Next Questions In Neutrino Physics with the NOvA and LBNE Experiments

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Colloquium Towards CP violation in neutrino physics
Faculty of Mathematics and Physics, Charles University in Prague
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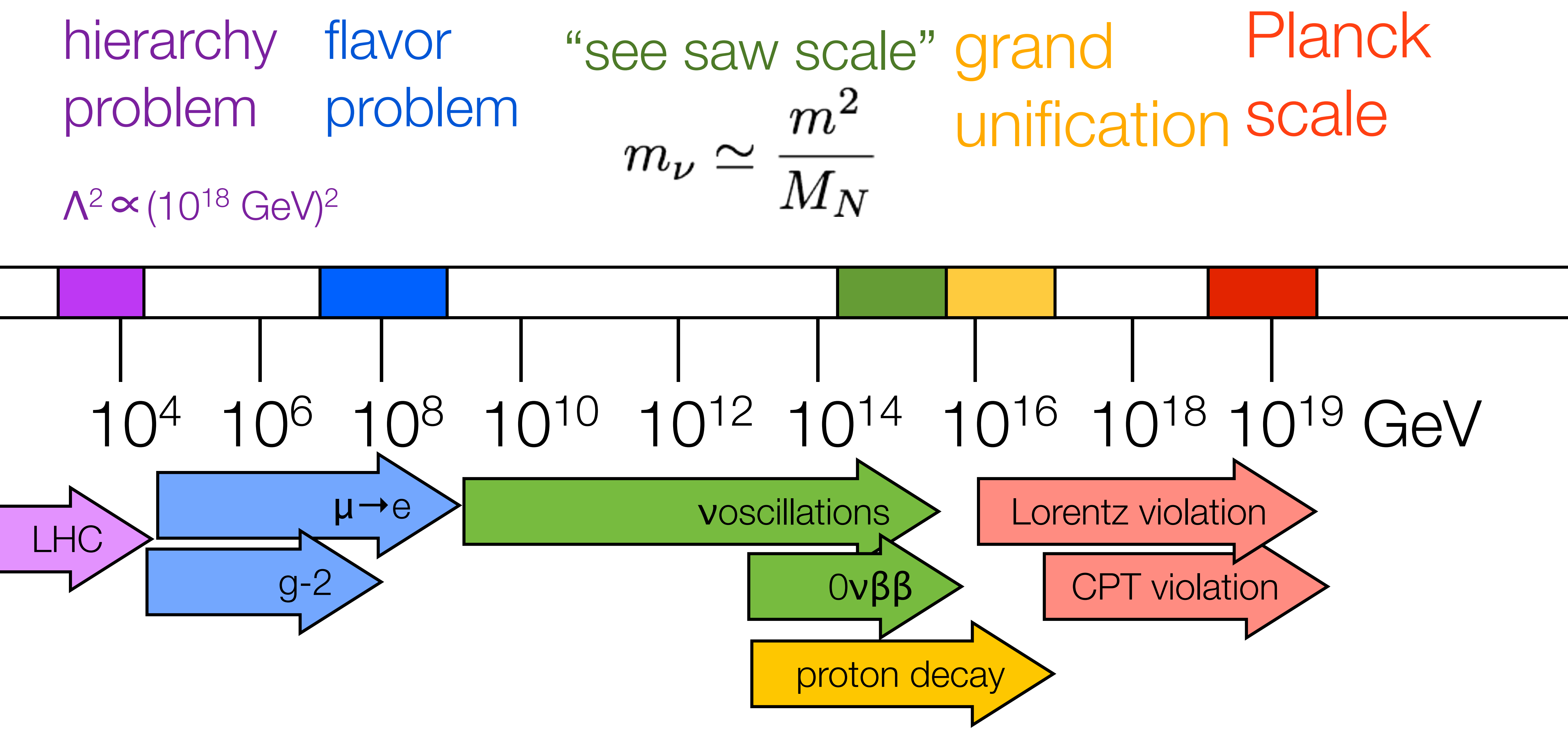
Where to look for new physics?



Next questions in neutrino physics

- What is the nature of ν_3?
- What is the neutrino mass hierarchy?
- Is the neutrino Majorana or Dirac?
- Is CP violated by neutrinos?
- Is the PMNS matrix description of neutrinos complete? Are there any more surprises in store for us in the study of neutrino oscillations?

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

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

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

"$-$" : ν

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

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

long baseline experiments measure this combination

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

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 matter:

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

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

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

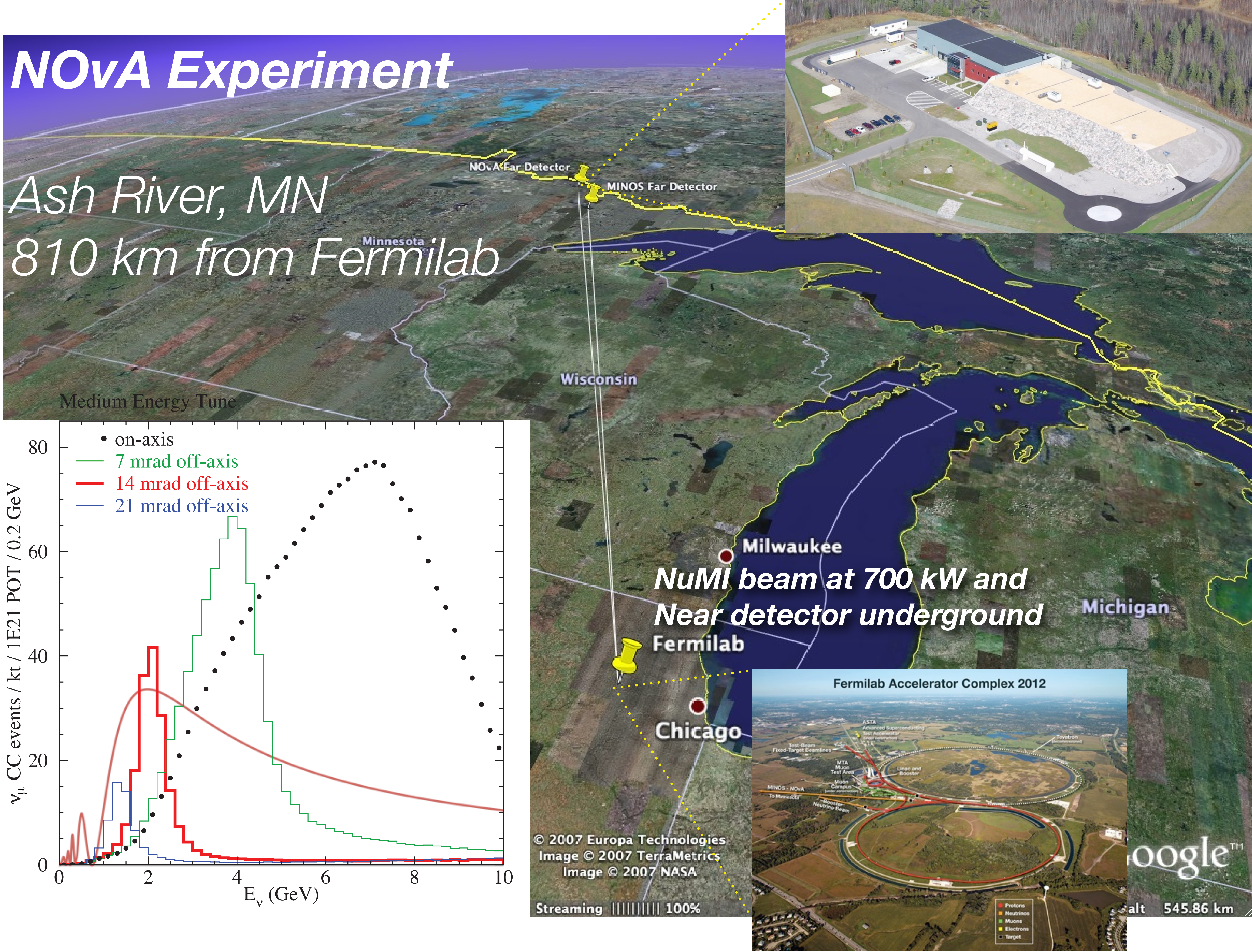
dependence on relative sign of ***Δ_{31}*** *and* ***a***

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

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

$$aL = 0.08 \text{ for } L = 295\ \rm km$$
$$aL = 0.23 \text{ for } L = 810\ \rm km$$
$$aL = 0.37 \text{ for } L = 1300\ \rm km$$

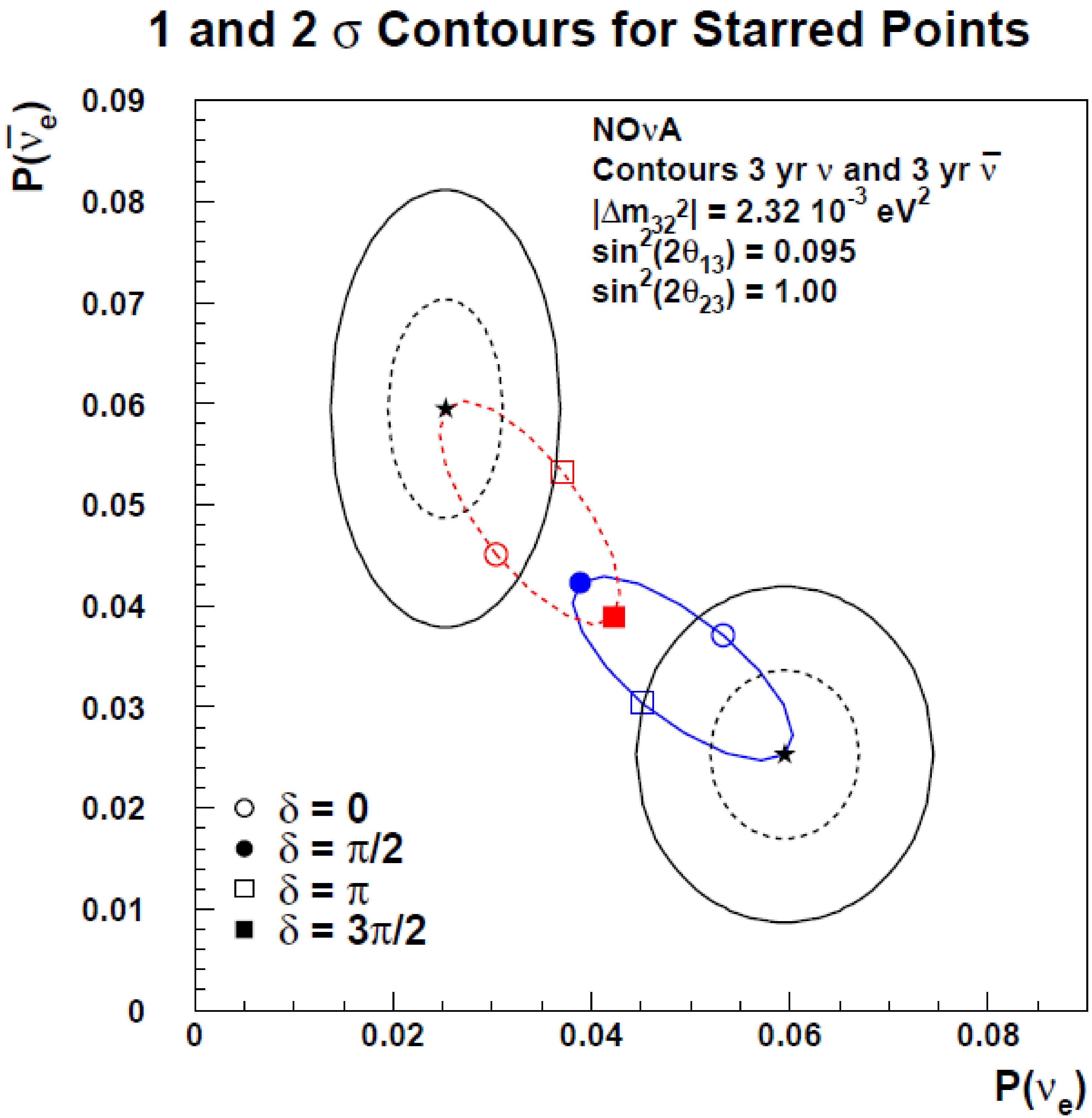
NOvA Experiment



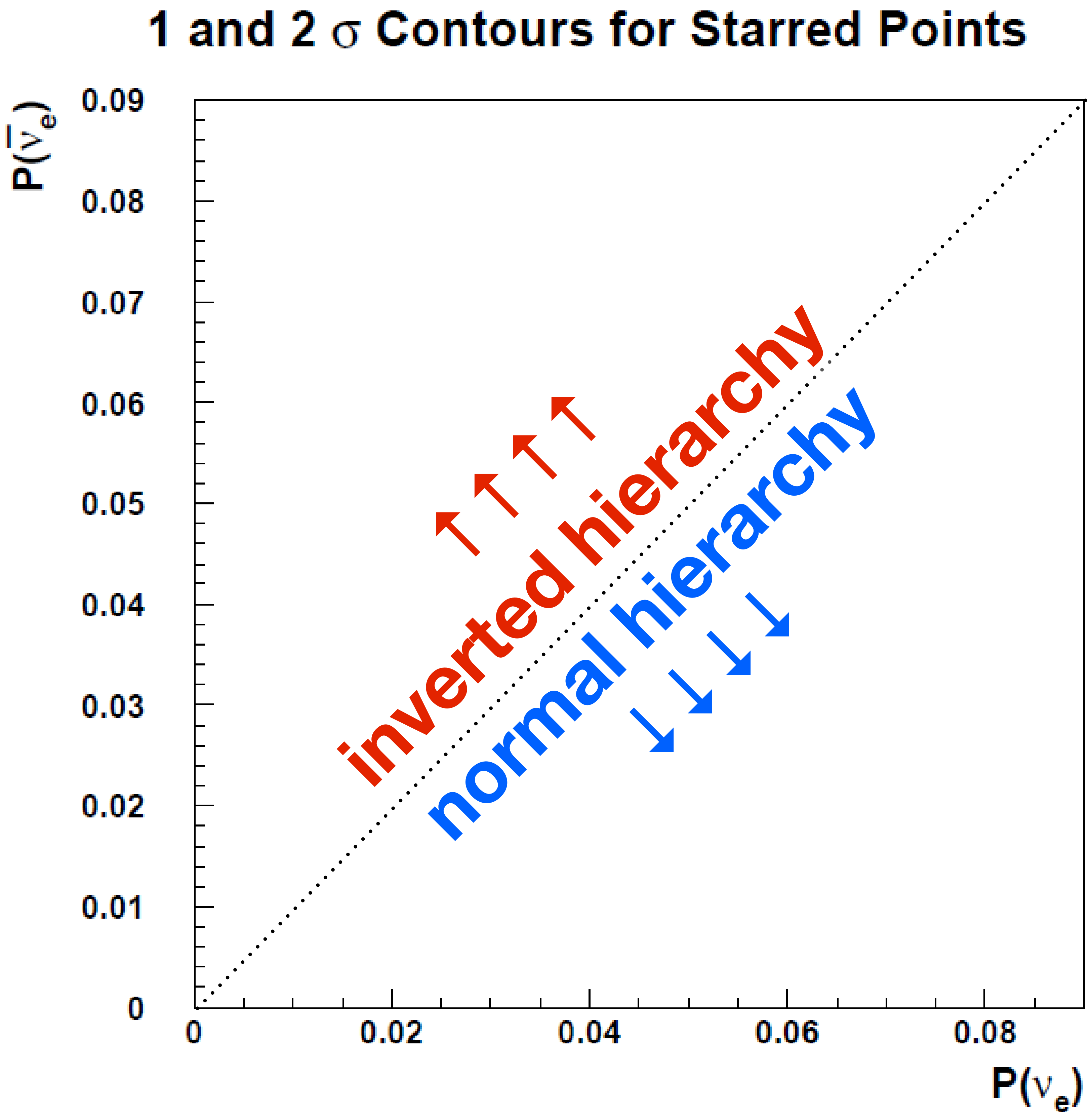
NOvA Collaboration

35 Institutions from 7 countries
181 collaborators
122 PhD physicists/ 23 Graduate students

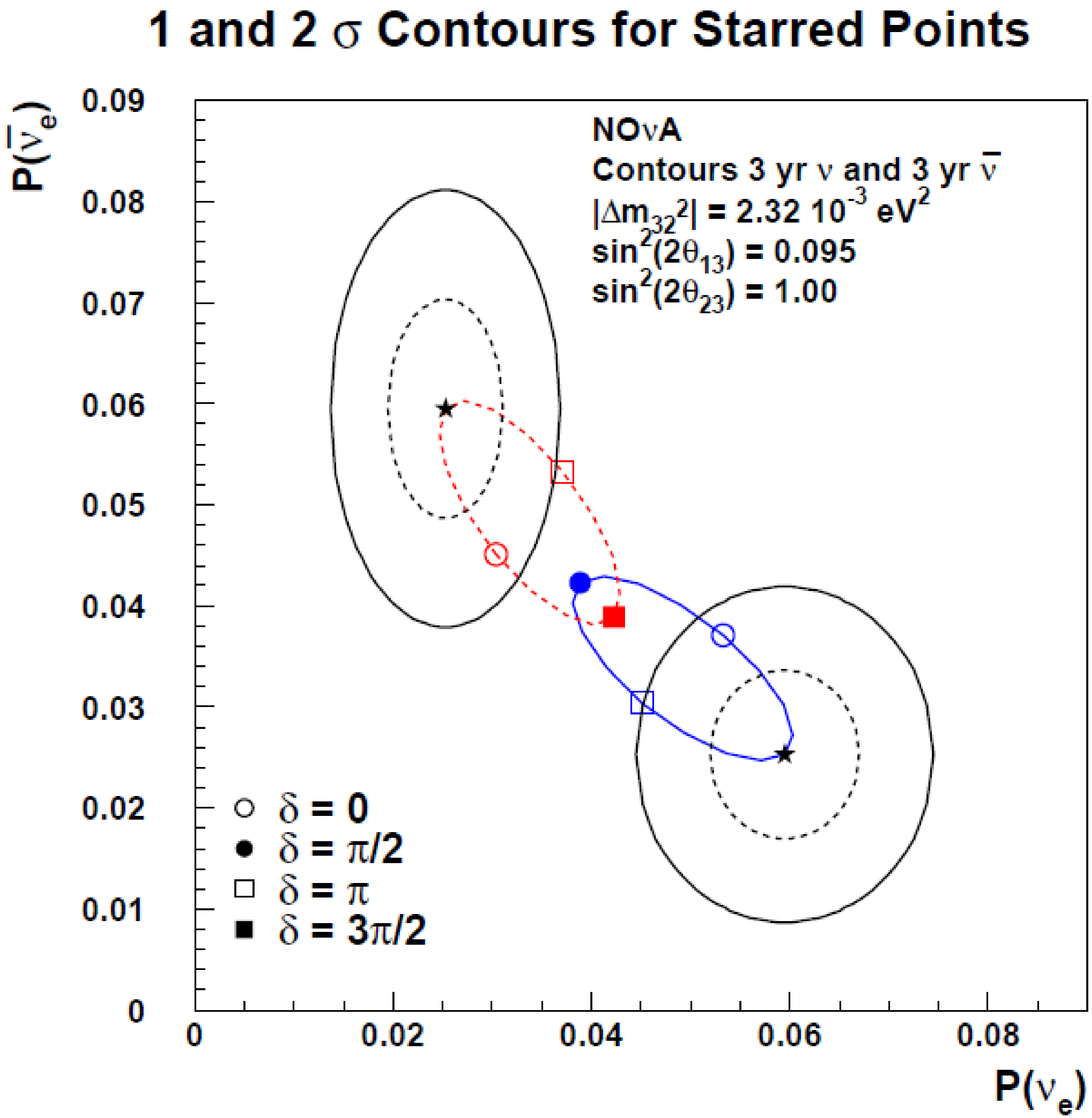
Argonne National Laboratory · University of Athens · Banaras Hindu University · California Institute of Technology · Institute of Physics of the Academy of Sciences of the Czech Republic · Charles University, Prague · University of Cincinnati · Czech Technical University · University of Delhi · Fermilab · Indian Institute of Technology, Guwahati · Harvard University · Indian Institute of Technology · University of Hyderabad · Indiana University · Iowa State University · University of Jammu · Lebedev Physical Institute · Michigan State University · University of Minnesota, Crookston · University of Minnesota, Duluth · University of Minnesota, Twin Cities · Institute for Nuclear Research, Moscow · Panjab University · University of South Carolina · Southern Methodist University · Stanford University · University of Sussex · University of Tennessee · University of Texas at Austin · Tufts University · University of Virginia · Wichita State University · College of William and Mary



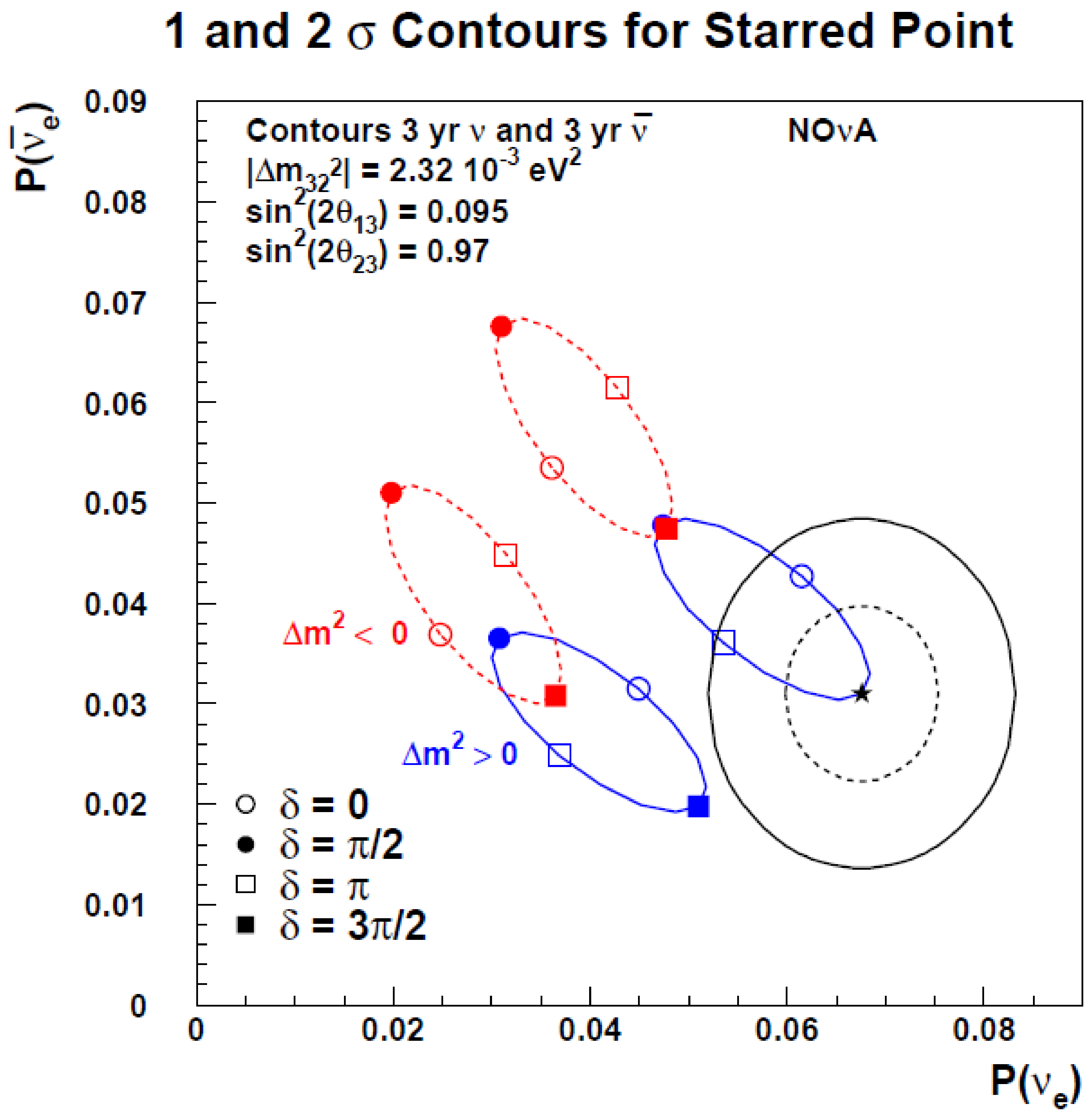
Principle of NOvA measurements | Hierarchy resolution



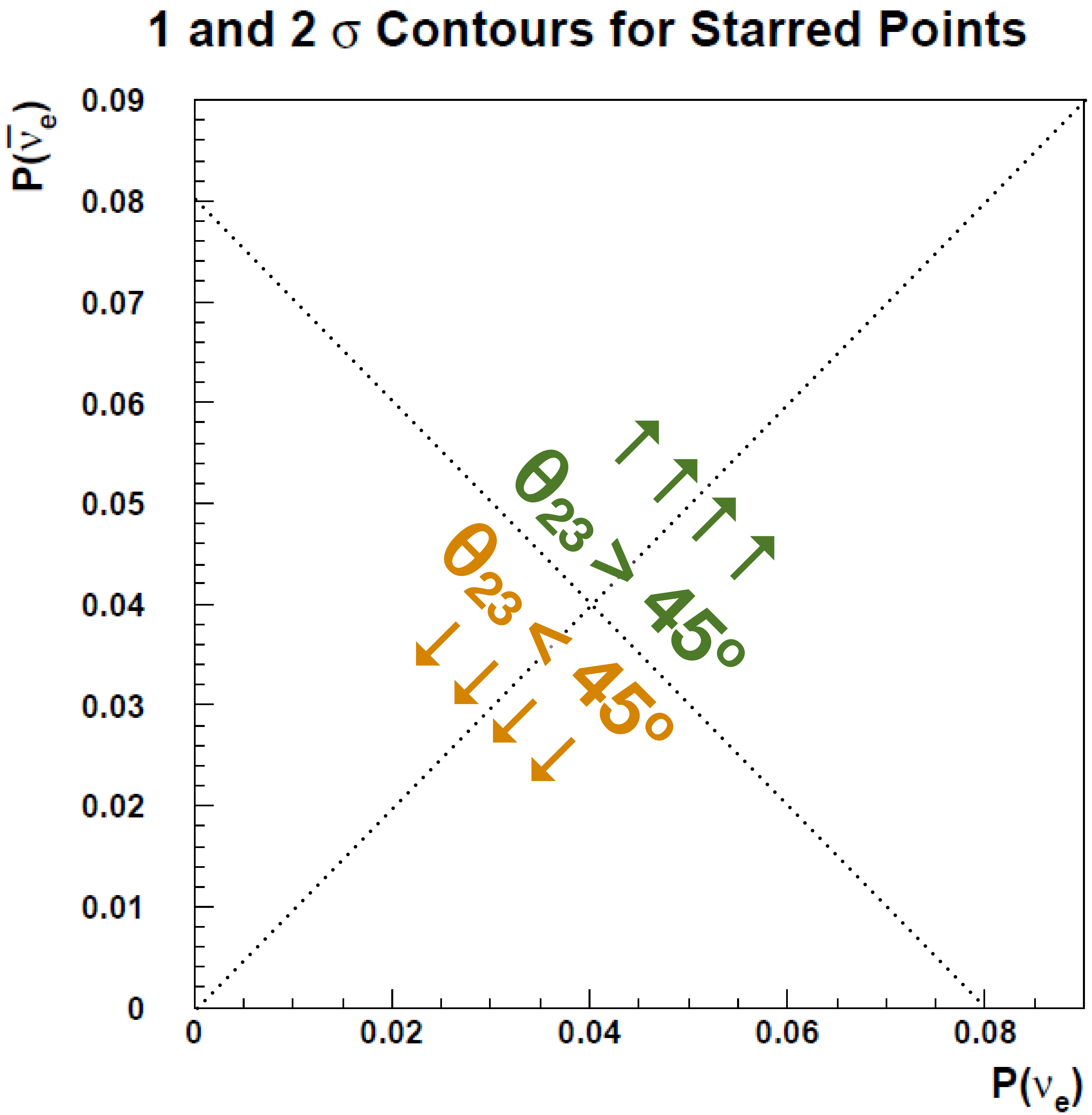
Principle of NOvA measurements | Hierarchy resolution



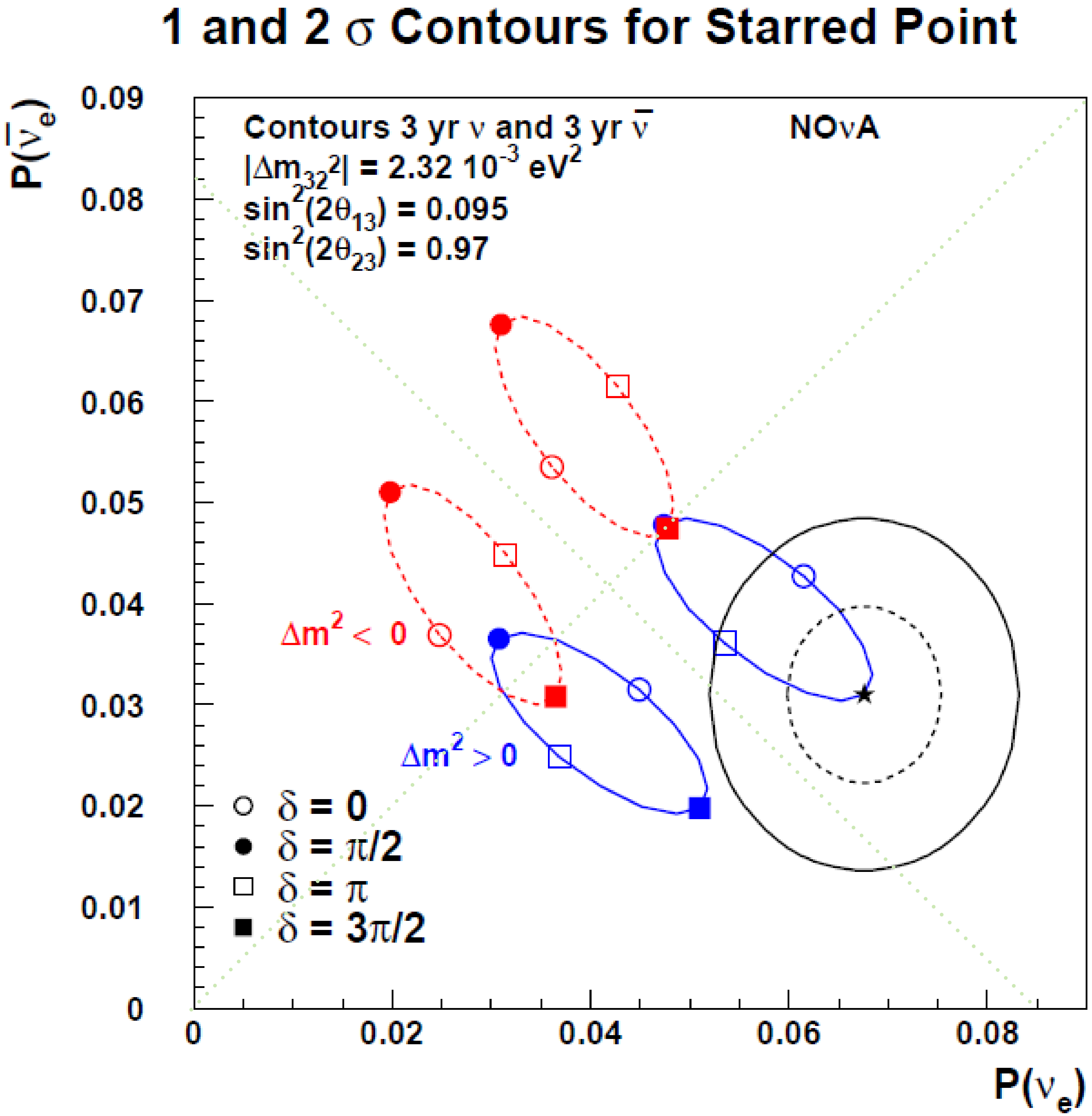
Principle of NOvA measurements | Hierarchy resolution



Principle of NOvA measurements | Octant resolution



Principle of NOvA measurements | Octant resolution

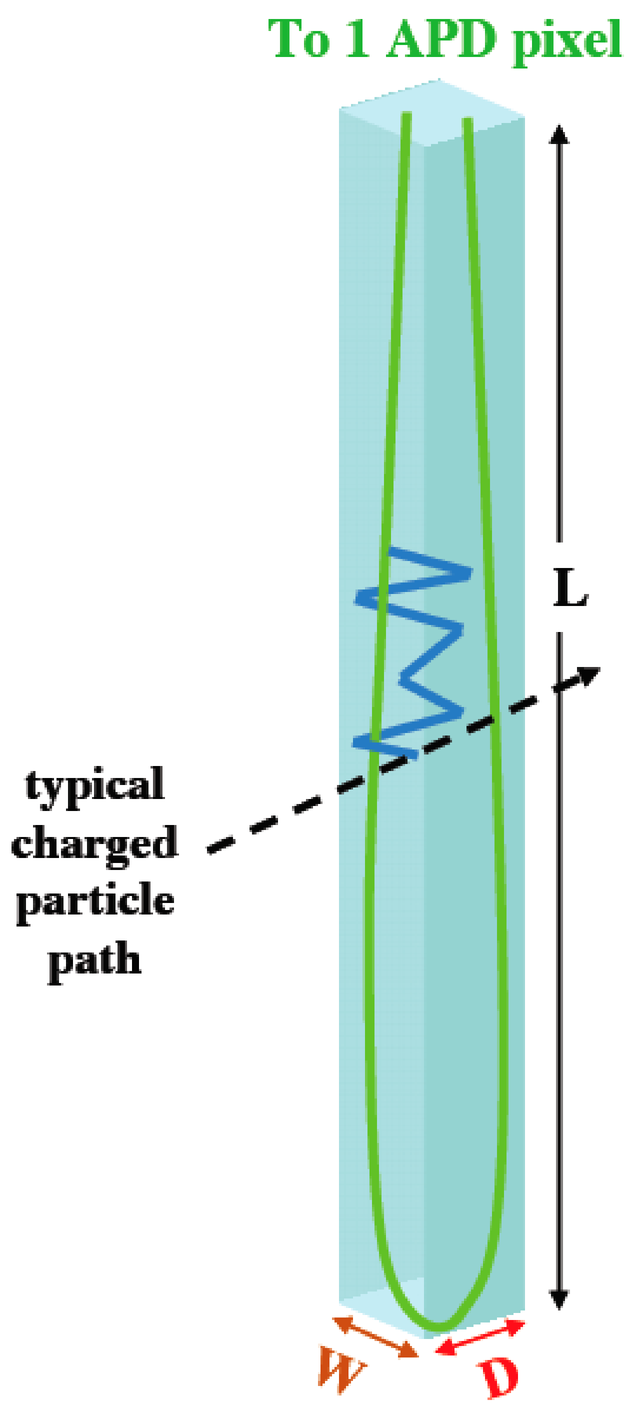


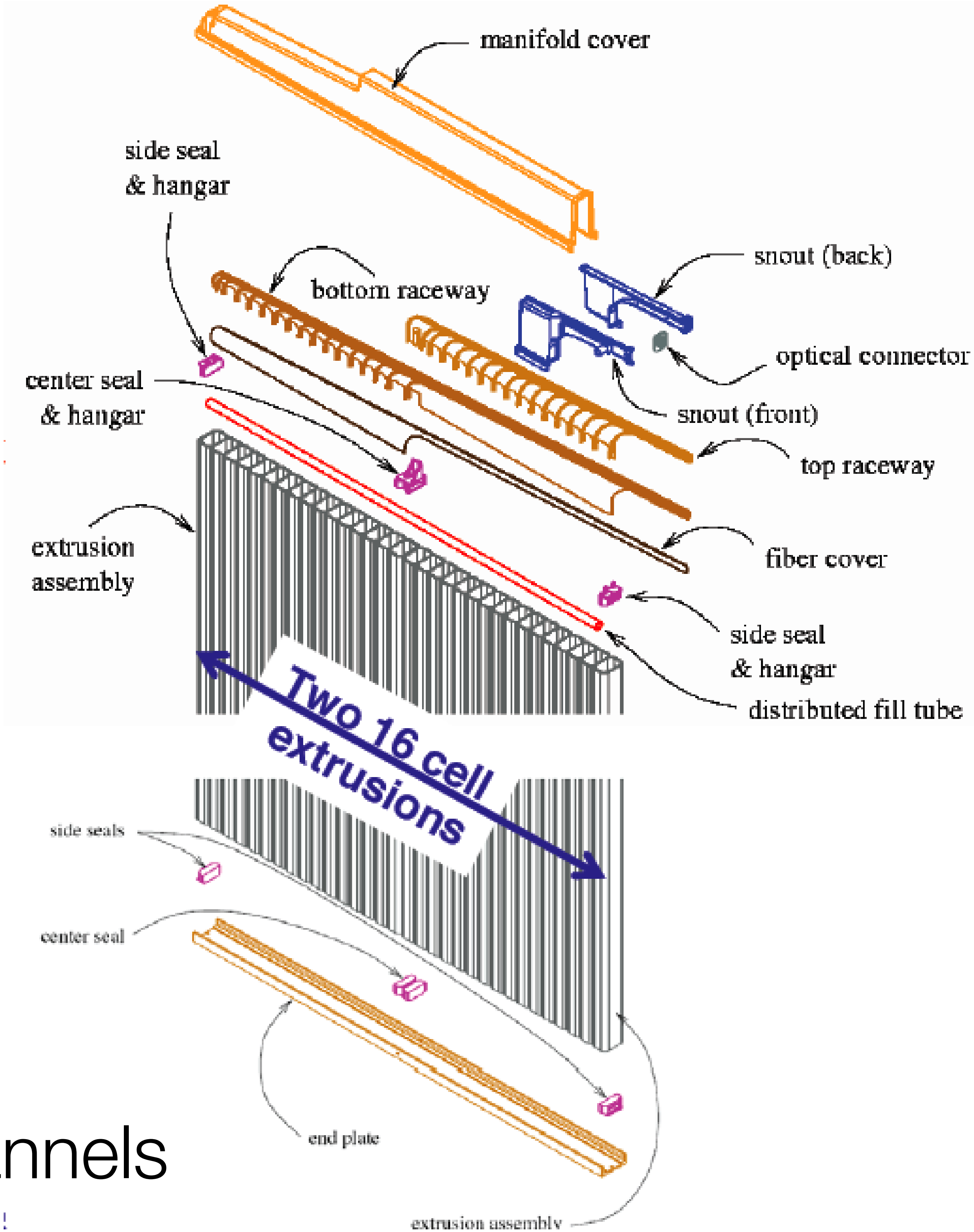
Principle of NOvA measurements | Octant resolution

14 kt total mass

9 kt liquid scintillator

5 kt PVC plastic





344,064 total channels

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*

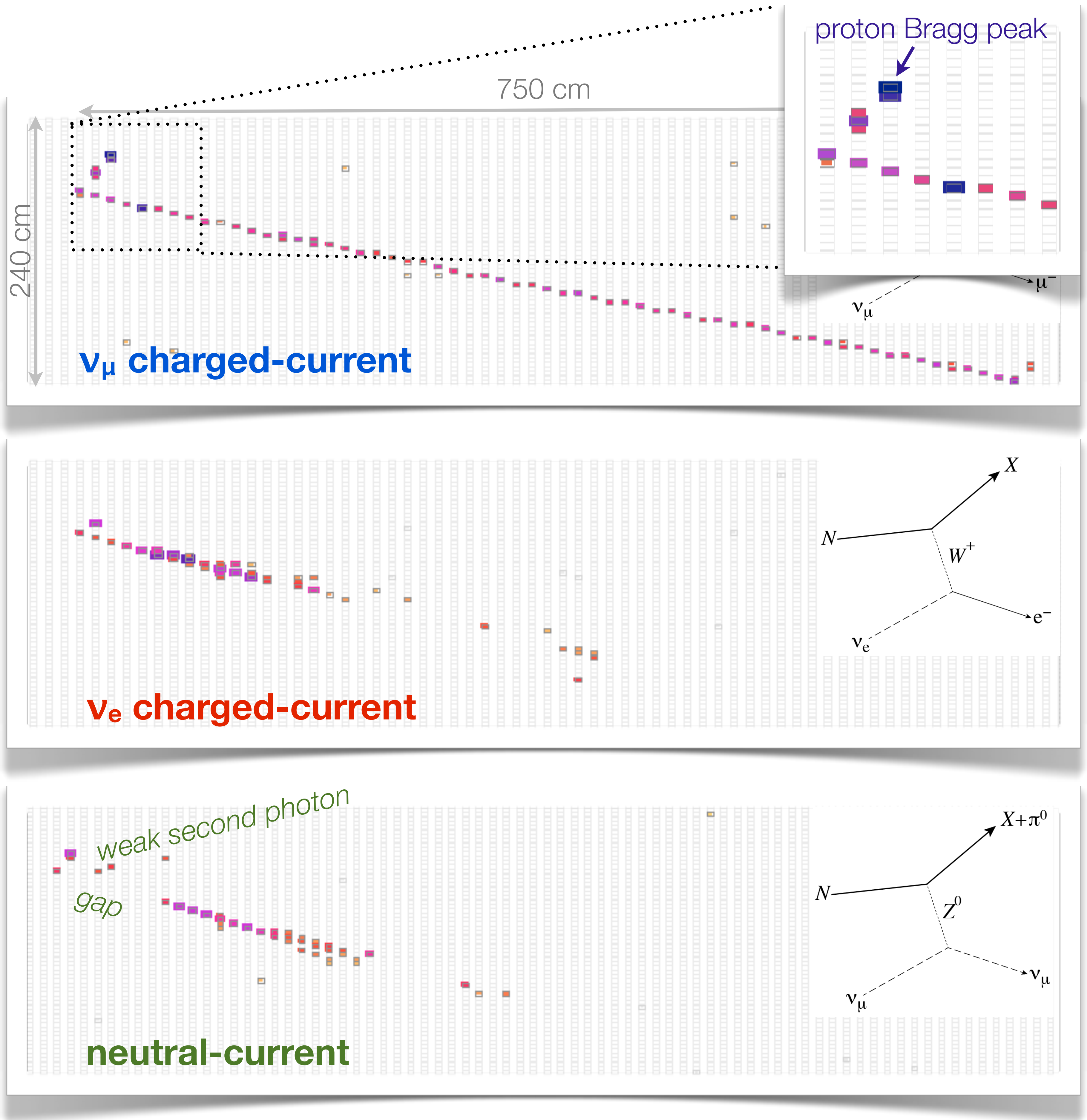
Center: ν_e *charged-current*

Bottom: *neutral-current*

Need >100:1 rejection against background

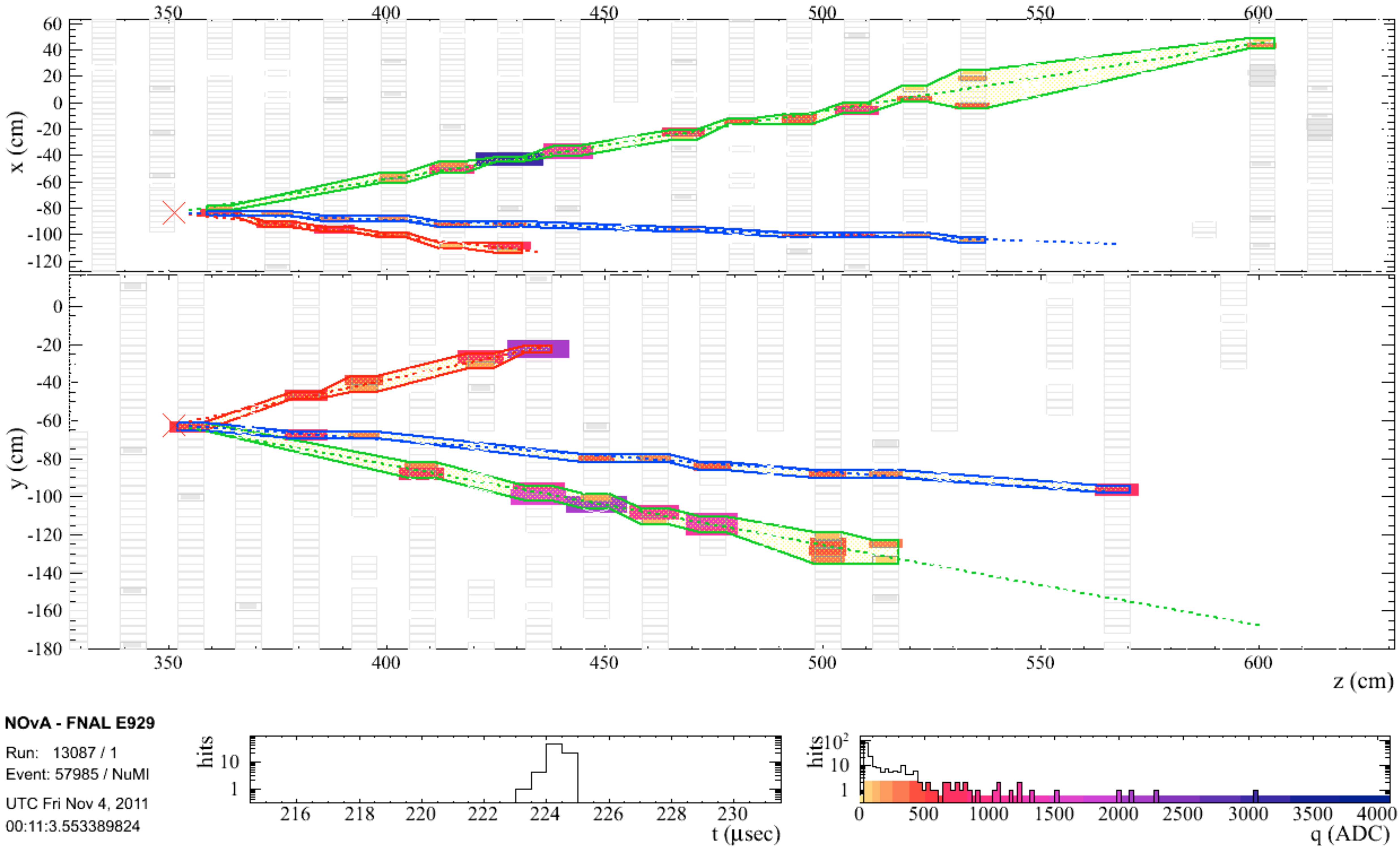
Detector challenge: Achieve large target mass (10’s+ kilotons) while maintaining high granularity to avoid confusing the detection channels

NOvA achieves 40% efficiency for ν_e CC while limiting NC→ν_e CC fake rate to 0.1%



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

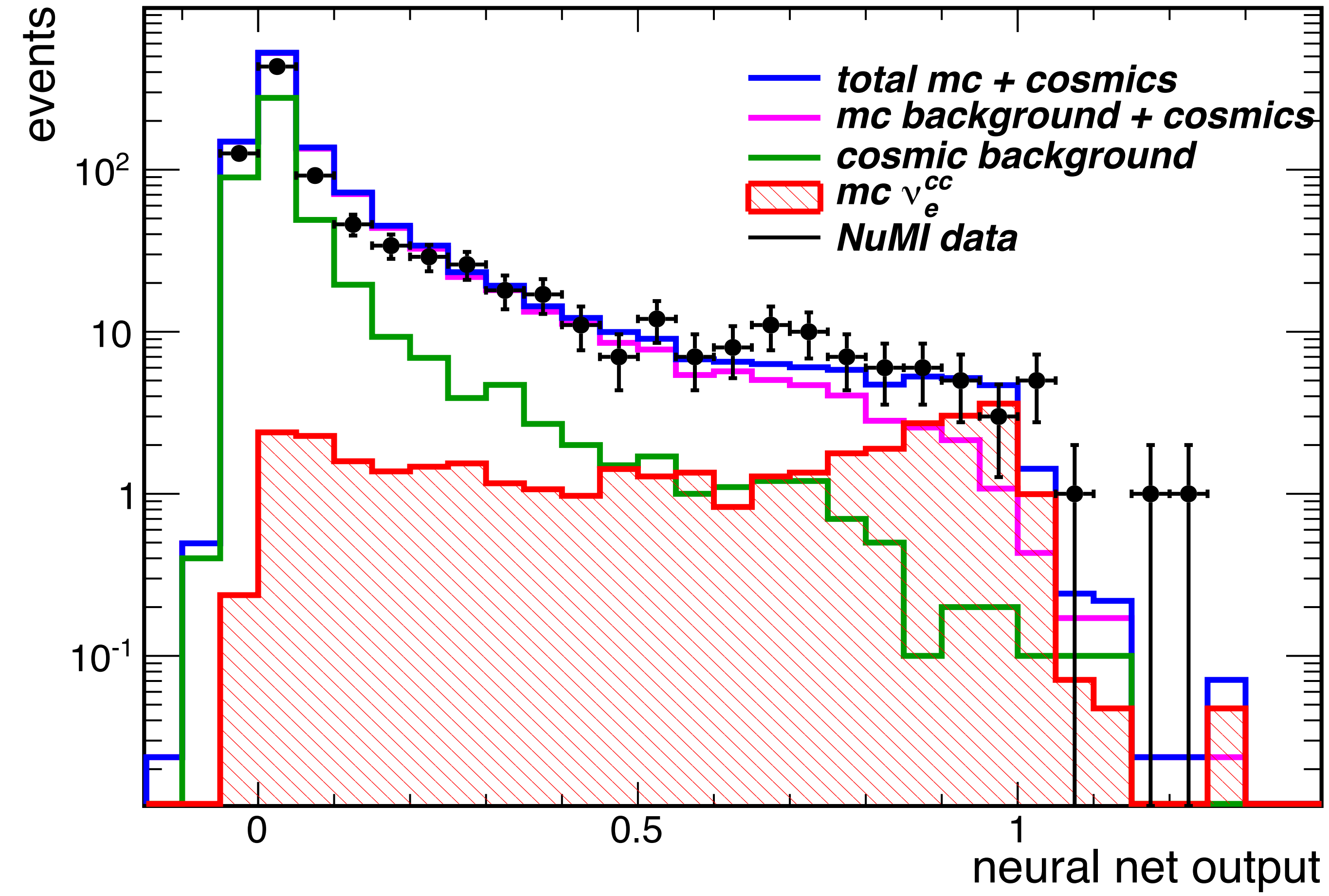


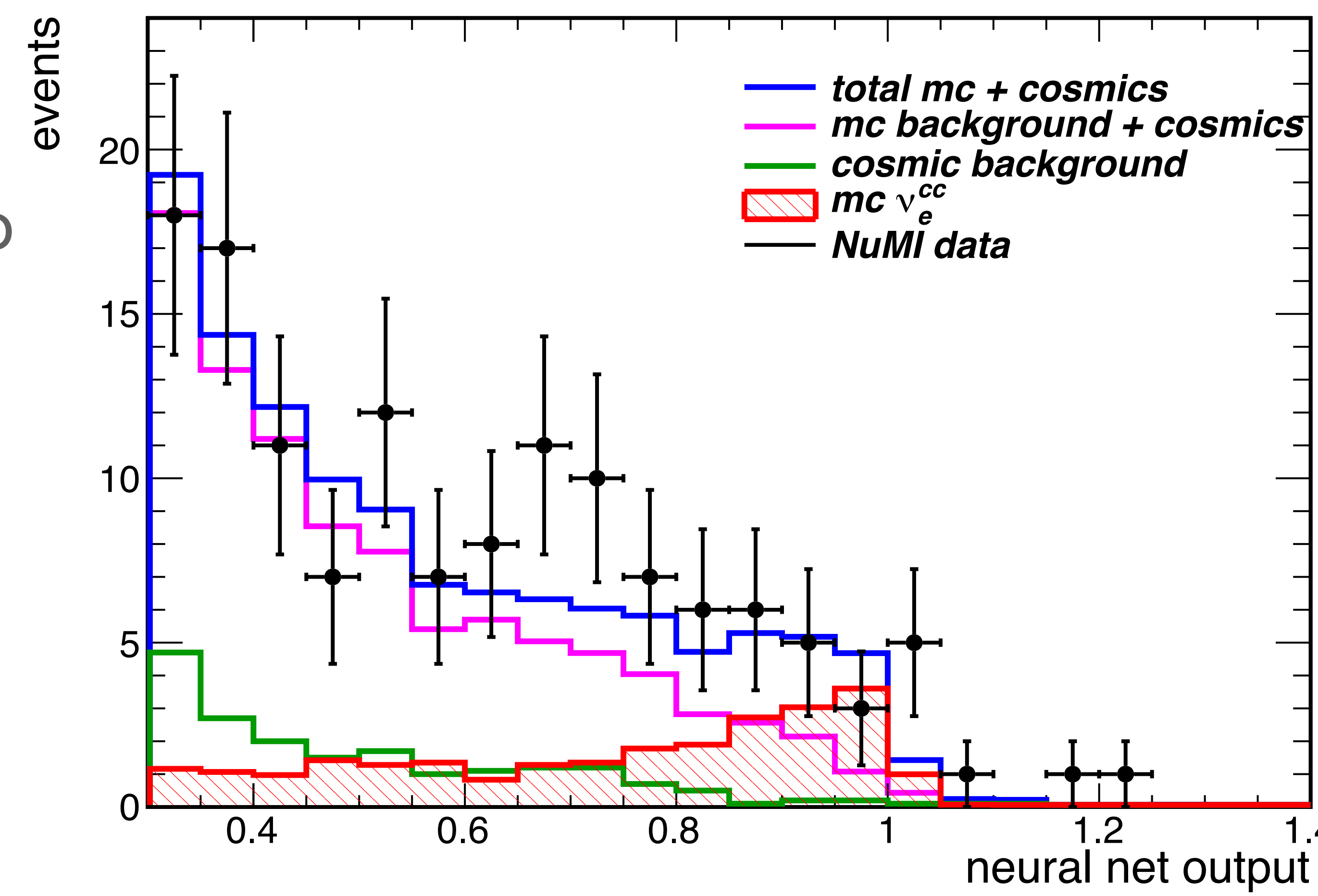
$\nu_\mu + n \rightarrow p + \mu^- + \pi^0$ candidate in NDOS

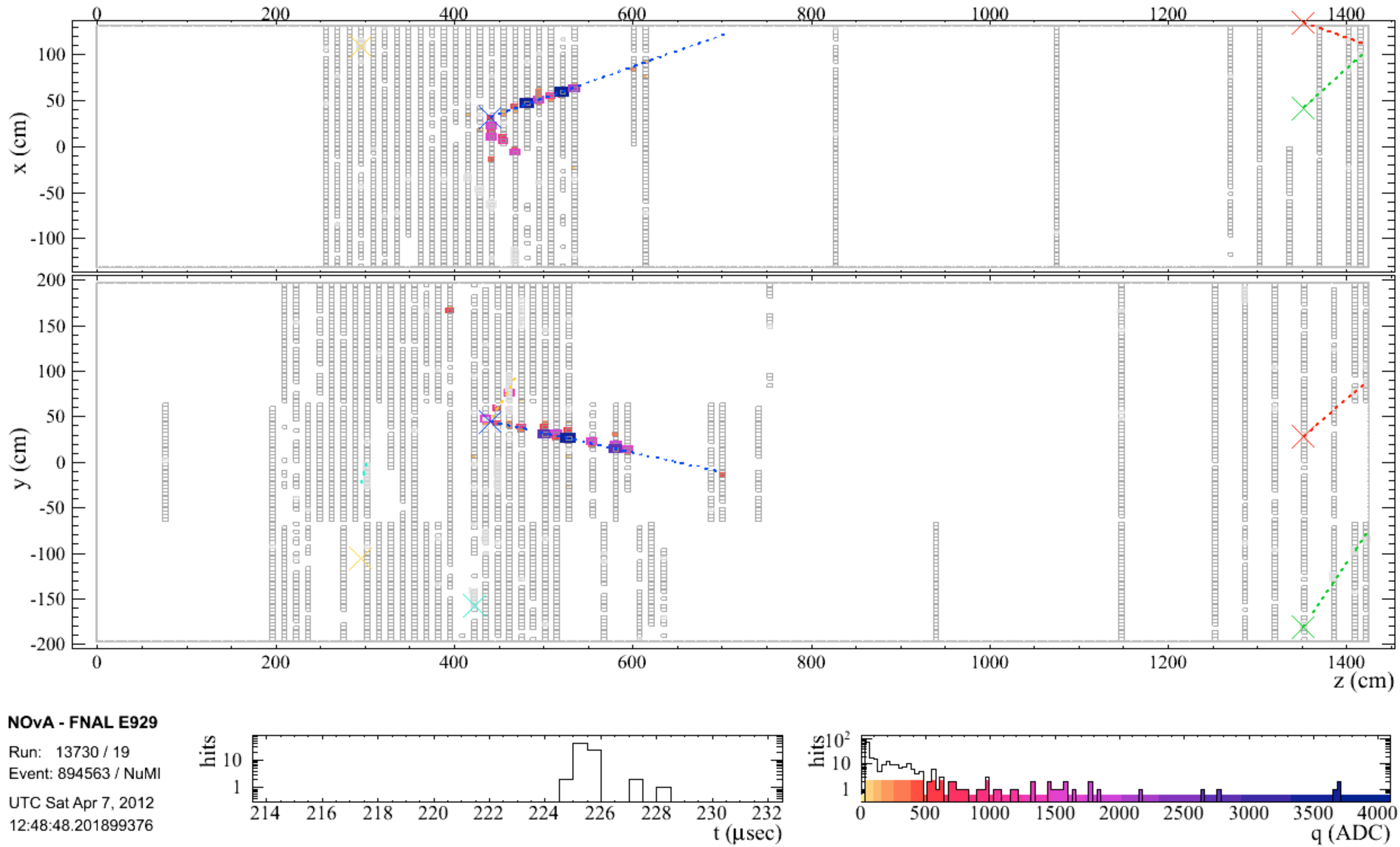
Reconstruction works even in the sparsely instrumented NDOS detector (shown here).
Performance on fully instrumented far detector is much better.

Electron neutrinos in NDOS

- In addition the the MDC we ran the analysis chain on the NuMI data recorded at NDOS
- Ran it "as is". Situation at NDOS is much harder than far detector will be
  - Sparsely instrumented
  - No overburden
  - Large surface area / volume ratio
  - Lower energy neutrino spectrum
- Measured the electron neutrino component of the beam (data pulls away from magenta histogram):

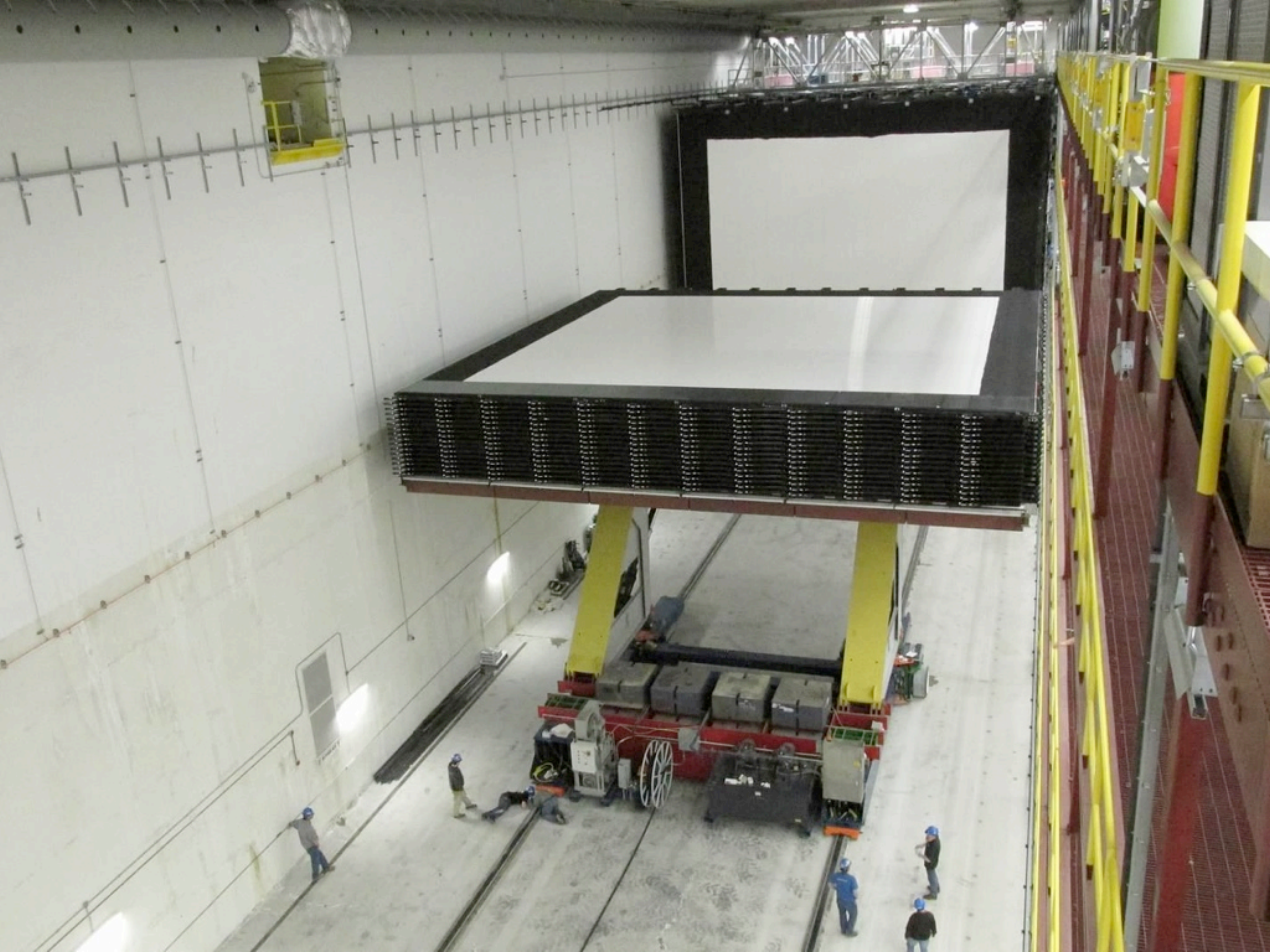






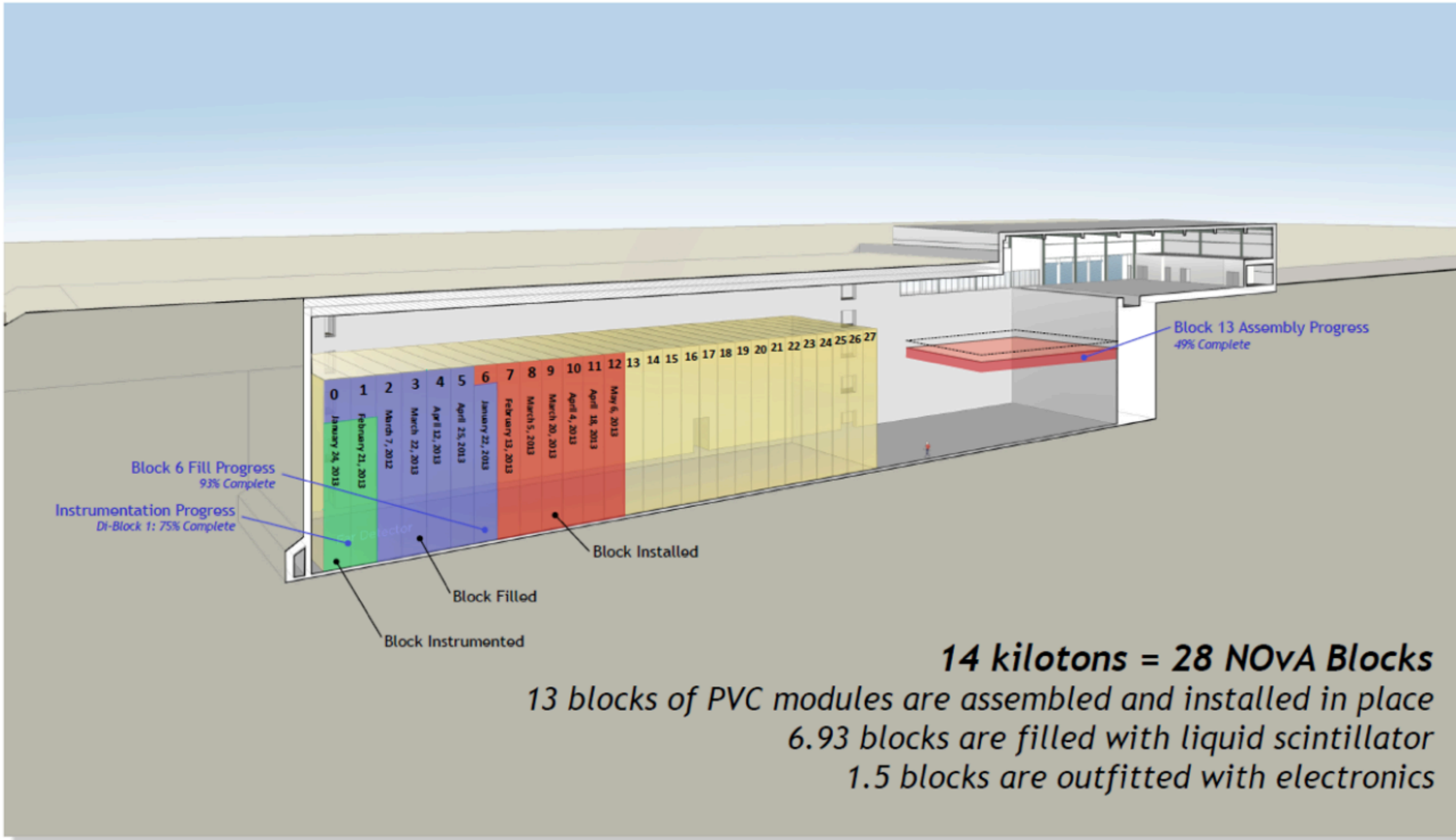
ν_e charged-current quasi-elastic event at NDOS

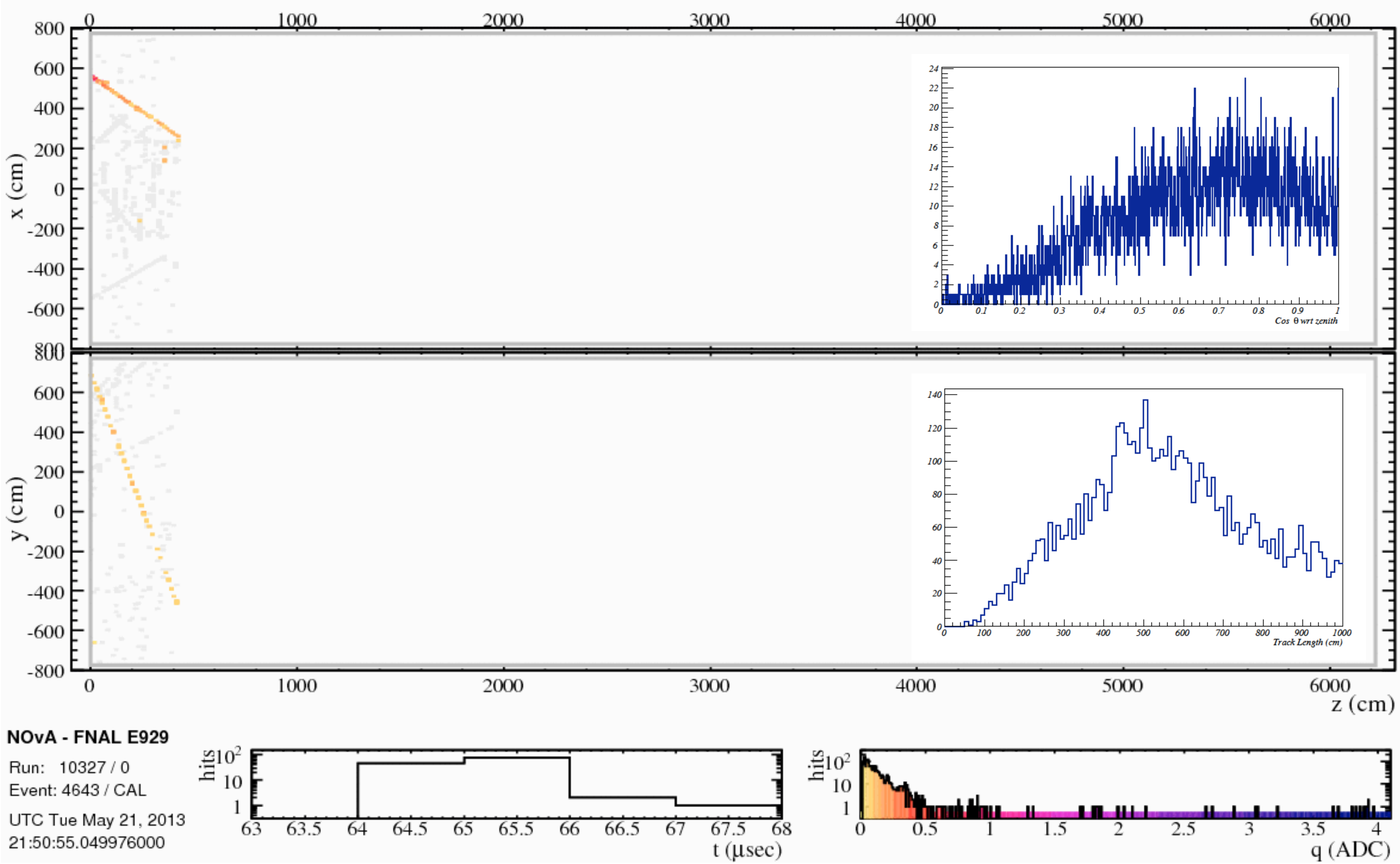
Far Detector Assembly Progress



Construction status

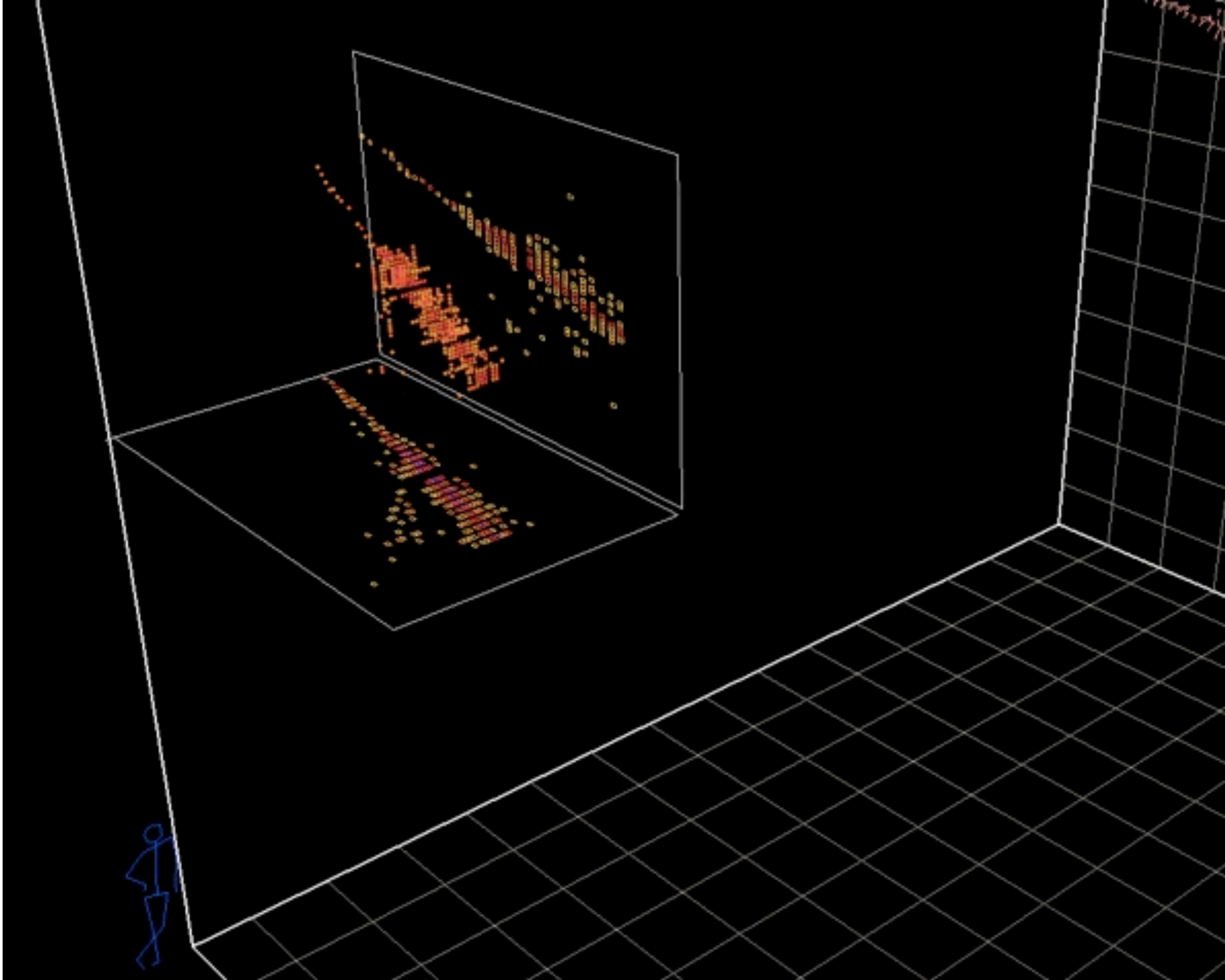
First kiloton operating now
14 kilotons completed in June 2014



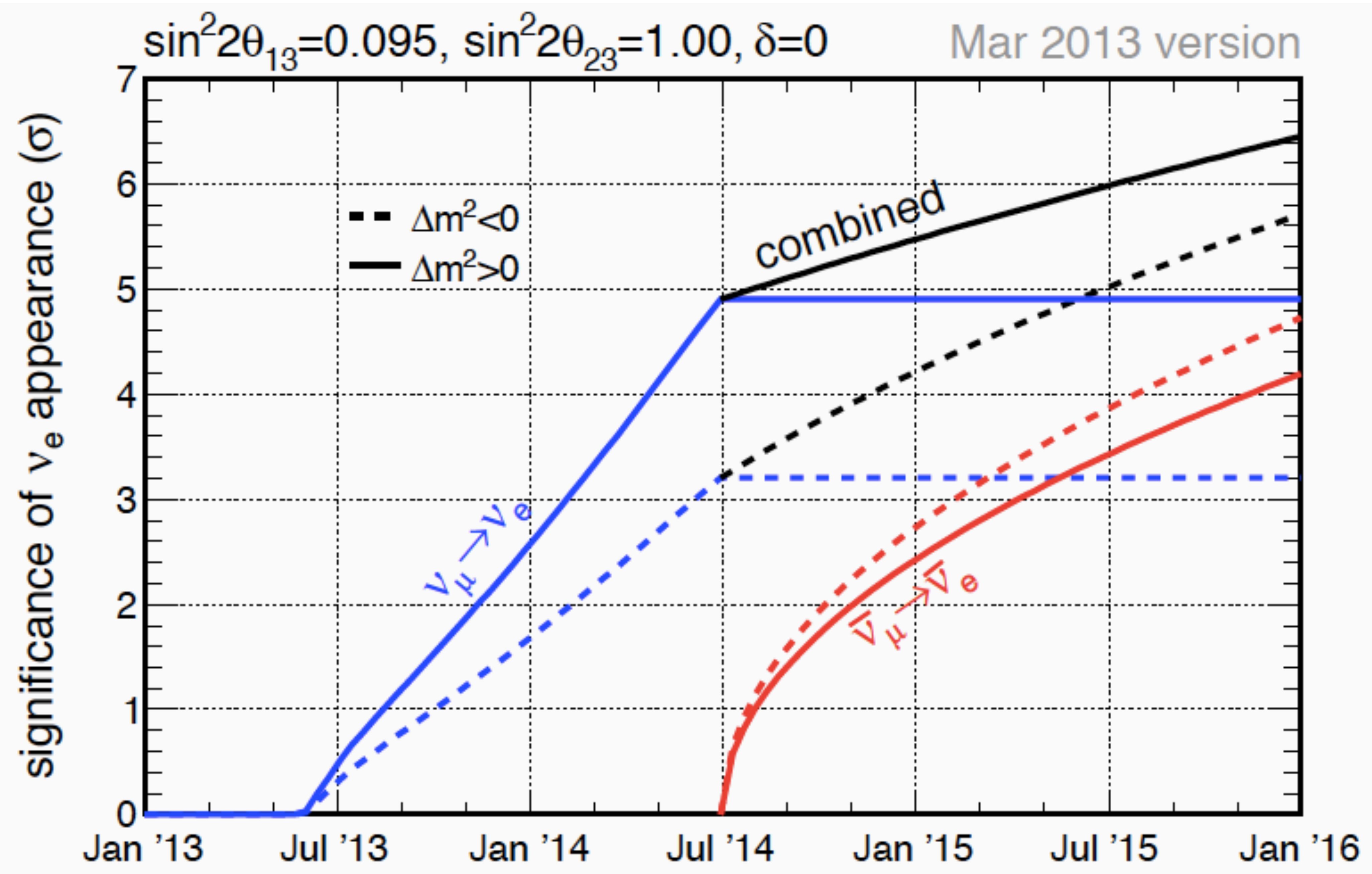


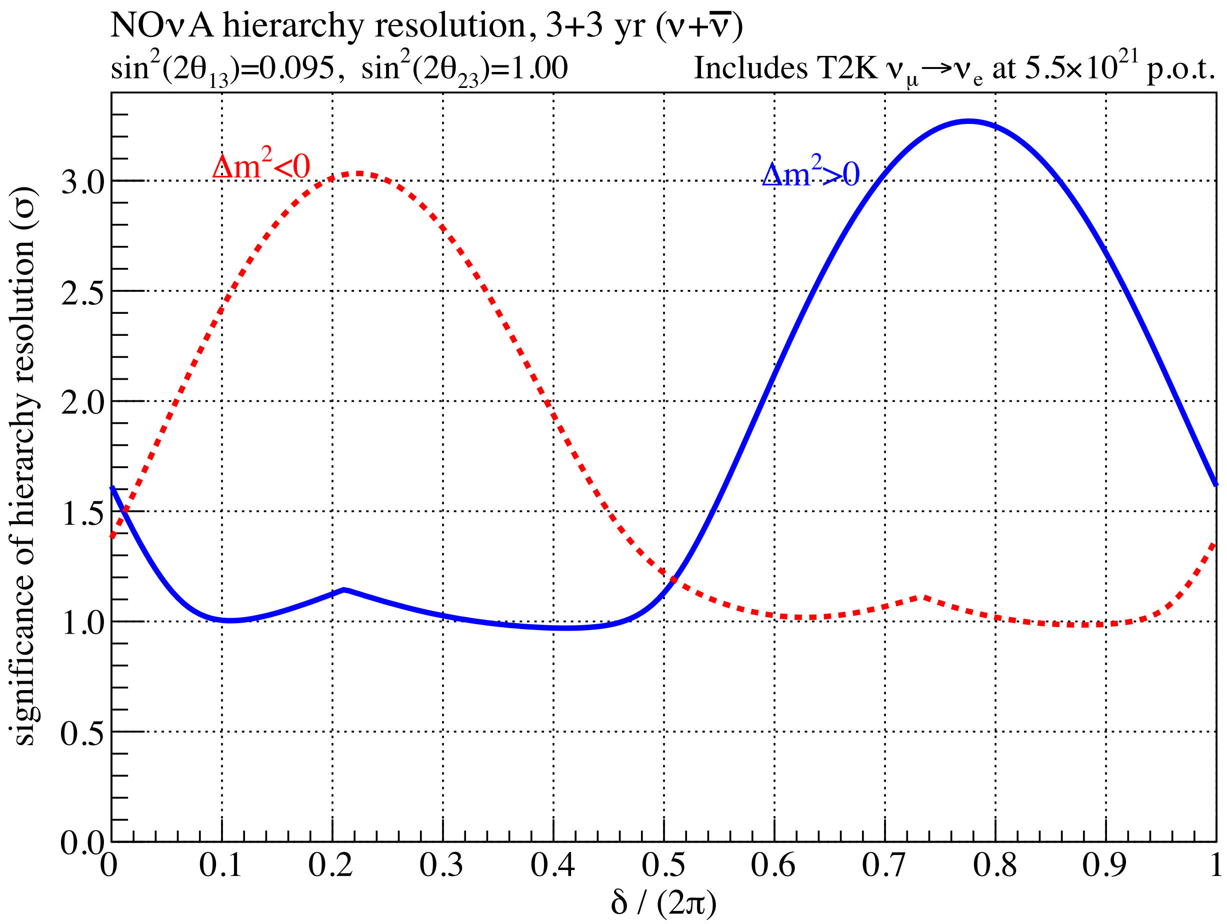
Cosmic-ray in first completed kiloton

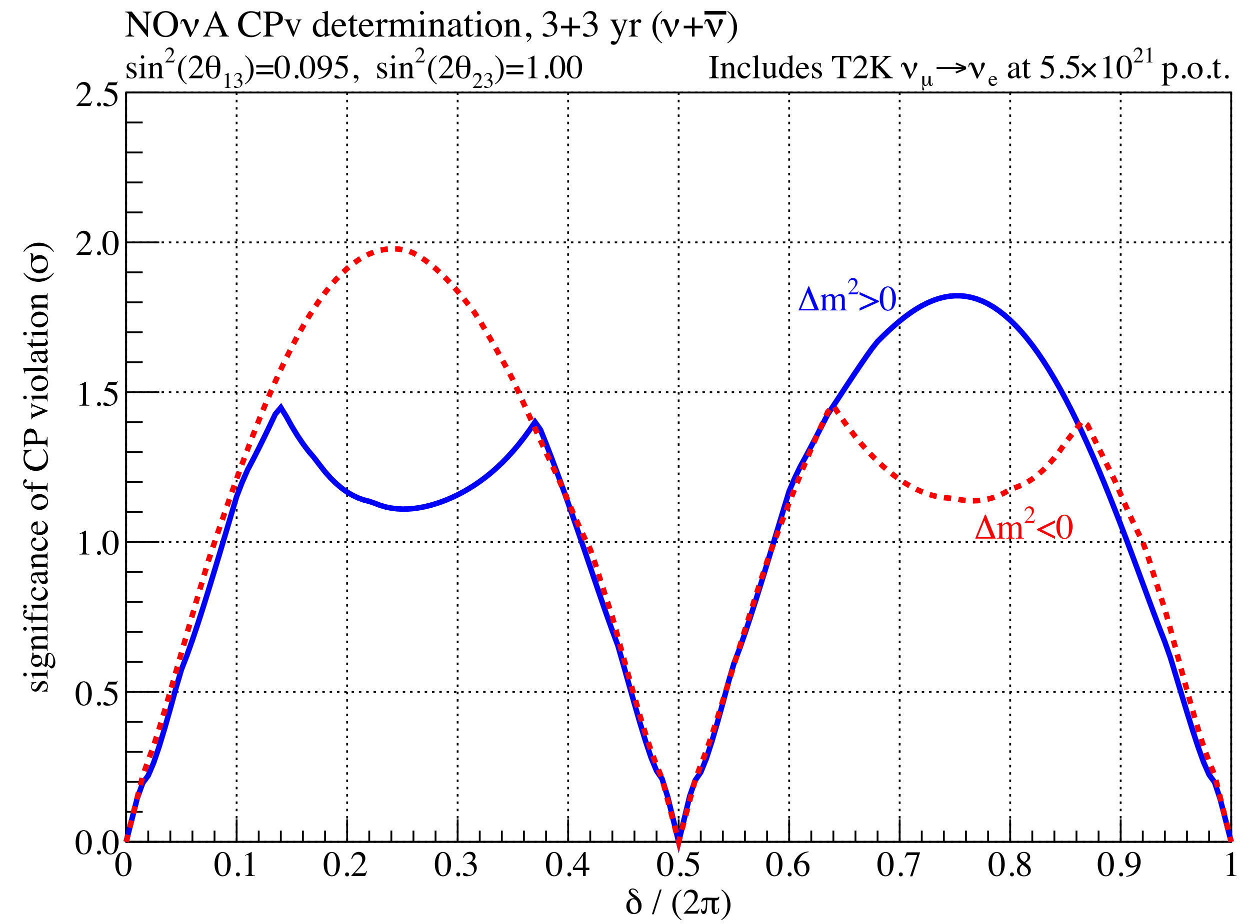
Ready for neutrino beam in mid June



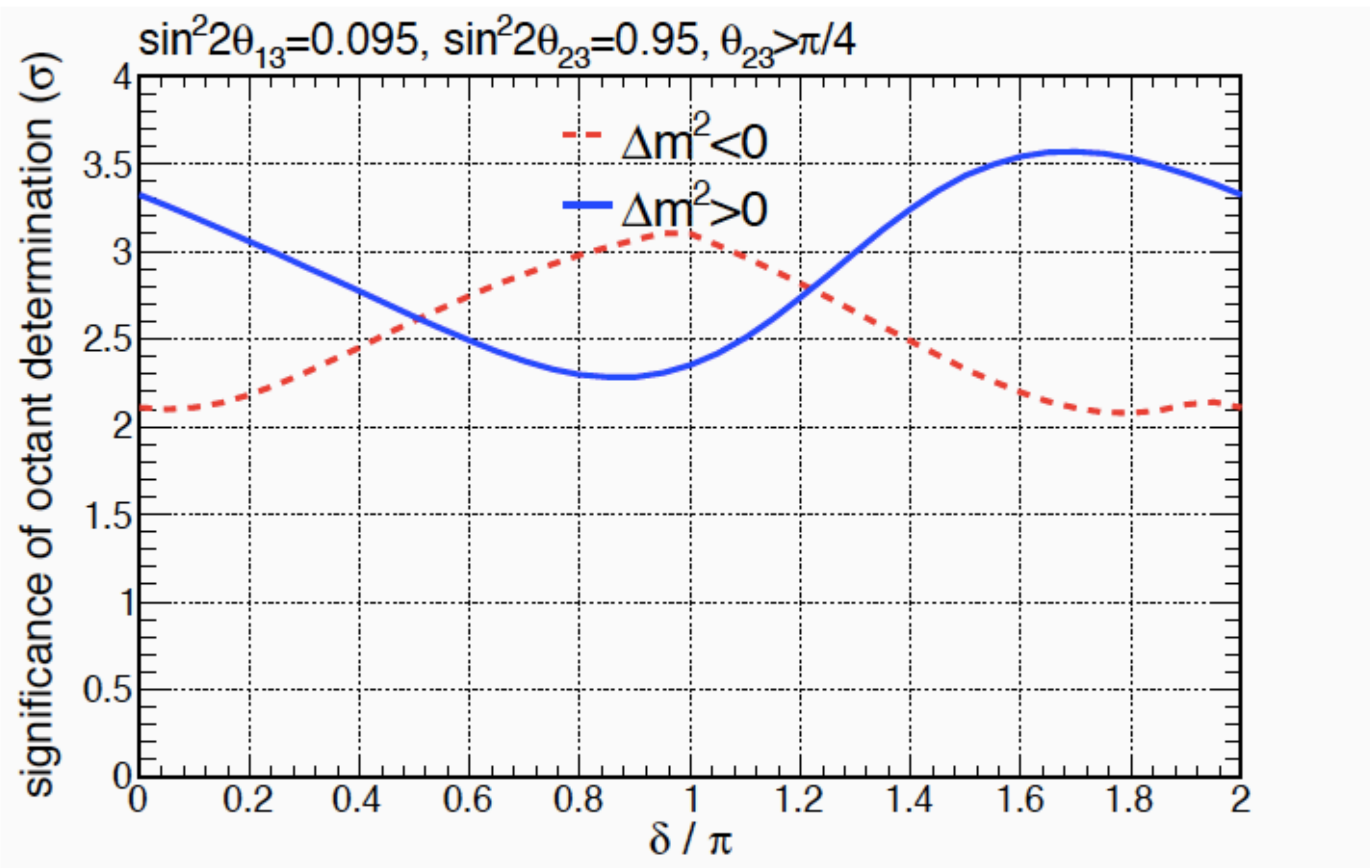
NOvA Early Reach



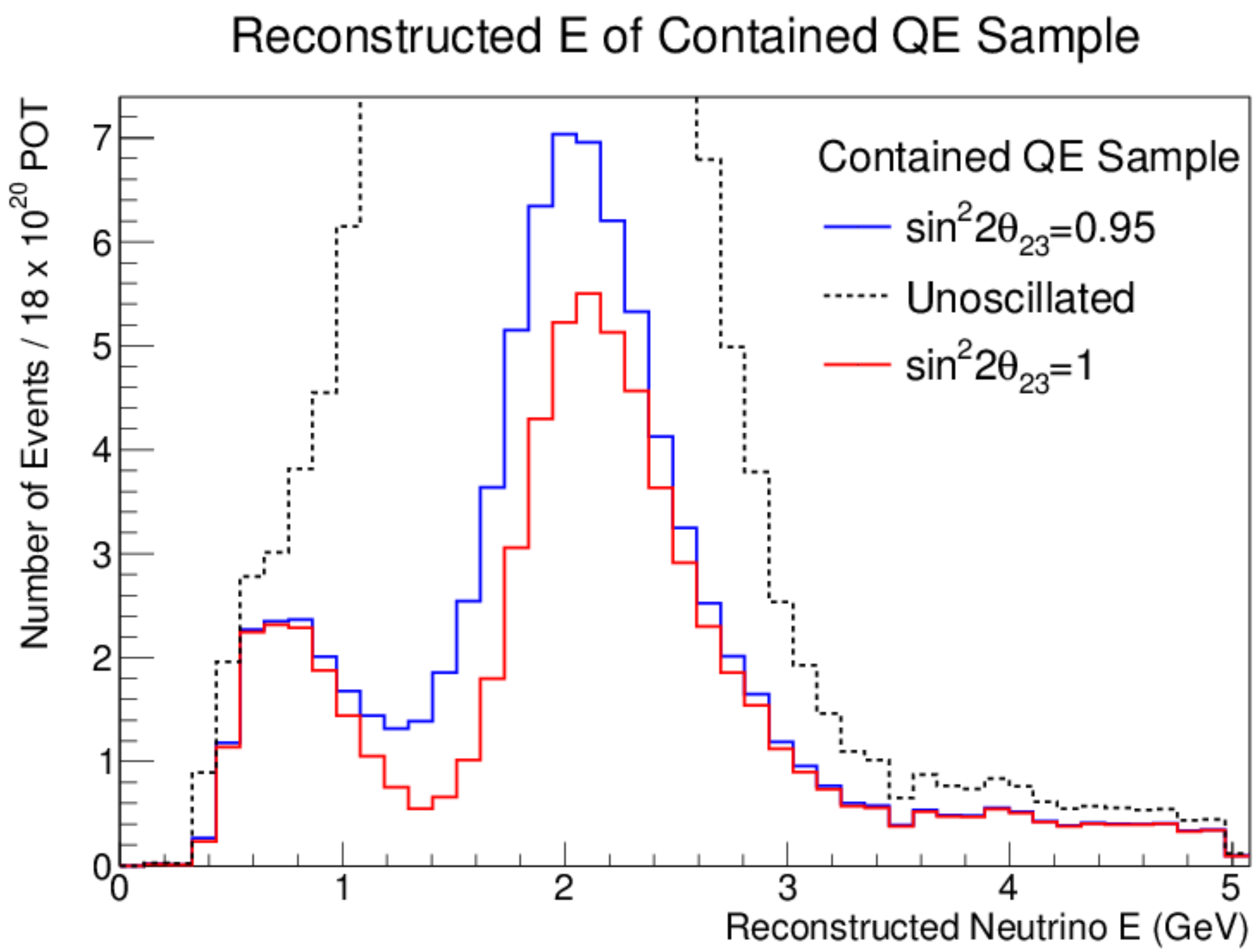


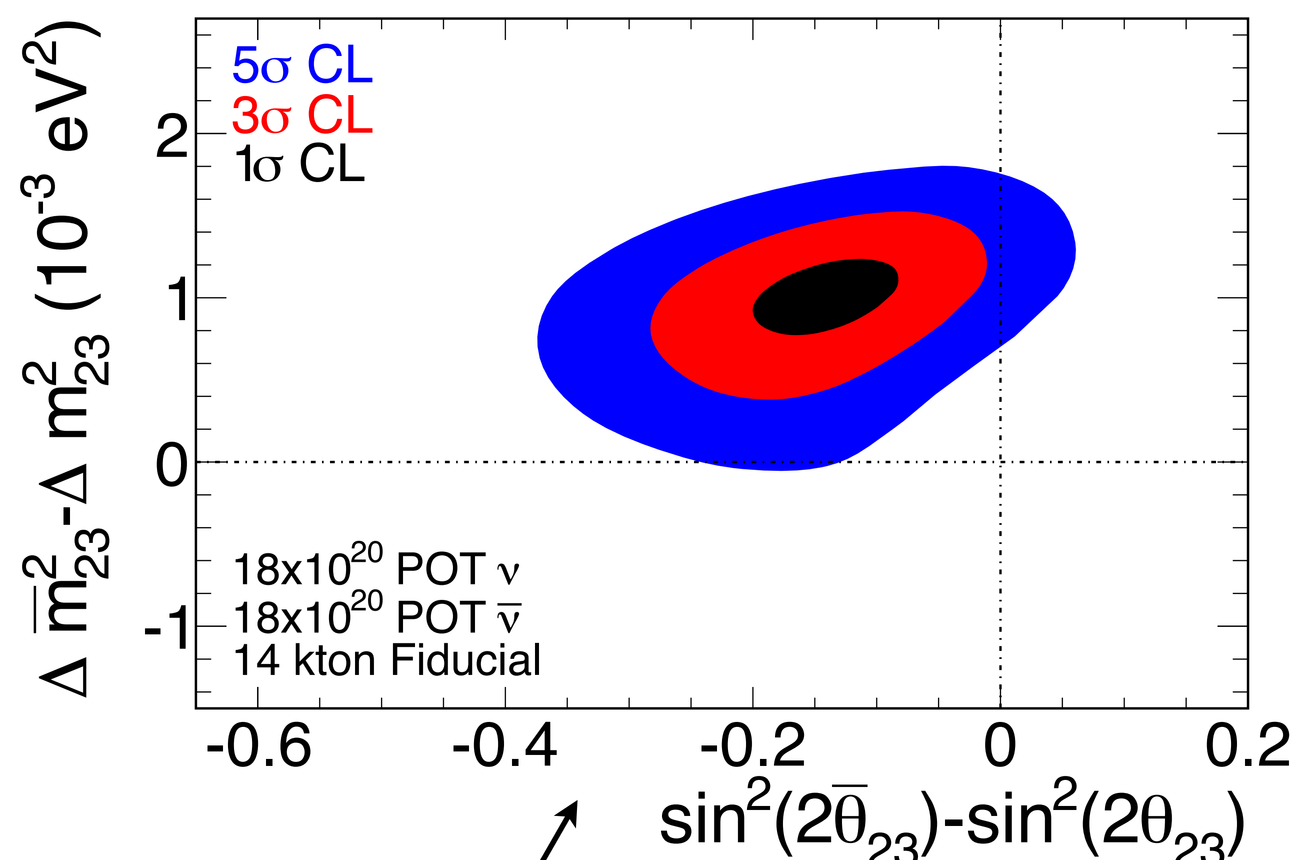


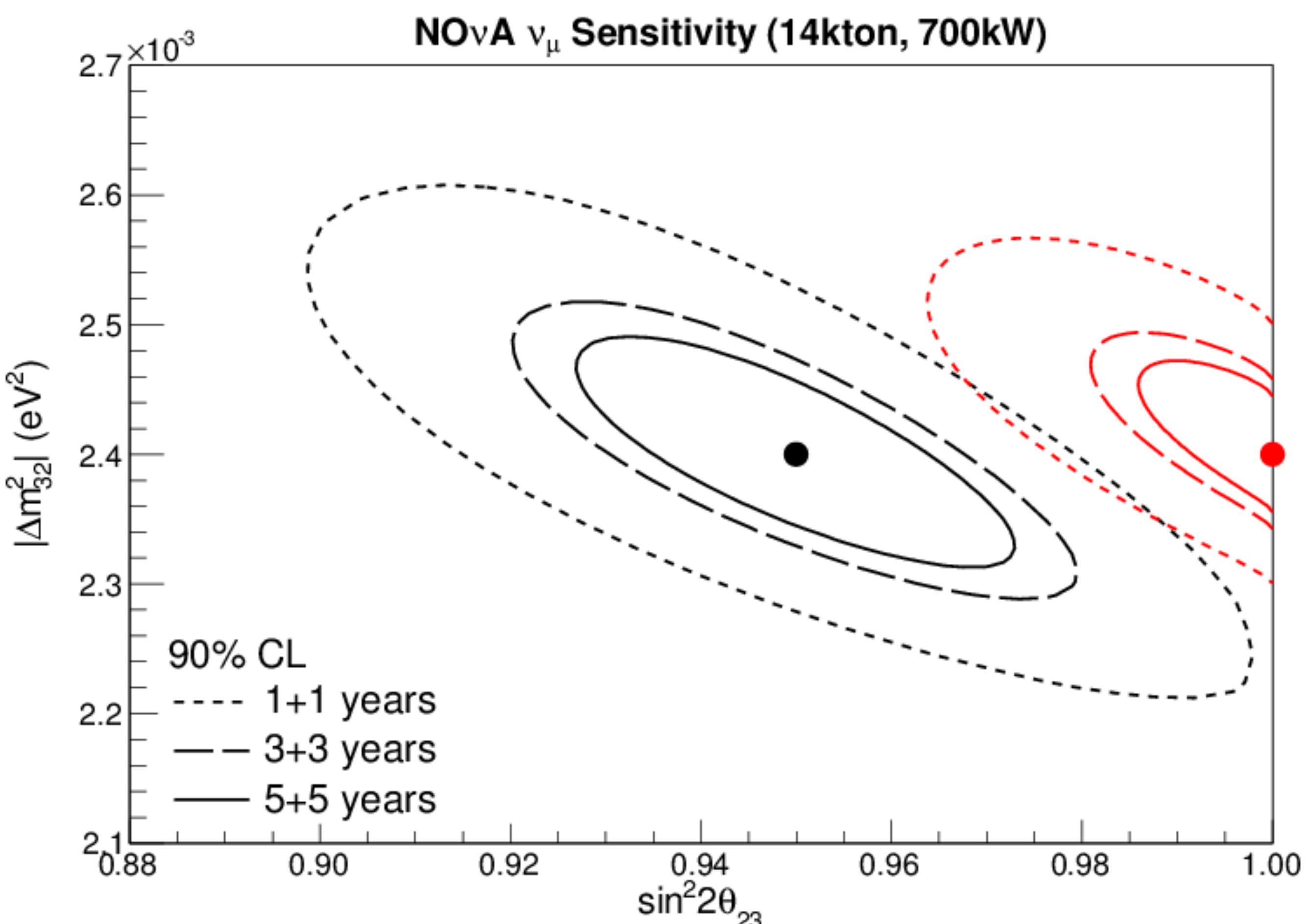
NOvA reach after 6 years
3 years neutrinos +
3 years antineutrinos



Muon neutrino disappearance



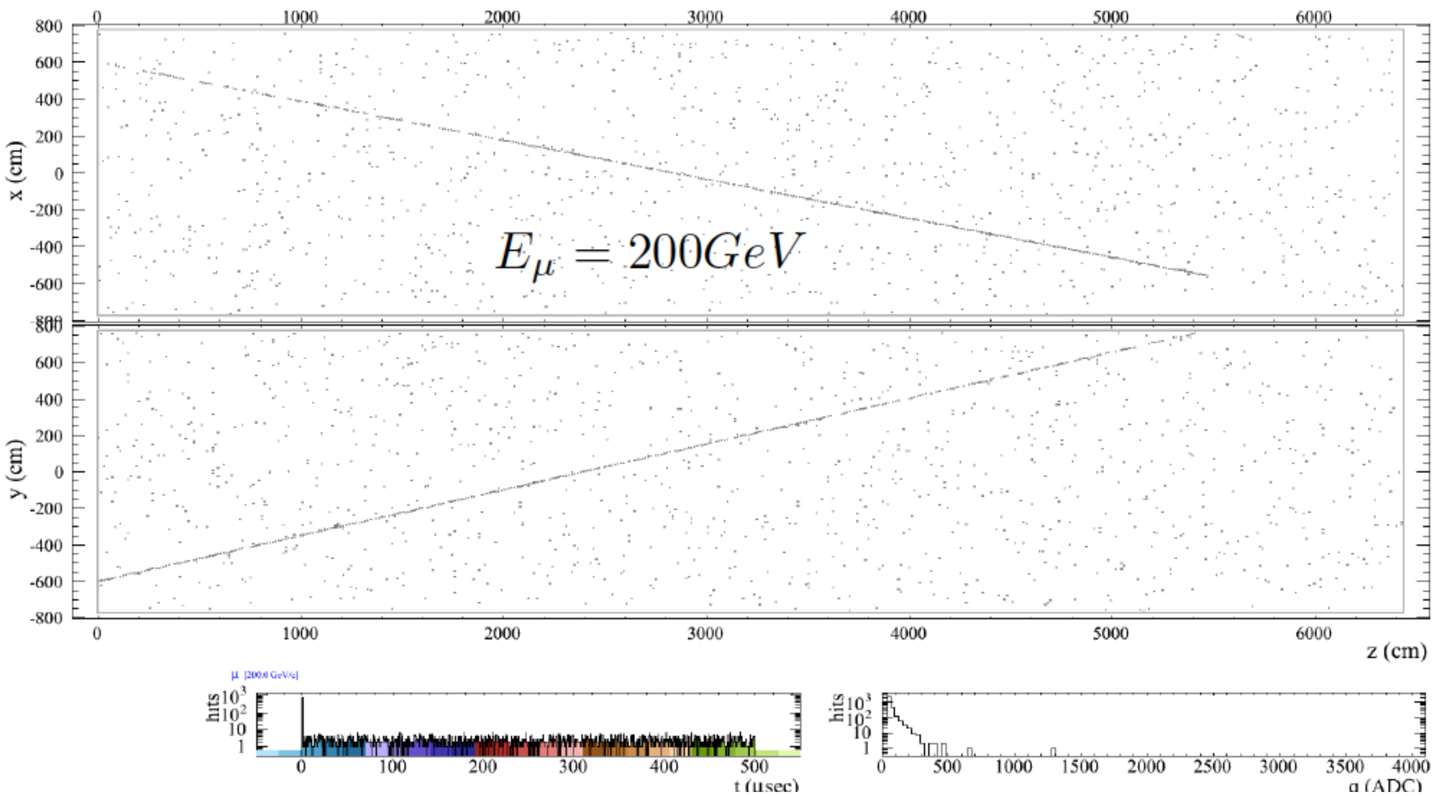


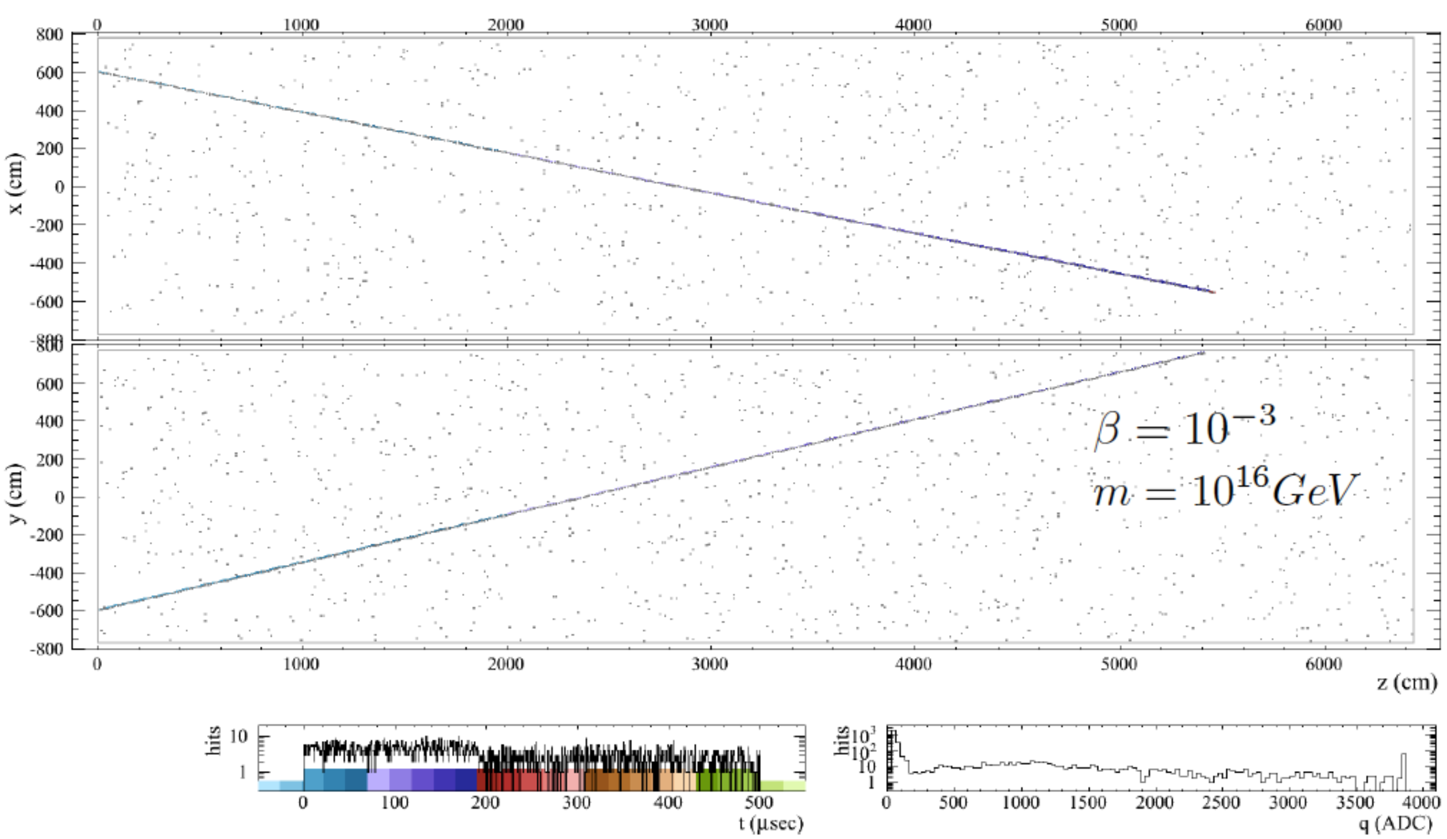


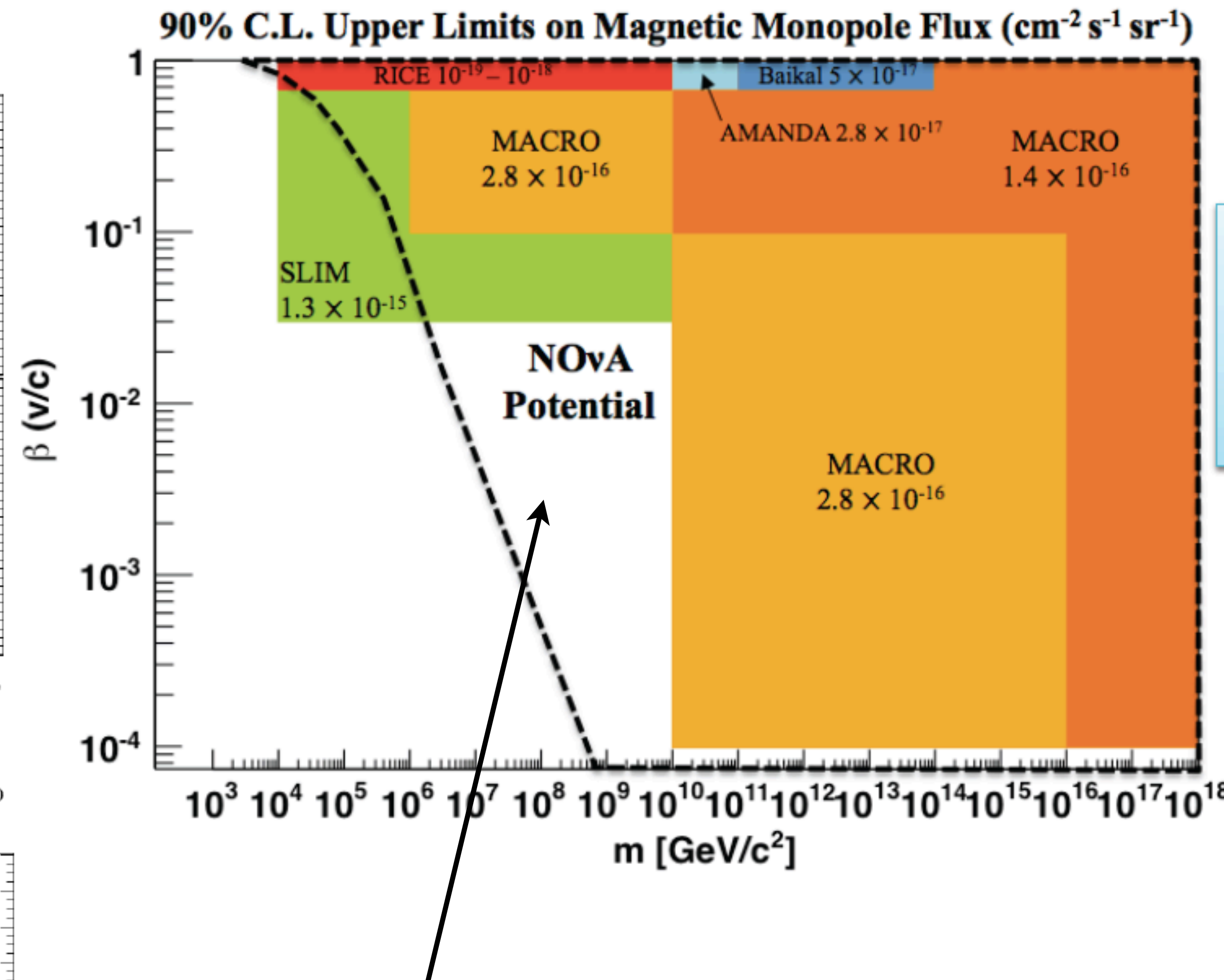
Allowing for possibility that new physics causes muon neutrinos and antineutrinos oscillate differently

Assuming muon neutrinos and antineutrinos oscillate the same way.

Extending NOvA physics with online triggers: Magnetic Monopole searches



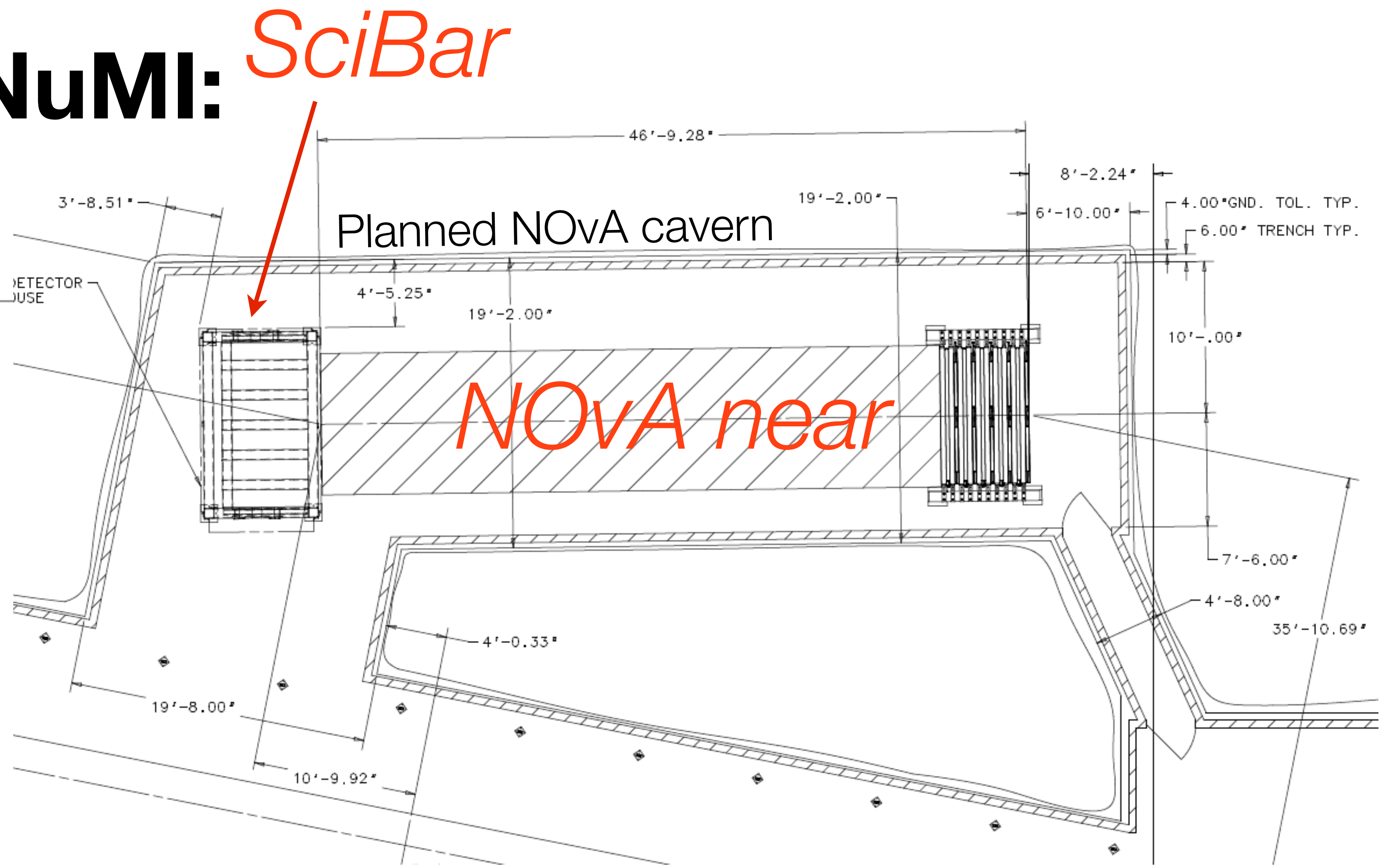


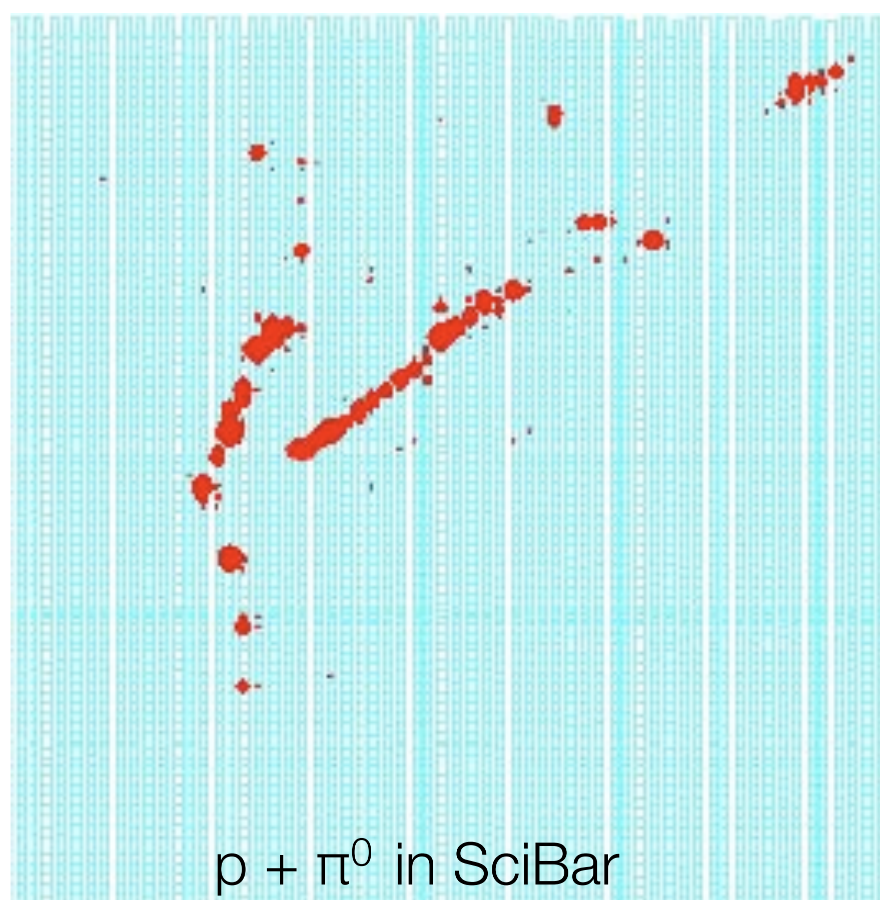


NOvA's shallow overburden is advantage in this low mass / low beta range

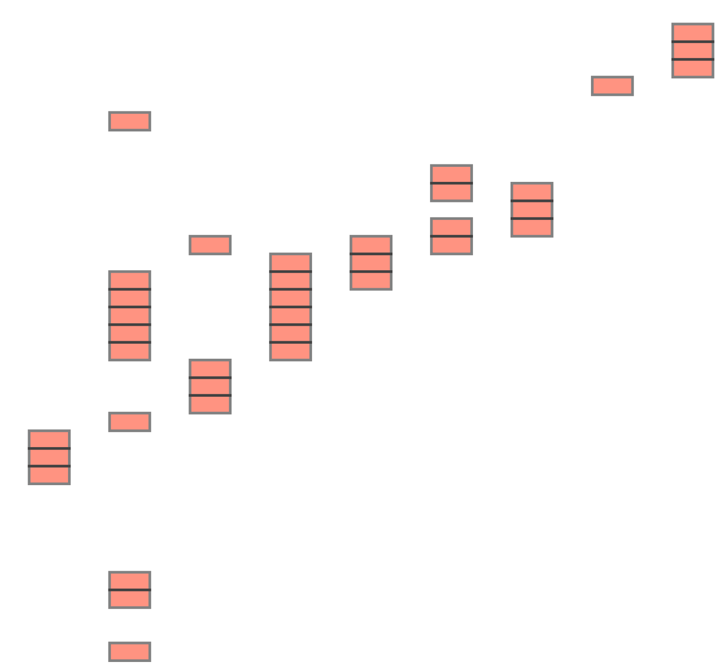
New ideas for NuMI: SciNOvA

- 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



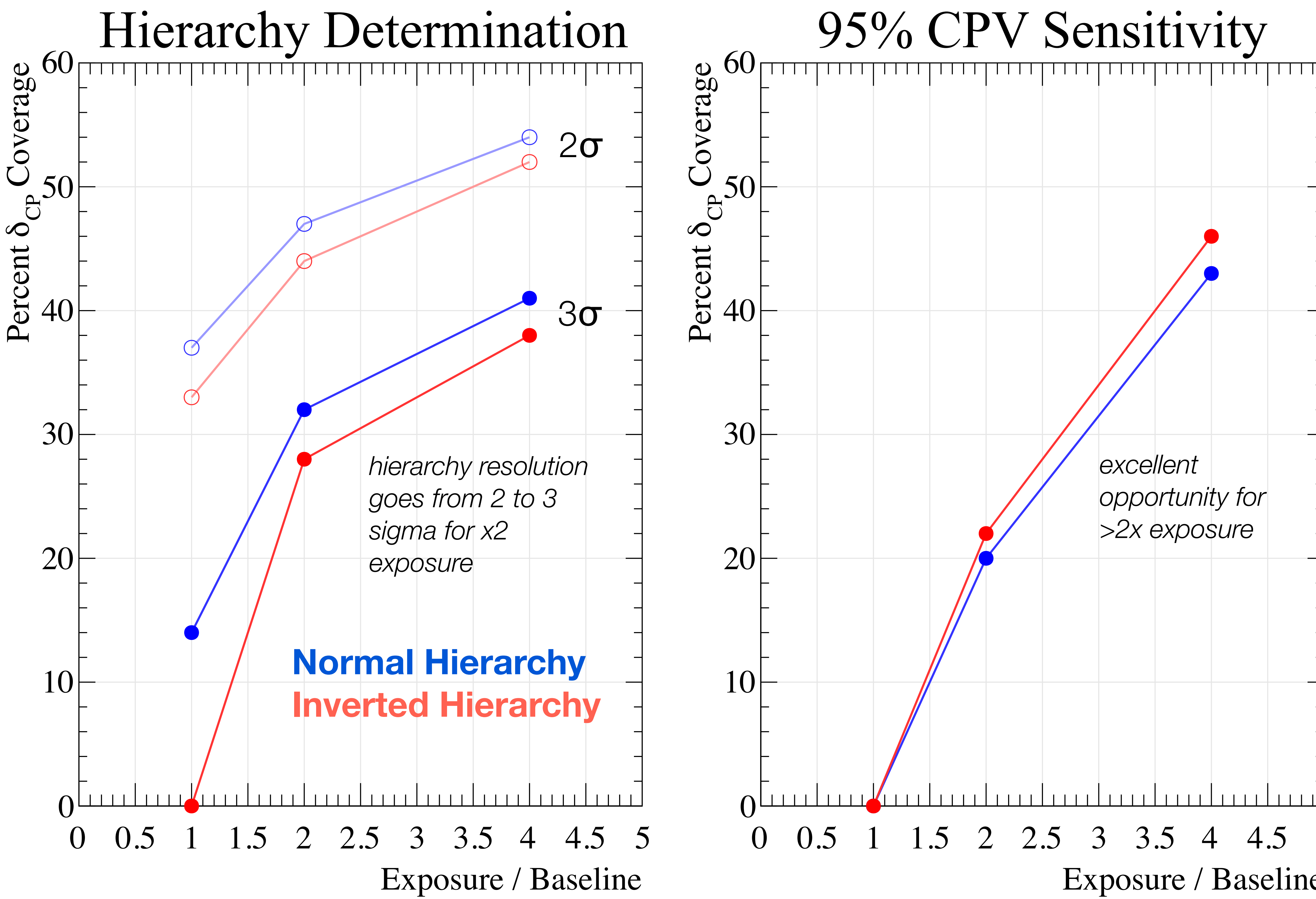


$p + \pi^0$ in SciBar

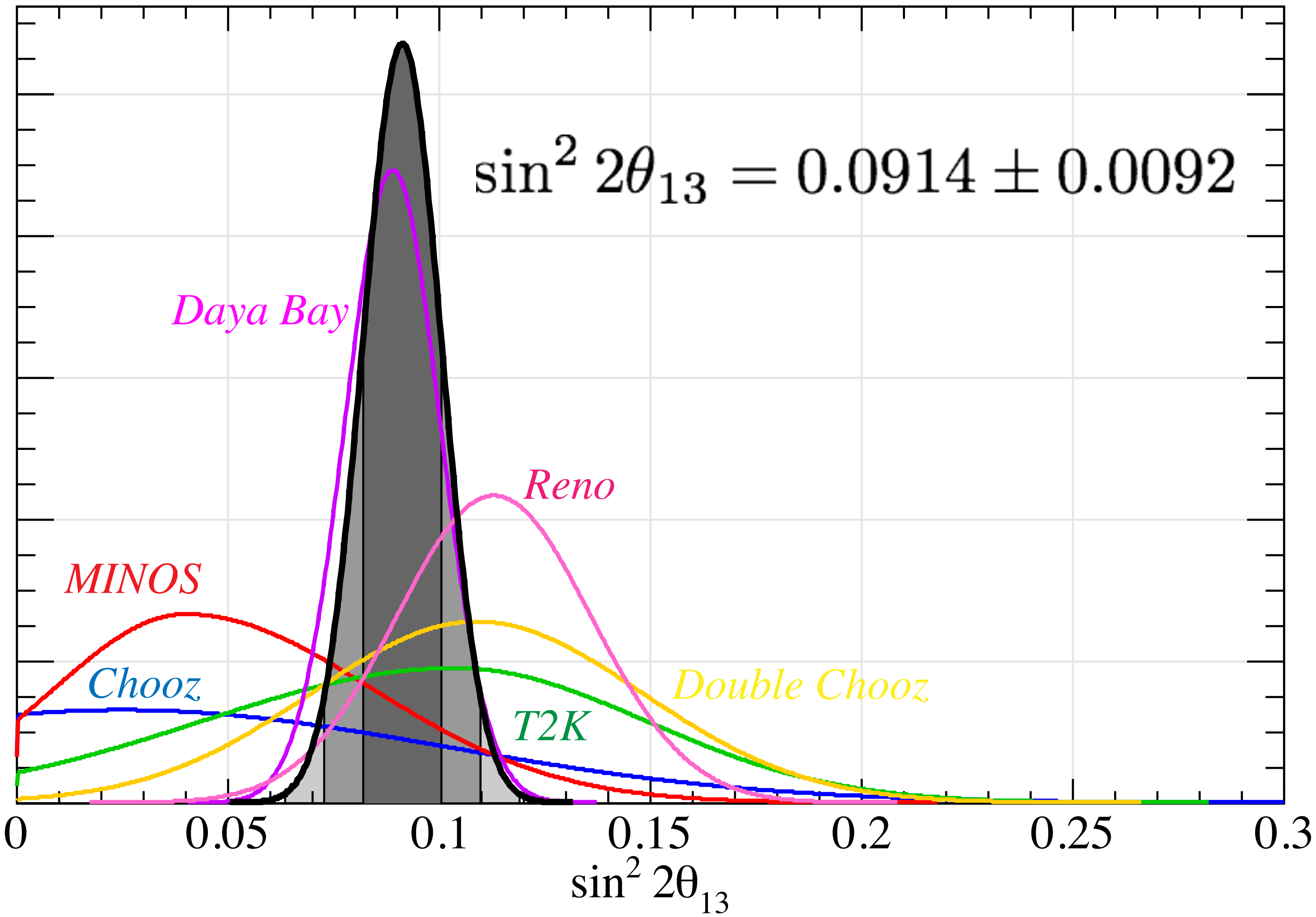


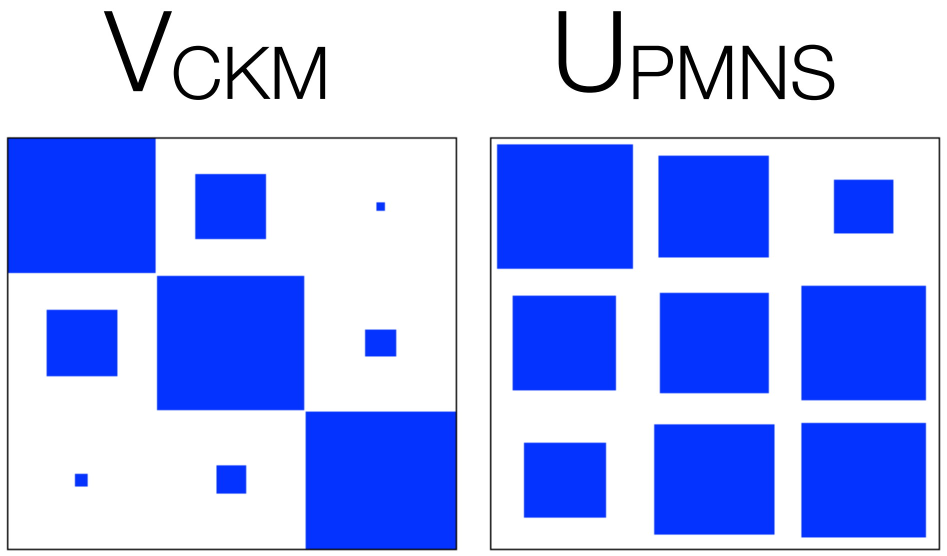
Same event resampled in NOvA

Extending NOvA's Reach



Discovering CP violation in neutrinos





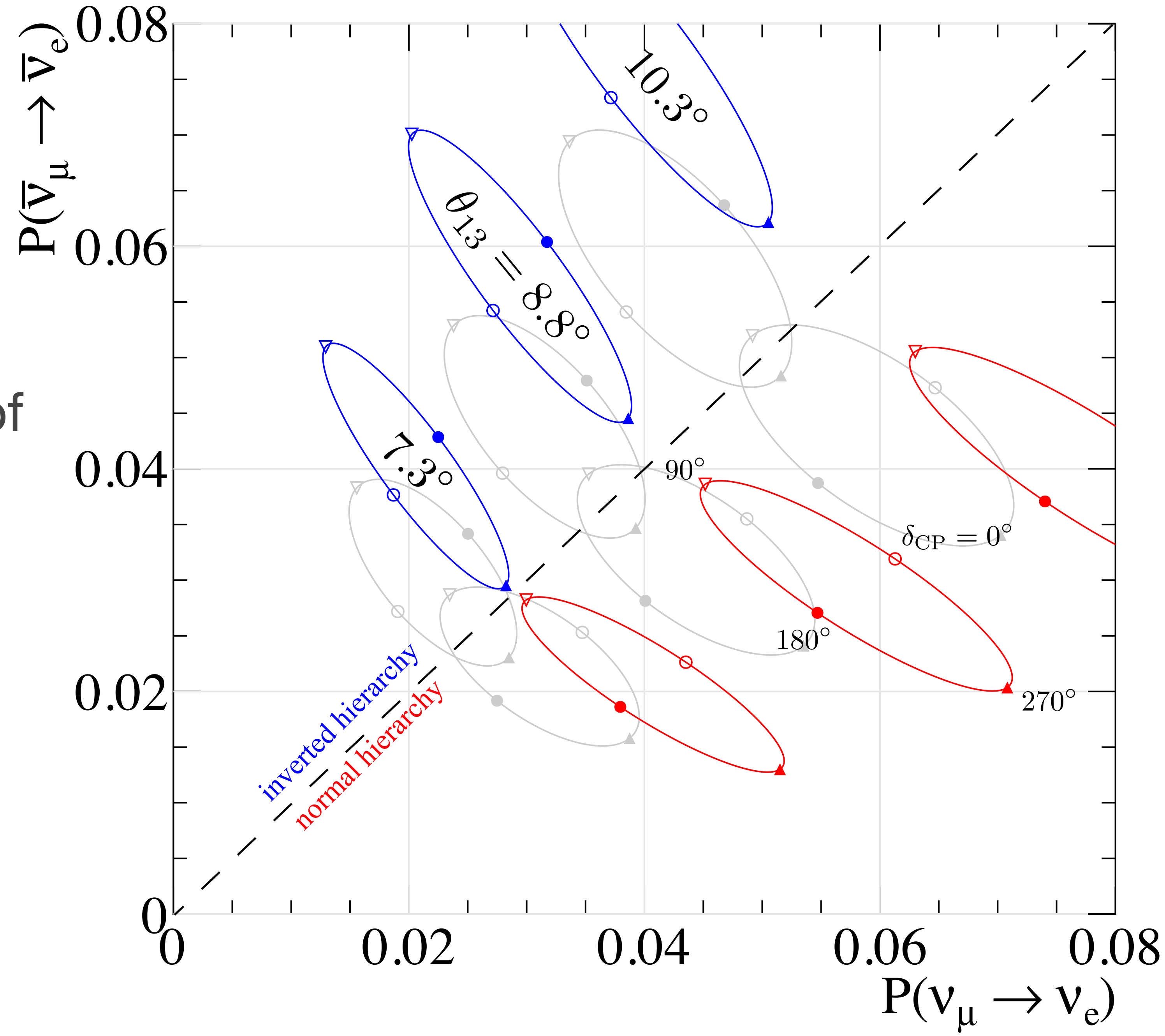
$$\frac{J_{\mathrm{PMNS}}}{J_{\mathrm{CKM}}} = \frac{3 \times 10^{-2}}{3 \times 10^{-5}} \sin(\delta_{\mathrm{PMNS}})$$

Leptonic CPV can be 1000x larger than in quark sector!

Going beyond NOvA: LBNE

LBNE will continue the NOvA oscillation program with the goal of several key enhancements:

- Larger, more efficient detector based on liquid argon TPC technology
- Beam line capable of 2.3 MW beam intensity
- Longer baseline (1300 km vs. 810 km) which helps resolve parameter ambiguities



- Wide-band beam to study oscillation probability over variety of neutrino energies
- Underground detector to enhance non-accelerator physics program; proton decay, atmospheric neutrinos, super-nova neutrinos.

The LBNE collaboration

Alabama
Argonne
Boston
Brookhaven
Cambridge
Catania
Columbia
Chicago
Colorado
Colorado State
Columbia
Dakota State
Davis
Drexel
Duke
Duluth
Fermilab
Hawaii
Indian Group
Indiana
Iowa State
Irvine
Kansas State
Kavli/IPMU-Tokyo
Lawrence Berkeley NL
Livermore NL
London UCL
Los Alamos NL
Louisiana State
Maryland
Michigan State
Minnesota
MIT

372 collaborators, 62 institutions, 5 countries

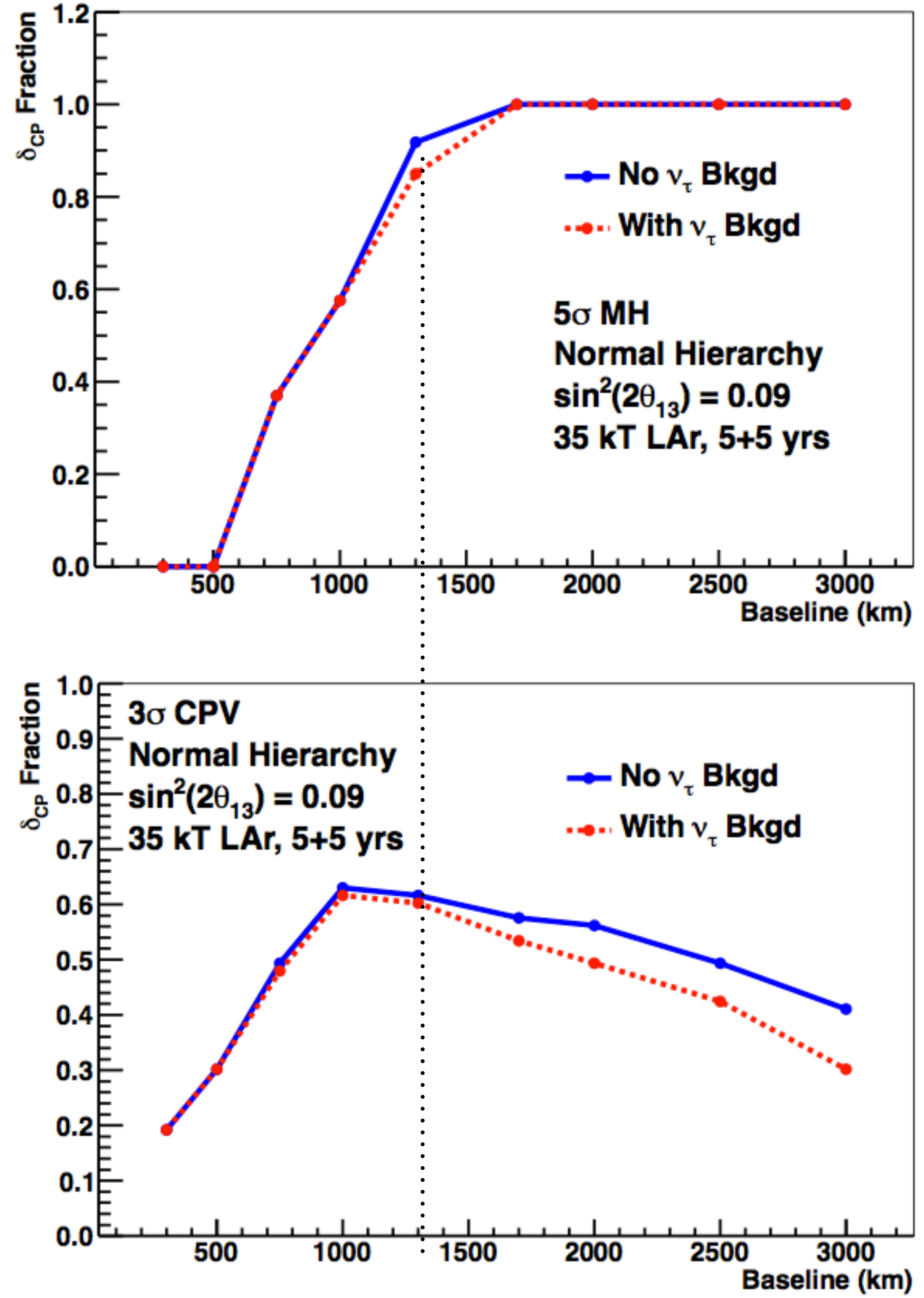
NGA
New Mexico
Northwestern
Notre Dame
Oxford
Pennsylvania
Pittsburgh
Princeton
Rensselaer
Rochester
Sanford Lab
Sheffield
SLAC
South Carolina
South Dakota
South Dakota State
SDSMT
Southern Methodist
Sussex
Syracuse
Tennessee
Texas, Arlington
Texas, Austin
Tufts
UCLA
Virginia Tech
Washington
William and Mary
Wisconsin
Yale

Optimization of baseline

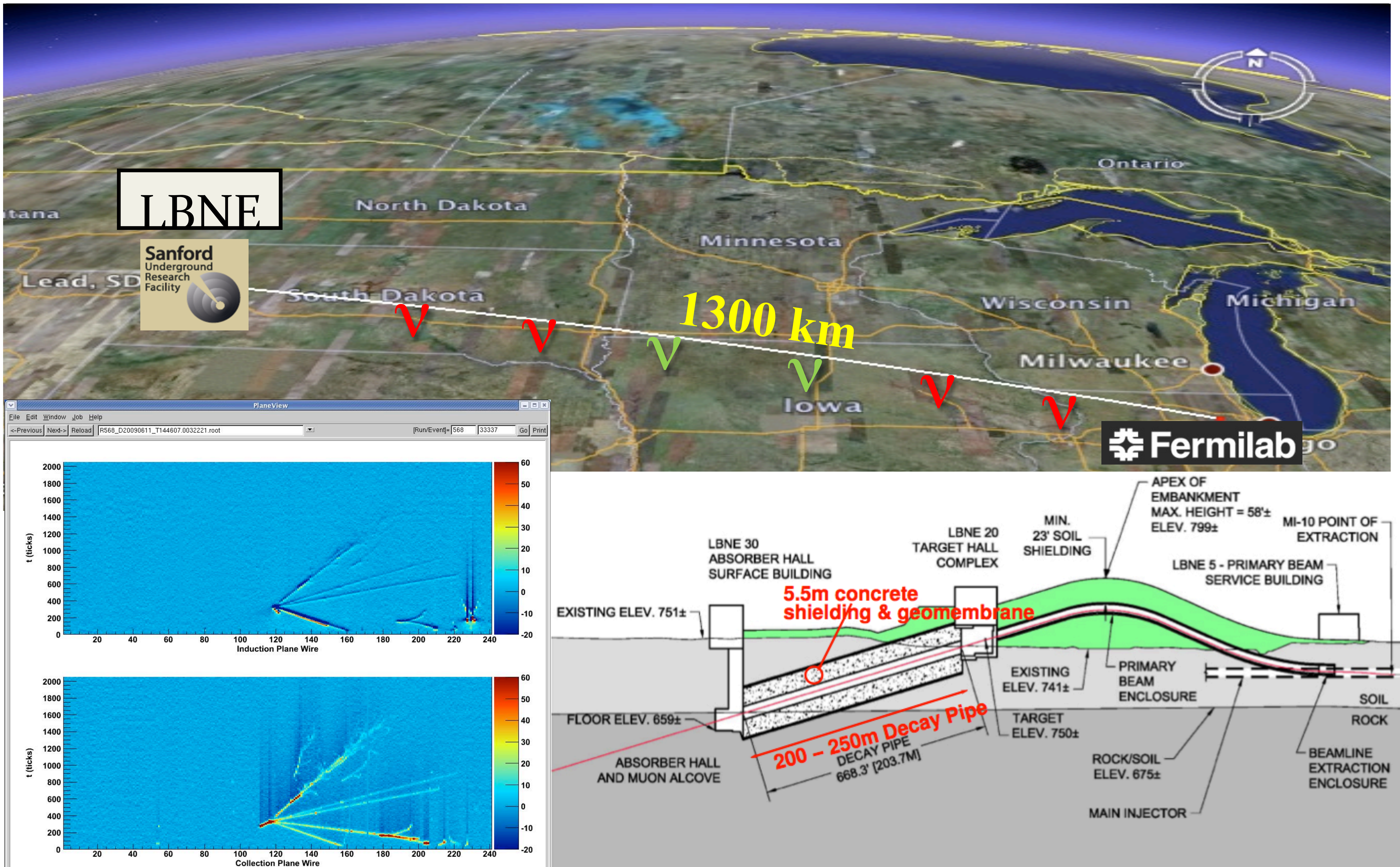
Hierarchy sensitivity
prefers baseline>1600 km

CPV sensitivity
prefers baseline=1000 km

1300 km baseline is close to optimum for both measurements and conveniently, there is an underground laboratory at that baseline



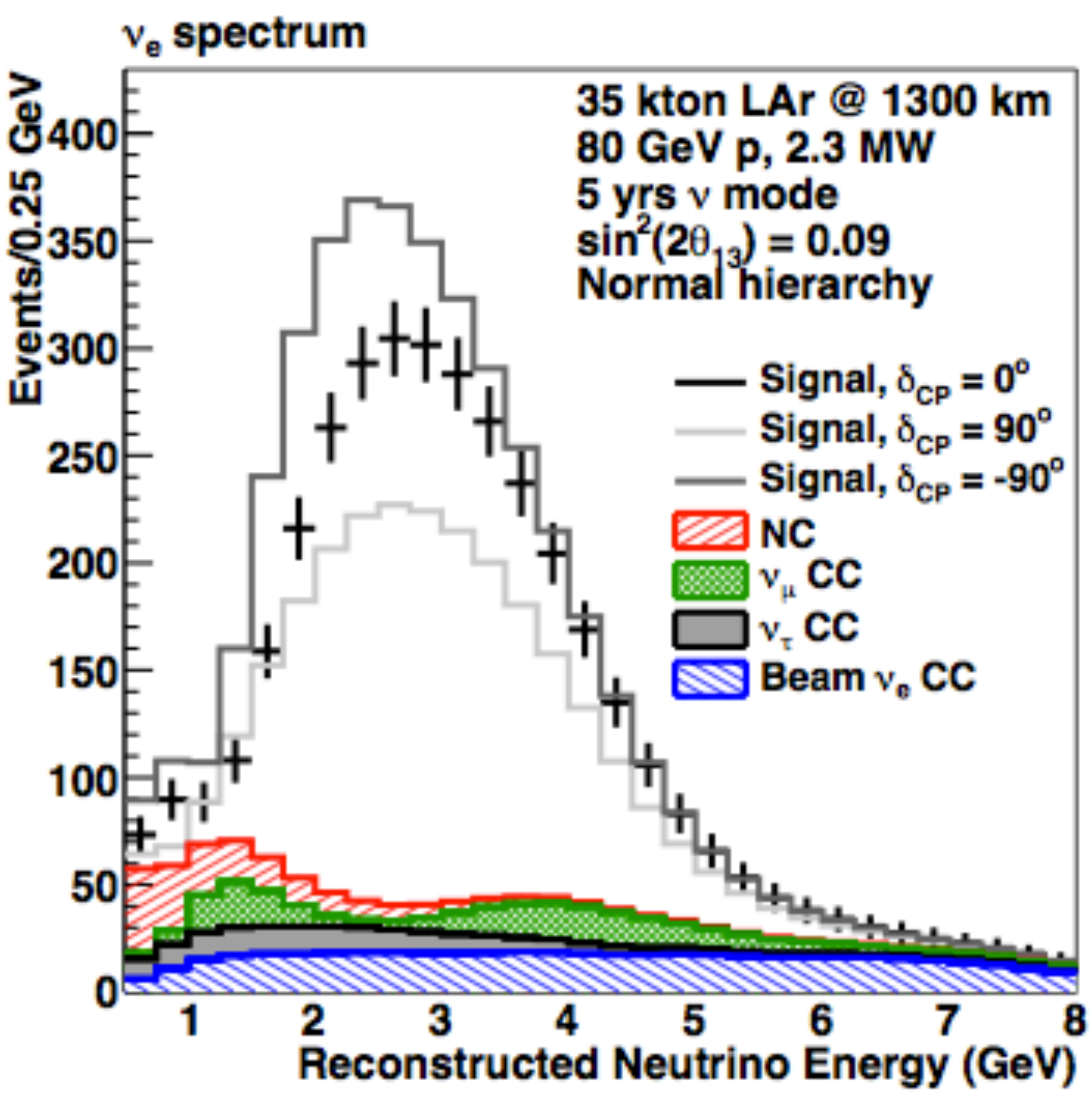
LBNE experiment

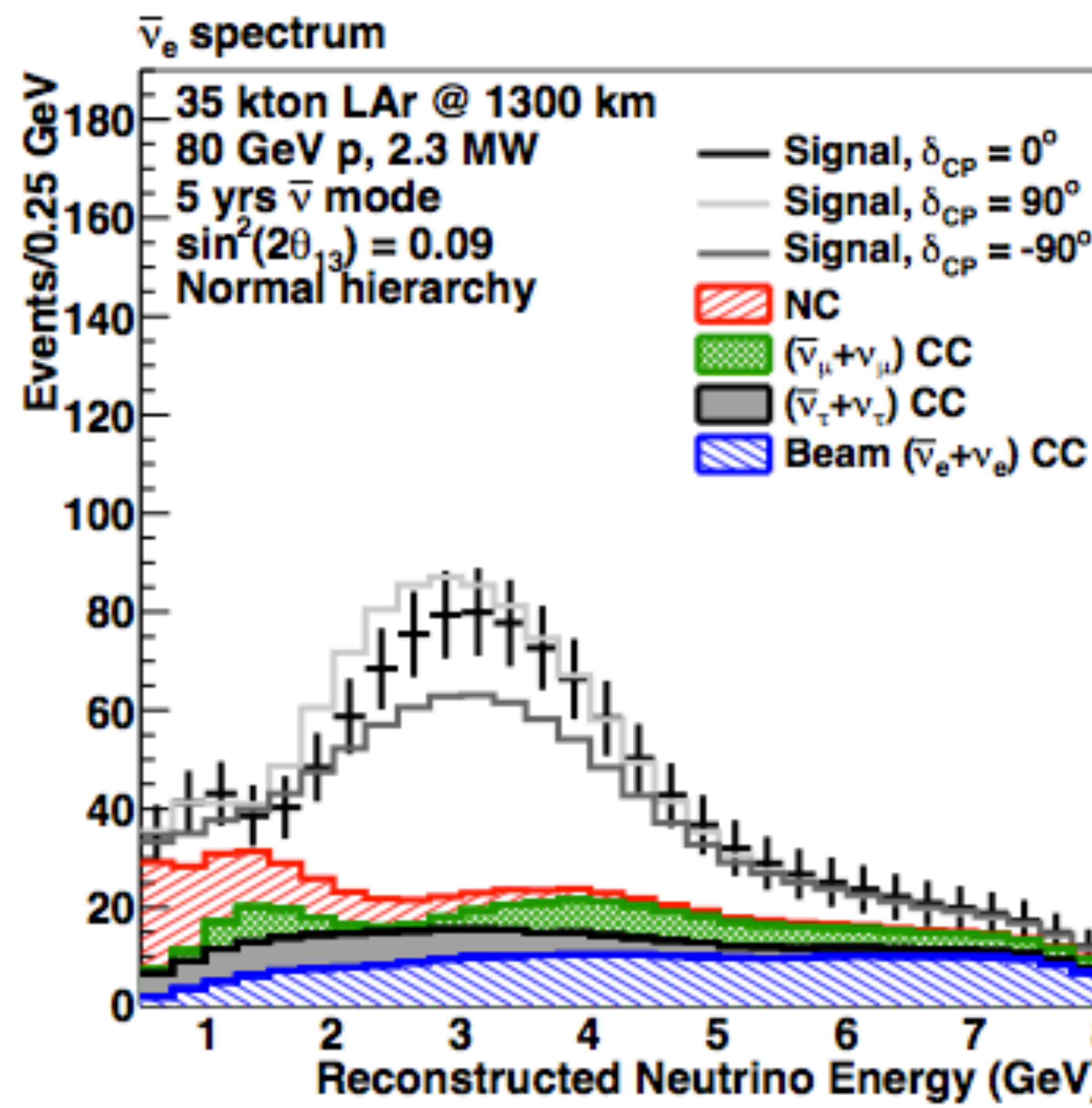


LBNE: Fully realized configuration

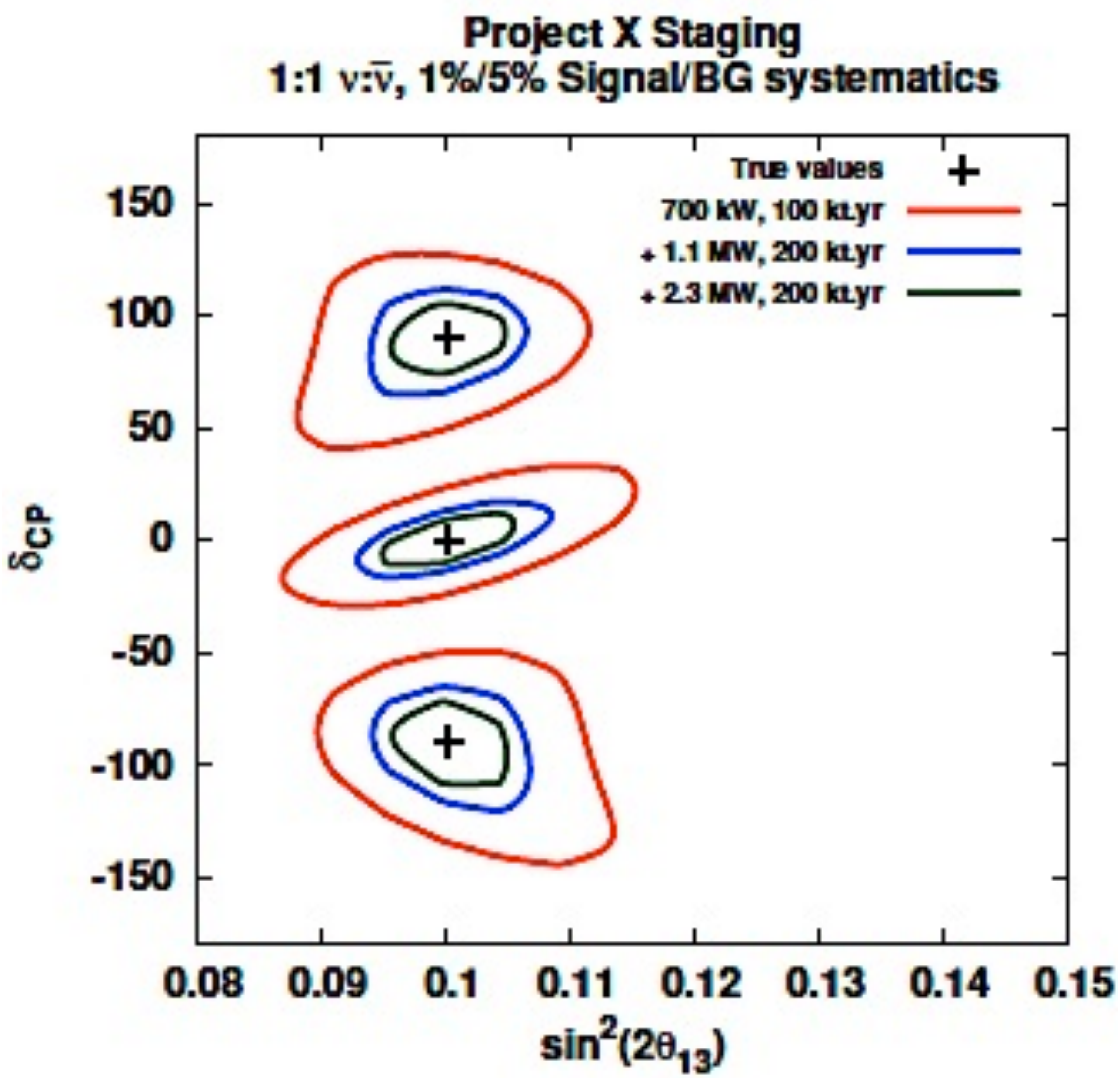
- New neutrino beam from Fermilab to Homestake mine. Originally to be operated at 700 kW with proton energies between 60 and 120 GeV. Built to be capable of future 2.3 MW operation.
- A near neutrino detector on the Fermilab site
- A 34 kt liquid argon TPC underground at the Homestake mine, L=1300 km, 4850’ (1480 m) overburden.
- This configuration was highly recommended by the U.S. high energy physics strategic planning committee (“P5”)
- Conceptual design was subject to a highly detailed cost and schedule review
- Using U.S. accounting, including contingency, and escalation, this configuration was estimated to have a total project cost of $1.5B

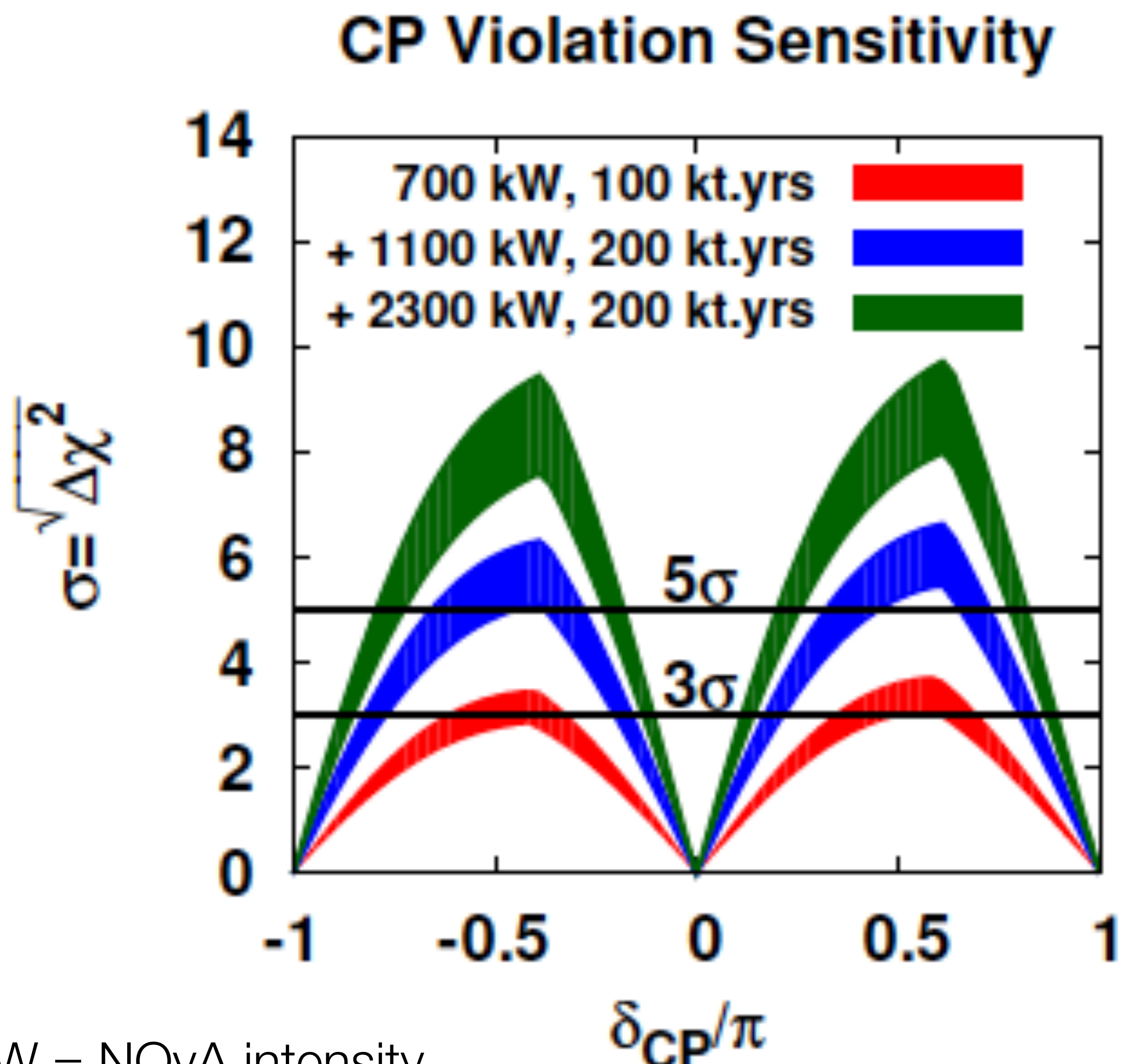
Neutrino spectra for a fully realized LBNE





LBNE CPV reach

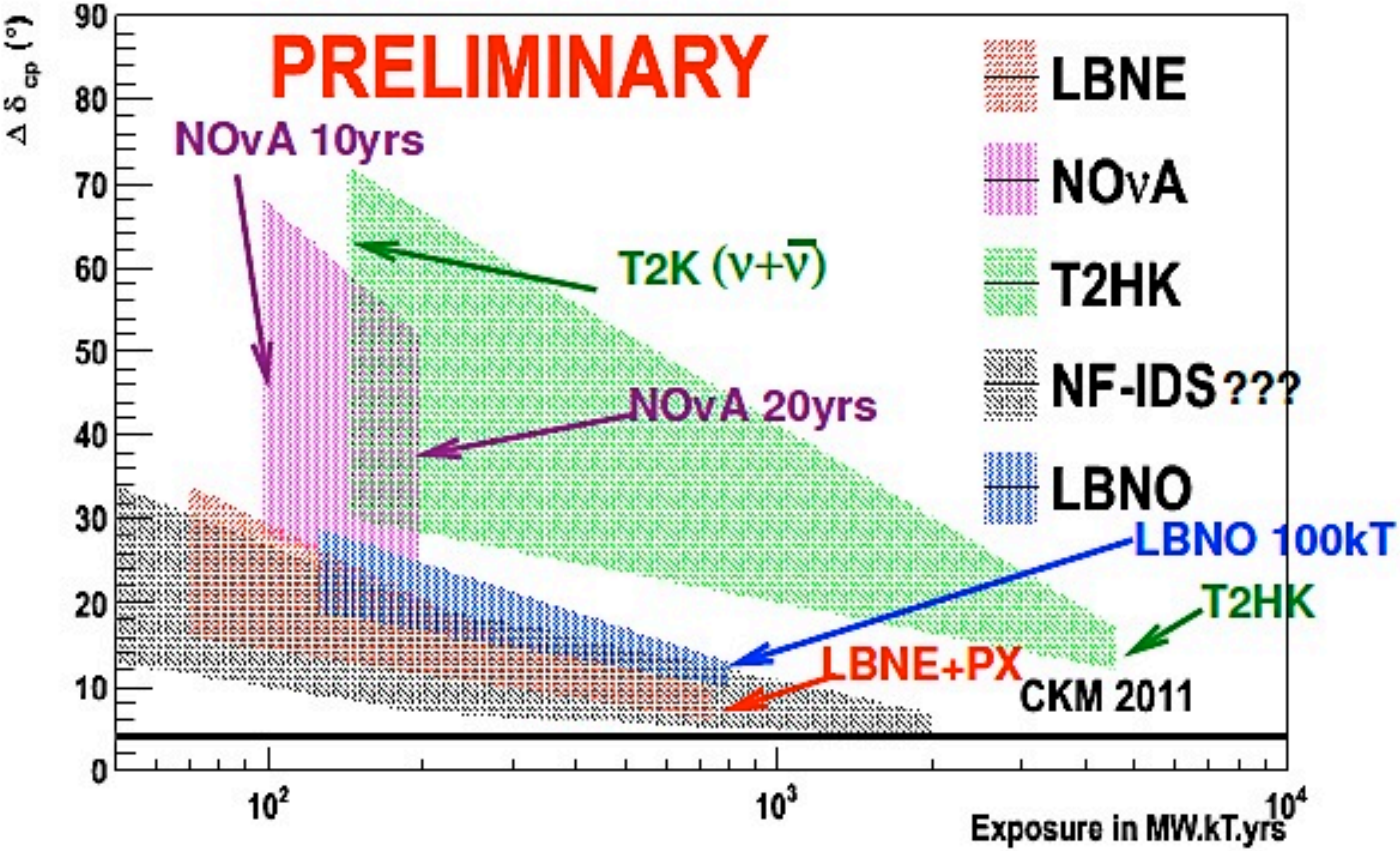




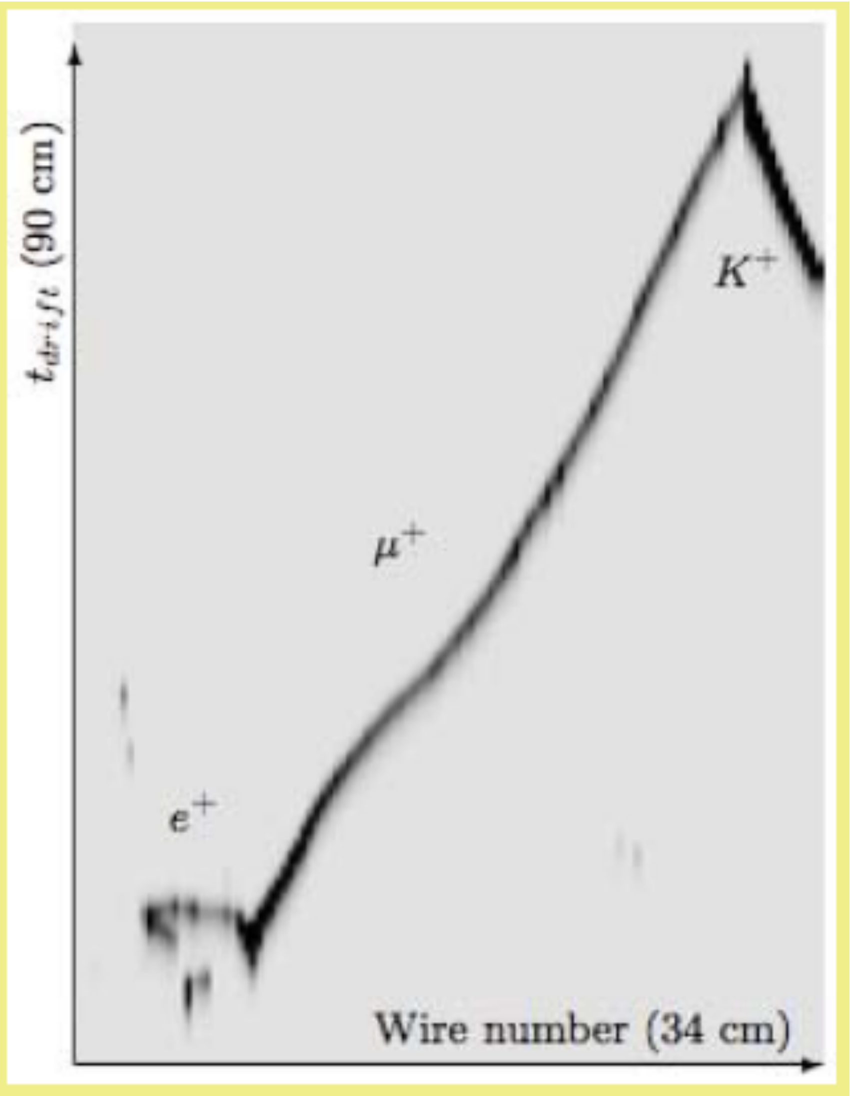
100 kt-yrs = 10 kt x 10 years
200 kt-yrs = 34 kt x 6 years

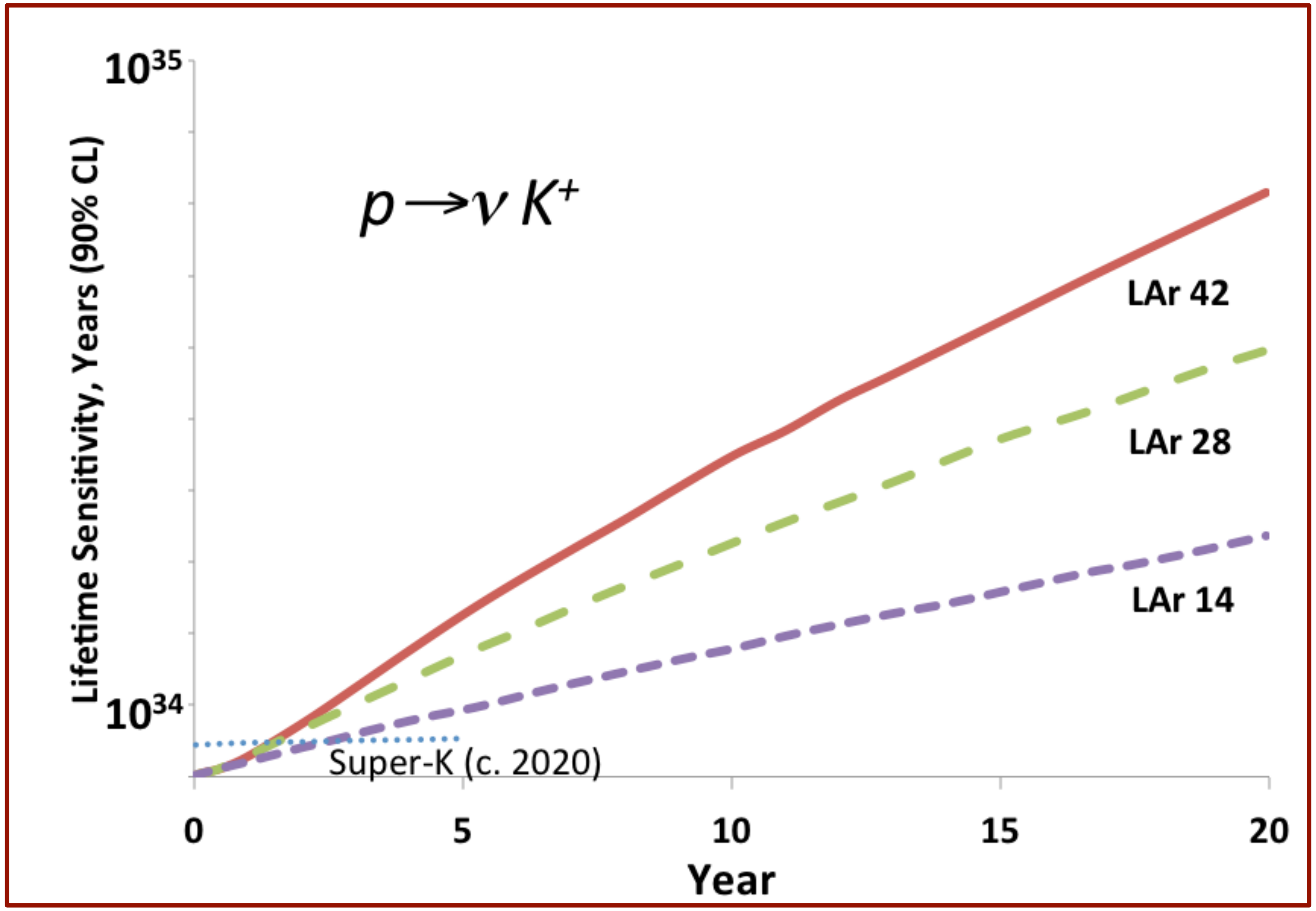
700 kW = NOvA intensity
1100 kW = Project X proton source, early phase
2300 kW = Project X proton source, final phase

Can we measure δ_{PMNS} as well as δ_{CKM}?

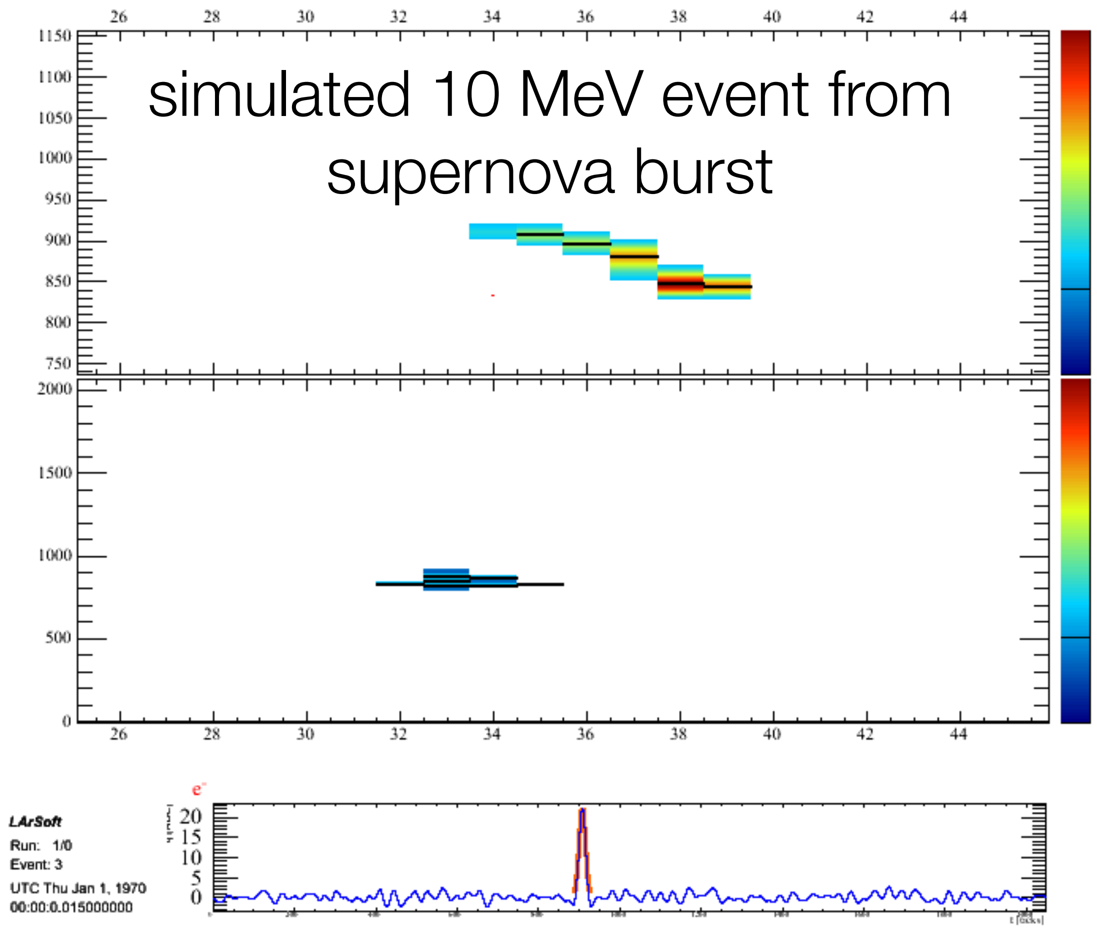


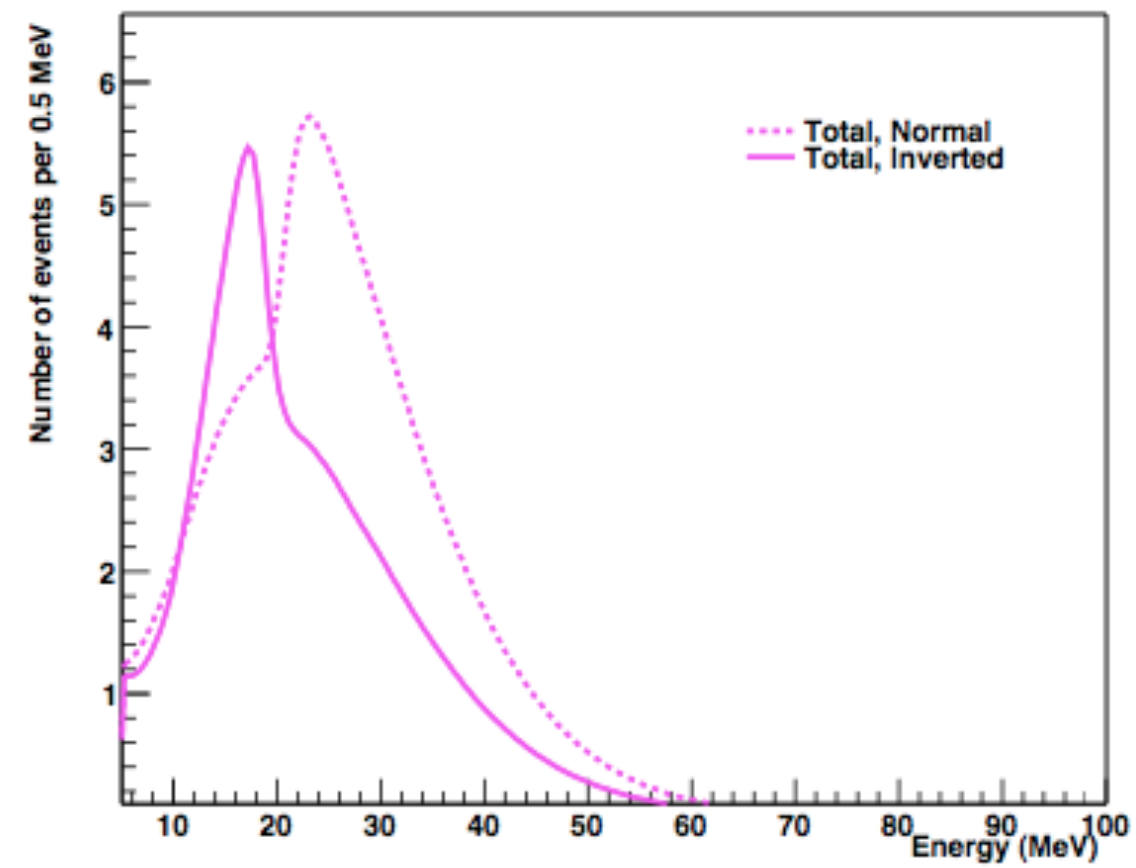
Proton decay





Supernova burst detection





Channel	Events, "Livermore" model	Events, "GKVM" model
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	2308	2848
$\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	194	134
$\nu_x + e^- \rightarrow \nu_x + e^-$	296	178
Total	2798	3160

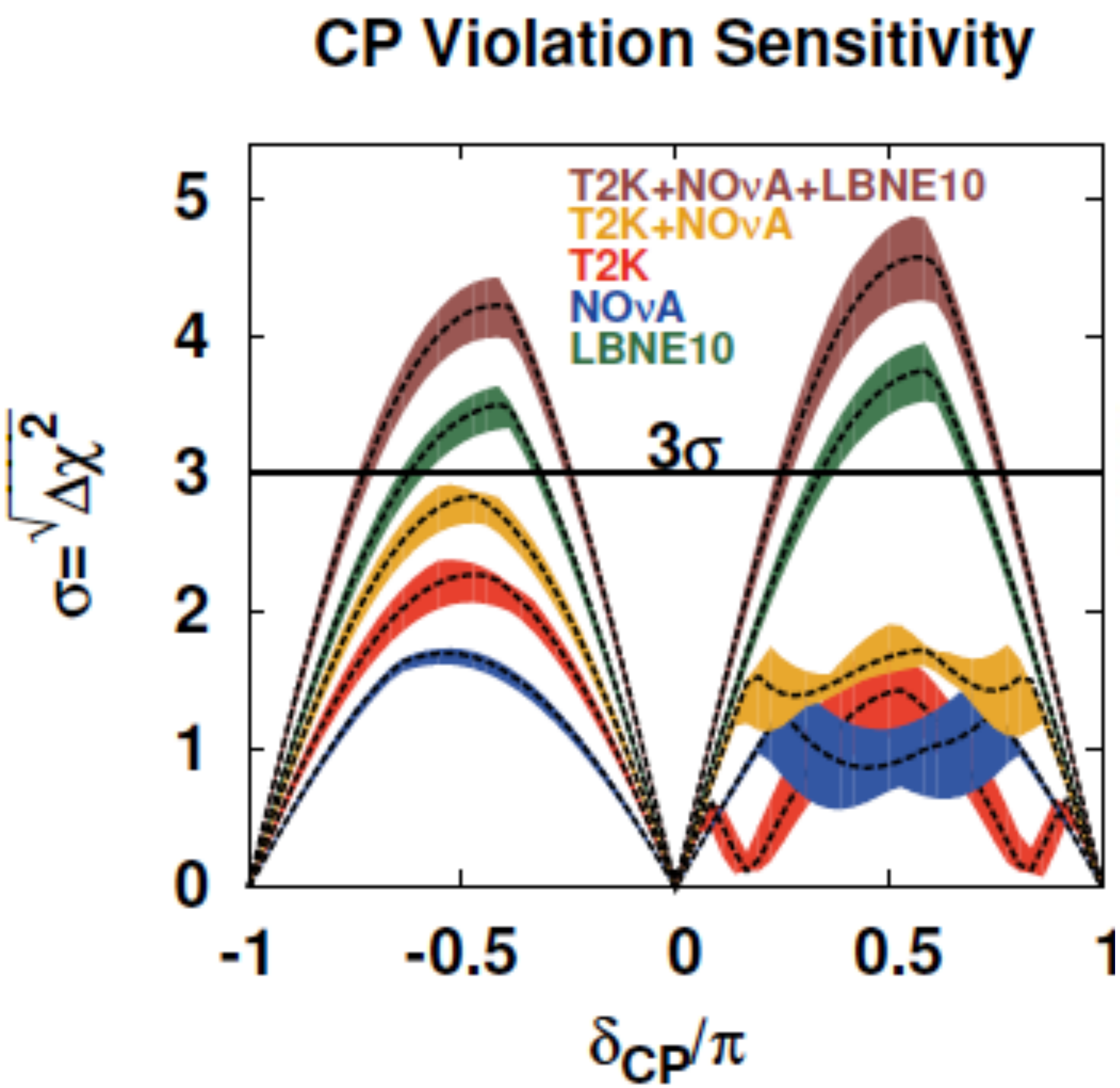
34 kt

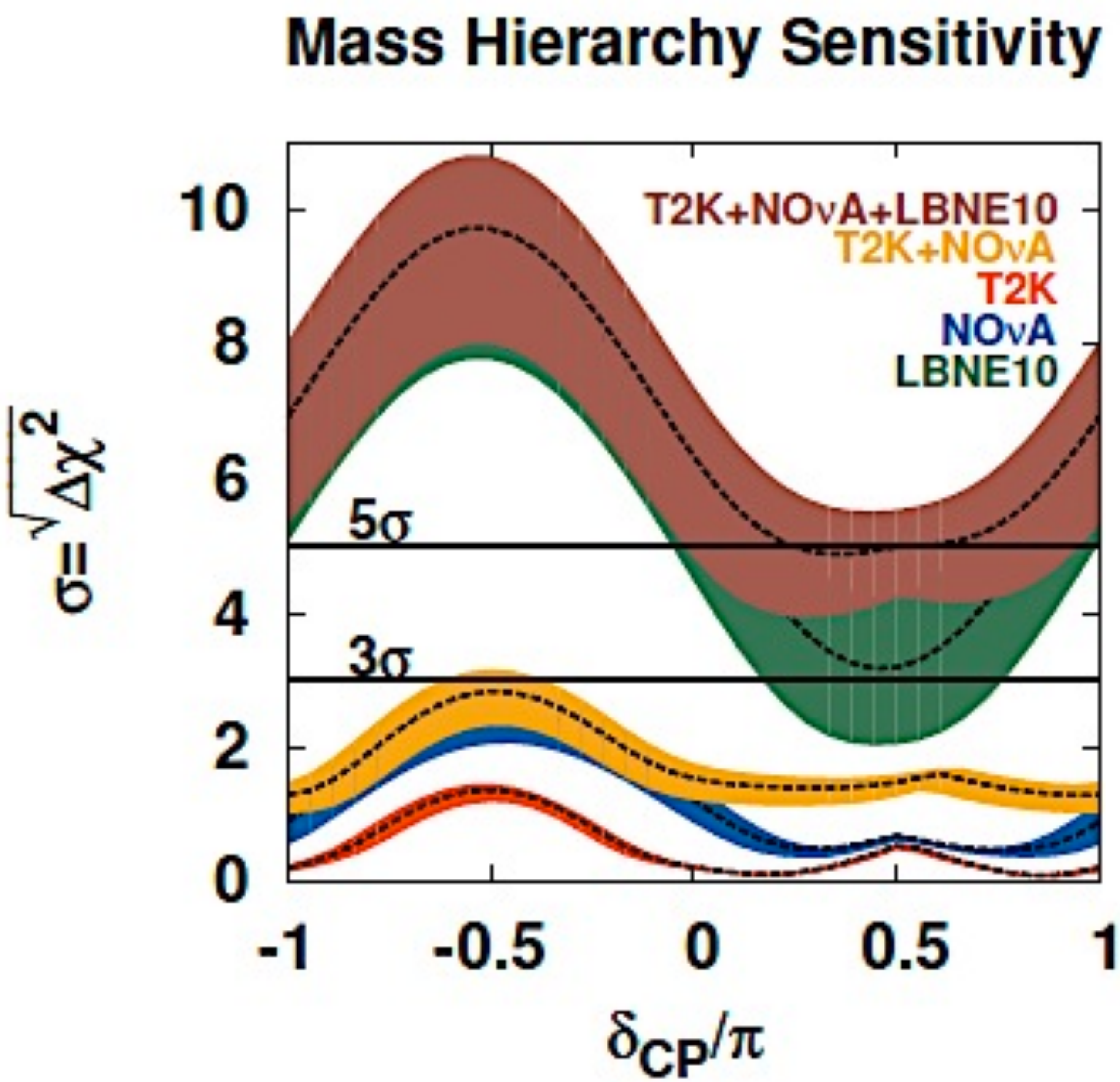
10 kpc

LBNE reconfiguration: “LBNE 10”

- In light of estimated cost of fully-scoped LBNE, the Department of Energy asked that the experiment be broken into stages with each stage <$1B and maximizing the physics reach at each stage.
- An independent committee was formed to consider the options and recommended that a first stage consisting of the
    - 2.3 MW-capable beam line pointed to Homestake, initially to be operated at 700 kW
    - 10 kt liquid argon detector on the surface at Homestake
    - Option does not have near detector.
- This configuration has passed its conceptual design review with a project cost of $867M

Physics reach of “LBNE10”





Recovering scope of LBNE

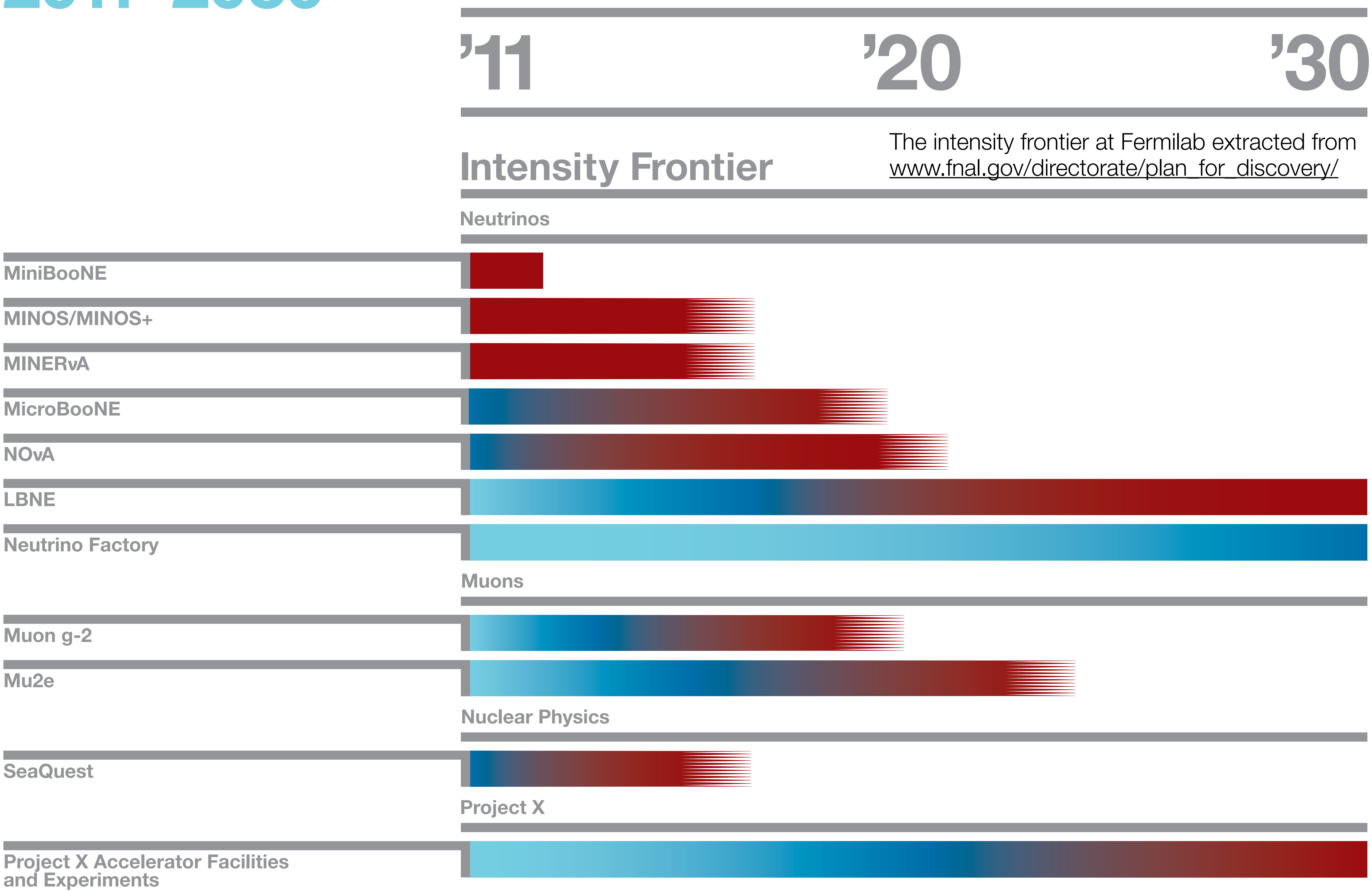
Additional Investment (TPC)	Capability Added	Science Gained	Science Priority
+ $140M *	Underground placement	ATM nus, p-decay, SNB nus	Very High
+ $130-190	Near Detector	Enhanced LB physics, near detector physics	Very High
+ $200-350	Add FD mass (>30 kt)	Precision CP and other 3-flavor paradigm measurements; p-decay	Very High

* Project, with collaboration support, has decided to pursue geo-technical studies of *underground* site and not surface location accepting risk that the studies would need to be done should an underground detector not prove possible.

Opportunities for Discovery 2011–2030

Legend

- R&D
- Construction
- Operation



The intensity frontier at Fermilab extracted from www.fnal.gov/directorate/plan_for_discovery/

Neutrino oscillations

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

$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2\ [\mathrm{eV}^2]\frac{L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]}\right)$$

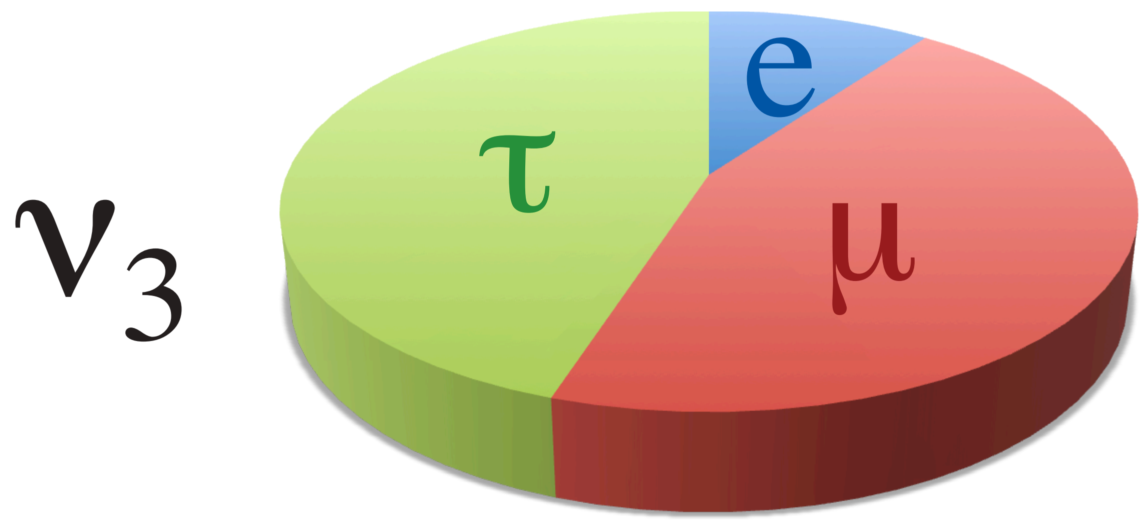
$\lvert\Delta m^2_{32}\rvert \equiv \lvert m_3^2 - m_2^2\rvert$ $\simeq 2\times 10^{-3}\ \mathrm{eV}^2$	$\Delta m^2_{31} \simeq \Delta m^2_{32}$	$\Delta m^2_{21} \simeq 8\times 10^{-5}\ \mathrm{eV}^2$
$\nu_\mu \longrightarrow \nu_\mu$ $\nu_\mu \longrightarrow \nu_\tau$	$\nu_e \longrightarrow \nu_e$ $\nu_\mu \longrightarrow \nu_e$	$\nu_e \longrightarrow \nu_e$ $\nu_e \longrightarrow \nu_\mu + \nu_\tau$
atmospheric and long baseline	reactor and long baseline	solar and reactor
$\theta_{23} \simeq 45^\circ$	$\theta_{13} = 9^\circ$	$\theta_{12} \simeq 35^\circ$

$\theta_{23} = 45^\circ, > 45^\circ, < 45^\circ$

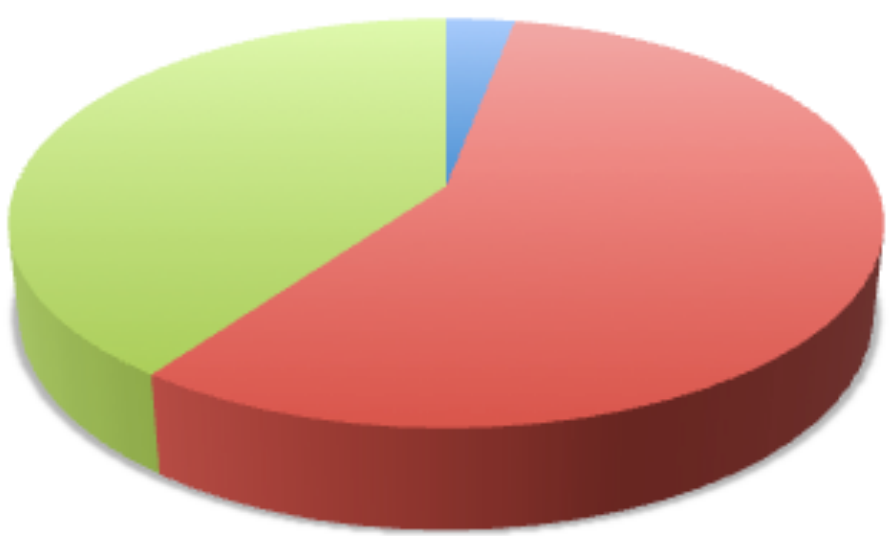
$\delta = ?$

$\mathrm{sgn}(\Delta m^2_{31})?$

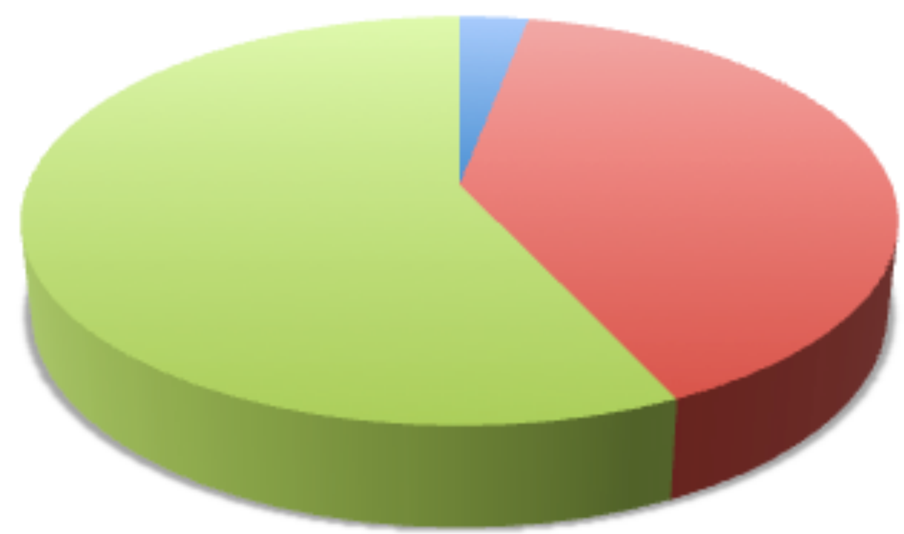
θ_{23} octant: The nature of ν_3



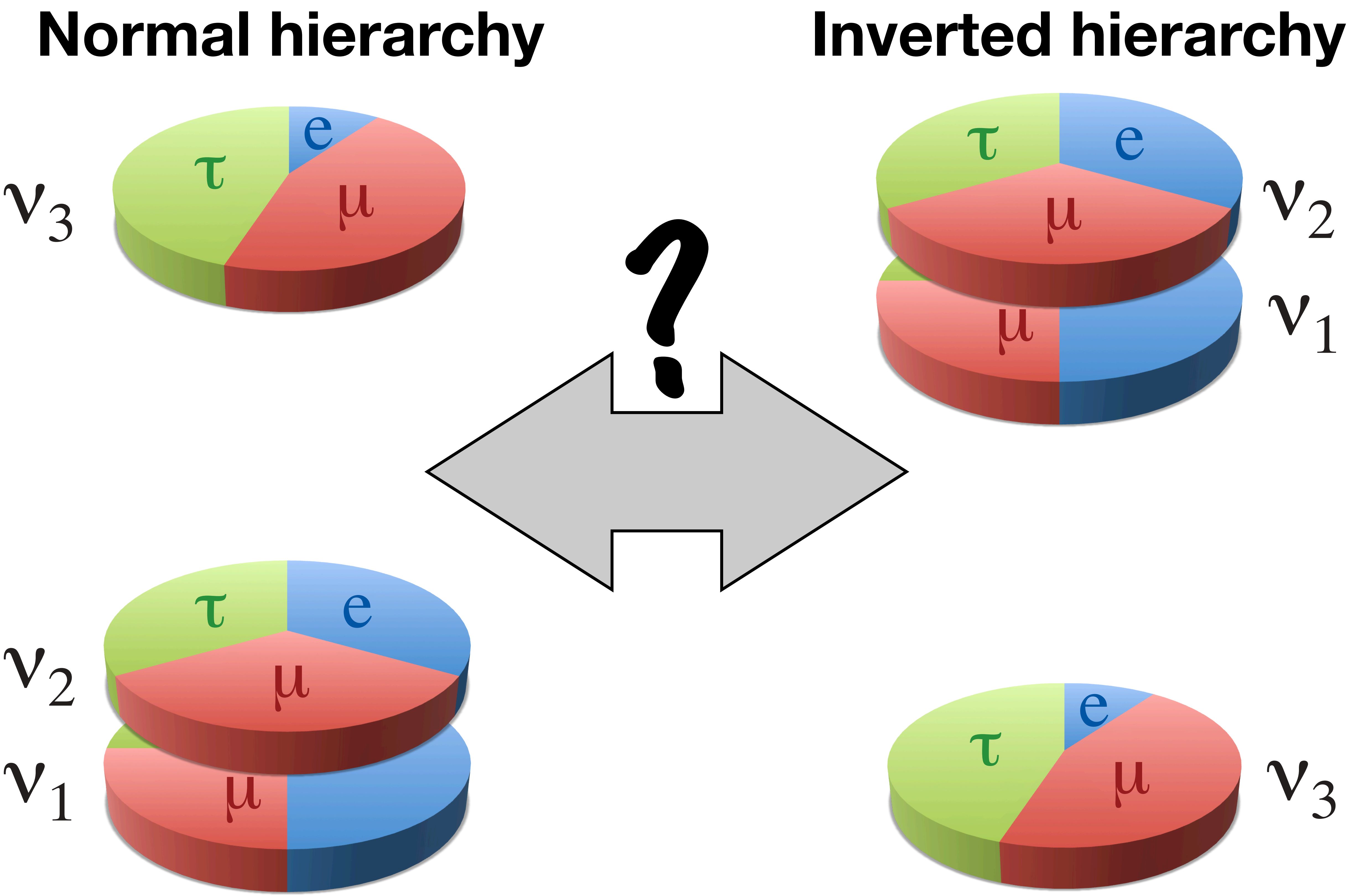
$\theta_{23} = 45^\circ$



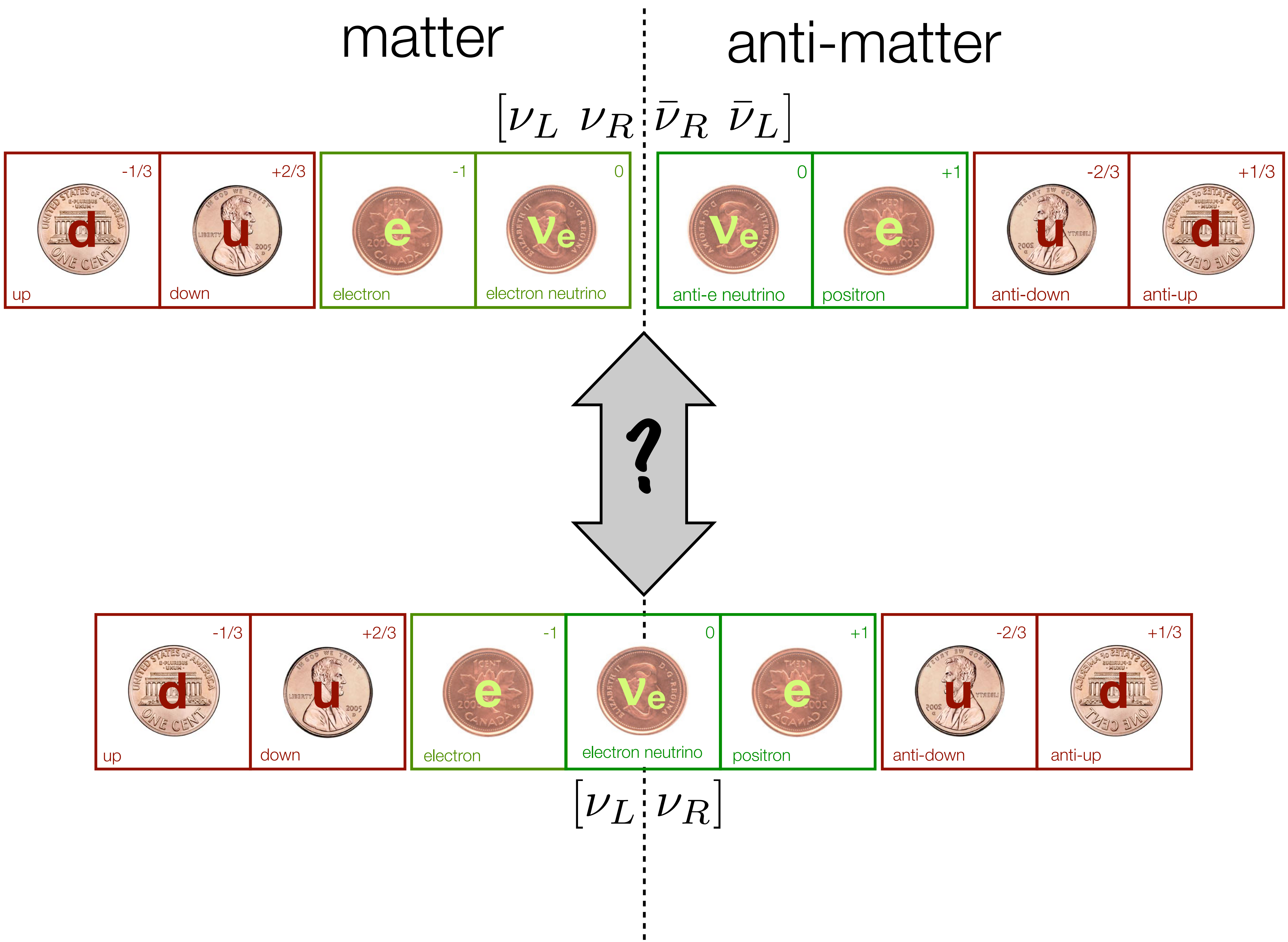
$\theta_{23} = 40^\circ$



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


Normal hierarchy
Inverted hierarchy
ν3
e
τ
μ
ν2
ν1
?
ν3

Is the Neutrino a Majorana or Dirac Particle?



Neutrino-less double beta decay