

Neutrino detectors Status and prospects

2nd World Summit on Exploring the Dark Side of the Universe
25-29 June 2018
Guadeloupe islands

Mark Messier
Indiana University

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TOKYO, JAPAN, June 3 -- In what colleagues hailed as a historic landmark, 128 physicists from 22 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, as it turns out was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to adjust the paradigm that a significant portion of the mass of the universe might lie in the form of neutrinos. The discovery will also compel scientists to refine a highly successful theory of the composition of matter known as the Standard Model.

Word of the discovery had drawn some 200 physicists here to discuss neutrino research. Among other things, the finding of neutrino mass might affect theories about the mass and evolution of galaxies and the ultimate fate of the universe. If neutrinos have substantial mass, their presence throughout the universe would increase the overall mass of the universe, possibly driving its present expansion.

Others said the newly detected but yet unconfirmed mass of the neutrino must be too small to cause cosmological effects. But whatever the case, there was general agreement here that the discovery will have far-reaching consequences for the investigation of the nature of matter.

Speaking for the collaboration of scientists who discovered the mass of neutrinos using a huge underground detector called Super-Kamiokande, Dr. Takaaki Kajita of the Institute for Cosmic Ray Research of Tokyo University said that all explanations for the data collected by the detector except the existence of neutrino mass had been eliminated yesterday.

After Dr. Kajita's remarks, the powerful audience he presented cheered prolonged applause from an audience of physicists from dozens of countries who packed the conference hall here.

Dr. Yoji Totsuka, leader of the committee and director of the Kavli Institute for Particle Astrophysics where the underground detector is situated, 30 miles north of here in the Japanese Alps, acknowledged that his group's announcement was "very strong," but said, "We have investigated all other possible causes of the effects we have measured and only neutrino mass remains."

Dr. John N. Bahcall, a leading neu-

tron researcher

Continued on Page A10

Banks Give Jakarta Longer Time to Pay \$80 Billion in Debt

By MICHAEL NEIBURG

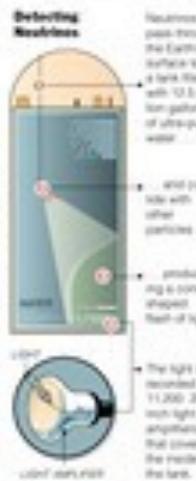
JAKARTA, Indonesia, June 4 -- Indonesia and a group of foreign bankers agreed today on a framework for reworking the repayment of nearly \$80 billion in corporate and bank debt, which constitutes one of the biggest burdens on restructuring the economy.

While the agreement is simply a framework for renegotiating the debt on a case-by-case basis, the unexpectedly quick action by 13 foreign banks meeting with Indonesian officials in Jakarta gives Indonesia the best economic news it has received in months.

It is also a boon to the new government of President B. J. Habibie, who is struggling to assert his legitimacy in the face of calls for an early election.

The agreement provides for a three-year suspension of principal payments on perhaps \$60 billion of debt. It also sets up a government debt agency to facilitate negotiations in corporate-debt cases.

In individual cases, borrowers and



OKLAHOMA BLAST BRINGS LIFE TERM FOR TERRY NICHOLS

ENEMY OF CONSTITUTION: Judge Denounces Conspiracy and Hears from the Victims of a Terrifying Ordeal

By ROB THOMAS

OKLAHOMA CITY, June 4 -- Calling him "an enemy of the Constitution," a Federal judge today sentenced Terry L. Nichols to life in prison without the possibility of parole for conspiring to bomb the Oklahoma City Federal Building, the deadliest terrorist attack ever on American soil.

In passing sentence after hearing from survivors of the blast and relatives of some of the 168 people who died in it, the judge, Richard P. March, of Federal District Court, said, "This was not a murder case."

He added, "It is a crime and the victims have spoken eloquently here. But it is not a crime as in there is much as it is a crime against the Constitution of the United States. That's the crime."

Last December, Mr. Nichols was convicted of conspiring with Timothy J. McVeigh to set a weapon of mass destruction in the April 19, 1995, bombing of the Alfred P. Murrah Federal Building, but was acquitted of federal murder charges in the deaths of eight Federal agents who died. Mr. Nichols was found guilty of involuntary manslaughter in those deaths and today was given the maximum sentence of 10 years in prison for each, to run consecutively with his life sentence. He was also acquitted of actually committing the bombing.

While the conspiracy charge can result in a death sentence, the jurors need to vote unanimously for such punishment, and they could not do so. The sentencing then fell to Judge March.

Mr. McVeigh was convicted on all counts in an earlier trial and was sentenced to death.

None of the jurors in the Nichols case and after the verdict that they believed that evidence of a wider conspiracy had not been presented.

In March, Judge March offered to consider some leniency if Mr. Nichols helped the Government learn

Continued on Page A10



JUSTICES REBUFF STARR'S REQUEST TO SPEED REVIEW

BORDERS WITH NO DISSENT: Court Denies an Early Hearing on Claims of Privilege for 4 in Inquiry on President

By LOUIS GREENBERG

WASHINGTON, June 4 -- The Supreme Court delivered a swift rebuff today to Kenneth W. Starr's effort to short circuit the ordinary appellate process and get a quick ruling from the Justices on disputed claims of privilege for four grand jury witnesses.

The Court said in two brief orders, issued without dissent, that it would not grant expedited hearings -- or indeed any hearings at all at this stage -- on the scope of the attorney-client privilege for White House lawyers or on the existence of a previously unrecognized "protective function privilege" for former Service agents.

Mr. Starr, the Whitewater independent counsel, is seeking testimony from Bruce Lindsey, the deputy White House counsel and former Presidential confidant, and from three former Service employees as part of his investigation into whether President Clinton had a sexual relationship with Monica S. Lewinsky, a former White House intern, and might have had sex with her as well.

"Everyone is being attacked from three sides," he said. "Only the best defense is a good offense."

Mr. Lewinsky is trying to crack the separation between him, a province in Serbia, where ethnic Albanians number 800,000, and ethnic Serbs, who number 1.5 million. The Serbs are aiming at stopping the flow of fighters and weapons from Albania by driving ethnic Albanian guerrillas out of the rebellion and villages on the border.

"It is estimated that the Court of Appeals will proceed expeditiously to decide this case," the Court said in each of its two one-paragraph orders.

While the appeals court could schedule arguments as early as next month, even such an accelerated schedule would effectively preclude the Justices, whose current term ends in a matter of weeks, from having a final say on the issue before the November Congressional elections.

Now that fact may affect Mr. Starr's case considerably, either by making an indictment of Ms. Lewinsky for perjury and other charges or by sending an impeachment report to the House of Representatives, as he himself is one of the impeachment trials this week, is the most obvious question raised by the developments today.

The independent counsel made no reference to his long-range strategy.

"It looks as if the Serbs are going

Continued on Page A10

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Refugees From Kosovo Cite A Bitter Choice: Flee or Die

By CHRISTOPHER HEDGES

PATRIARX, Albania, June 4 -- President Slobodan Milosevic of Yugoslavia has unleashed the longest military operation in the Balkans since the end of the war in Bosnia, driving thousands of ethnic Albanians from the border area with Albania and reducing their village to rubble.

At least 15,000 refugees have streamed through the mountain passes and thousands more are heading to forests on the other side of the border, according to United Nations officials, refugees and refugee organizations.

People are trying to hang on, desperately hoping that the world will intervene to save them," said Besim Aliti, 36, as he stood with some 20 people from his village who had been walking for two days. "We could not hold out any longer. There

are thousands more behind us. Once they realize there is no hope, they will follow."

"Everyone is being attacked from three sides," he said. "Only the best defense is a good offense."

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"It looks as if the Serbs are going

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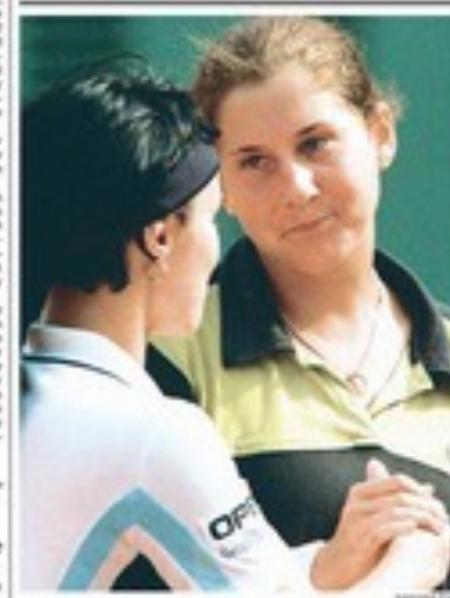
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Yankee Owner Warns Vallone On Referendum

By MICHAEL NEIBURG

OPENING DAY: Yankees owner George M. Steinbrenner, left, and Peter P. Vallone, the City Council speaker, announced their plan for a referendum on whether or not money should be used to help build a new ball park.

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Celebrating Day in Their Honor, Firefighters Brawl in Restaurant

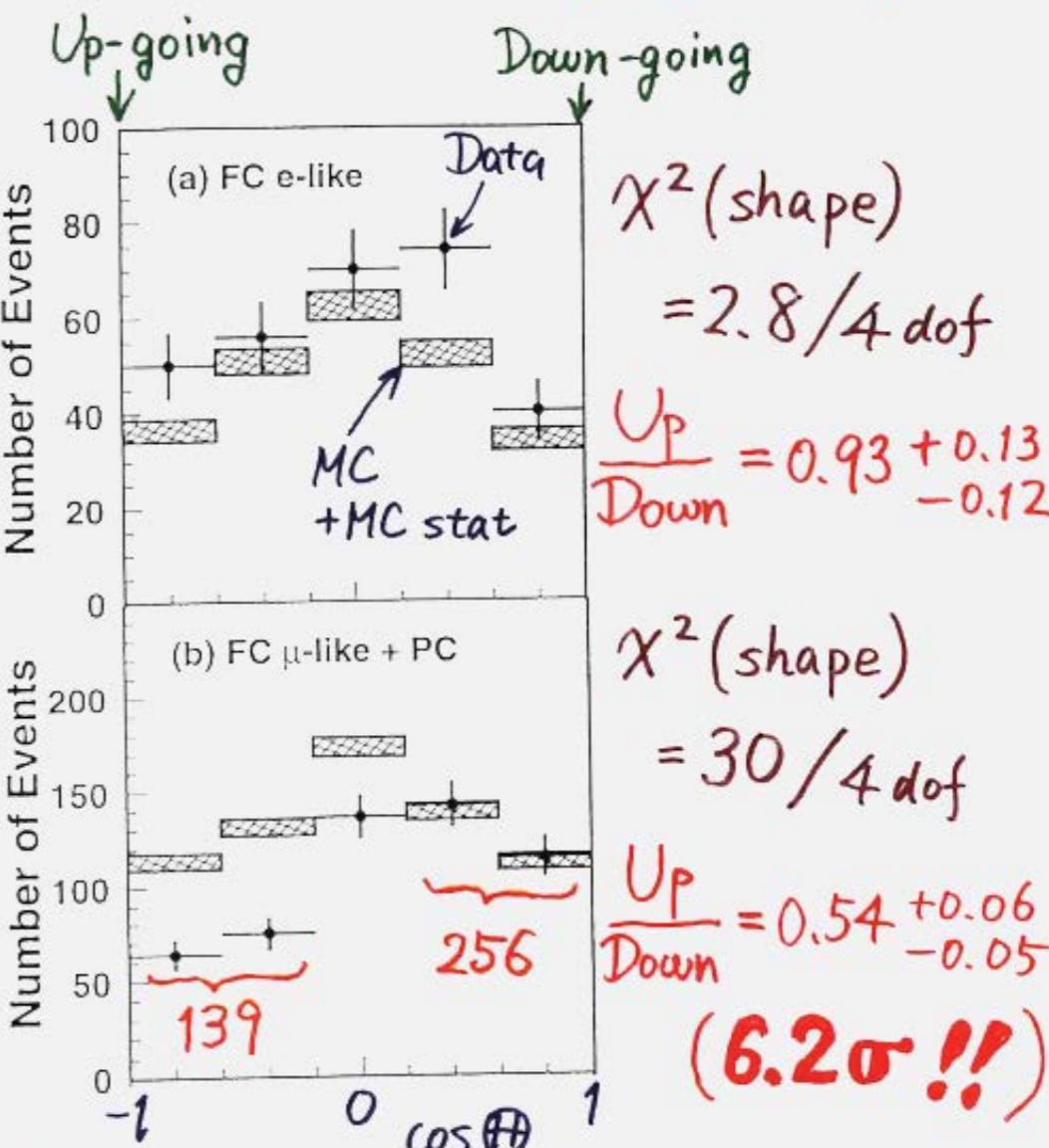
By ROBERT C. McFADDEN

A celebration of heroes at New York City Hall degenerated into a belligerent brawl at a restaurant last night as thousands of firefighters, unionized and unaffiliated, expressed themselves, ran through a window of windows and got into hand-to-hand fights with each other and anyone who tried to intervene, outraged city officials acknowledged yesterday.

It was the most serious breach of conduct by members of the city's uniformed services since 1986, when dozens of New York police officers went on a drunken rampage at several hotels in Washington, groping women, spitting fire extinguishers, running around half-nude and ending their so-called benders.

It also appeared to be one of the most embarrassing episodes in the

Zenith angle dependence (Multi-GeV)



* Up/Down syst. error for μ-like

Prediction (flux calculation ~1%
1km rock above SK 1.5%) 1.8%
Data (Energy calib. for ↑↓ 0.7%
Non ν Background < 2%) 2.1%

T. Kajita June 5th, at Neutrino 1998

NEUTRINO 2018

XXVIII INTERNATIONAL CONFERENCE ON NEUTRINO PHYSICS AND ASTROPHYSICS

4-9 June

Heidelberg

TOPICS

- Neutrino Oscillations and Mass Measurements
- Accelerator Neutrinos
- Reactor Neutrinos
- Solar Neutrinos
- Atmospheric Neutrinos
- Neutrinoless Double Beta Decay
- Leptonic CP-violation
- Coherent Scattering
- Neutrino Interactions
- Sterile Neutrinos
- Connections to Dark Matter and BSM Physics
- Theory of Masses and Mixings
- Astrophysical Neutrinos
- Neutrino Cosmology
- Supernova Neutrinos
- Geoneutrinos
- Future Projects



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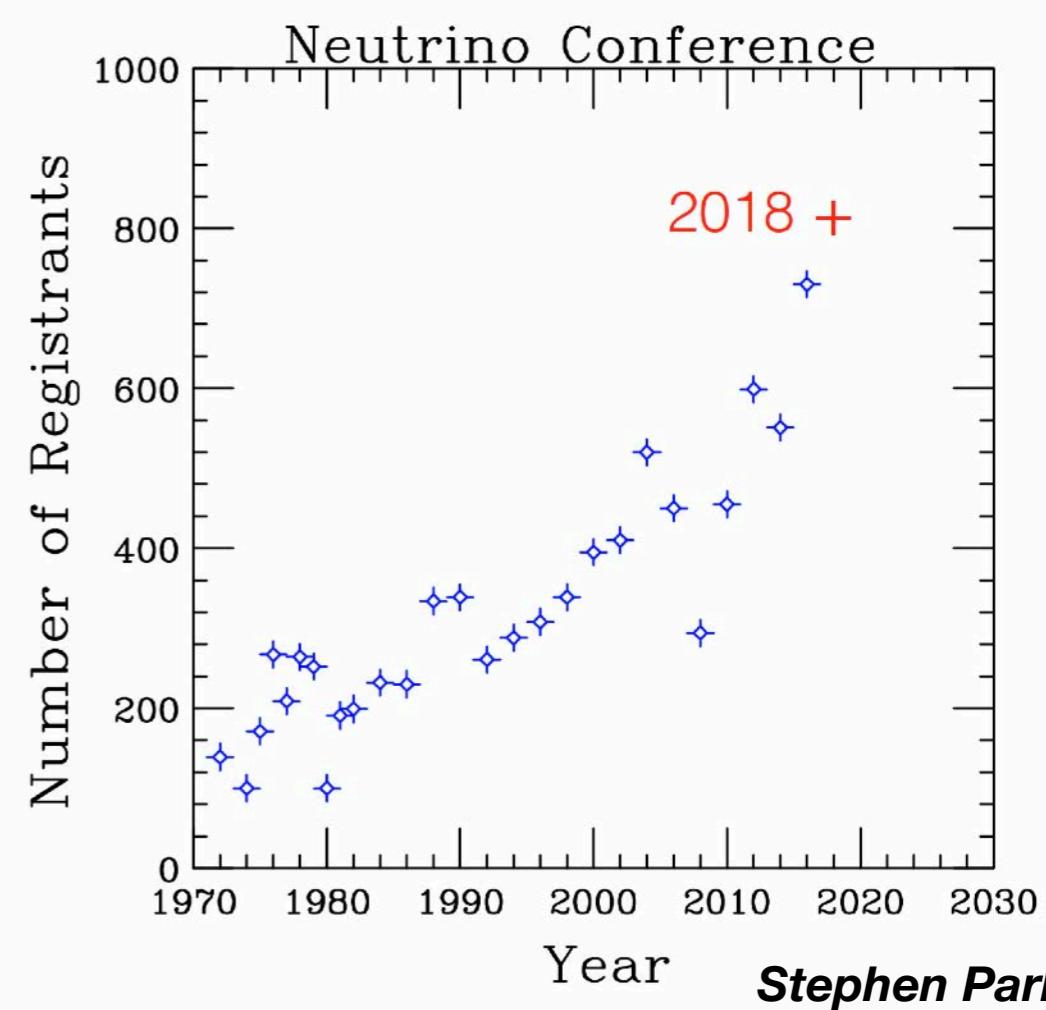
Scan to discover!



N: HELENA ALMAZÁN

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<https://www.mpi-hd.mpg.de/nu2018/>

My Questions

Do neutrinos have mass > 0.2 eV?

Are neutrinos Majorana or Dirac?

- Direct neutrino mass searches
- Searches for neutrino less double beta decay

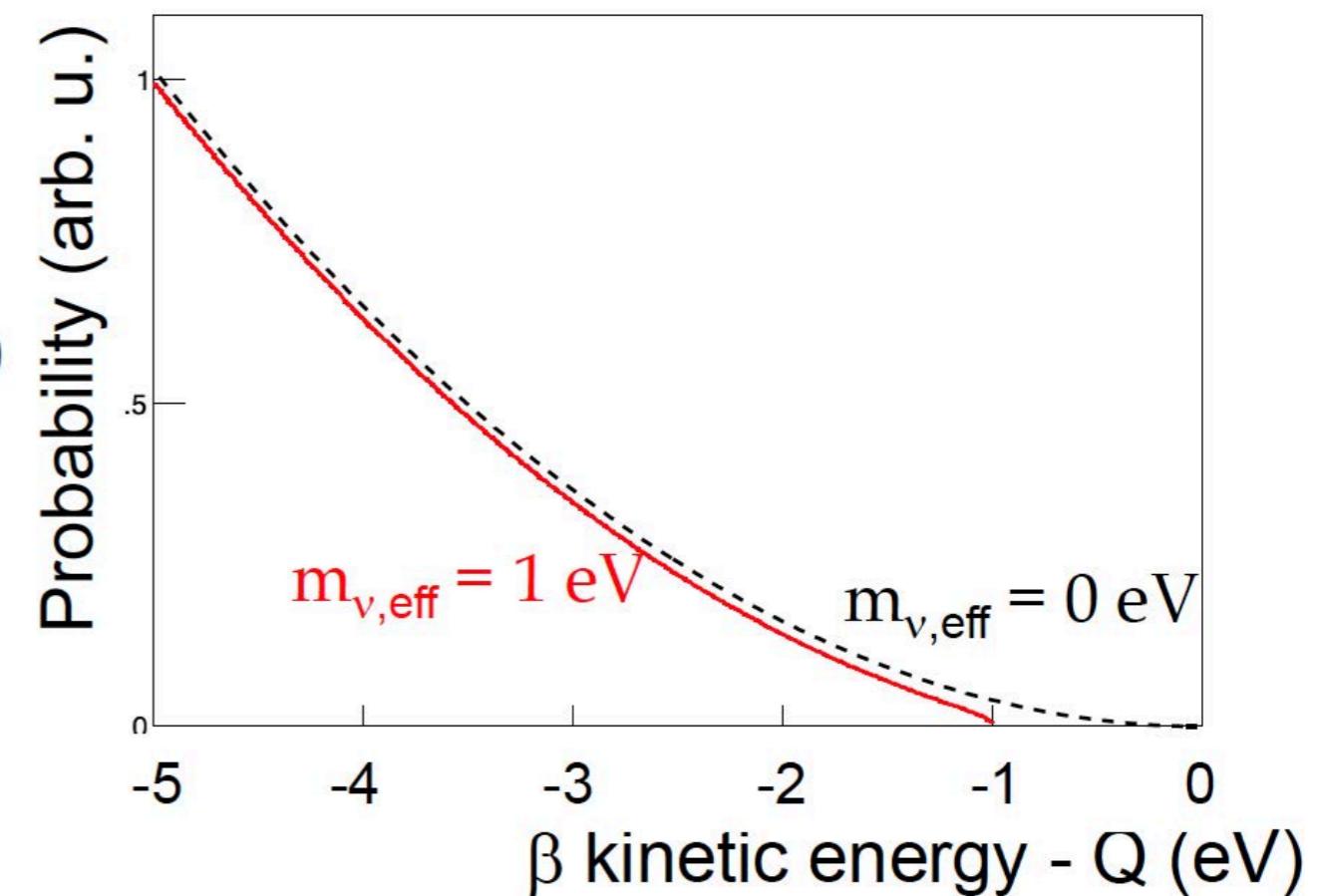
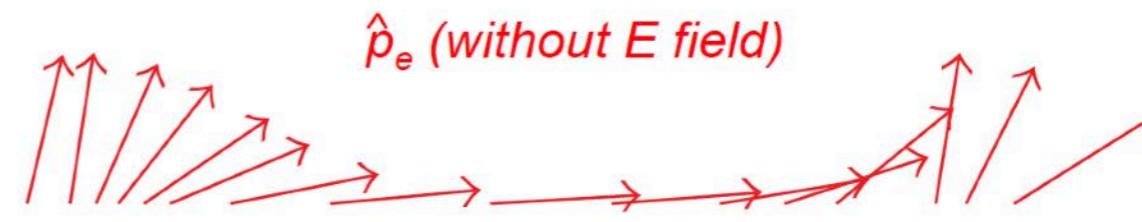
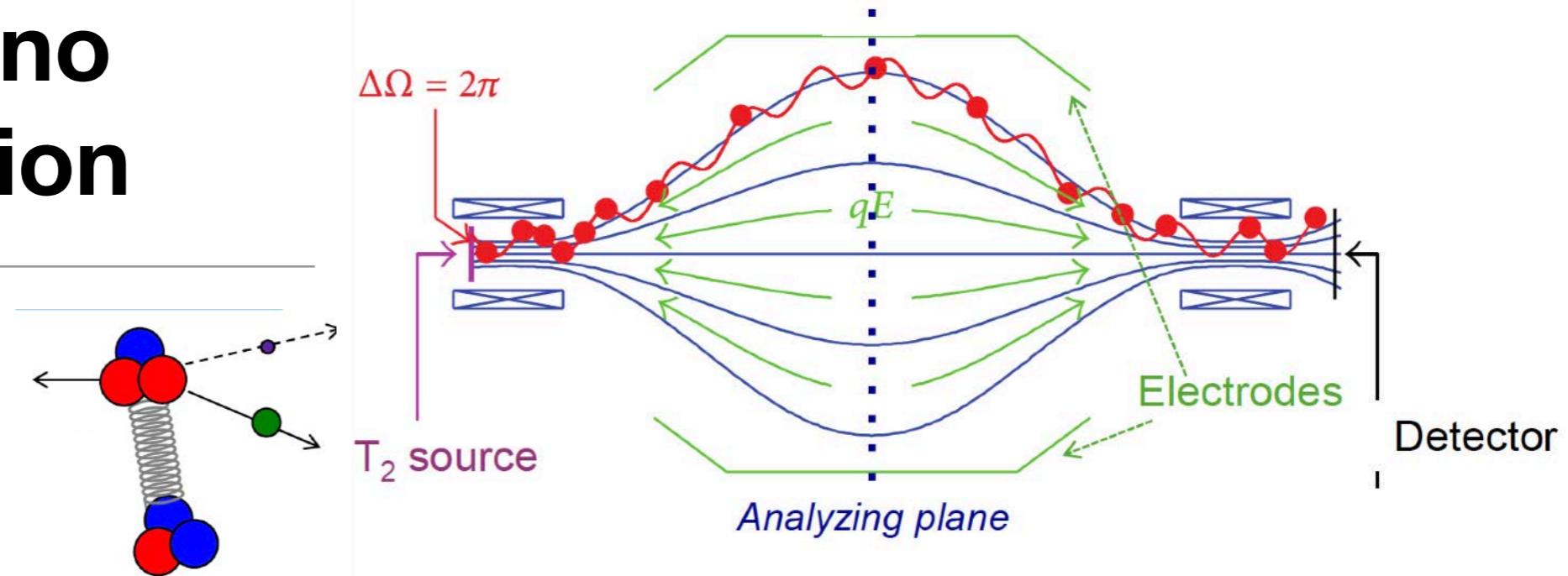
Prospects for measuring CPV in lepton sector

- Status of neutrino oscillation measurements including status of **searches for sterile neutrinos**

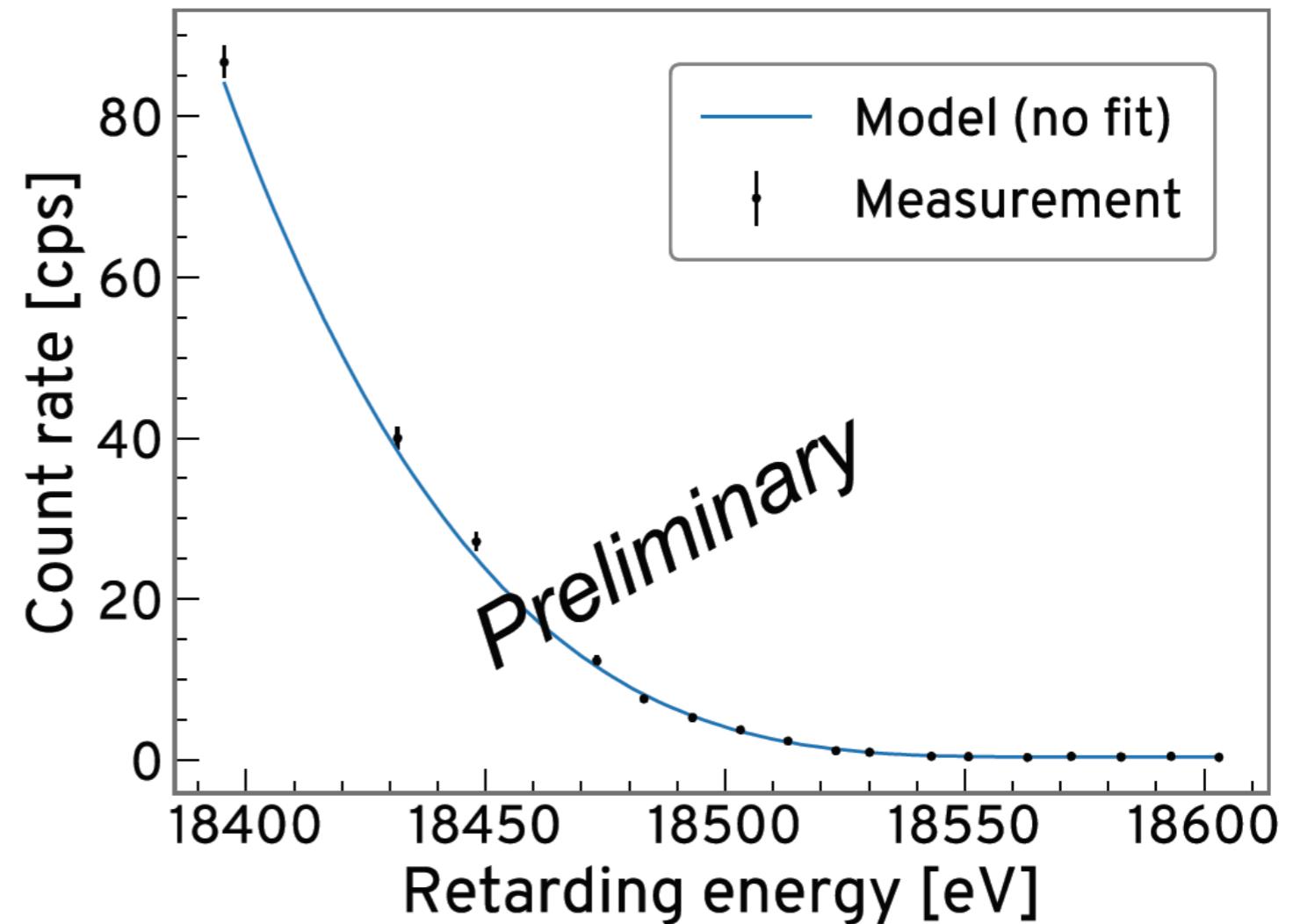
DIRECT DETECTION

Direct Neutrino Mass Detection

- To date best limits on neutrino mass come from the study of molecular tritium decay
- Beta spectrum analyzed using MAC-E filters (Magnetic Adiabatic Cooling and Electrostatic filter)
- Mainz:** $m(\nu_e) < 2.05 \text{ eV}$ (95% C.L.)
- Troitsk:** $m(\nu_e) < 2.3 \text{ eV}$ (95% C.L.)



KATRIN Experiment: First scans

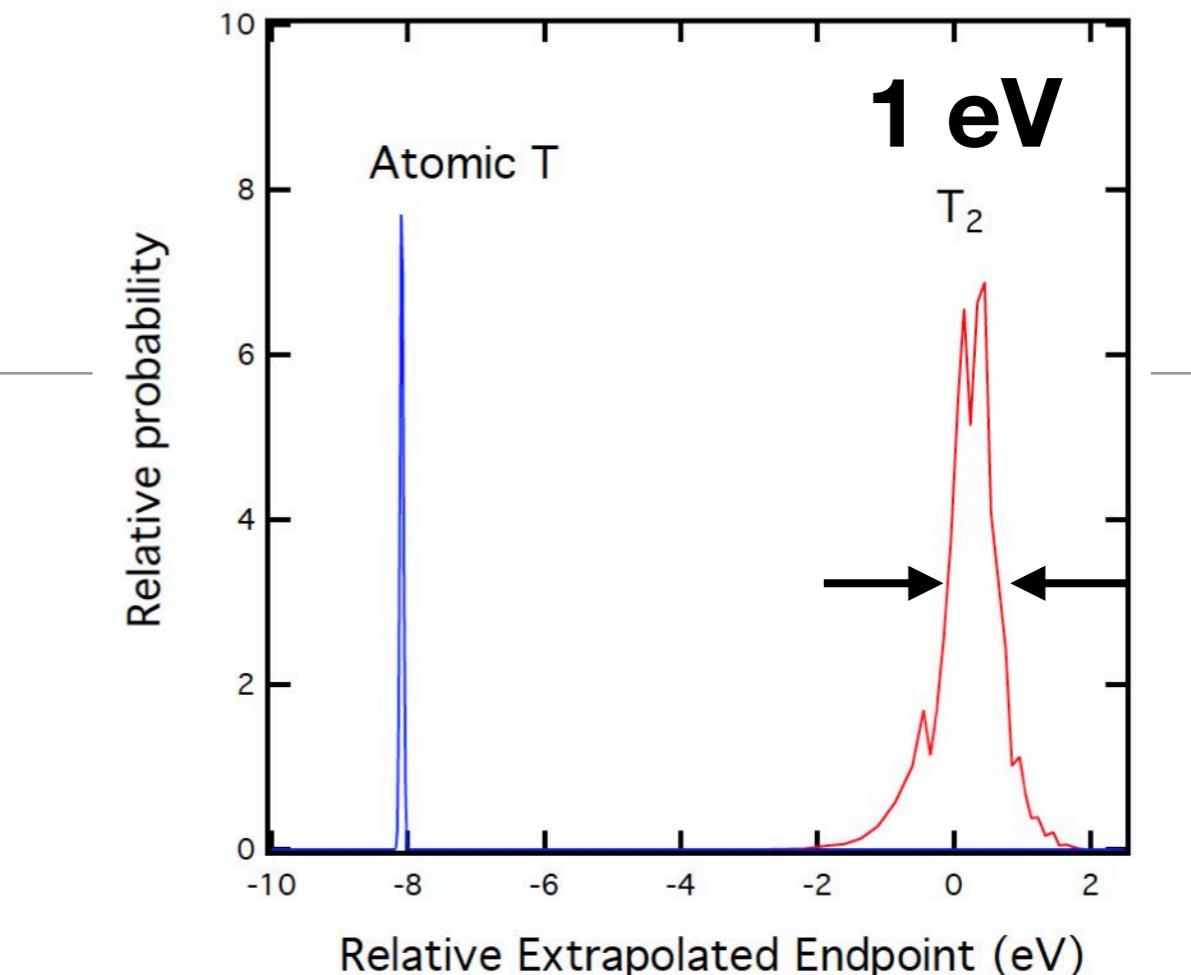


Expect first results in 2019.

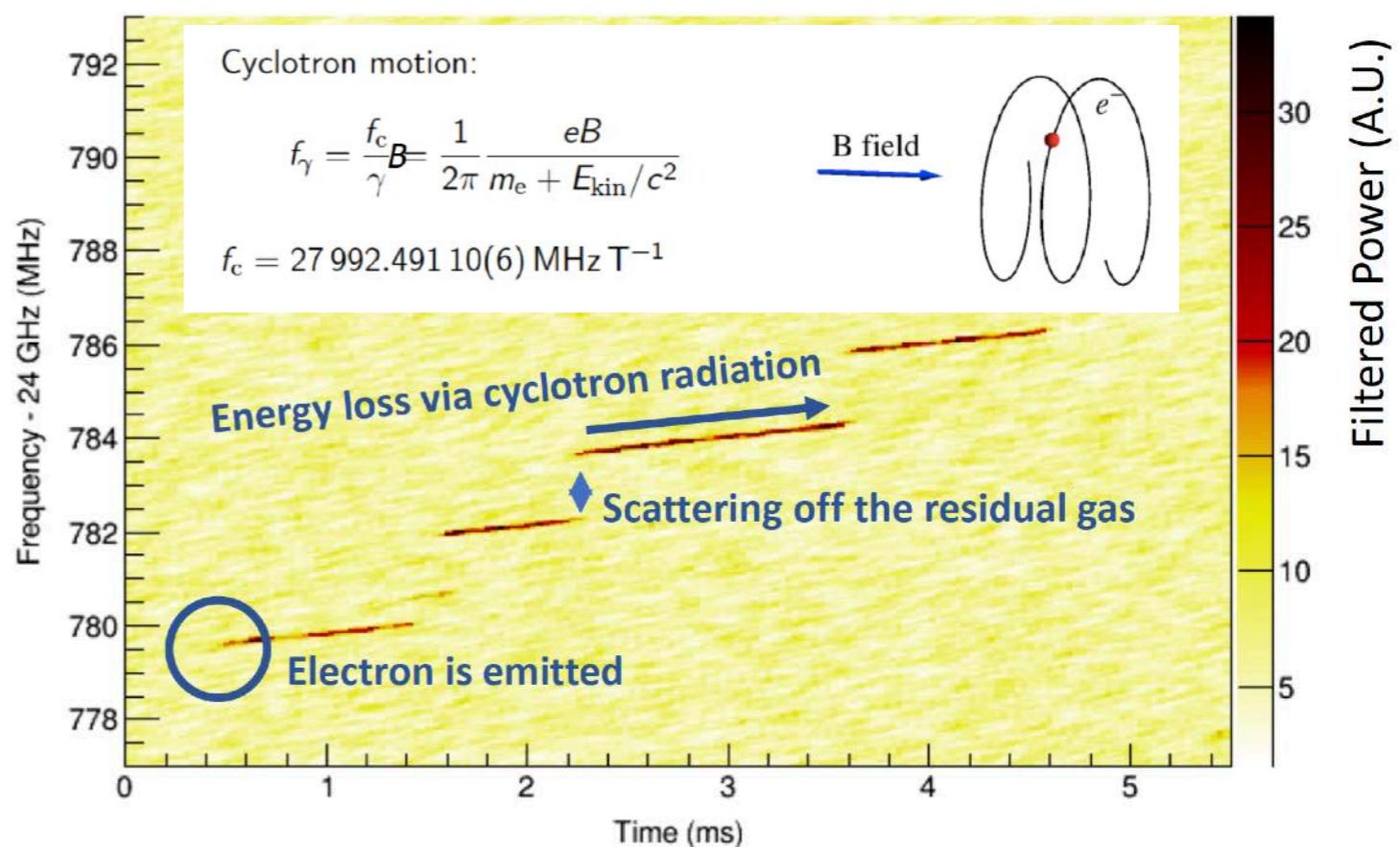
Eventual reach ~ 0.2 eV in about three years

Going beyond KATRIN?

- KATRIN is probably the limit of MAC-E filters
- Future experiments will need to use atomic tritium and find a better way to measure the beta spectrum



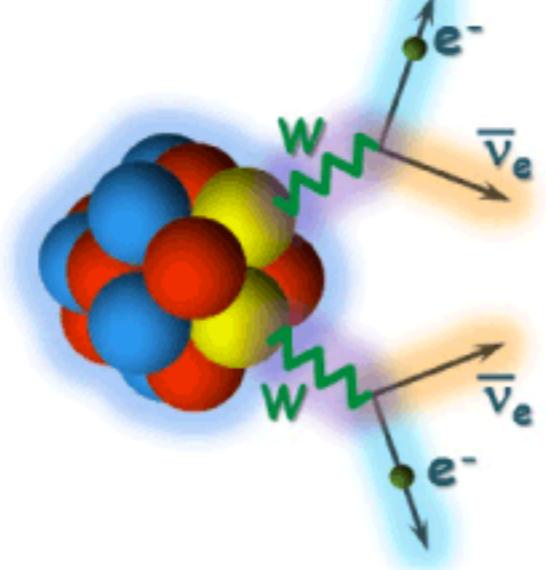
Project 8 Electron Event with Energy 18 keV



Neutrinoless Double Beta Decay

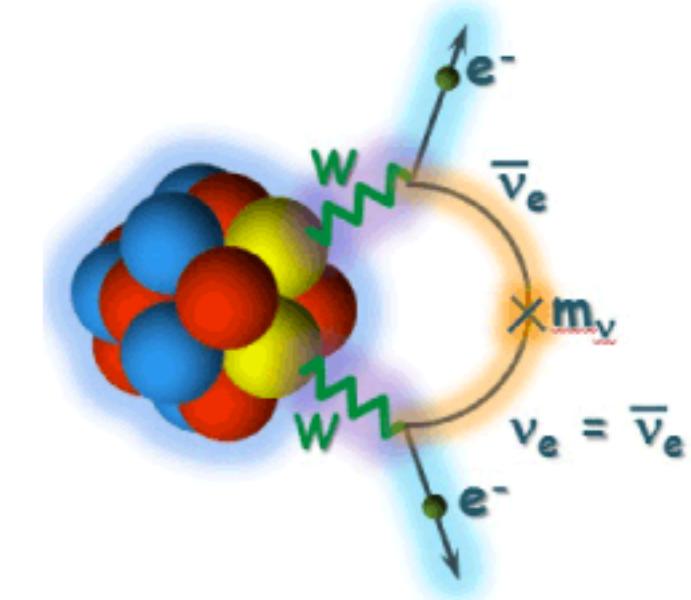
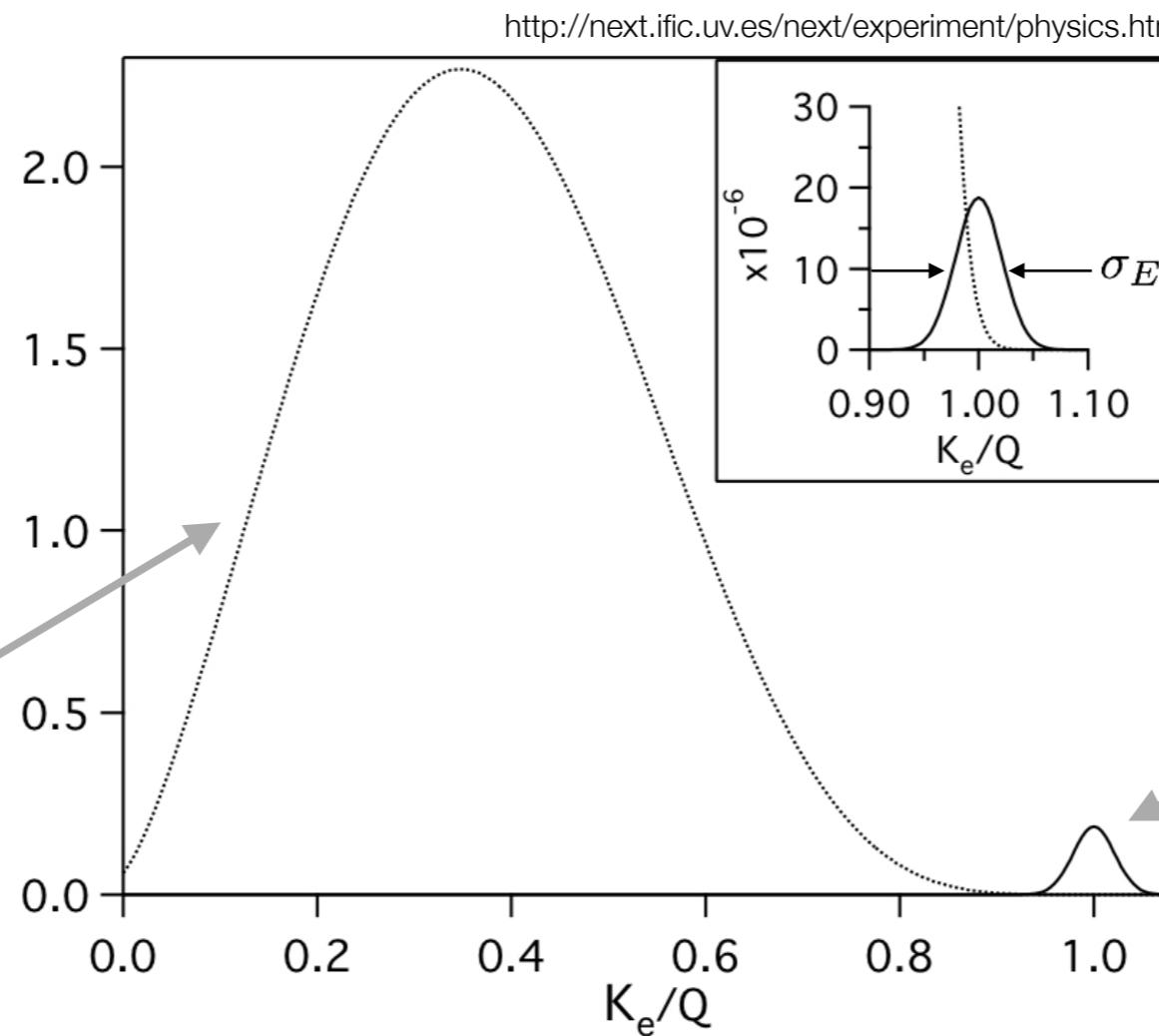
Double Beta Decay

[Double beta decay]



Double beta decay
which emits anti-neutrinos

continuous
spectrum up to end
point at Q value



Neutrinoless
double beta decay

mono energetic at
Q value

Allowed in Standard Model

$T_{1/2} \sim 10^{21}$ years

Not allowed in Standard Model

Requires:

- Massive neutrinos
- $\Delta L = 2$
- Neutrinos to be Majorana

$T_{1/2} > 10^{25}$ years

Lifetime, effective mass, and mass ordering

$$(T_{1/2})^{-1} = G|\mathcal{M}|^2 m_{\beta\beta}^2$$

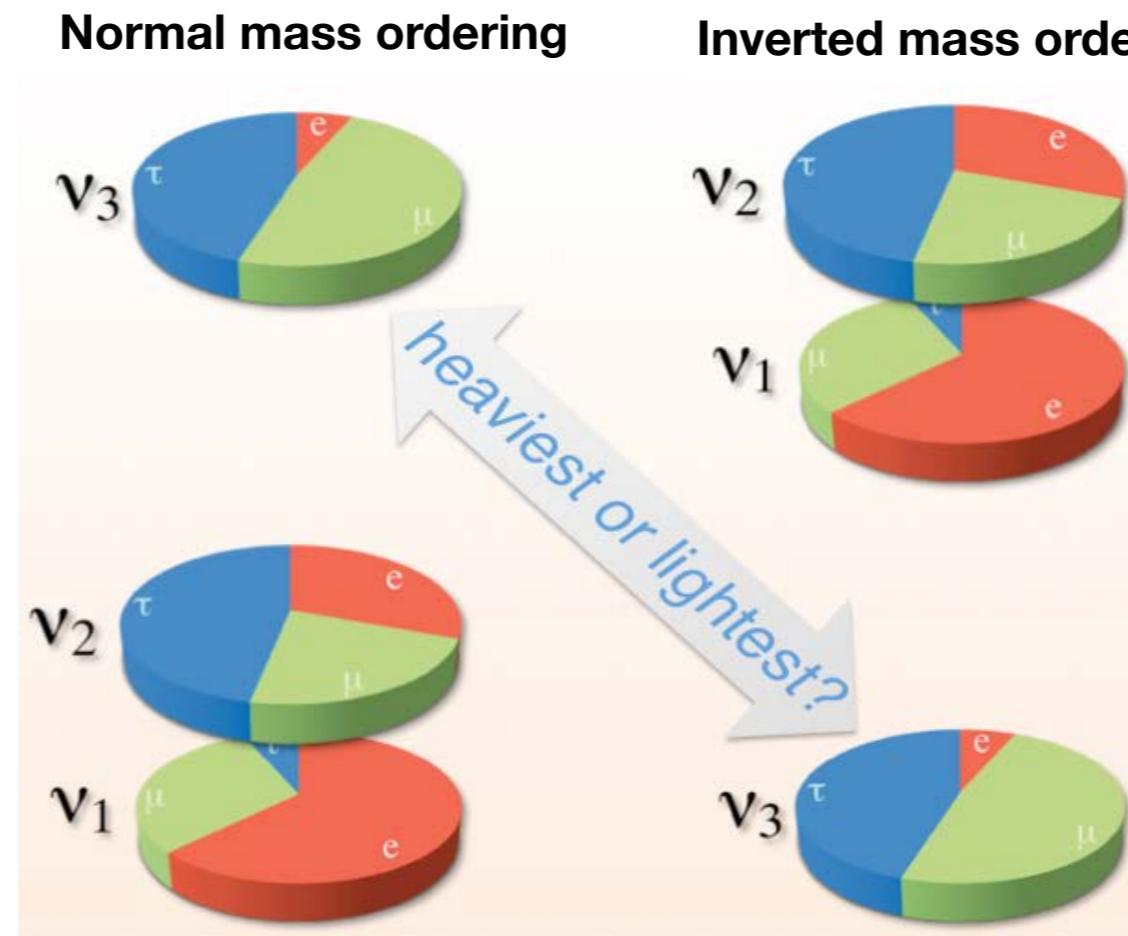
lifetime for $0\nu\beta\beta$ phase space nuclear physics effective neutrino mass

$m_{\beta\beta} \equiv |m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i(\alpha_{31}-\delta)}|$

mass-flavor mixing parameters from oscillation experiments

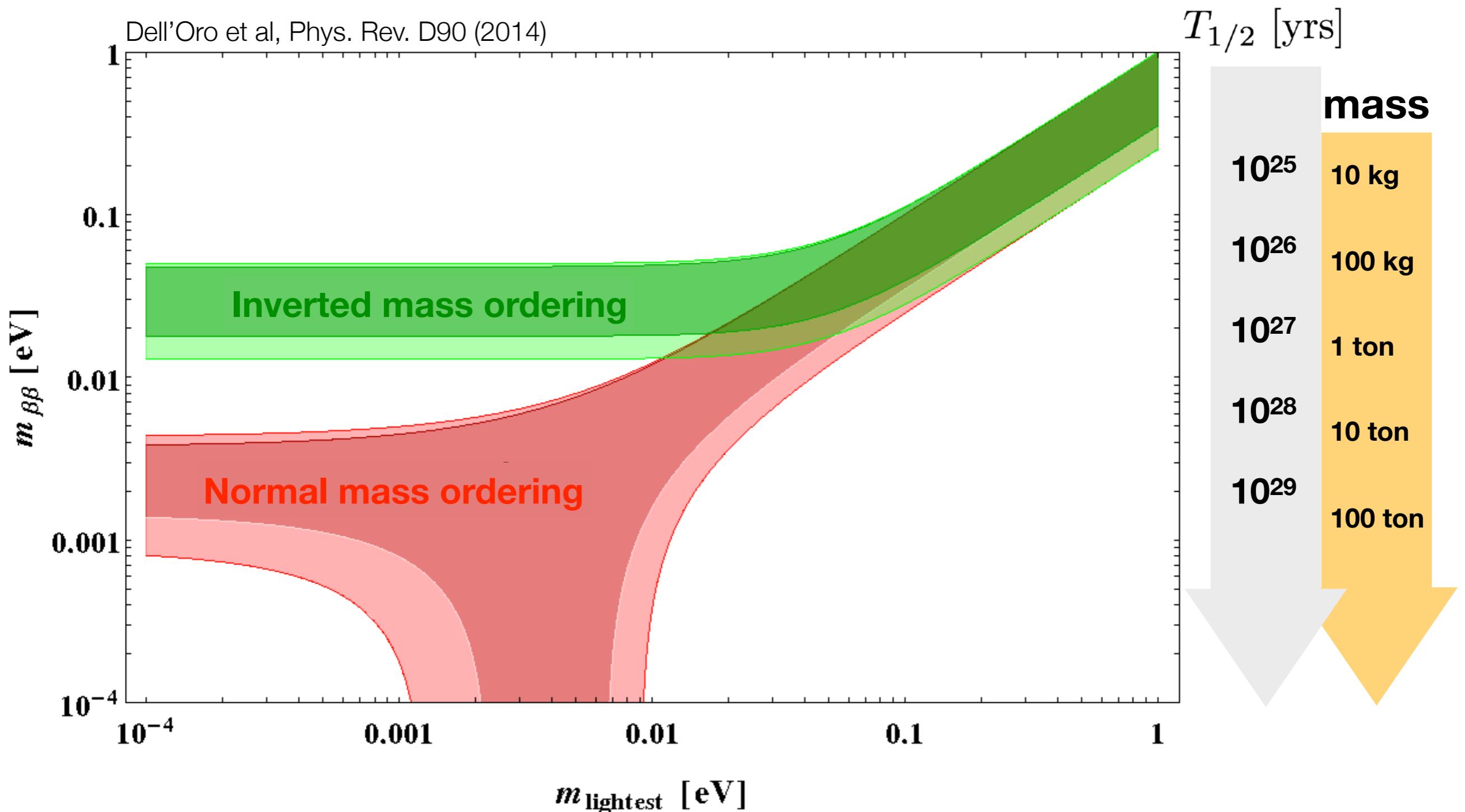
In the normal ordering most of the **electron** flavor is associated with the lighter states giving generally smaller $m_{\beta\beta}$ values.

Accidental cancellations may result in $m_{\beta\beta} \rightarrow 0$.



In the inverted ordering most of the **electron** flavor is associated with the heavier states giving generally higher values of $m_{\beta\beta}$,

Neutrino oscillation measurements set a lower limit at $\approx 15-50$ meV, $T_{1/2} \approx 10^{27-28}$ years





EXO

PRL 120 072701 (2018)

CUORE

PRL 120, 132501 (2018)

GERDA/Majorana

Eur. Phys. J. C78 (2018) 388

KamLAND-Zen

PRL. 117, 082503 (2016)

^{136}Xe

^{130}Te

^{76}Ge

^{136}Xe

TPC

Bolometer

Solid state

Scintillator

Exposure [kg-yr]

175

86

82

504

σ_E [keV]

30

5

3-3.6

100

$T_{1/2}$ @ 90% CL

1.8×10^{25}

1.5×10^{25}

1.1×10^{26}

1.1×10^{26}

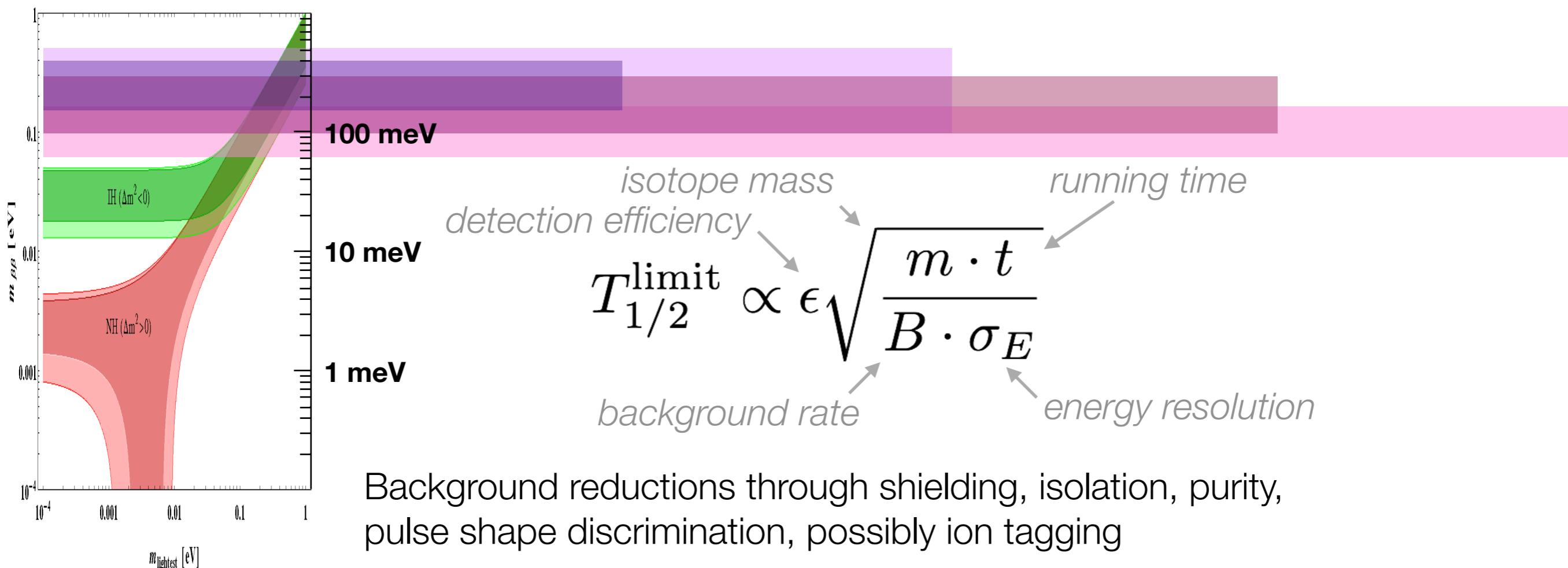
$m_{\beta\beta}$ @ 90%CL

147-398

110-520

100-300

61-165



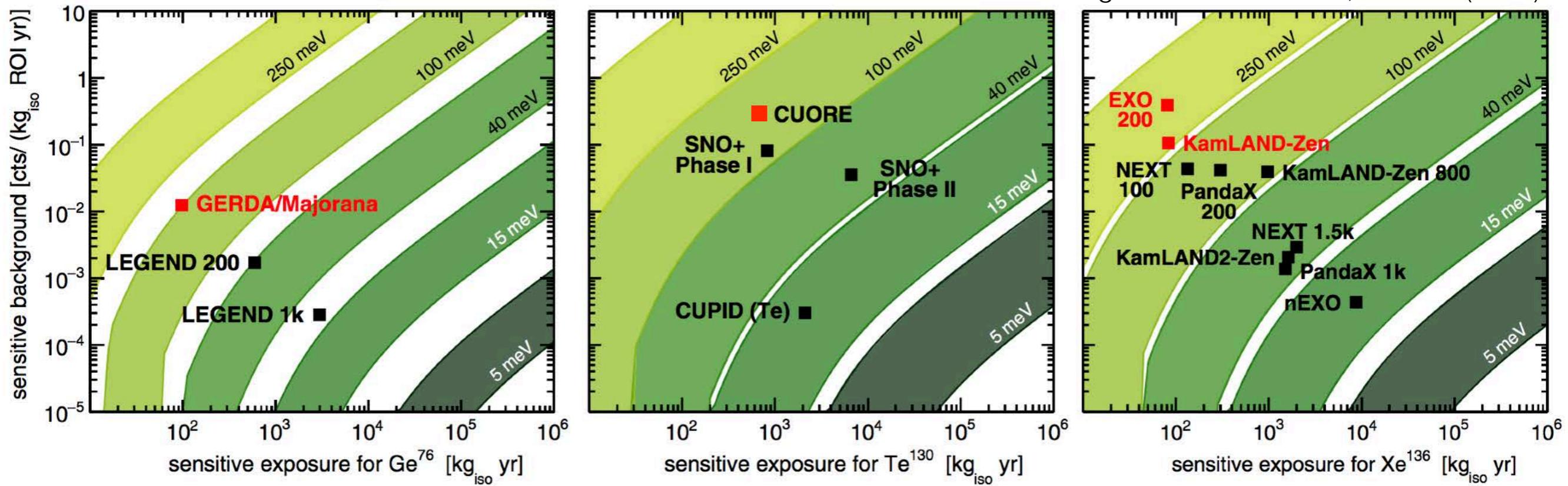
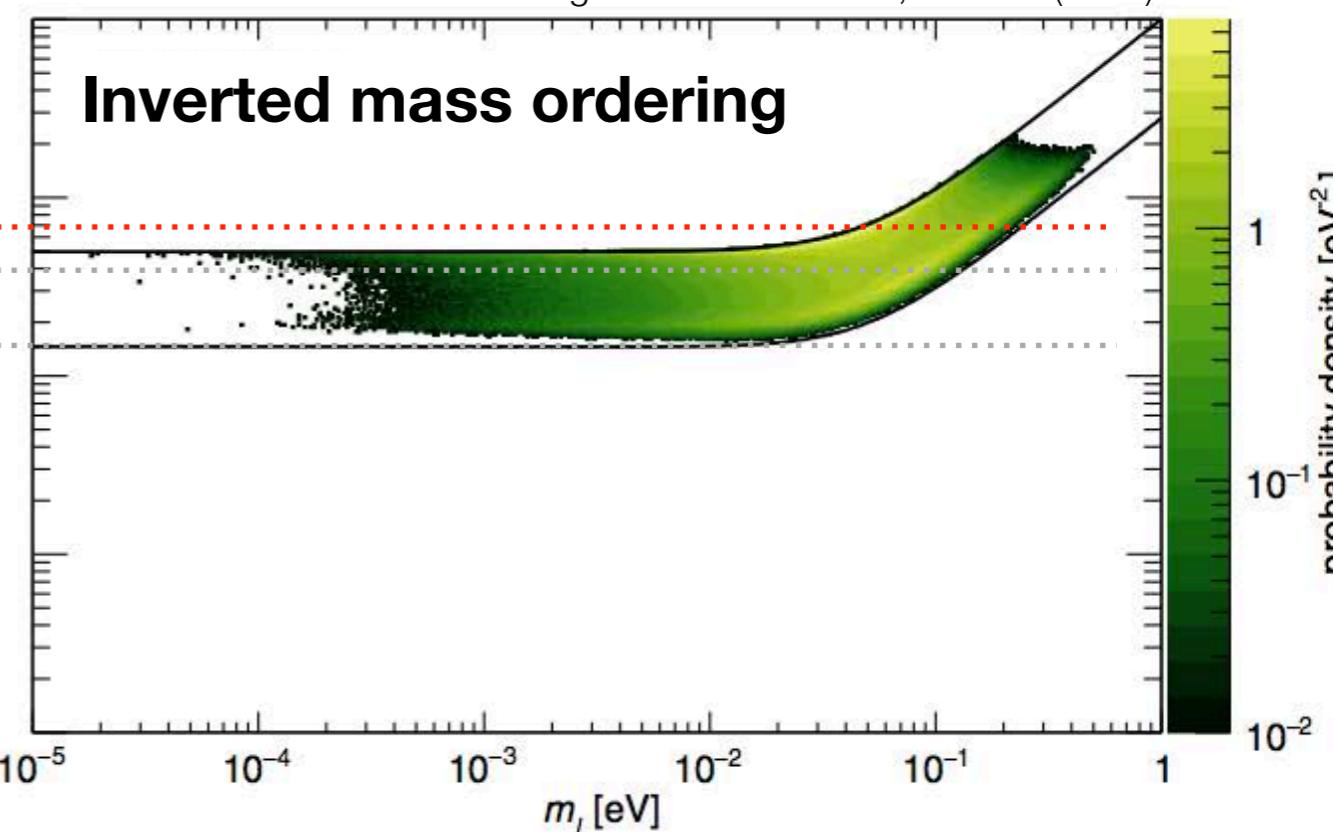
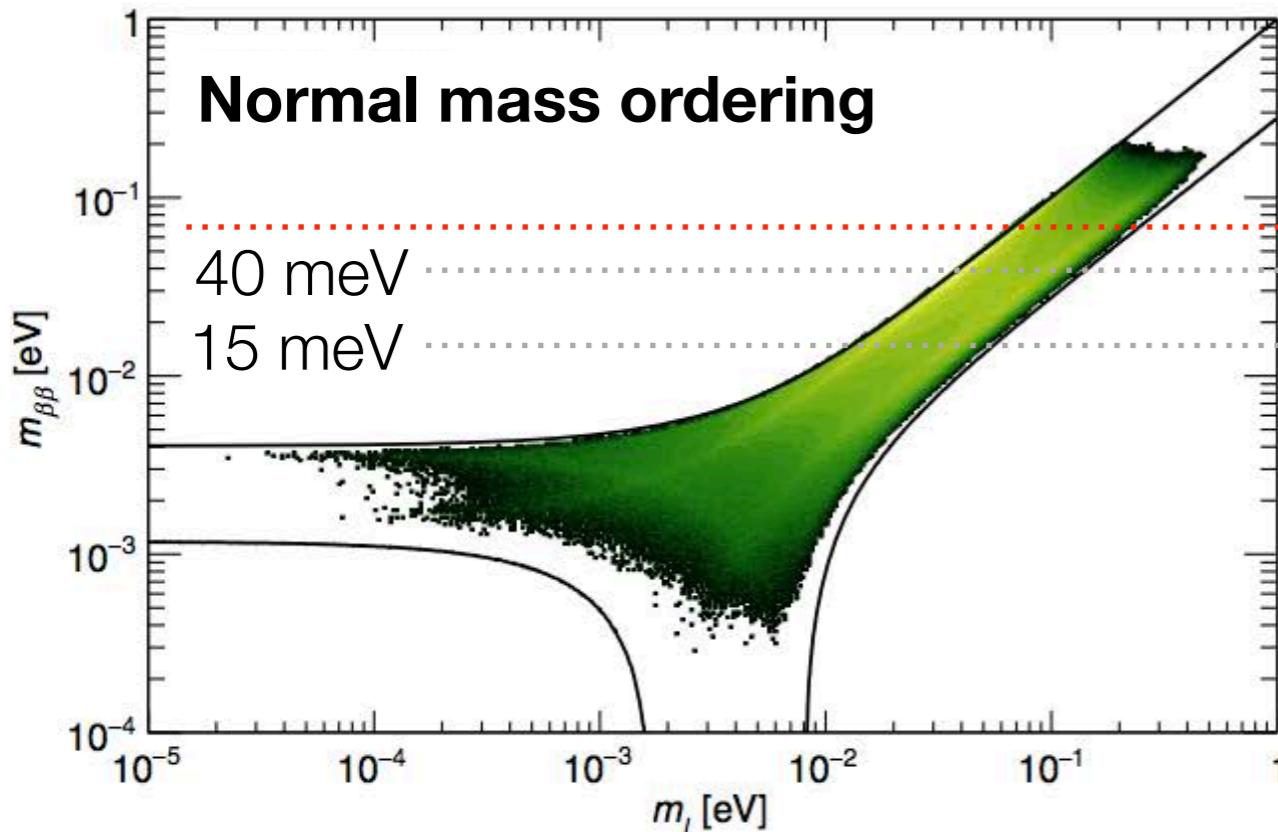


FIG. 3. Discovery sensitivity for ^{76}Ge , ^{130}Te , and ^{136}Xe as a function of sensitive exposure and sensitive background. Contours in $m_{\beta\beta}$ are represented as bands spanning the range of considered NME values. The experimental sensitivities of future or running experiments are marked after 5 years of live time. Past or current experiments with published background level and energy resolution (red marks) are shown according to the average performance in their latest data-taking phase.

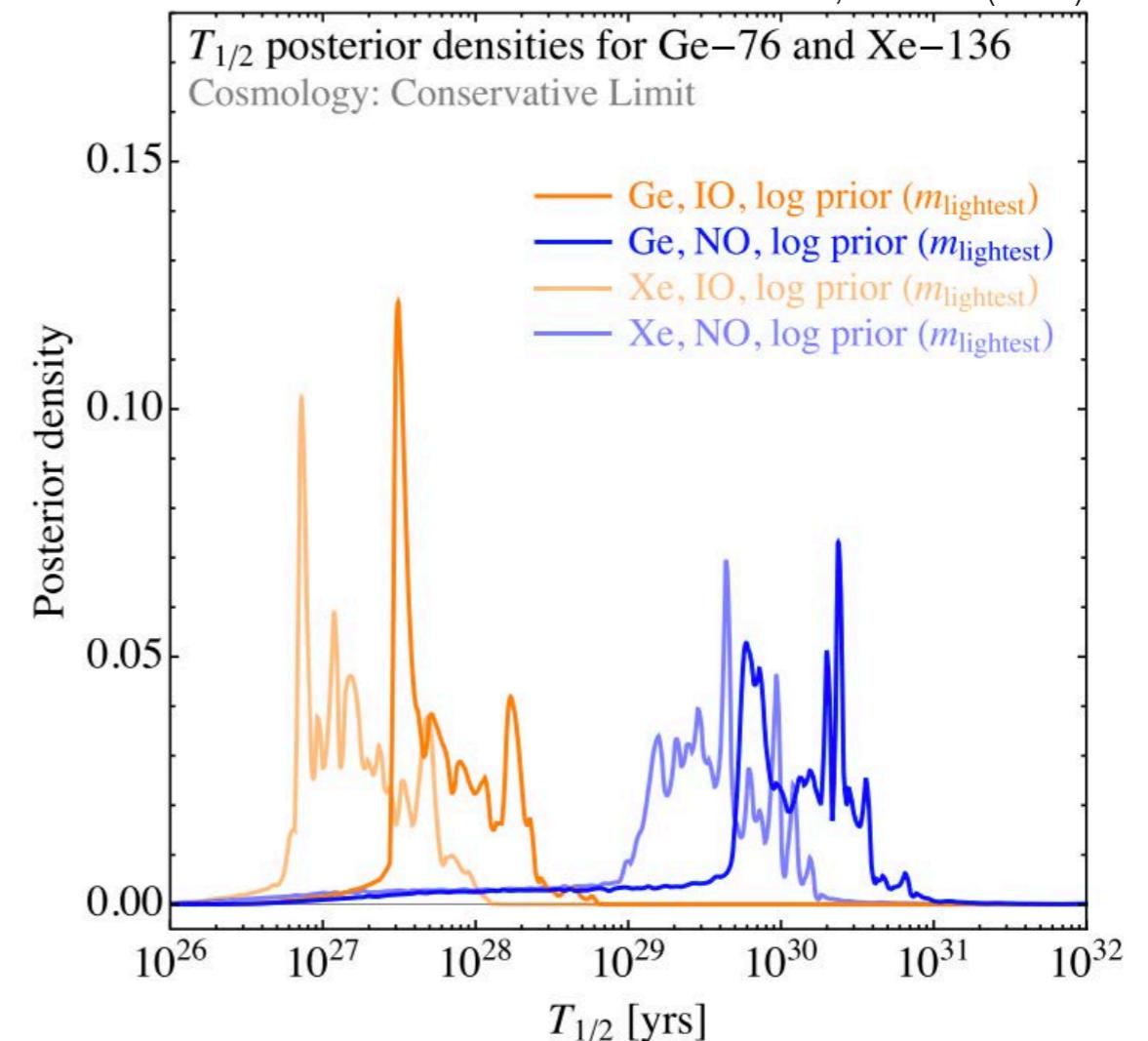
Next generation experiments

Reach down to 40 to 15 meV



Using current oscillation, direct mass, and cosmological data as prior inputs, how likely is the next generation of experiments to discover $0\nu\beta\beta$?

- Good coverage of most of the inverted ordering parameter space (top right)
- Reasonable coverage of most likely parameters in normal ordering (top left).
- Agostini et al.: 50% change of 3 σ observation in next generation.
- Watch the assumptions! Caldwell et al. (right), for example, finds normal ordering harder to reach than does Agostini et al.



OSCILLATIONS

Solar neutrinos, T2K + NOvA, atmospheric neutrinos, reactor neutrinos

Neutrino oscillations

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

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

$$\begin{aligned} |\Delta m_{32}^2| &\equiv |m_3^2 - m_2^2| \\ &\simeq 2 \times 10^{-3} \text{ eV}^2 \end{aligned}$$

$$\Delta m_{31}^2 \simeq \Delta m_{32}^2$$

$$\Delta m_{21}^2 \simeq 8 \times 10^{-5} \text{ eV}^2$$

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

$$\nu_e \rightarrow \nu_e$$

$$\nu_e \rightarrow \nu_e$$

$$\nu_\mu \rightarrow \nu_\tau$$

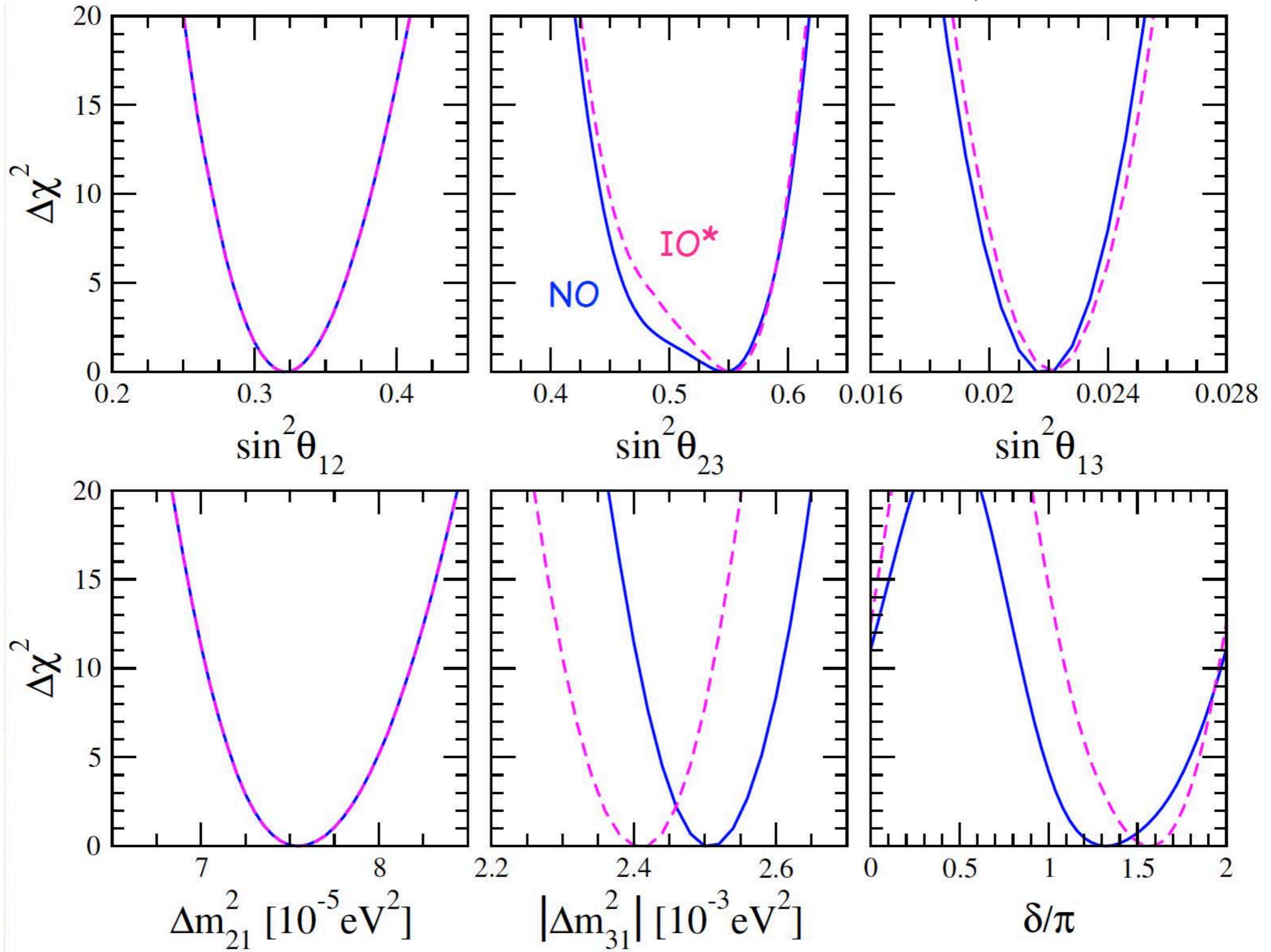
$$\nu_\mu \rightarrow \nu_e$$

$$\nu_e \rightarrow \nu_\mu + \nu_\tau$$

atmospheric and
long baseline

reactor and
long baseline

solar and
reactor



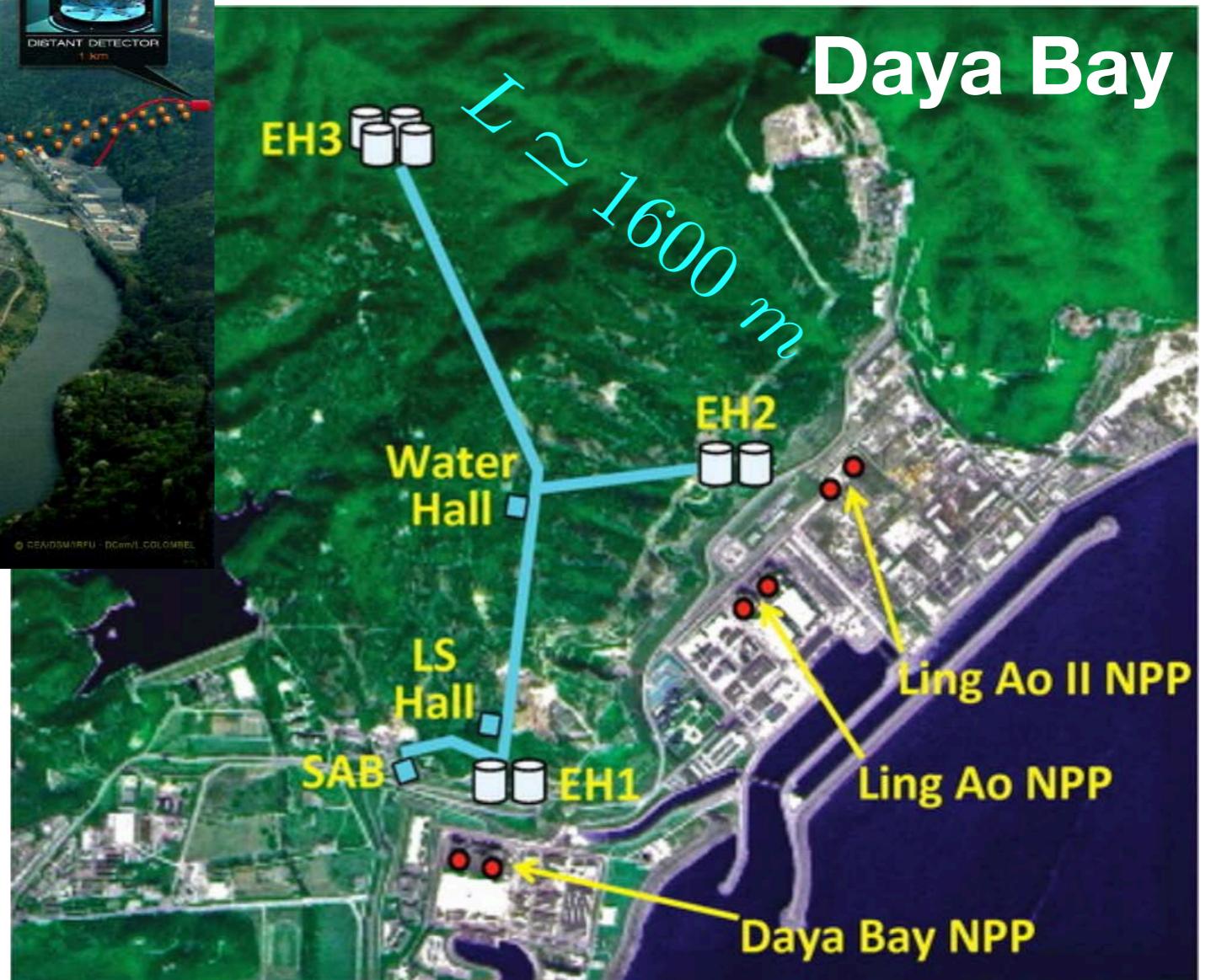
θ_{13} : Daya Bay, RENO, and Double CHOOZ



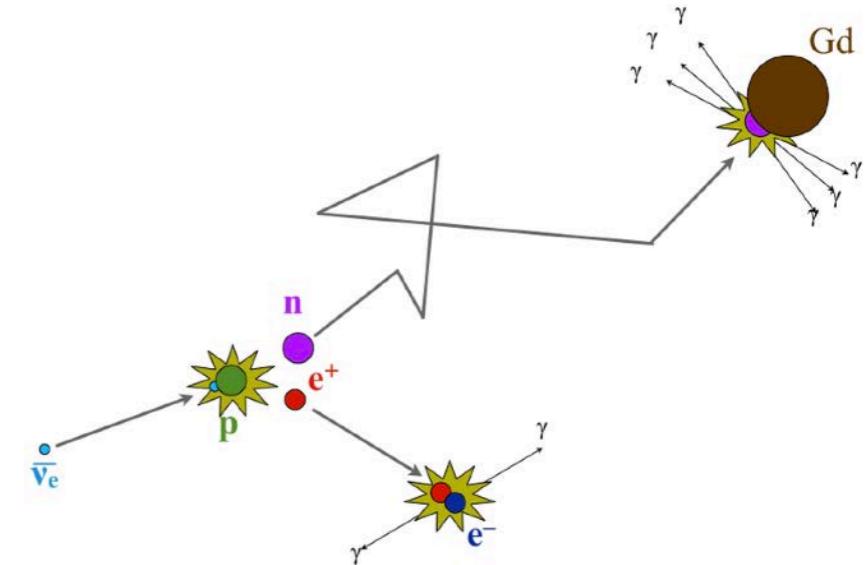
$$E \simeq 4 \text{ MeV}$$

$$\Delta = \frac{1.27 \cdot 0.0025 \text{ eV}^2 \cdot 1600 \text{ m}}{4 \text{ MeV}} \simeq \frac{\pi}{2}$$

$\bar{\nu}_e \rightarrow \bar{\nu}_e$ at atmospheric mass scale



Daya Bay



GIANT LIQUID SCINTILLATION DETECTORS AND THEIR APPLICATIONS*

FREDERICK REINES

Los Alamos Scientific Laboratory, Los Alamos, New Mexico

I. GENERAL CONSIDERATIONS LEADING TO THE DEVELOPMENT OF LARGE DETECTORS

WHEN Clyde Cowan and I started in 1951 to pursue the free neutrino,¹ we knew that an essential ingredient in any successful scheme would be a solid or liquid target consisting largely of protons and measuring approximately a cubic meter. Furthermore, the events which occurred in this target had to



Reines-Cowan experiment

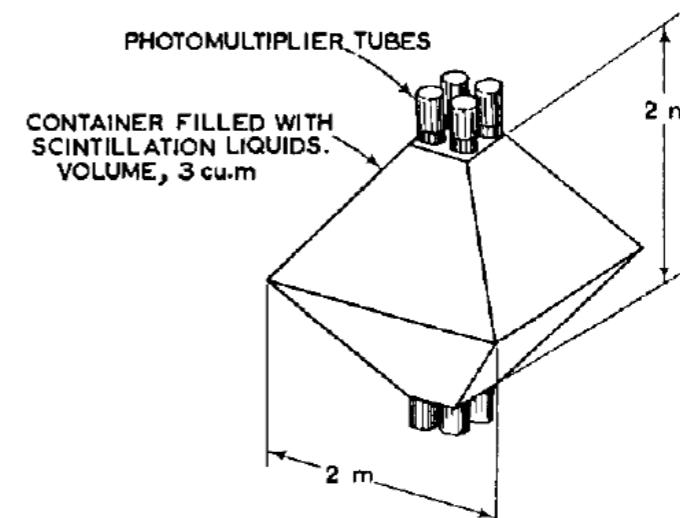
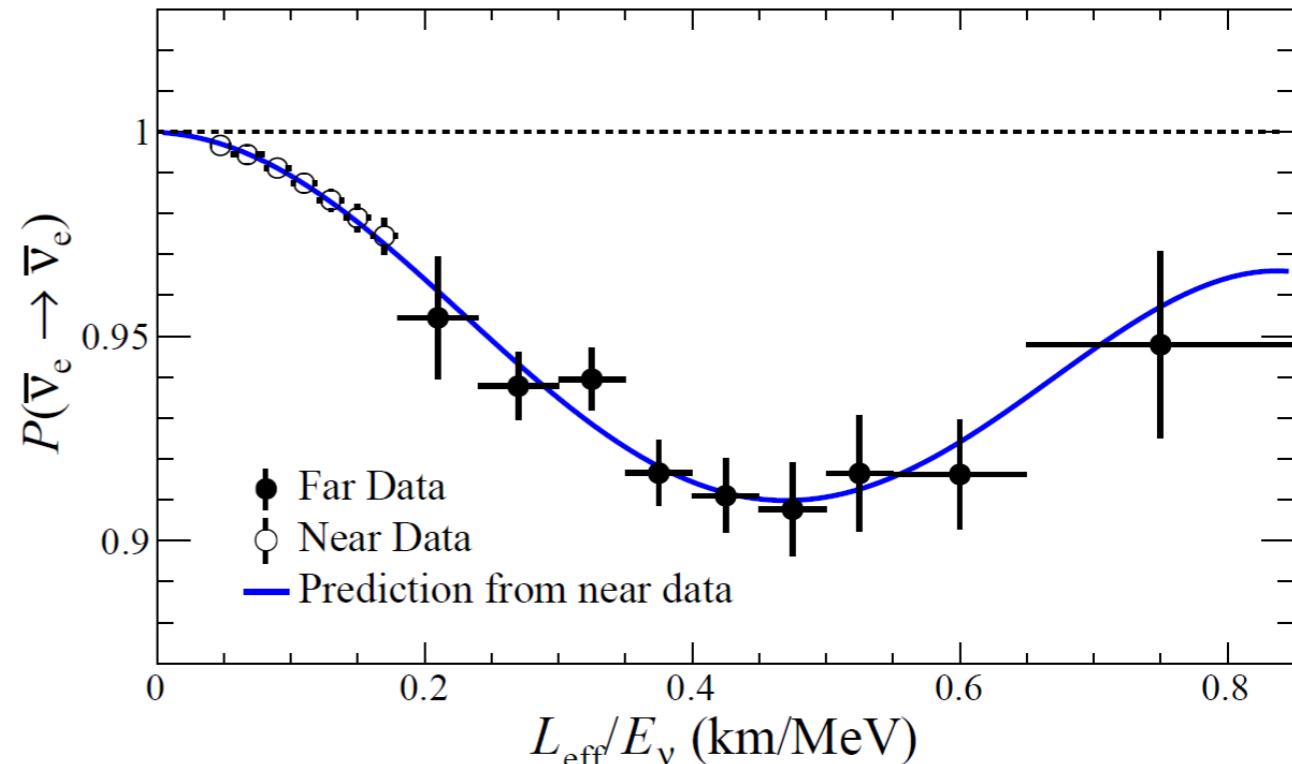
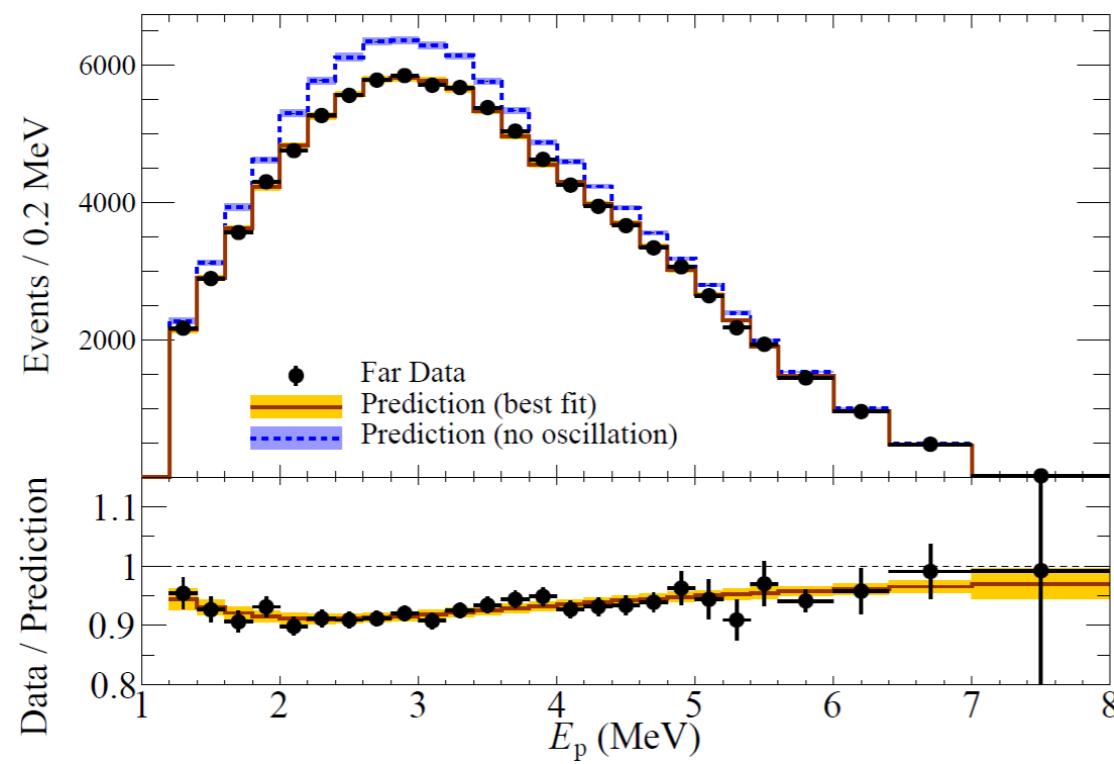
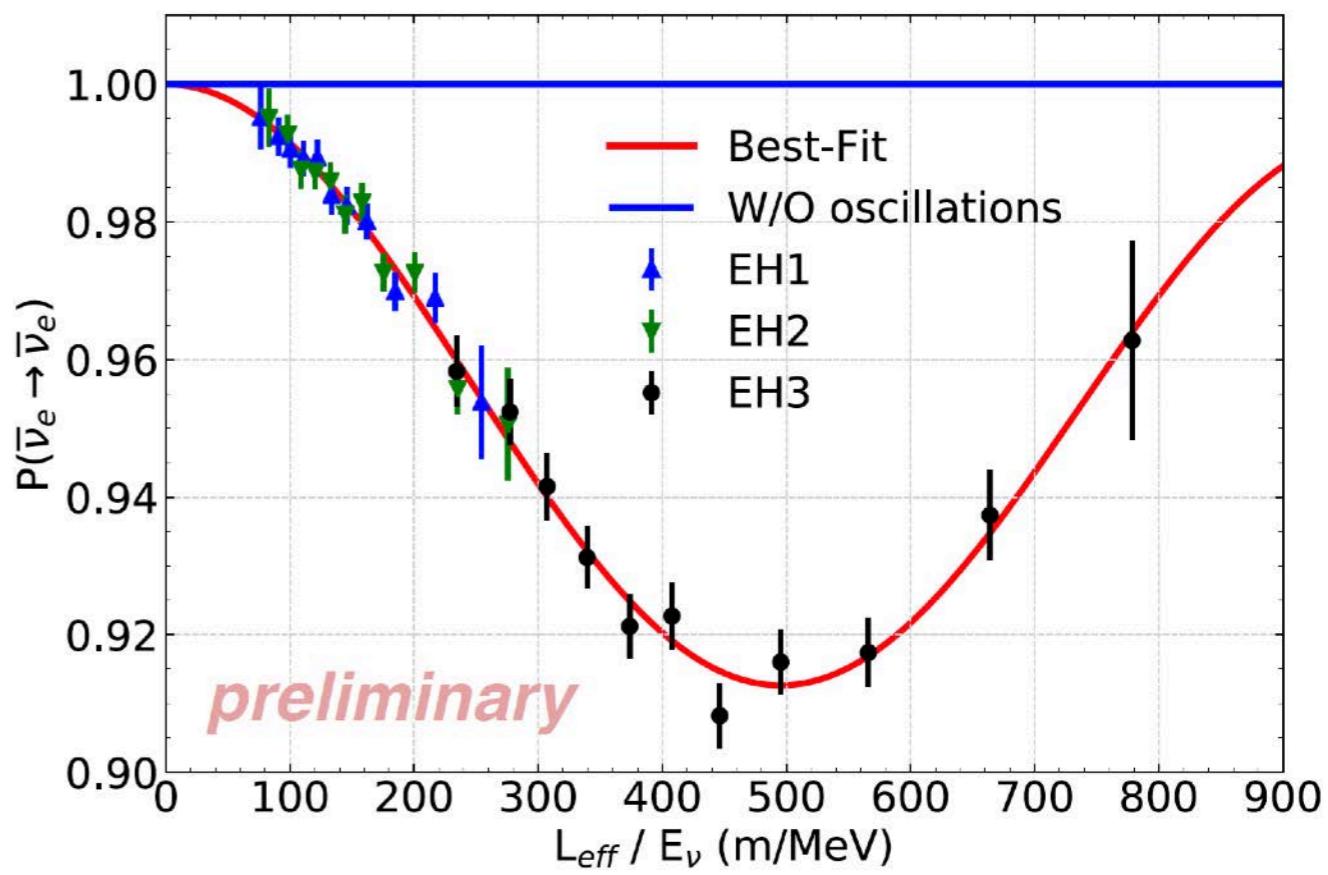
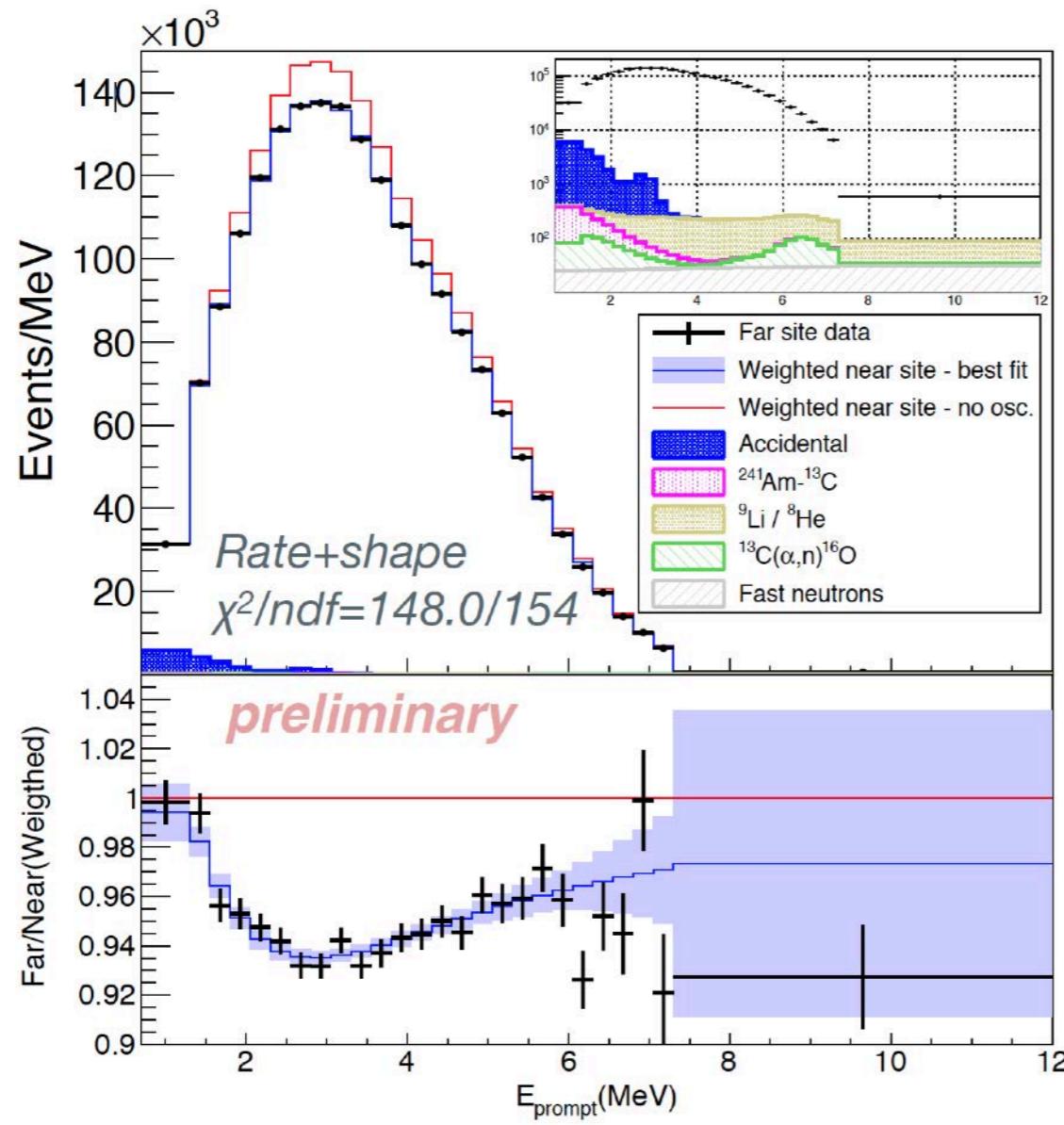


Fig. 1. Sketch of 'El Monstro', first Los Alamos attempt at a giant liquid scintillation detector (1952).

RENO

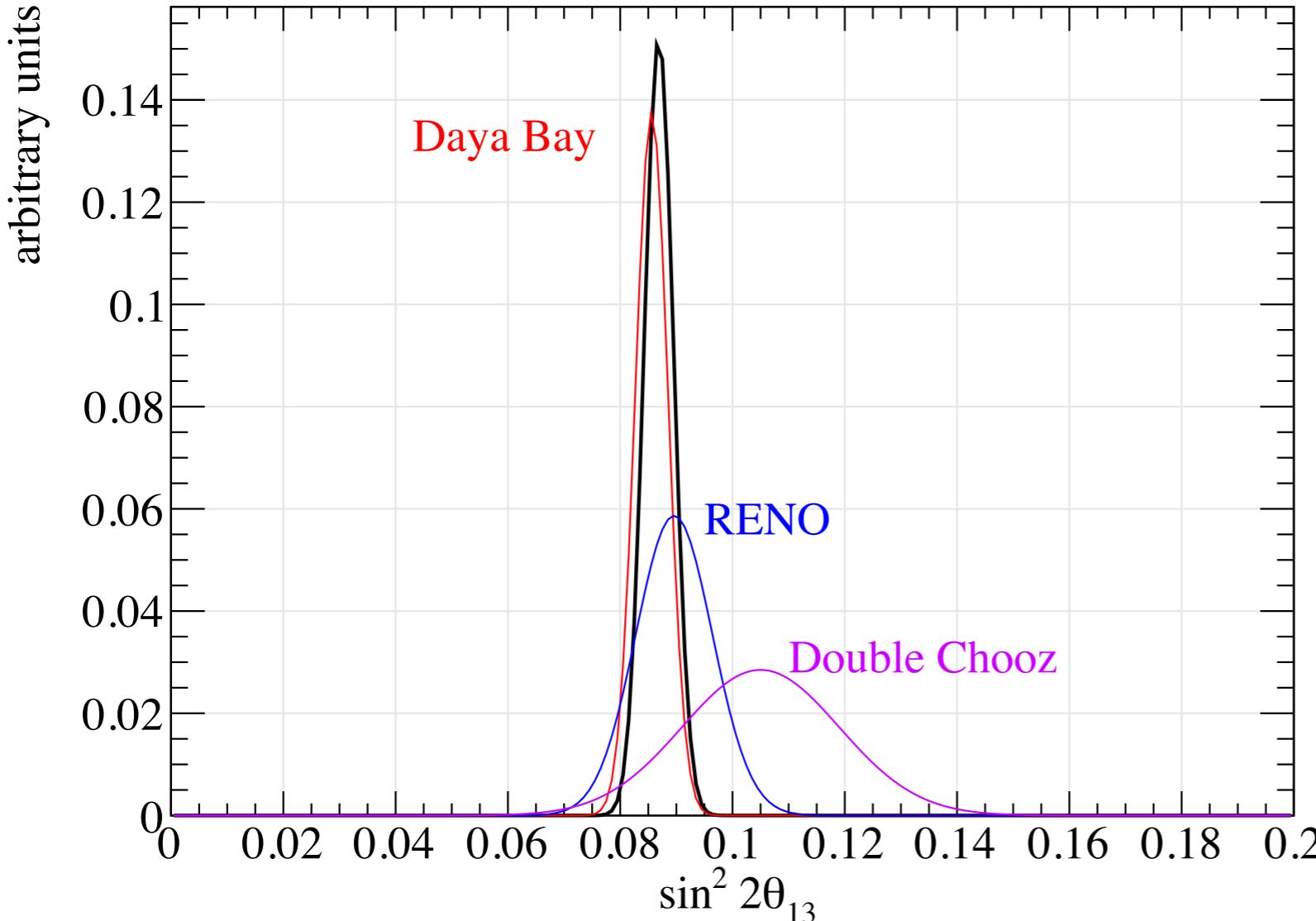


Daya Bay



$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{1.267 \Delta m^2 L}{E} - P_{\text{solar}}$$

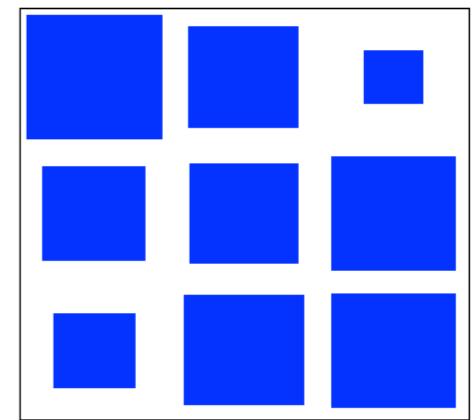
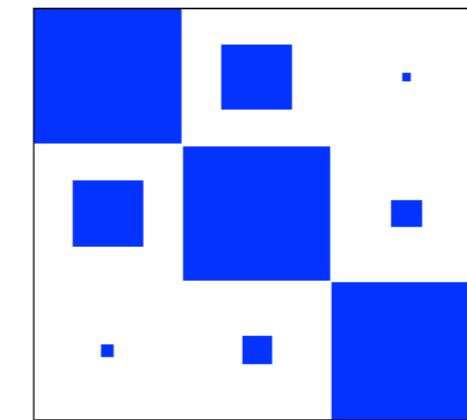
$$\sin^2 2\theta_{13} = 0.0869 \pm 0.0026$$



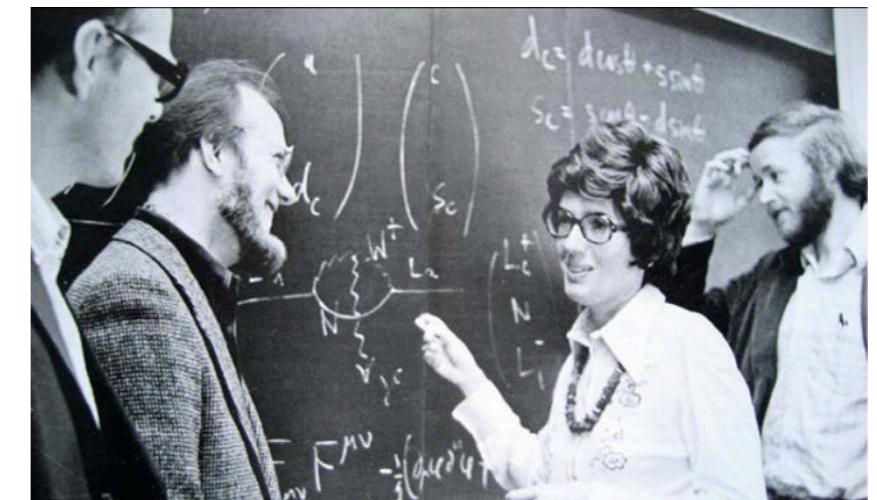
Daya Bay will run through 2020, will reach precision of 3%.

V_{CKM}

U_{PMNS}



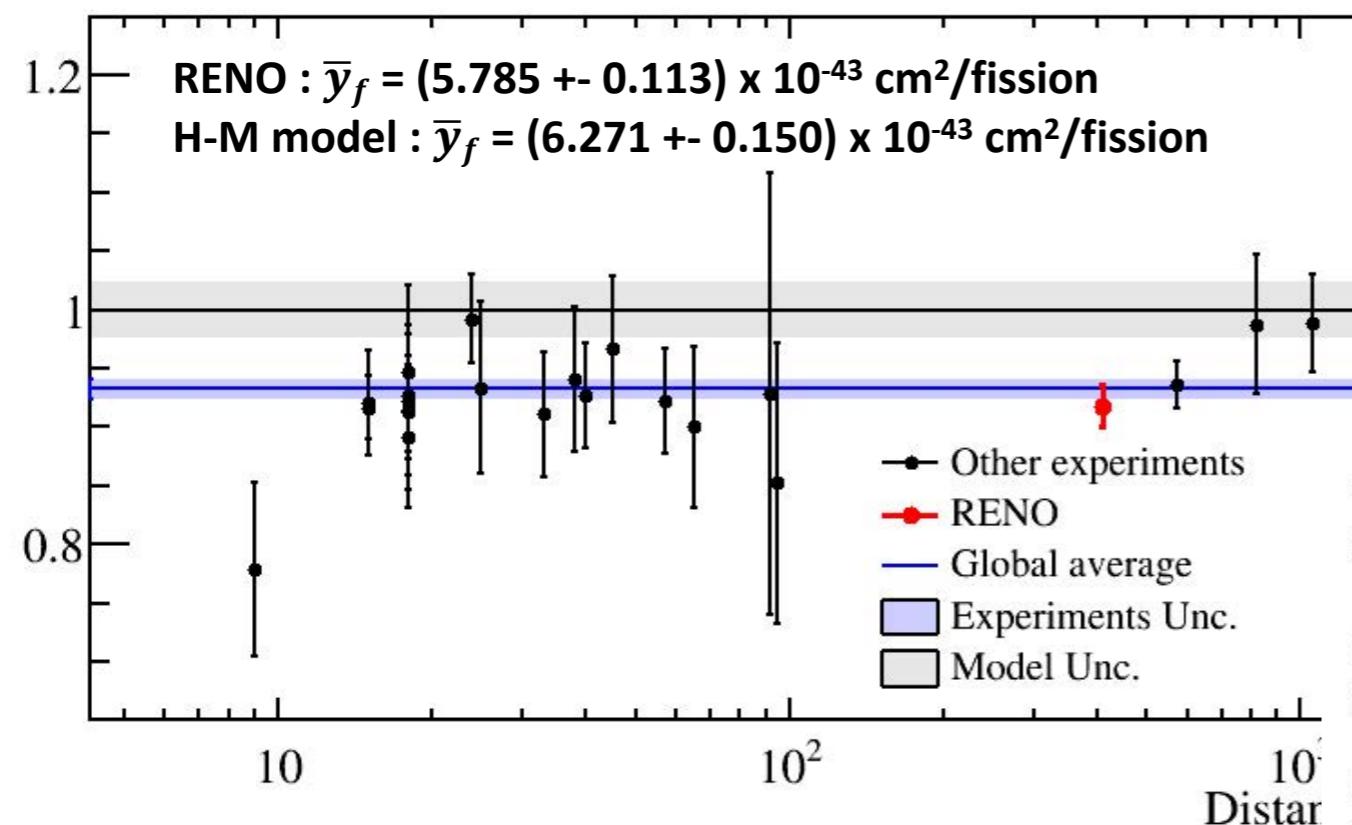
$$\frac{J_{PMNS}}{J_{CKM}} = \frac{3 \times 10^{-2}}{3 \times 10^{-5}} \sin(\delta_{PMNS})$$



CP violation in leptons

Leptonic CP violation can be 1000x larger than in the quark sector!

RENO

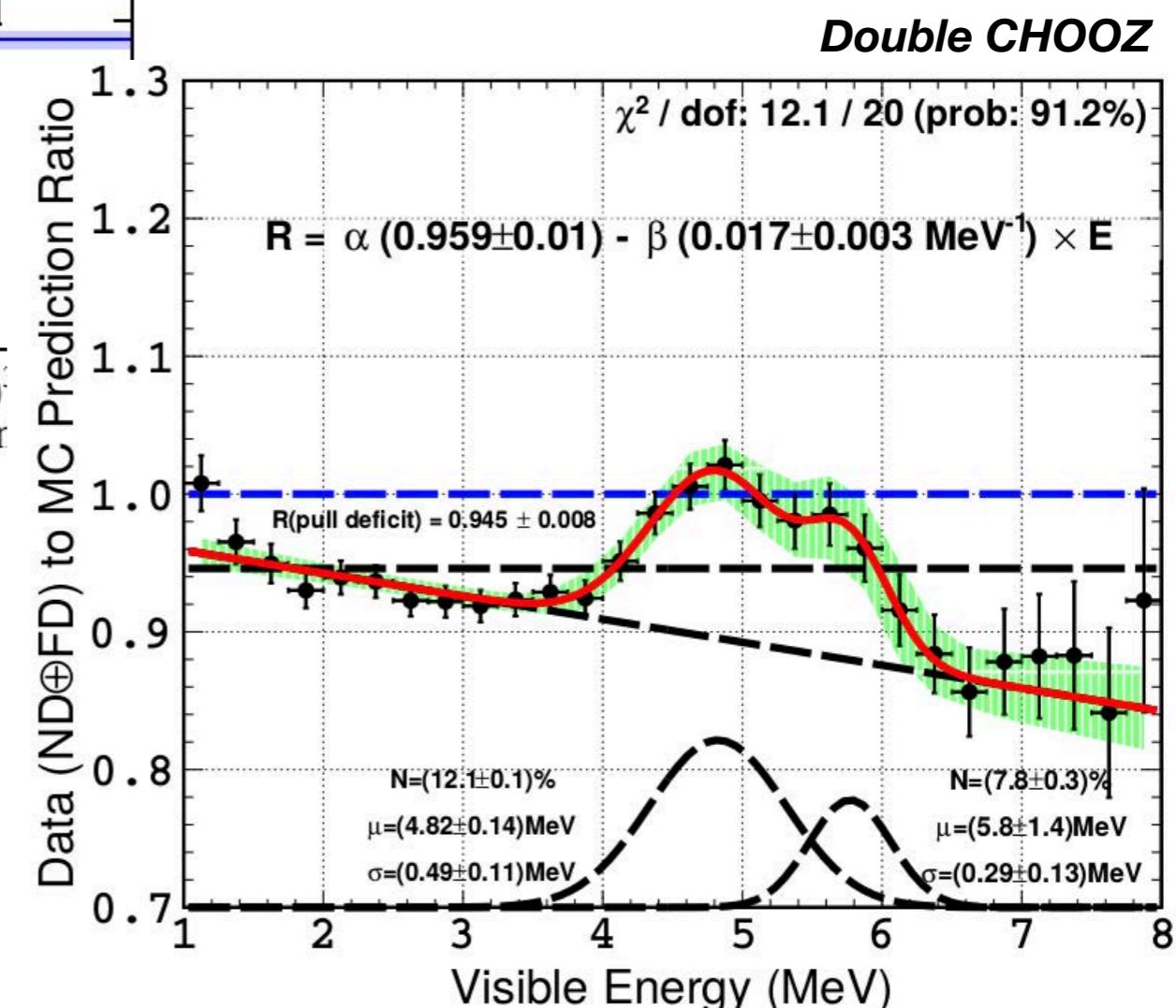


All experiments low by 5% compared to current models

Daya Bay: Phys. Rev. Lett. 182, 251801 (2017), correlates with reactor burn time hence likely associated with reactor modeling of fission fragments

Understanding reactor neutrino fluxes

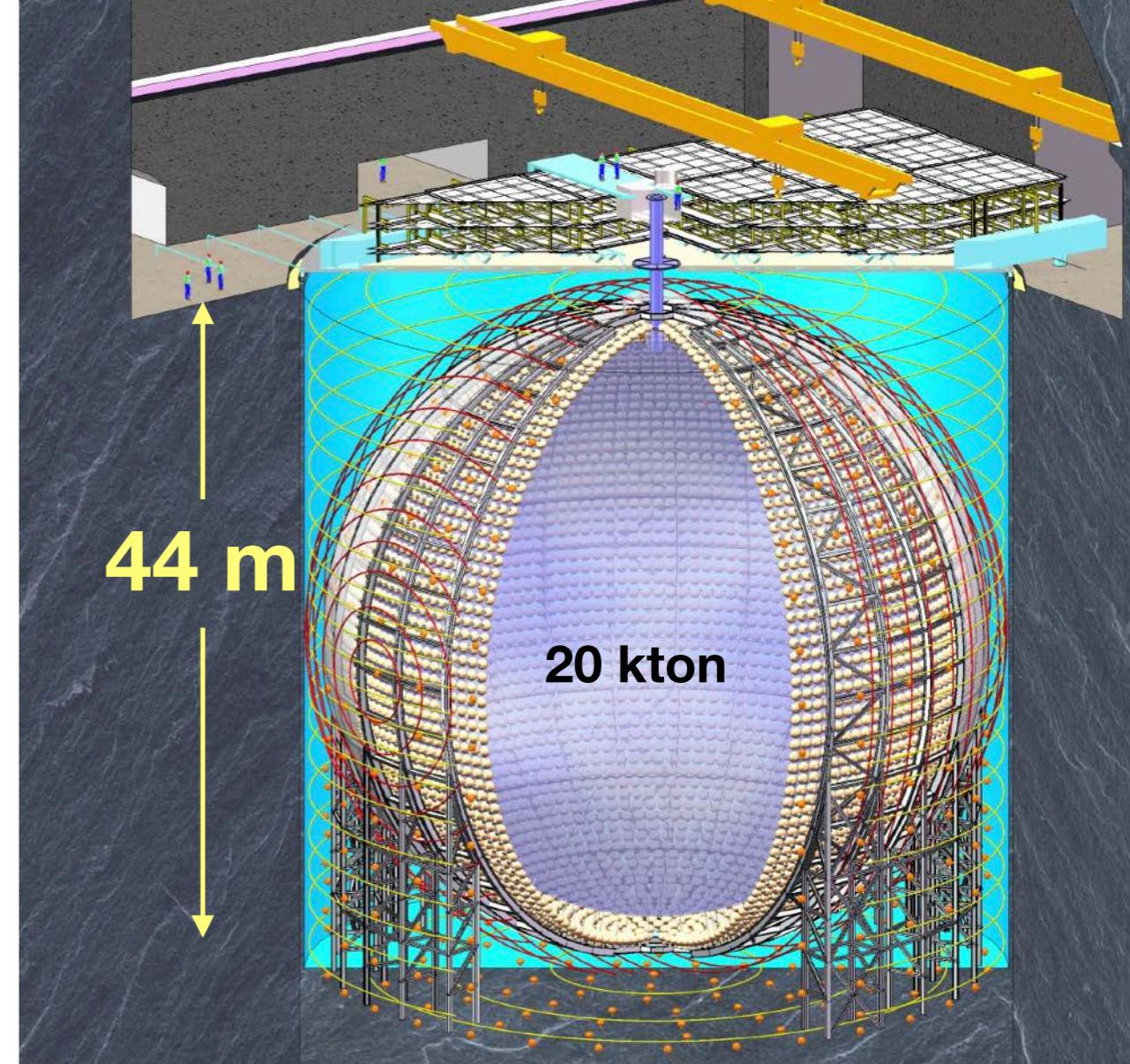
5 MeV “bump” Seen in all three experiments



Anna Hayes at Neutrino 2018: “Improved treatments reduce the size of the anomaly”. “The BUMP is due to standard nuclear physics...may be from ^{238}U ”

JUNO Experiment

- 20 kton liquid scintillator placed 53 km from two high powered reactors.
- Goal is to measure neutrino mass hierarchy through precise measurement of oscillation phase at 3-4 σ
- Also has very strong program in 21 and 31 sectors.
- Data taking ~2021

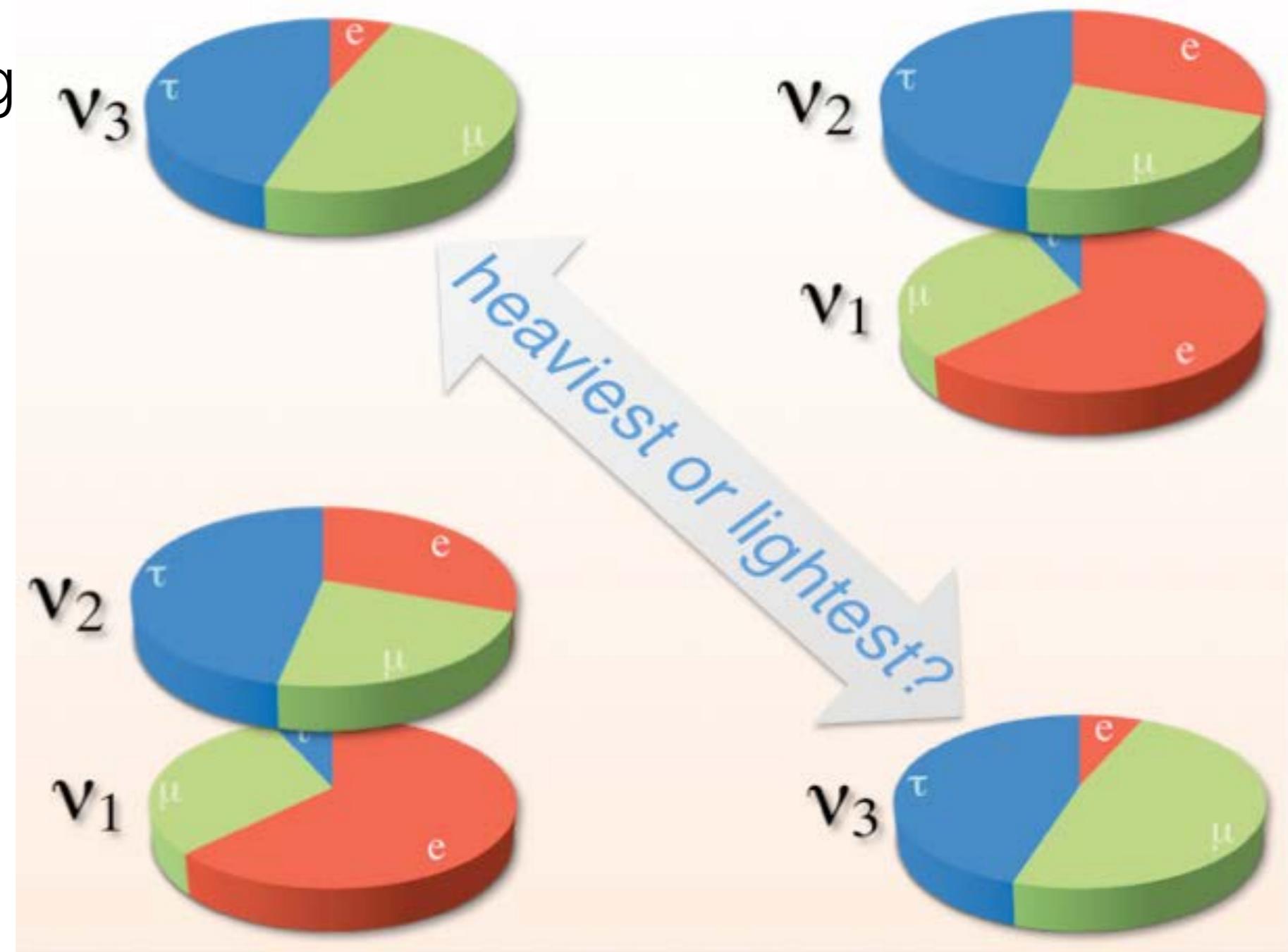


	Δm^2_{21}	$\sin^2\theta_{12}$	$ \Delta m^2_{31} $	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
Dominant experiment	KamLAND	SNO	T2K & NOvA /Daya Bay	Daya Bay	T2K
Individual 1 σ	2.4%	6.7%	3.2%/3.5%	4.0%	9.8%
Global 1 σ *	2.2%	3.9%	1.2%	3.4%	5%
JUNO expected 1σ	0.6%	0.7%	0.4%	~15%	-

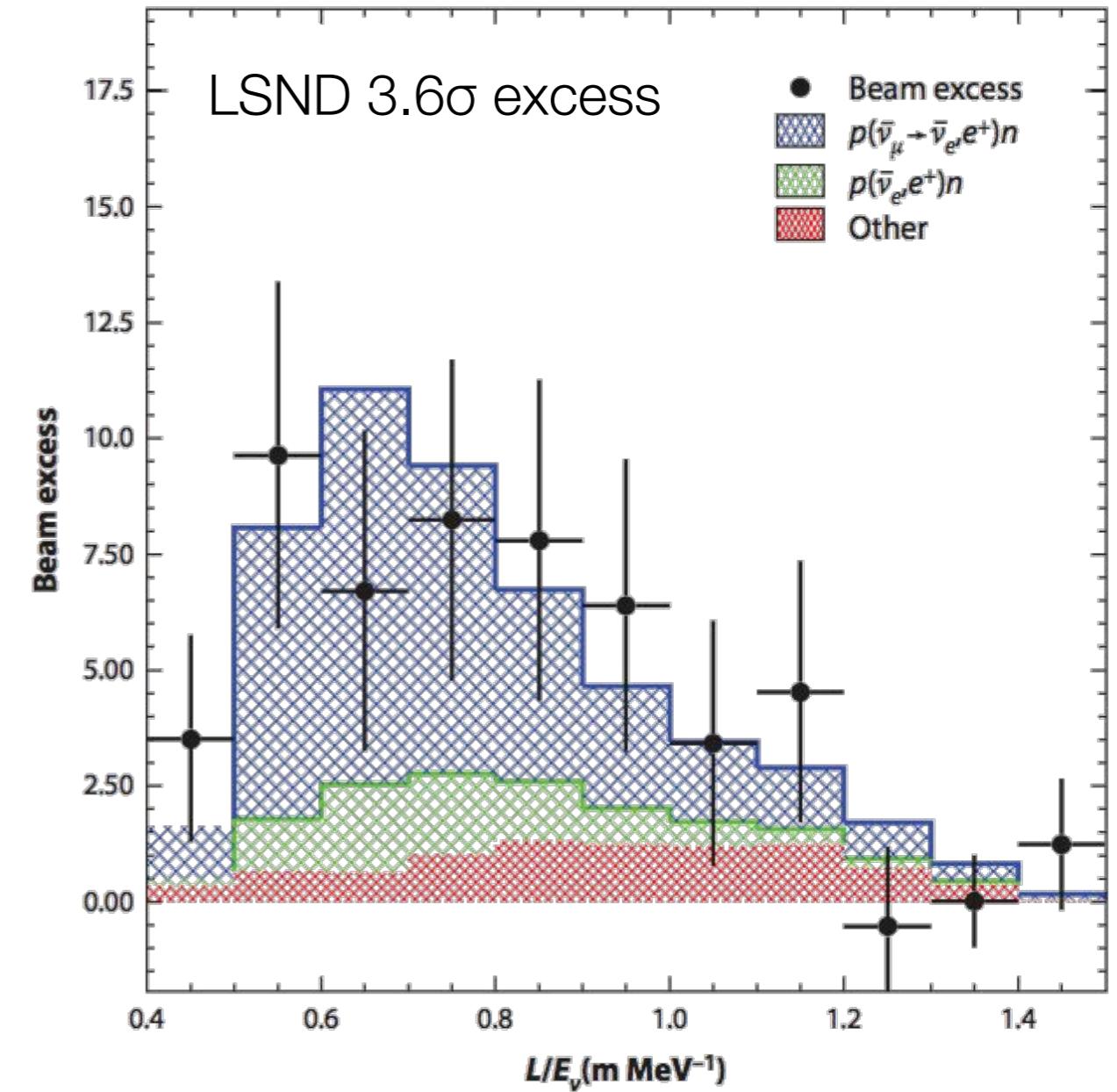
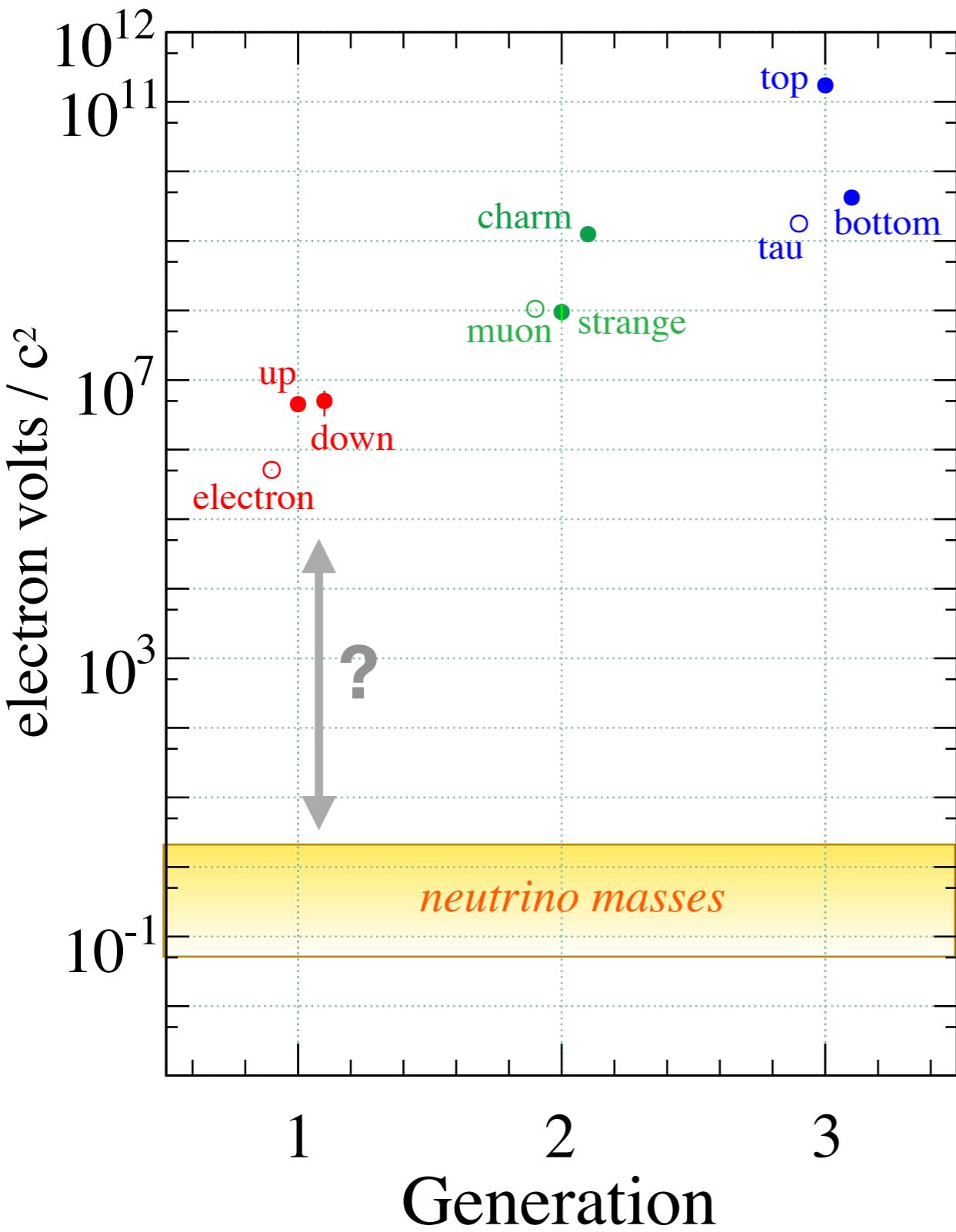
Δm^2_{ee}

Next Questions In Neutrino Physics

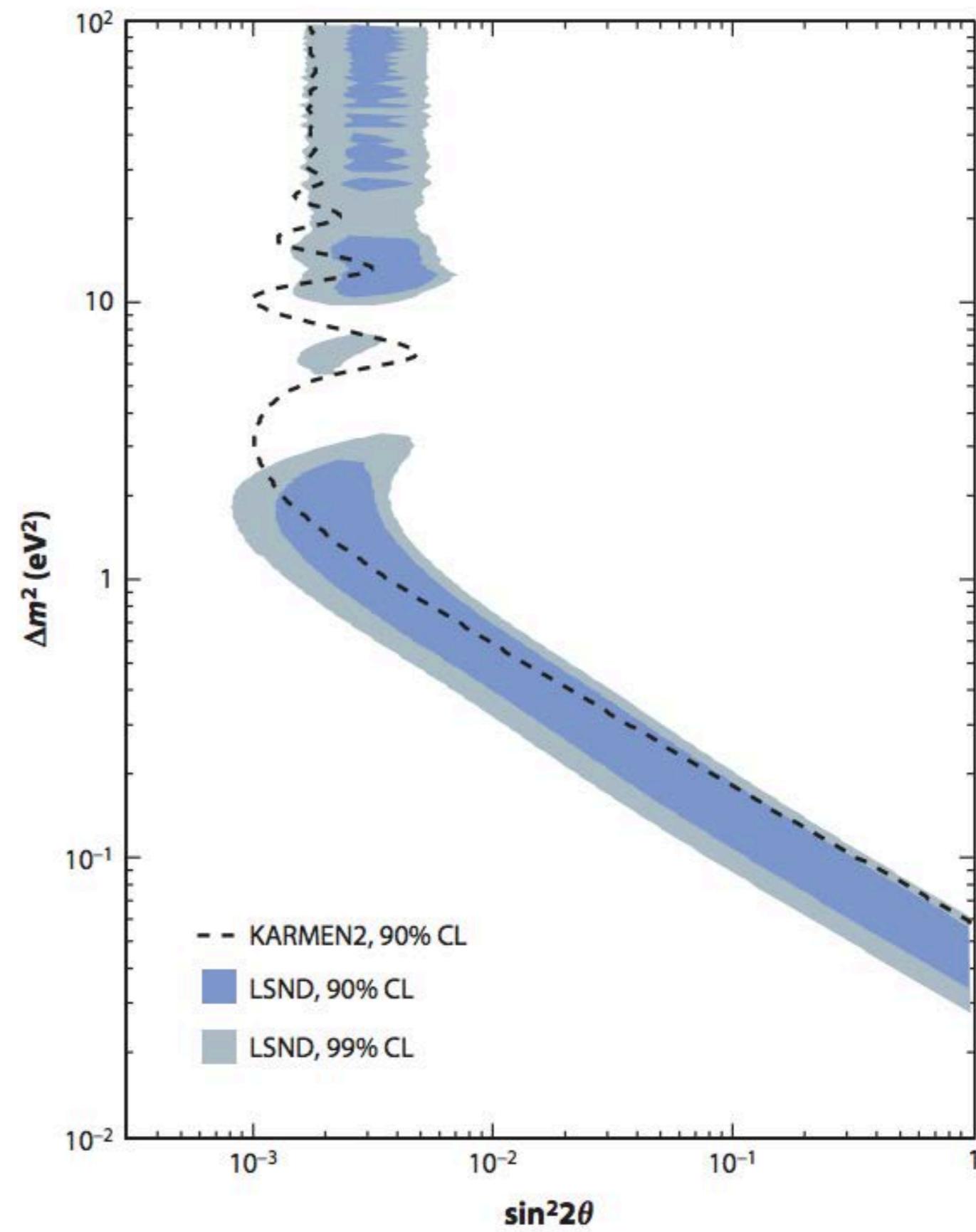
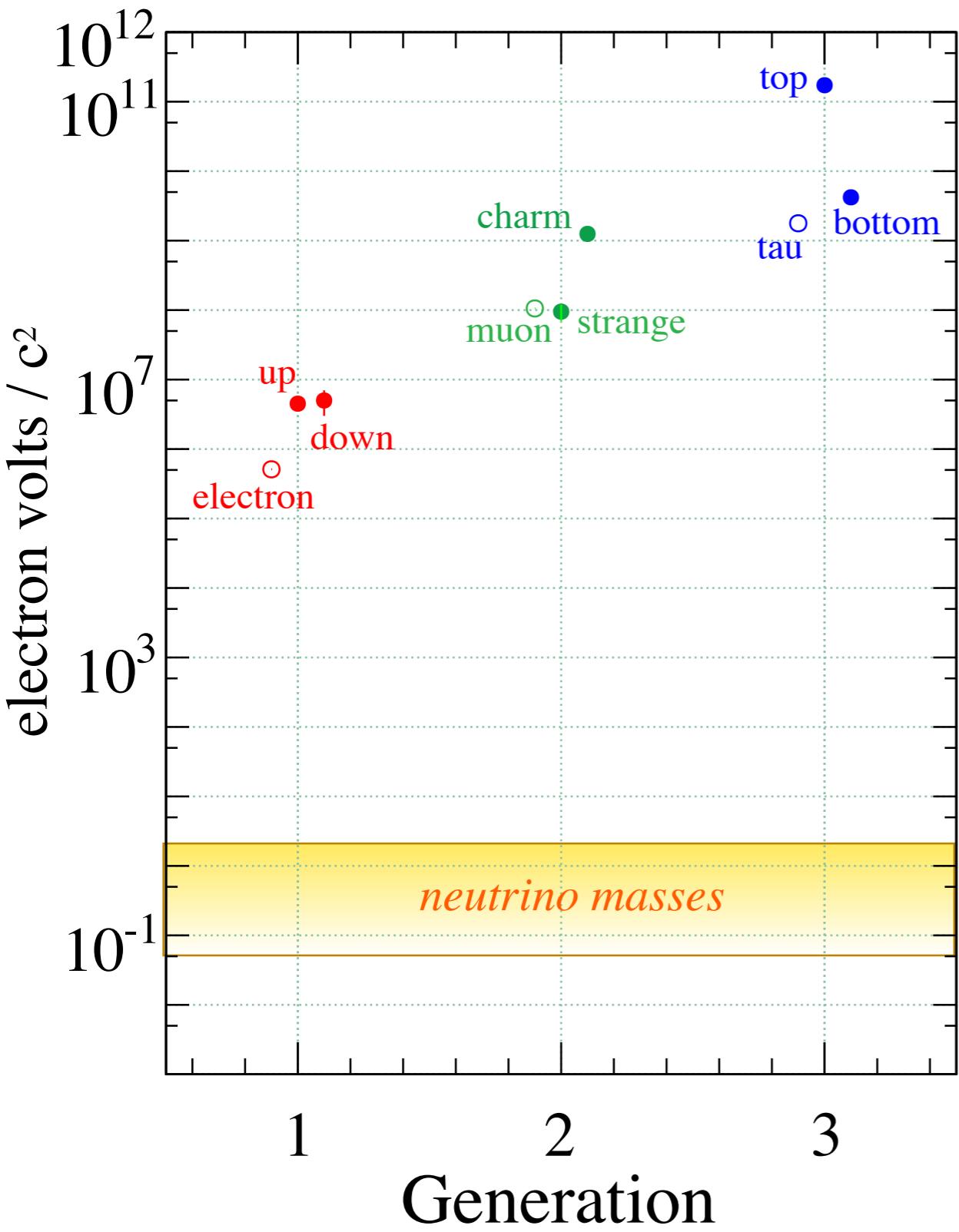
- Mass ordering
- Nature of ν_3 -
 θ_{23} octant
- Is CP
violated?
- Is there more
to this
picture?



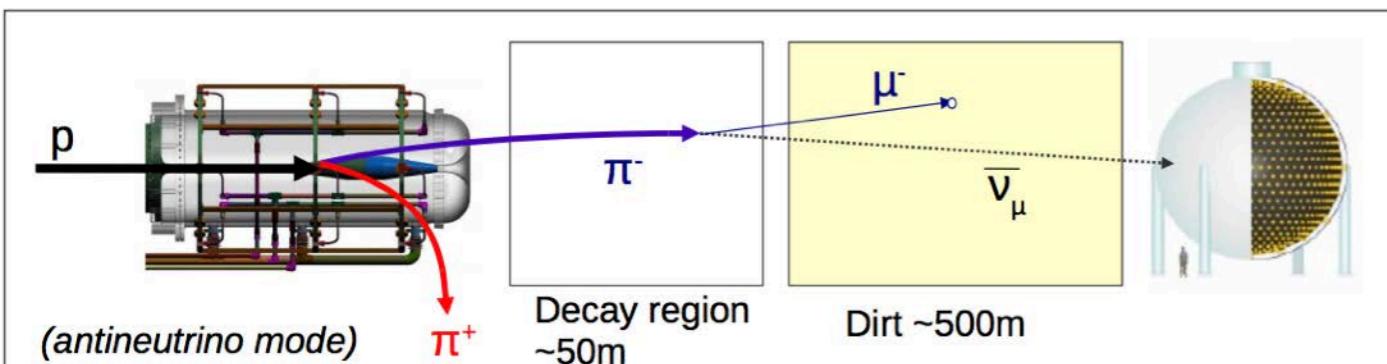
Motivation for sterile neutrino searches



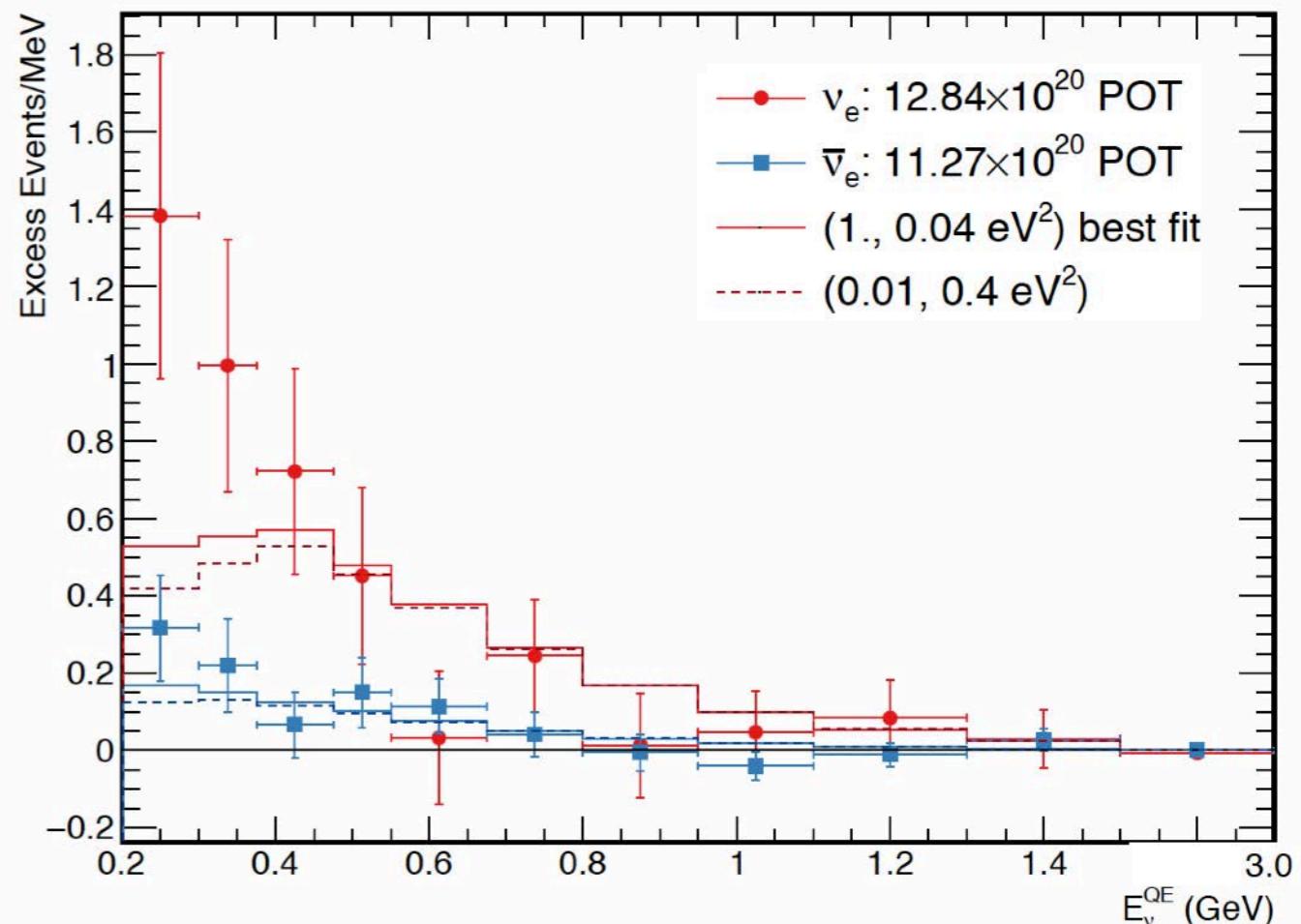
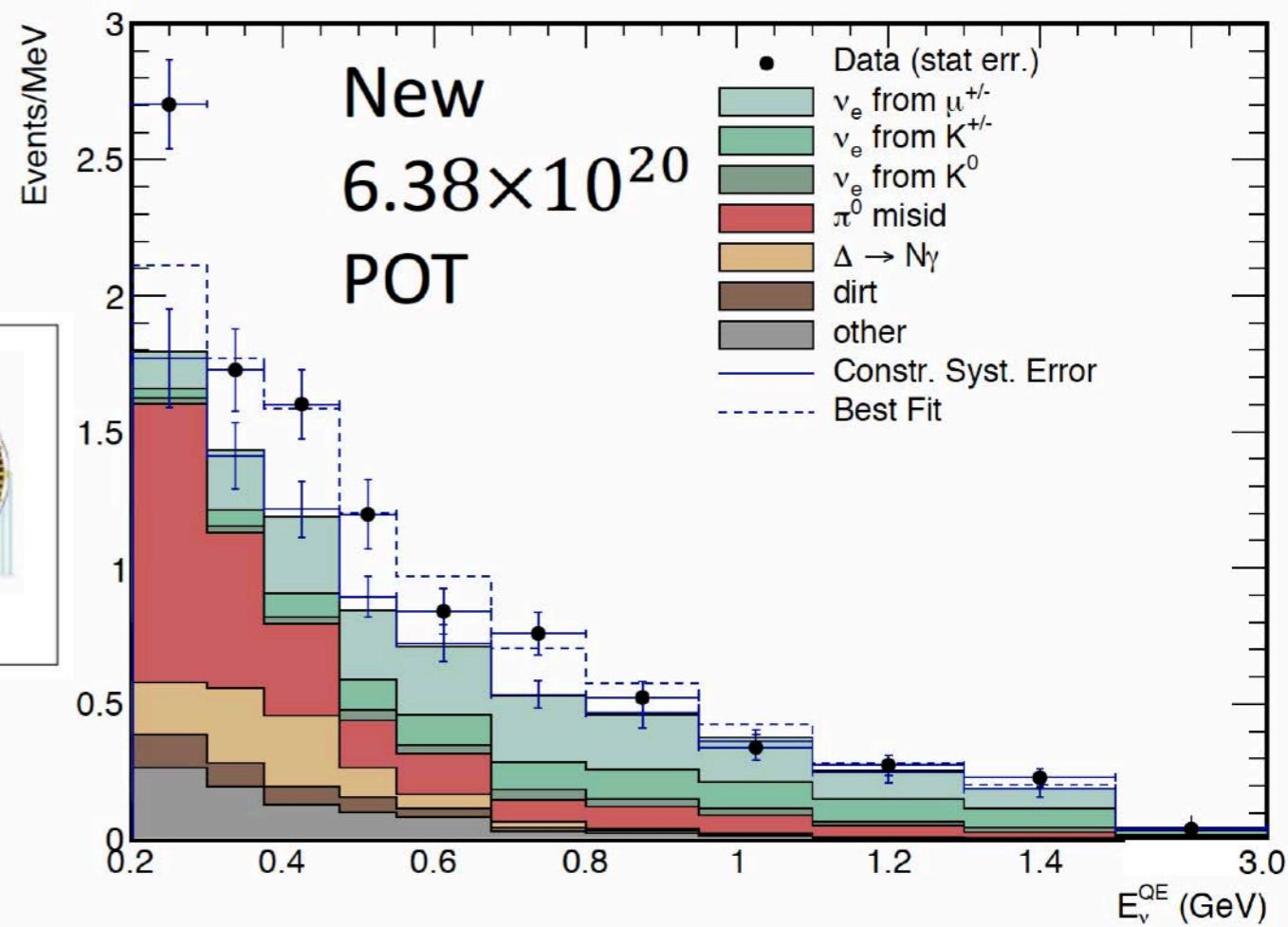
Motivation for sterile neutrino searches

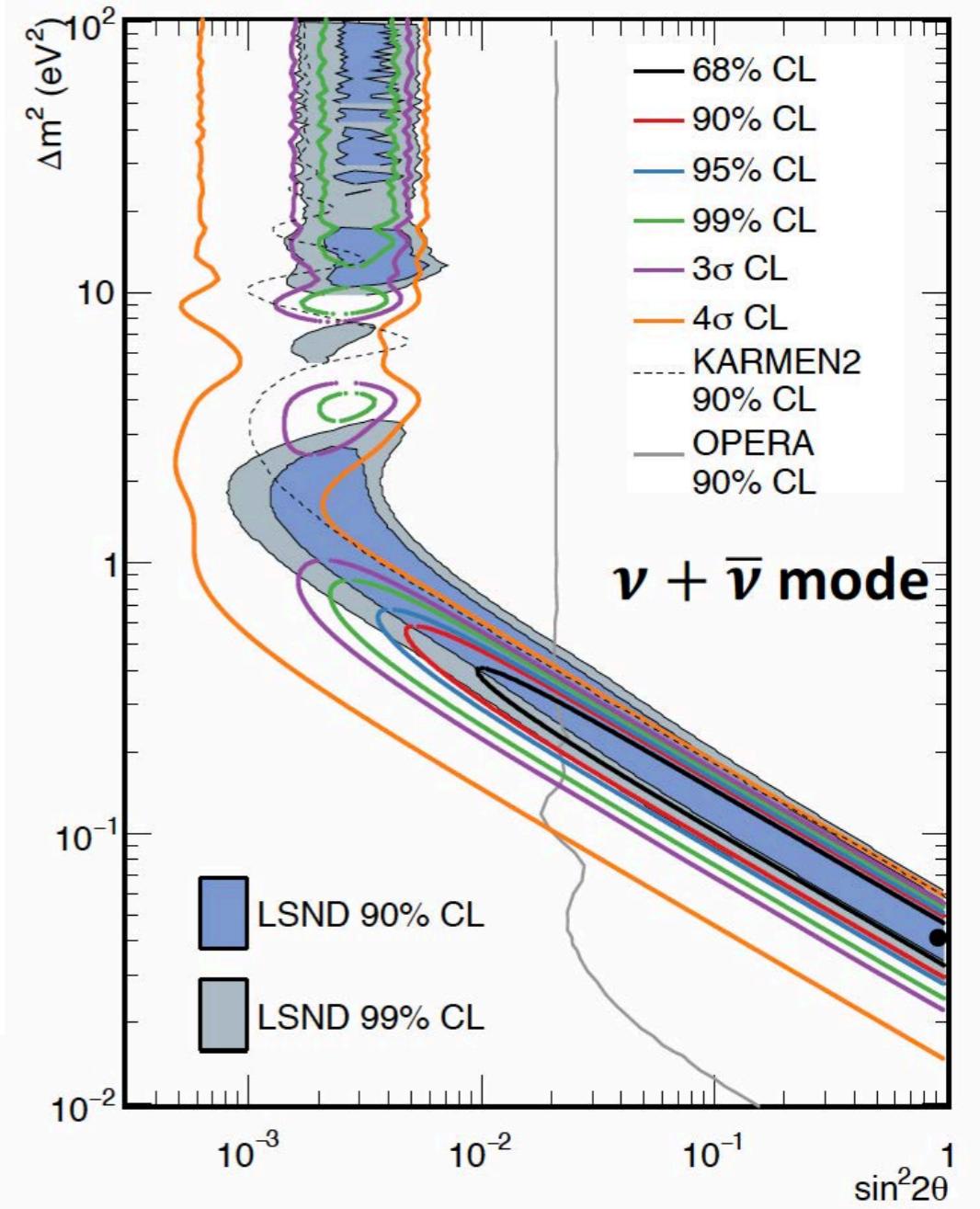
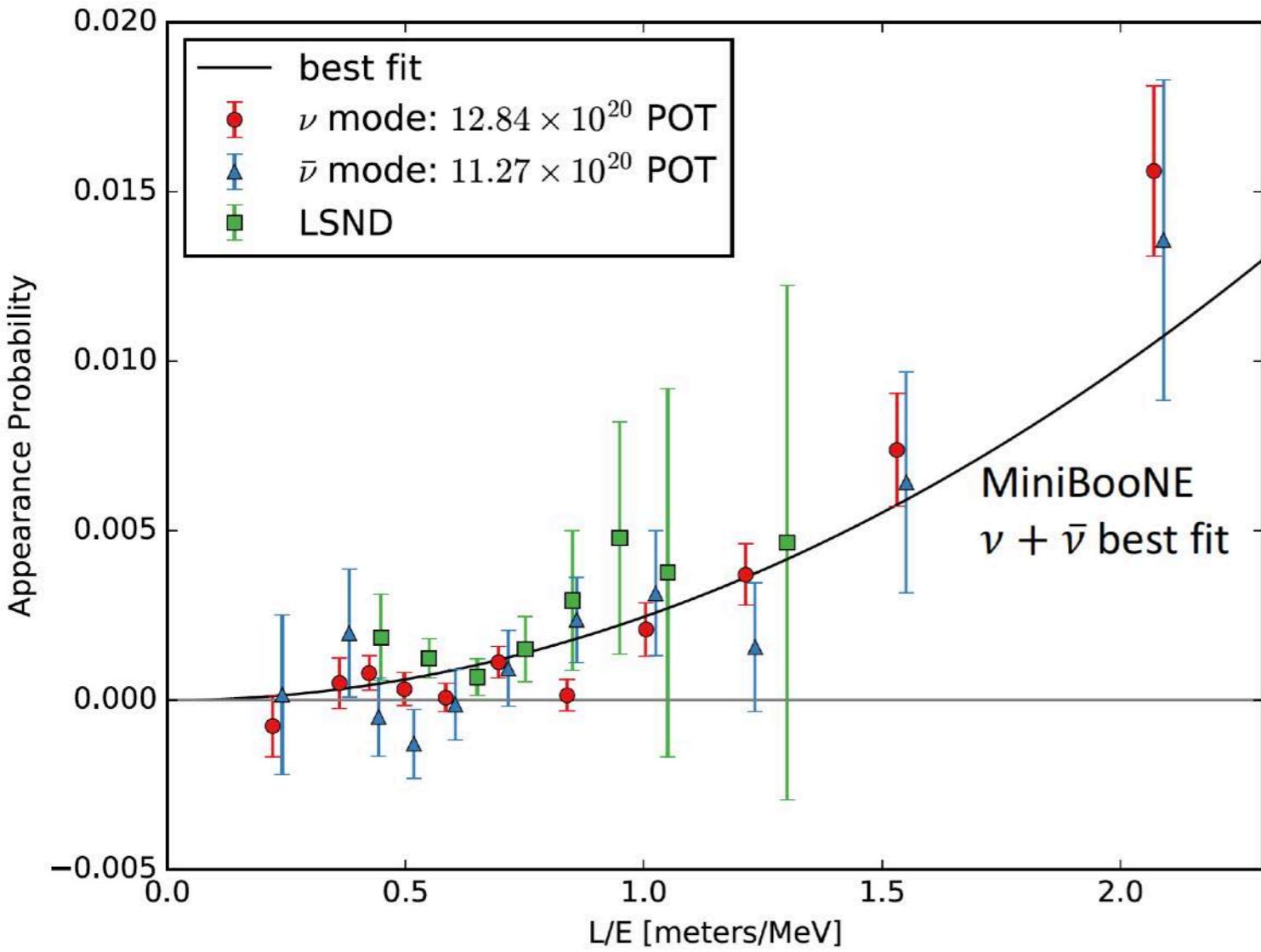


MiniBooNE excess



- MiniBooNE is a single-detector experiment on the Fermilab 8 GeV Booster neutrino beam line intended to explore the LSND reported excess.
- MiniBooNE sees an excess over backgrounds at low energies in both neutrino and antineutrino beams.

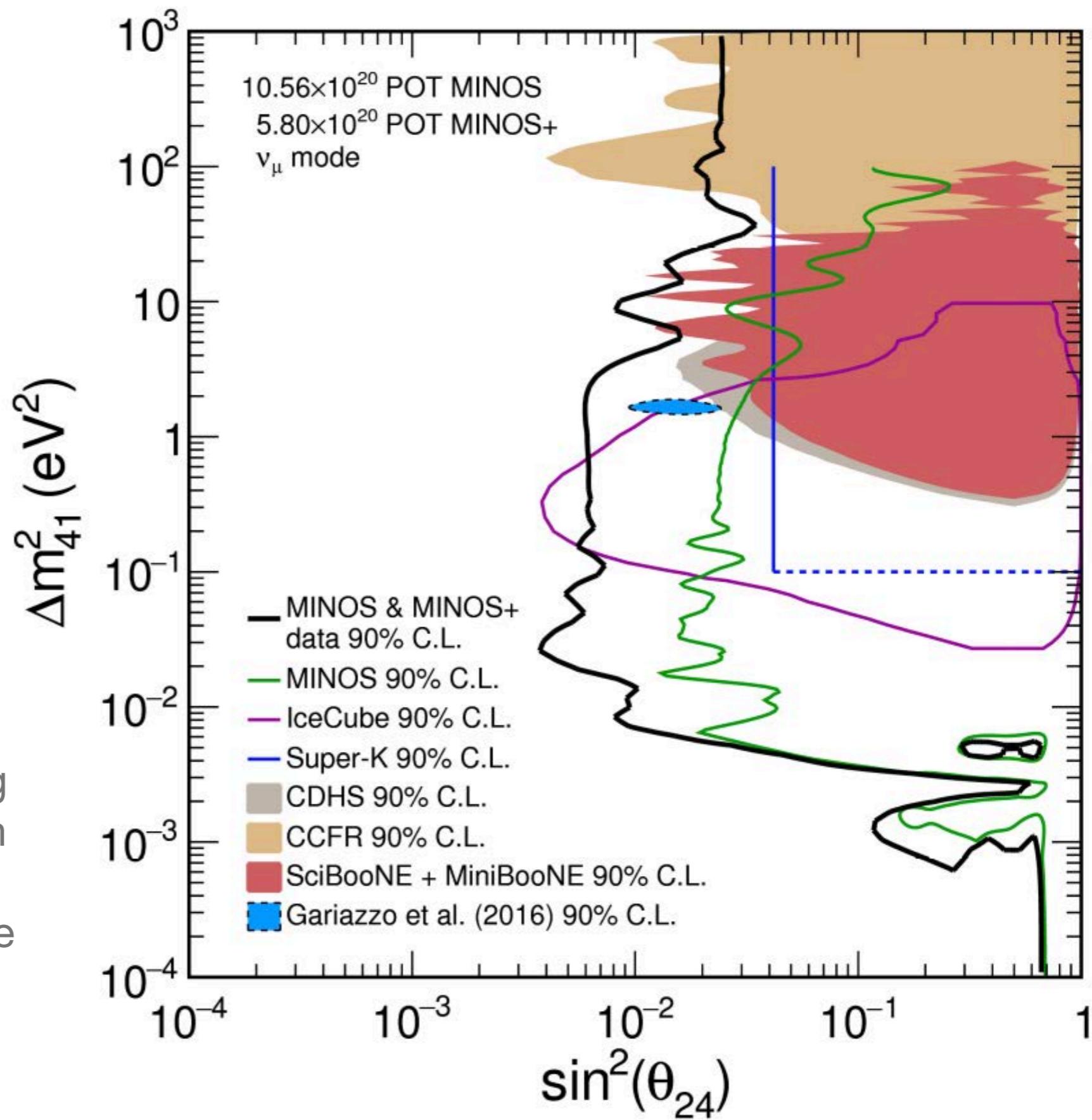




Interpretations of LSND and MiniBooNE in 3+1

Search for sterile neutrinos in disappearance channel

- Electron neutrino appearance through $\nu_\mu \rightarrow \nu_e$ with eV-scale sterile neutrinos implies additional disappearance in $\nu_\mu \rightarrow \nu_\mu$
- This is not seen by a number of experiments, esp. MINOS and IceCUBE
- This creates a tension: there is no model involving sterile neutrinos which can simultaneously fit the appearance claims and the disappearance measurements.



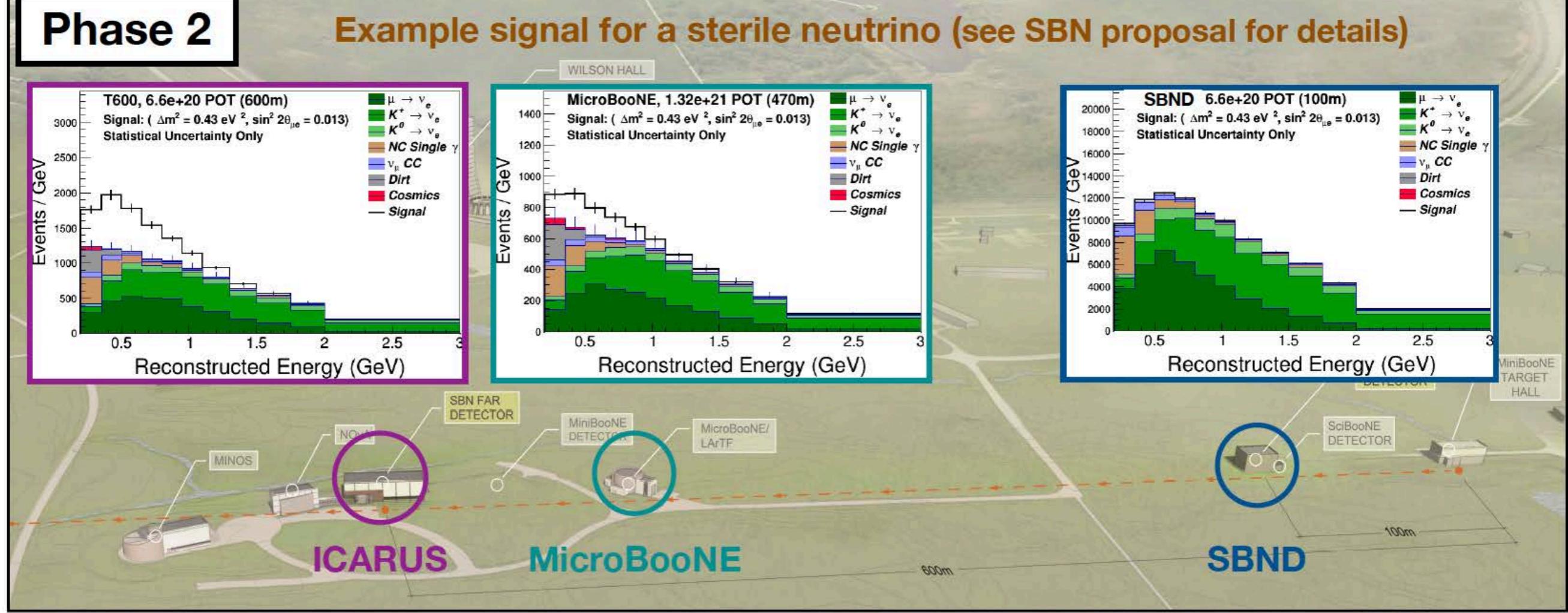
Fermilab Short Baseline Program

3-5 σ resolution of SBN anomalies in 5 years

A three liquid argon detector experiment:

Phase 2

Example signal for a sterile neutrino (see SBN proposal for details)



Far detector
 $L = 600 \text{ m}$
 $M = 476 \text{ ton}$



First detector
 $L = 470 \text{ m}$
 $M = 85 \text{ ton}$

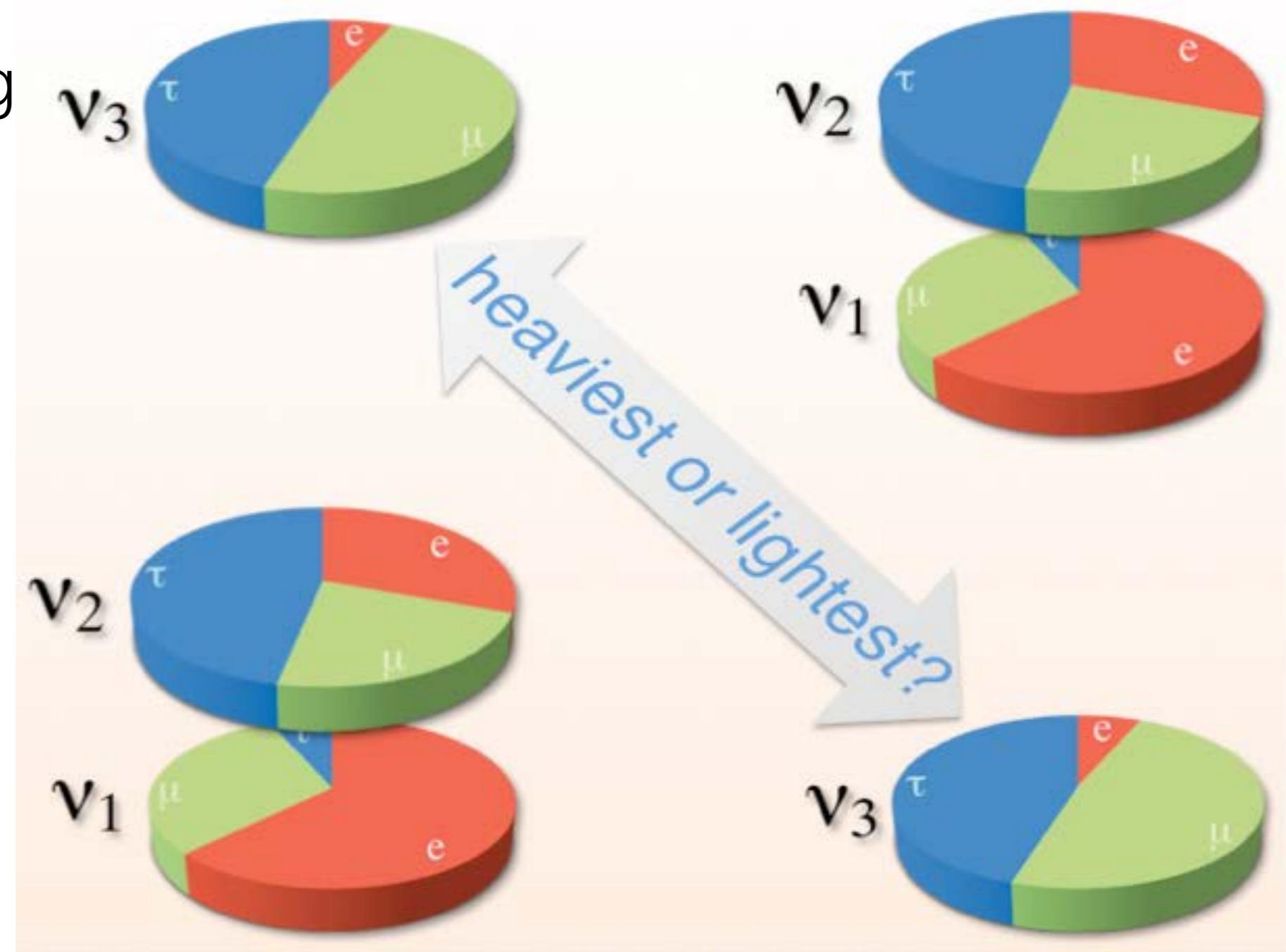


Near detector
 $L = 110 \text{ m}$
 $M = 112 \text{ ton}$



Next Questions In Neutrino Physics

- Mass ordering
- Nature of ν_3 - θ_{23} octant
- Is CP violated?
- Is there more to this picture?



Neutrino oscillations at long baseline

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]

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - 4 \cos^2 \theta_{13} \sin^2 \theta_{23} [1 - \cos^2 \theta_{13} \sin^2 \theta_{23}] \sin^2 \Delta_{3i}$$

$$\simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{3i}$$

$$P(\nu_\mu \rightarrow \nu_e) \simeq |\sqrt{P_{\text{atm}}} e^{-i(\Delta_{32} + \delta)} + \sqrt{P_{\text{sol}}}|^2$$

$$= P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}}P_{\text{sol}}} (\cos \Delta_{32} \cos \delta \mp \sin \Delta_{32} \sin \delta)$$

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

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

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

$aL = 0.08$ for $L = 295$ km

$aL = 0.23$ for $L = 810$ km

$aL = 0.37$ for $L = 1300$ km

Parameter

Channels

Question

$\sin^2 2\theta_{23}$: $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$:

Is θ_{23} maximal?

$\sin^2 \theta_{23} \sin^2 2\theta_{13}$: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

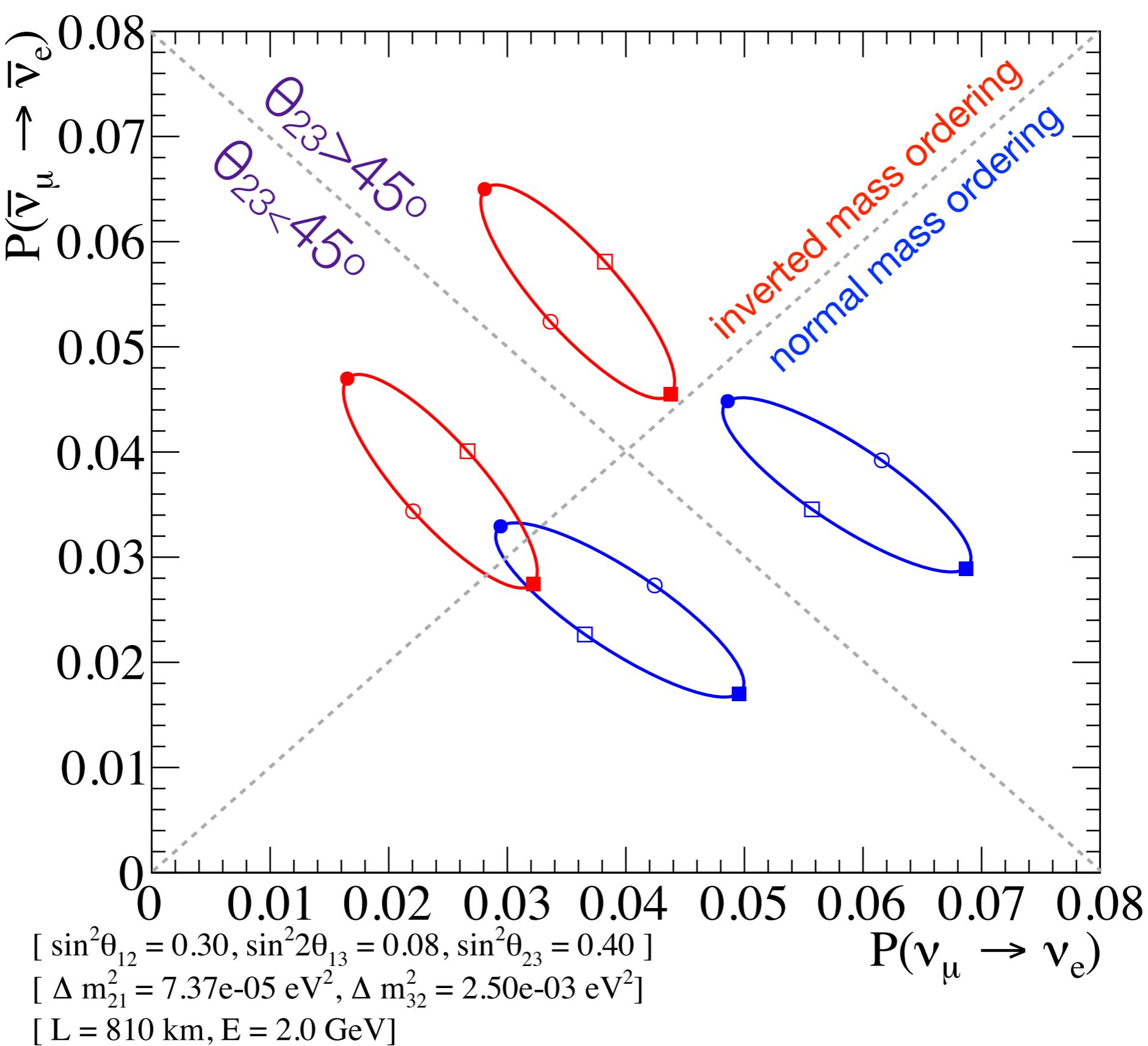
Octant of θ_{23}

sign $[\Delta_{31}]$: $\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Neutrino mass hierarchy

δ_{CP} : $\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Is CP violated?



Neutrino oscillations

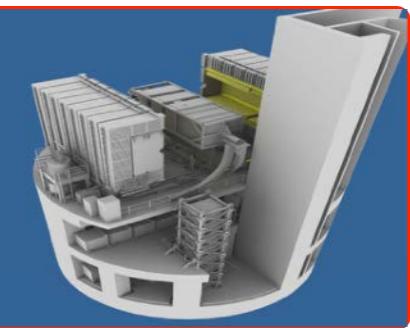
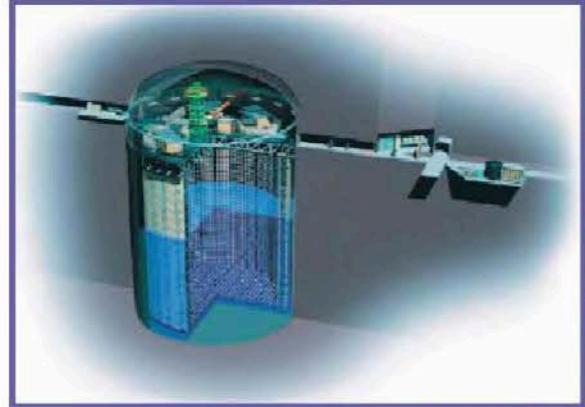
Bi-probability plots for the NOvA experiment

T2K

$E_\nu \simeq 0.7 \text{ GeV}$,

$$\Delta \equiv \frac{1.27 \cdot 0.0025 \text{ eV}^2 \cdot 295 \text{ km}}{0.7 \text{ GeV}} \simeq \frac{\pi}{2}$$

Super-Kamiokande
(ICRR, Univ. Tokyo)



INGRID + ND280

J-PARC Main Ring
(KEK-JAEA, Tokai)



NOvA

$E_\nu \simeq 2 \text{ GeV}$,

$$\Delta \equiv \frac{1.27 \cdot 0.0025 \text{ eV}^2 \cdot 810 \text{ km}}{2 \text{ GeV}} \simeq \frac{\pi}{2}$$

NOvA Far Detector



NOvA
Near
Detector

Fermilab Main Injector



Summary of sensitivity of $\nu_\mu \rightarrow \nu_e$ rates to physics parameters

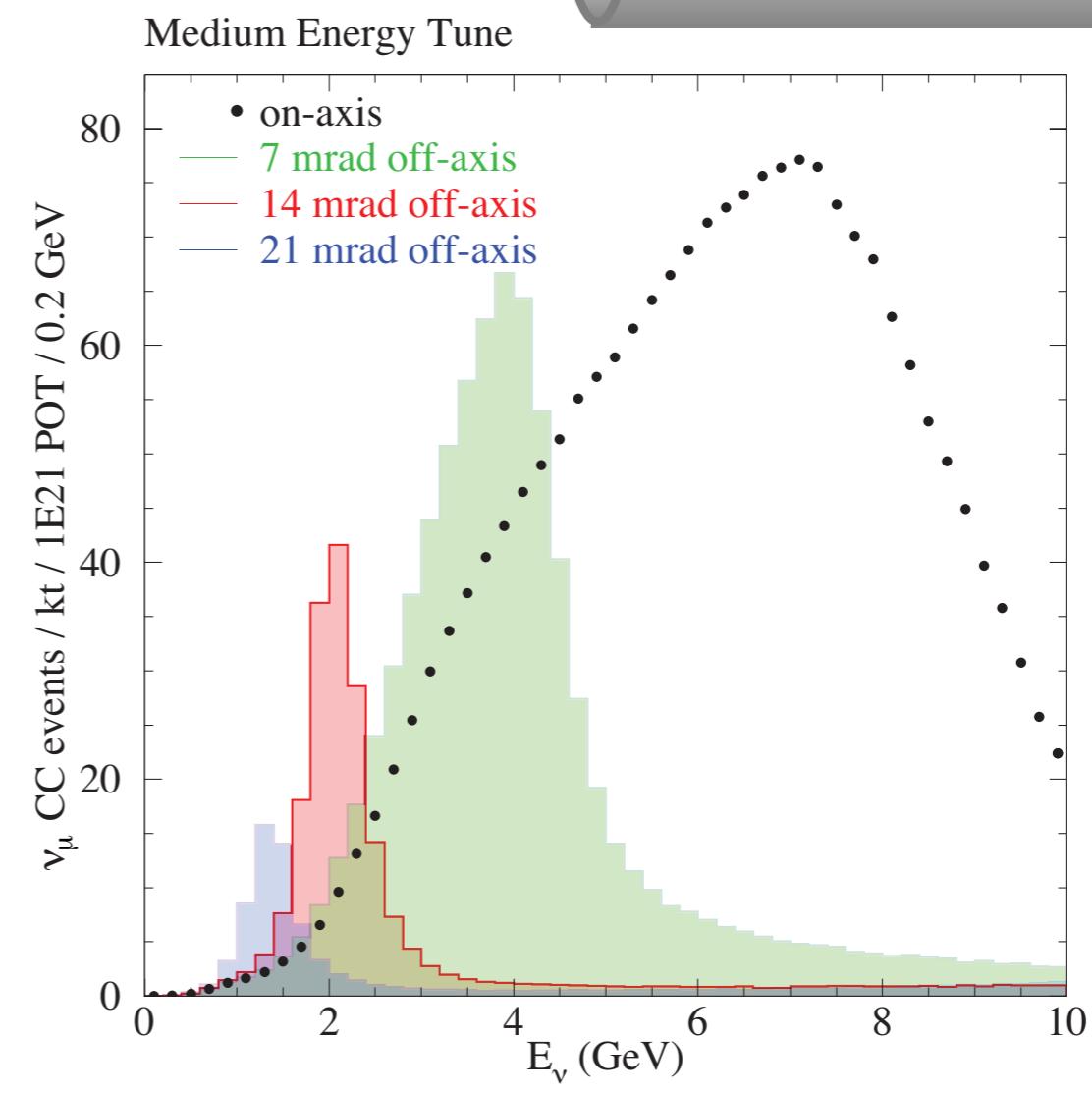
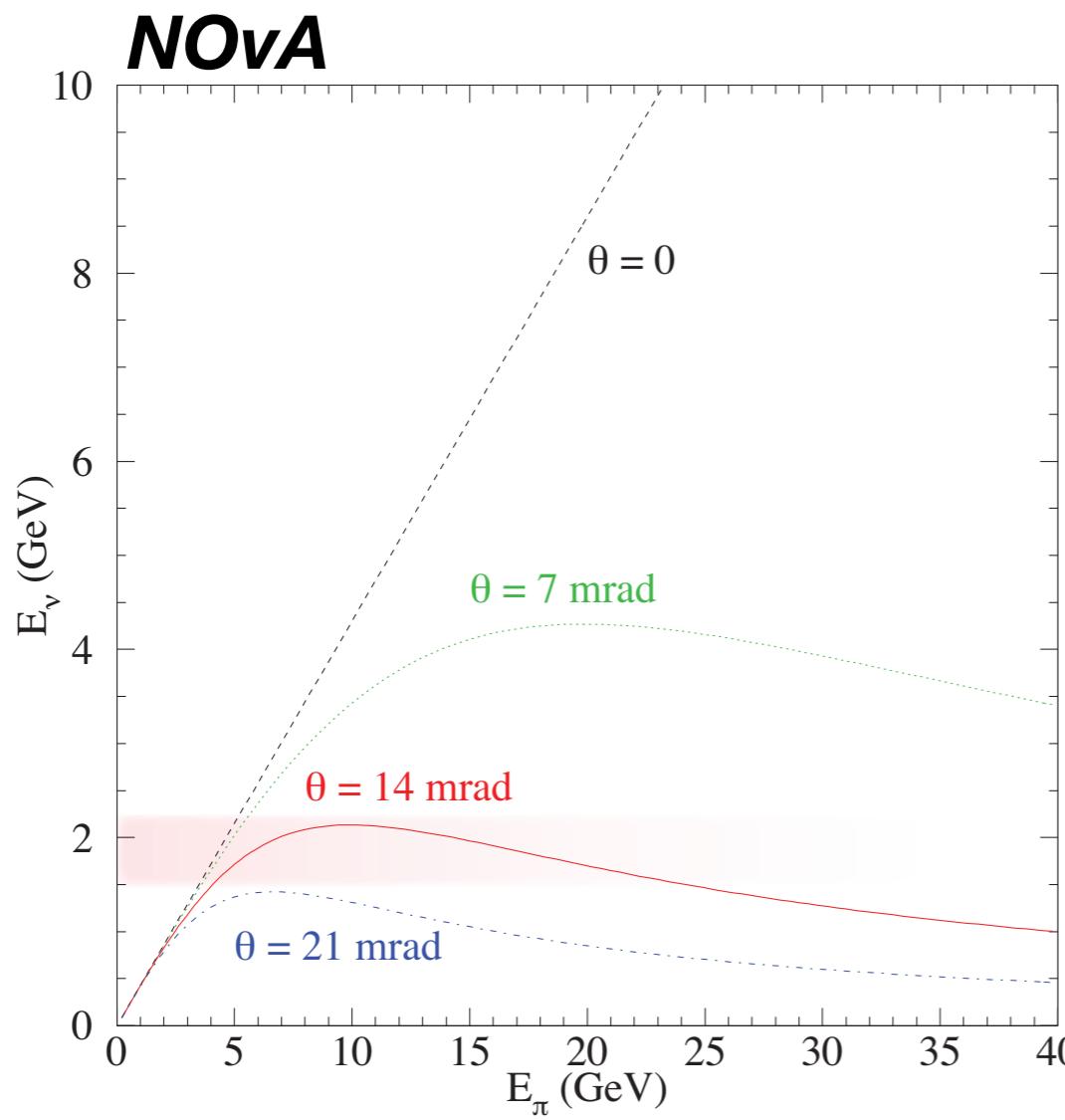
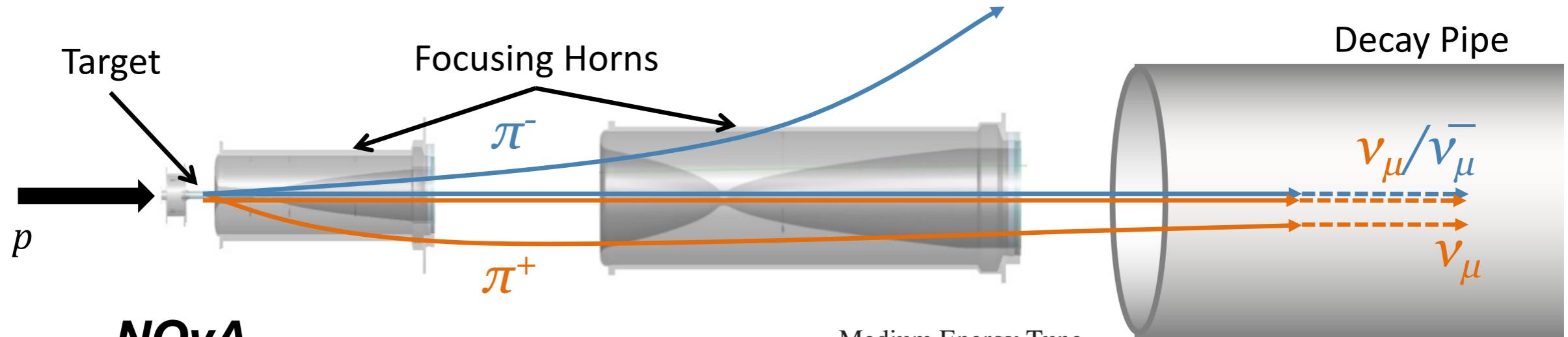
Factor	Type	Inverts for $\bar{\nu}$?	NOvA	T2K
Matter effect (mass ordering)	Binary	Yes	$\pm 19\%$	$\pm 10\%$
CP violation	Bounded, continuous	Yes	$[-22...+22]\%$	$[-29...+29]\%$
θ_{23} octant	Unbounded, continuous	No	$[-22...+22]\%$	$[-22...+22]\%$

Nota bene:

- Calculations are for rate only; there is some additional information in the energy spectrum
- These estimates neglect non-linearities in combining different effects
- In the calculation of the matter effect and CP violation effects the calculated values account for the fact that T2K runs at an energy on the first oscillation maximum while NOvA runs at an energy slightly above the oscillation maximum
- θ_{23} was varied inside the $\pm 2\sigma$ range found by a recent global fit (PRD 90, 093006)

Making a neutrino beam

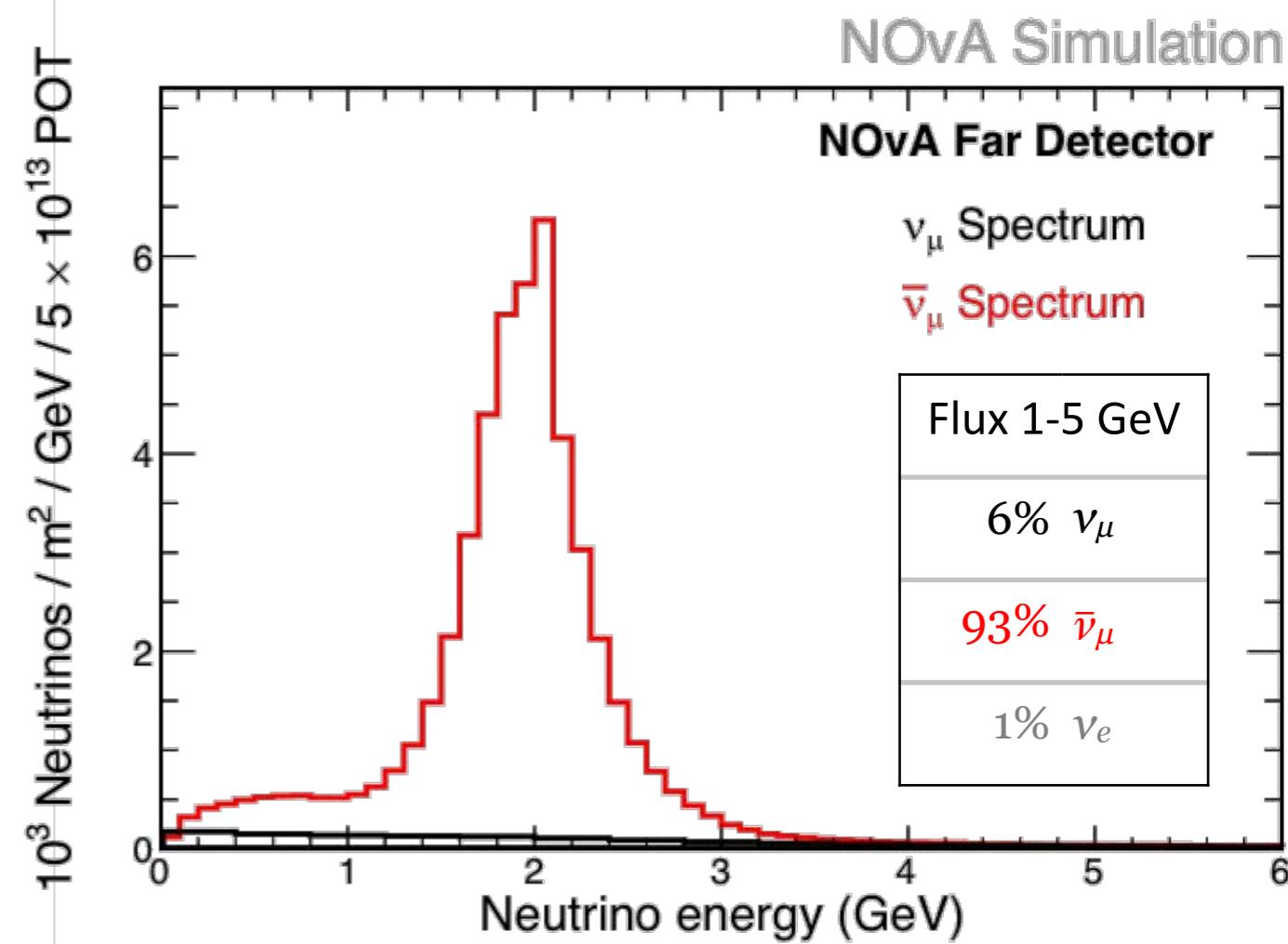
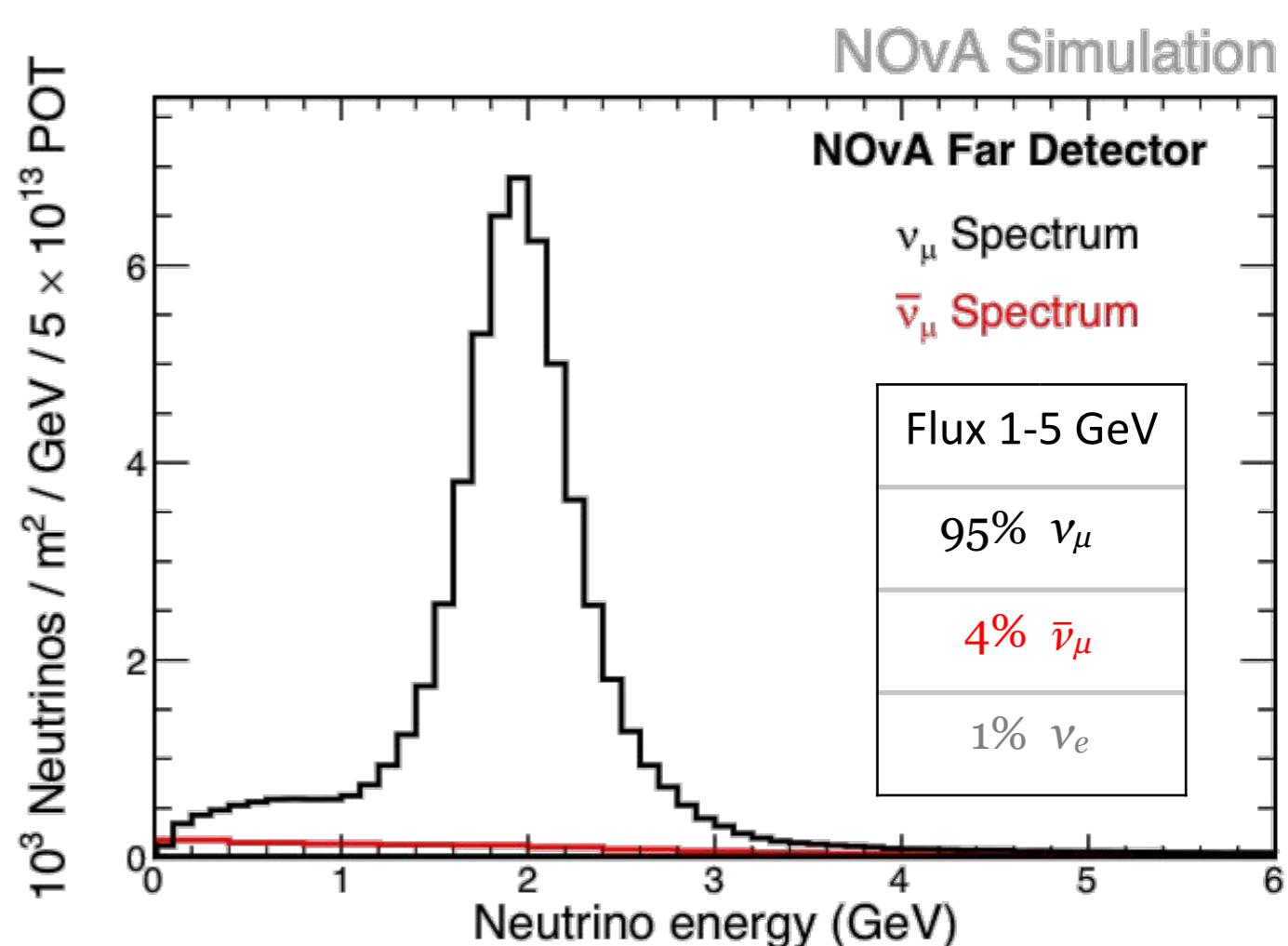
$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{m_\pi^2} \frac{E_\pi}{1 + \gamma^2 \theta_{\text{Lab}}^2}$$

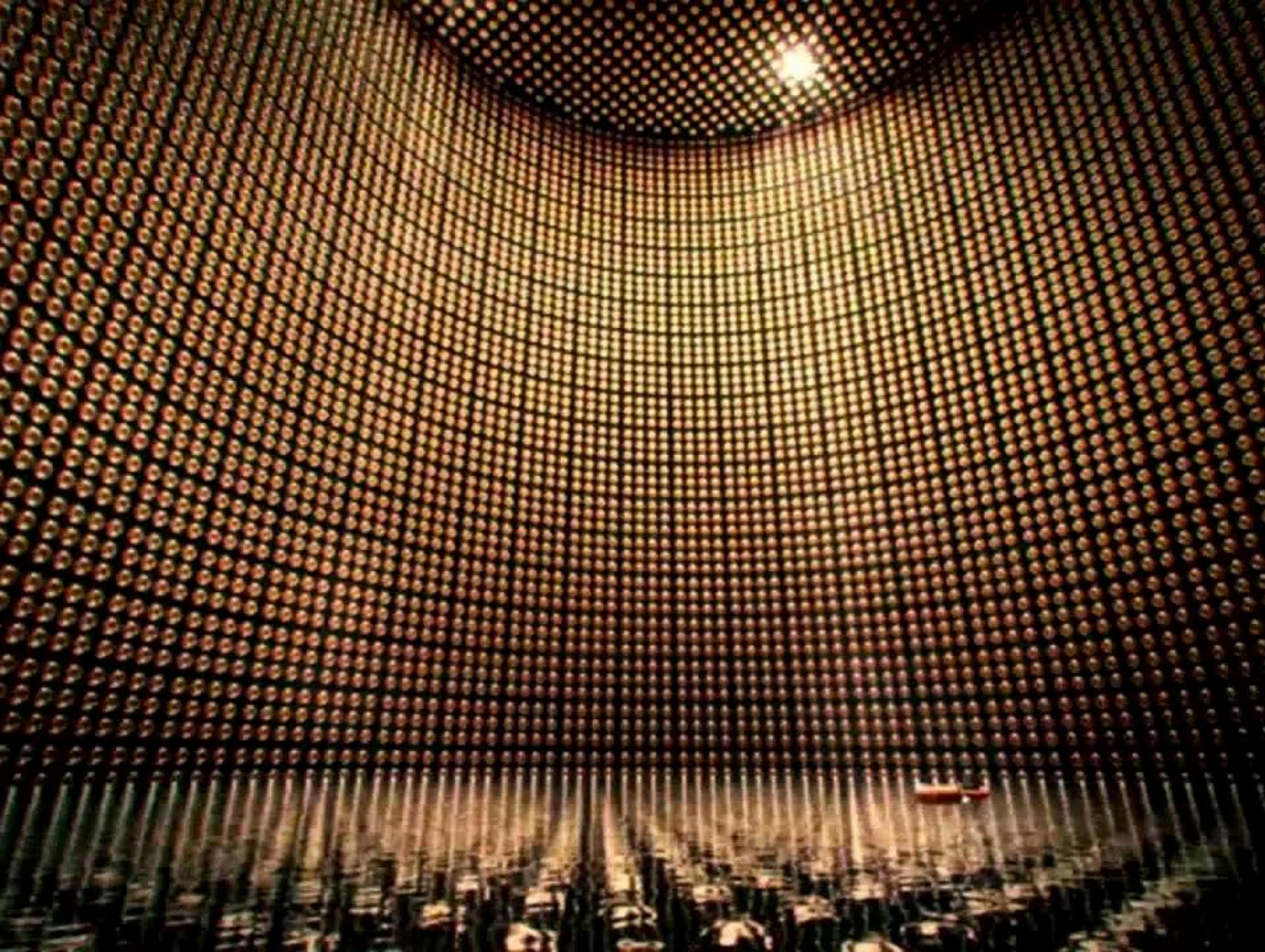


Making neutrino and antineutrino beams

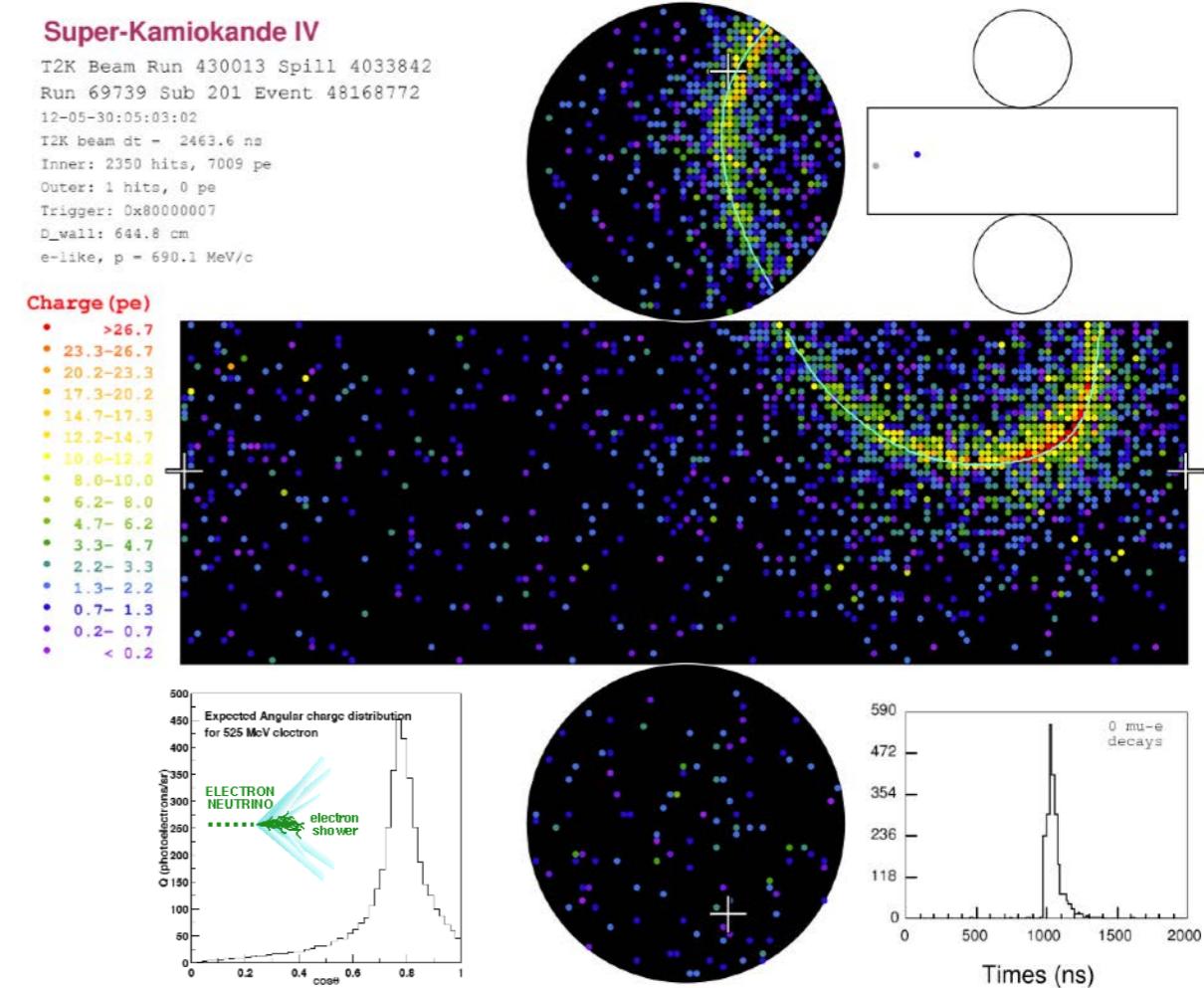
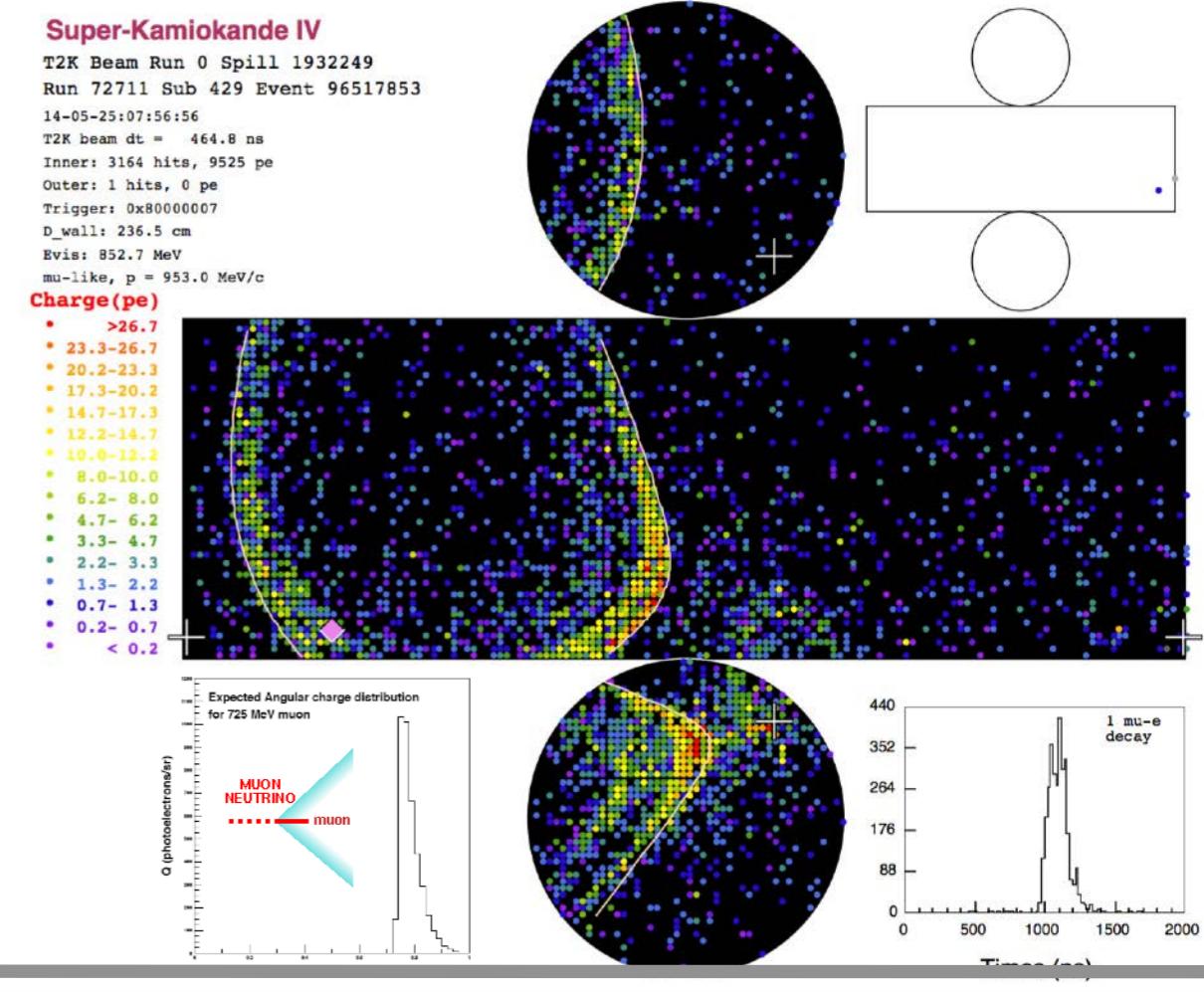
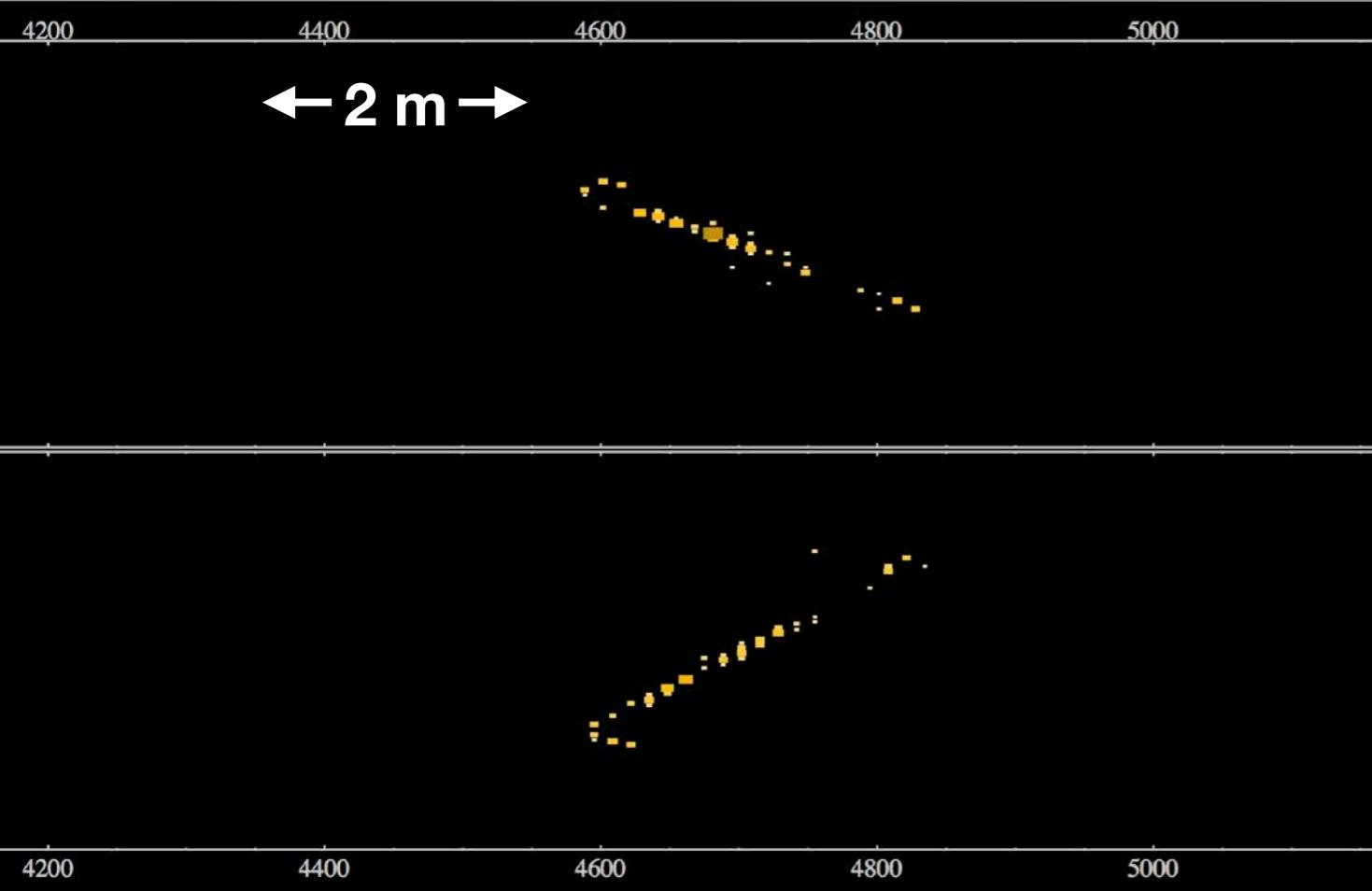
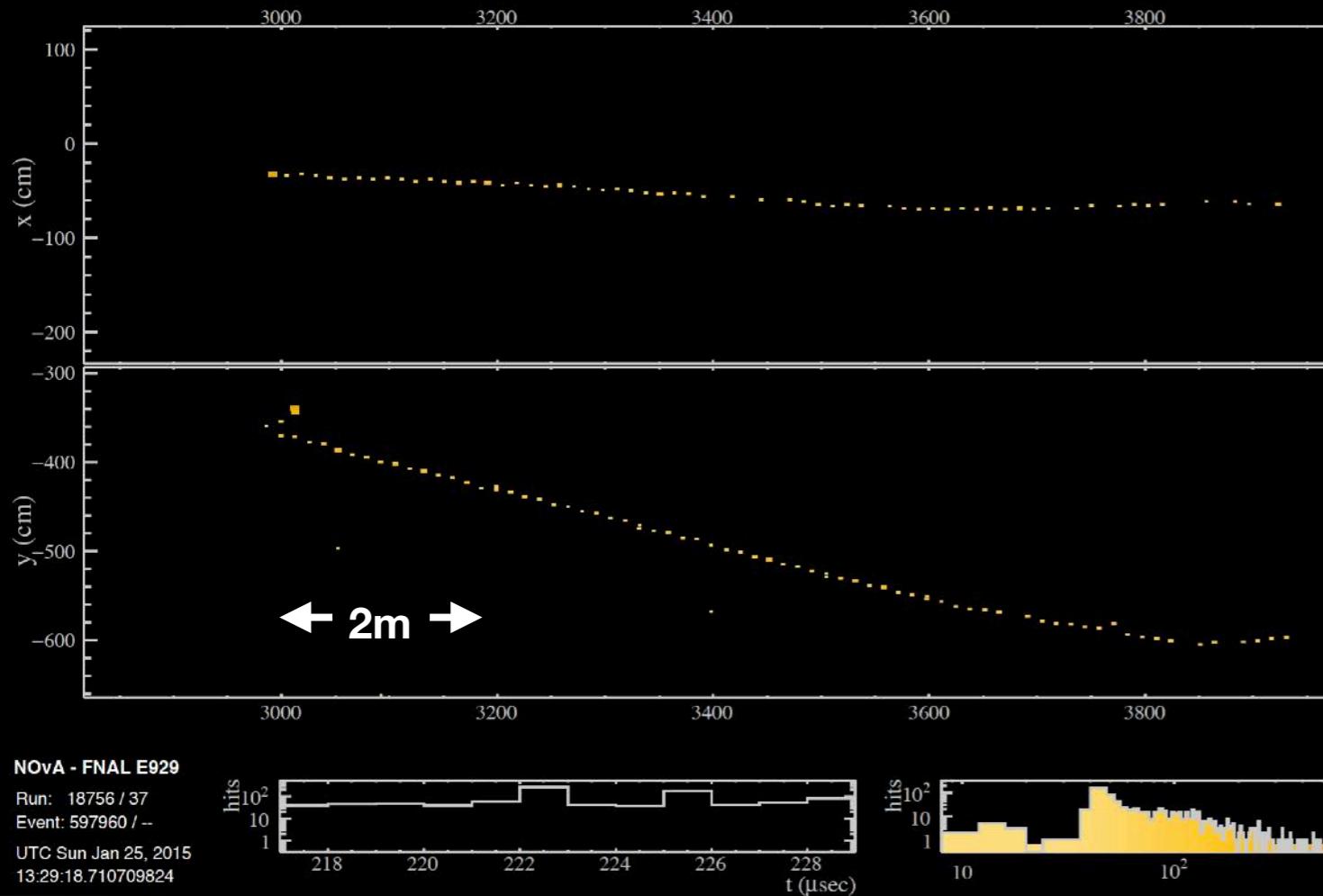
Top: Neutrino beam flux

Bottom: Antineutrino beam flux







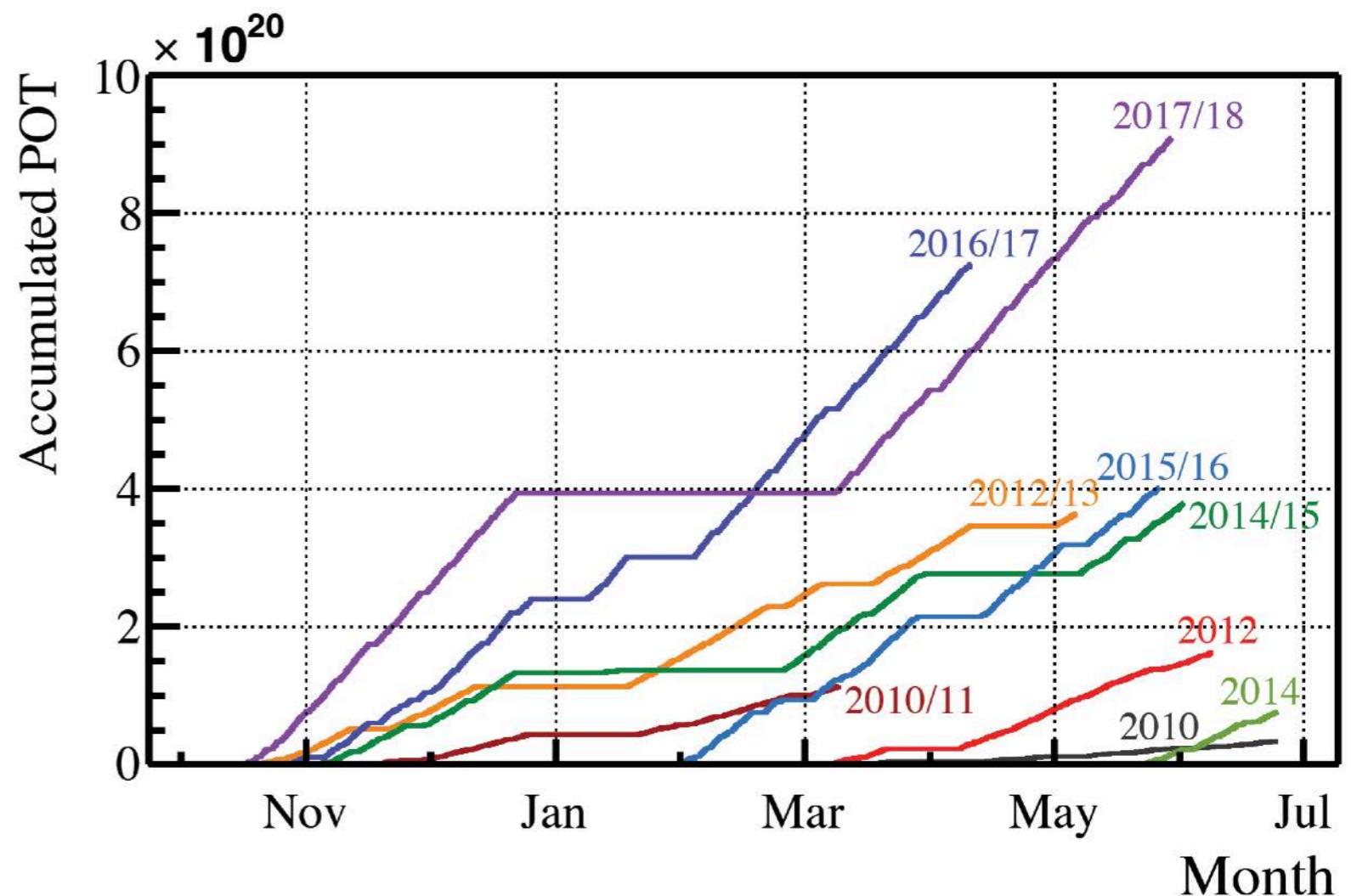


T2K Beam Delivery

Began operations in 2010

This year:

- ▶ 485 kW operations
- ▶ 9E20 protons-on-target delivered at 30 GeV
- ▶ Doubled the antineutrino exposure previous reports

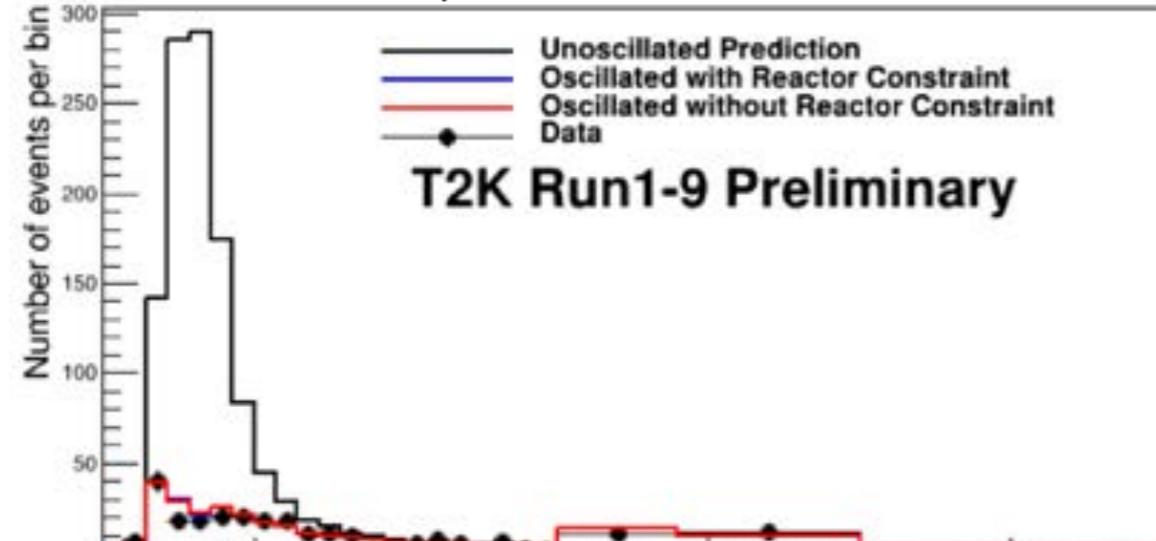


Totals to date:

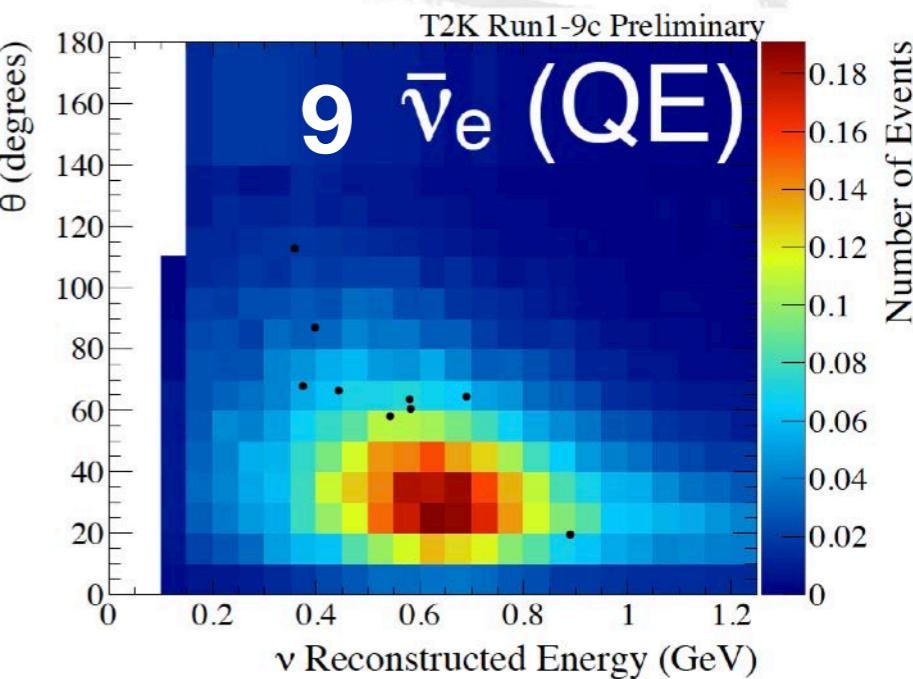
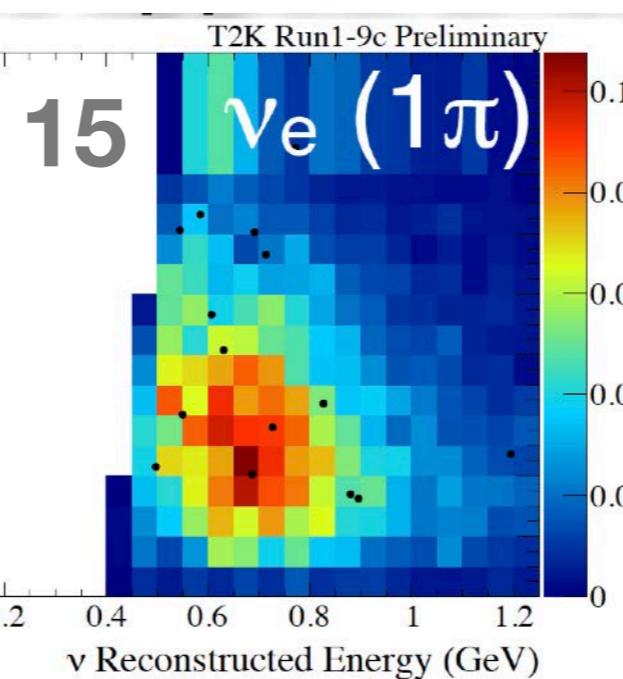
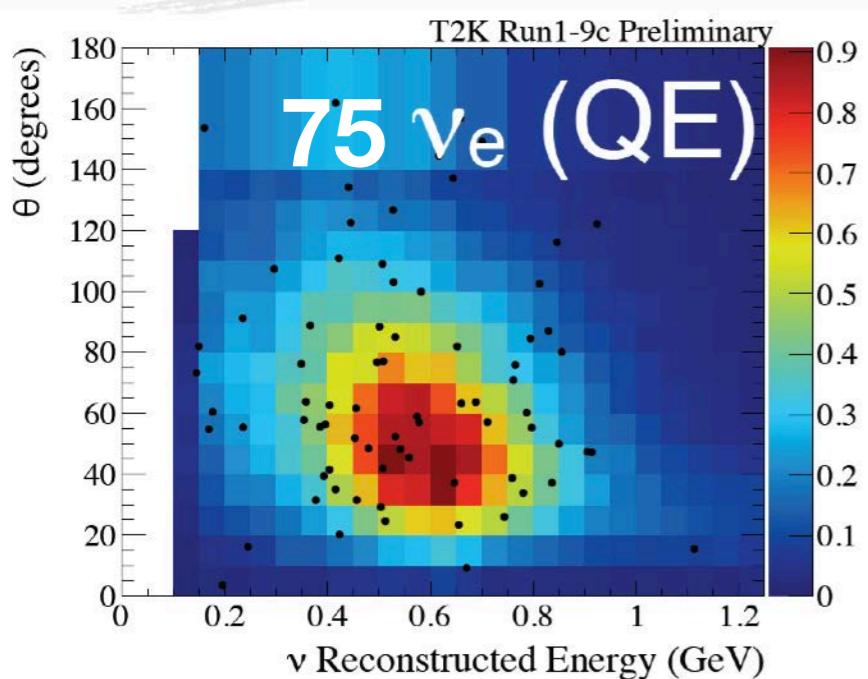
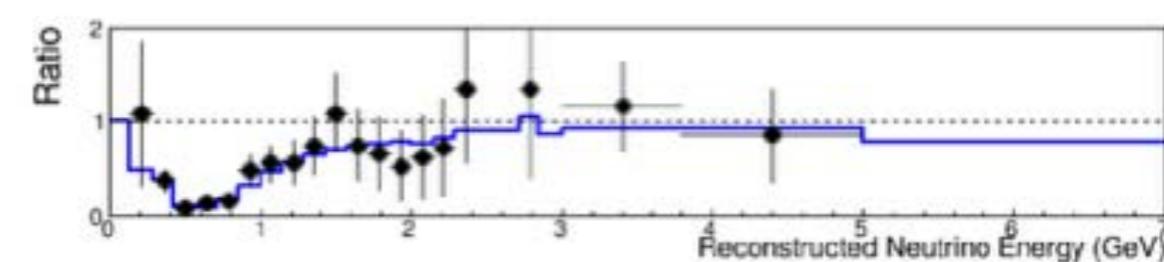
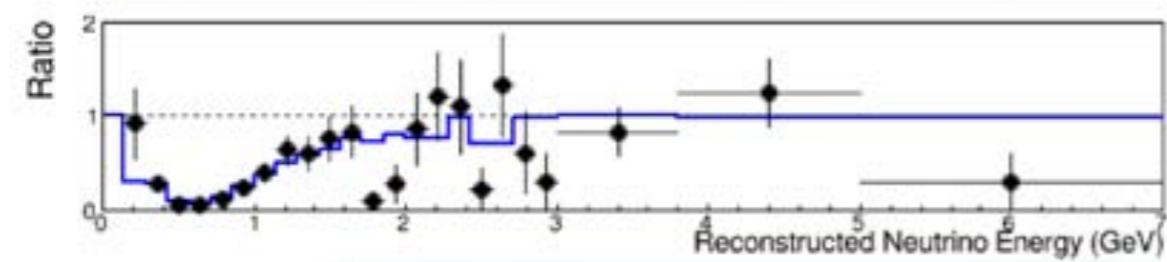
14.9E20 protons neutrino beam at 30 GeV

11.2E20 protons in antineutrino beam at 30 GeV

$243 \nu_\mu - \text{CC events}$



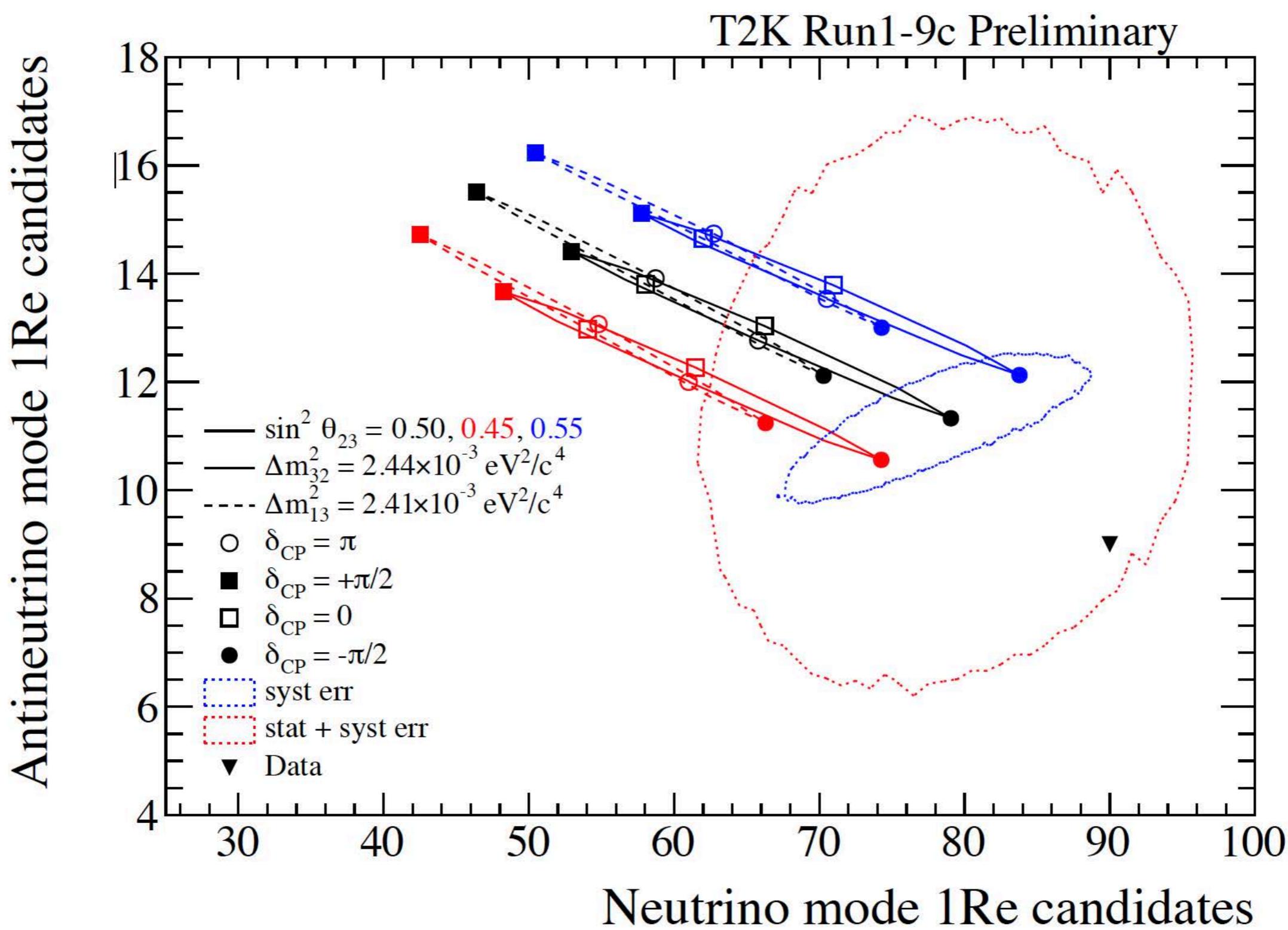
$102 \bar{\nu}_\mu - \text{CC events}$



T2K event spectra

$9 \bar{\nu}_e$ CC events sit on background of 6.5 events

Curiously, the $\bar{\nu}_e$ events fit the background shape ($P=23\%$) better than the signal shape ($P=9\%$)

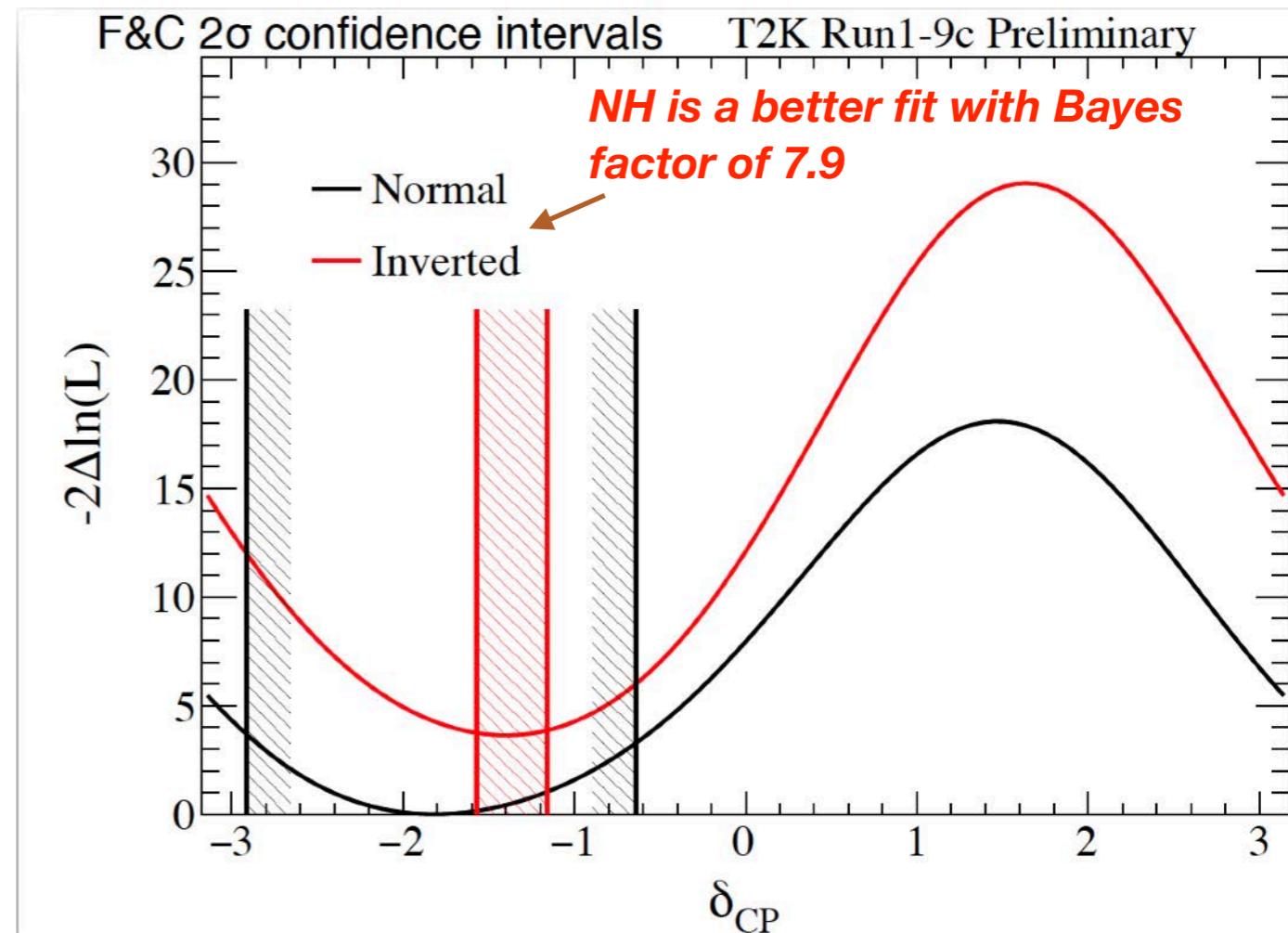
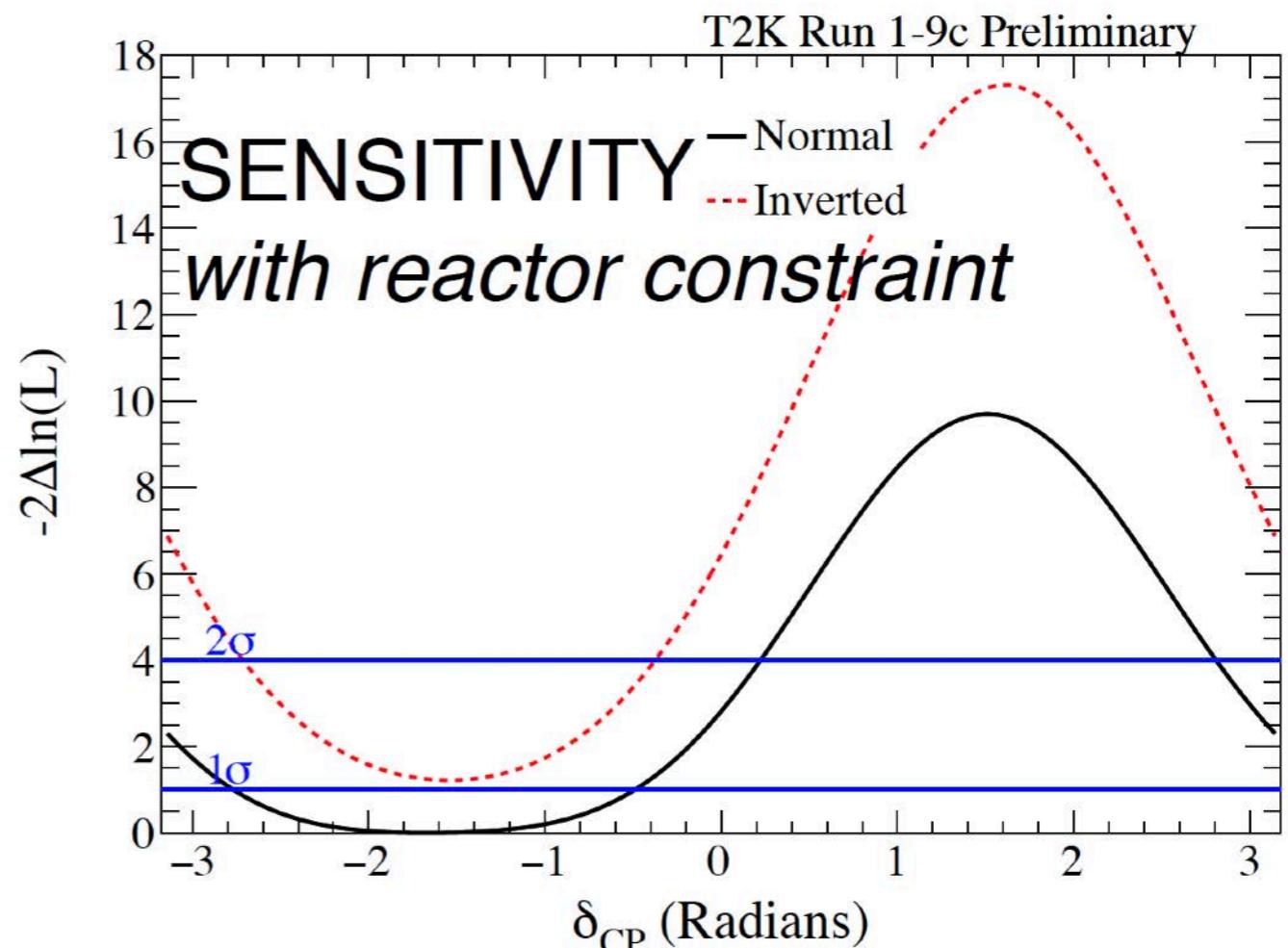


**T2K neutrino and
antineutrino event counts**

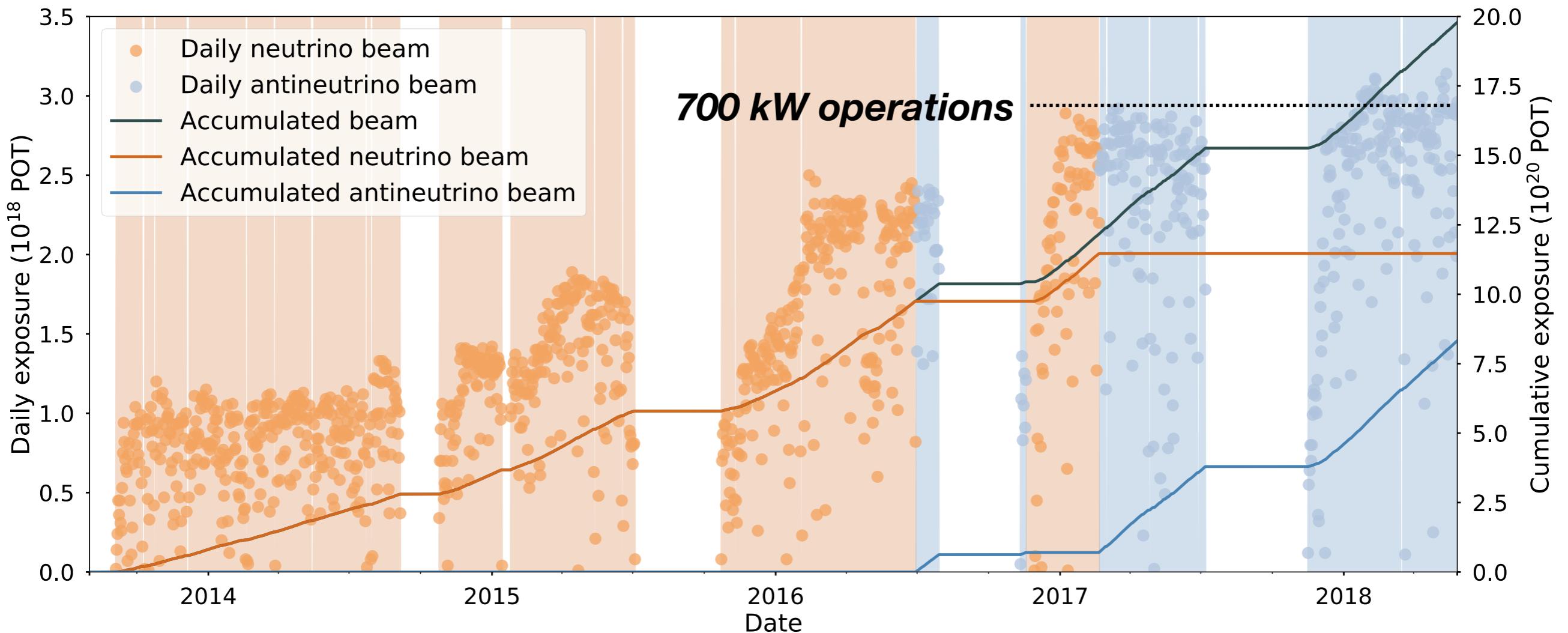
Relative to the best-fit parameters
T2K has seen an upward fluctuation
in neutrino events and a downward
fluctuation in antineutrino events.

T2K measurement of CP phase δ

- Expected sensitivity (top) using current exposure to exclude CP conserving values is CP violation is maximal is currently just less than 2σ . Expect 20% of experiments to exclude at 2σ or more.
- Current measurement (bottom) favors nearly maximal CP violation and excludes CP conserving values at $>2\sigma$.



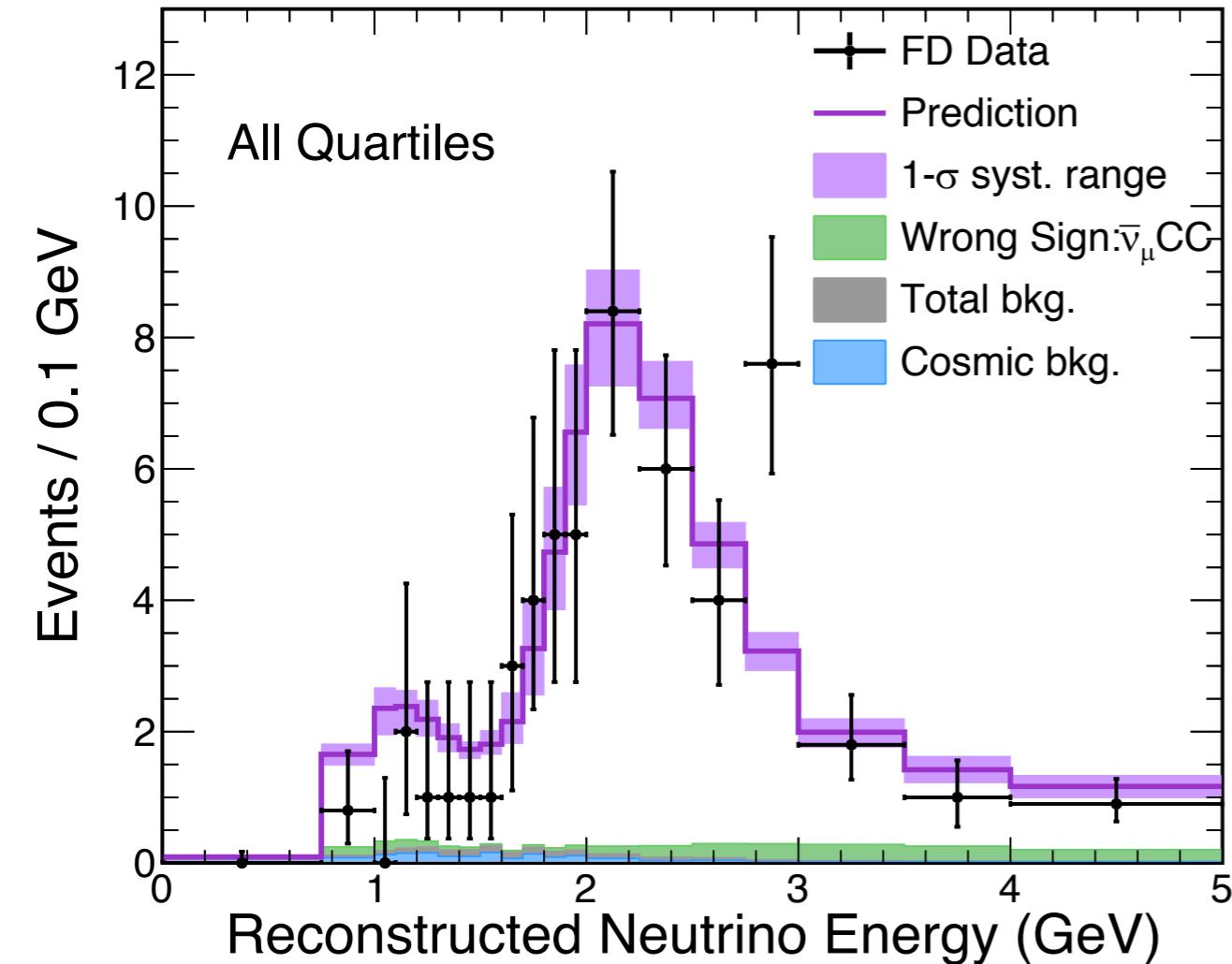
NOvA neutrino and antineutrino running



- Reported results from 9E20 protons-on-target delivered at 120 GeV in neutrino mode
- New results using 7E20 protons-on-target delivered at 120 GeV in antineutrino mode

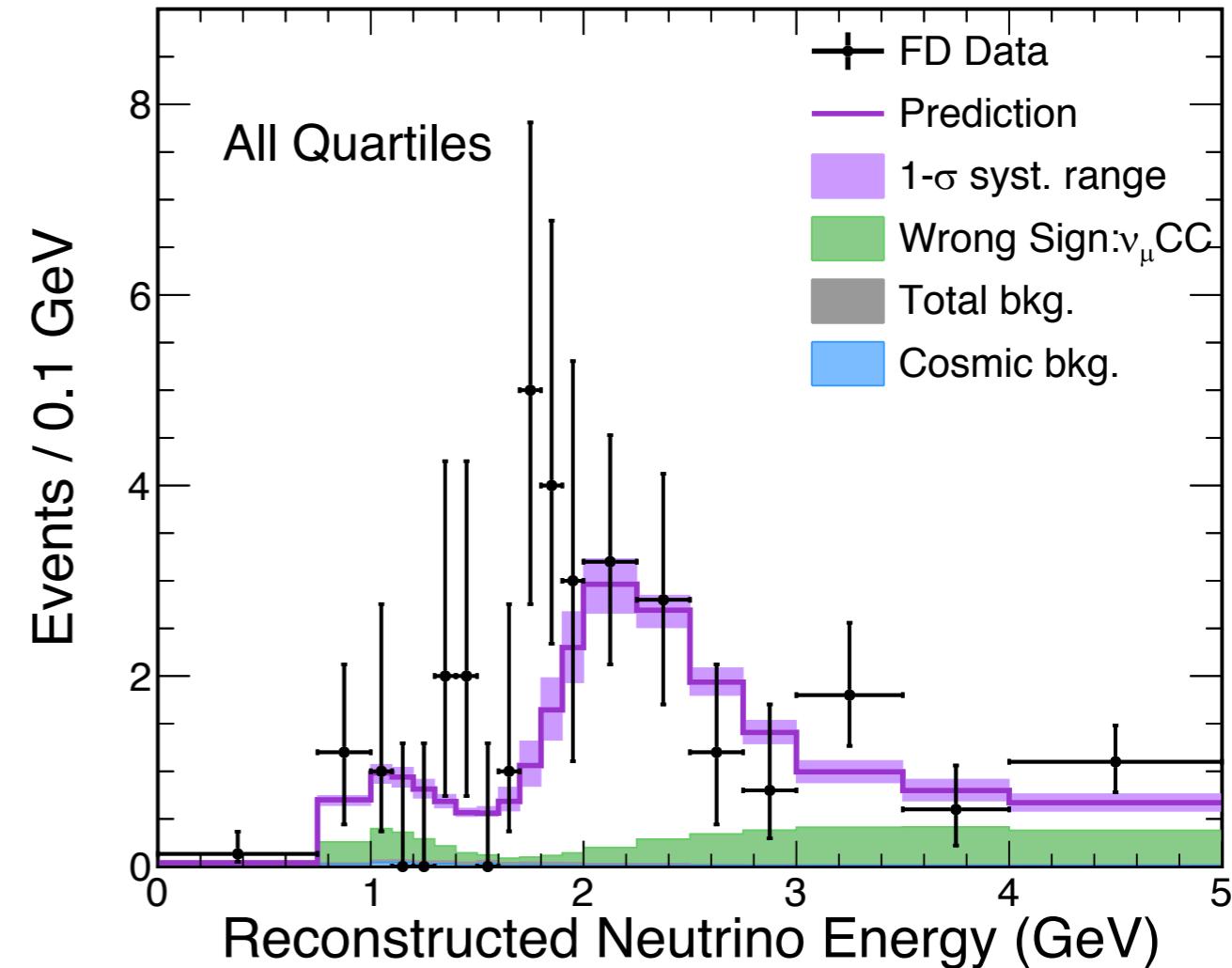
Neutrino beam

NOvA Preliminary



Antineutrino beam

NOvA Preliminary



Total Observed

113

Best fit prediction

121

Cosmic Bkgd.

2.1

Beam Bkgd.

1.2

Unoscillated

730

Total Observed

65

Best fit prediction

50

Cosmic Bkgd.

0.5

Beam Bkgd.

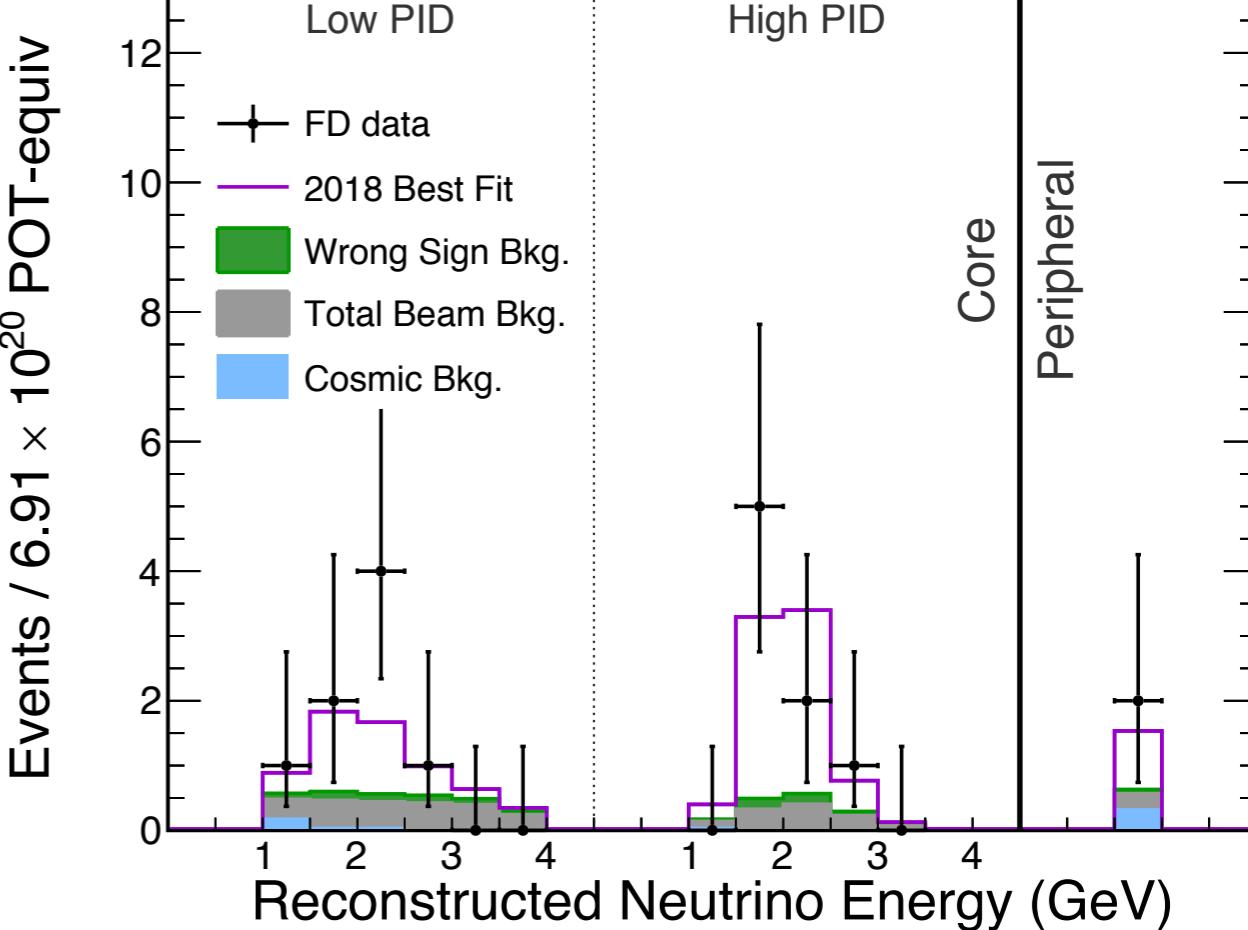
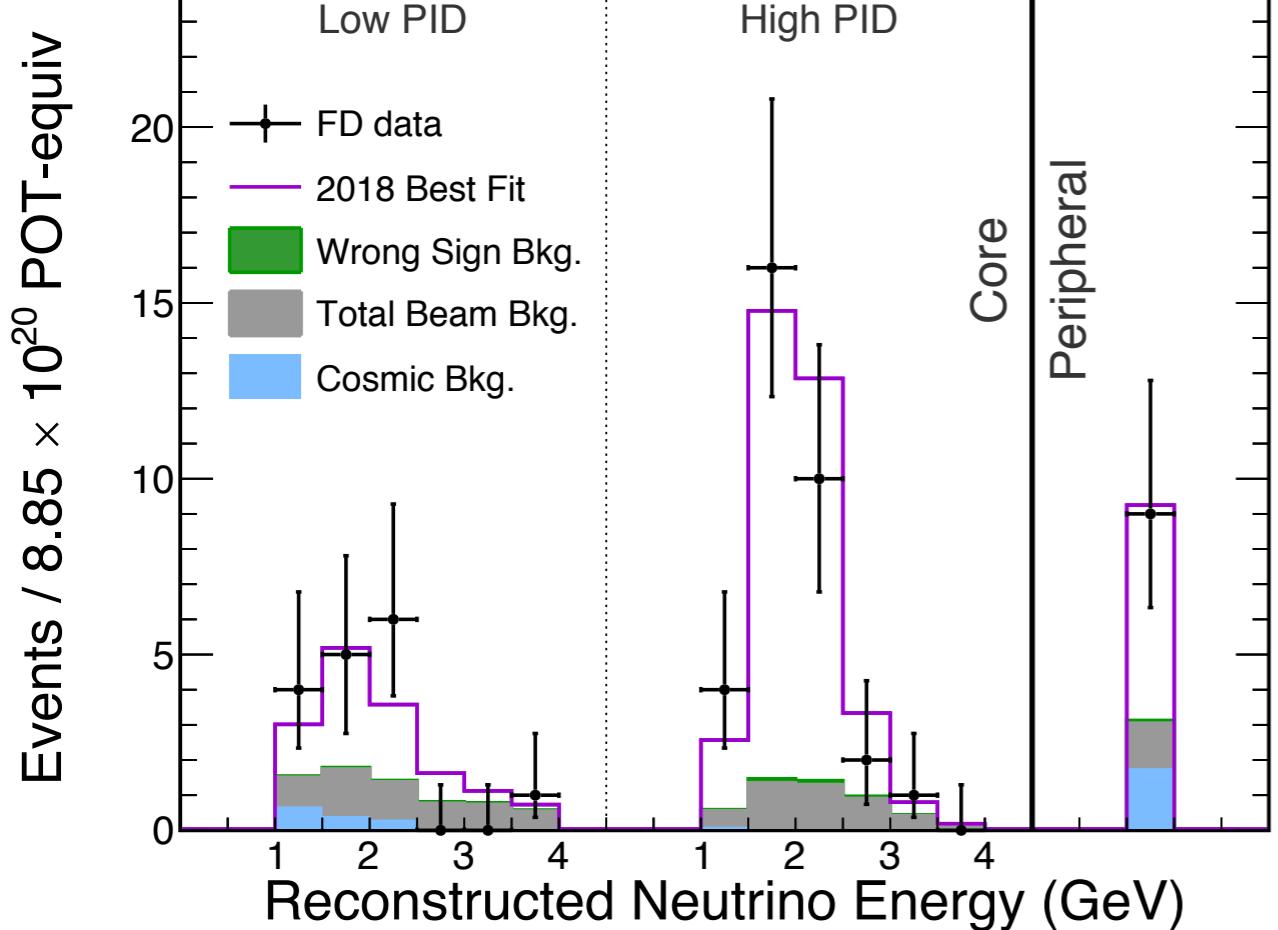
0.6

Unoscillated

266

NOvA Preliminary

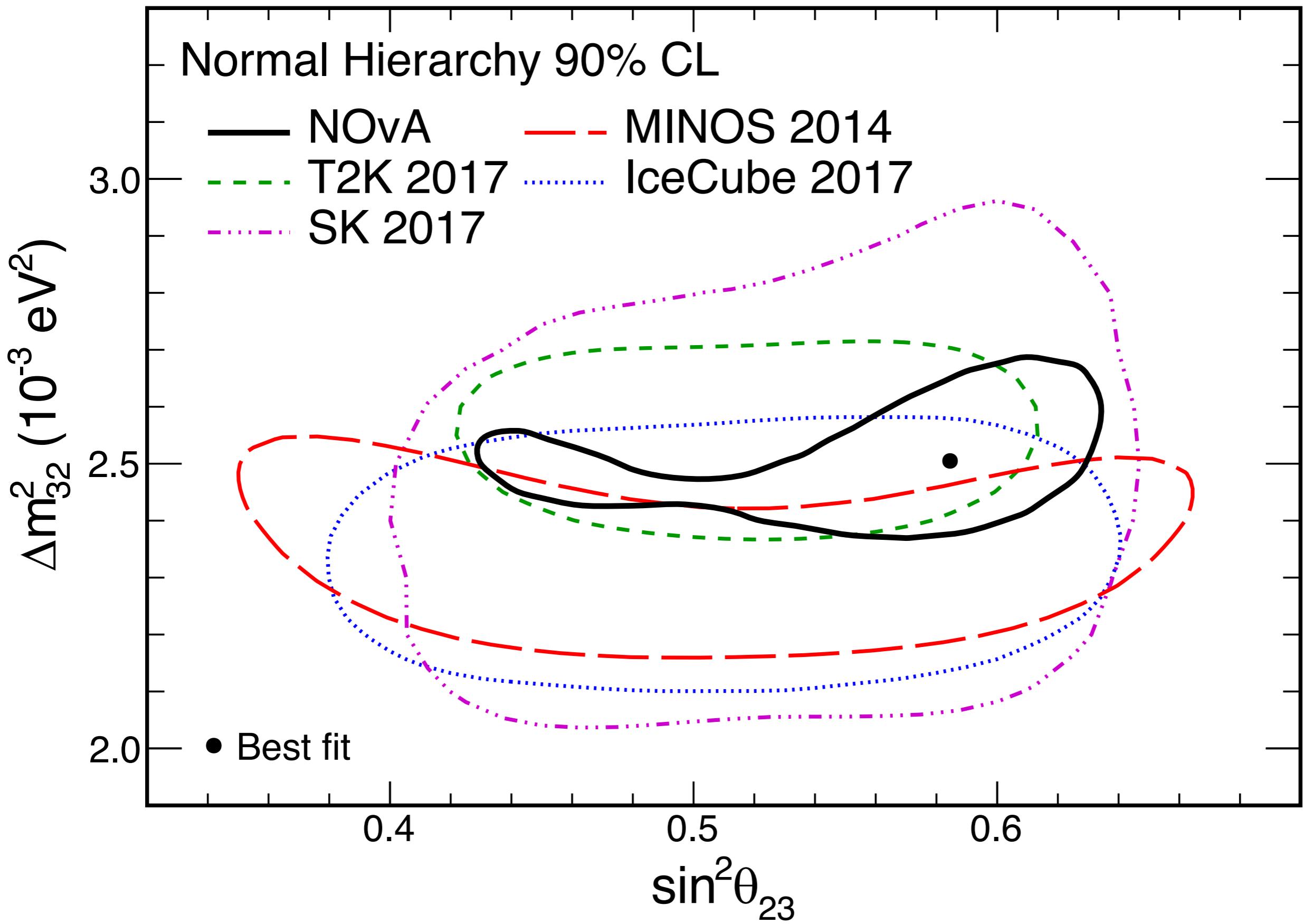
NOvA Preliminary

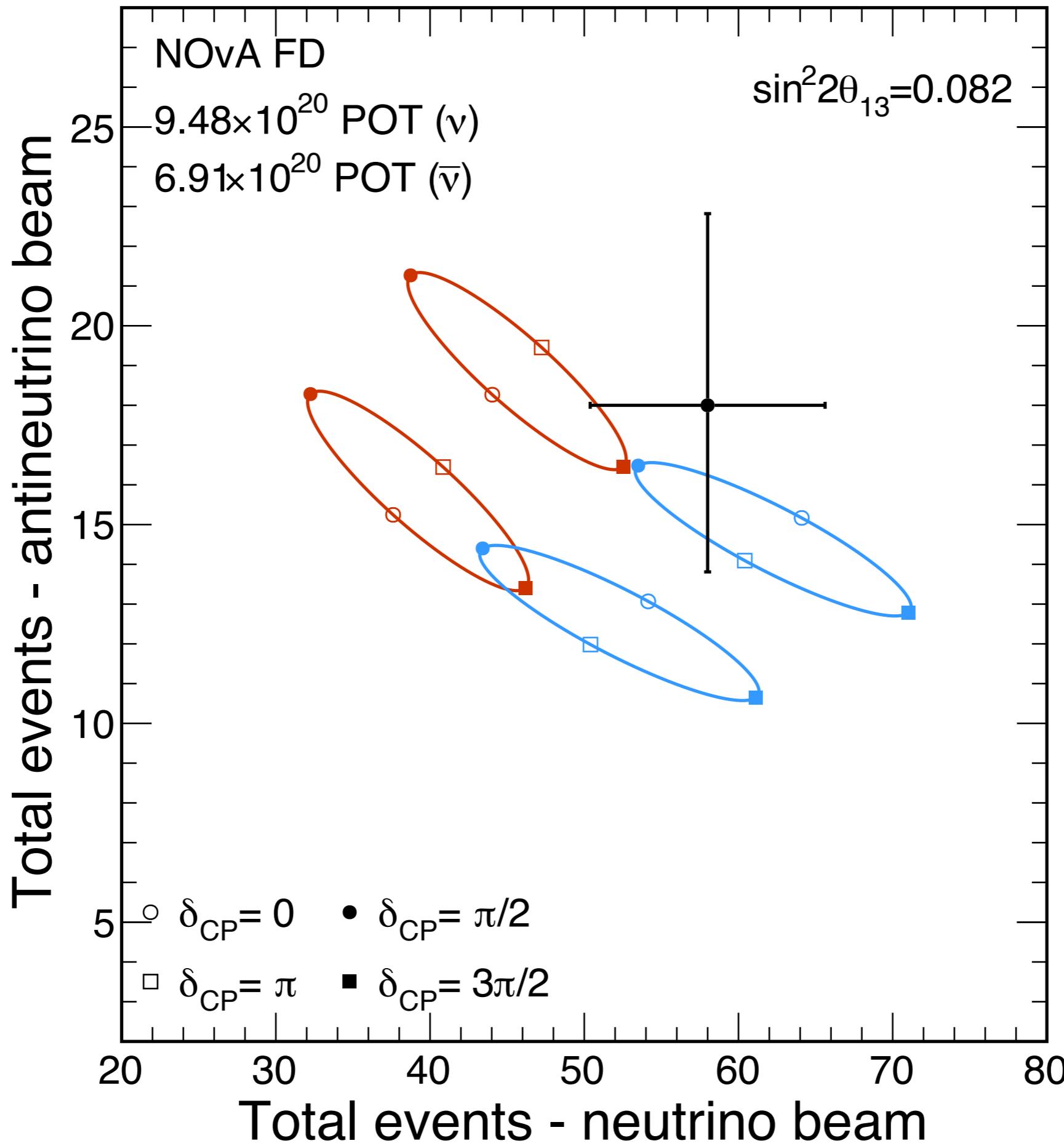


Total Observed	58	Range
Total Prediction	59.0	30-75
Wrong-sign	0.7	0.3-1.0
Beam Bkgd.	11.1	
Cosmic Bkgd.	3.3	
Total Bkgd.	15.1	14.7-15.4

Total Observed	18	Range
Total Prediction	15.9	10-22
Wrong-sign	1.1	0.5-1.5
Beam Bkgd.	3.5	
Cosmic Bkgd.	0.7	
Total Bkgd.	5.3	4.7-5.7

Strong ($>4\sigma$) evidence of $\bar{\nu}_e$ appearance



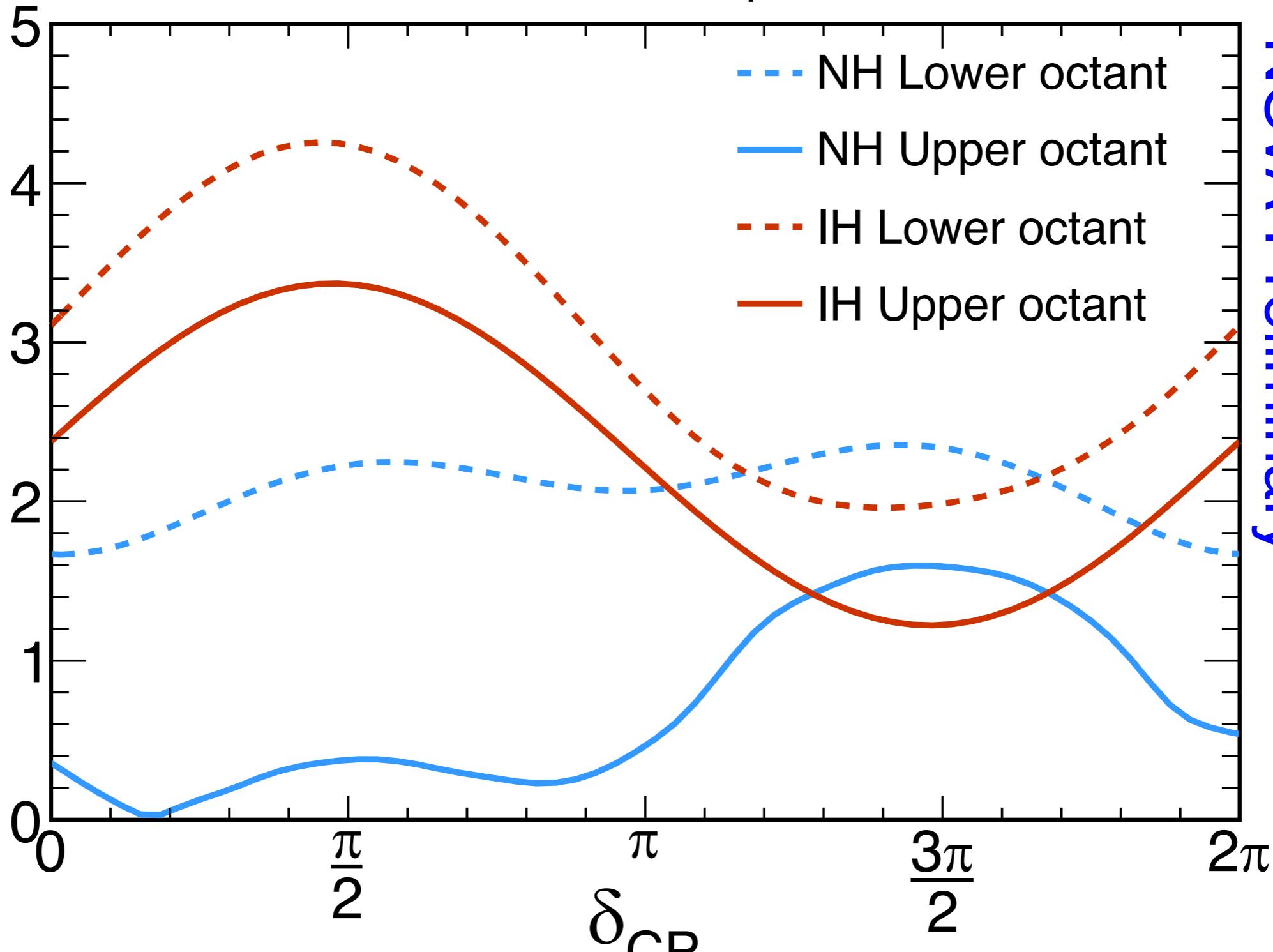


NOvA FD 8.85×10^{20} POT equiv ν + 6.9×10^{20} POT $\bar{\nu}$

Significance (σ)

- NH Lower octant
- NH Upper octant
- IH Lower octant
- IH Upper octant

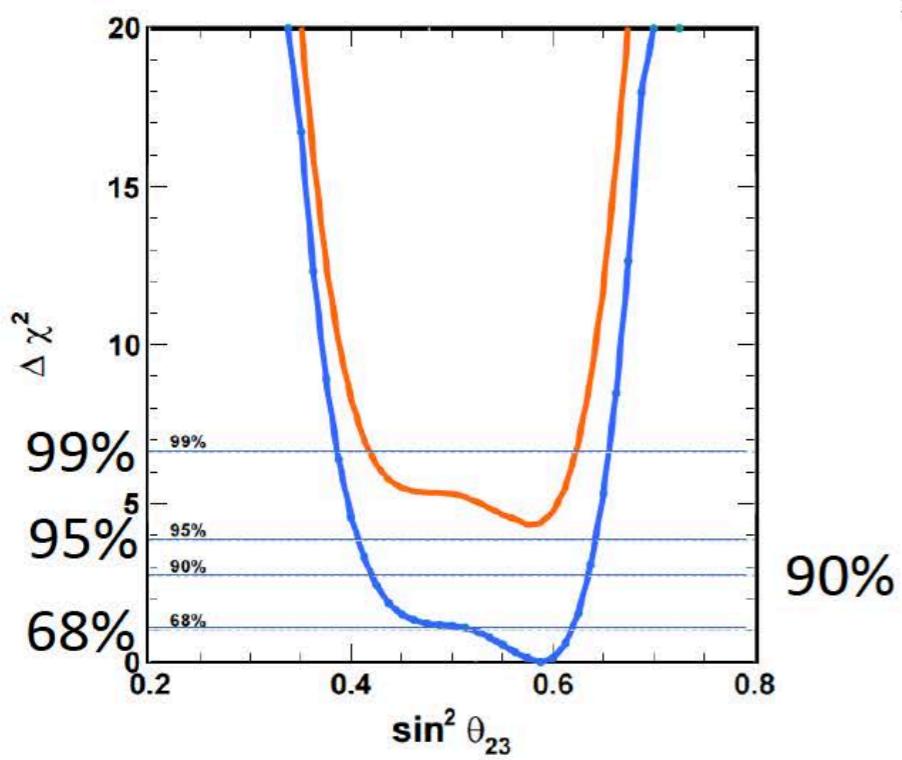
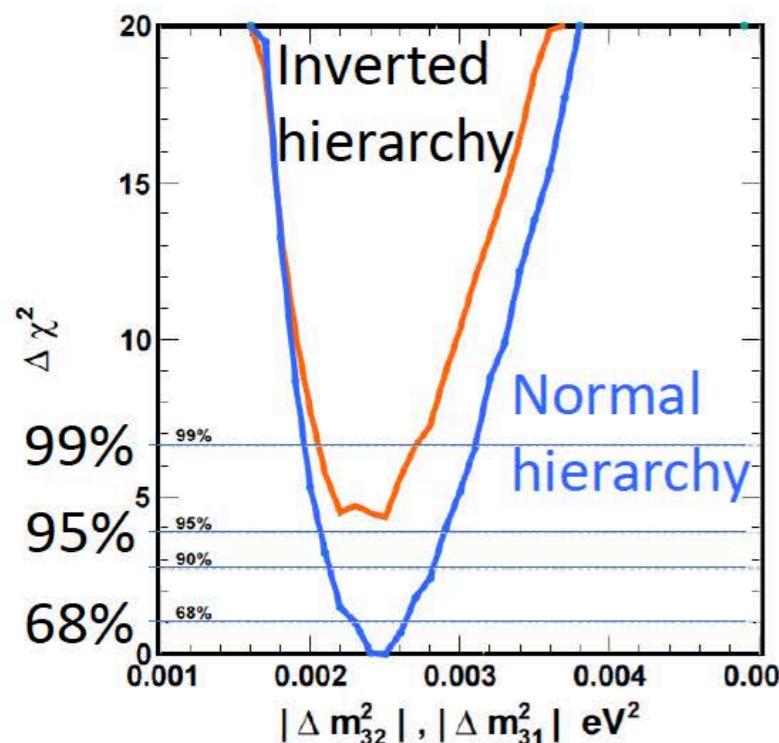
NOvA Preliminary



$$\chi^2_{\text{IH}} - \chi^2_{\text{NH}} = 2.47$$

P value based on Feldman-Cousins calculation = 0.076, or **1.8 σ**

Oscillation parameters from Super-Kamiokande atmospheric neutrinos

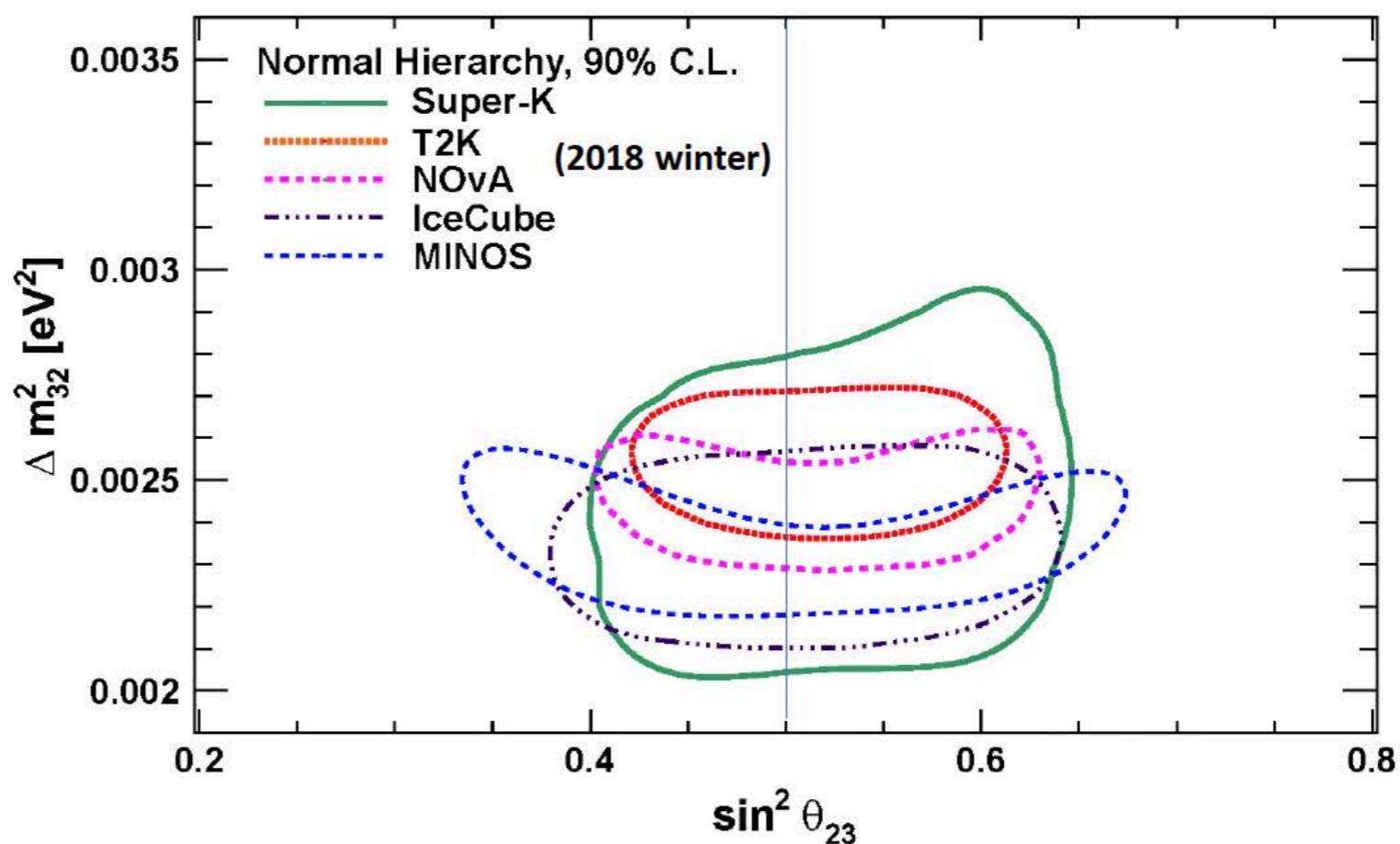


[Phys. Rev. D 97, 072001 \(2018\)](#)

$$\Delta m_{21}^2 = (7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2,$$

$$\sin^2 \theta_{12} = 0.304 \pm 0.014,$$

$$\sin^2 \theta_{13} = 0.0219 \pm 0.012$$

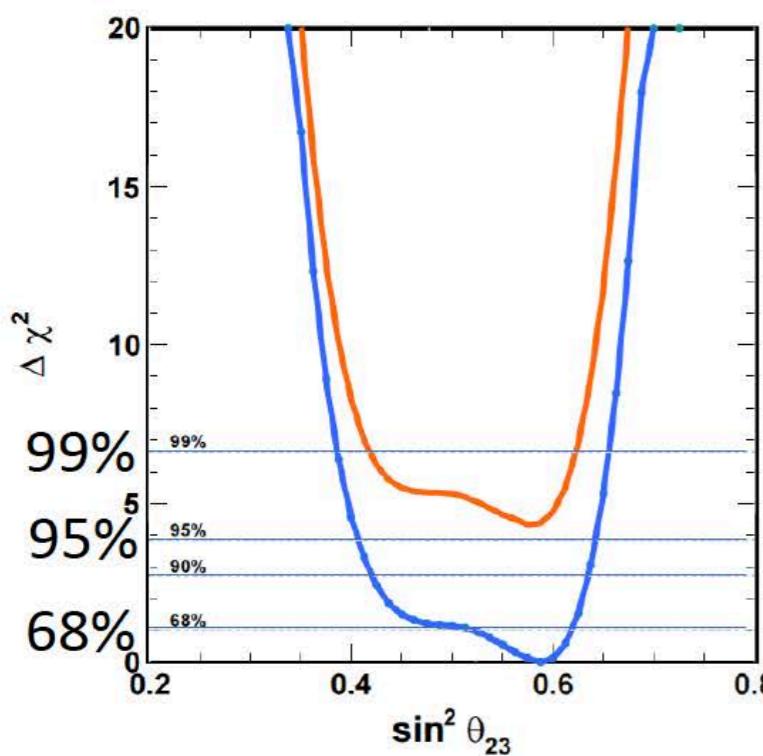
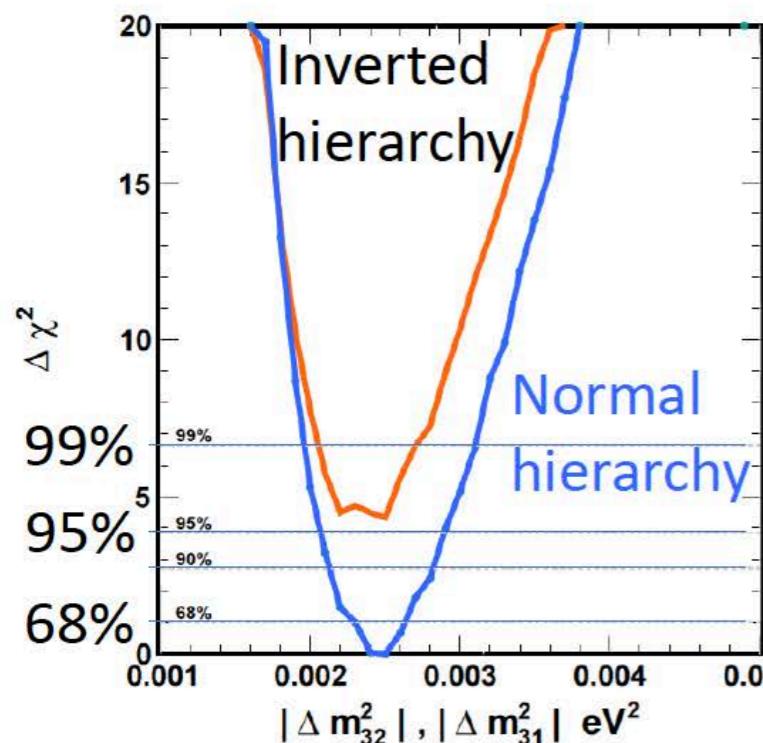


$$|\Delta m_{32}^2| = 2.50^{+0.13}_{-0.20} \times 10^{-3} \text{ eV}^2$$

$$\sin^2 \theta_{23} = 0.588 \pm 0.031$$

$$(\chi^2_{NH,min} - \chi^2_{IH,min} = -4.34)$$

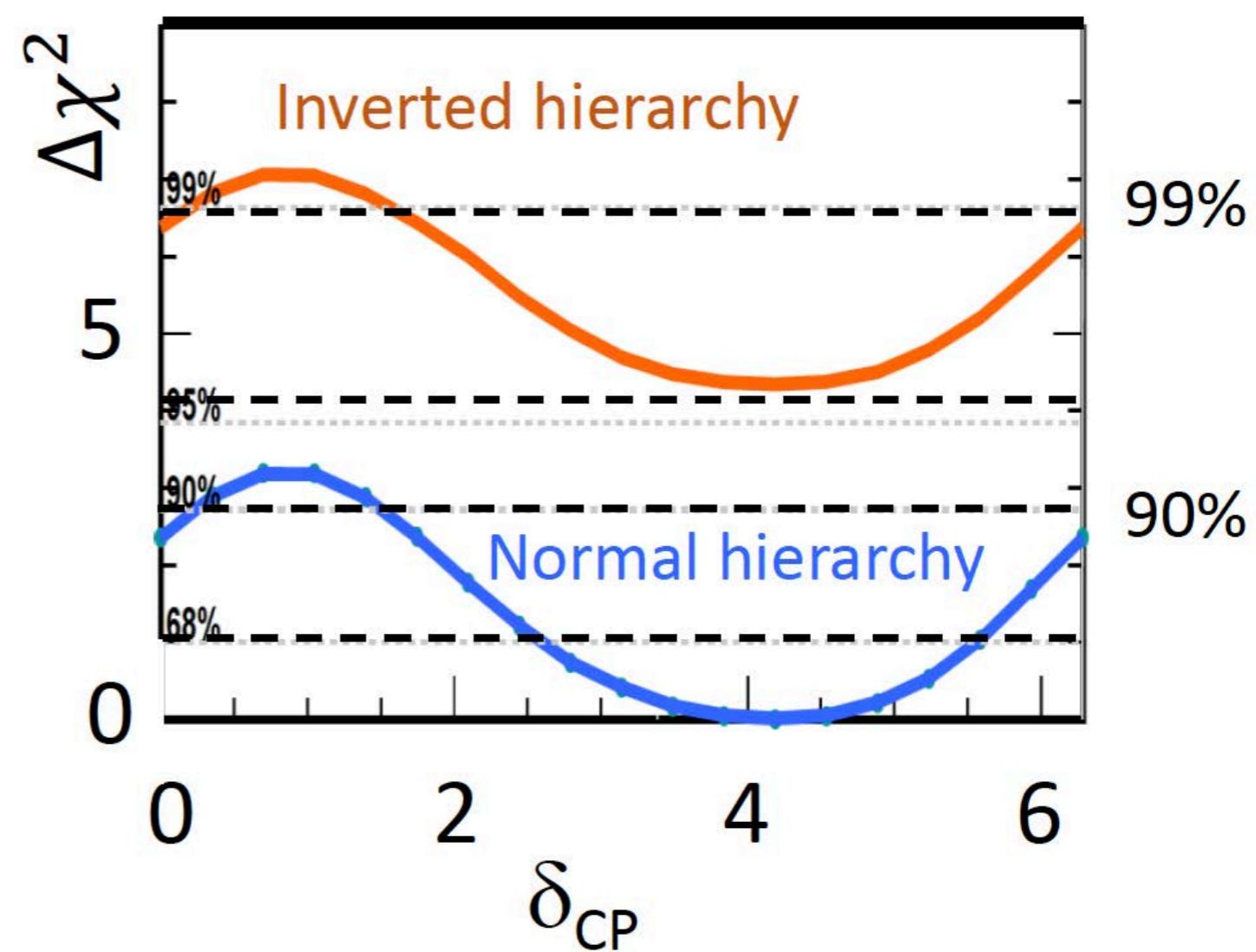
Oscillation parameters from Super-Kamiokande atmospheric neutrinos



[Phys. Rev. D 97, 072001 \(2018\)](#)

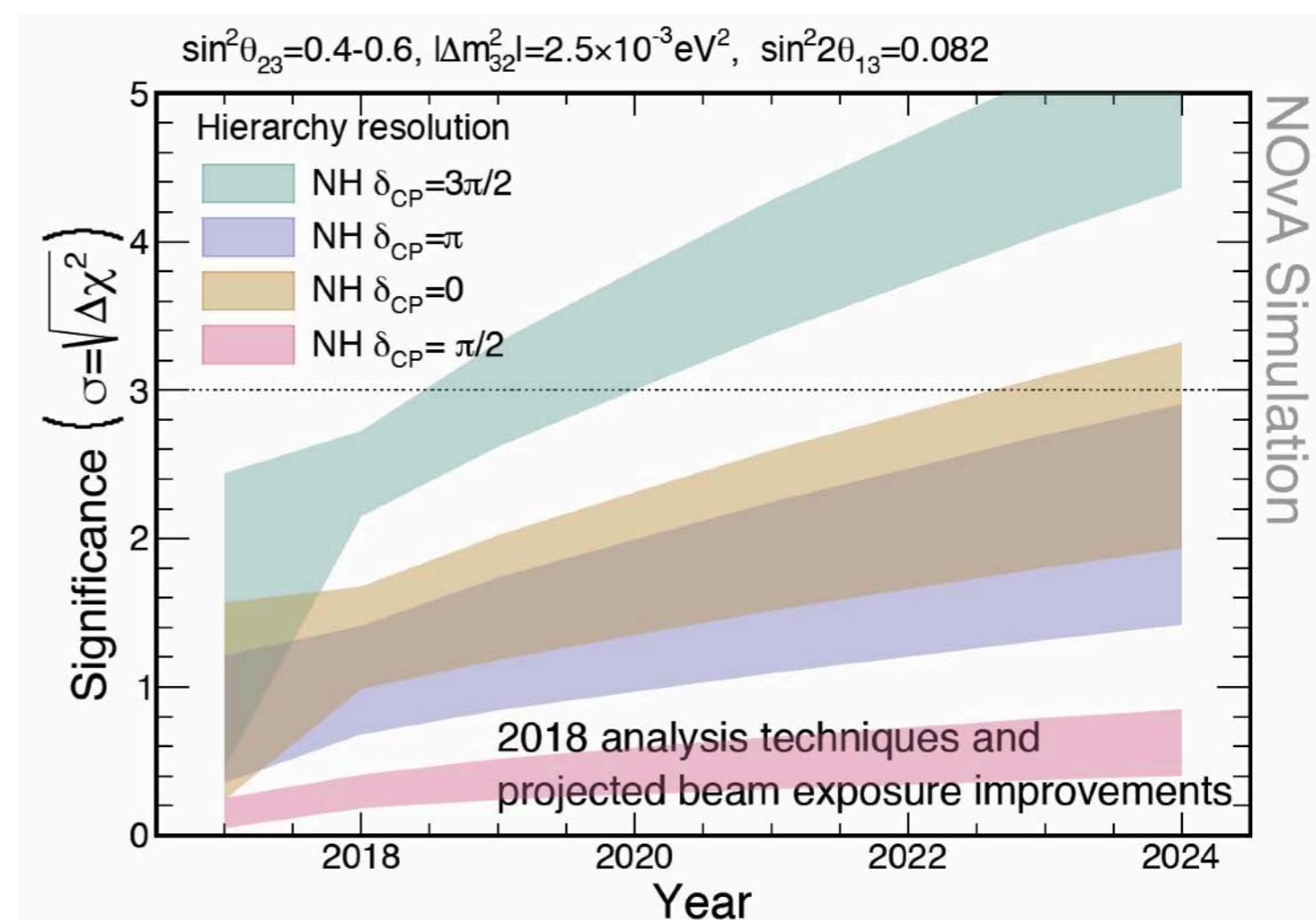
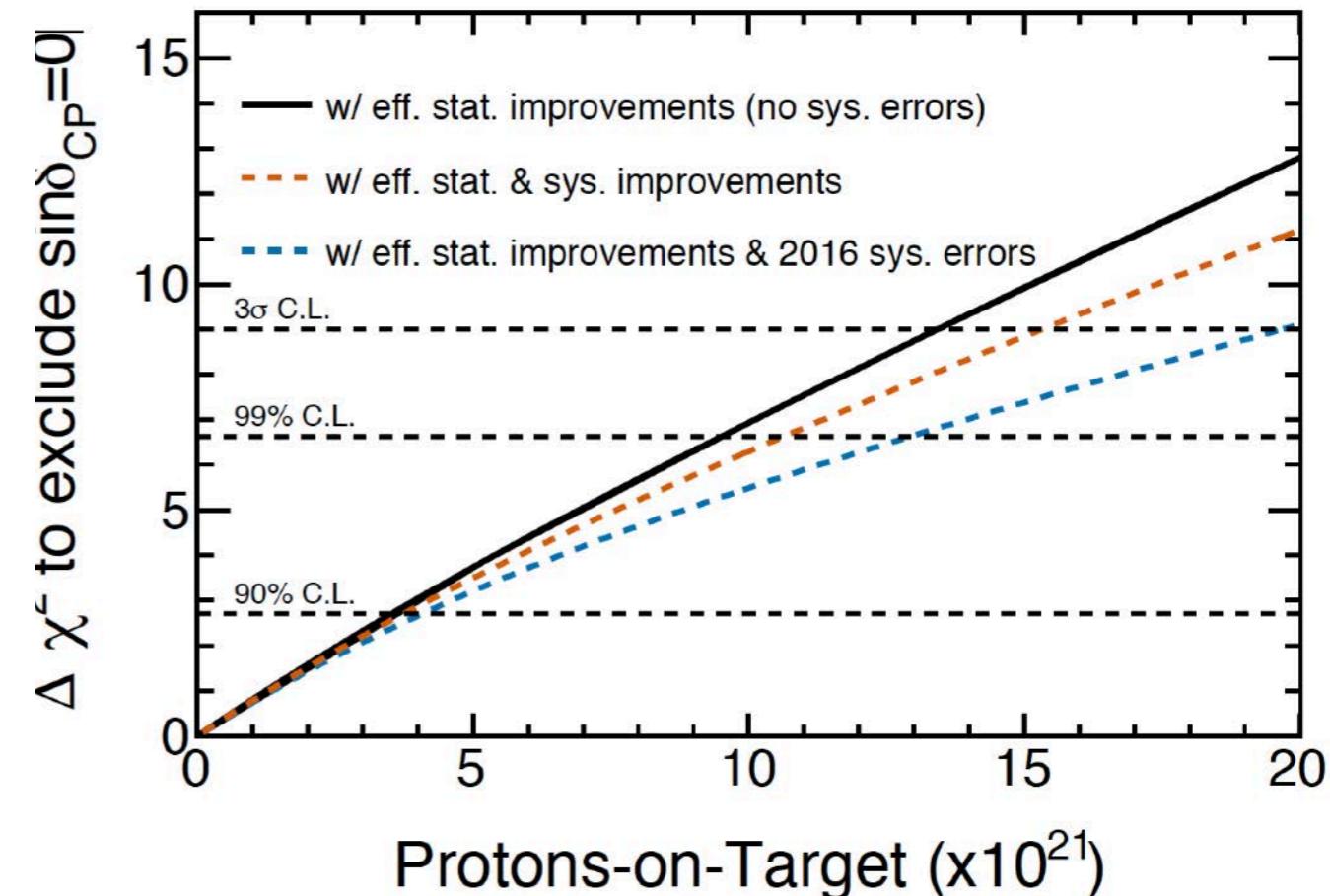
$$\Delta m_{21}^2 = (7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2,$$
$$\sin^2 \theta_{12} = 0.304 \pm 0.014,$$
$$\sin^2 \theta_{13} = 0.0219 \pm 0.012$$

CP violation parameter δ_{CP}

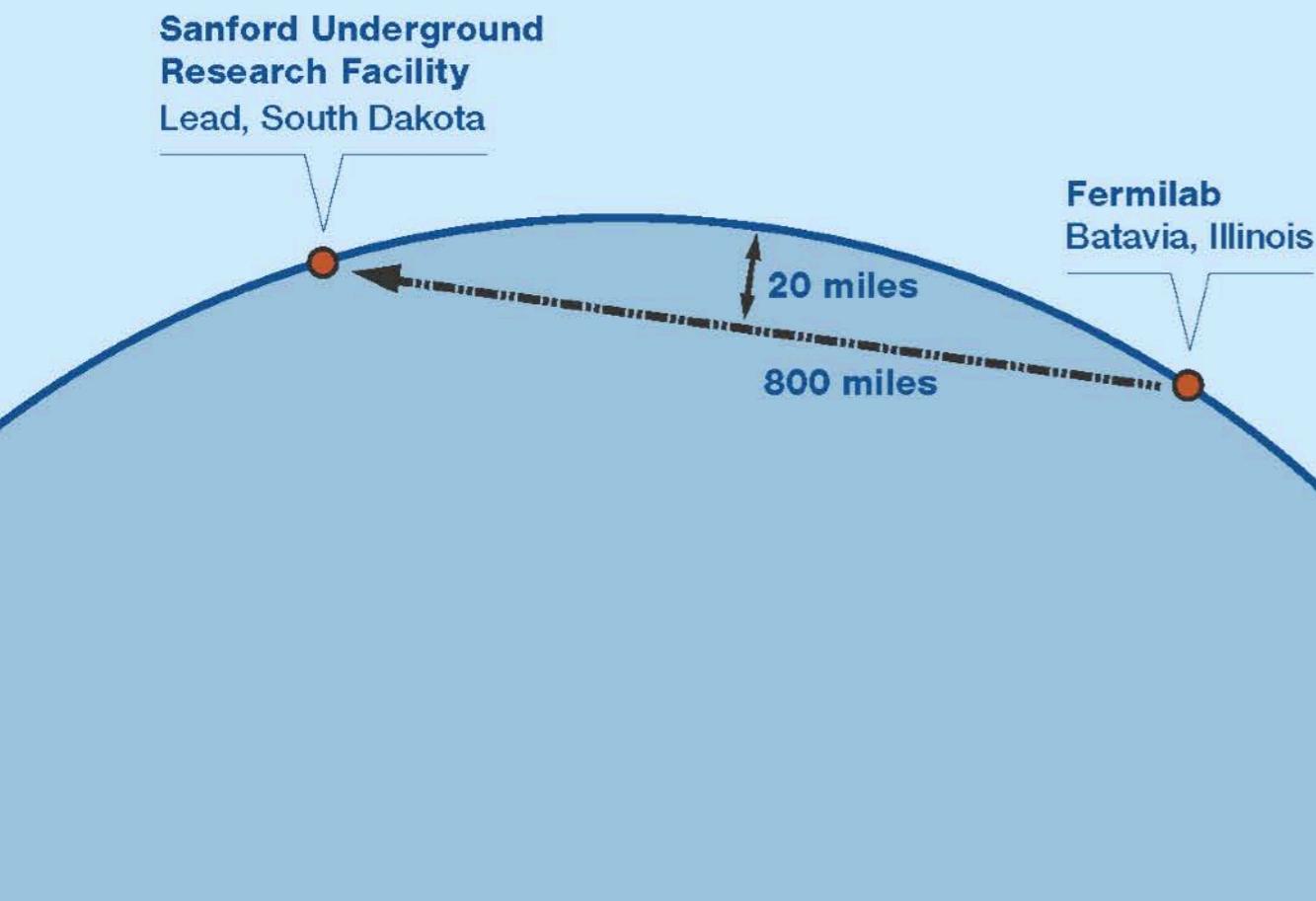


T2K and NOvA Extended Running

- T2K has KEK/JPARC Stage 1 approval to extend its run to 2026. See arXiv: 1609.0411
- Incremental investments in JPARC beam intensity raise the intensity from 500 kW to 1.3 MW by 2024
- These would deliver 20E21 protons-on-target by 2026 and enable 3σ sensitivity to CP violation if CP violation is maximal.
- NOvA will run through 2024 with incremental upgrades to beam intensity to 1 MW
- With those NOvA will have $>3\sigma$ sensitivity to the mass hierarchy and up to 2σ sensitivity to CP violation



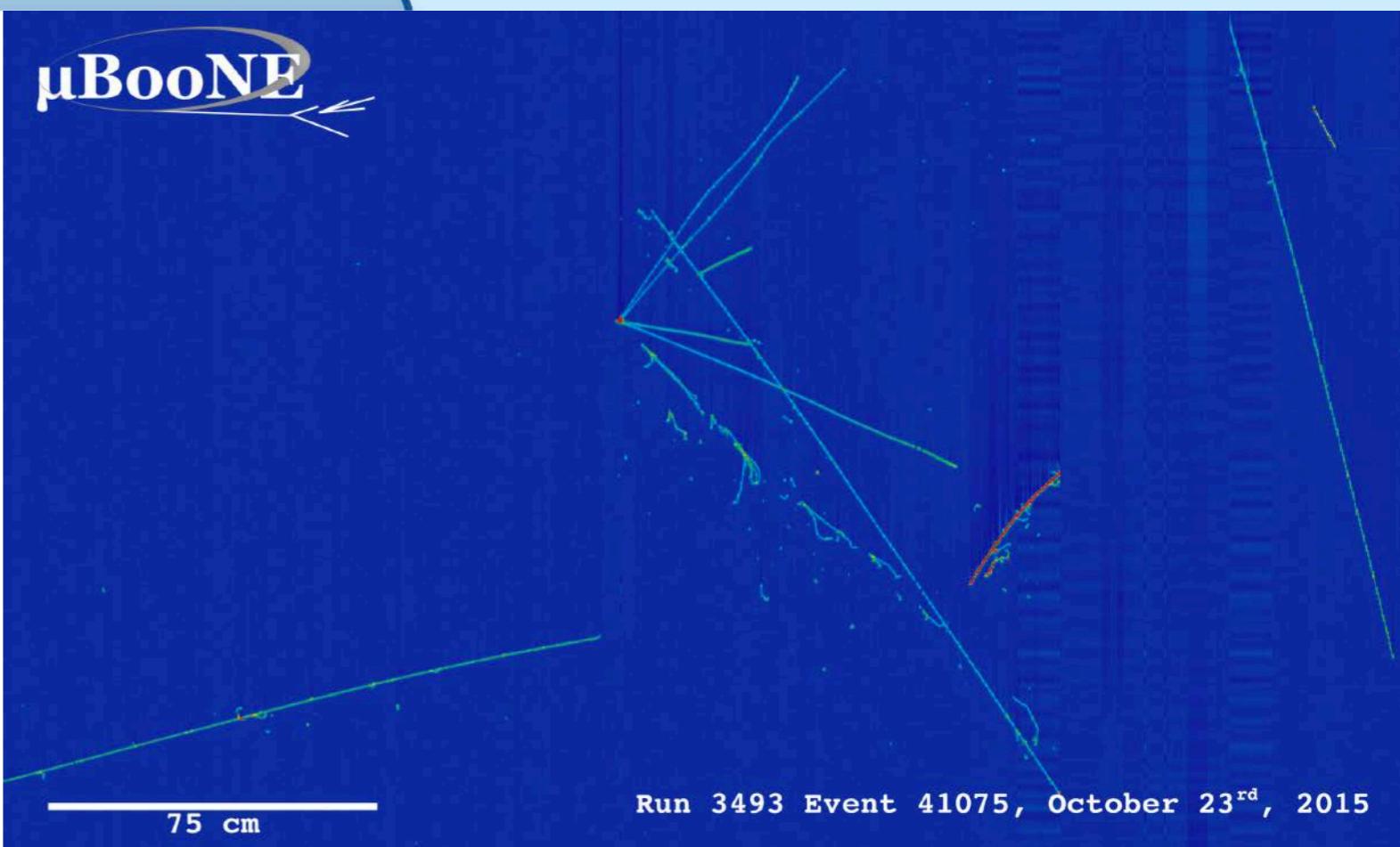
Deep Underground Neutrino Experiment



DUNE Experiment

Upgrade beam to 1.2 then 2 MW
4x17 kt detector modules with millimeter resolution located 4850 feet underground

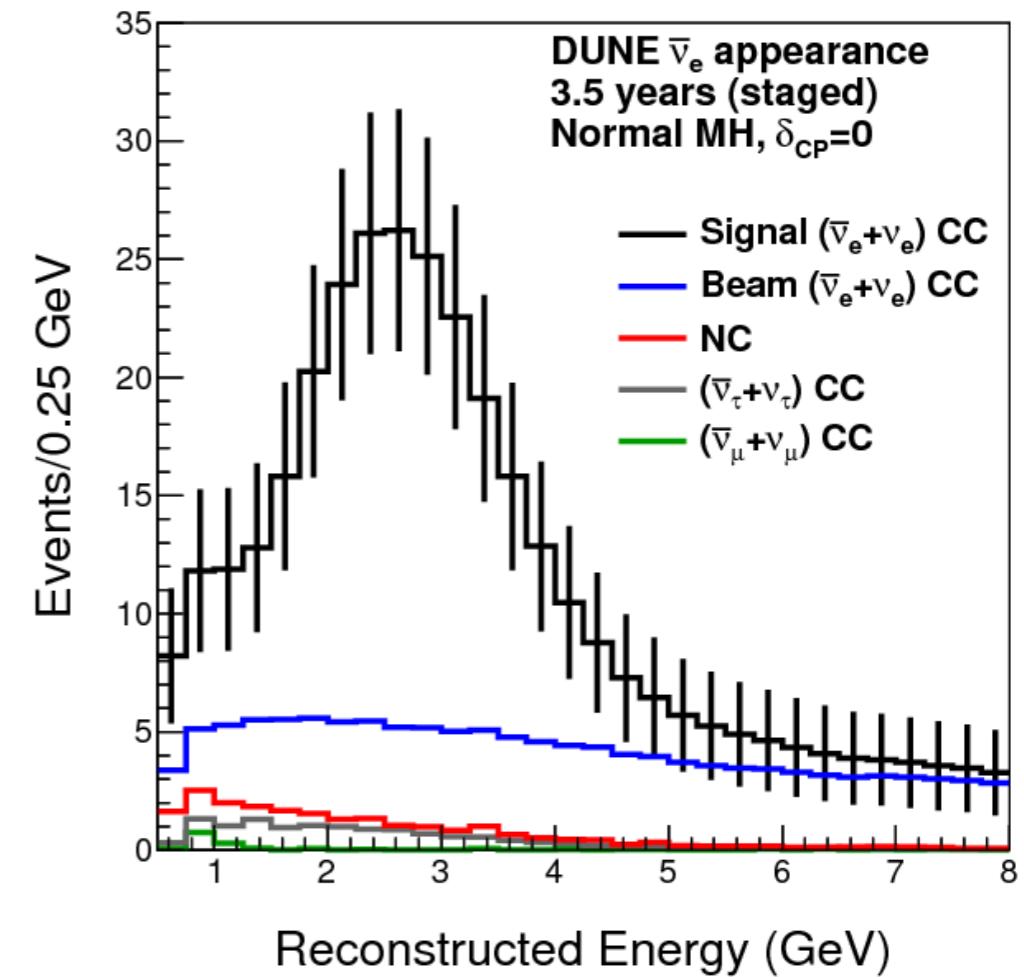
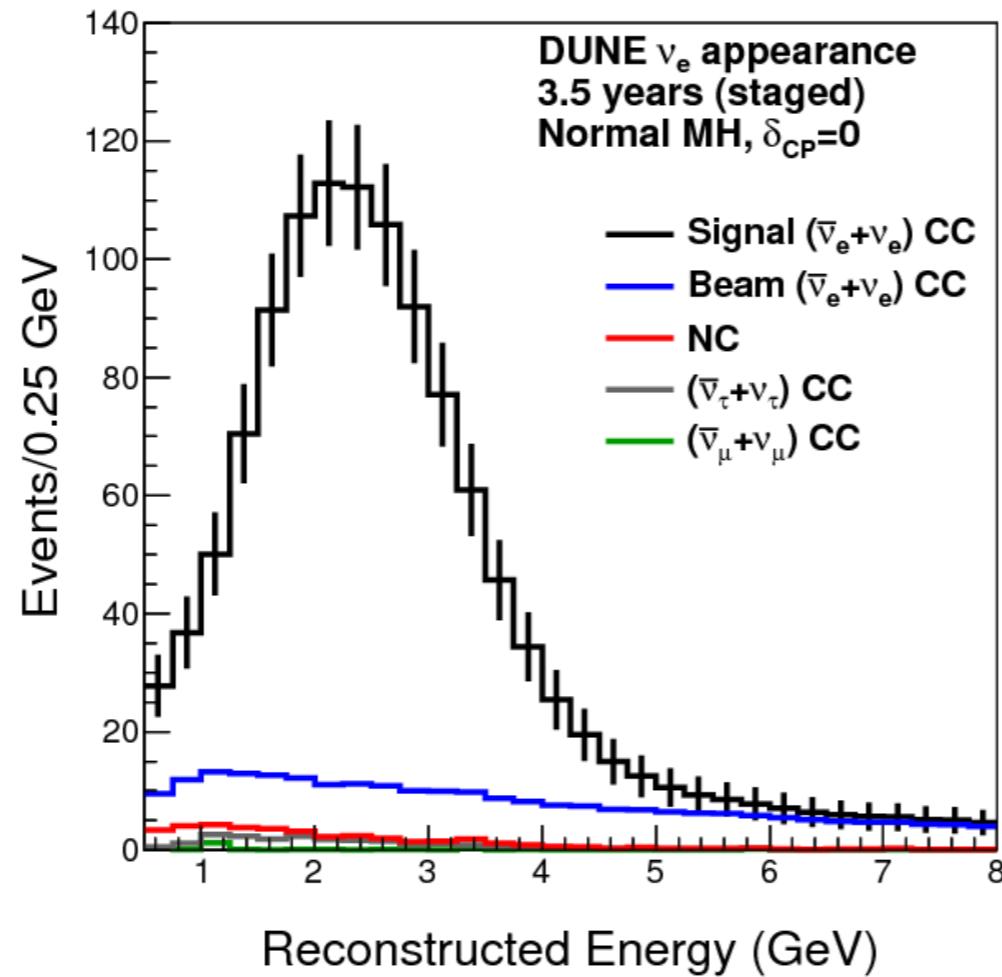
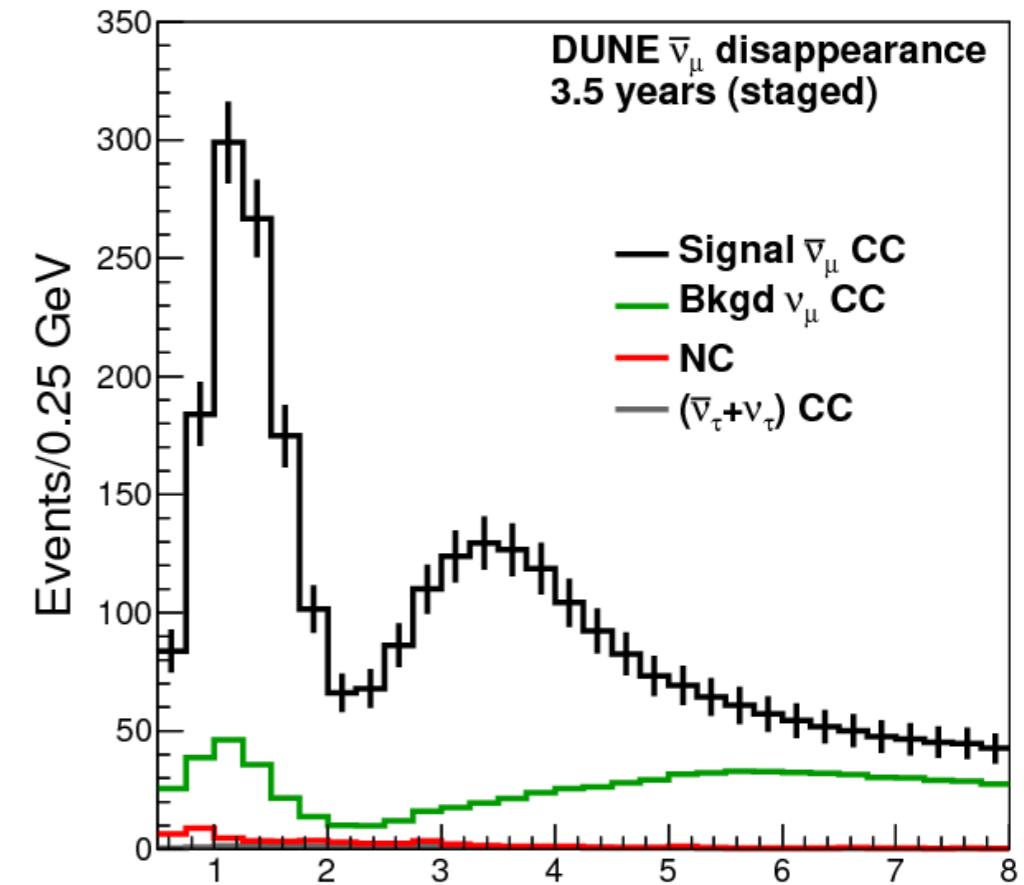
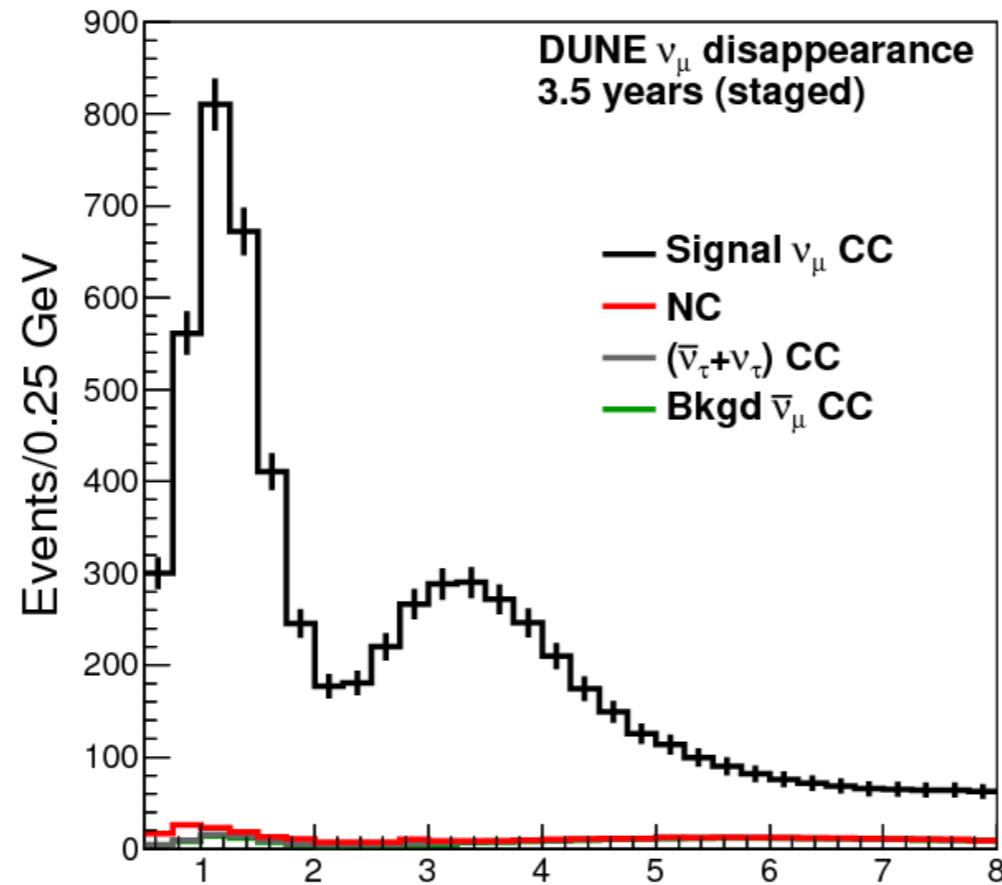
>5 σ resolution of mass hierarchy
>5 σ resolution of CP violation



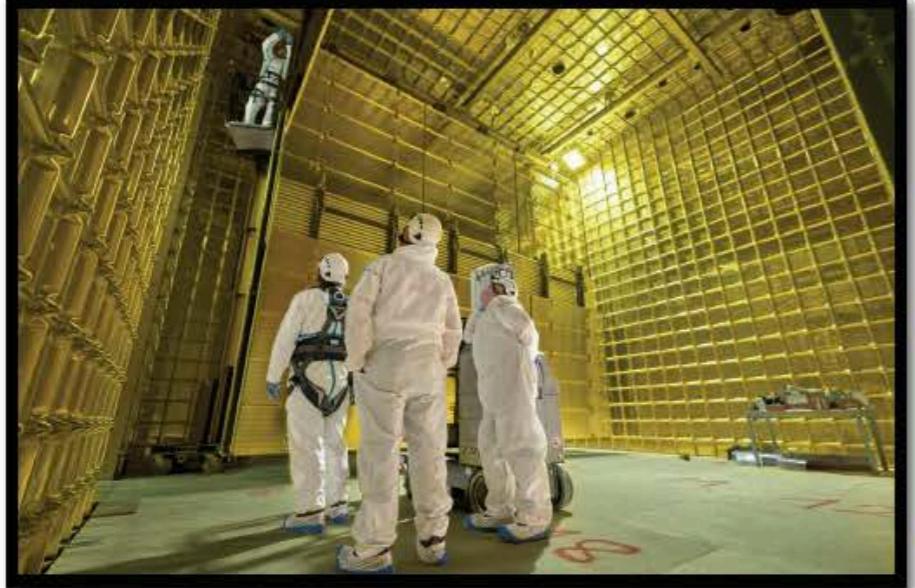
DUNE

Event

Spectra



Timeline



2018: protoDUNE at CERN



2019: Technical Design Report



2019: Far Site Primary Excavation Begins



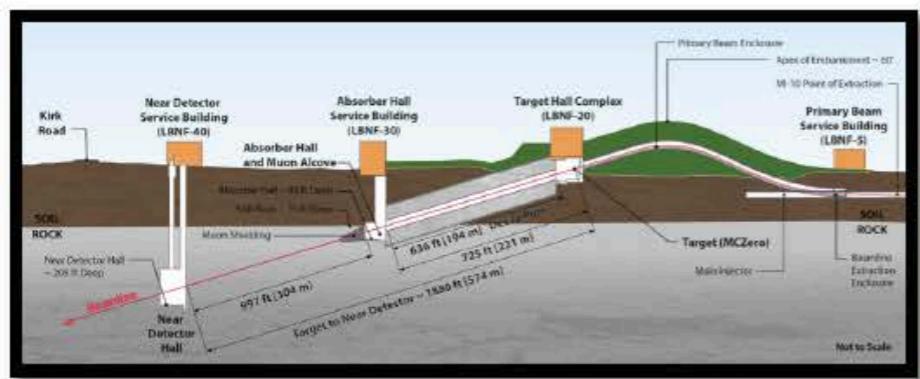
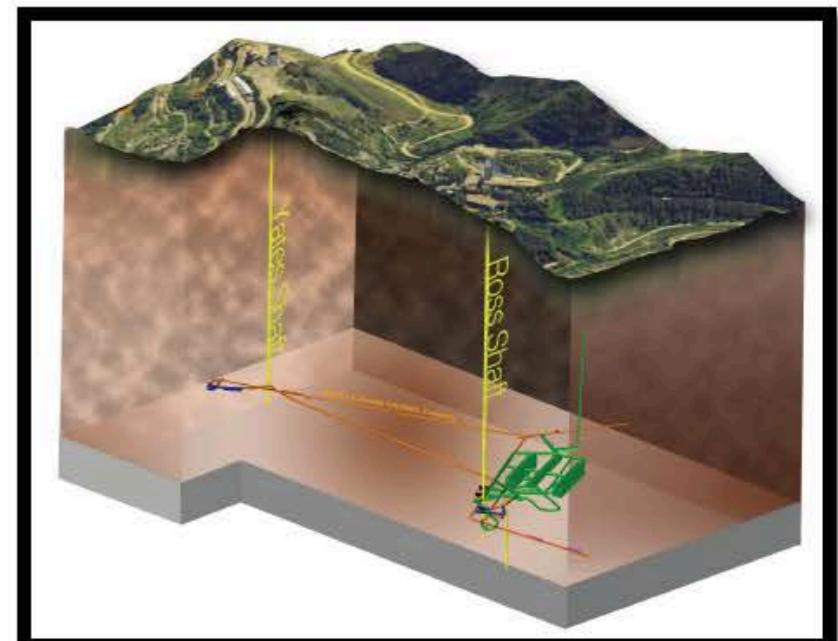
2022: First Module Installation Begins



2026: Neutrino Beam Available

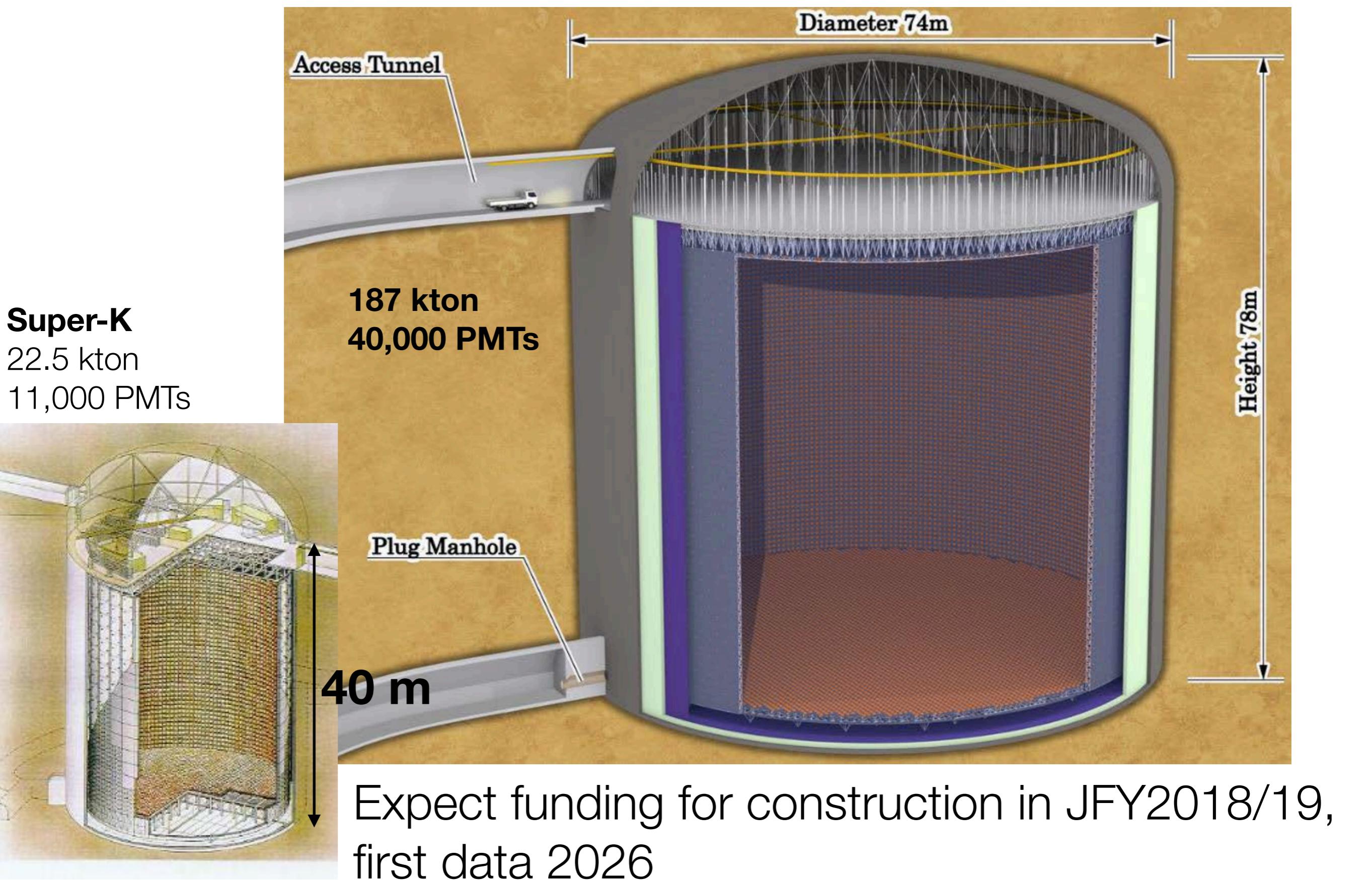
DUNE Far Detector Interim Design Report (2018)

Will be made public soon...



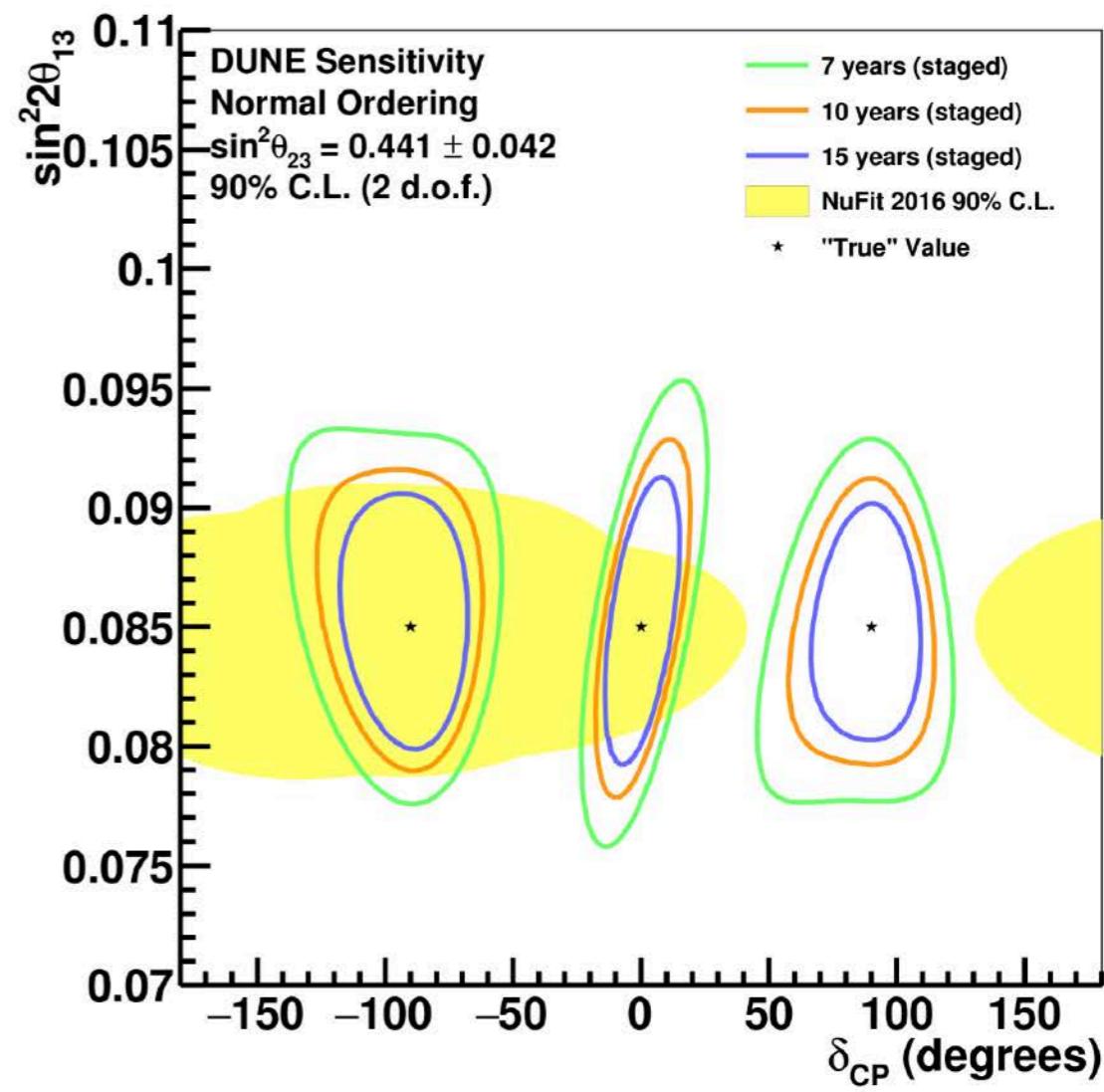
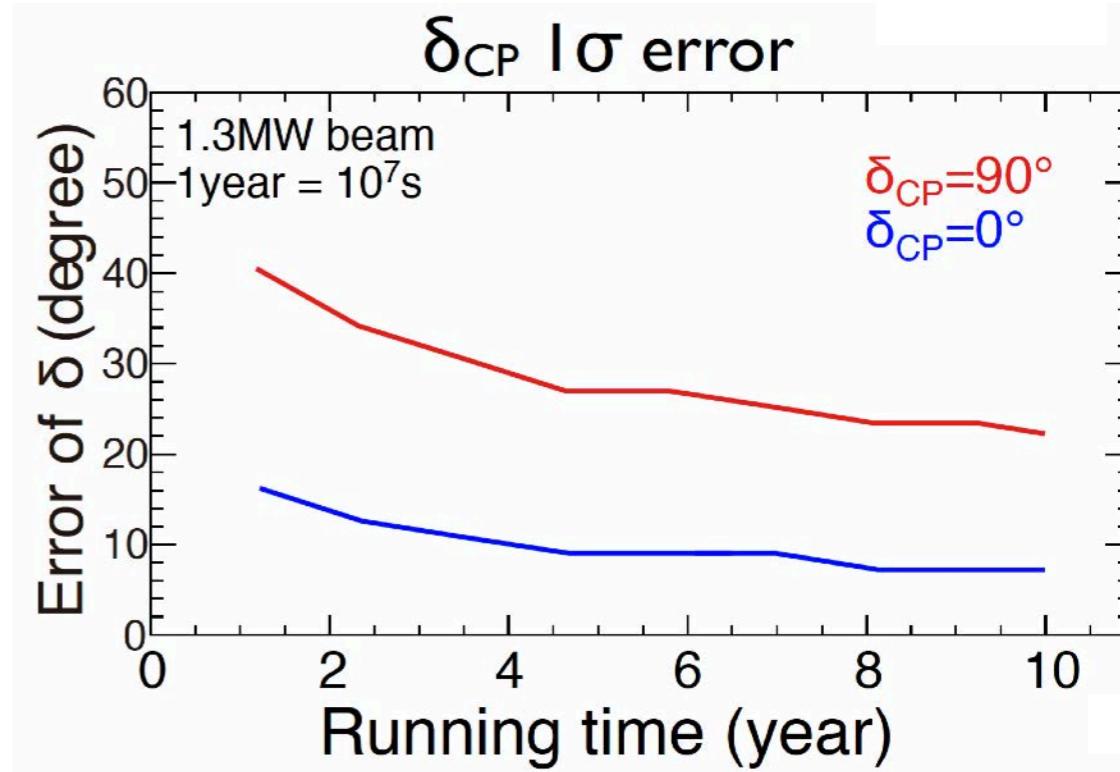
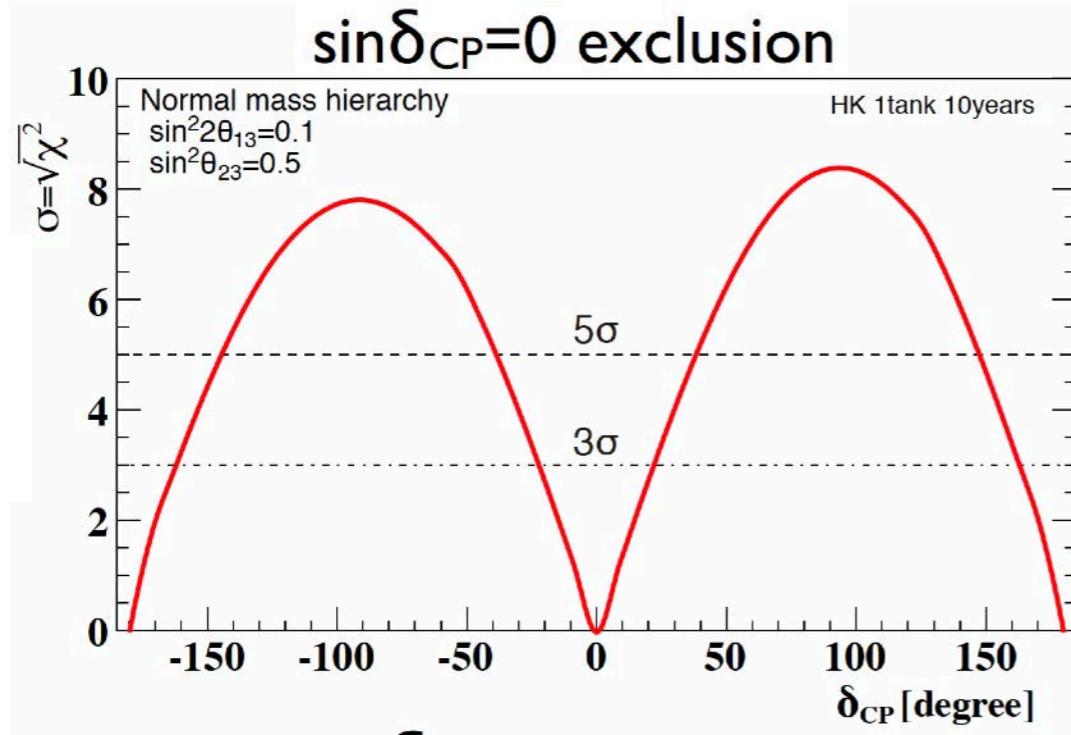
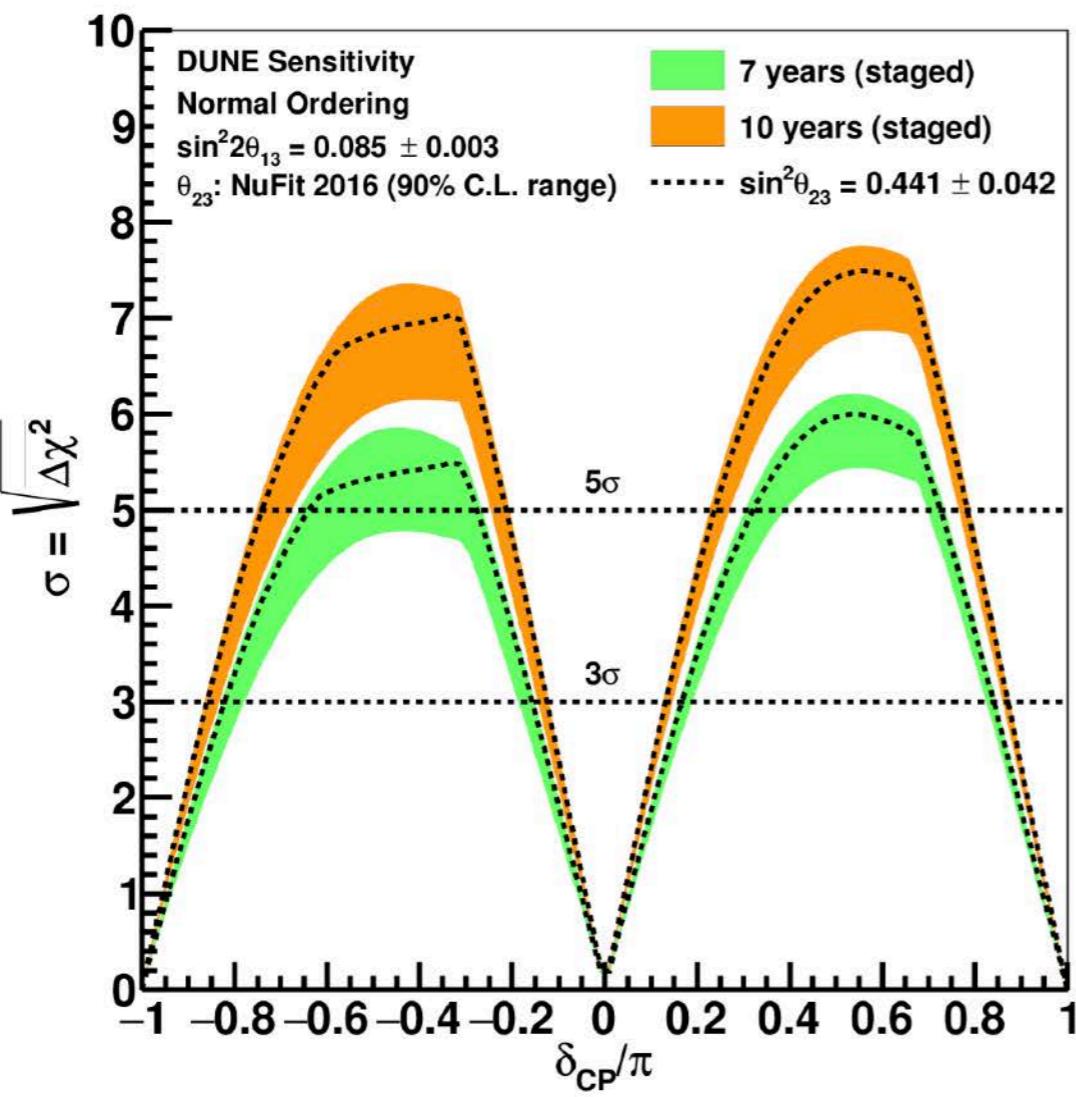
LBNF/DUNE PROJECT GROUNDBREAKING

Hyper-Kamiokande



DUNE

Hyper-K



Summary

- KATRIN will push limits on neutrino mass to 200 meV
- Current and next generation searches for neutrino less double beta decay are approaching the inverted ordering region; mass ranges of 15 to 40 meV
- Neutrino oscillation experiments have made great progress in past 20 years to detail the masses and mixing. Next questions (hierarchy, 23-symmetry, octant, CPV) to be addressed by currently running experiments: NOvA and T2K. With new antineutrino data from NOvA we have begun measurements of antineutrino oscillations at long baseline.
- Search for sterile neutrinos has turned up anomalies which do not yet fit into a good model. Expect new information from the FNAL short baseline program in coming years.
- Next generation is underway (JUNO, DUNE) and in advanced planning stages (HyperK). JUNO will make major progress in precision. DUNE and HK have excellent prospects for discovering CP violation in neutrinos.