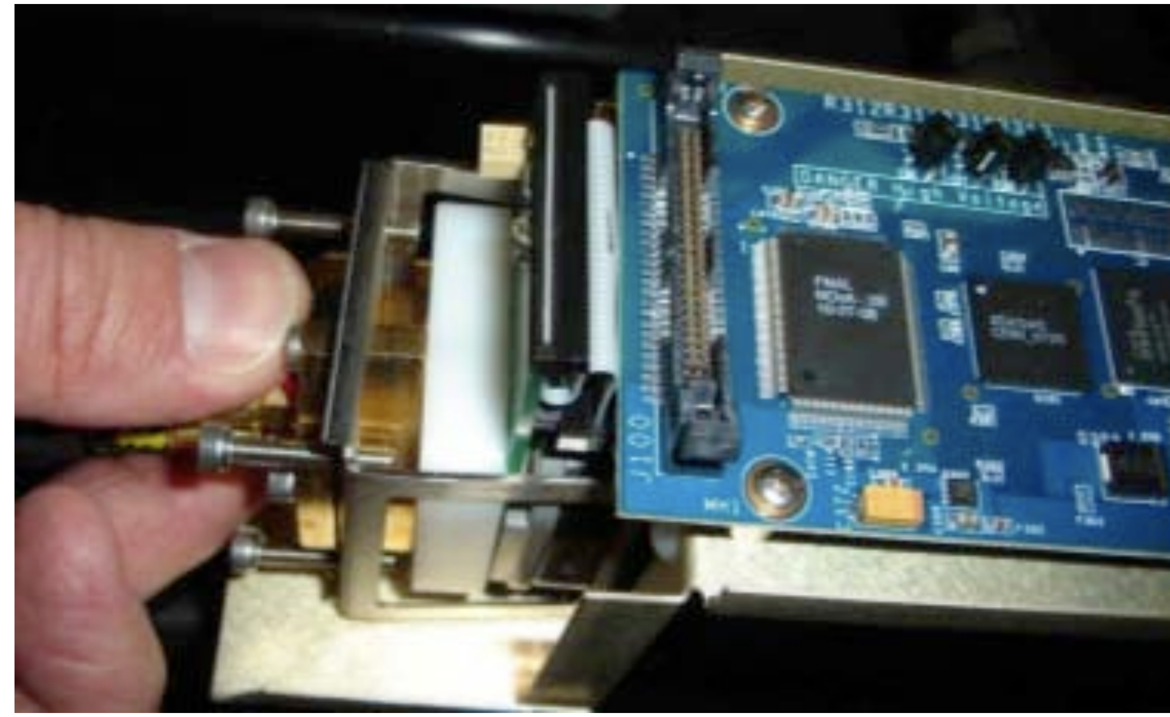
- NDOS has allowed us to work out numerous installation and integration issues; accessibility of hardware components, interference between various hardware components, etc. etc.
- A few major issues that NDOS has highlighted and allowed to address
  - Manifold cracks - Cracks were found to open up in manifold cover. Part redesigned to eliminate stress concentrations and strengthened
  - APD/FEB noise - Interference between thermal electric cooler control circuit produced too much noise. Added capacitive coupling to heat sink.
  - APD installation - Under real detector installation conditions it is very difficult to keep the silicon face of the APDs sufficiently clean. Hammamatsu has developed a coating which meets our specifications. It has also proved difficult to keep the APDs sealed against the environment. Redesign of these seals in progress.



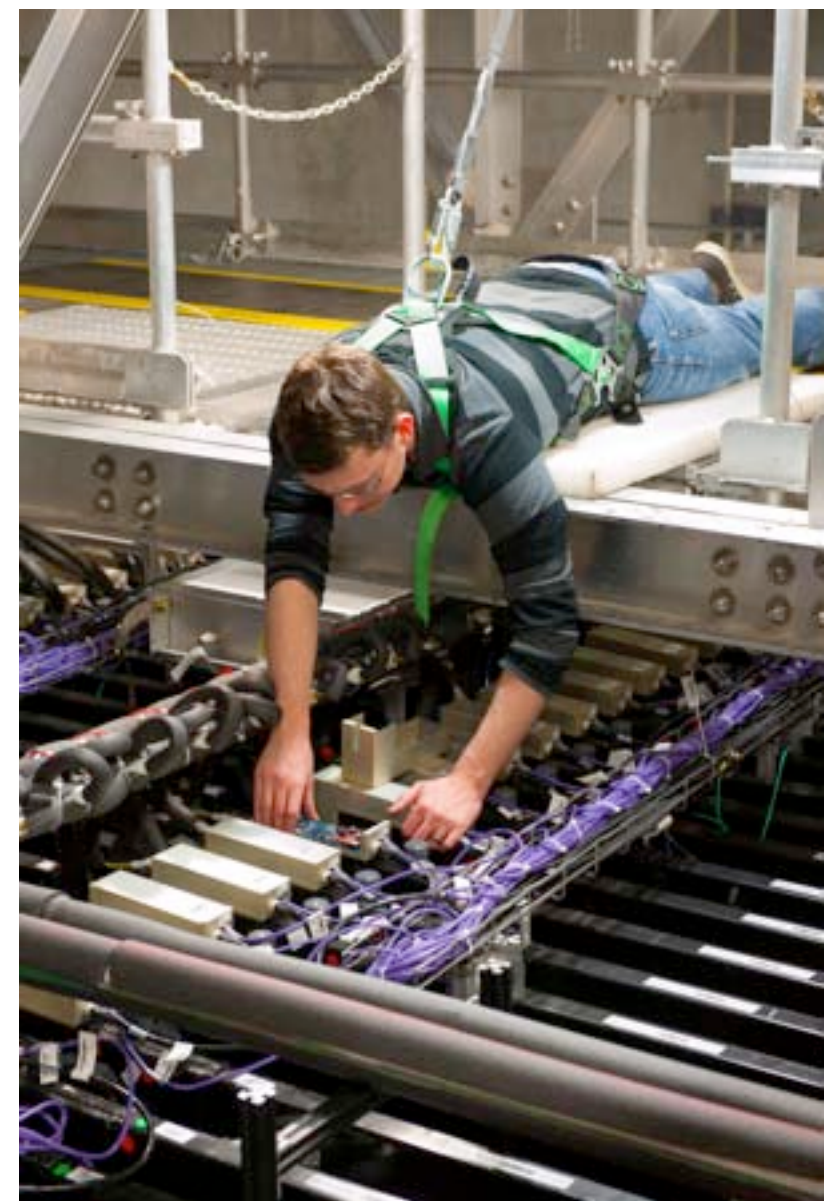
APD and carrier board attached to spacer



APD attached to heat sink



APD assembly attached to front end board which is preinstalled on the detector



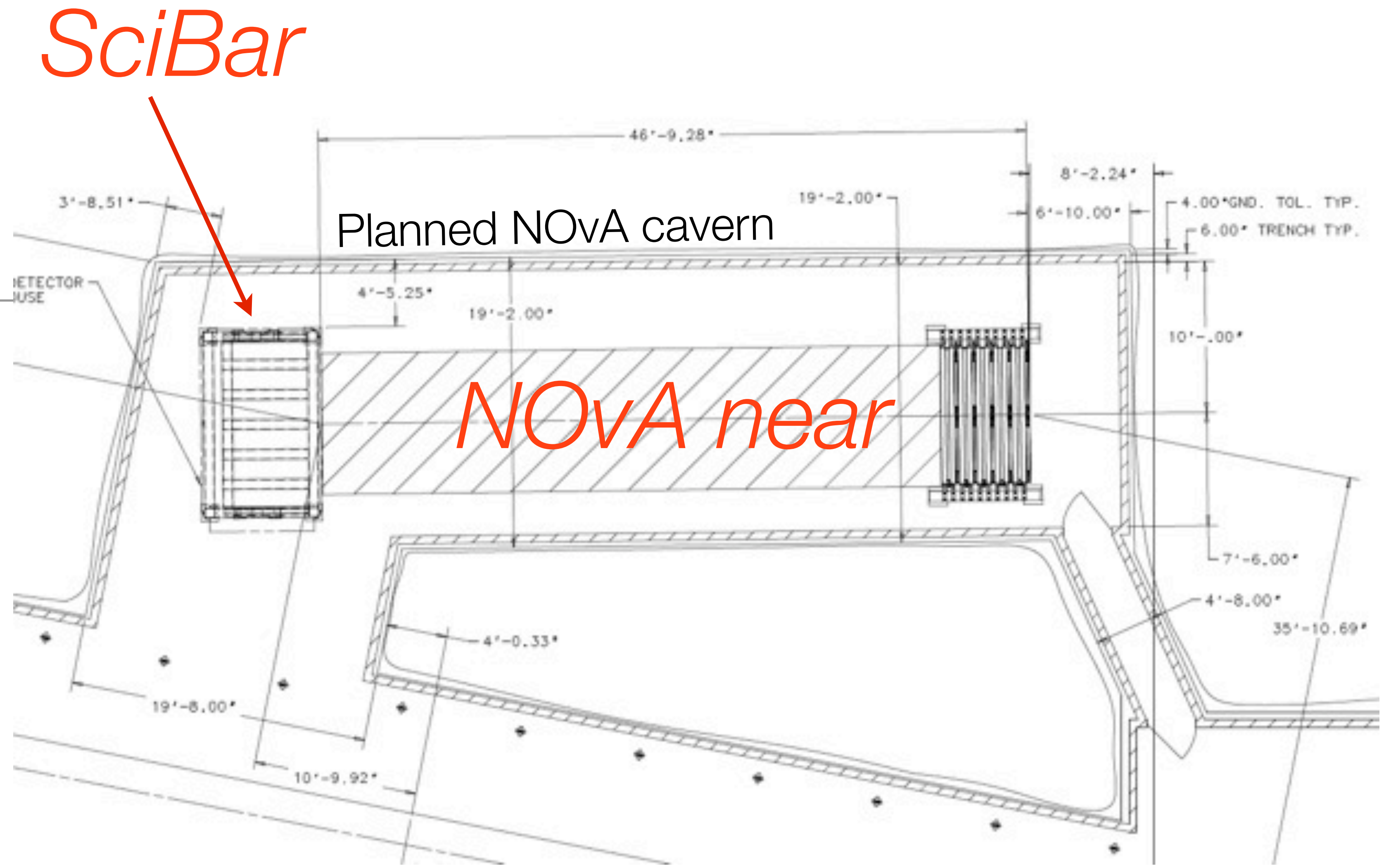
APD installation

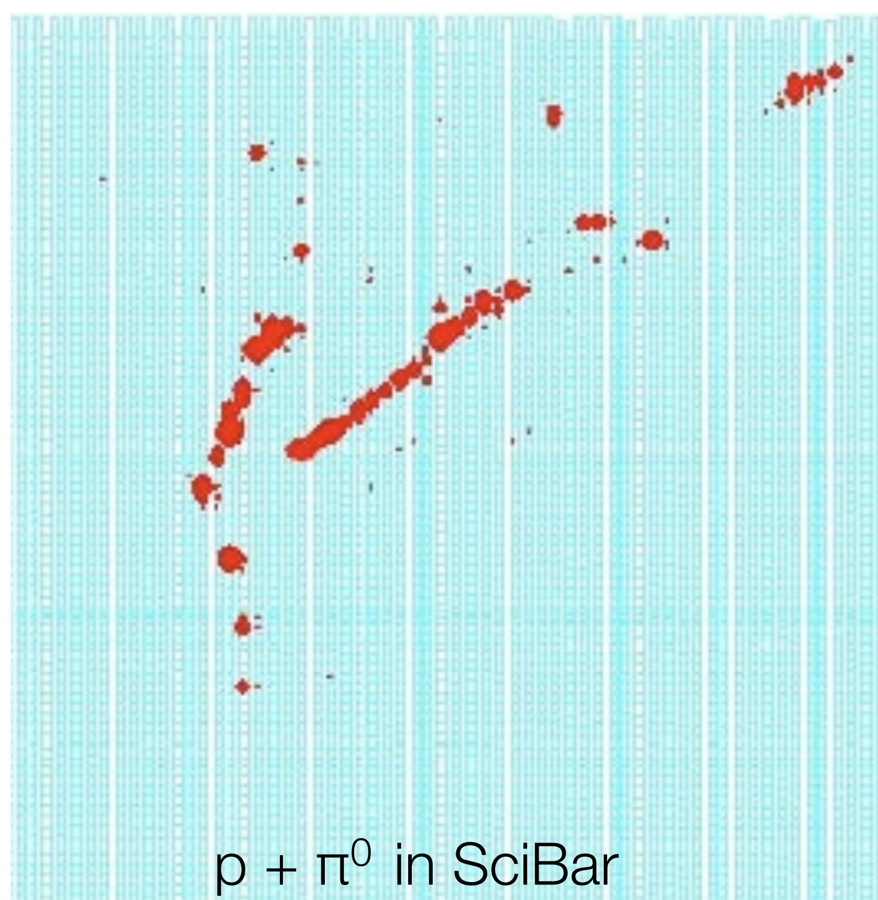
Ideas for NOvA contingency use

	Summary	Cost	Status
Rebuild near detector	Rebuild the near detector to match the far detector geometry and apply lessons learned from prototype detector.	\$5M	Need to do this.
Test beam module	Construct a small NOvA test beam module to measure response to e/π/μ in a test beam.	\$<1M	No concrete plans yet, but small enough that it could happen on the margins of far detector.
Additional far detector mass	Add 16th, 17th, 18th kiloton to the far detector. Improves statistics but not systematics.	\$9M/kt	Some procurements made toward 18 kt, but may prove difficult to orchestrate.
Wider near detector	A wider near detector will improve containment of EM showers and π^0 events and sample a large range of off-axis angles allowing in situ studies of neutrino flux extrapolation. Incurs some excavation risk as pillar separating NOvA and MINOS halls is stressed.	\$2-3M	Under study. Proceeding with cavern designs.
SciNOvA	A 15 ton fine grained detector to be placed in front of NOvA. Would allow for in situ studies of backgrounds and cross-section measurements at 2 GeV.	~\$3M	Joint study group formed NOvA/SciNOvA
Additional cavern further off-axis	A new cavern to house the current prototype. The cavern would access off-axis angles of up to 24 mrad where the neutrino spectrum peaks at 1.5 GeV. Could allow for study of oscillations at L/E ~= 1 km/GeV using fixed L and varying E as well as cross-section studies in the 1-2 GeV range.	~\$3M	Under study. Proceeding with cavern designs.
2 km detector	***Not being considers as part of the NOvA project*** but rather a new experiment to study the LSND effect. A microBooNE-style detector placed in NuMI at ~2 km + Project-X can cover the whole LSND range at 5σ.	\$30+M	Presented at short baseline workshop

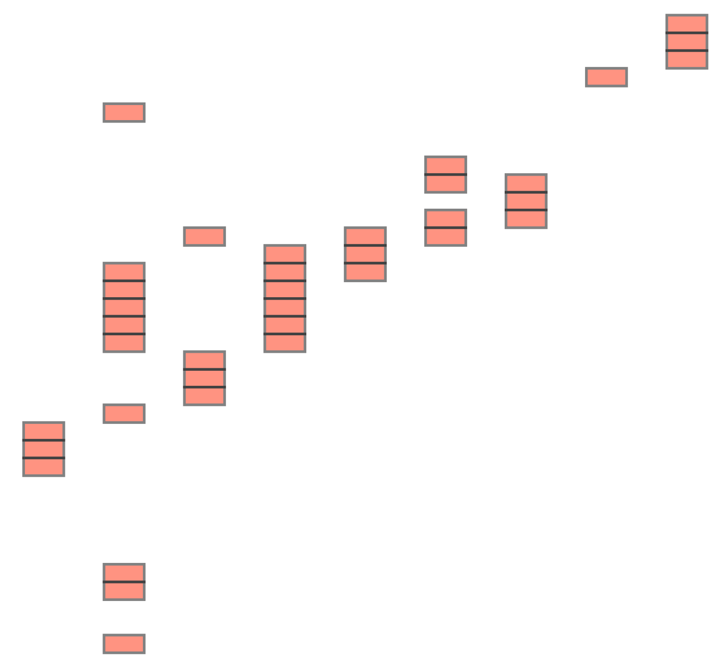
SciNOvA

- SciNOvA is an idea to rebuild the SciBar detector used by K2K and SciBooNE and deploy it in front of NOvA near detector.
- Main motivation is to allow an in situ check of NOvA backgrounds by sampling the same beam using very similar target material, but with higher granularity. Can nearly eliminate the need for Monte Carlo estimates of instrumental background rates.
- Also enables cross-section measurements in a narrow band beam at 2 GeV





$p + \pi^0$ in SciBar



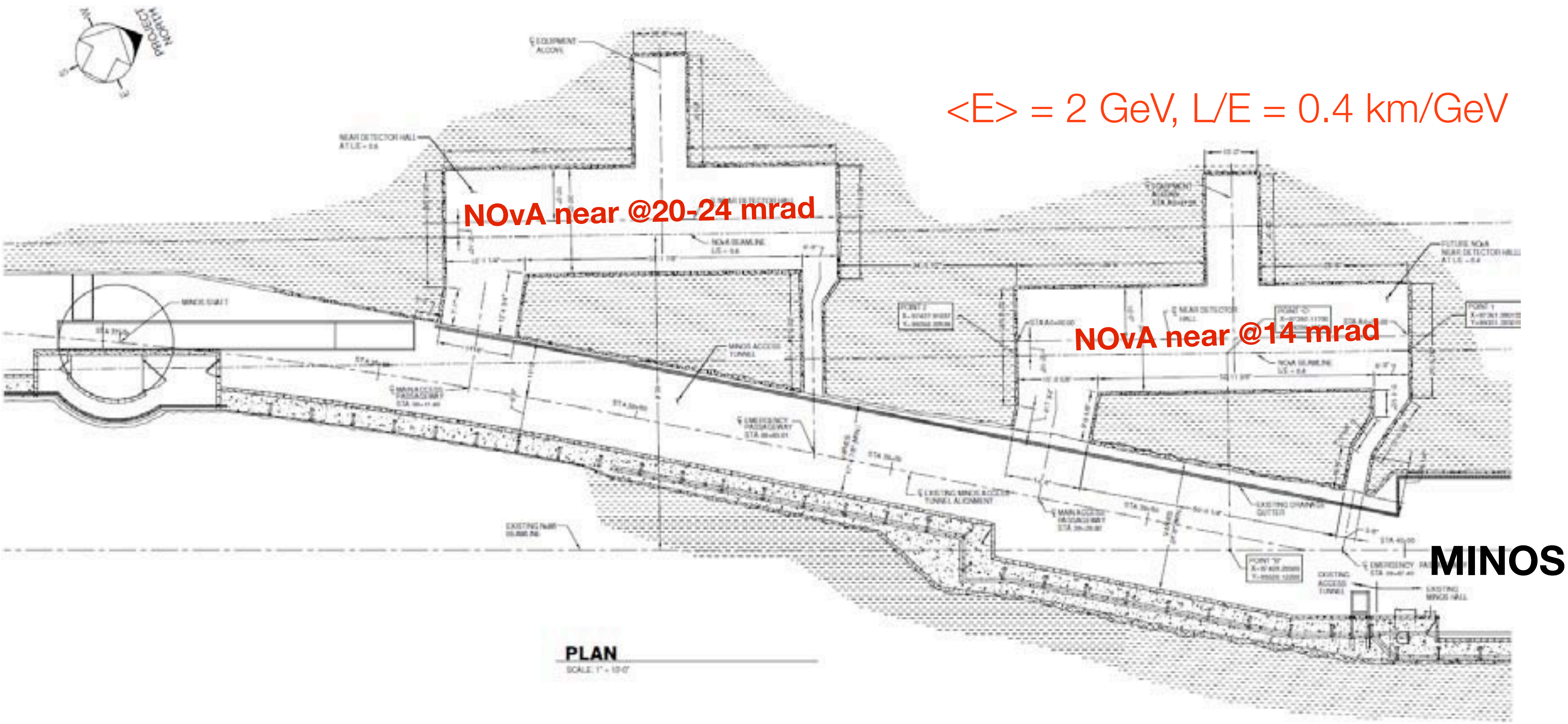
Same event resampled in NOvA

New cavern further off-axis

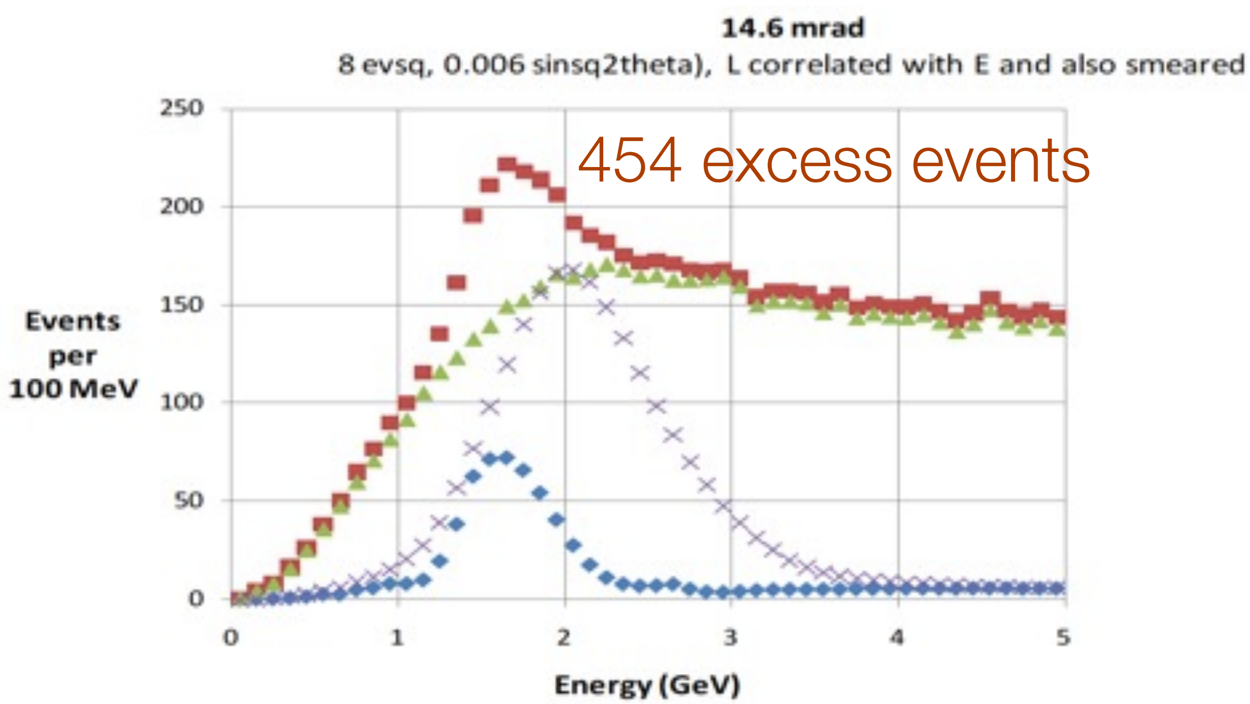
- If the MiniBooNE/LSND antineutrino signal is real and due to oscillations, those oscillations will develop downstream of the NOvA near detector
  - MiniBooNE/LSND signal is in the range of $0.4 < L/E < 1.2$ km/GeV
  - NOvA near detector is at $L/E = 0.4$ km/GeV.
  - Placing an additional NOvA near detector further off-axis (~24 mrad), reducing the beam energy to 1.5 GeV, NOvA can achieve an L/E of ~1 km/GeV
  - To get beam at 24 mrad would require a new cavern which could house the prototype detector we are now operating.
- Presented at Short Baseline workshop by John Cooper

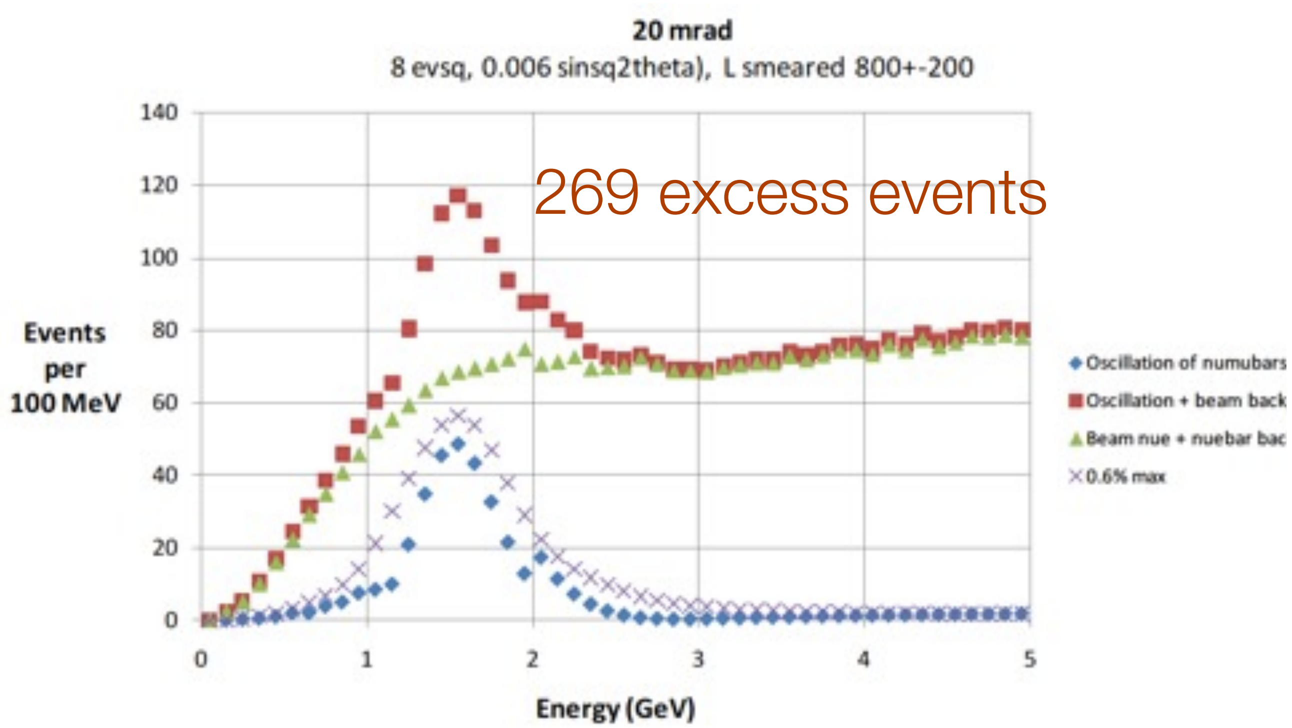
Possible new cavern at 24 mrad

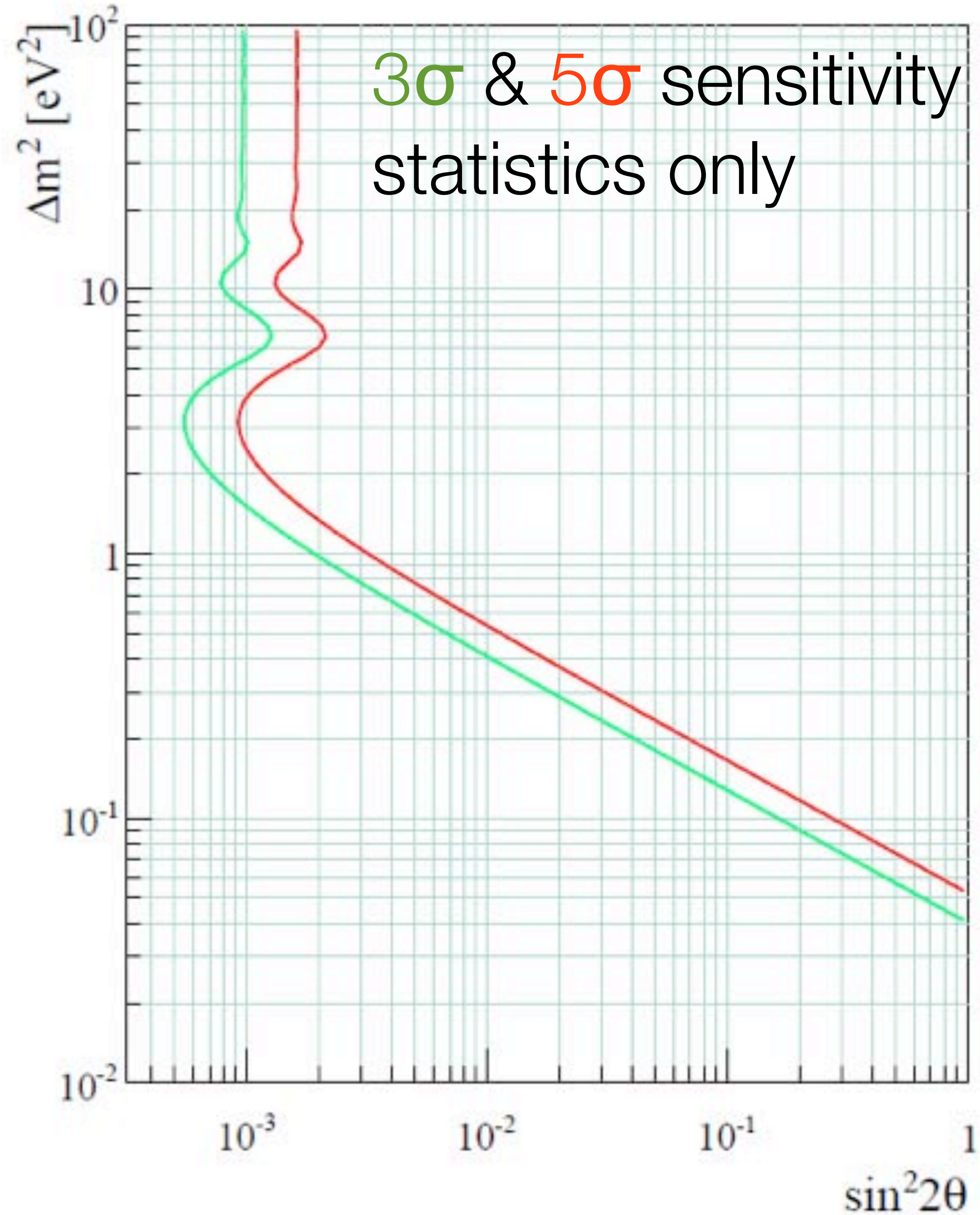
<E> = 1-1.5 GeV, L/E = 0.6 - 1 km/GeV

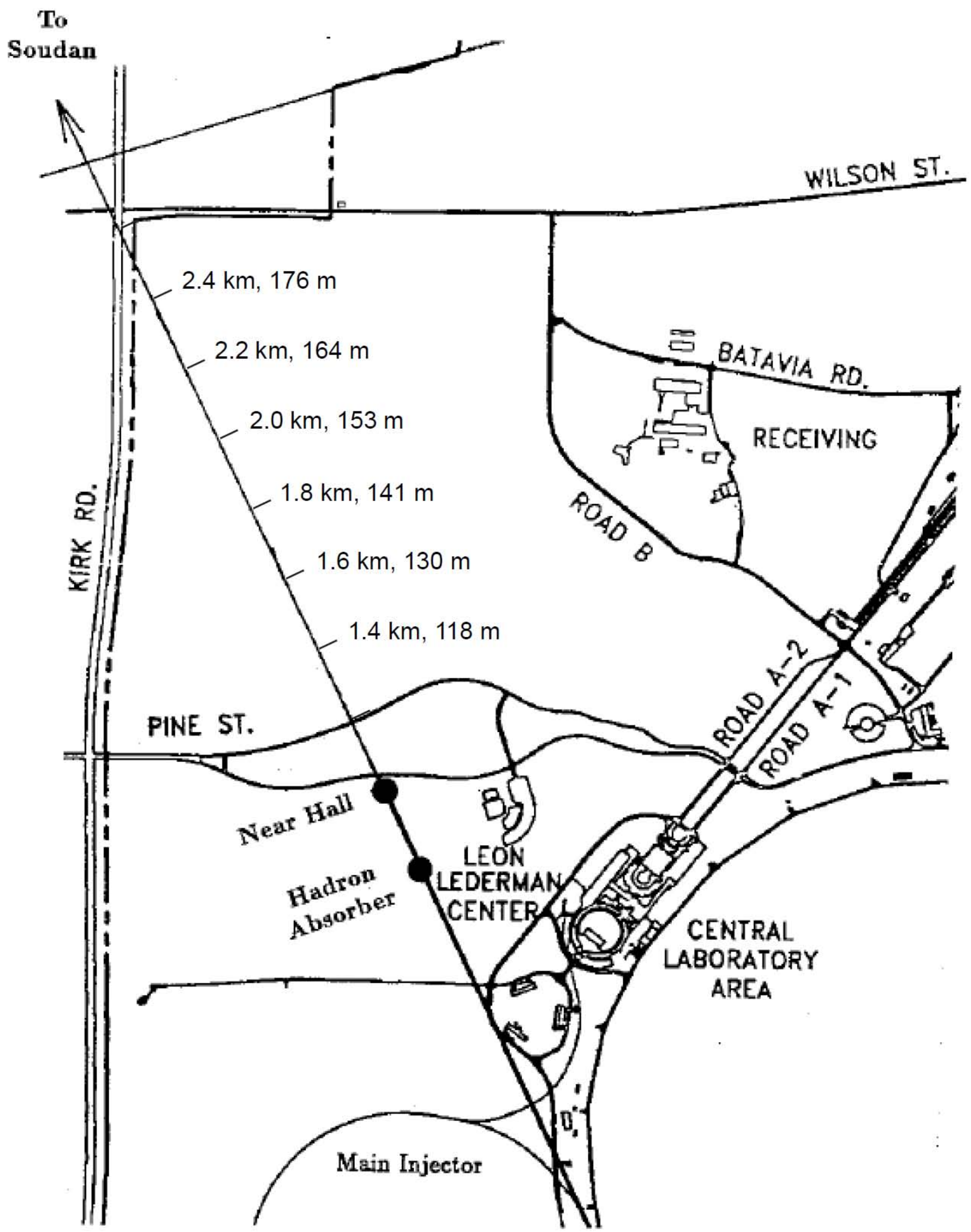


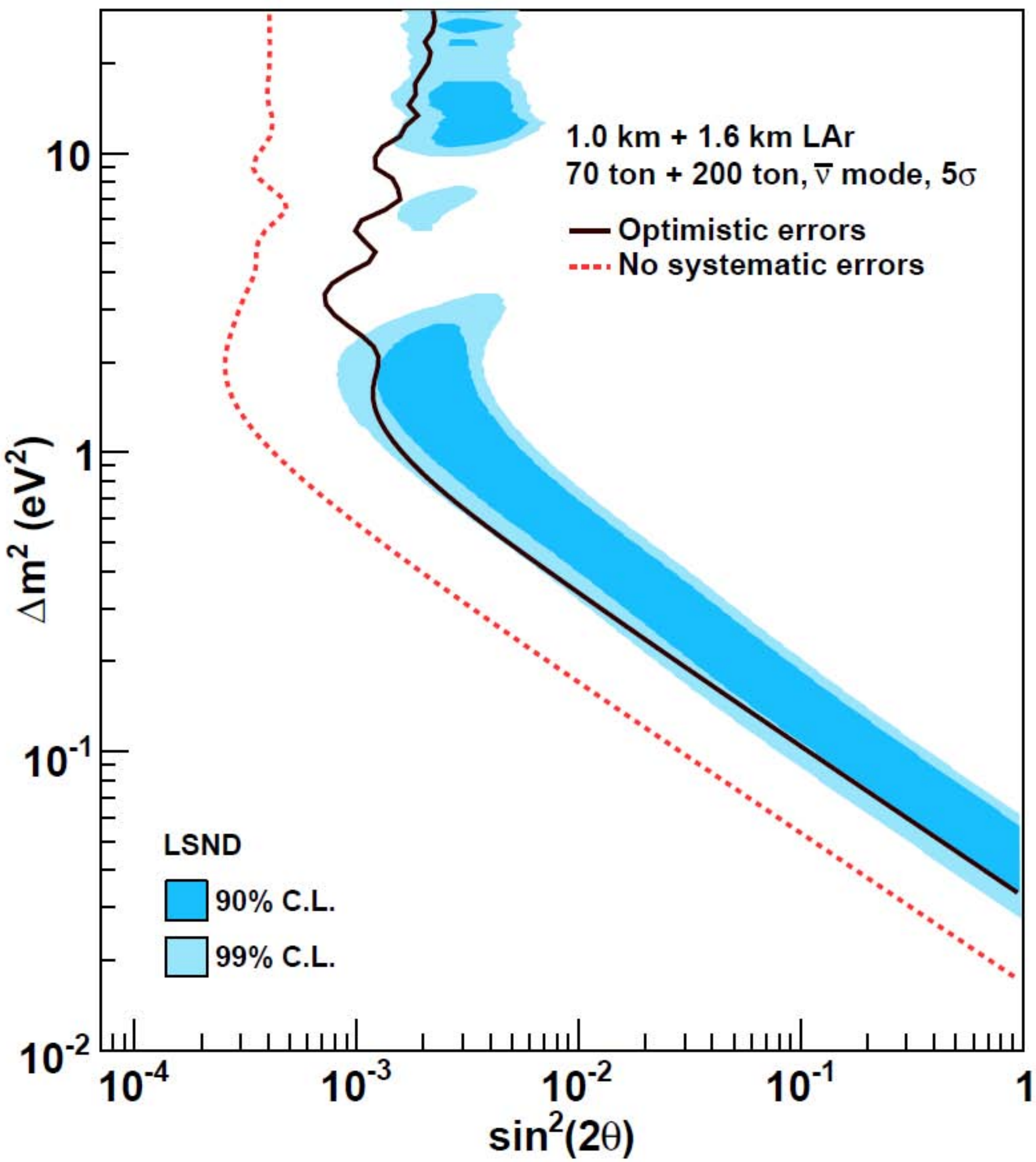
Possible signals in a new cavern









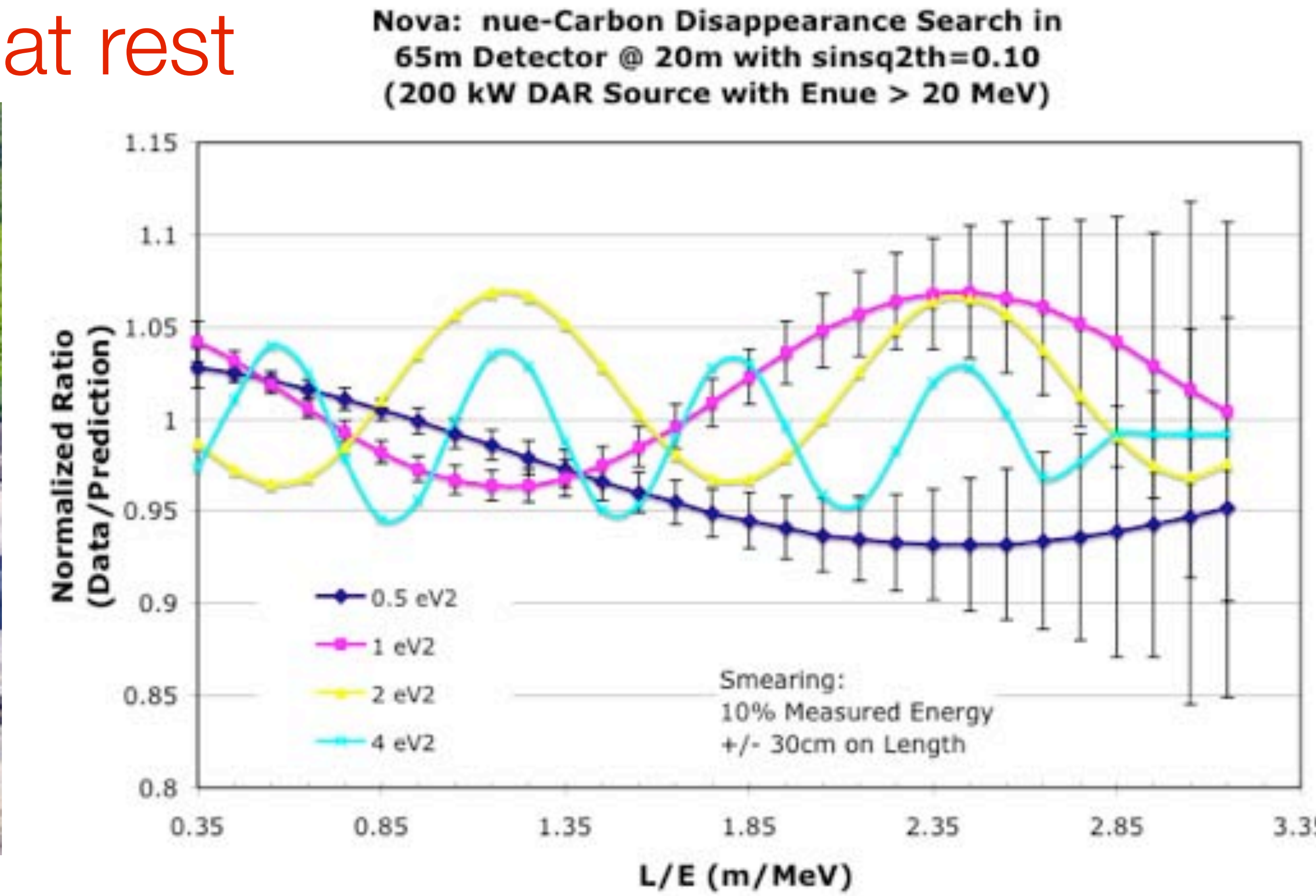


Beyong NOvA:

Using NuMI at 2 km to test LSND / MiniBooNE

Not part of NOvA, but a new idea for possible future use of NuMI. NuMI has several advantages over Booster beam: high power (700 kW vs 11 kW), relatively low wrong-sign contamination in antineutrino beam.

Locate a 100 kW cyclotron in assembly building to produce $\bar{\nu}_e$ from muon decay at rest



Short-baseline Neutrino Oscillation Waves in Ultra-large Liquid Scintillator Detectors

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[a] *Instituto de Física Corpuscular, CSIC-Universitat de València, Apartado de Correos 22085, E-46071 Valencia, Spain*
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[c] *Department of Physics, Columbia University, New York, New York 10027, USA*

Summary

- NOvA addresses 7 of P5's 8 "compelling issues" in neutrino physics
- Far detector construction is underway.
  - Far detector laboratory complete
  - NuMI upgrades begin in March of 2012
  - Plan to have first far detector block in place by then
  - Commissioning of 700 kW beam begins in 2013 with ~5 kt of far detector in place
  - 15 kt complete by end of 2013
- Prototype near detector operational on surface at Fermilab
  - Extremely valuable preparation for construction at Ash River
  - Early look at real cosmic rays and neutrinos