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

"All the News That's Fit to Print"

The New York Times

Late Edition

VOL. CXLVII . . . No. 51,179 — NEW YORK, FRIDAY, JUNE 5, 1998 — 60 CENTS

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

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

Detecting Neutrinos

And Detecting Their Mass

OKLAHOMA BLAST BRINGS LIFE TERM FOR TERRY NICHOLS

'ENEMY OF CONSTITUTION'

Judge Denounces Conspiracy and Hears From the Victims of a Terrifying Ordeal

By JO THOMAS

JUSTICES REBUFF STARR'S REQUEST TO SPEED REVIEW

2 ORDERS WITH NO DISSENT

Court Denies an Early Hearing on Claims of Privilege for 4 in Inquiry on President

By LINDA GREENHOUSE

Refugees From Kosovo Cite A Bitter Choice: Flee or Die

By CHRIS HEDGES

Yankee Owner Warns Vallone On Referendum

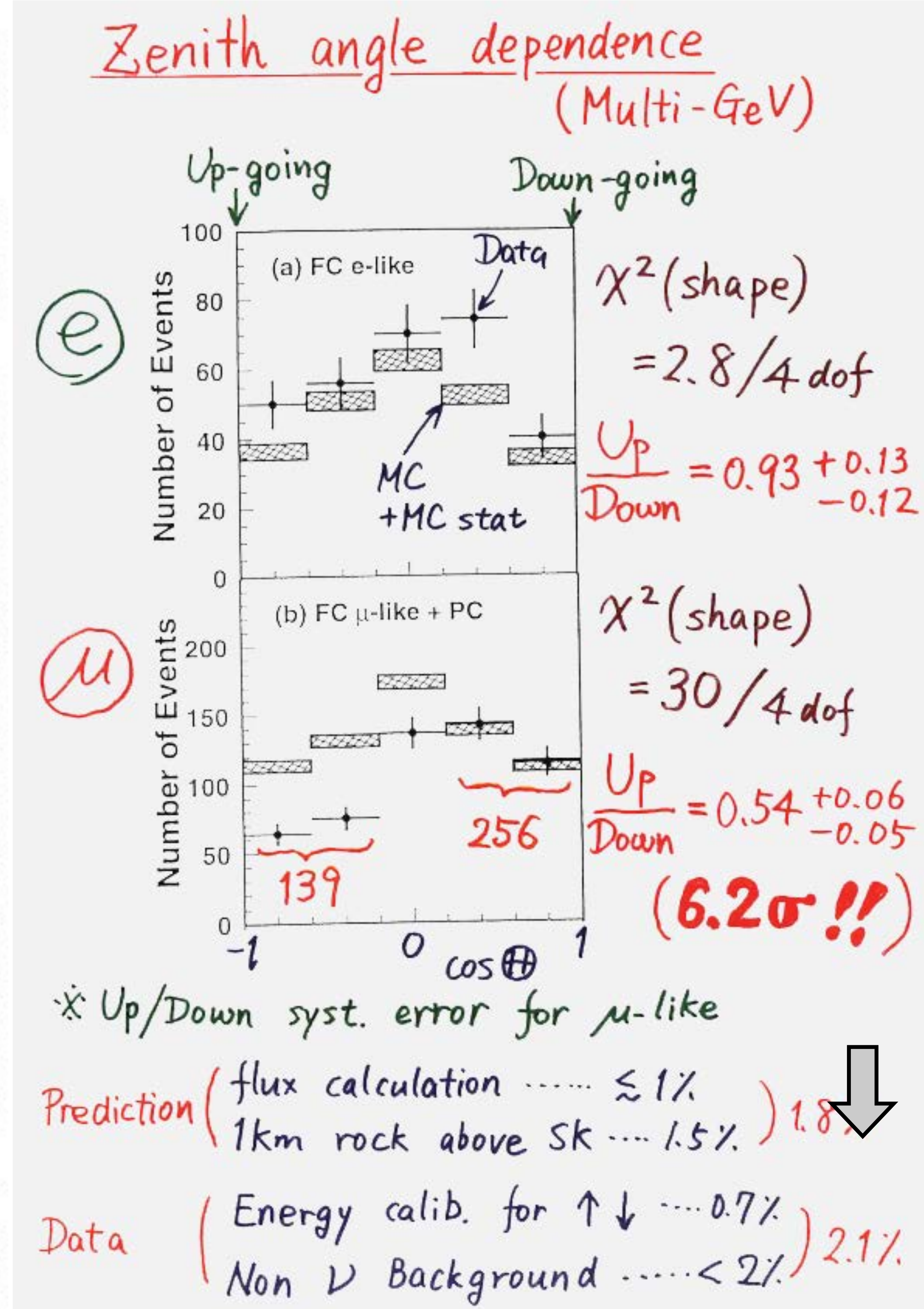
Banks Give Jakarta Longer Time to Pay $80 Billion in Debt

German Fast Trains Pulled Out of Service

Celebrating Day in Their Honor, Firefighters Brawl in Restaurant

By ROBERT D. McFADDEN

Seles Upsets Hingis in French Open



T. Kajita June 5th, at Neutrino 1998

NEVTRINO 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!

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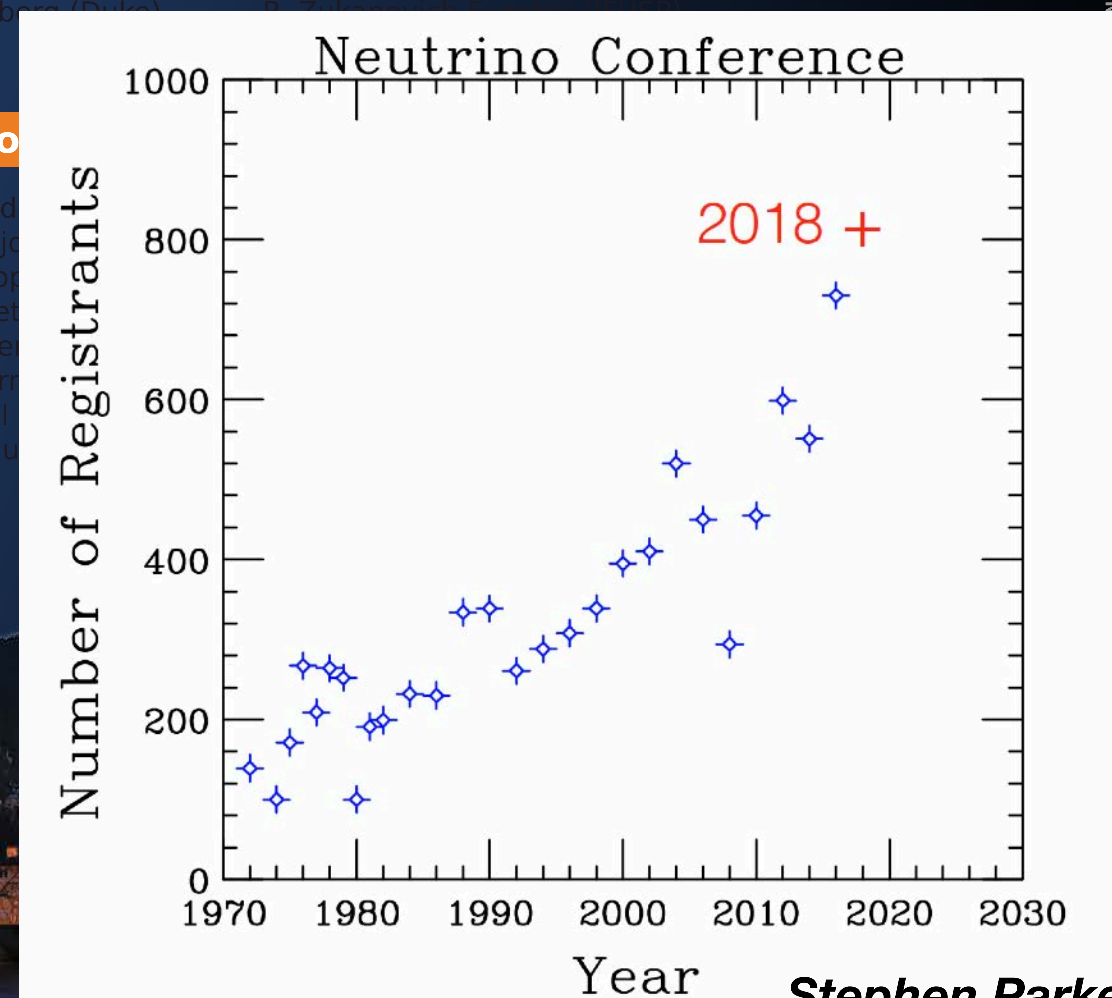


Stephen Parke

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

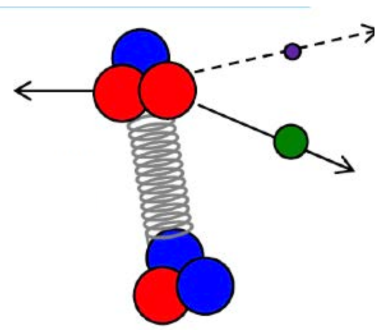
Prospects for measuring CPV in lepton sector

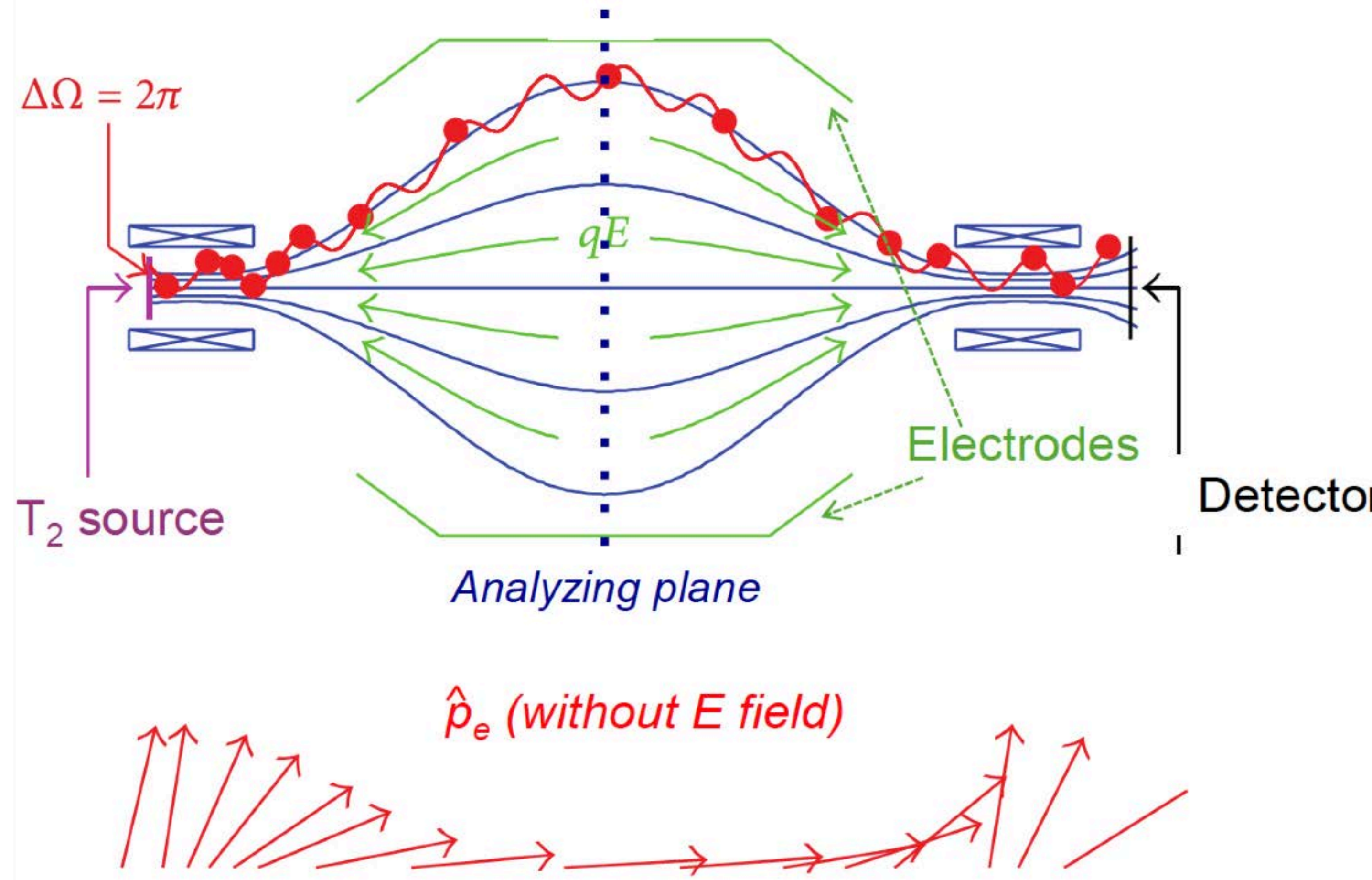
- Status of neutrino oscillation measurements including status of **searches for sterile neutrinos**

DIRECT DETECTION

Direct Neutrino Mass Detection

- To date best limits on neutrino mass come from the study of molecular tritium decay

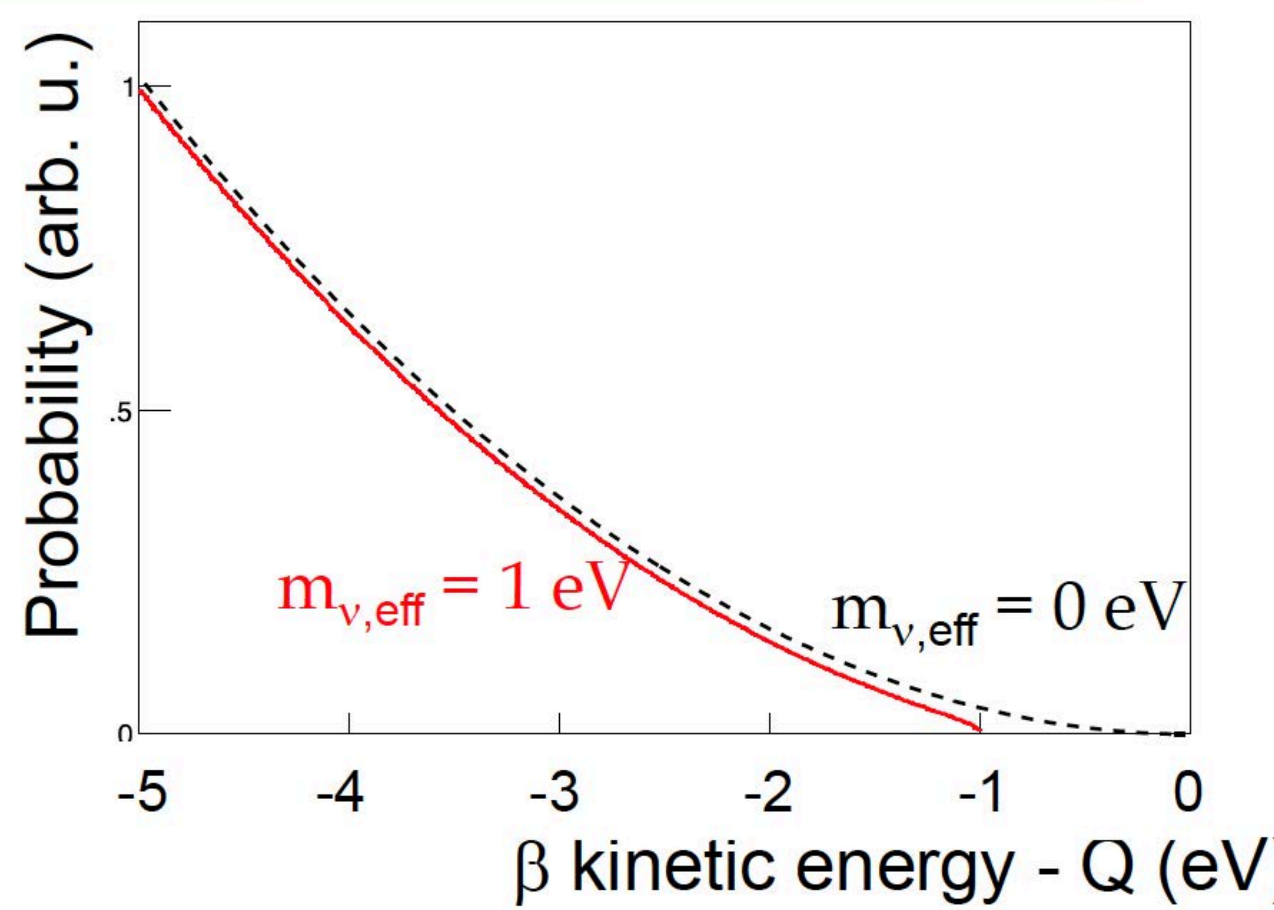




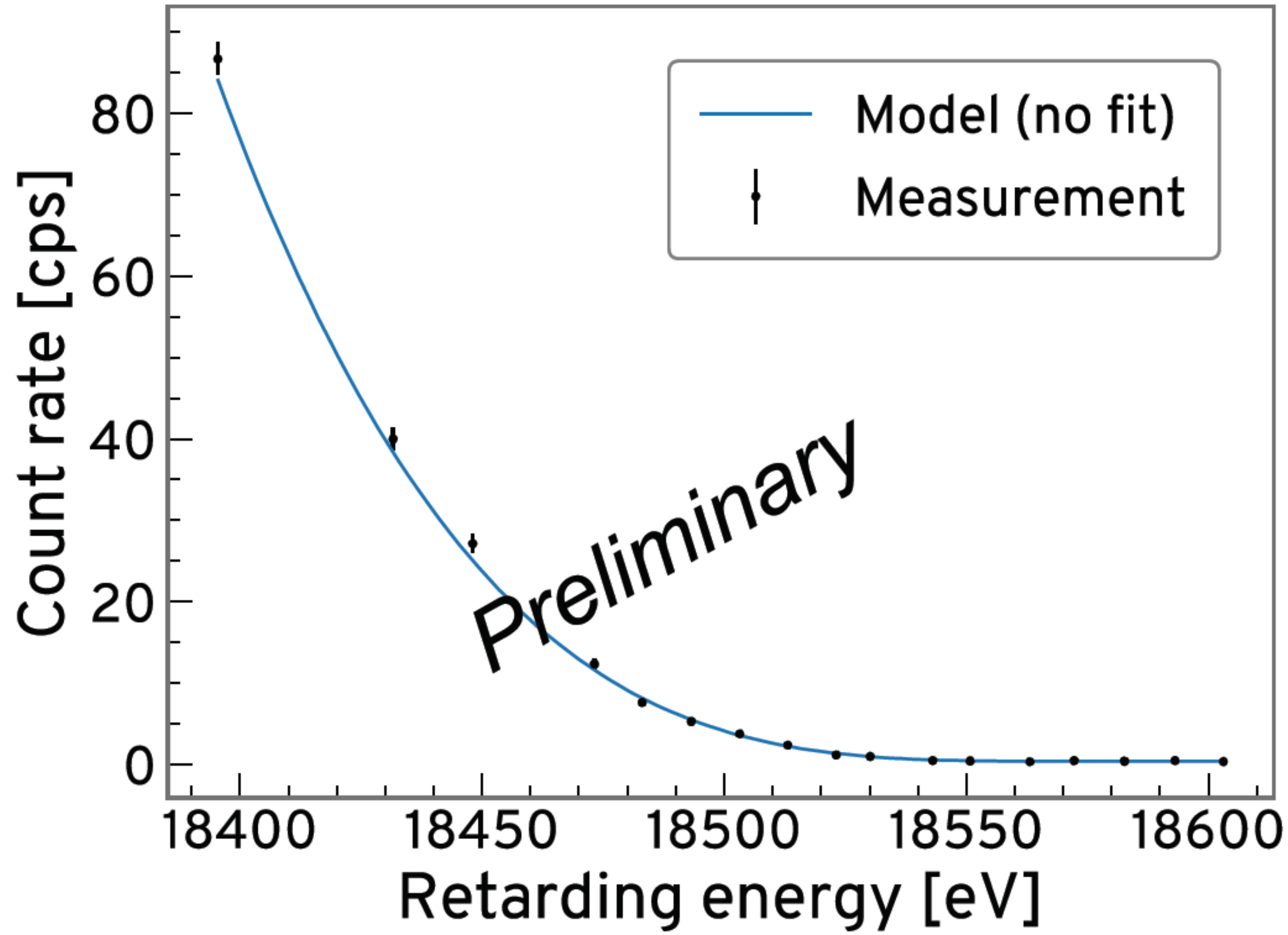
- Beta spectrum analyzed using MAC-E filters (Magnetic Adiabatic Cooling and Electrostatic filter)

- **Mainz:** $m(\nu_e) < 2.05\,\mathrm{eV} \quad (95\%\ \mathrm{C.L.})$

- **Troitsk:** $m(\nu_e) < 2.3\,\mathrm{eV} \quad (95\%\ \mathrm{C.L.})$



KATRIN Experiment: First scans

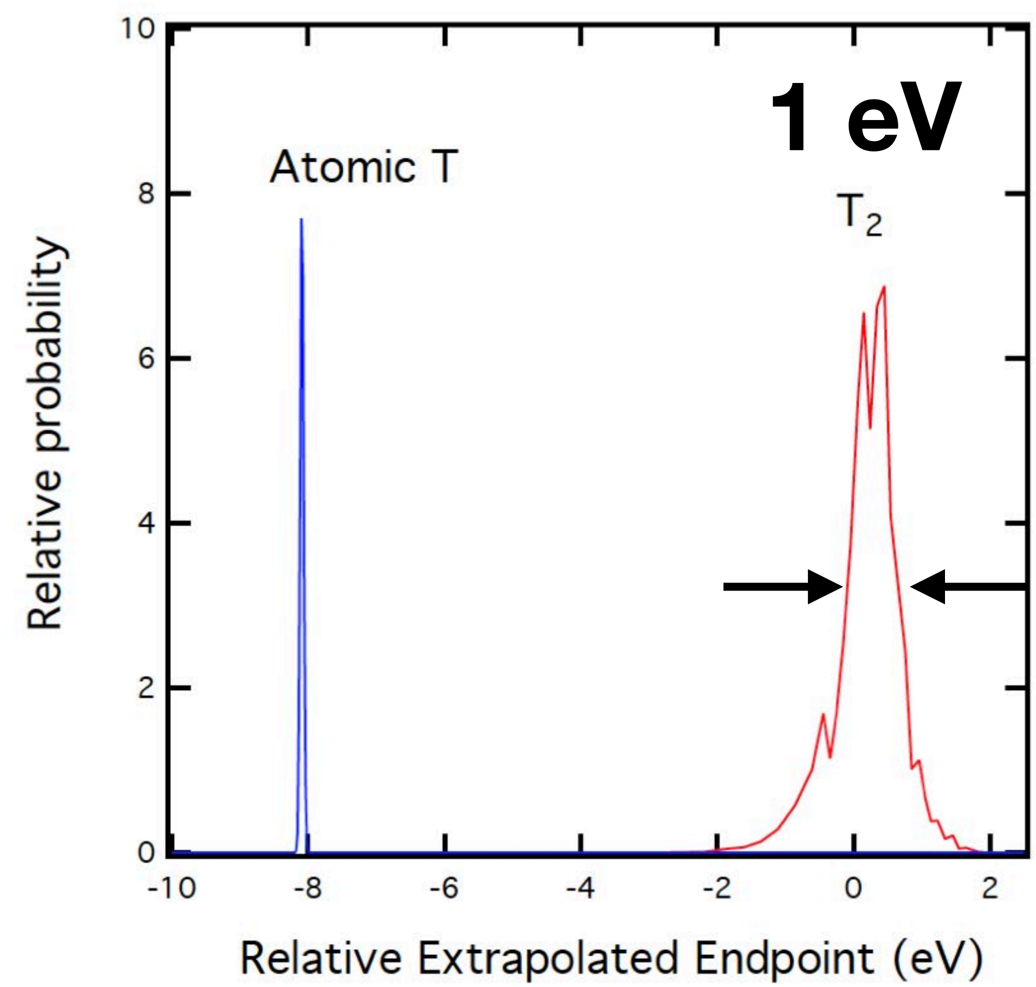


Expect first results in 2019.

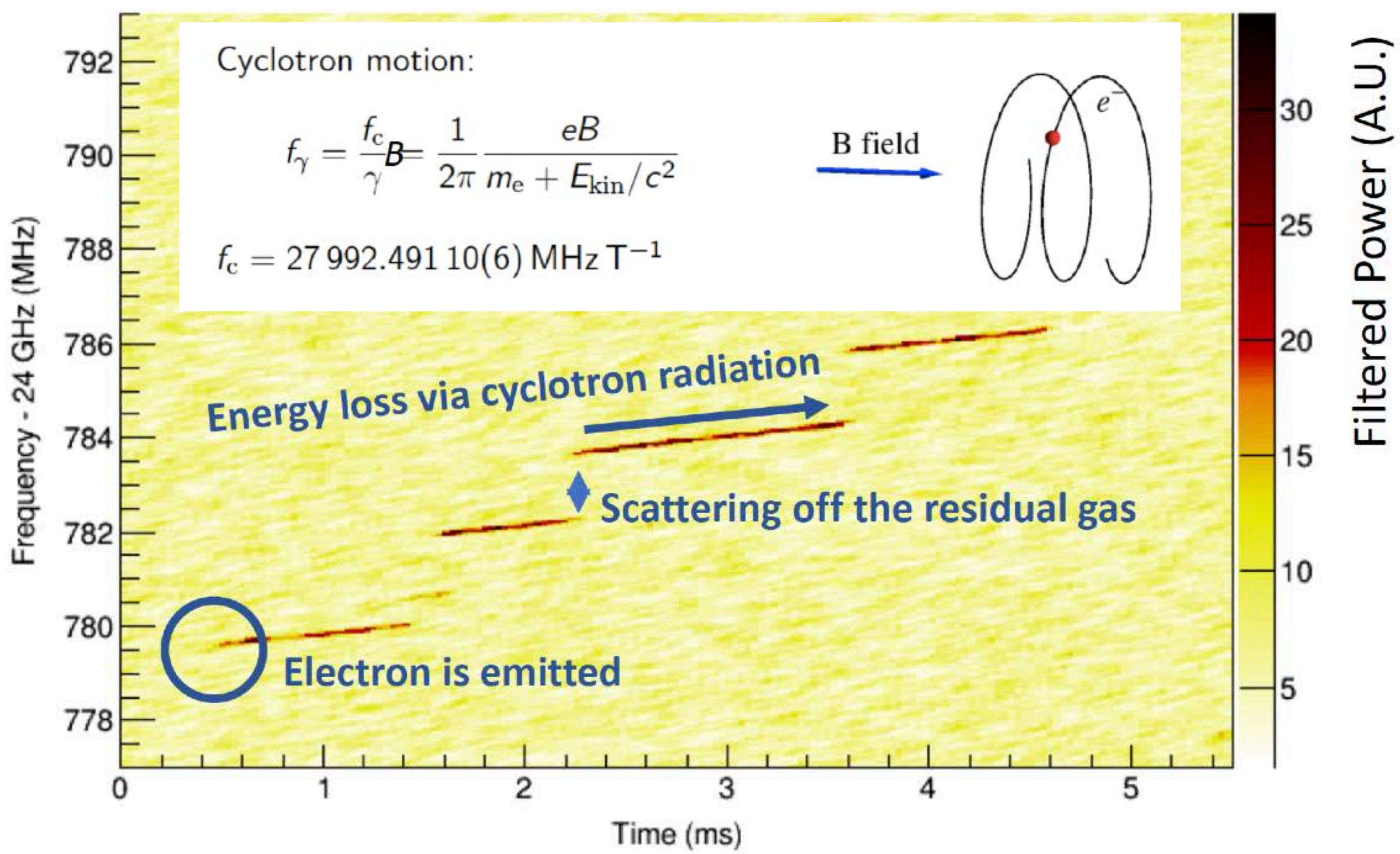
Eventual reach ~ 0.2 eV in about three years

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



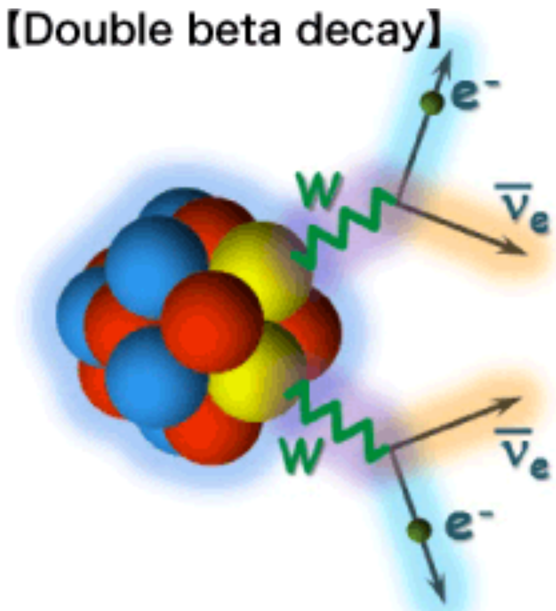
Project 8 Electron Event with Energy 18 keV



Neutrinoless Double Beta Decay

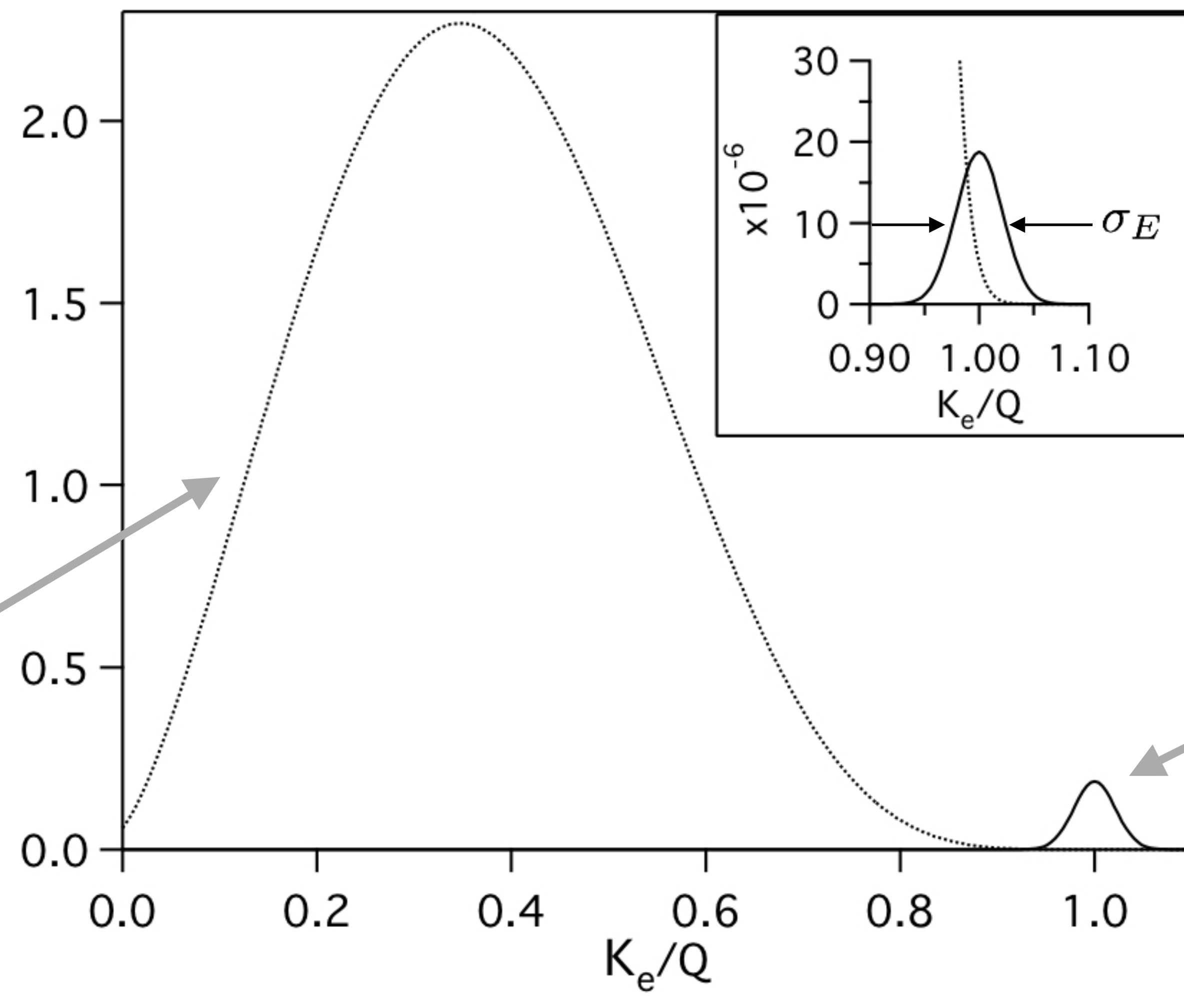
https://wwwkm.phys.sci.osaka-u.ac.jp/en/research/r01.html

Double Beta Decay



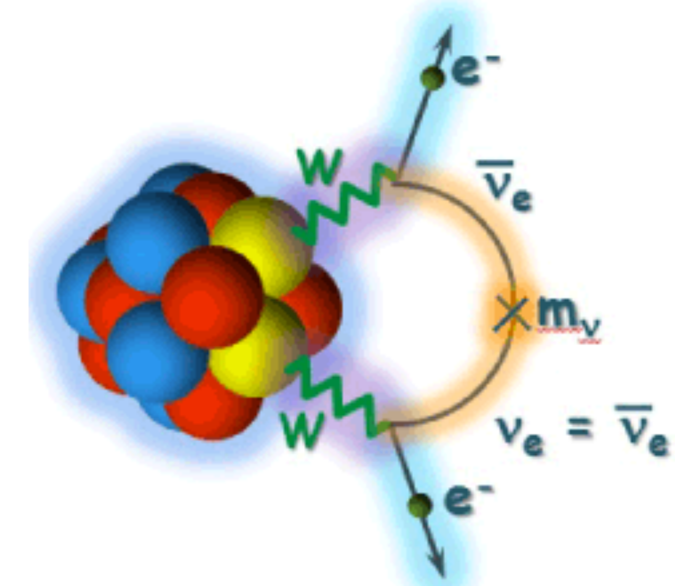
Double beta decay which emits anti-neutrinos

http://next.ific.uv.es/next/experiment/physics.html



continuous spectrum up to end point at Q value

mono energetic at Q value



Neutrinoless double beta decay

Allowed in Standard Model

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

Not allowed in Standard Model

Requires:

- Massive neutrinos
- $\triangle L = 2$
- 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 0νββ — *phase space* — *nuclear physics* — *effective neutrino mass*

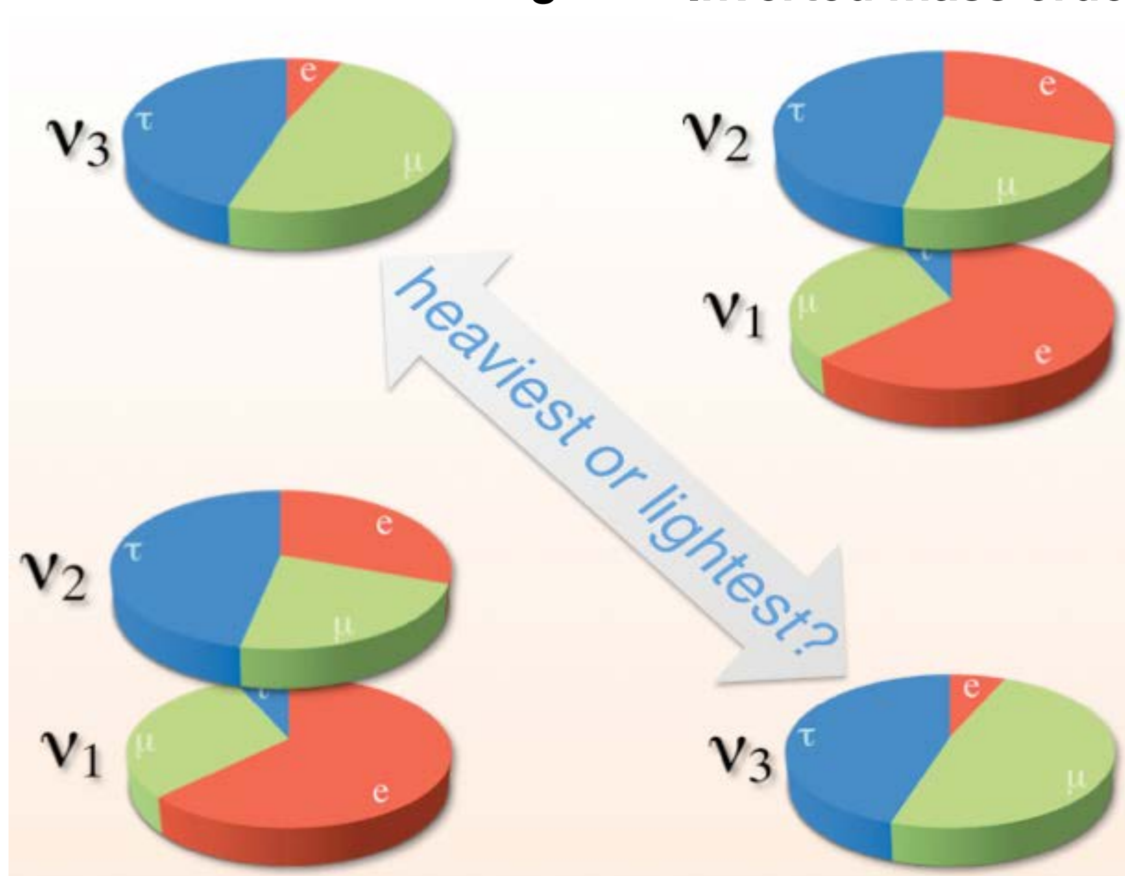
$$m_{\beta\beta} \equiv |m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i(\alpha_{31}-\delta)}|$$

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.

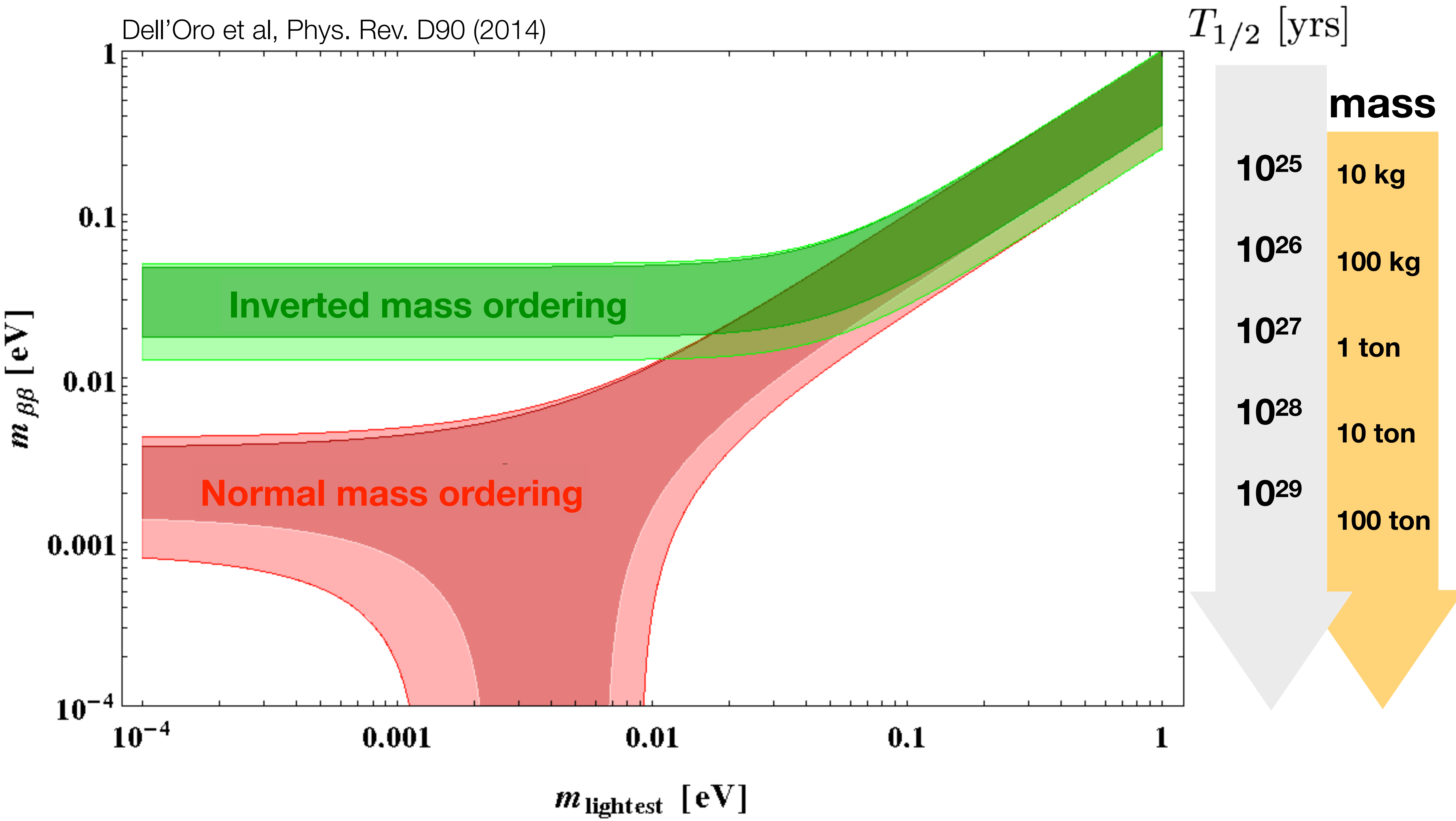
Accidental cancelations may result in $m_{\beta\beta} \to 0$.

Normal mass ordering **Inverted mass ordering**

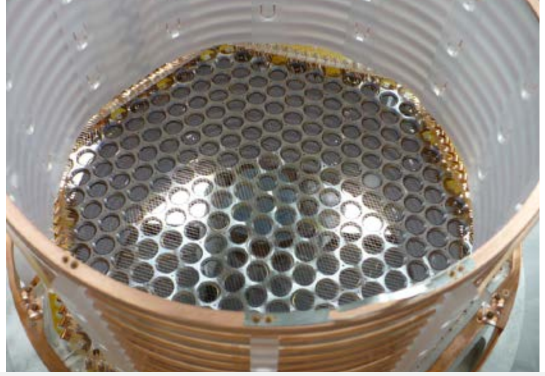


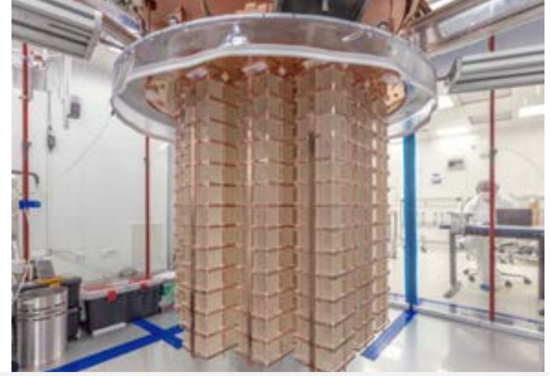
In the inverted ordering most of the electron flavor is associated with the heavier states giving generally higher values of $m_{\beta\beta}$,

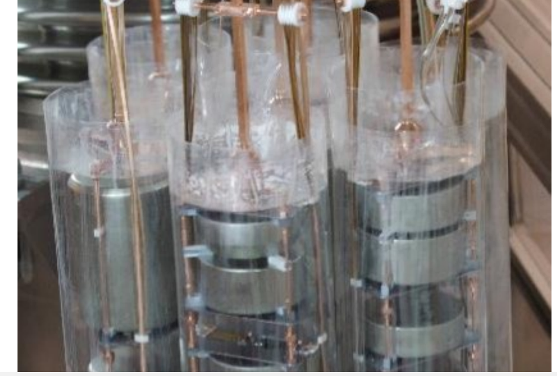
Neutrino oscillation measurements set a lower limit at ≈15-50 meV, $T_{1/2} \approx 10^{27\text{-}28}$ years

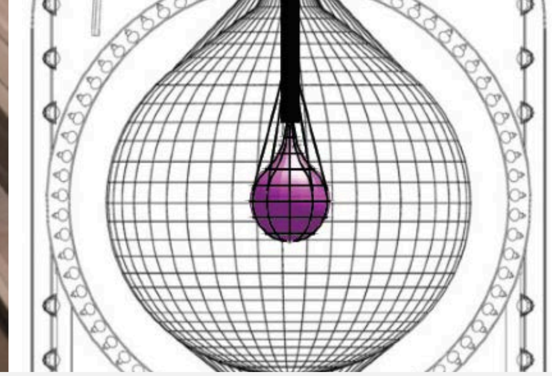


Following T. Kajita at Neutrino 2018

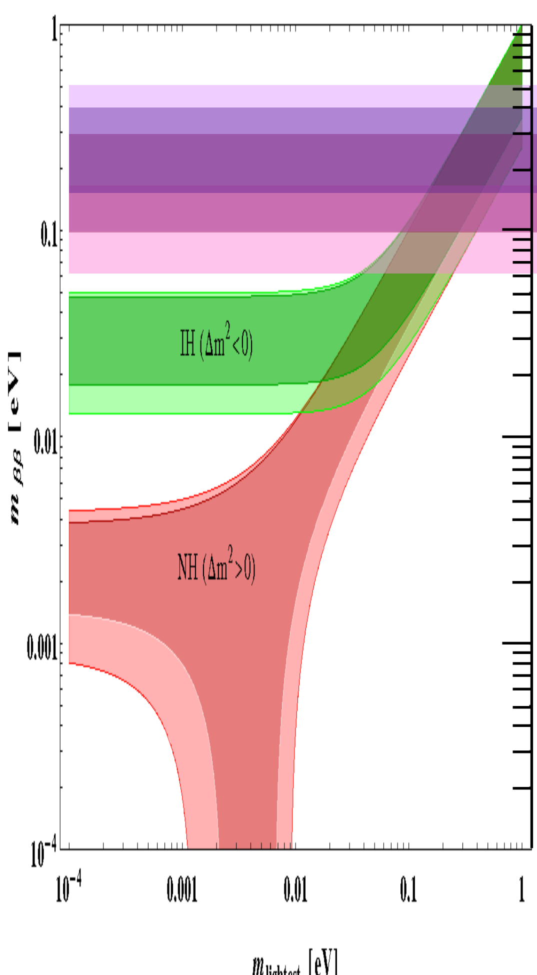


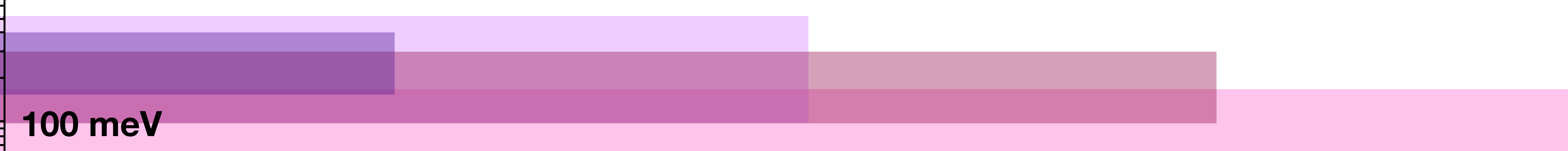






	EXO PRL 120 072701 (2018)	**CUORE** PRL 120, 132501 (2018)	**GERDA/Majorana** Eur. Phys. J. C78 (2018) 388	**KamLAND-Zen** PRL. 117, 082503 (2016)
	^{136}Xe	^{130}Te	^{76}Ge	^{136}Xe
	TPC	Bolometer	Solid state	Scintillator
Exposure [kg-yr]	175	86	82	504
σ_E [keV]	30	5	3-3.6	100
$T_{1/2}$ @ 90% CL	1.8×10^{25}	1.5×10^{25}	1.1×10^{26}	1.1×10^{26}
mββ @ 90%CL	147-398	110-520	100-300	61-165





isotope mass

running time

detection efficiency

$$T_{1/2}^{\text{limit}} \propto \epsilon \sqrt{\frac{m \cdot t}{B \cdot \sigma_E}}$$

background rate

energy resolution

Background reductions through shielding, isolation, purity, pulse shape discrimination, possibly ion tagging

Agostini et al. PRD 96, 053001 (2017)

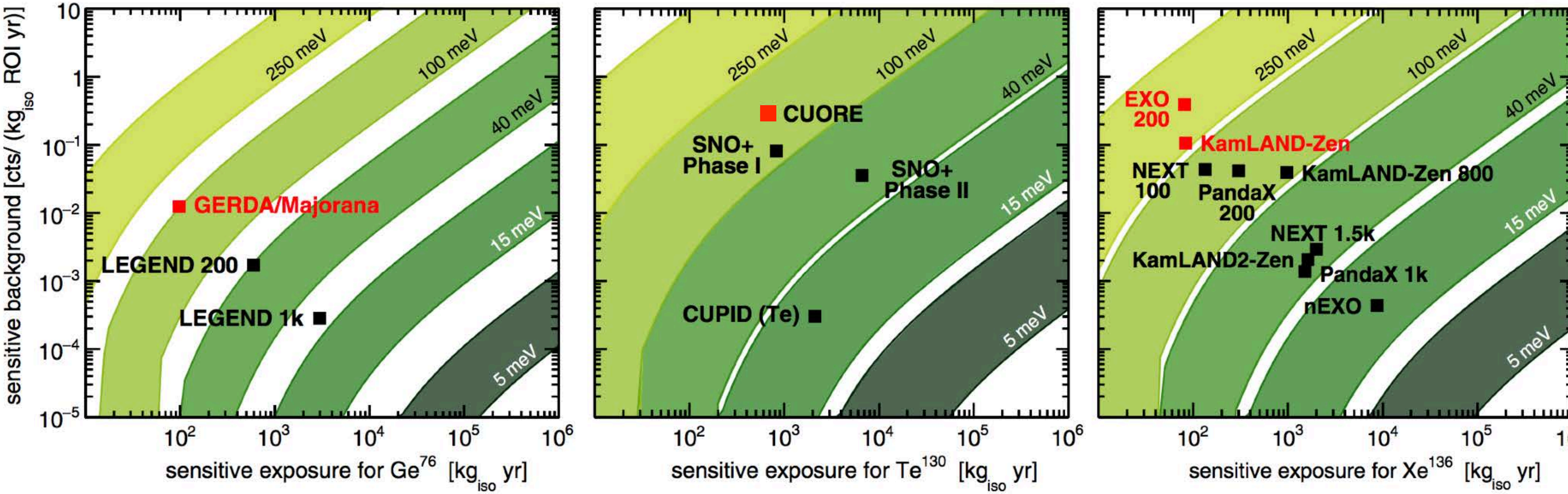
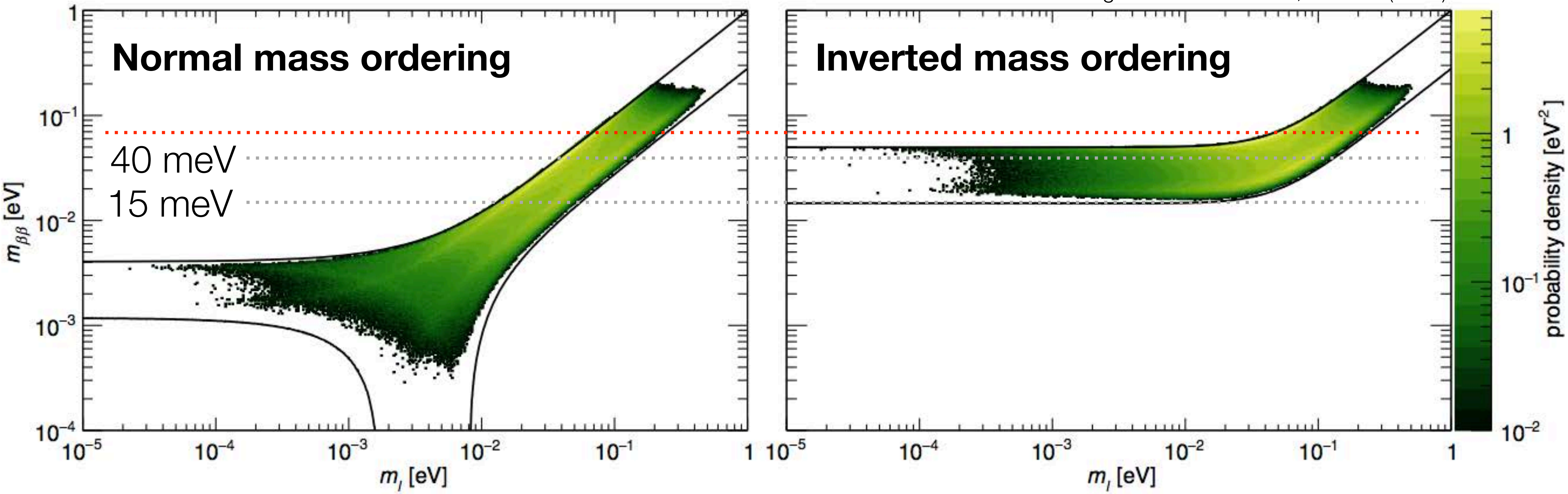


FIG. 3. Discovery sensitivity for ^{76}Ge, ^{130}Te, and ^{136}Xe as a function of sensitive exposure and sensitive background. Contours in $m_{\beta\beta}$ are represented as bands spanning the range of considered NME values. The experimental sensitivities of future or running experiments are marked 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

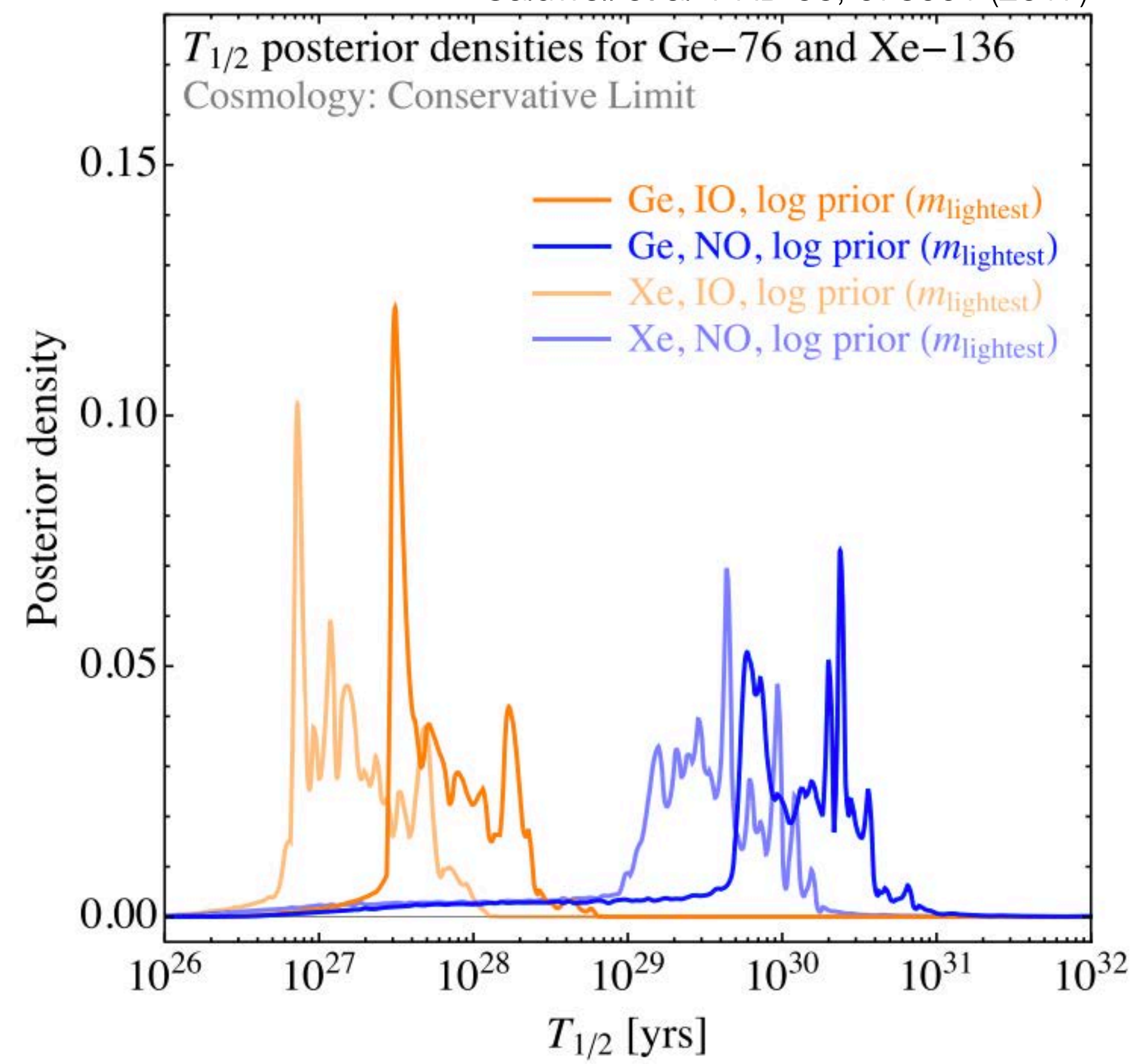
Agostini et al. PRD 96, 053001 (2017)



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

- 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 3σ observation in next generation.
- Watch the assumptions! Caldwell et al. (right), for example, finds normal ordering harder to reach than does Agostini et al.

Caldwell et al. PRD 96, 073001 (2017)



OSCILLATIONS

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

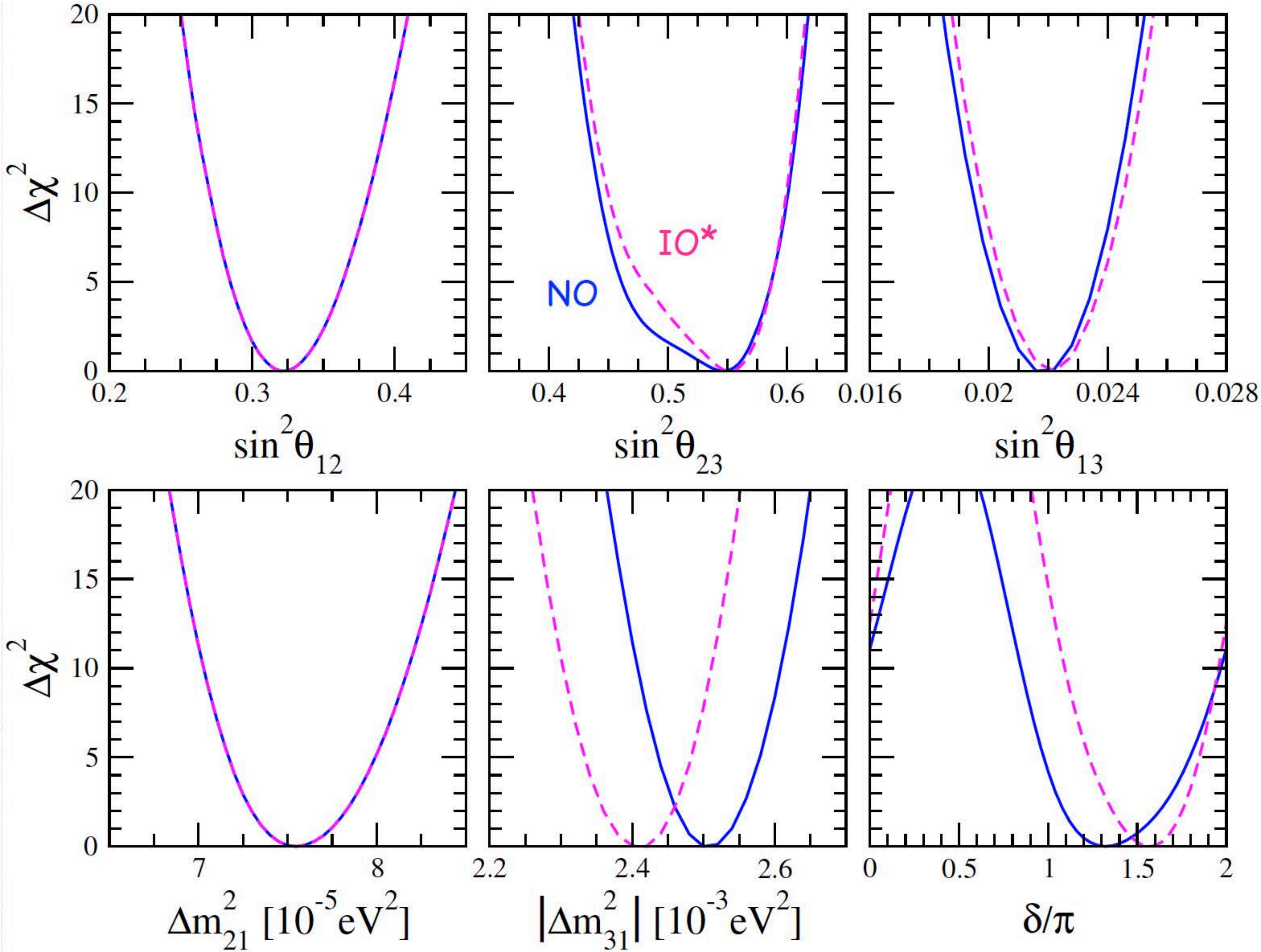
Neutrino oscillations

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

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

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

deSalas et al, 1708.01186

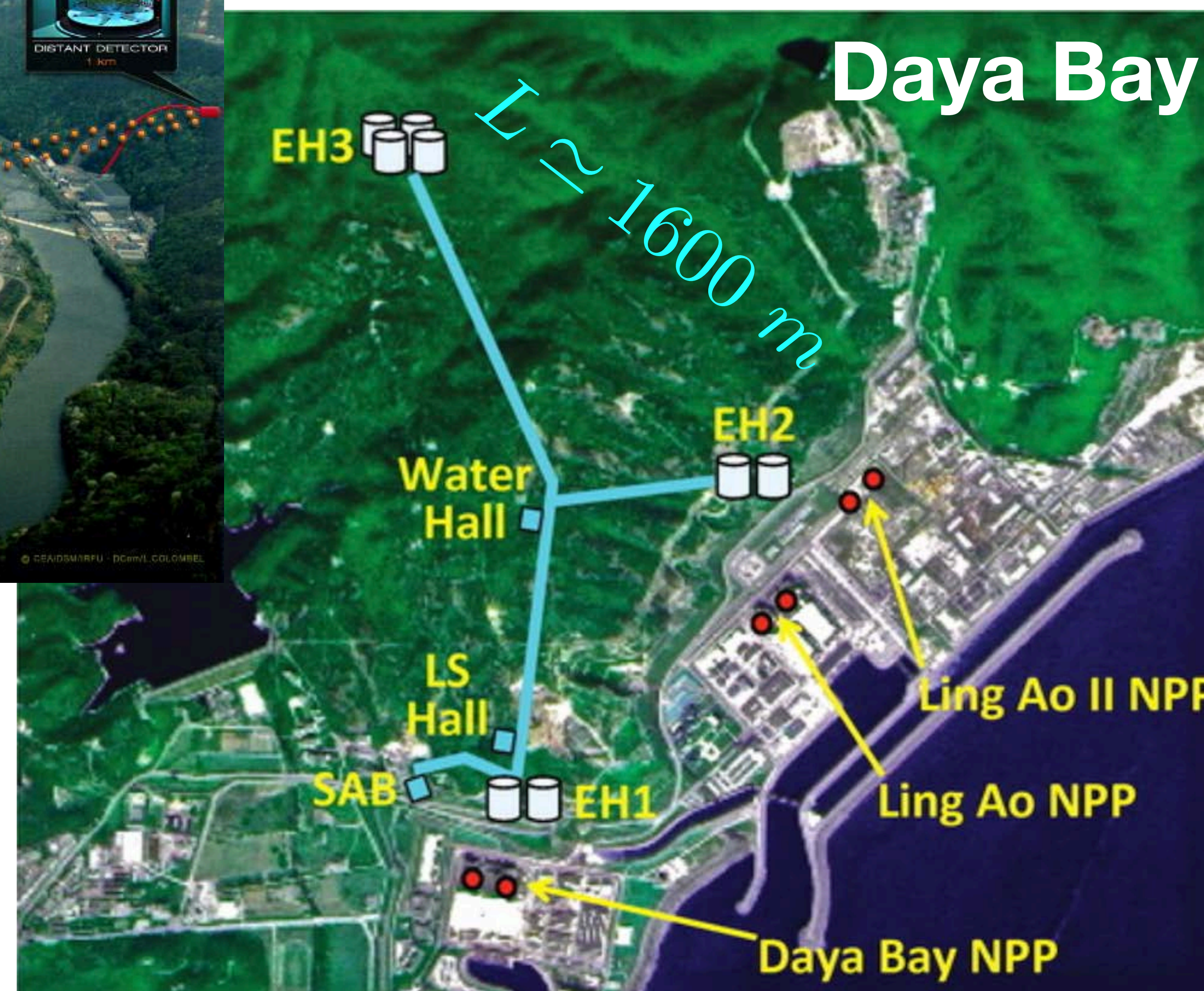


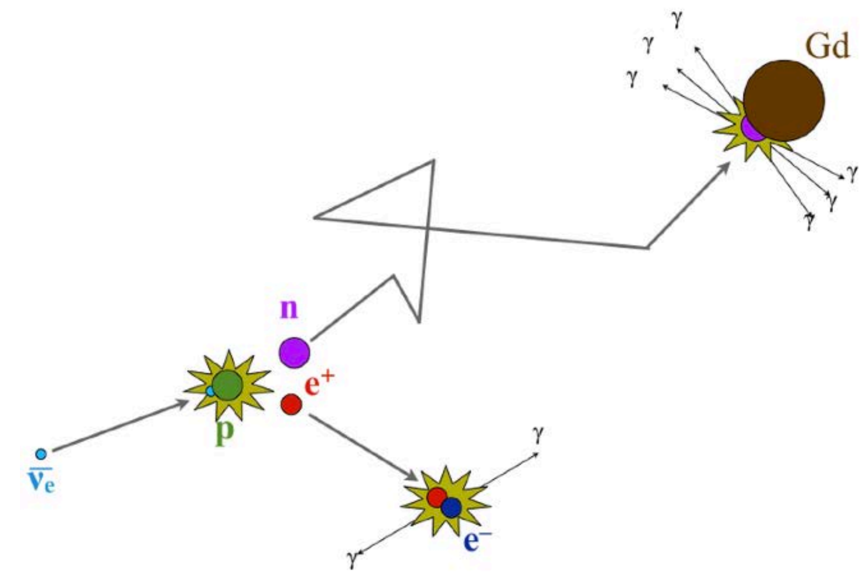
θ_{13}: Daya Bay, RENO, and Double CHOOZ

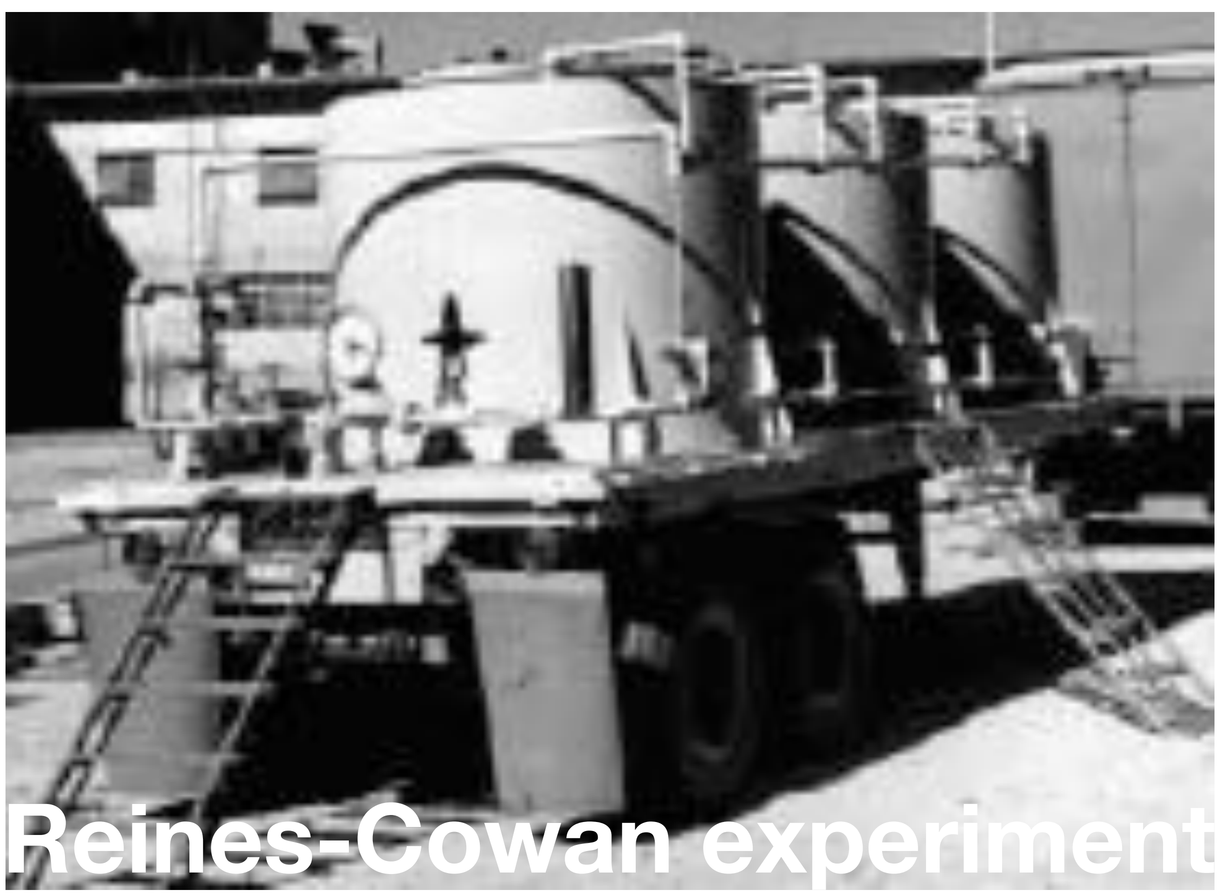
$$\Delta = \frac{1.27 \cdot 0.0025 \text{ eV}^2 \cdot 1600 \text{ m}}{4 \text{ MeV}} \simeq \frac{\pi}{2}$$

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

$E \simeq 4$ MeV







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

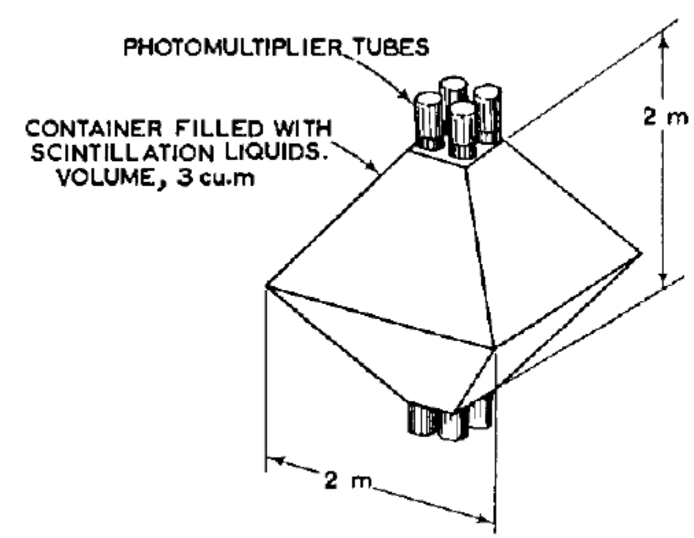
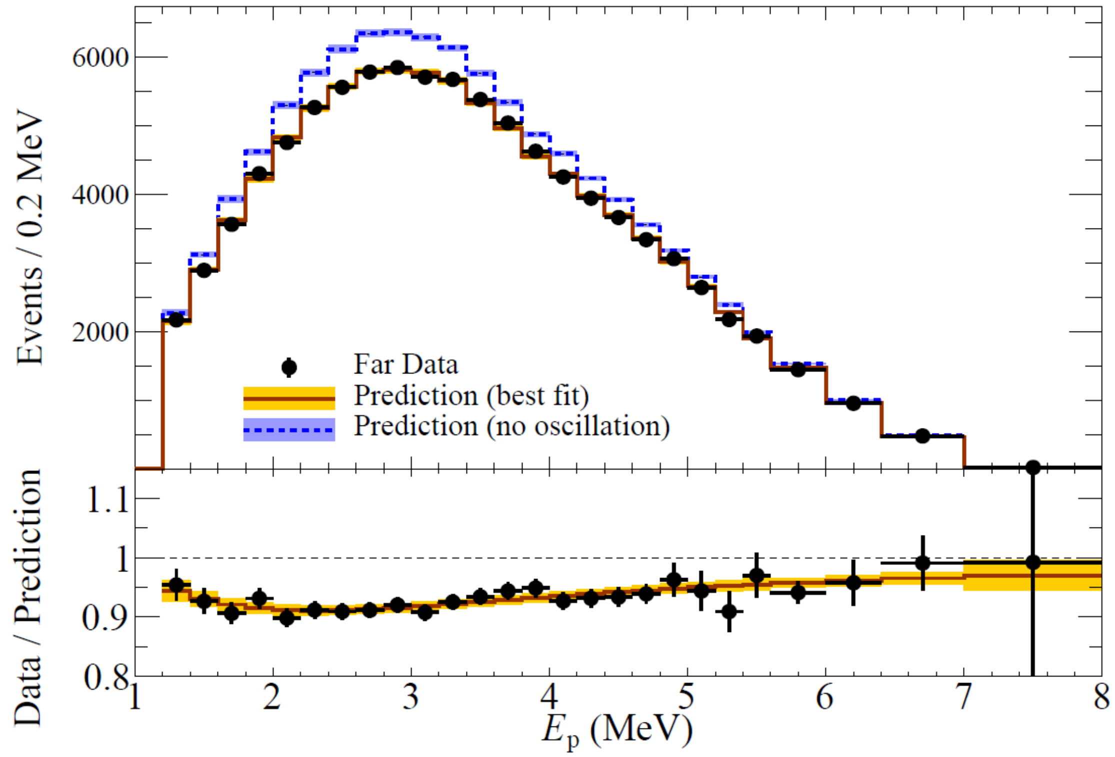
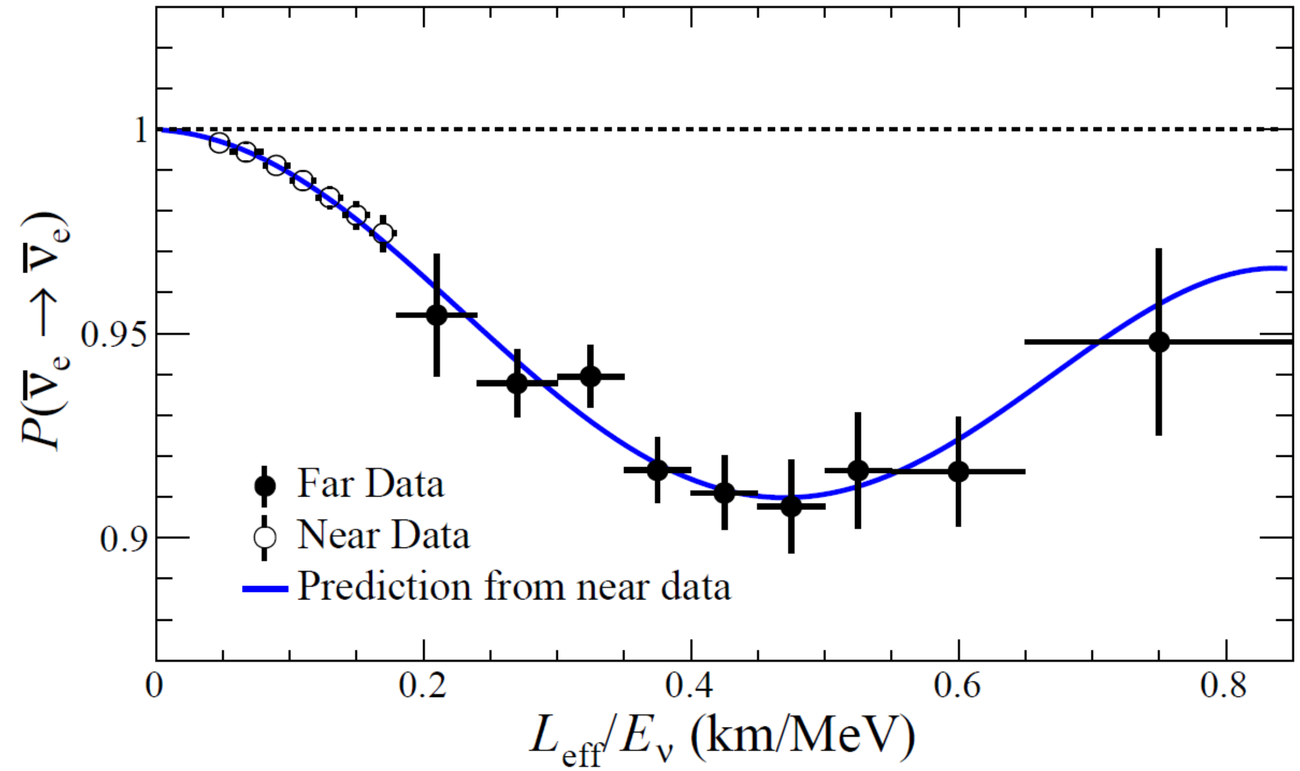


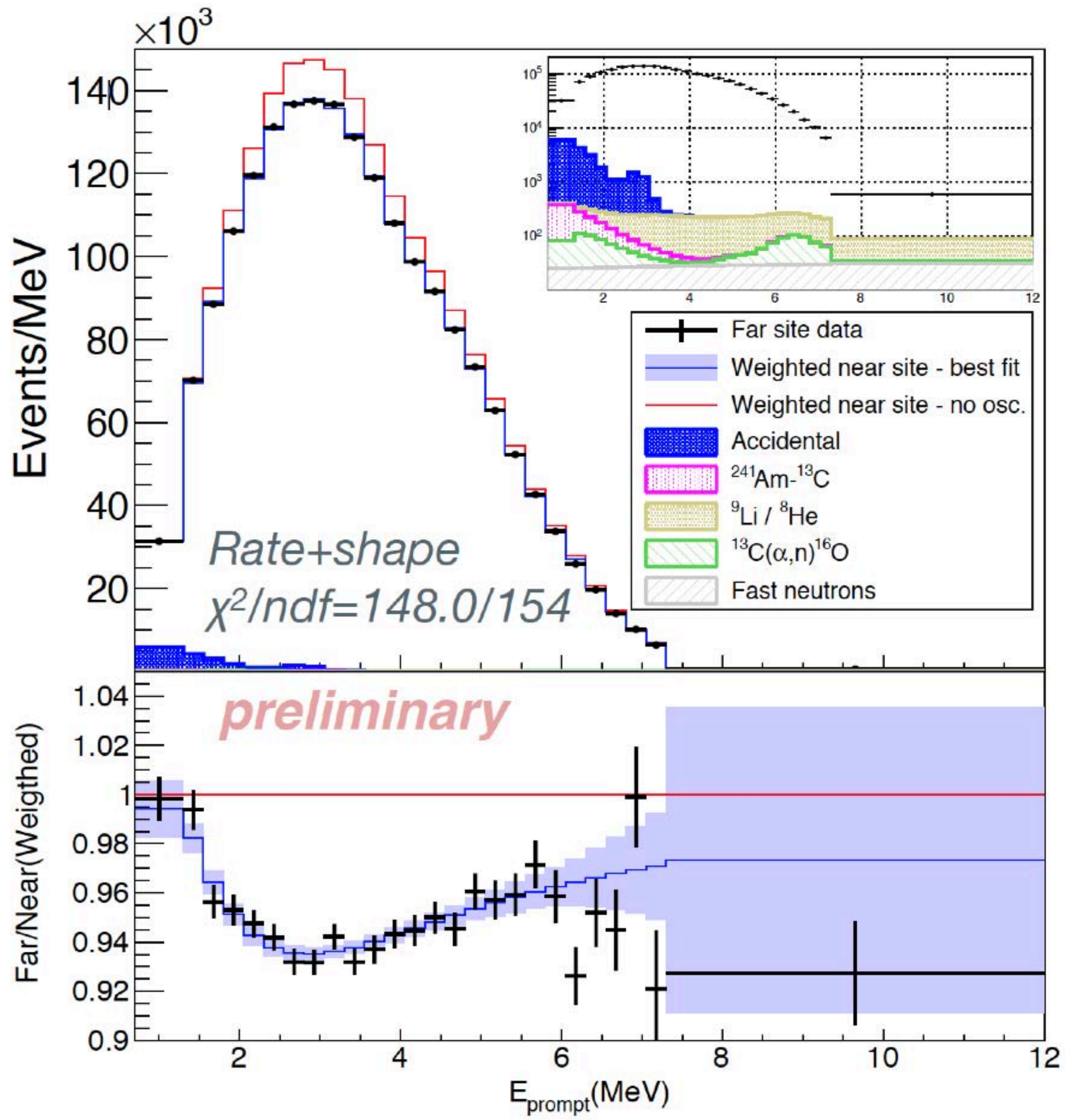
Fig. 1. Sketch of 'El Monstro', first Los Alamos attempt at a giant liquid scintillation detector (1952).

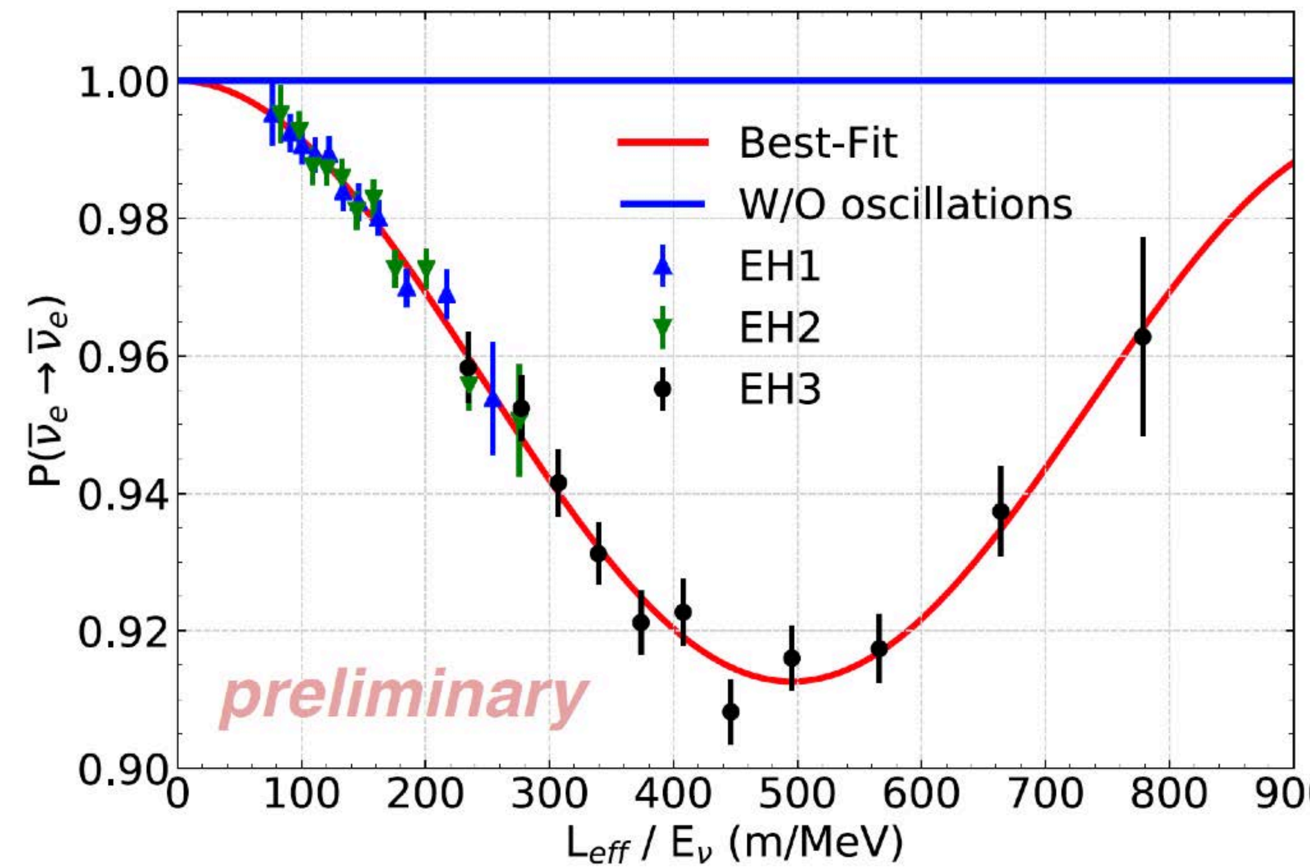
RENO





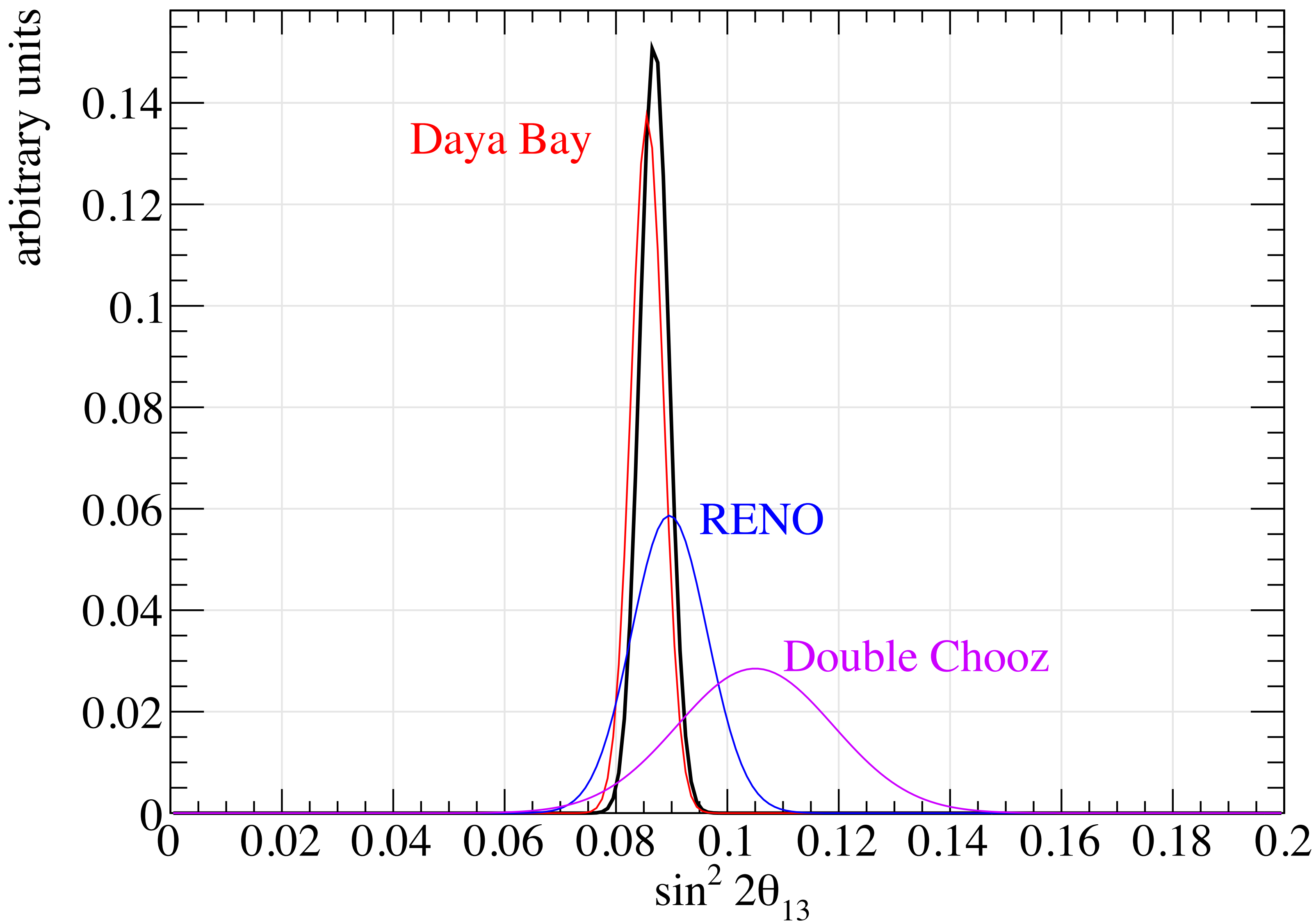
Daya Bay



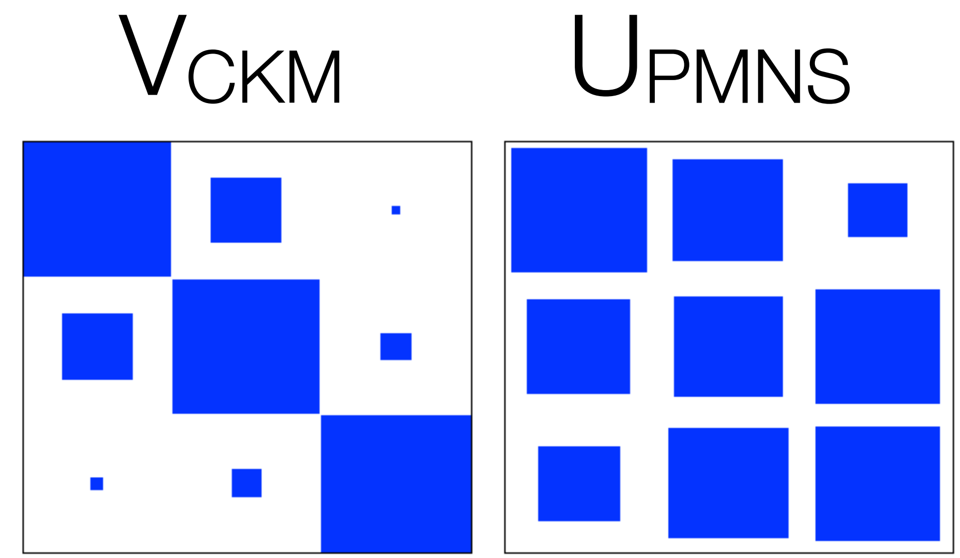


$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{1.267\Delta m^2 L}{E} - P_{\text{solar}}$$

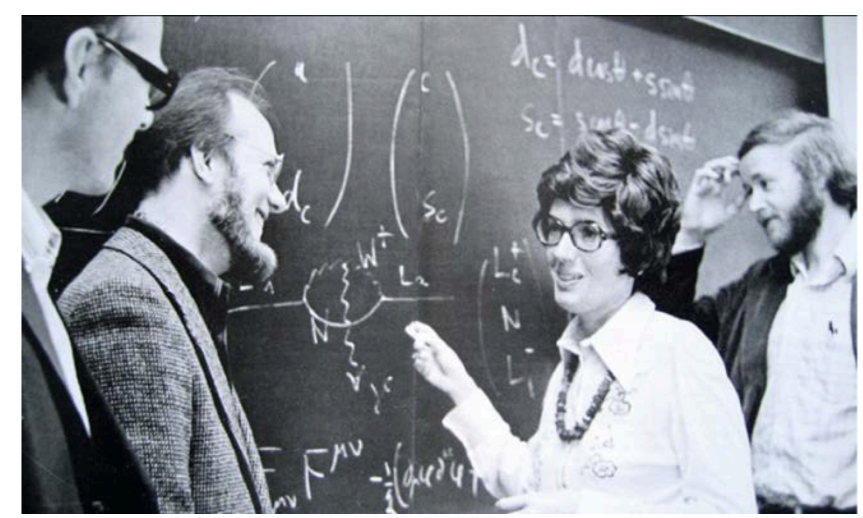
$$\sin^2 2\theta_{13} = 0.0869 \pm 0.0026$$



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



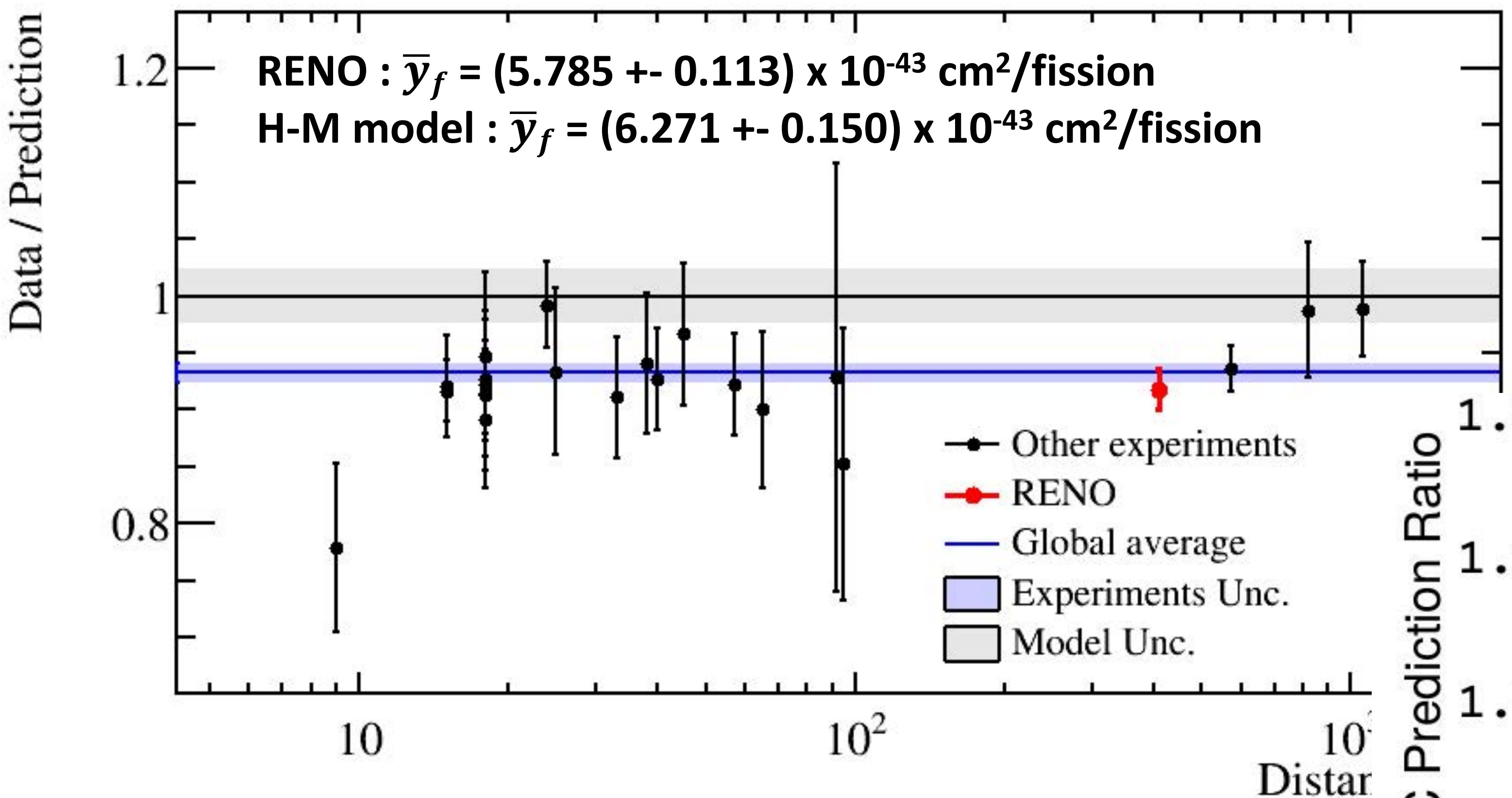
$$\frac{J_{\mathrm{PMNS}}}{J_{\mathrm{CKM}}} = \frac{3 \times 10^{-2}}{3 \times 10^{-5}} \sin(\delta_{\mathrm{PMNS}})$$



CP violation in leptons

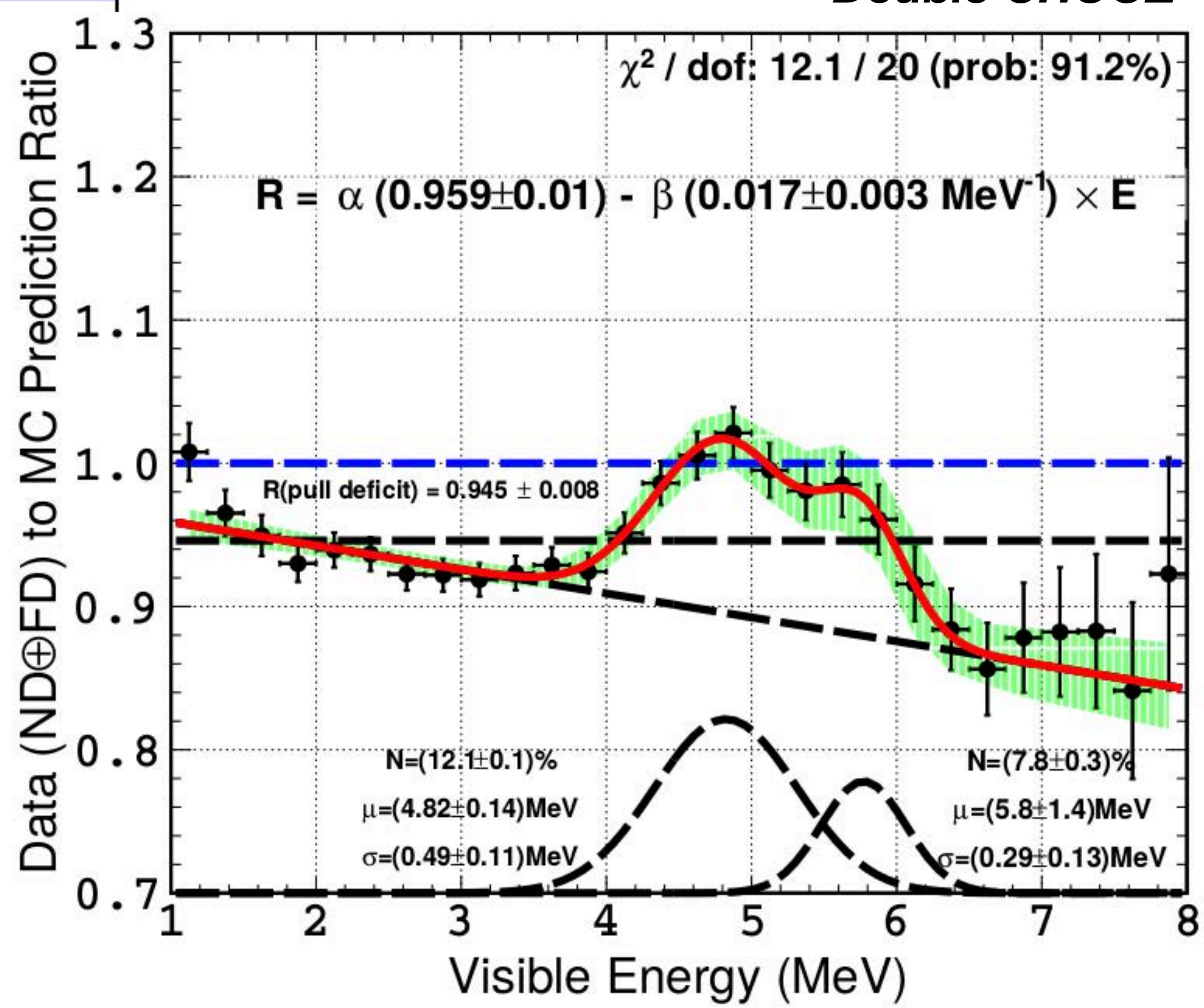
Leptonic CP violation can be 1000x larger than in the quark sector!

RENO



5 MeV "bump" Seen in all three experiments

Double CHOOZ



All experiments low by 5% compared to current models

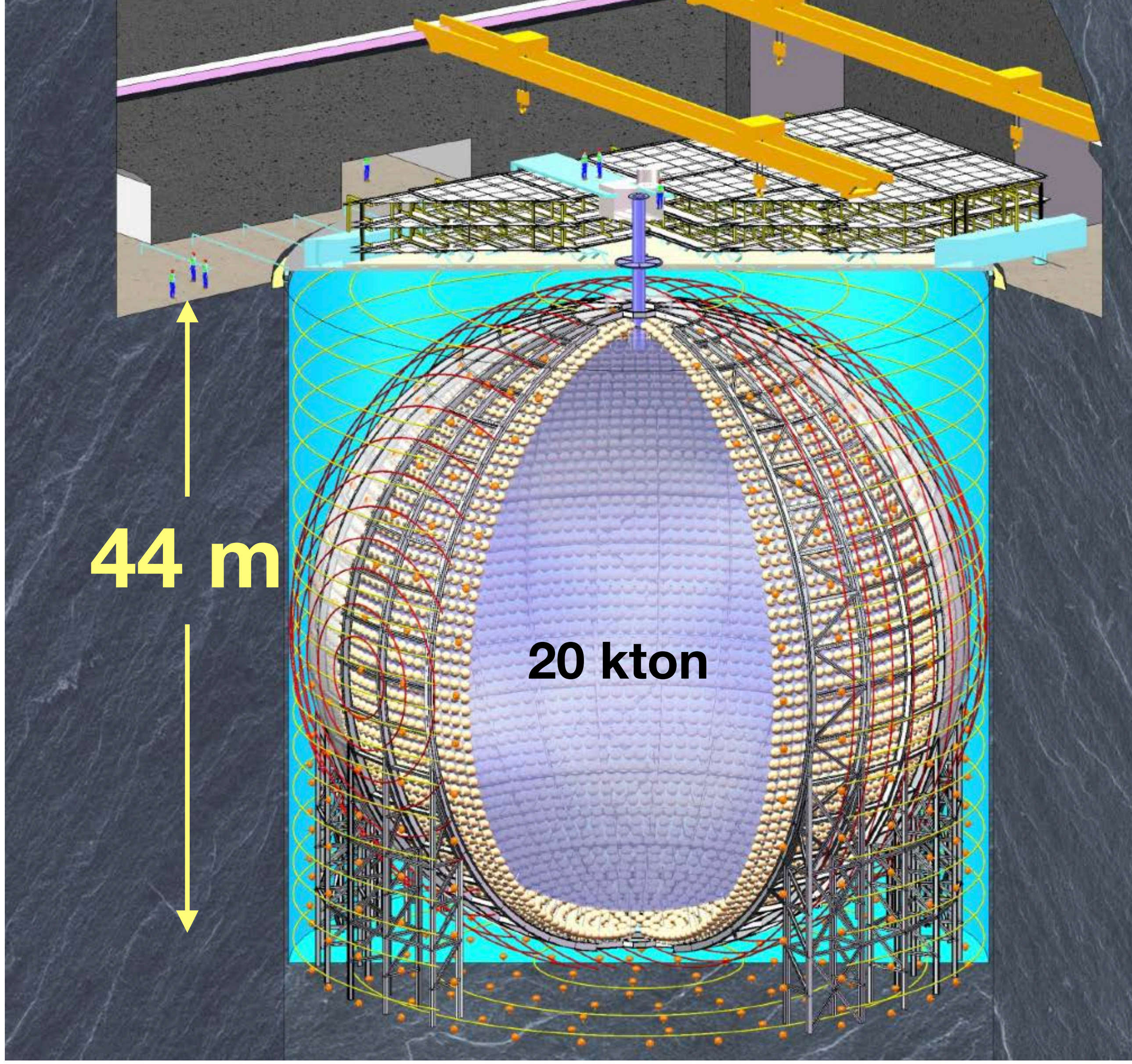
Daya Bay: Phys. Rev. Lett. 182, 251801 (2017), correlates with reactor burn time hence likely associated with reactor modeling of fission fragments

Understanding reactor neutrino fluxes

Anna Hayes at Neutrino 2018*: "Improved treatments reduce the size of the anomaly". "The BUMP is due to standard nuclear physics…may be from 238U"*

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 3-4σ
- Also has very strong program in 21 and 31 sectors.
- Data taking ~2021

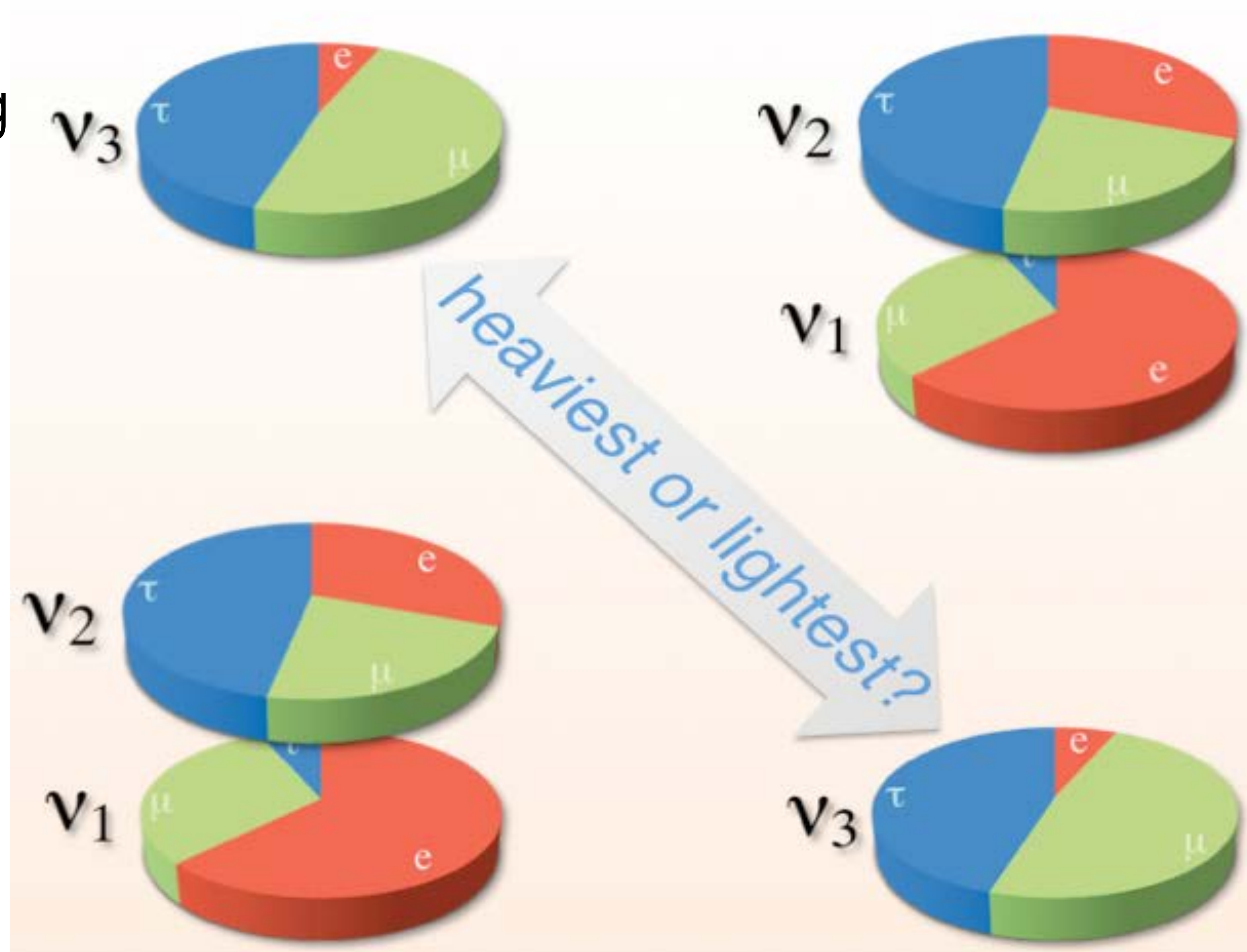


	Δm^2_{21}	$\sin^2\theta_{12}$	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
Dominant experiment	KamLAND	SNO	T2K & NOvA /Daya Bay	Daya Bay	T2K
Individual 1σ	2.4%	6.7%	3.2%/3.5%	4.0%	9.8%
Global 1σ *	2.2%	3.9%	1.2%	3.4%	5%
JUNO expected 1σ	0.6%	0.7%	0.4%	~15%	-

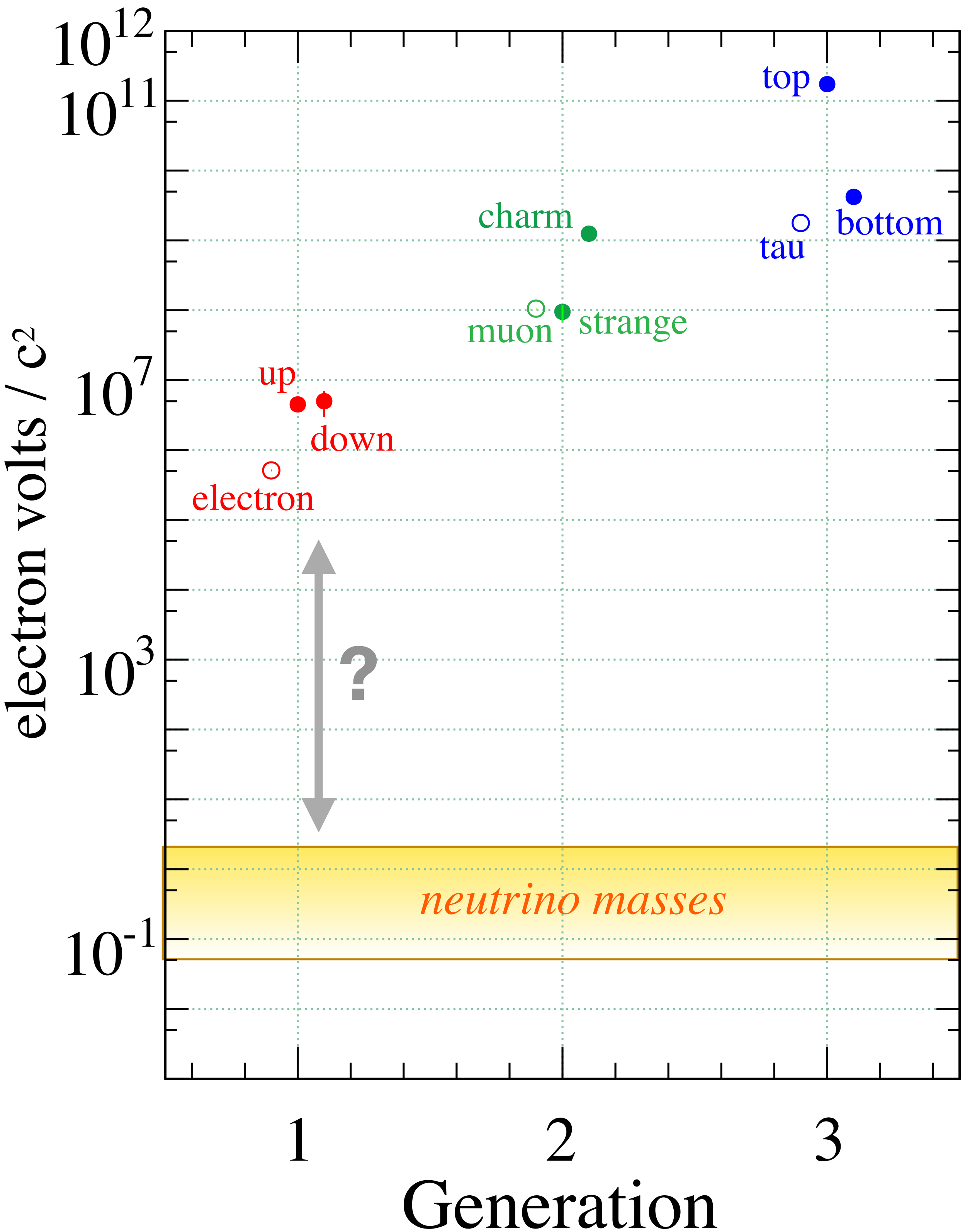
Δm^2_{ee}

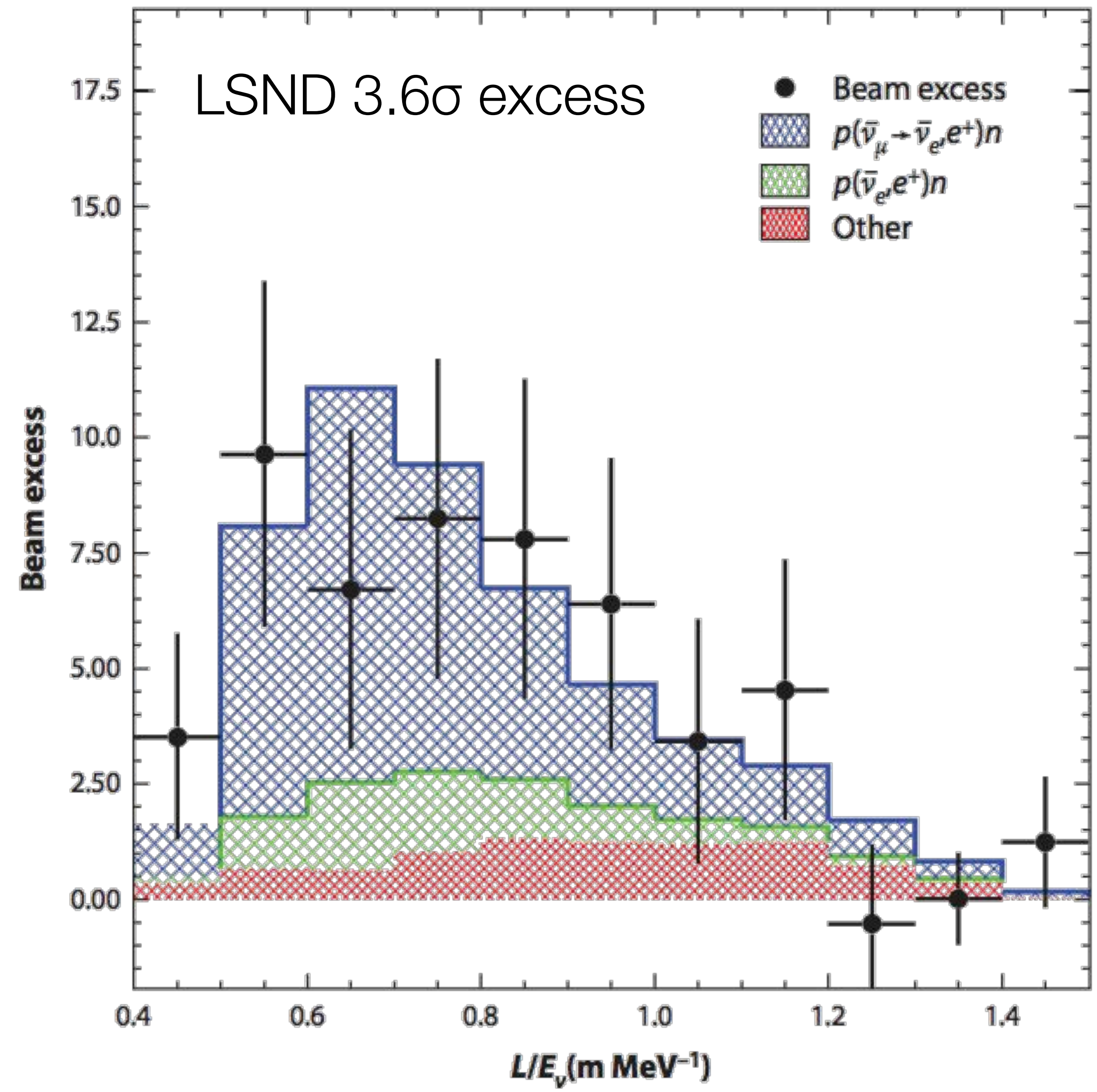
Next Questions In Neutrino Physics

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

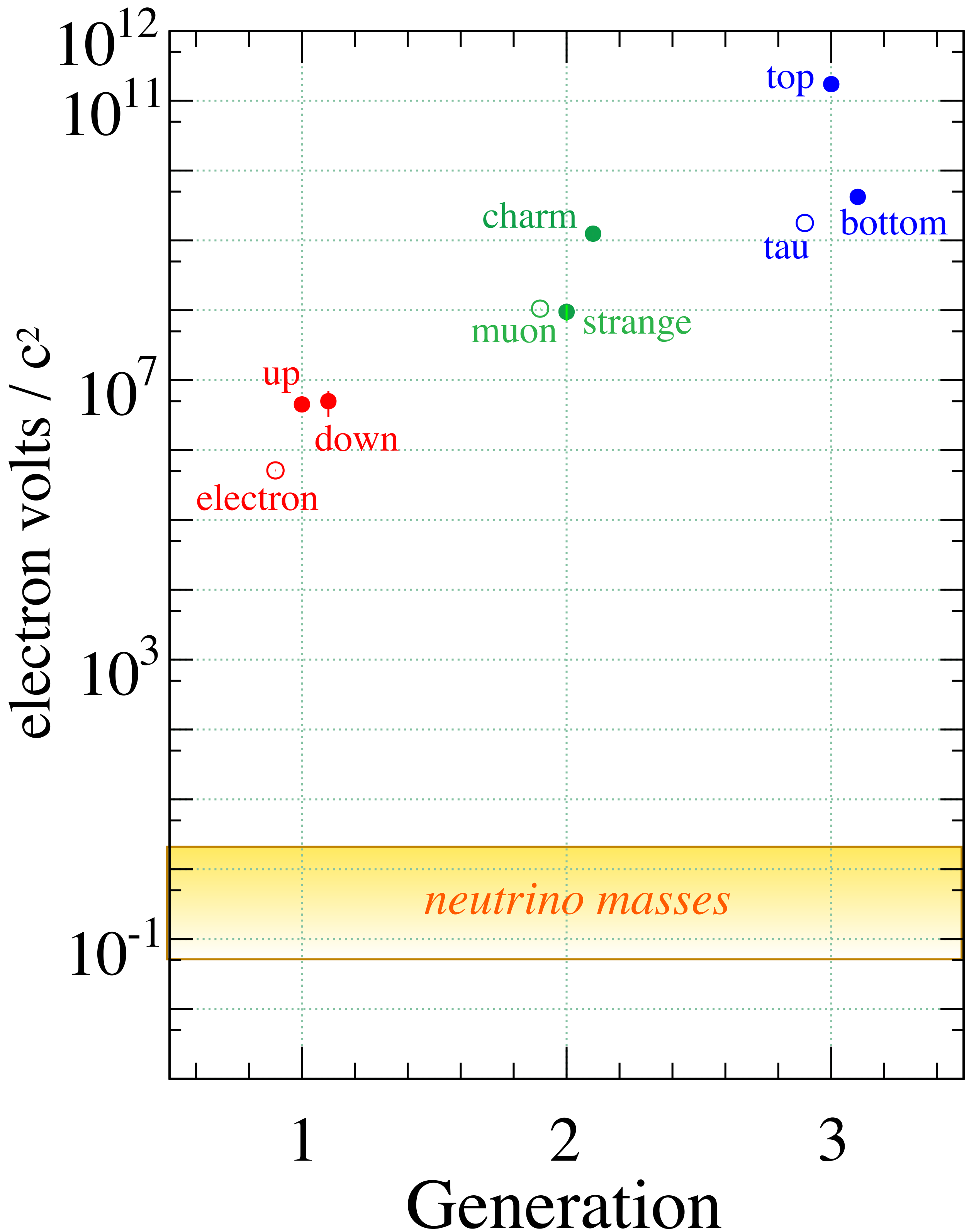


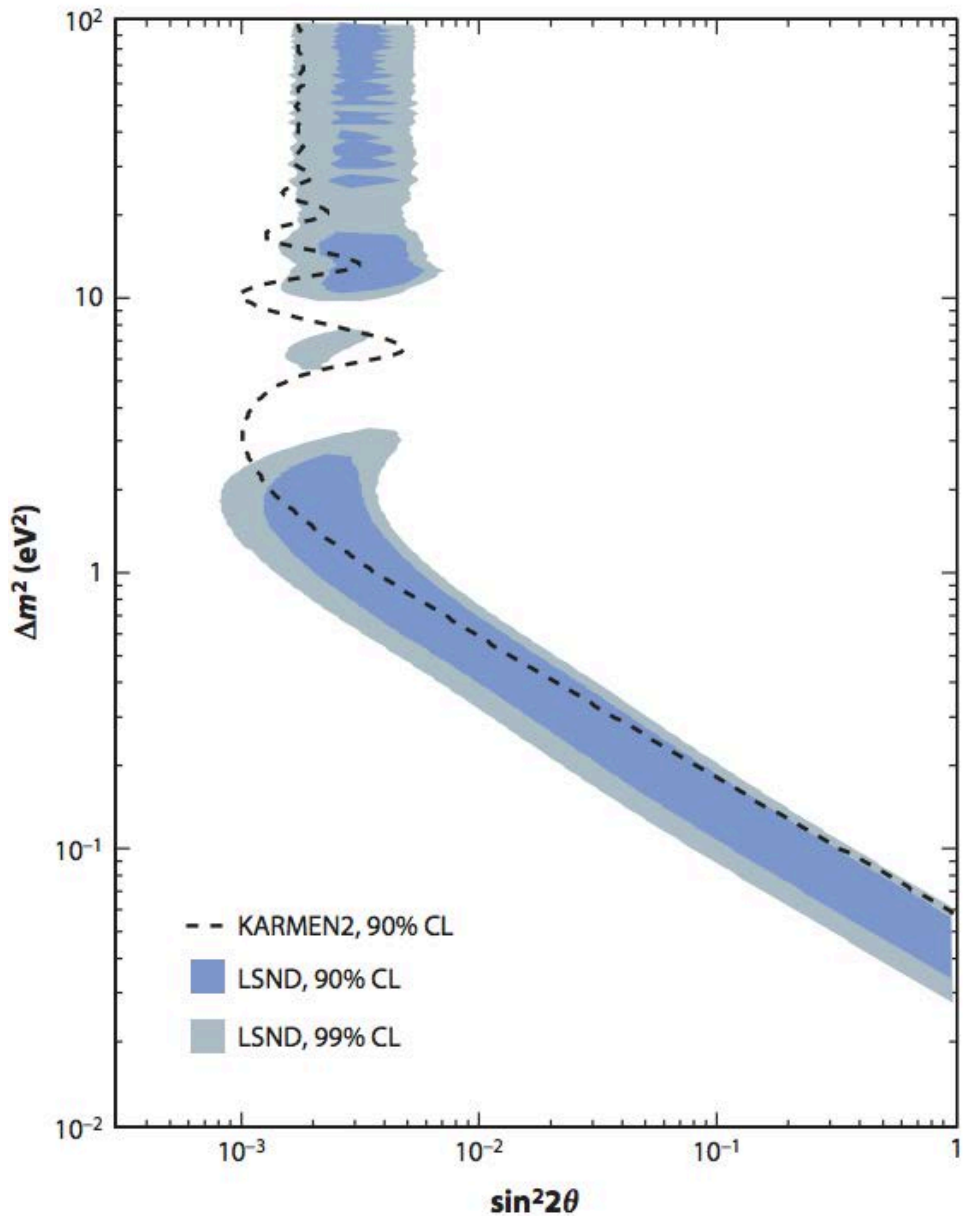
Motivation for sterile neutrino searches



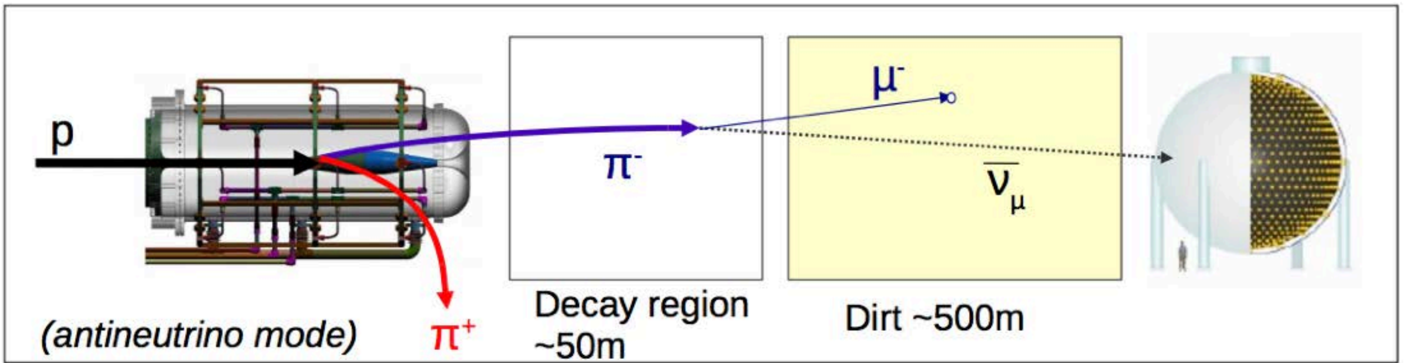


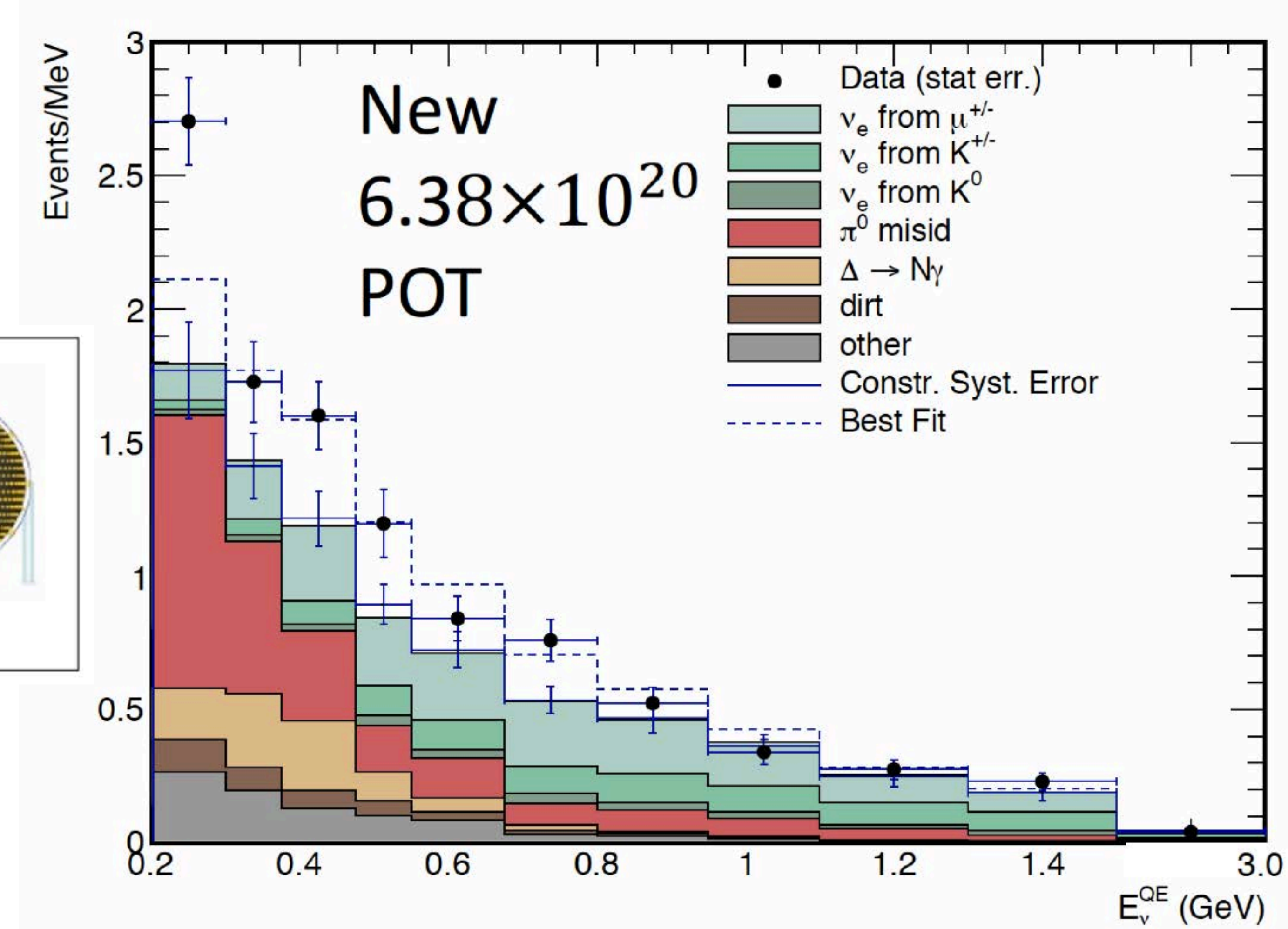
Motivation for sterile neutrino searches

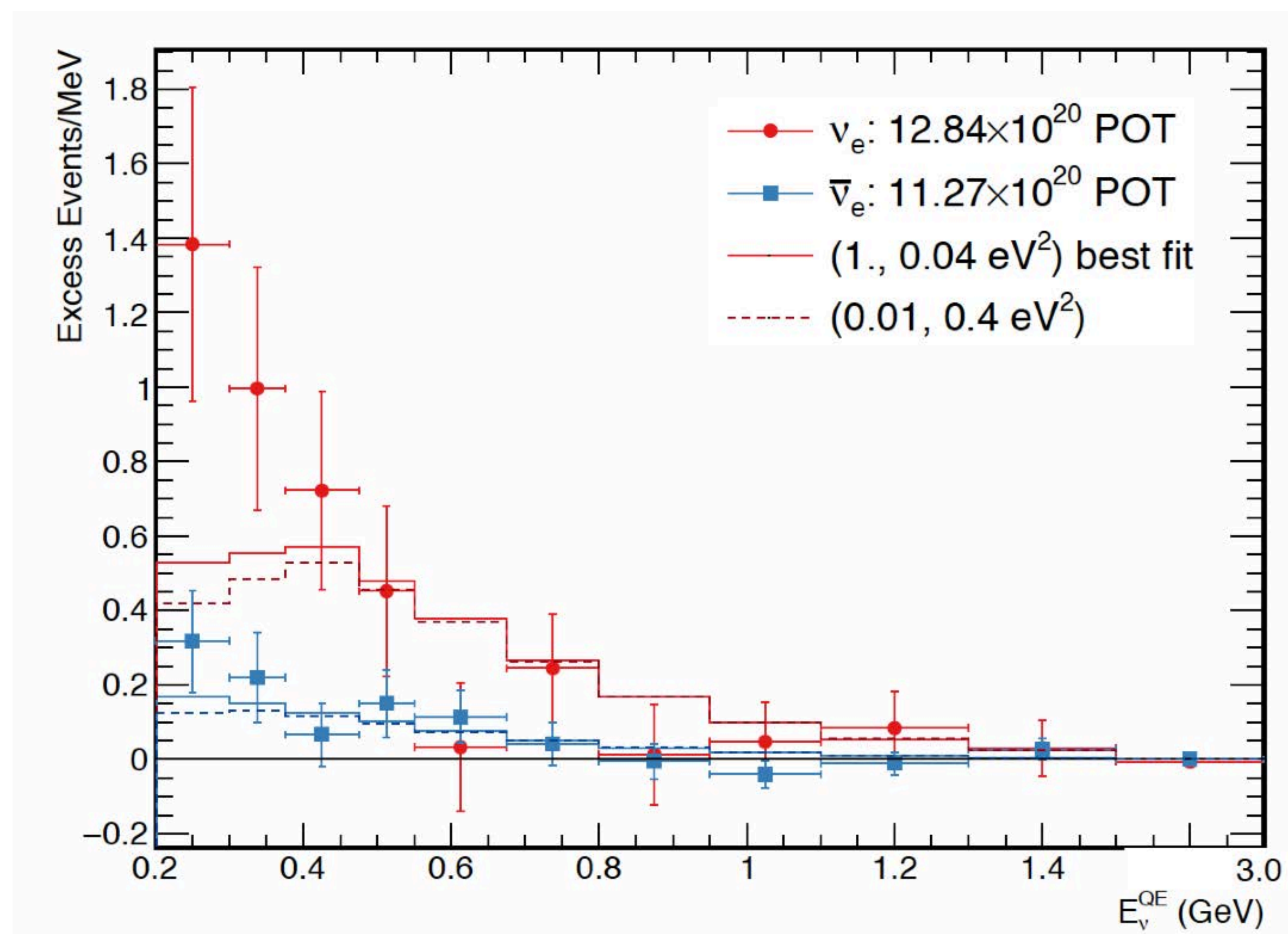




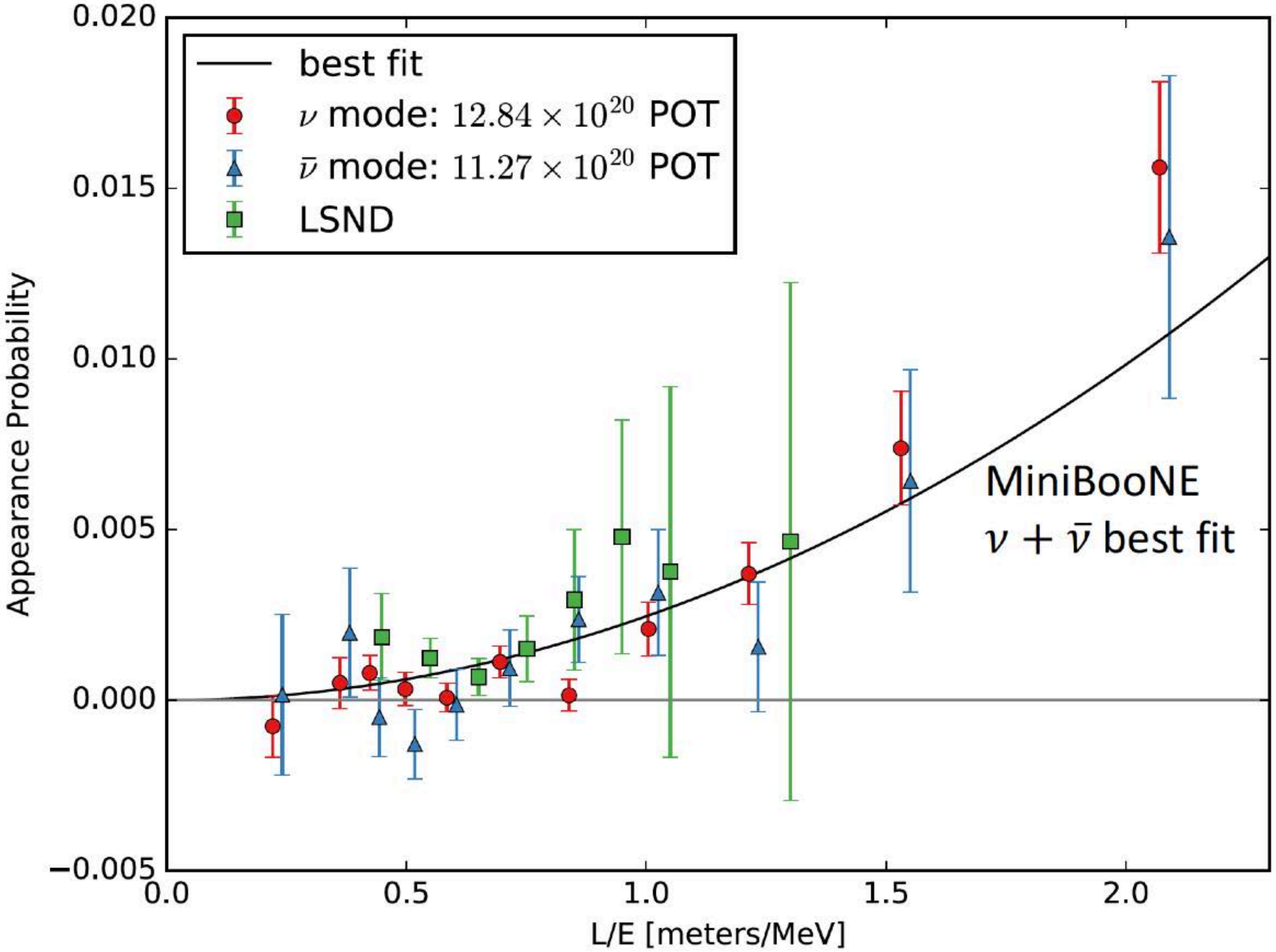
MiniBooNE excess

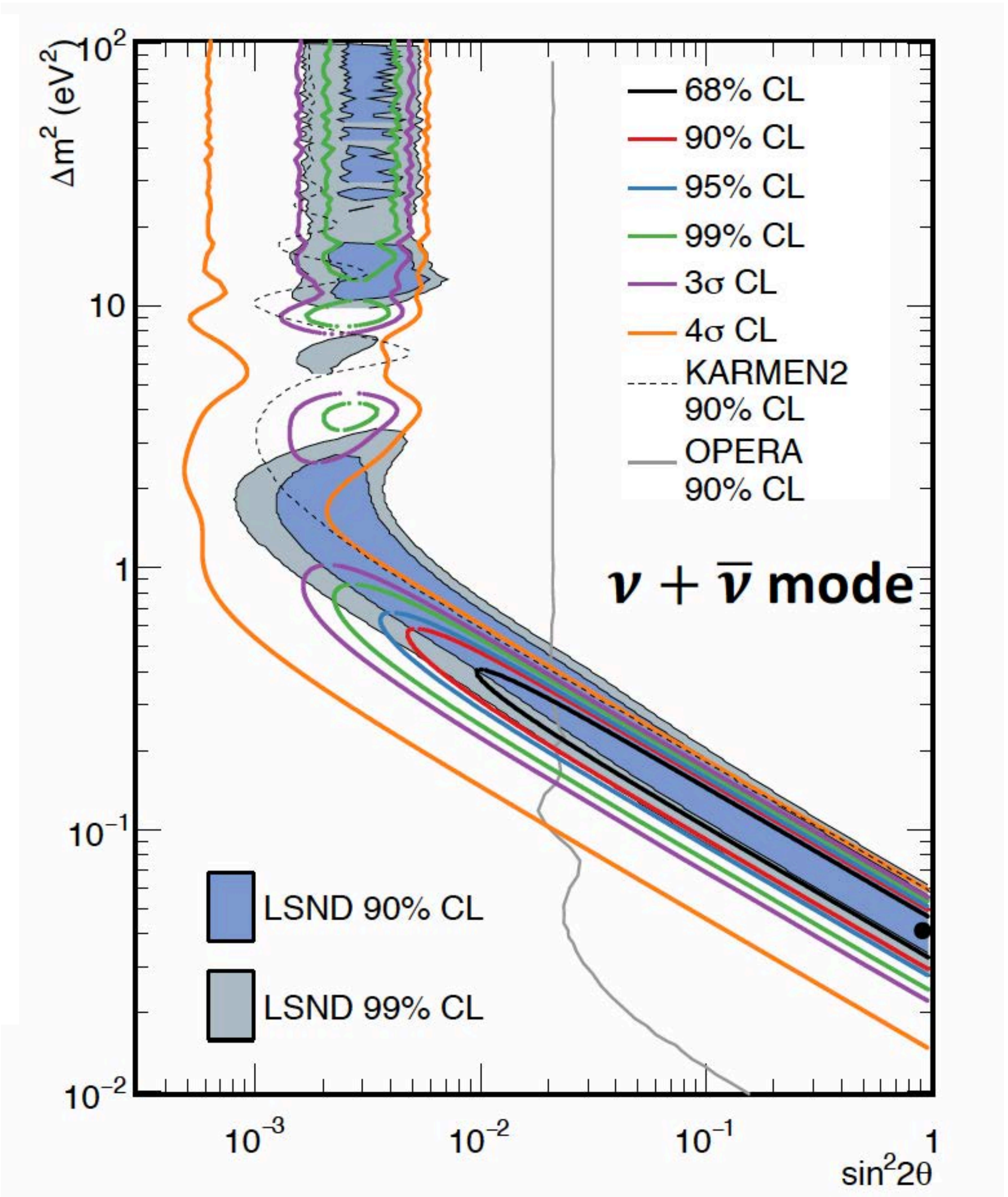






- MiniBooNE is a single-detector experiment on the Fermilab 8 GeV Booster neutrino beam line intended to explore the LSND reported excess.
- MiniBooNE sees an excess over backgrounds at low energies in both neutrino and antineutrino beams.

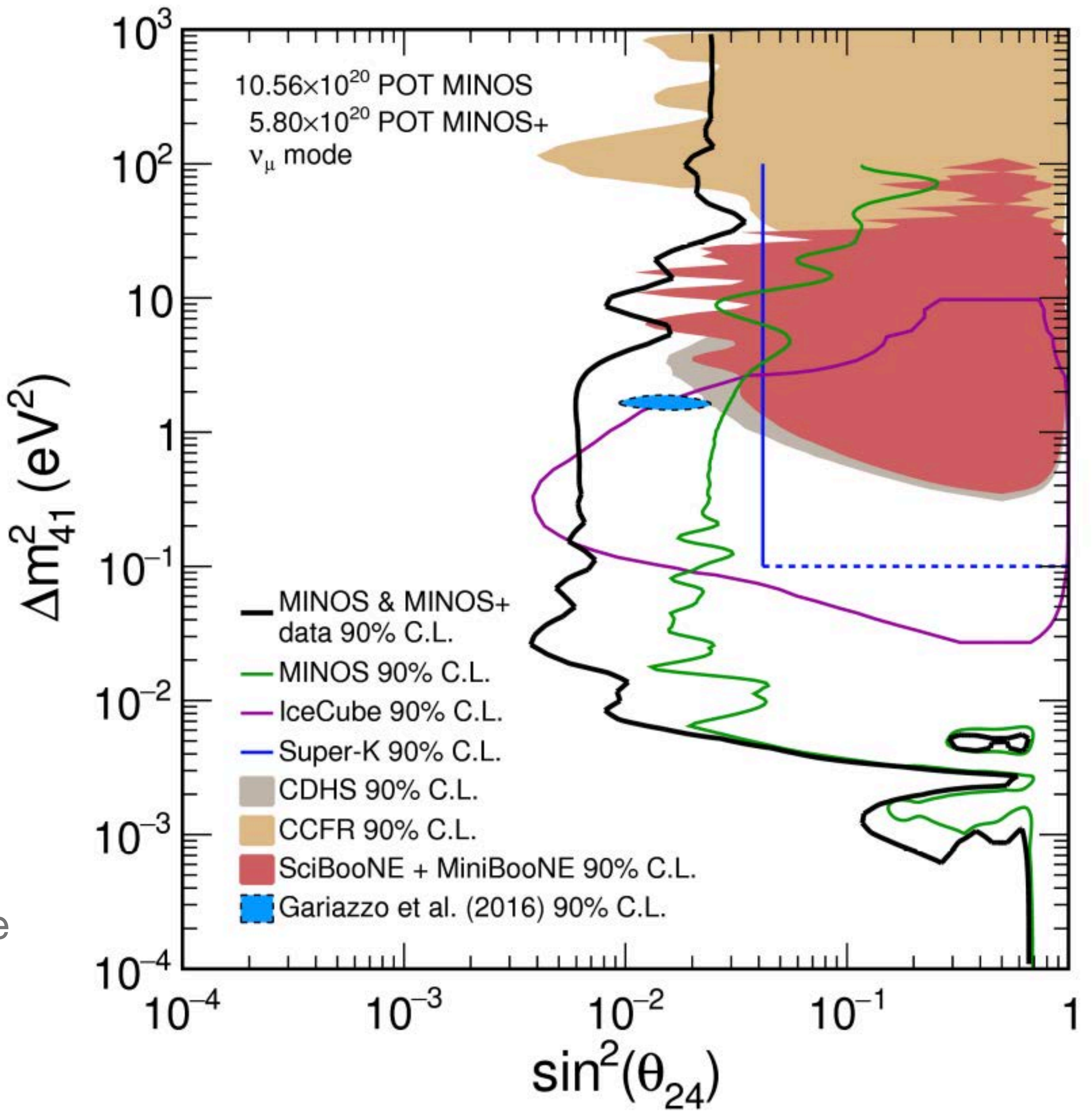




Interpretations of LSND and MiniBooNE in 3+1

Search for sterile neutrinos in disappearance channel

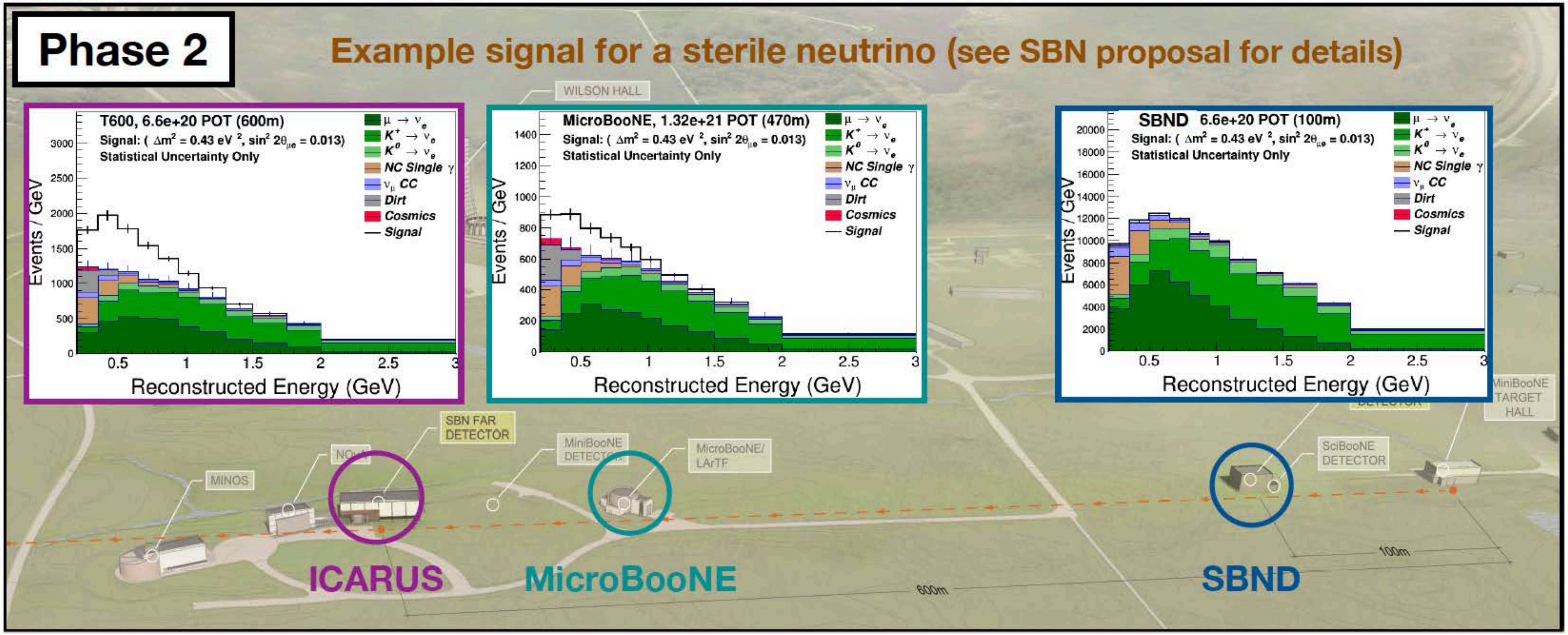
- Electron neutrino appearance through through $\nu_\mu \rightarrow \nu_e$ with eV-scale sterile neutrinos implies additional disappearance in $\nu_\mu \rightarrow \nu_\mu$
- This is not seen by a number of experiments, esp. MINOS and IceCUBE
- This creates a tension: there is no model involving sterile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



Fermilab Short Baseline Program

3-5σ resolution of SBN anomalies in 5 years

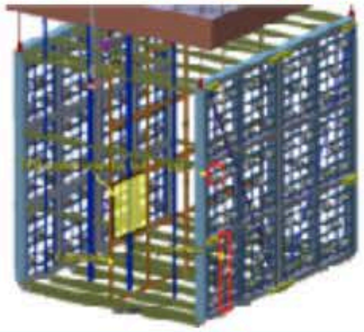
A three liquid argon detector experiment:



Far detector
L = 600 m
M = 476 ton

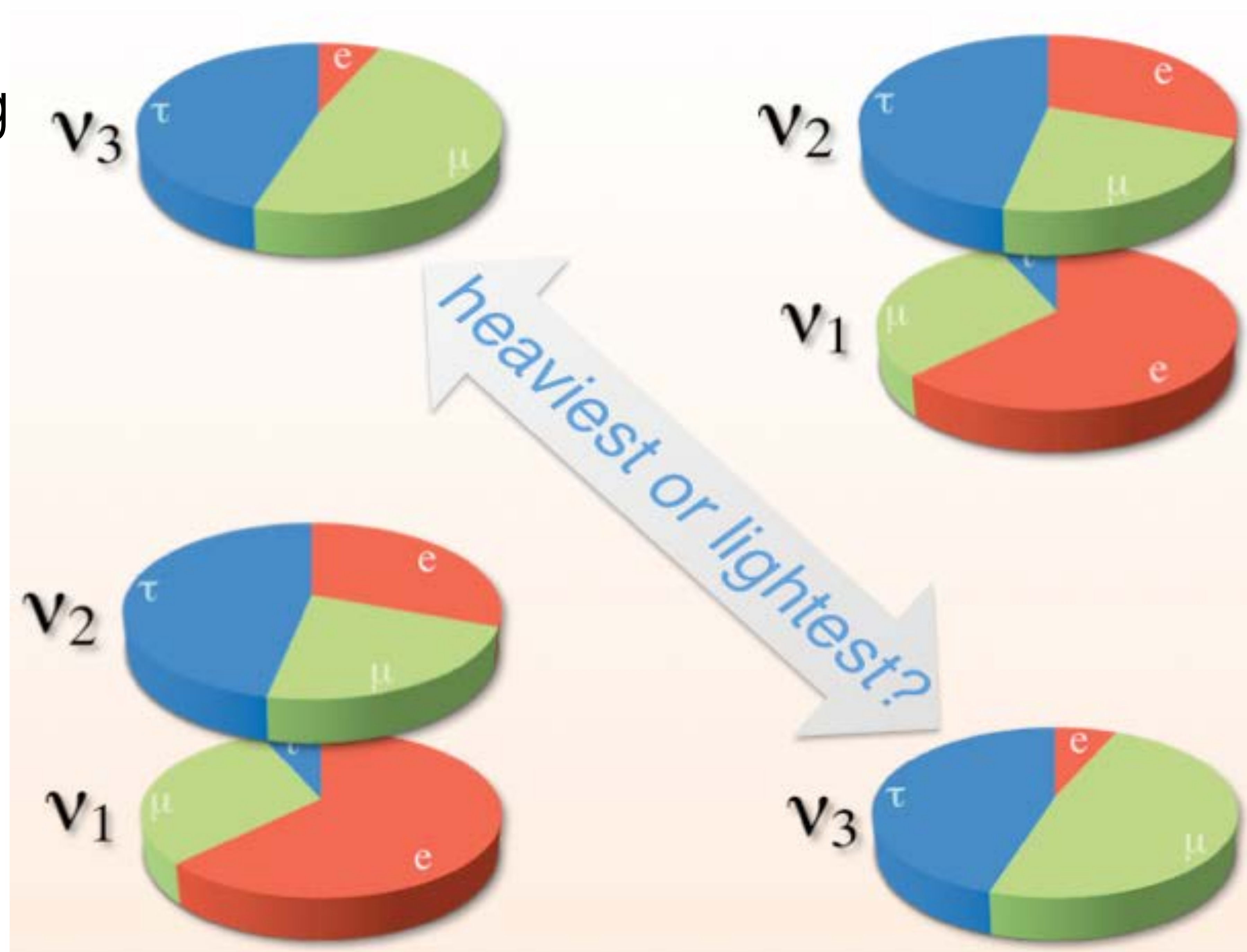
First detector
L = 470 m
M = 85 ton

Near detector
L = 110 m
M = 112 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]

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

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

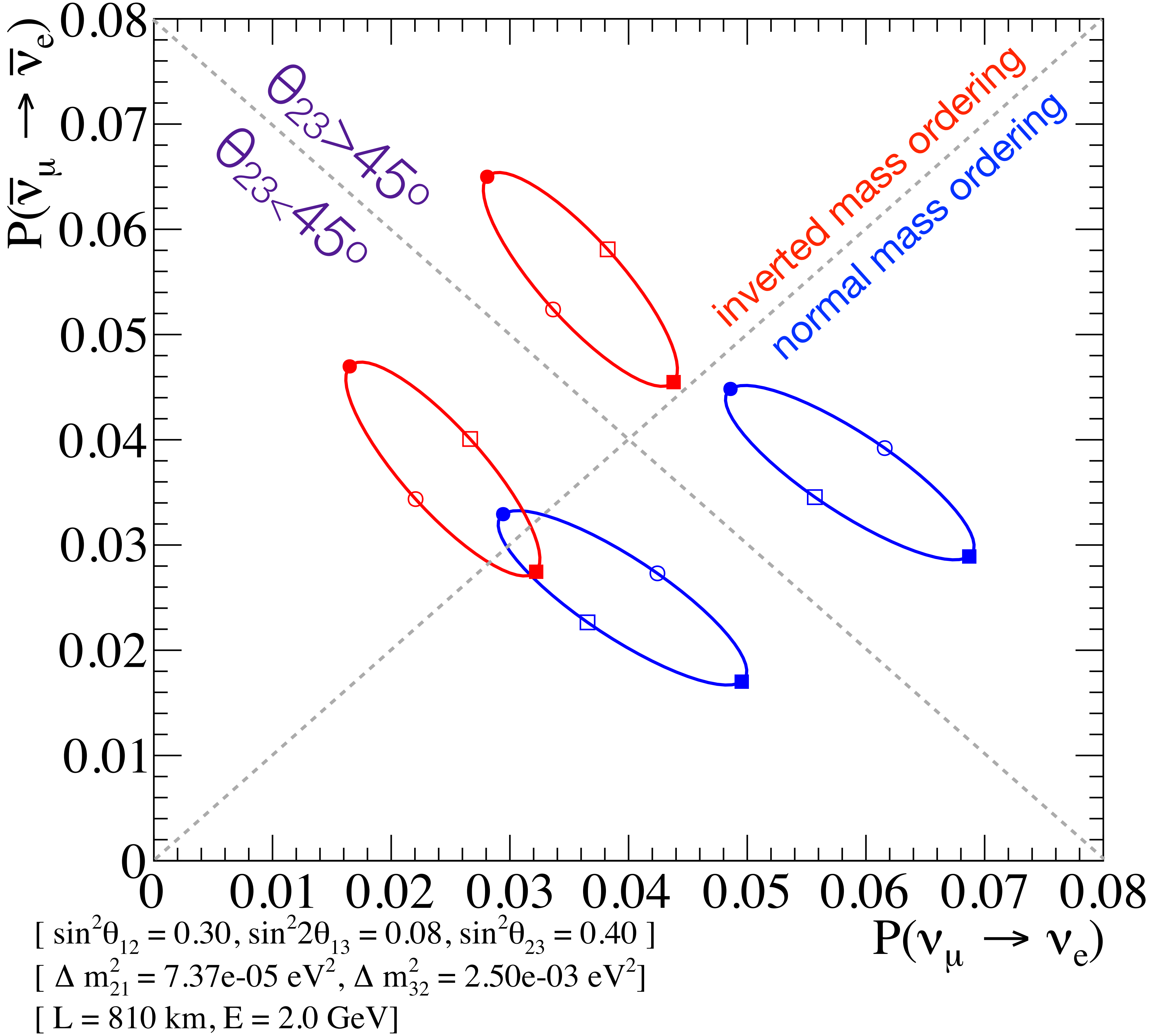
$$\sqrt{P_{\rm atm}} = \sin\theta_{23}\sin 2\theta_{13}\frac{\sin(\Delta_{31}\mp aL)}{\Delta_{31}\mp aL}\Delta_{31}$$

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

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

$aL = 0.08$ for $L = 295$ km
$aL = 0.23$ for $L = 810$ km
$aL = 0.37$ for $L = 1300$ km

Parameter	Channels	Question
$\sin^2 2\theta_{23}$:	$\nu_\mu \to \nu_\mu$ and $\bar\nu_\mu \to \bar\nu_\mu$:	Is θ_{23} maximal?
$\sin^2\theta_{23}\sin^2 2\theta_{13}$:	$\nu_\mu \to \nu_e$ and $\bar\nu_\mu \to \bar\nu_e$:	Octant of θ_{23}
sign $[\Delta_{31}]$:	$\nu_\mu \to \nu_e$ vs. $\bar\nu_\mu \to \bar\nu_e$:	Neutrino mass hierarchy
$\delta_{\rm CP}$:	$\nu_\mu \to \nu_e$ vs. $\bar\nu_\mu \to \bar\nu_e$:	Is CP violated?



Neutrino oscillations

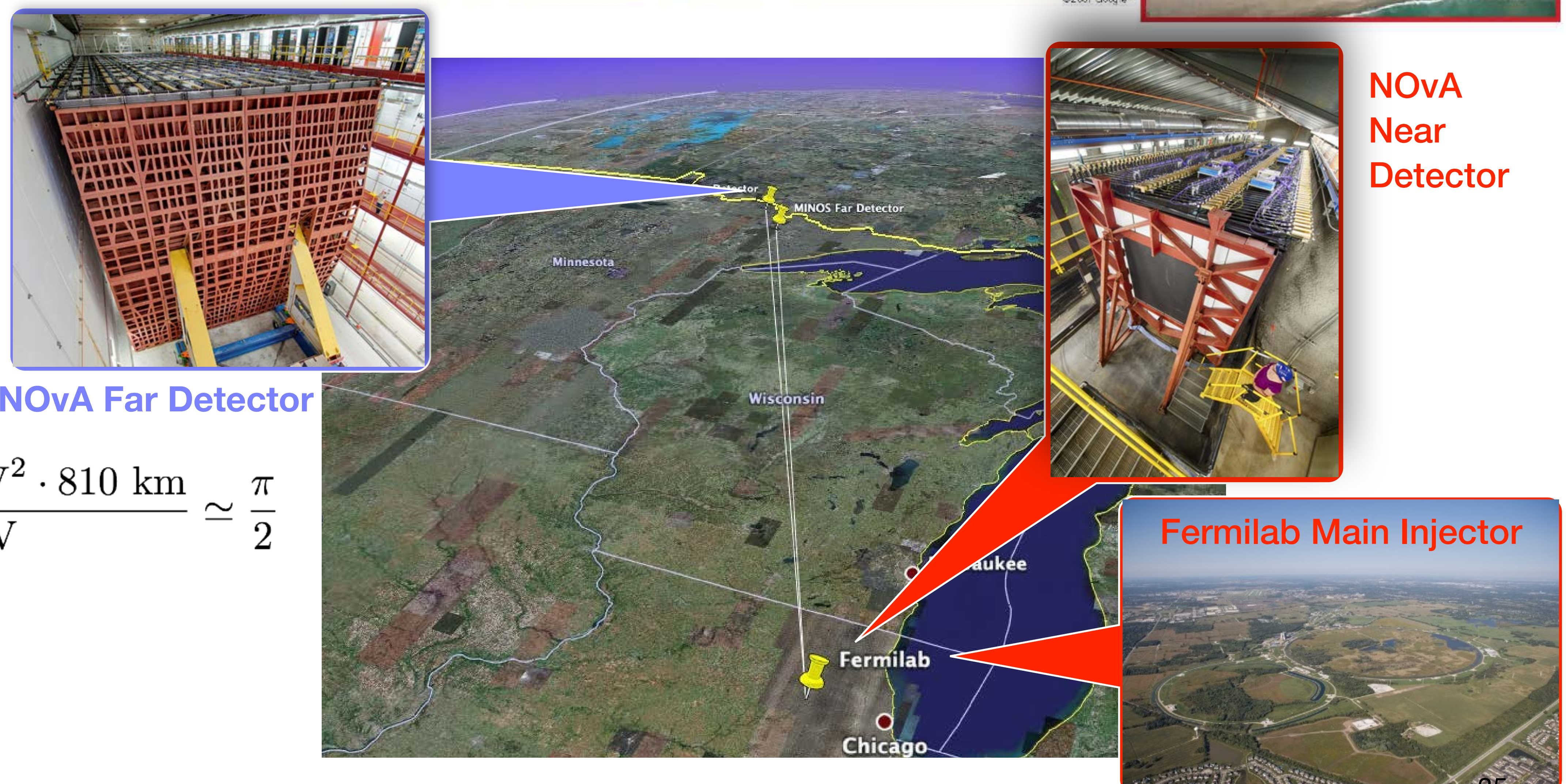
Bi-probability plots for the NOvA experiment

T2K

$E_\nu \simeq 0.7$ GeV,

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

NOvA



$E_\nu \simeq 2$ GeV,

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

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

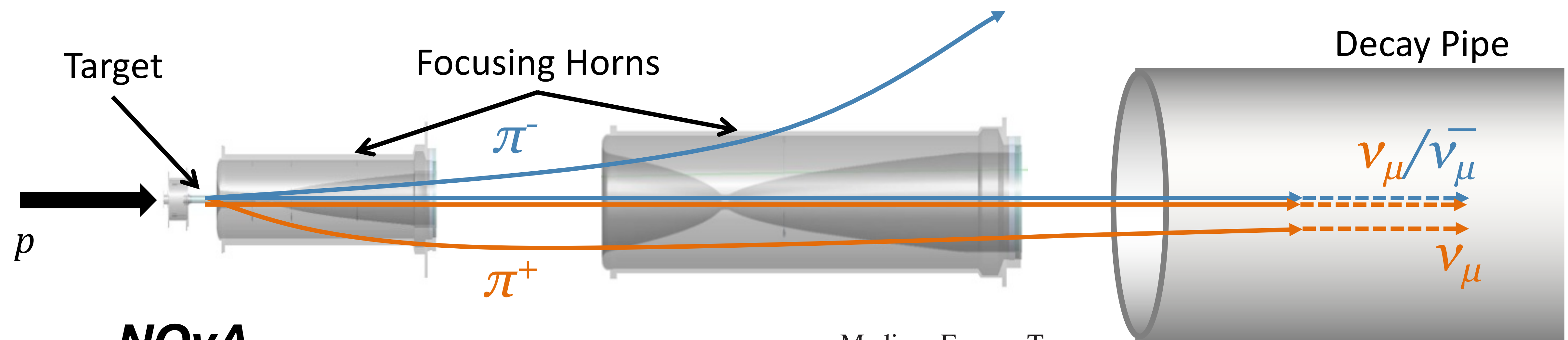
Factor	Type	Inverts for $\bar{\nu}$?	NOvA	T2K
Matter effect (mass ordering)	Binary	Yes	±19%	±10%
CP violation	Bounded, continuous	Yes	[-22…+22]%	[-29…+29]%
θ_{23} octant	Unbounded, continuous	No	[-22…+22]%	[-22…+22]%

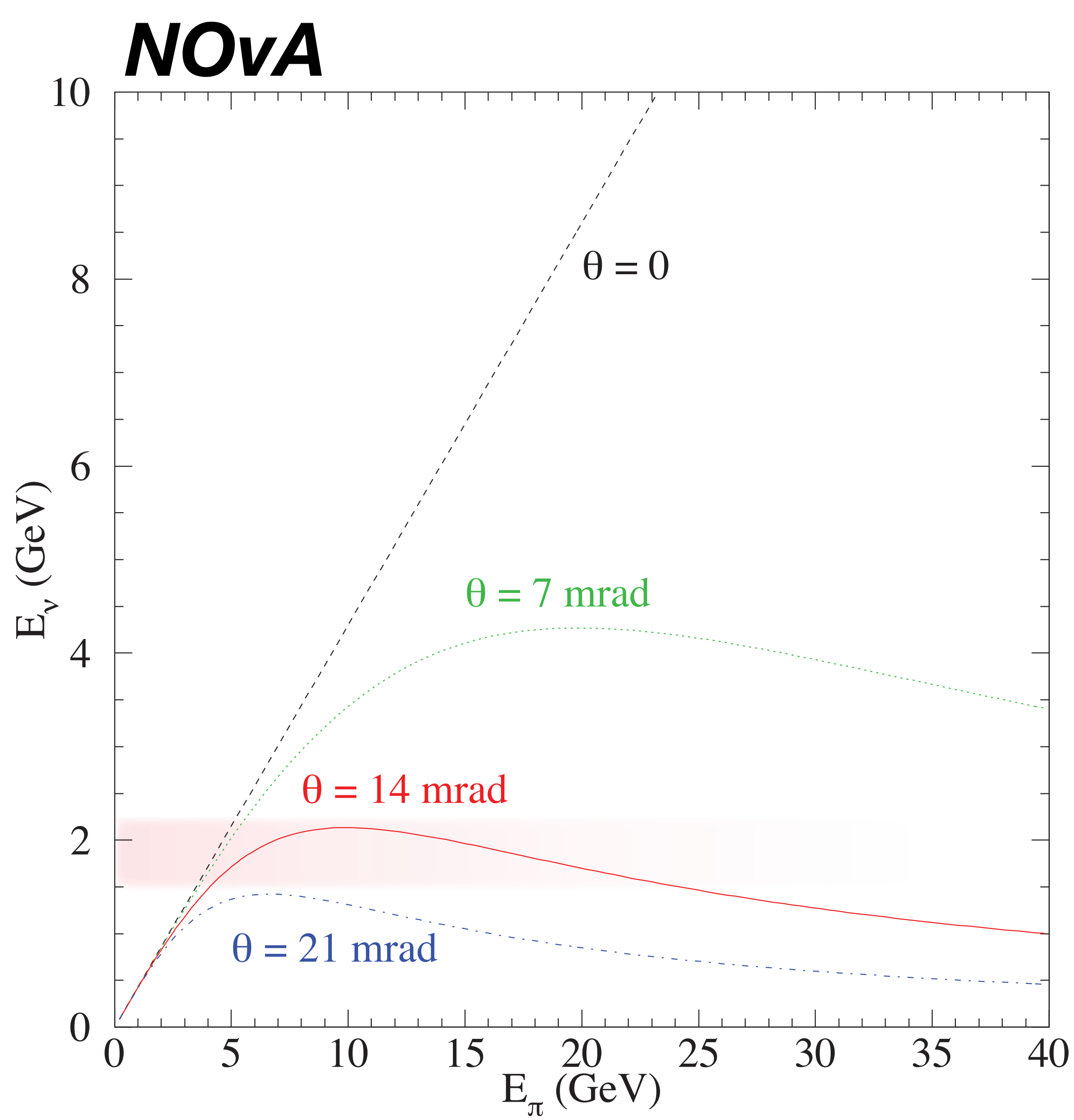
Nota bene:

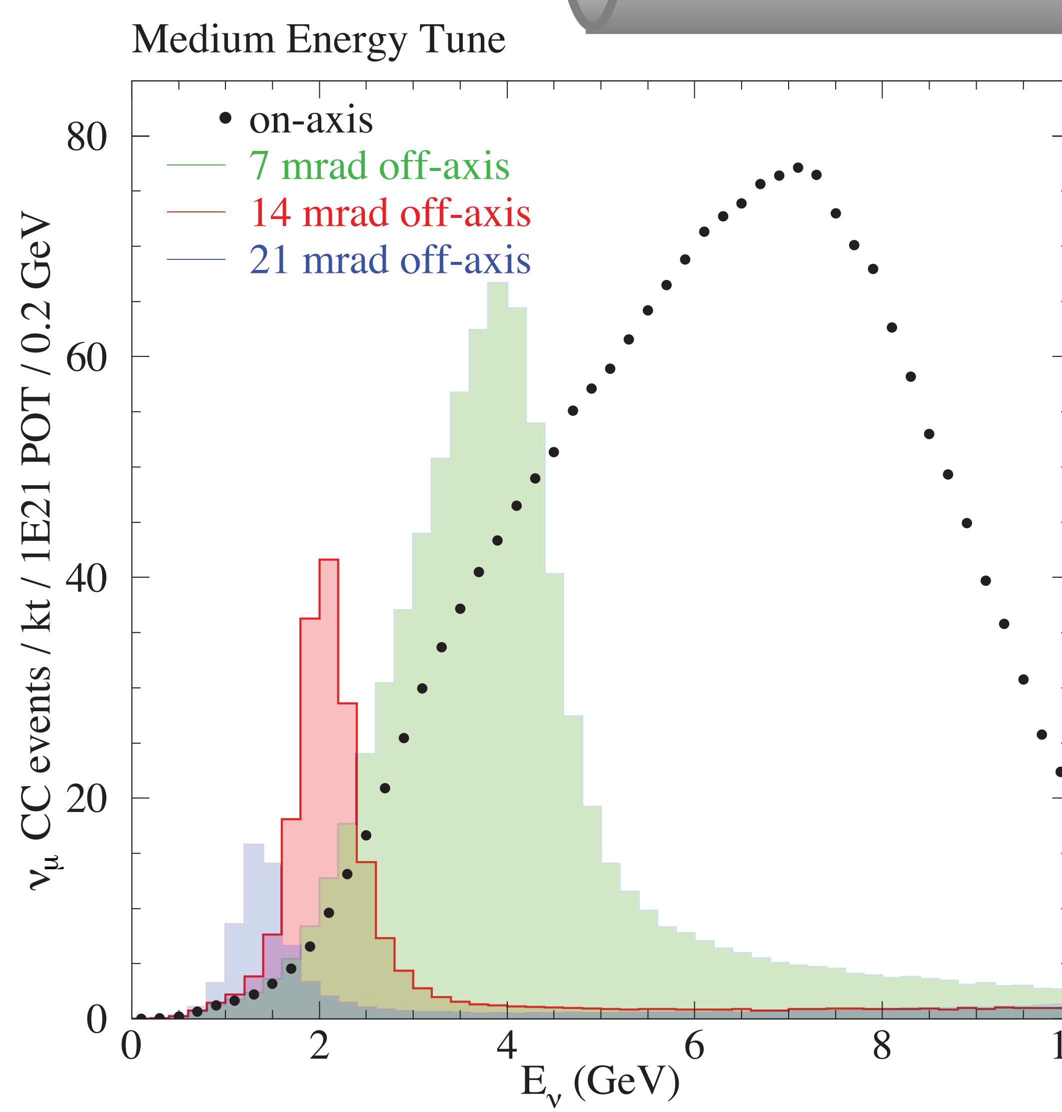
- Calculations are for rate only; there is some additional information in the energy spectrum
- These estimates neglect non-linearities in combining different effects
- In the calculation of the matter effect and CP violation effects the calculated values account for the fact that T2K runs at an energy 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

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



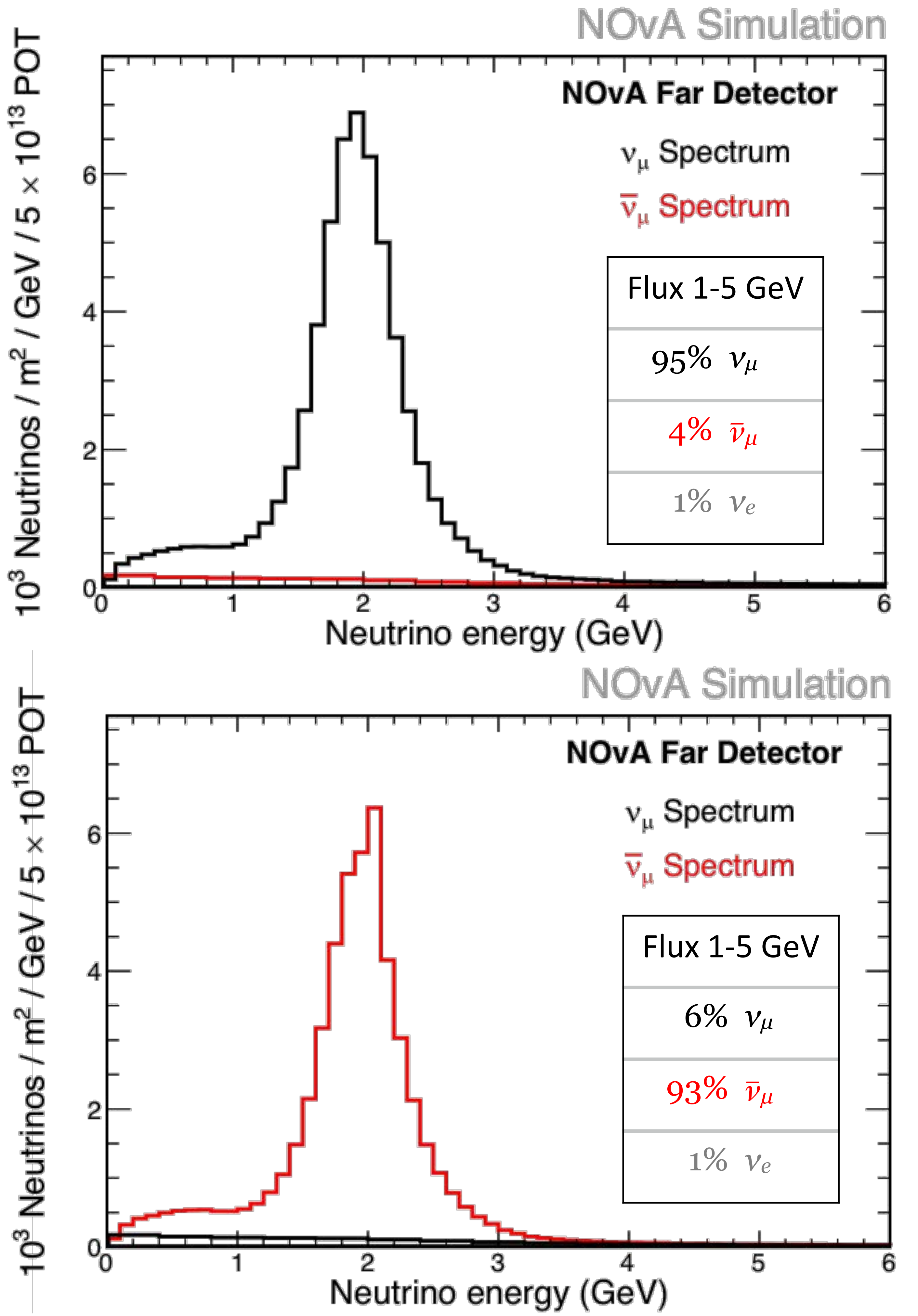


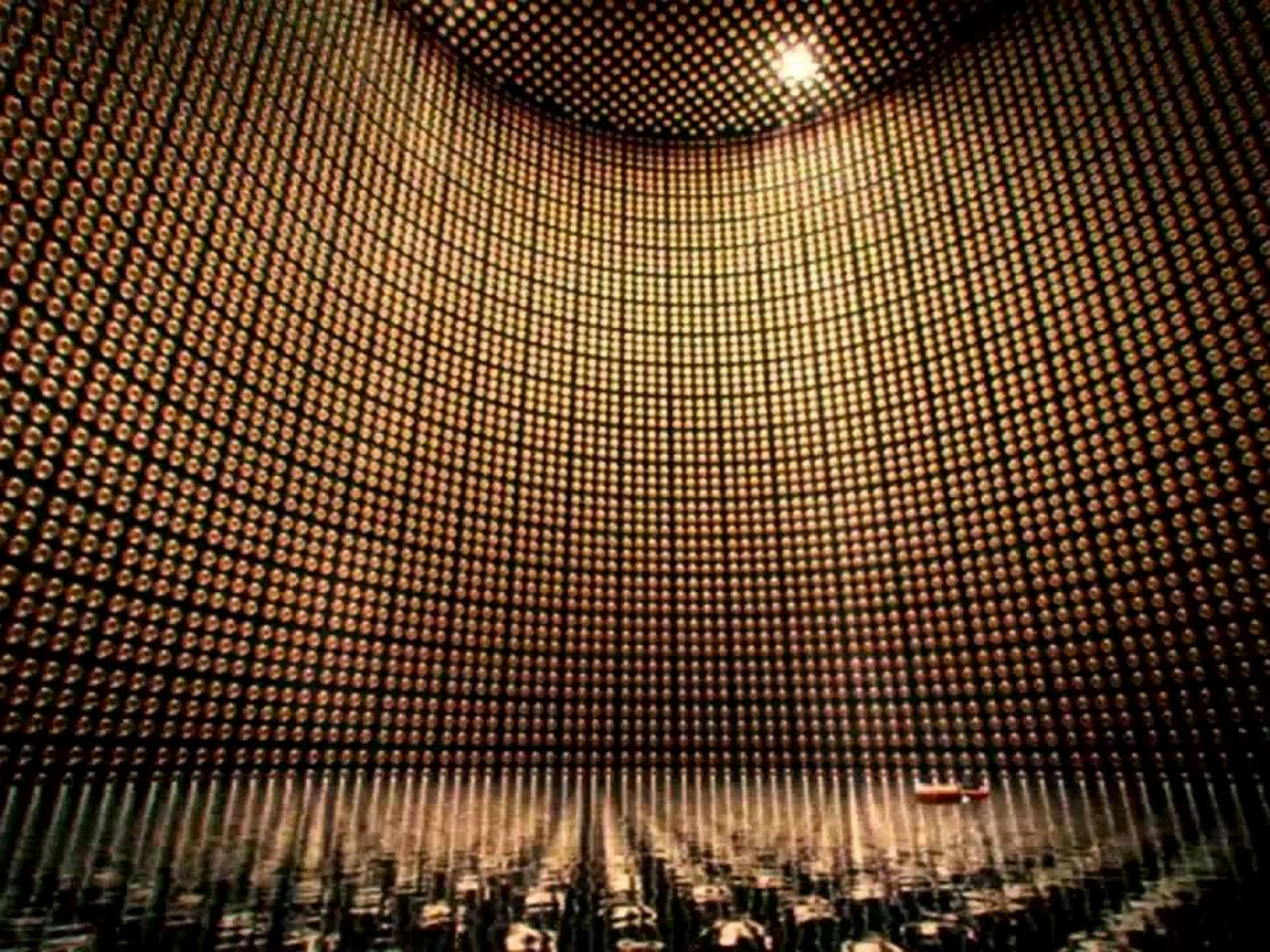


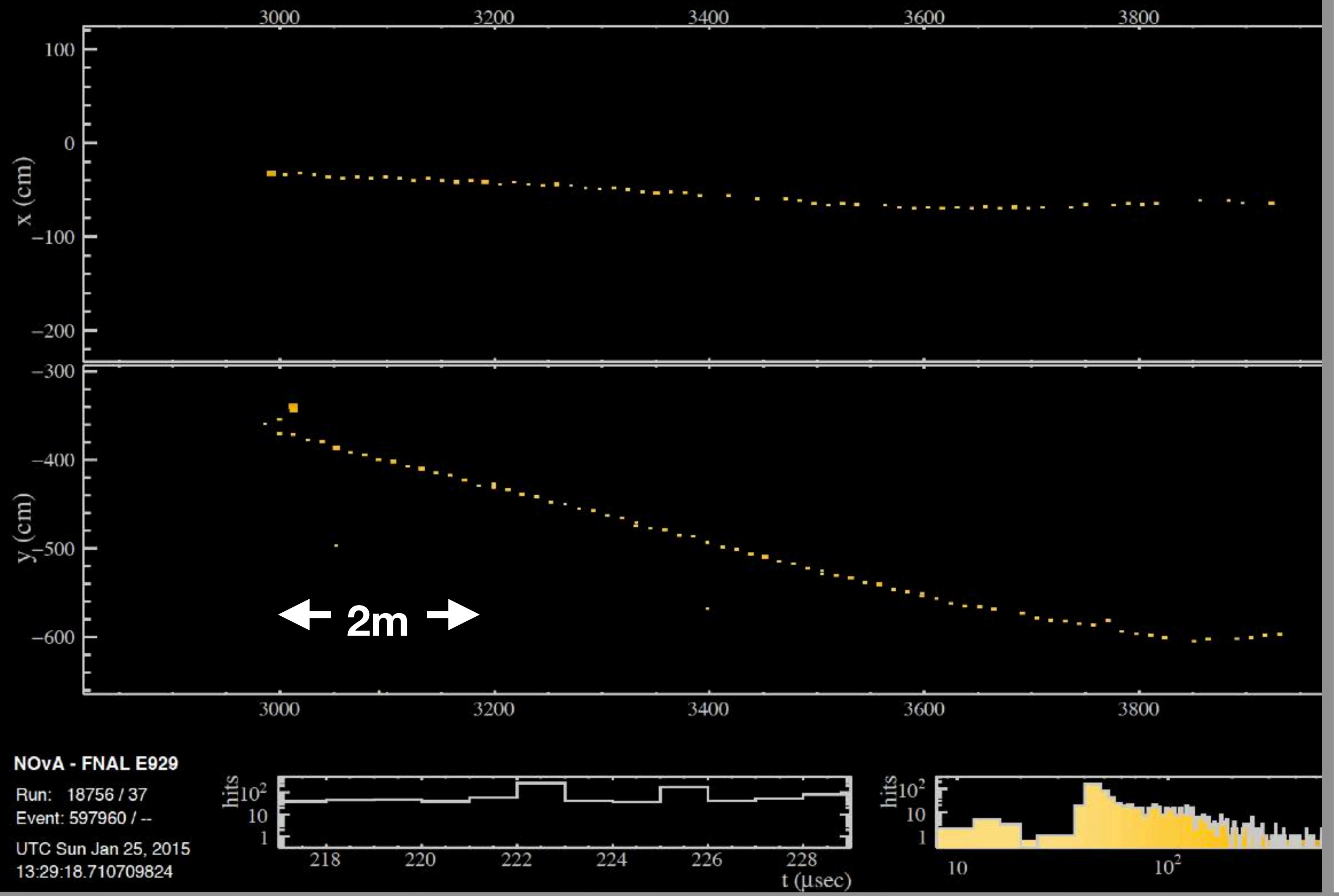
Making neutrino and antineutrino beams

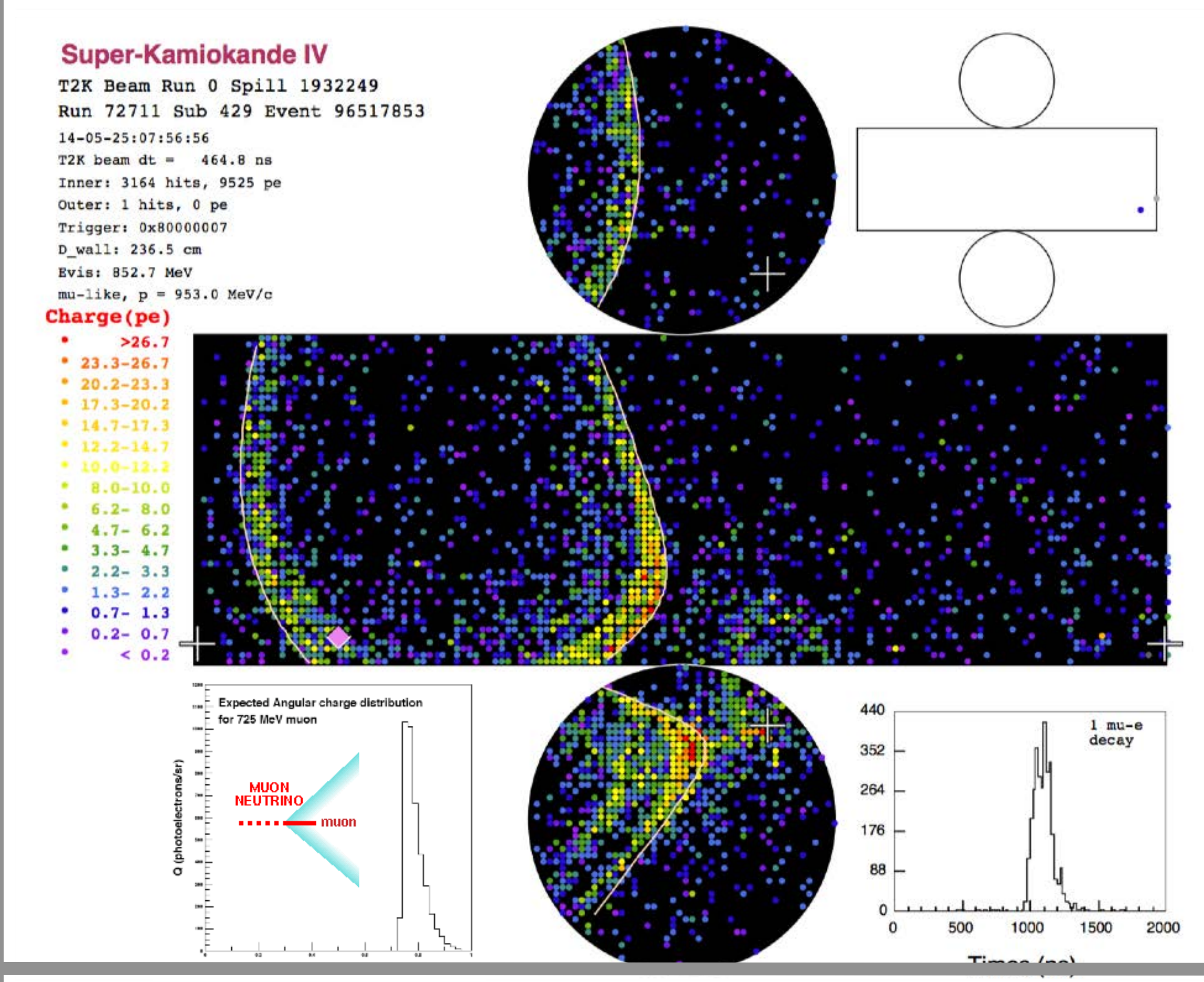
Top: Neutrino beam flux

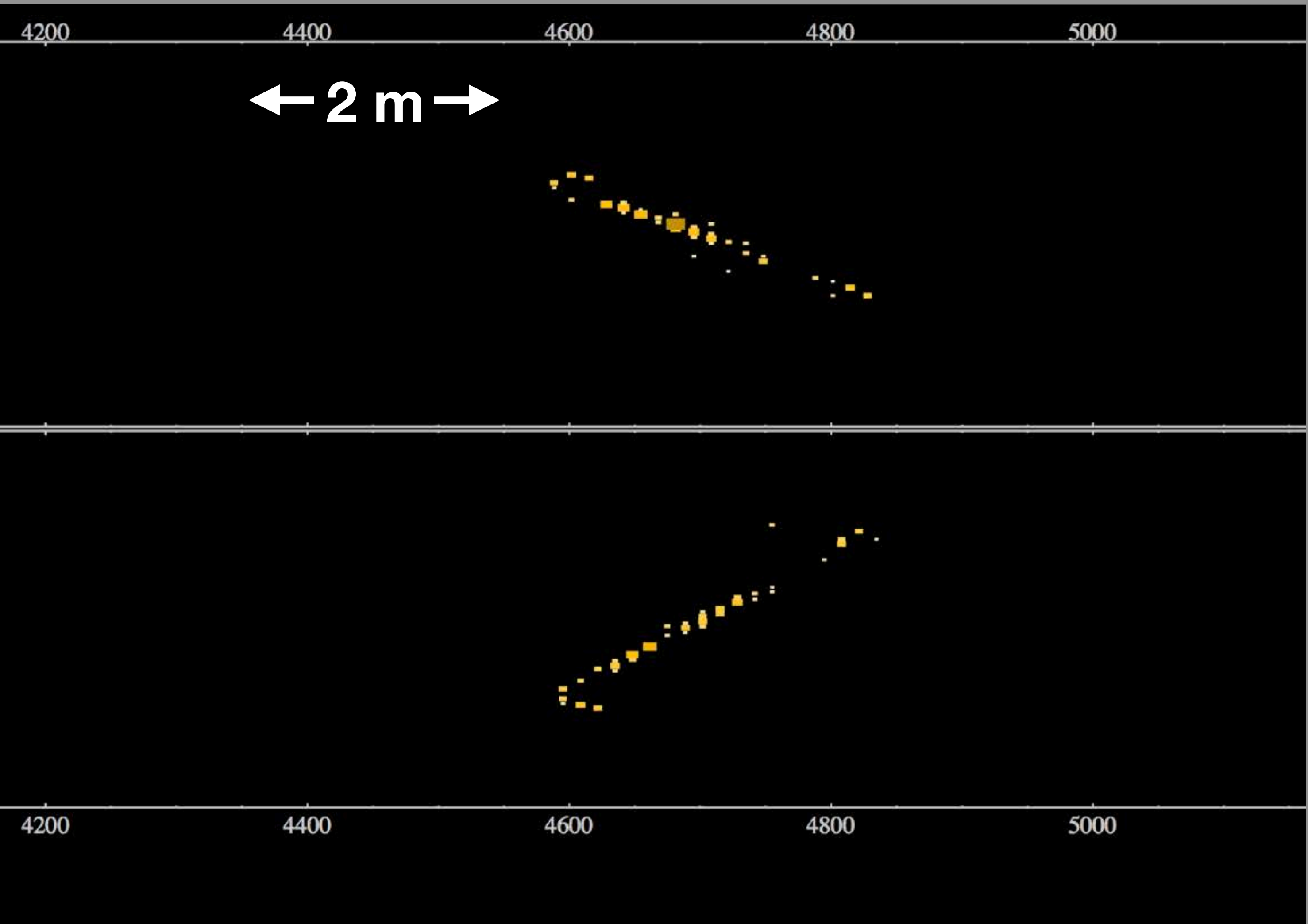
Bottom: Antineutrino beam flux

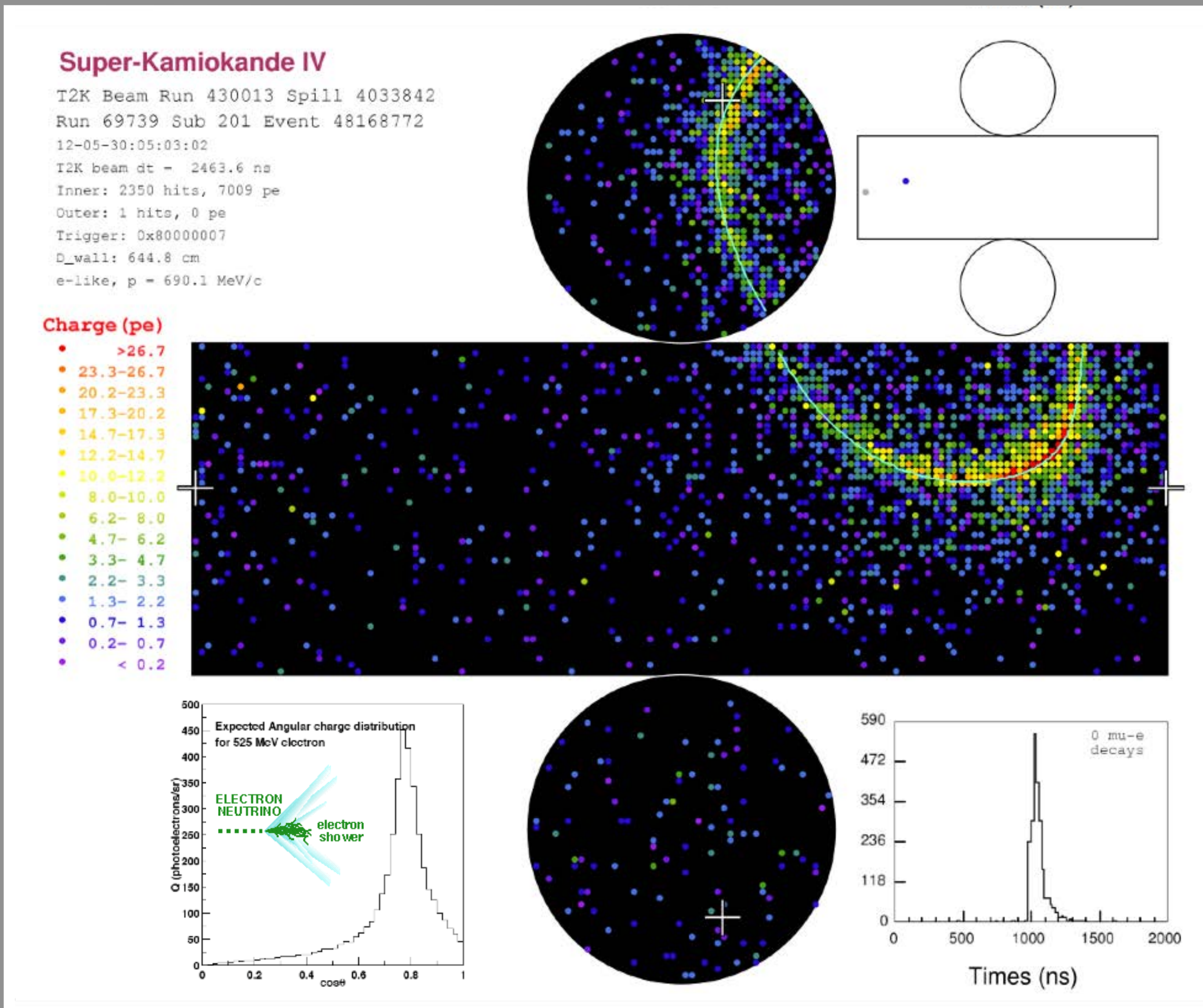





3000
3200
3400
3600
3800
100
0
−100
−200
−300
x (cm)
−400
−500
−600
y (cm)
← 2m →
NOvA - FNAL E929
Run: 18756 / 37
Event: 597960 / --
UTC Sun Jan 25, 2015
13:29:18.710709824
hits
218
220
222
224
226
228
t (μsec)
10
10^2


Super-Kamiokande IV
T2K Beam Run 0 Spill 1932249
Run 72711 Sub 429 Event 96517853
14-05-25:07:56:56
T2K beam dt = 464.8 ns
Inner: 3164 hits, 9525 pe
Outer: 1 hits, 0 pe
Trigger: 0x80000007
D_wall: 236.5 cm
Evis: 852.7 MeV
mu-like, p = 953.0 MeV/c
Charge(pe)
>26.7
23.3-26.7
20.2-23.3
17.3-20.2
14.7-17.3
12.2-14.7
10.0-12.2
8.0-10.0
6.2- 8.0
4.7- 6.2
3.3- 4.7
2.2- 3.3
1.3- 2.2
0.7- 1.3
0.2- 0.7
< 0.2
Expected Angular charge distribution for 725 MeV muon
MUON NEUTRINO
muon
1 mu-e decay
440
352
264
176
88
0
500
1000
1500
2000

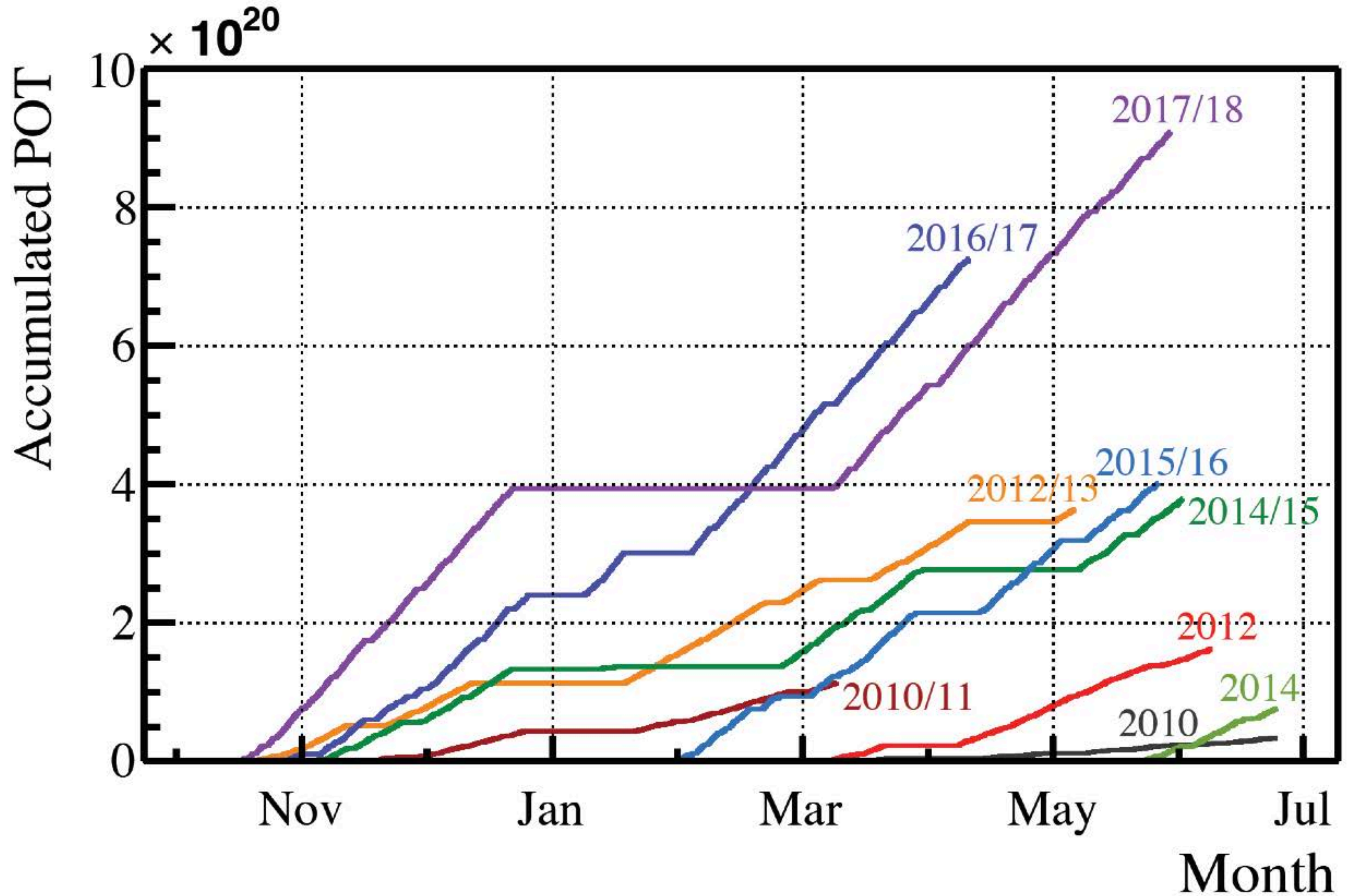

4200
4400
4600
4800
5000
← 2 m →


Super-Kamiokande IV
T2K Beam Run 430013 Spill 4033842
Run 69739 Sub 201 Event 48168772
12-05-30:05:03:02
T2K beam dt = 2463.6 ns
Inner: 2350 hits, 7009 pe
Outer: 1 hits, 0 pe
Trigger: 0x80000007
D_wall: 644.8 cm
e-like, p = 690.1 MeV/c
Charge(pe)
>26.7
23.3-26.7
20.2-23.3
17.3-20.2
14.7-17.3
12.2-14.7
10.0-12.2
8.0-10.0
6.2- 8.0
4.7- 6.2
3.3- 4.7
2.2- 3.3
1.3- 2.2
0.7- 1.3
0.2- 0.7
< 0.2
Expected Angular charge distribution for 525 MeV electron
ELECTRON NEUTRINO
electron shower
0 mu-e decays
590
472
354
236
118
0
500
1000
1500
2000
Times (ns)

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

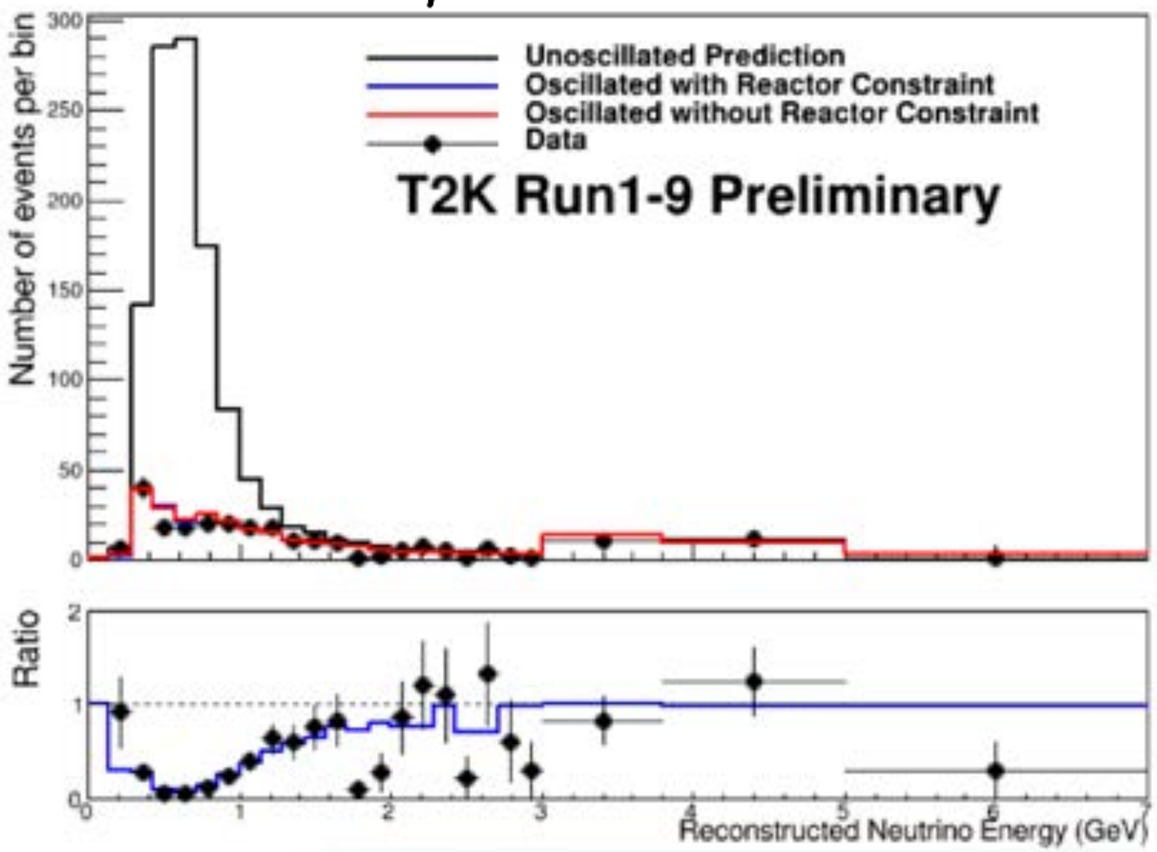


Totals to date:

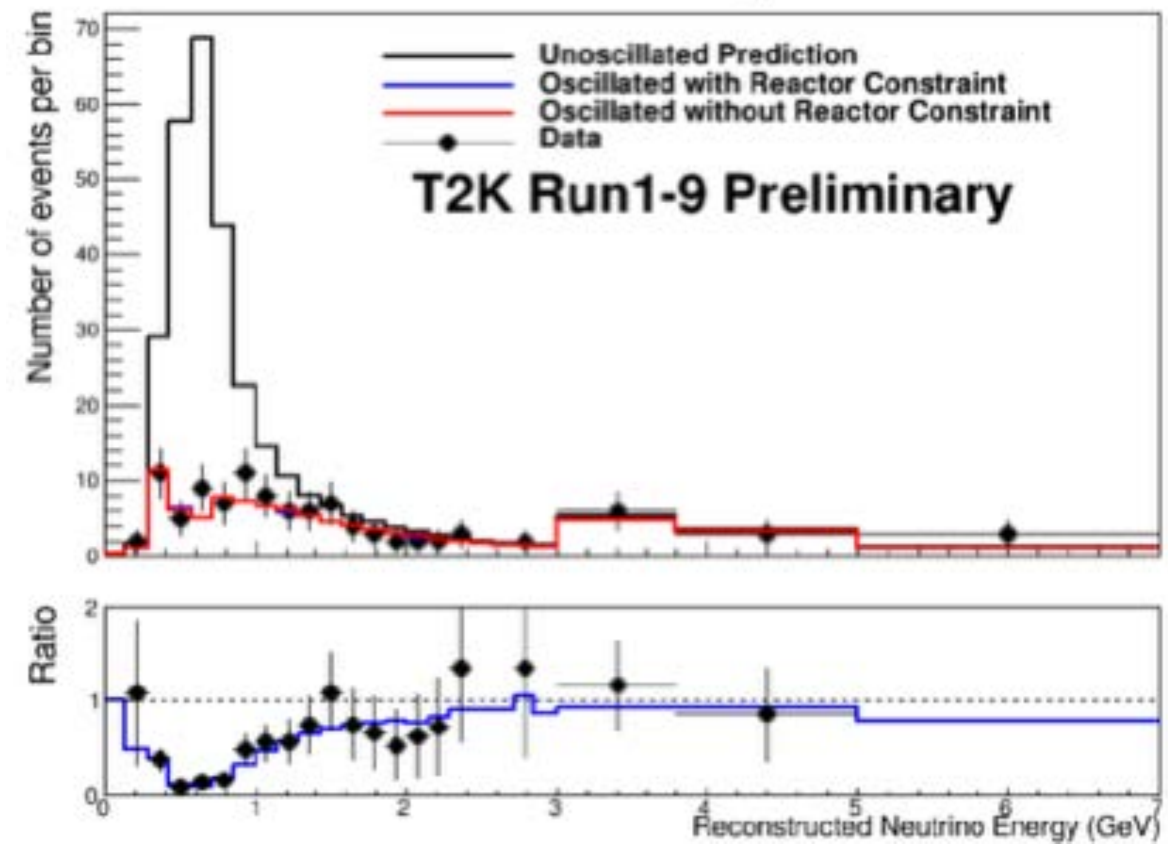
14.9E20 protons neutrino beam at 30 GeV

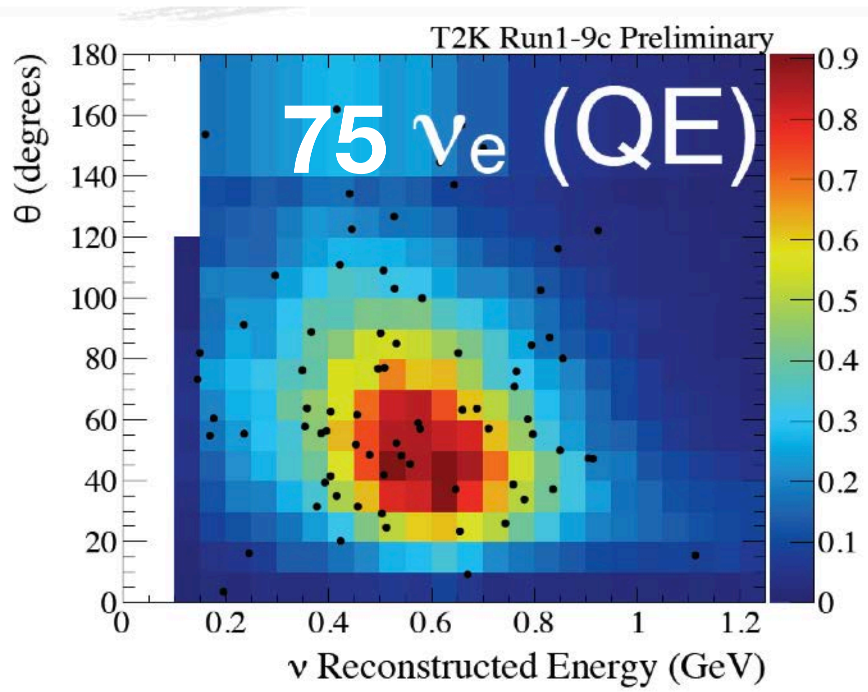
11.2E20 protons in antineutrino beam at 30 GeV

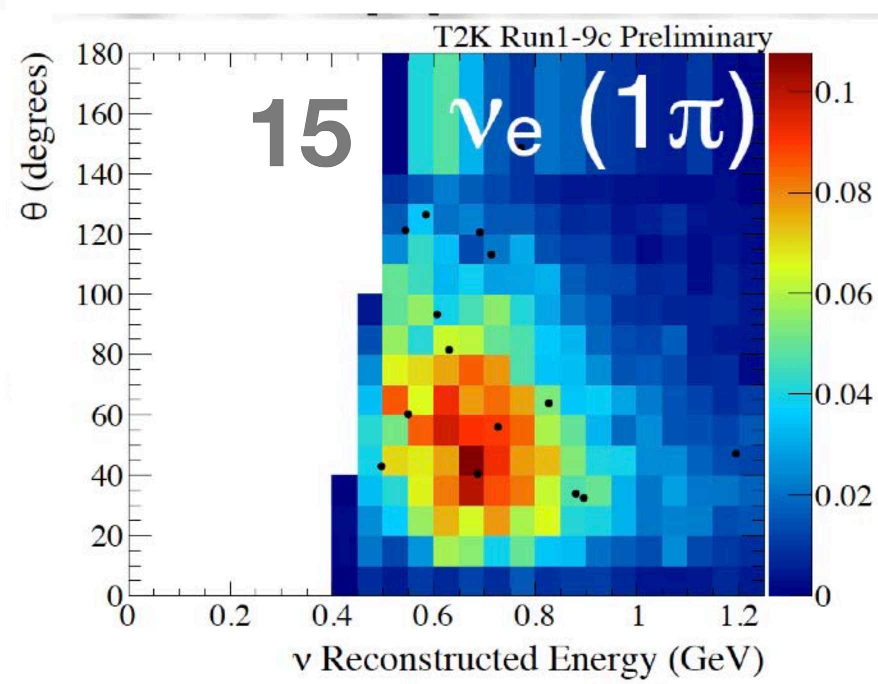
$243\ \nu_\mu - \mathrm{CC}$ events

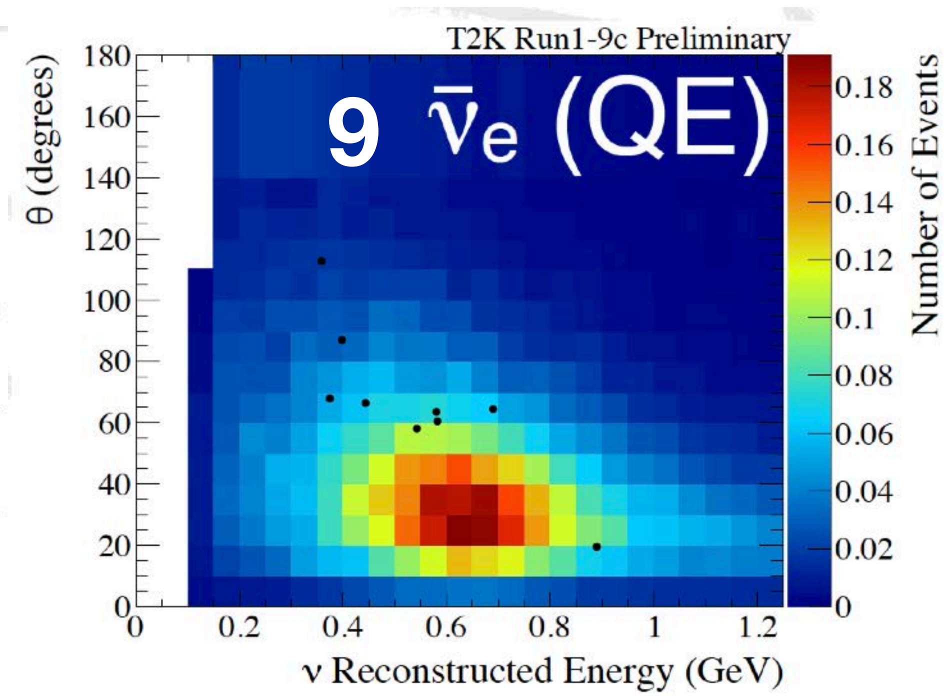


$102\ \bar{\nu}_\mu - \mathrm{CC}$ events





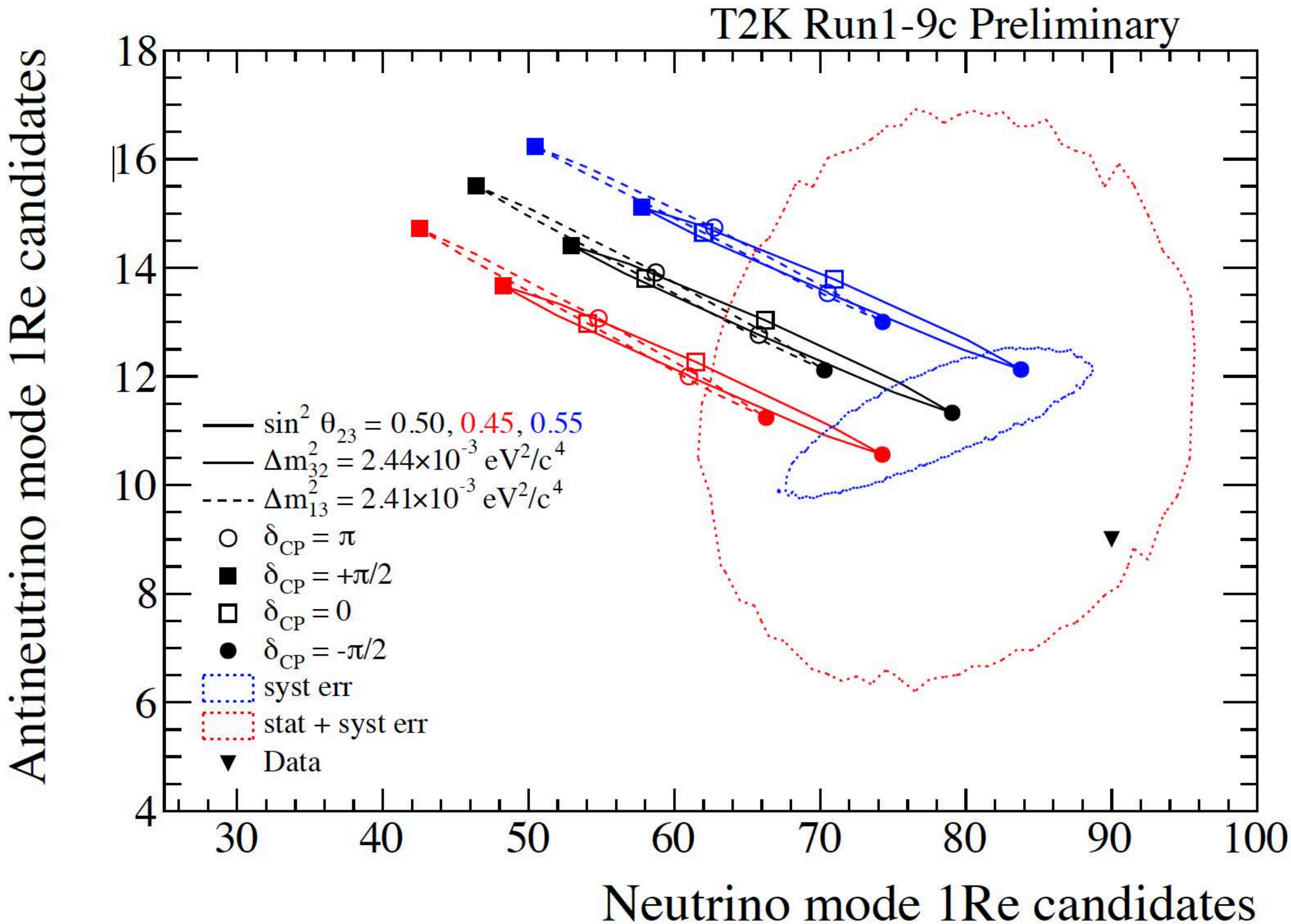




T2K event spectra

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%)

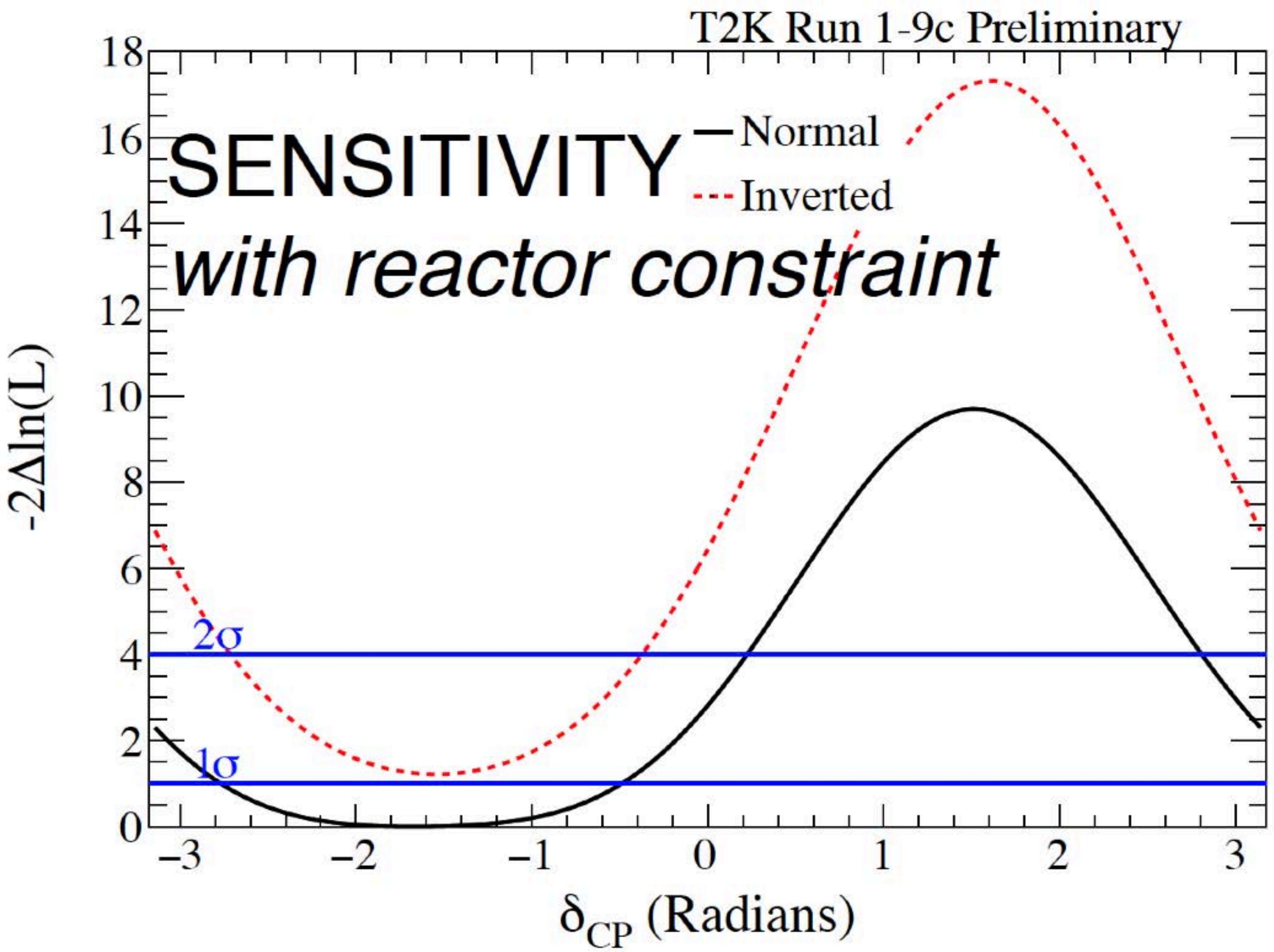


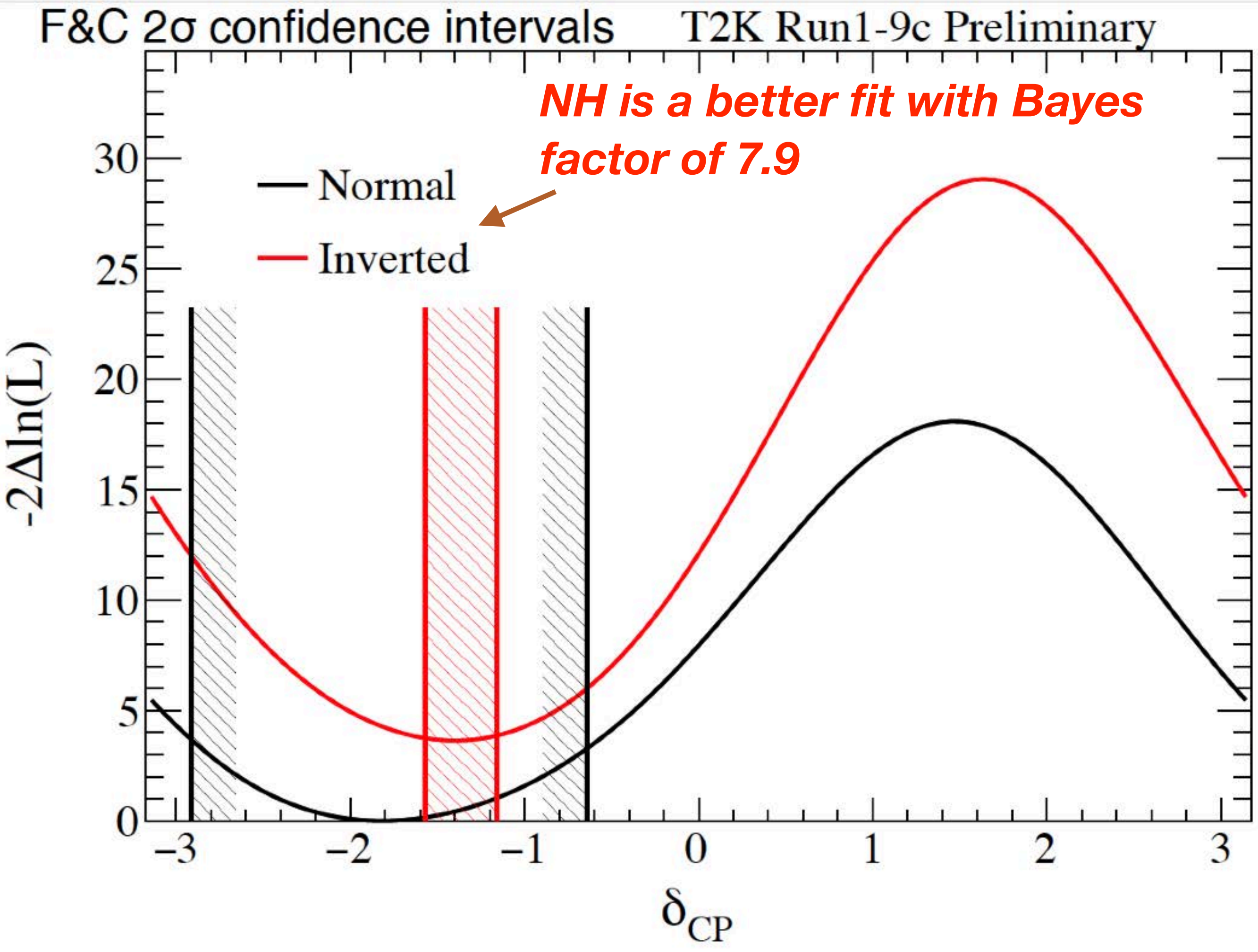
T2K neutrino and antineutrino event counts

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

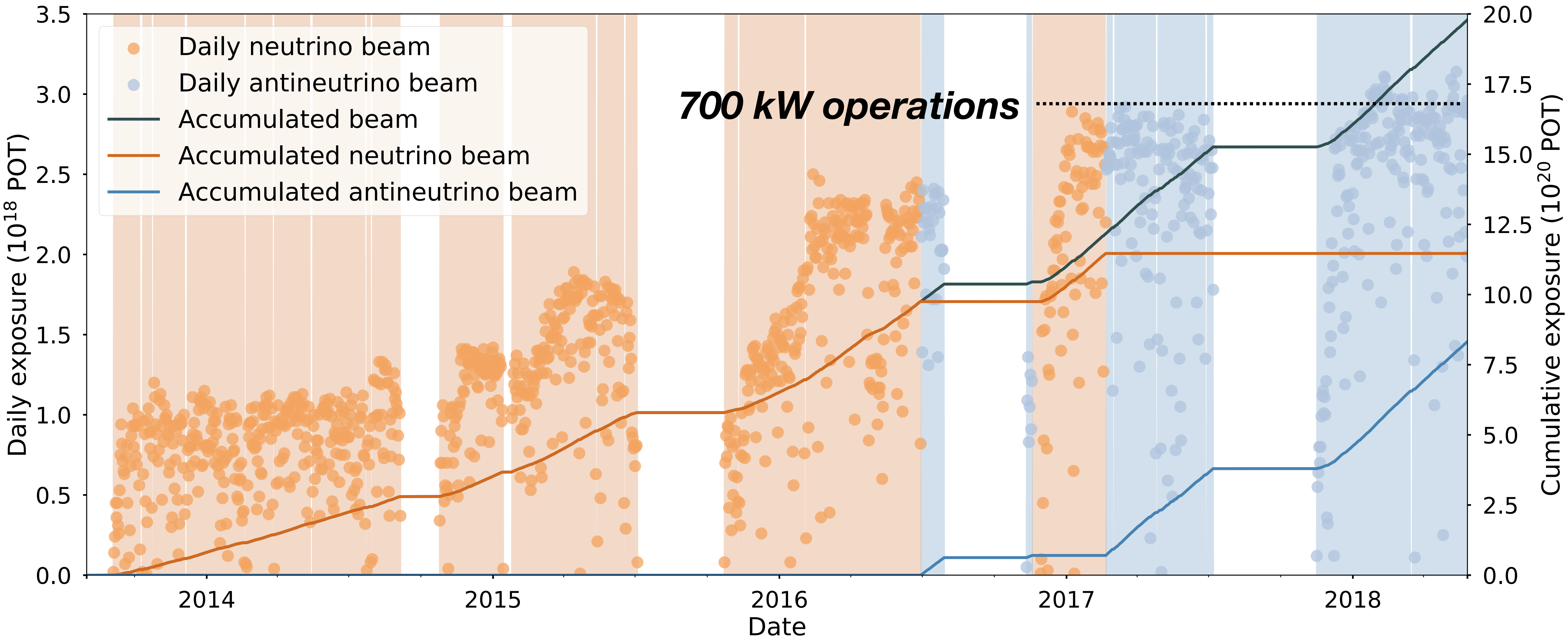
T2K measurement of CP phase δ

- 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 >2σ.

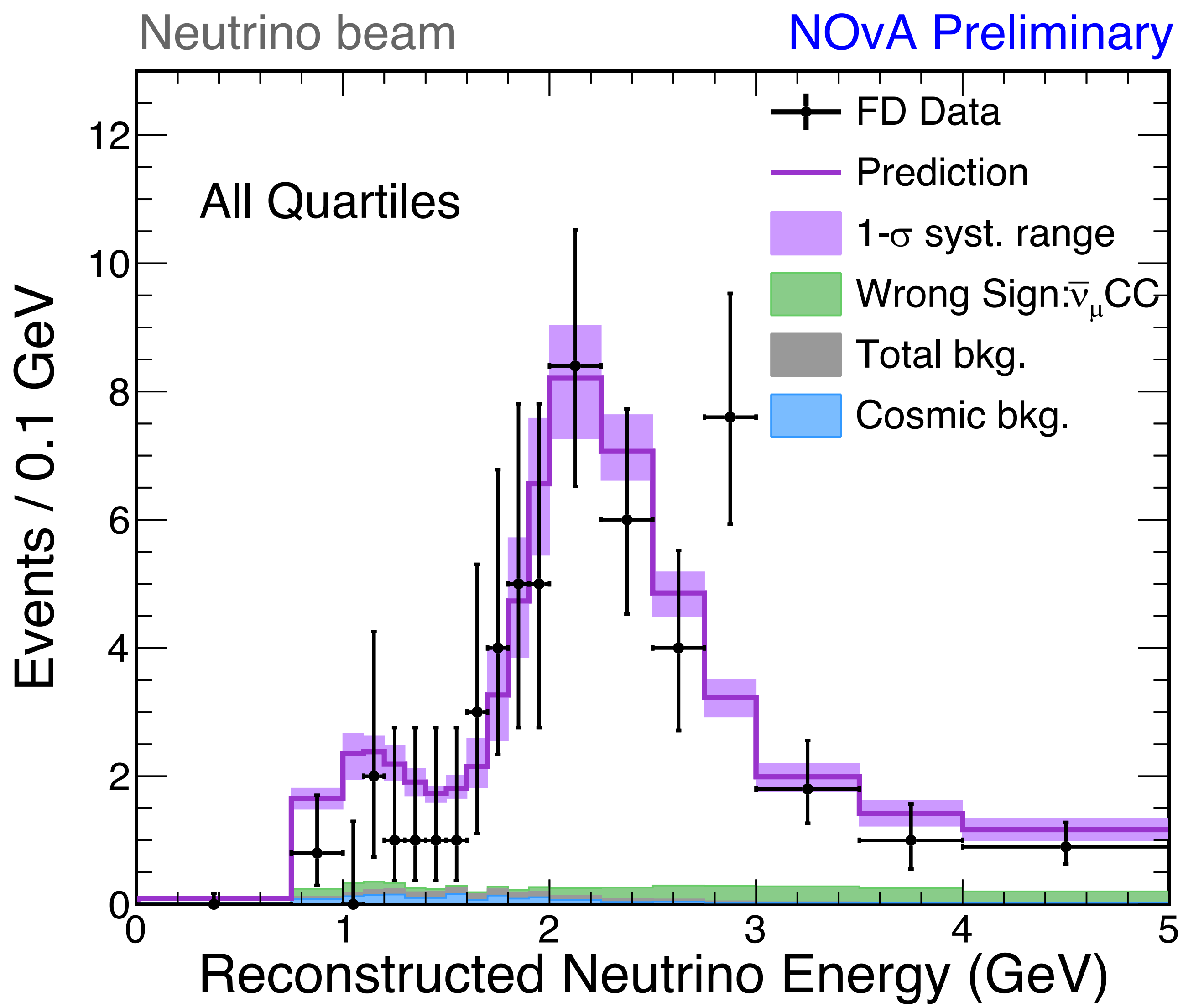


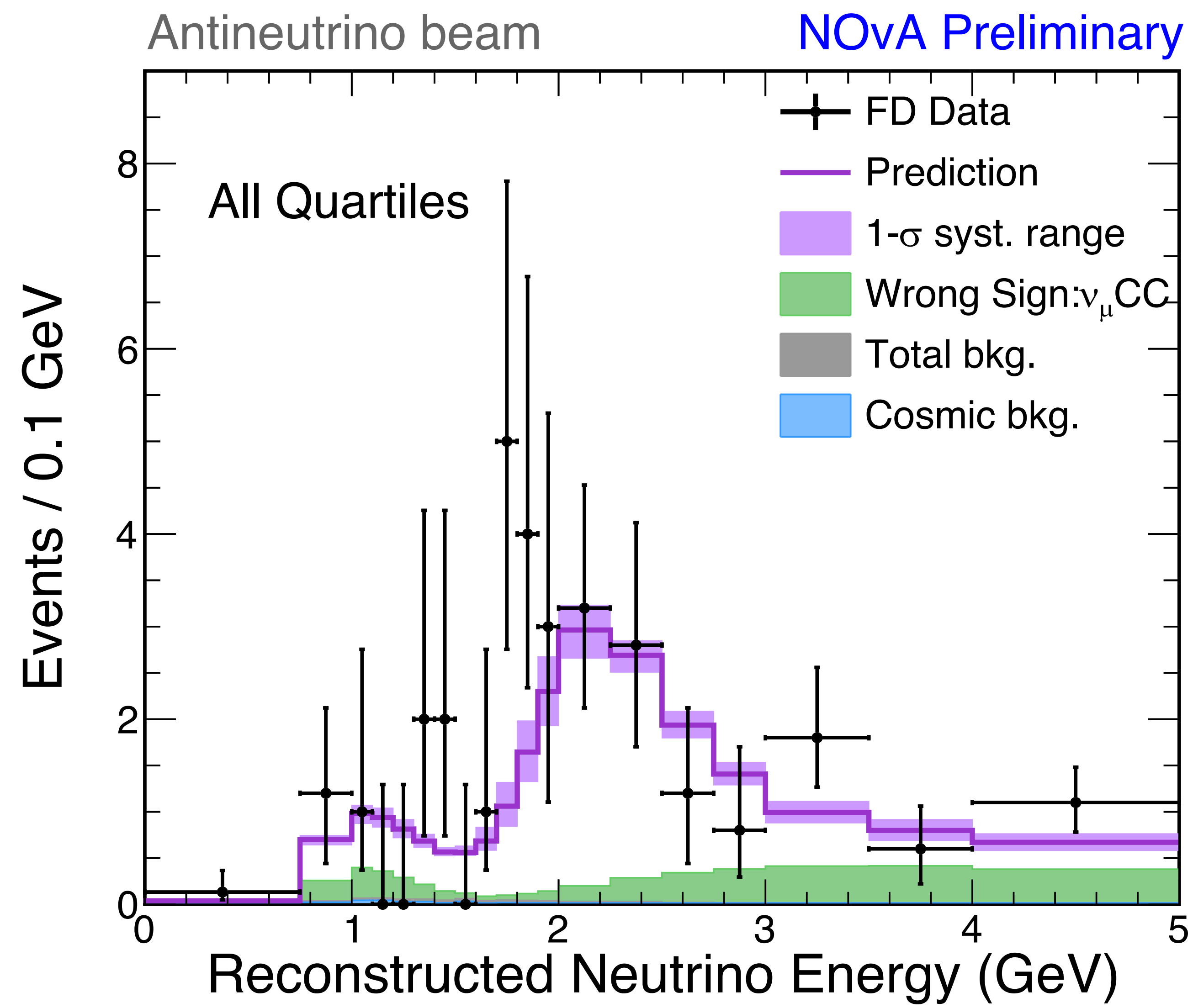


NOvA neutrino and antineutrino running



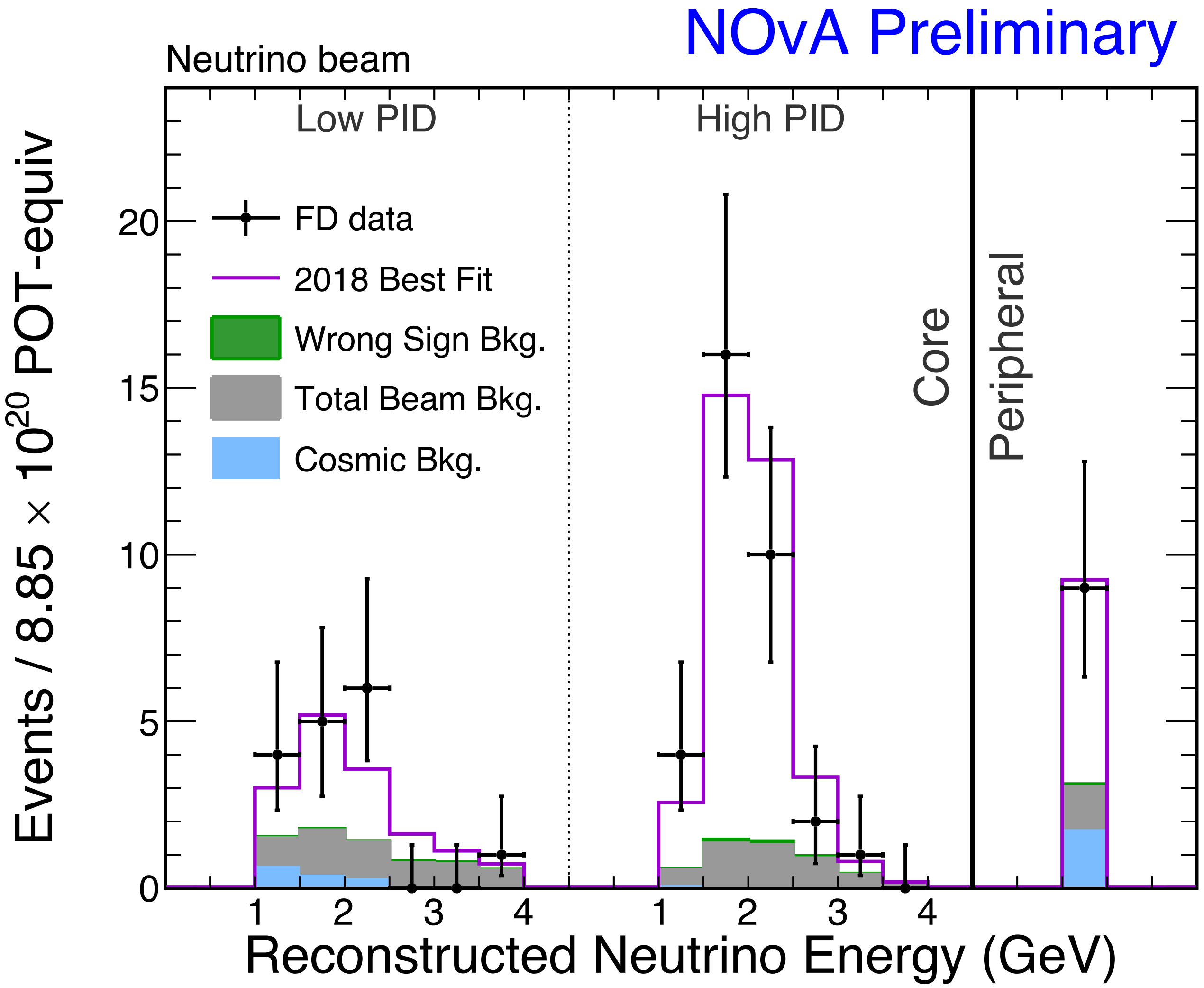
- Reported results from 9E20 protons-on-target delivered at 120 GeV in neutrino mode
- New results using 7E20 protons-on-target delivered at 120 GeV in antineutrino mode

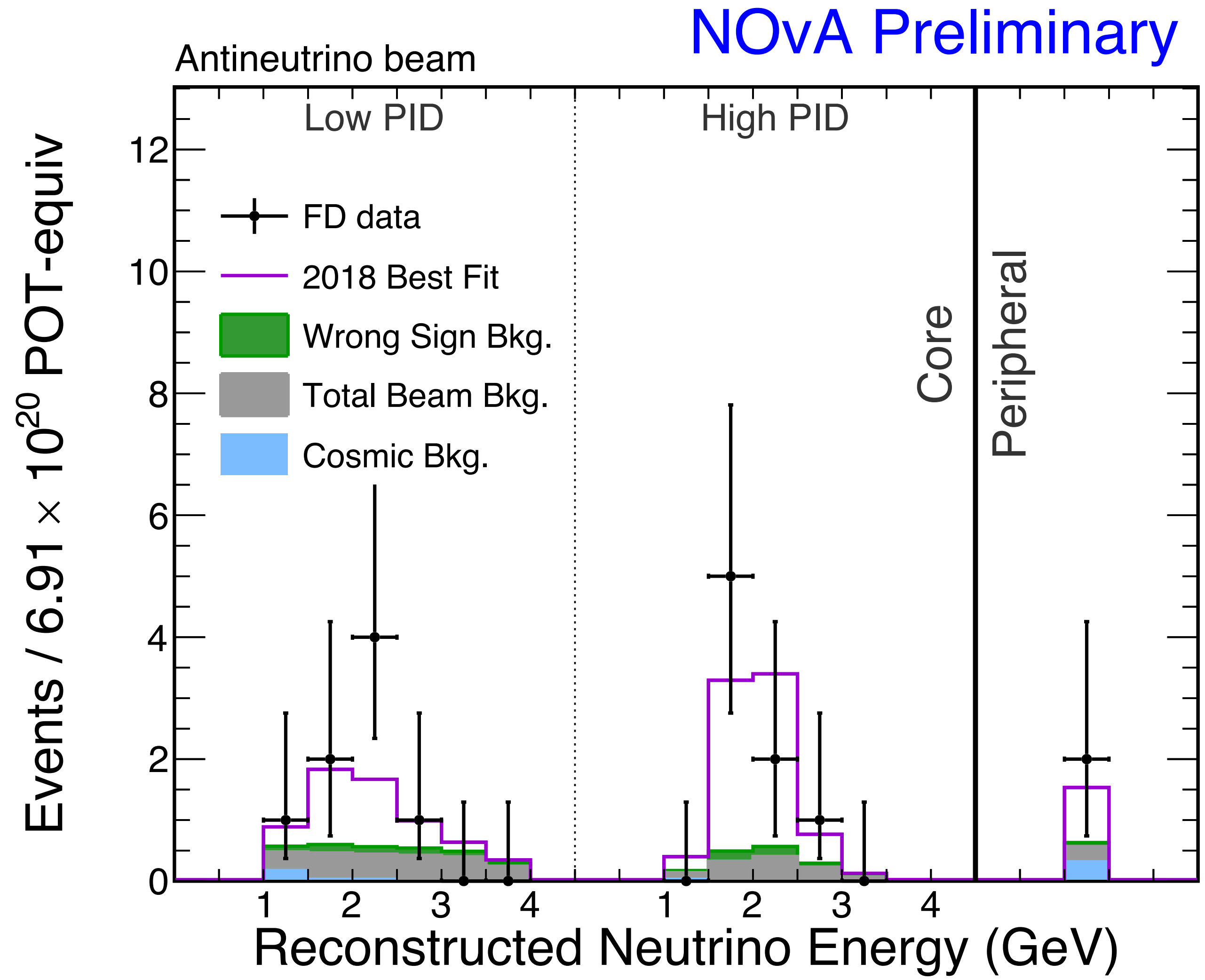




Total Observed	113
Best fit prediction	121
Cosmic Bkgd.	2.1
Beam Bkgd.	1.2
Unoscillated	730

Total Observed	65
Best fit prediction	50
Cosmic Bkgd.	0.5
Beam Bkgd.	0.6
Unoscillated	266

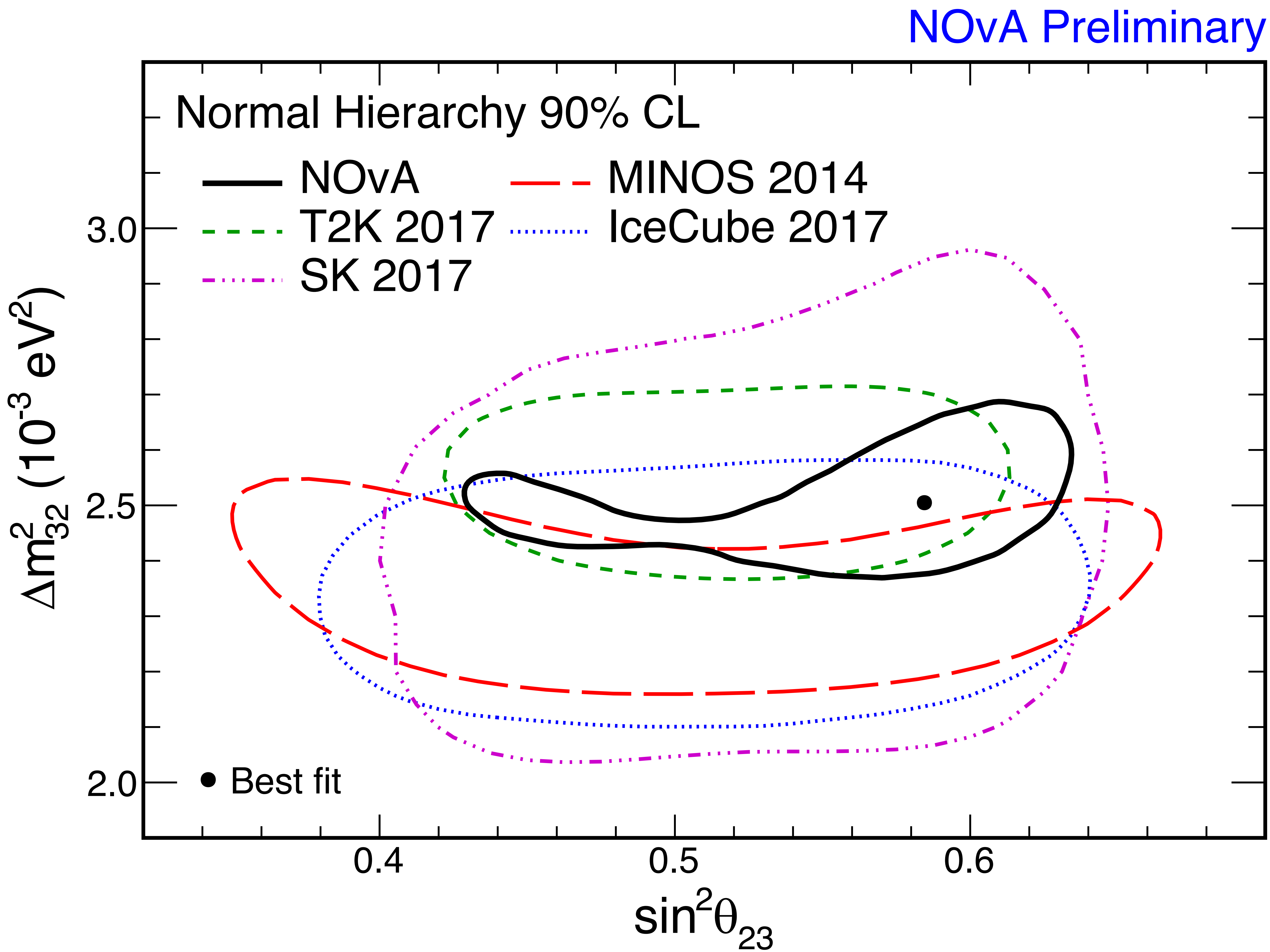




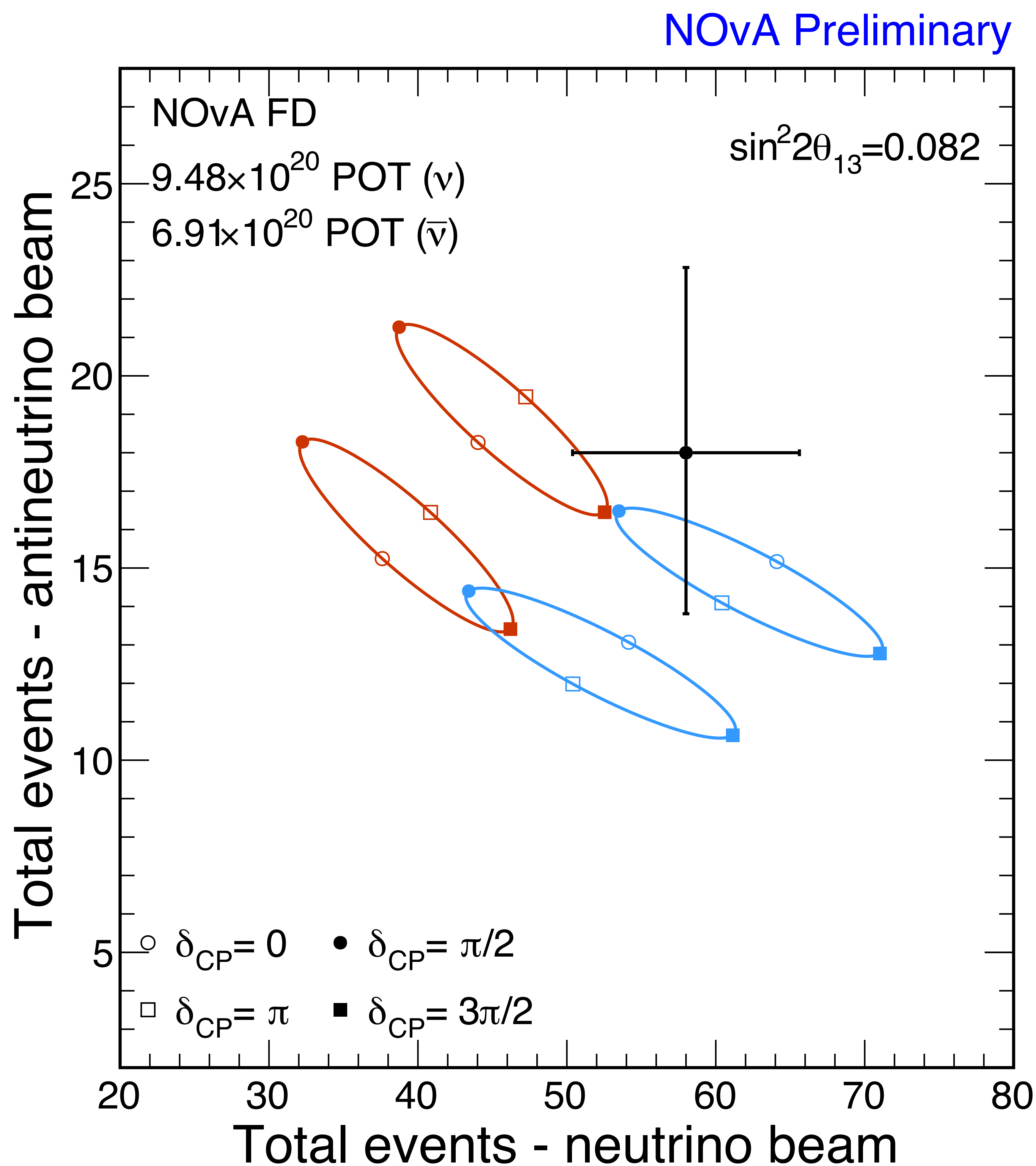
Total Observed	**58**	Range
Total Prediction	59.0	30-75
Wrong-sign	0.7	0.3-1.0
Beam Bkgd.	11.1	
Cosmic Bkgd.	3.3	
Total Bkgd.	15.1	14.7-15.4

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

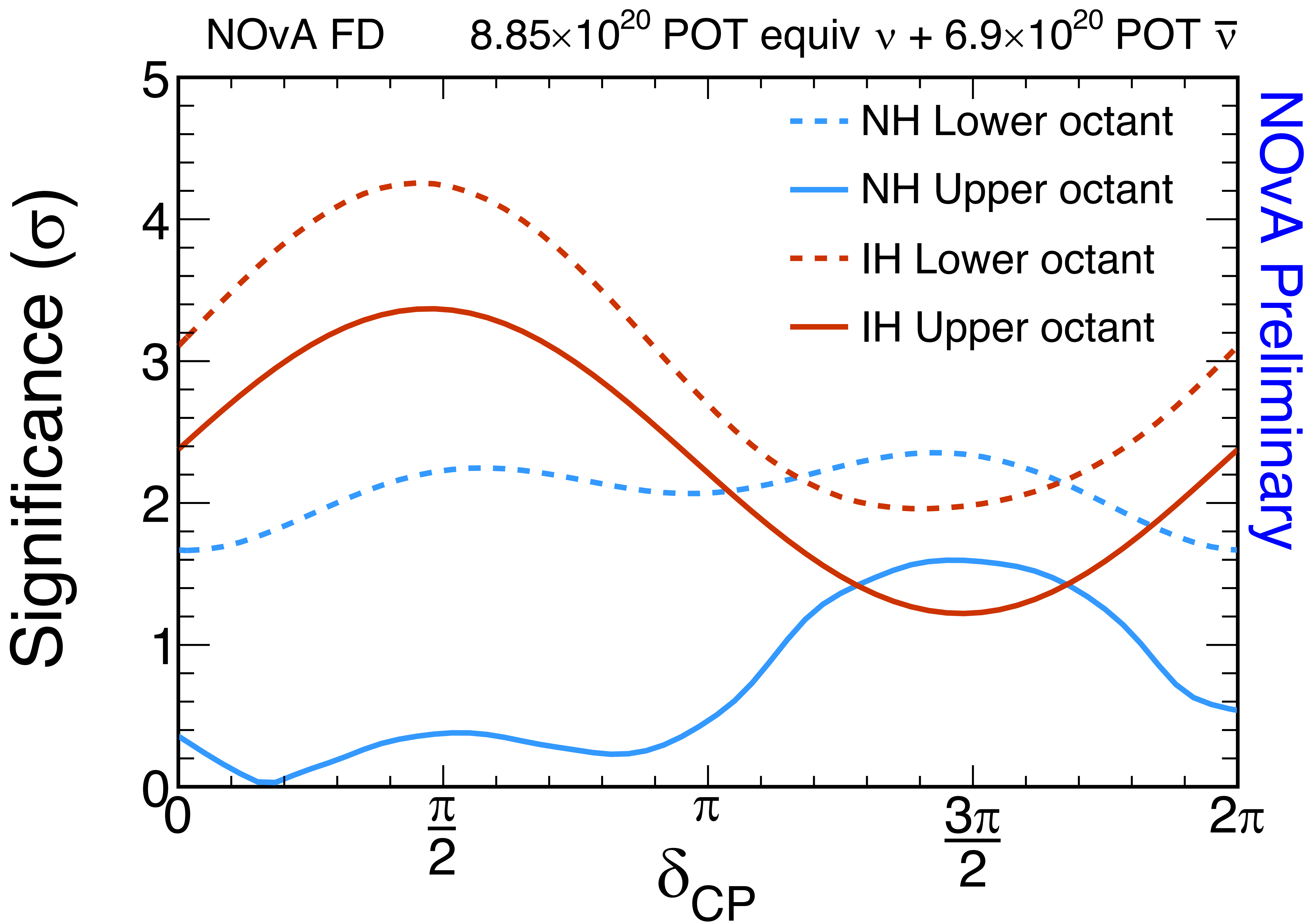
Strong (>4σ) evidence of $\bar{\nu}_e$ appearance



NOvA Preliminary
Normal Hierarchy 90% CL
NOvA
MINOS 2014
T2K 2017
IceCube 2017
SK 2017
Best fit
3.0
2.5
2.0
0.4
0.5
0.6
Δm^2_{32} (10^{-3} eV^2)
$\sin^2\theta_{23}$



NOvA Preliminary
NOvA FD
9.48×10^20 POT (ν)
6.91×10^20 POT (ν̄)
sin²2θ₁₃=0.082
δCP= 0
δCP= π/2
δCP= π
δCP= 3π/2
Total events - antineutrino beam
Total events - neutrino beam
5
10
15
20
25
20
30
40
50
60
70
80



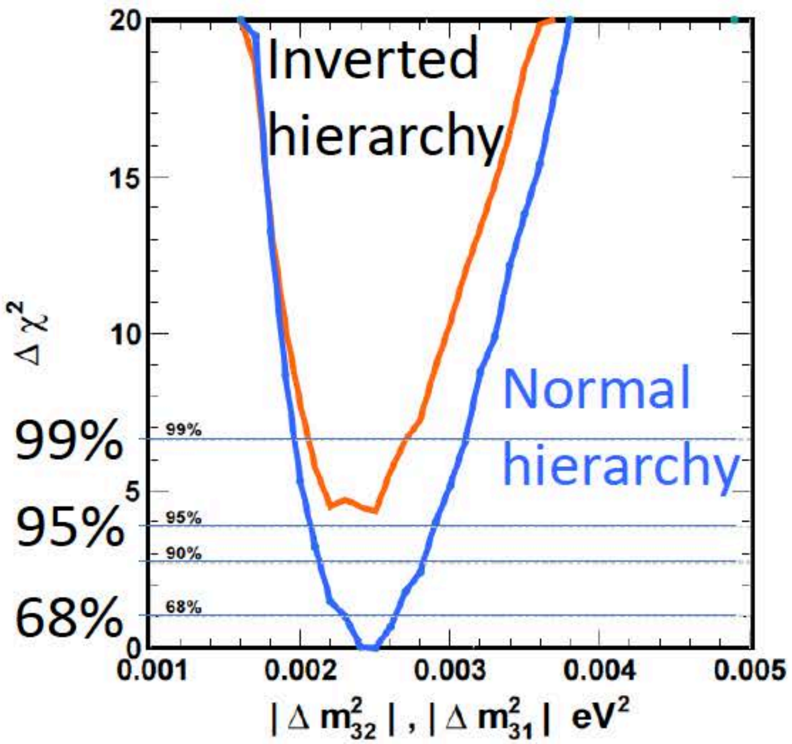
$$\chi^2_{\rm IH} - \chi^2_{\rm NH} = 2.47$$

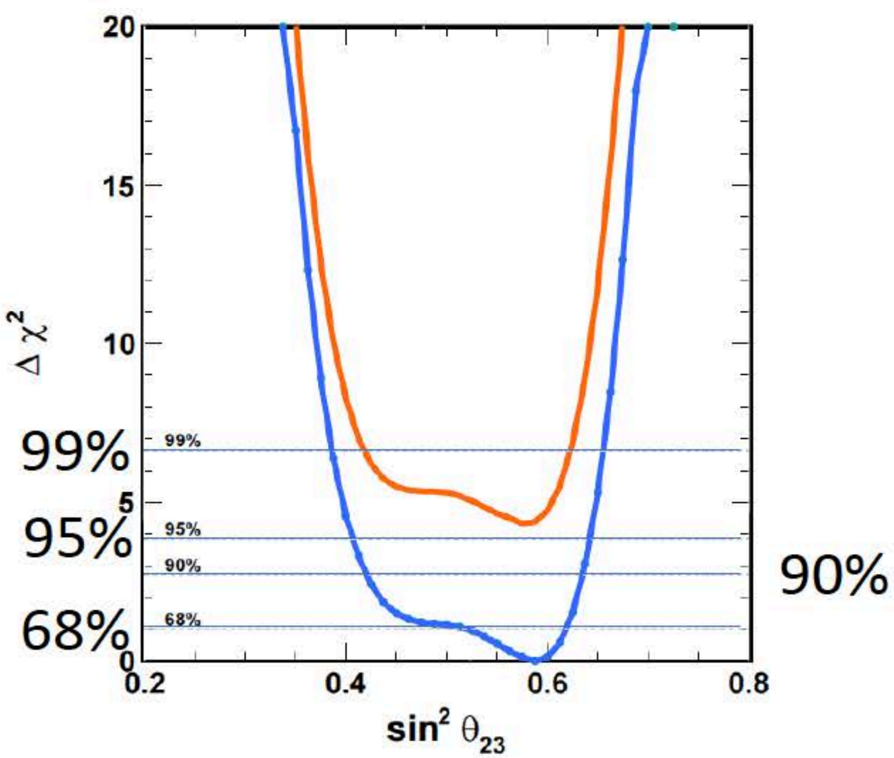
P value based on Feldman-Cousins calculation = 0.076, or **1.8σ**

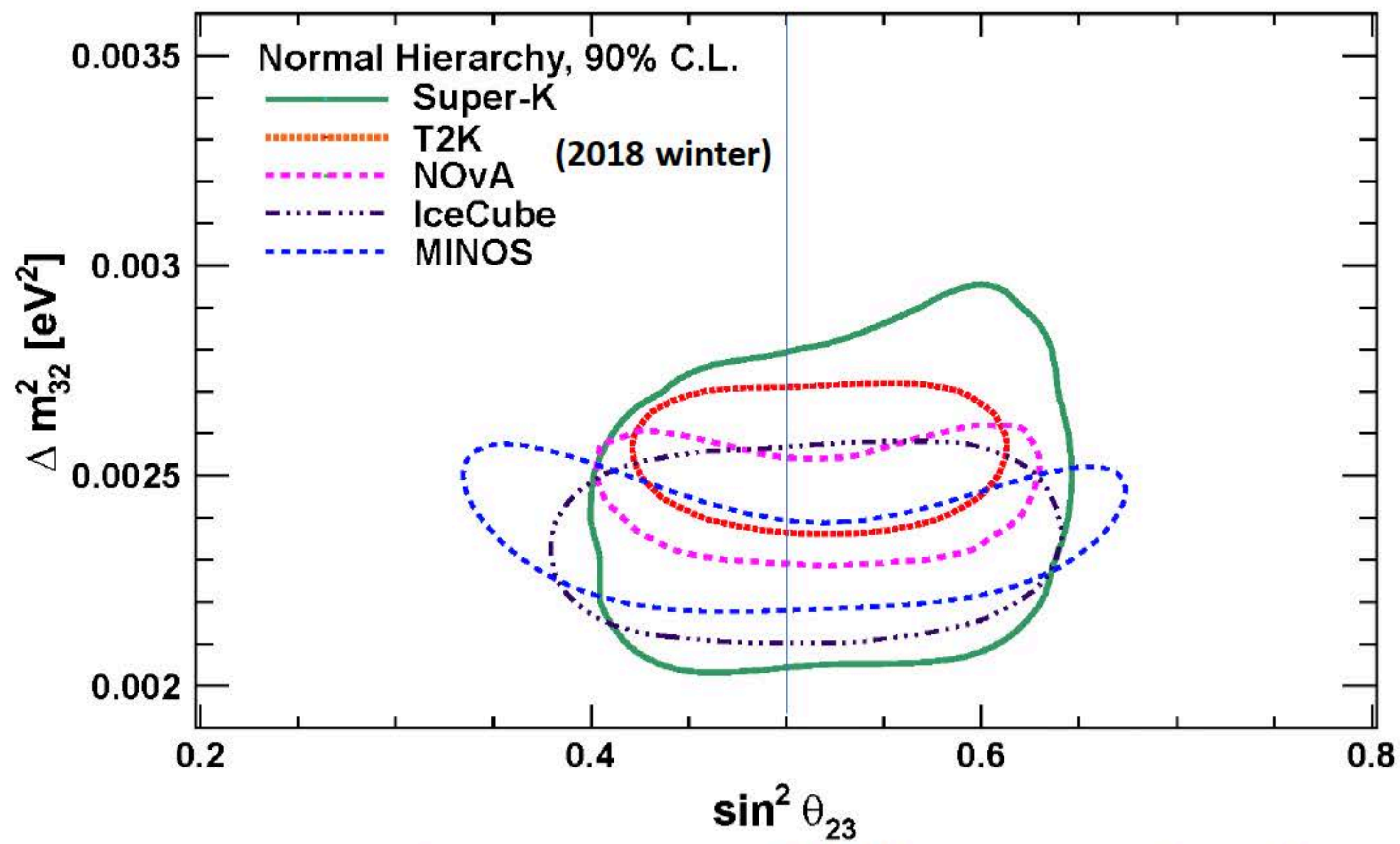
Oscillation parameters from Super-Kamiokande atmospheric neutrinos

Phys. Rev. D 97, 072001 (2018)

$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5} \mathrm{ev}^2,$$
$$\sin^2\theta_{12} = 0.304 \pm 0.014,$$
$$\sin^2\theta_{13} = 0.0219 \pm 0.012$$



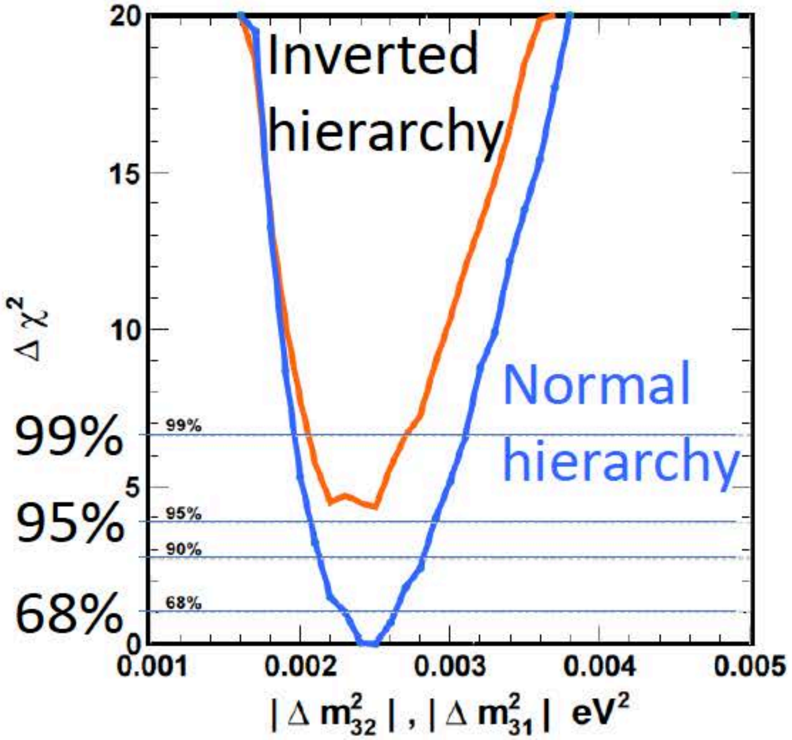


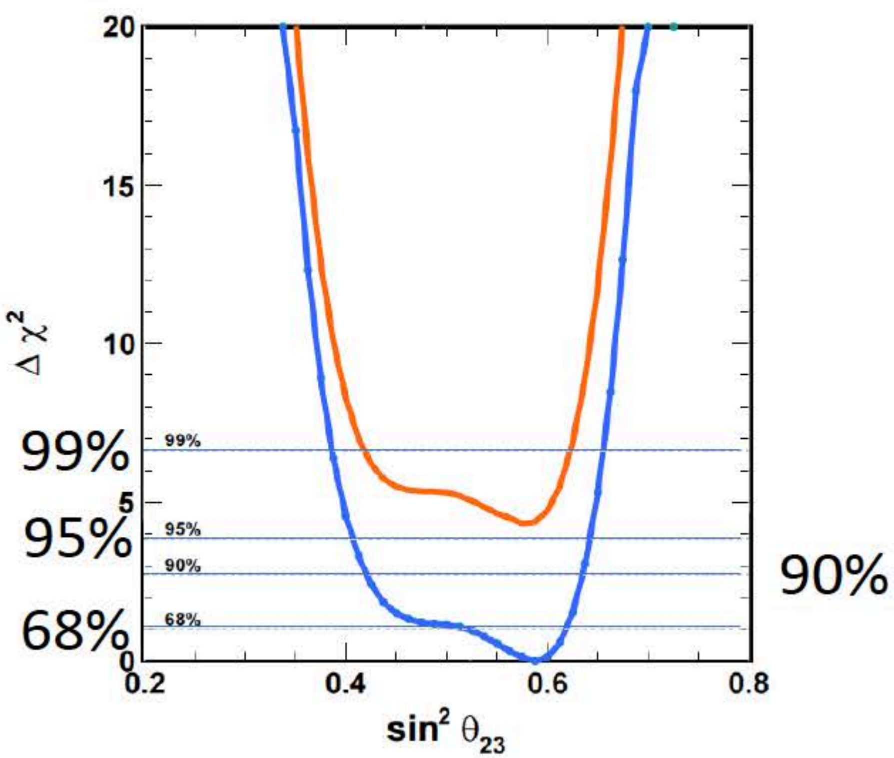


$$|\Delta m^2_{32}| = 2.50^{+0.13}_{-0.20} \times 10^{-3} \mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.588 \pm^{0.031}_{0.067}$$

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

Oscillation parameters from Super-Kamiokande atmospheric neutrinos

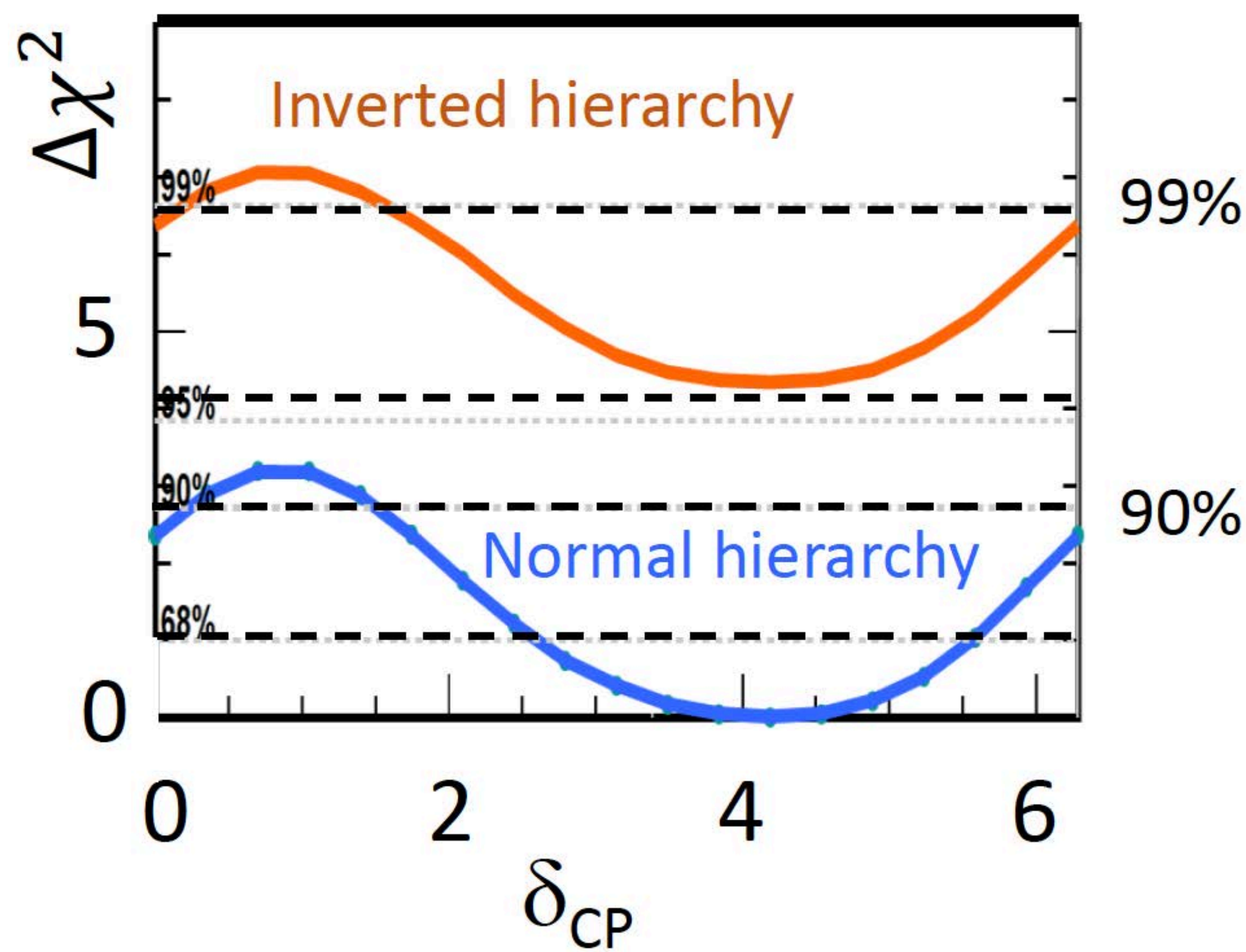




Phys. Rev. D 97, 072001 (2018)

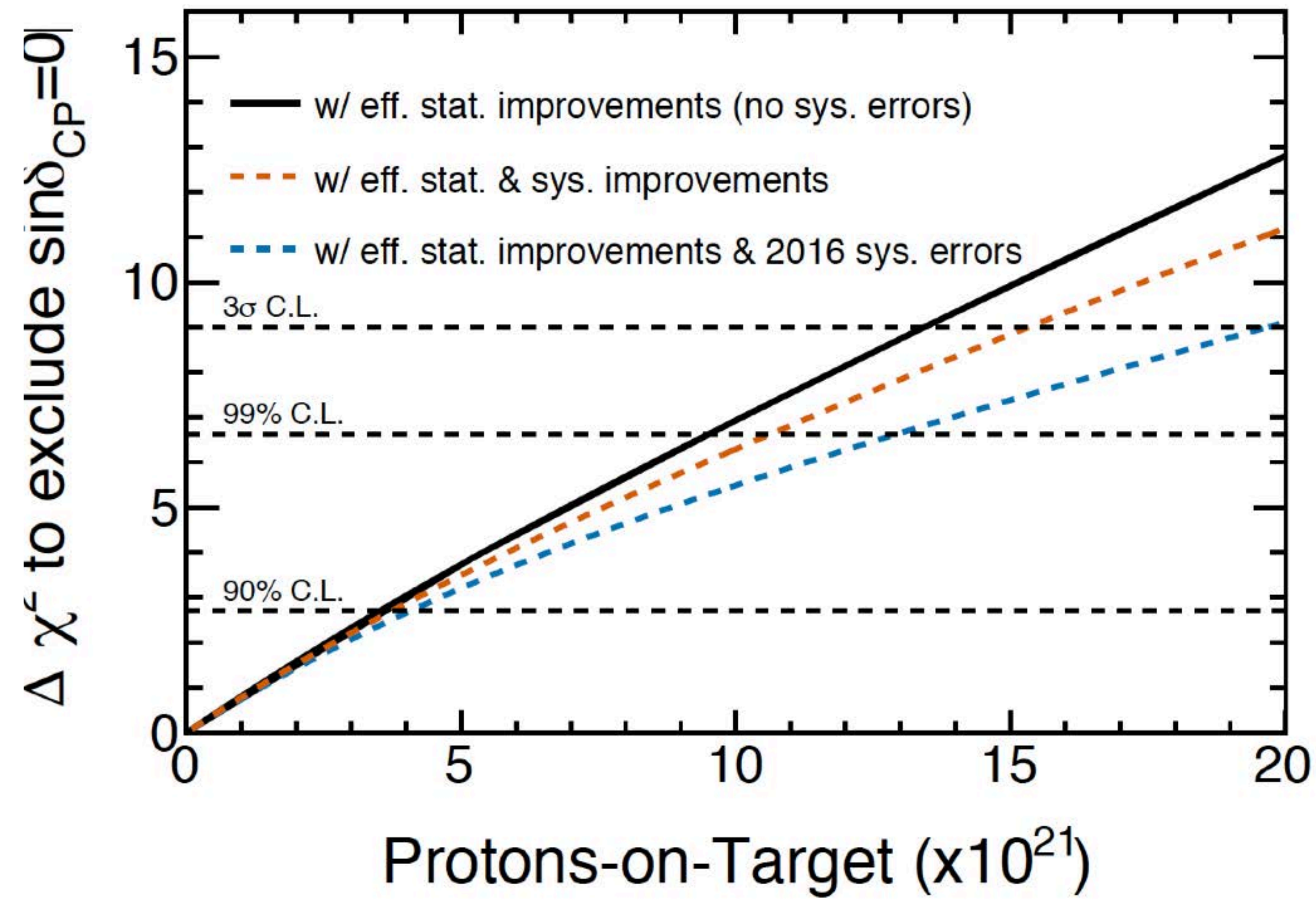
$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5} \mathrm{ev}^2,$$
$$\sin^2\theta_{12} = 0.304 \pm 0.014,$$
$$\sin^2\theta_{13} = 0.0219 \pm 0.012$$

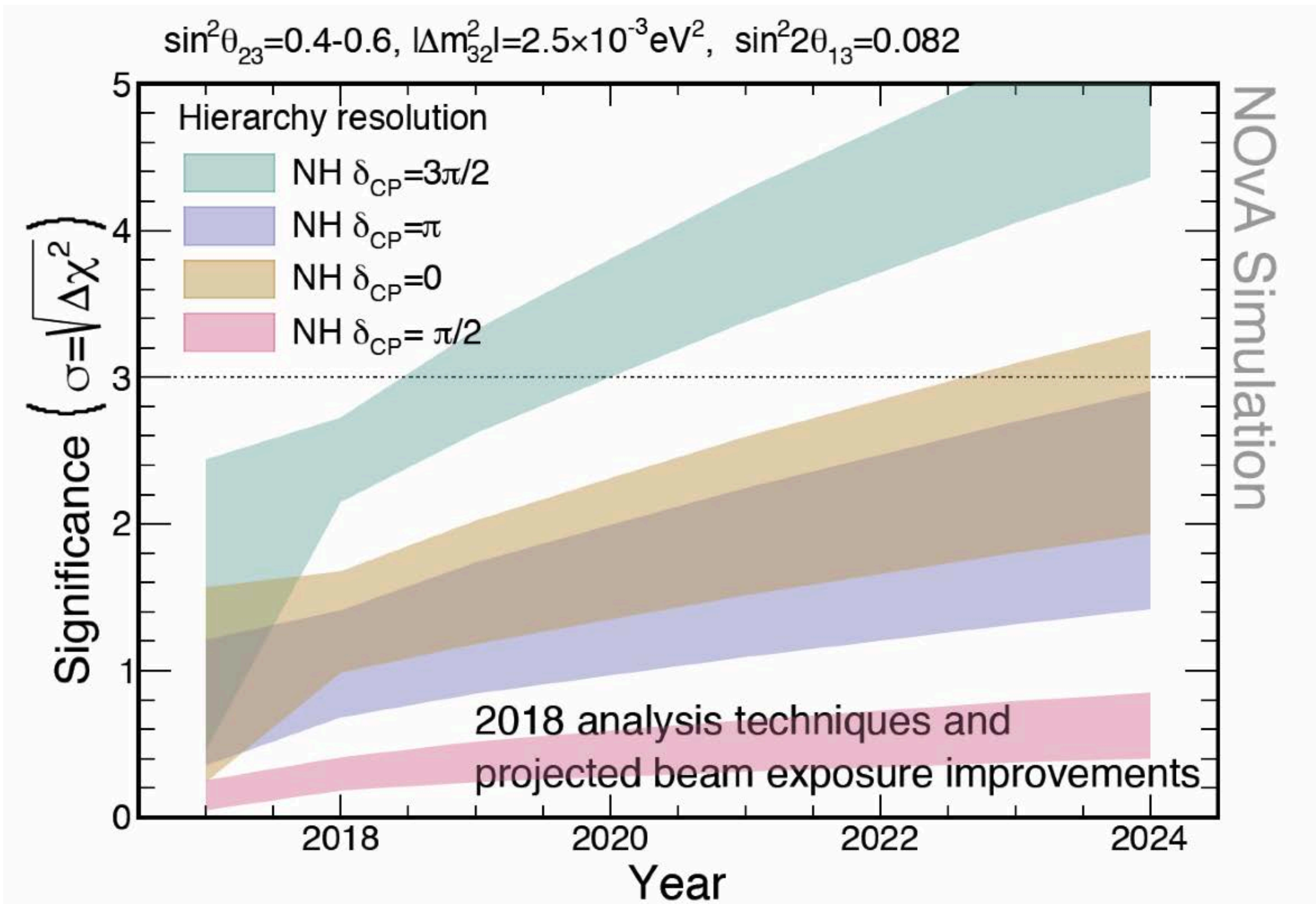
CP violation parameter δ_{CP}

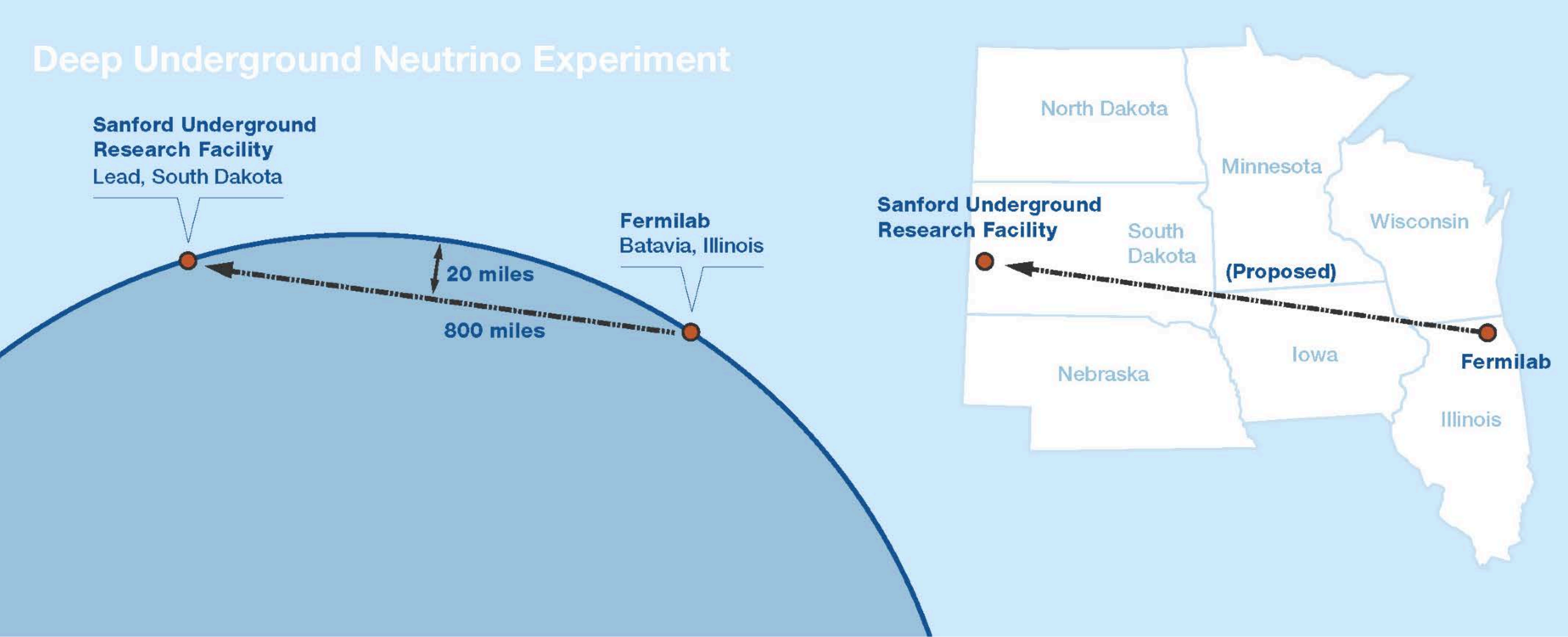


T2K and NOvA Extended Running

- 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 >3σ sensitivity to the mass hierarchy and up to 2σ sensitivity to CP violation



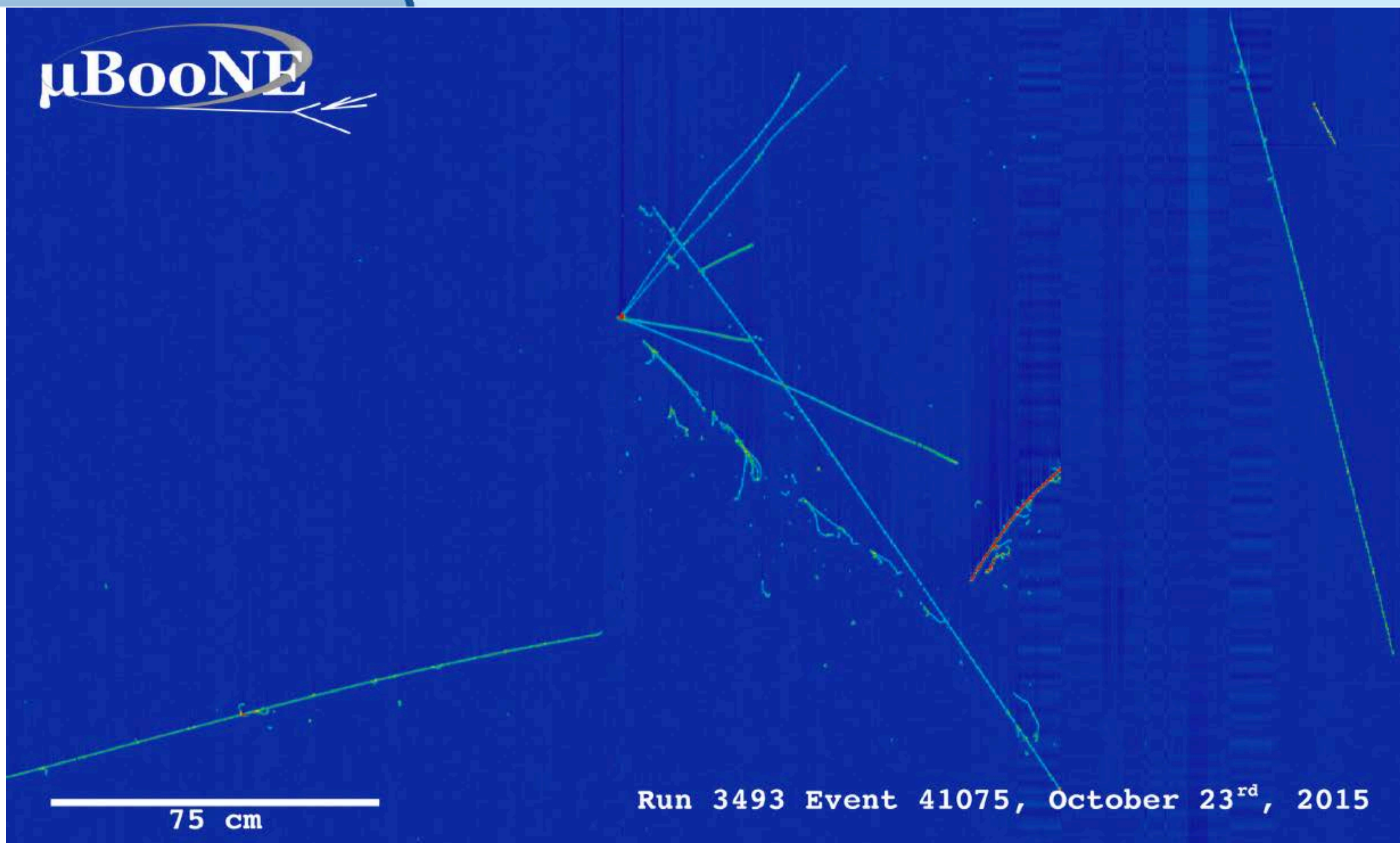




DUNE Experiment

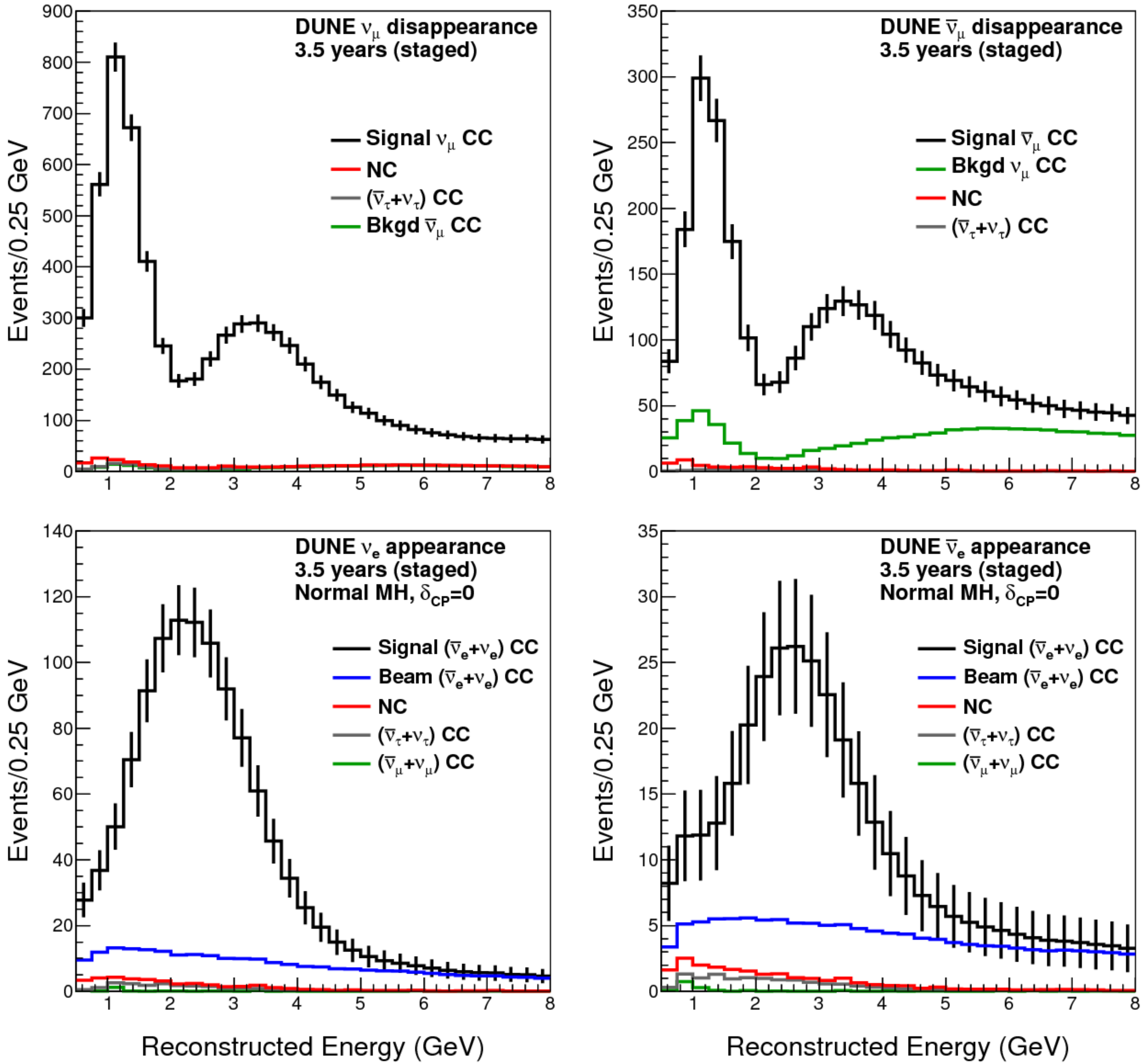
Upgrade beam to 1.2 then 2 MW
4x17 kt detector modules with millimeter resolution located 4850 feet underground

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

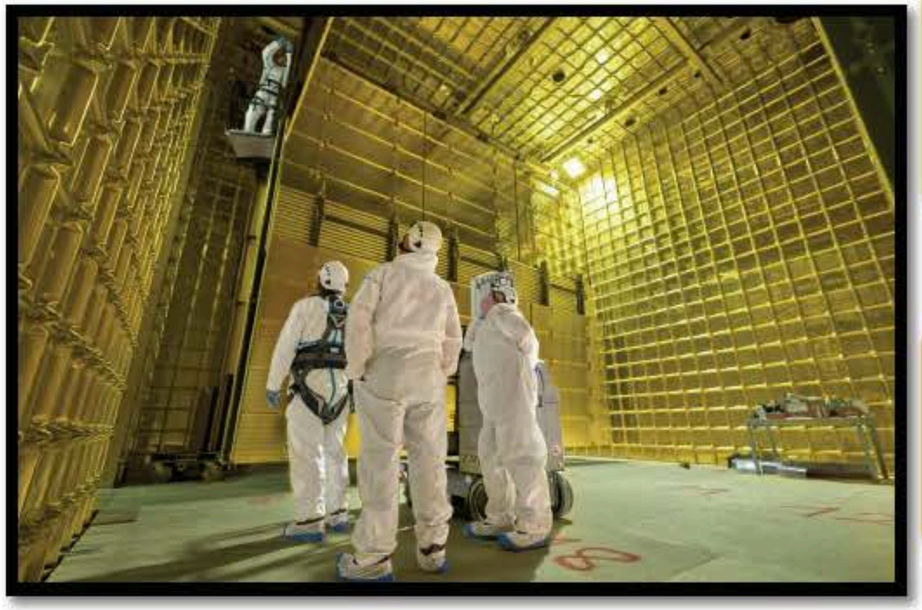


DUNE

Event Spectra



Timeline



2018: protoDUNEs at CERN

2019: Technical Design Report

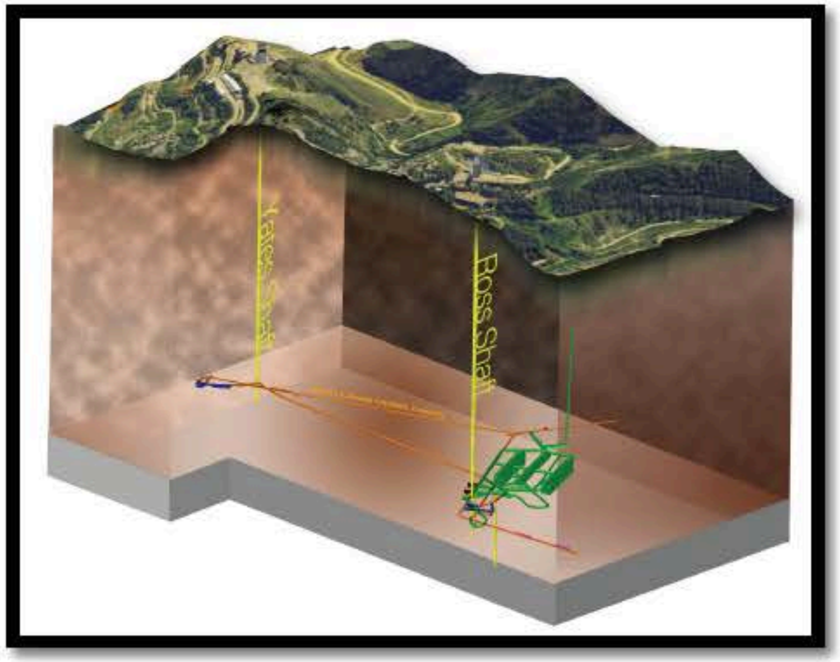
2019: Far Site Primary Excavation Begins

2022: First Module Installation Begins

2026: Neutrino Beam Available

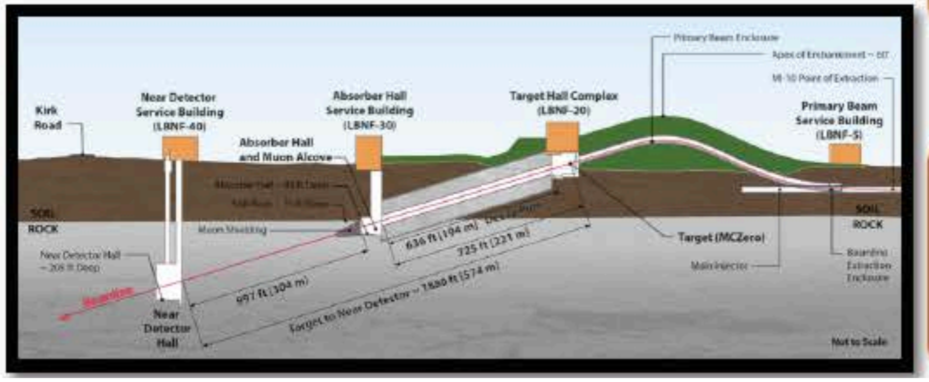
DUNE Far Detector Interim Design Report (2018)

Will be made public soon…

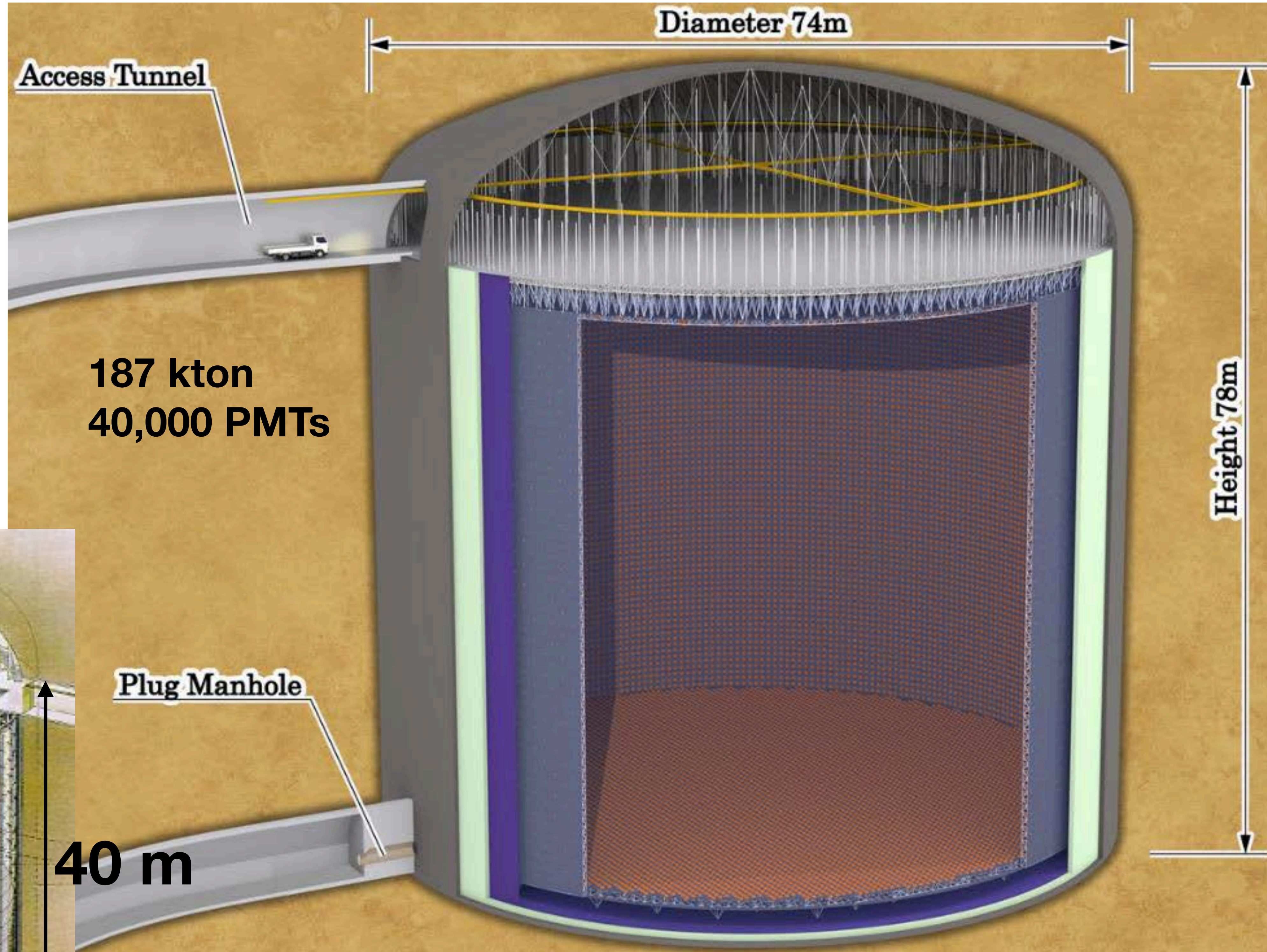


Physics data as soon as 1st module complete

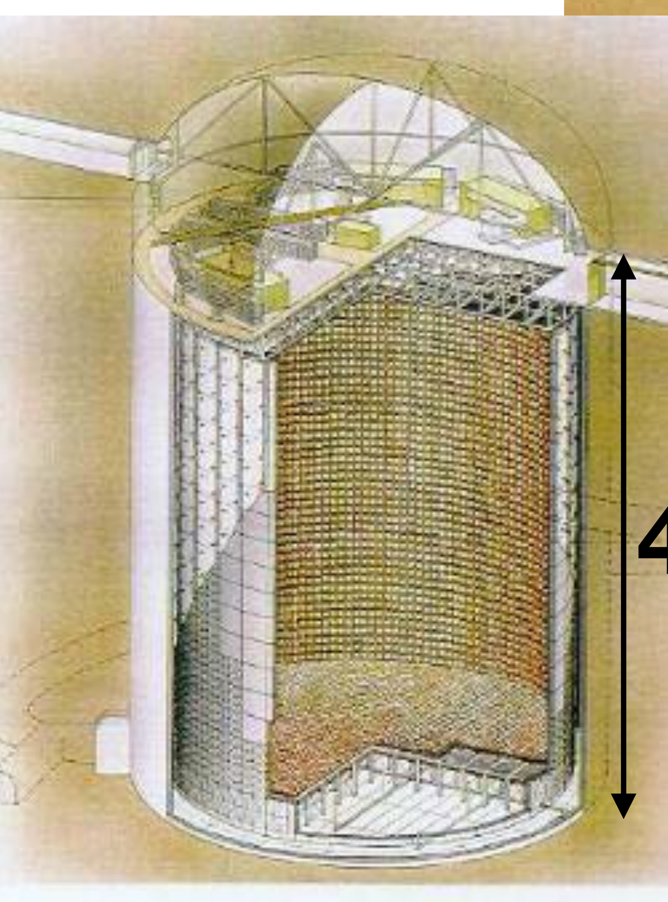
- Atmospheric νs
- SNB and solar νs
- Baryon number violation
- Detector calibration



Hyper-Kamiokande

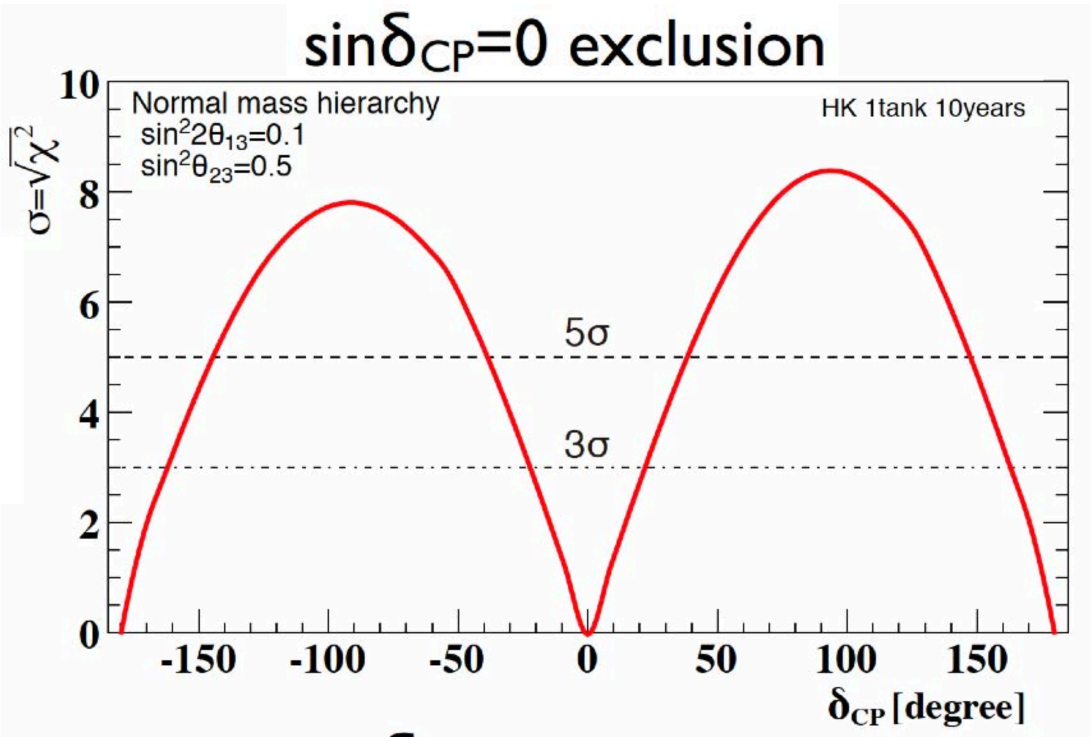


Super-K
22.5 kton
11,000 PMTs

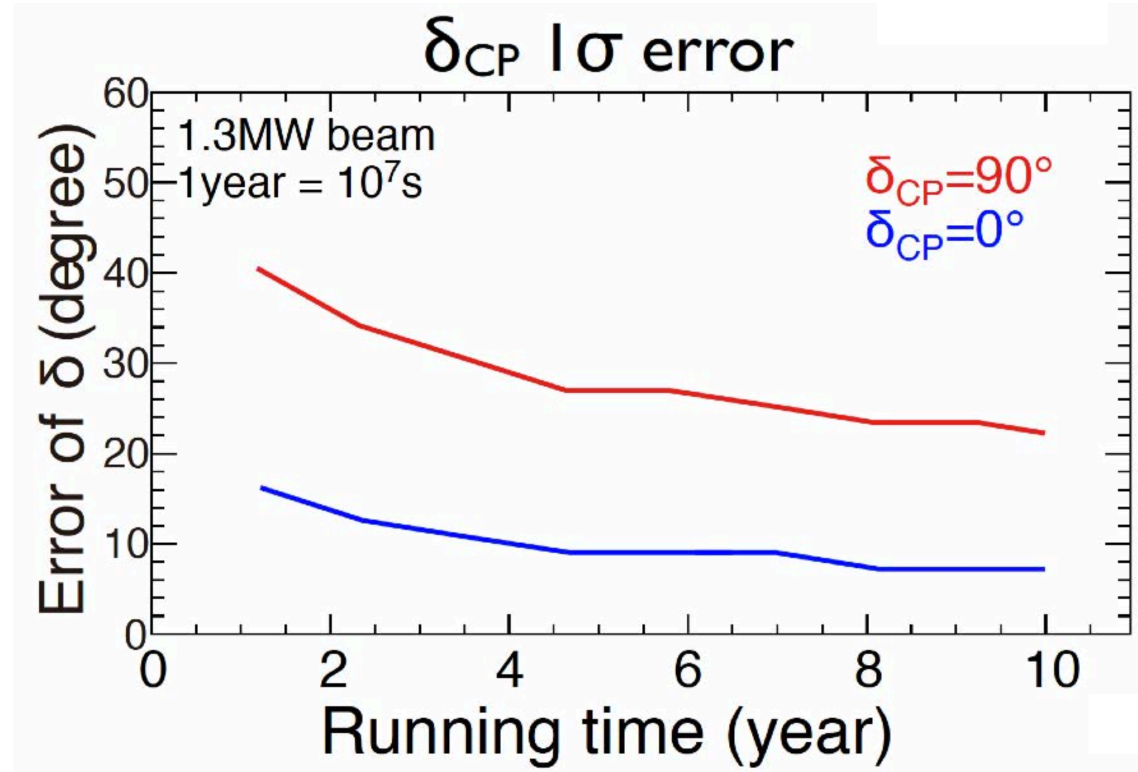


Expect funding for construction in JFY2018/19, first data 2026

Hyper-K

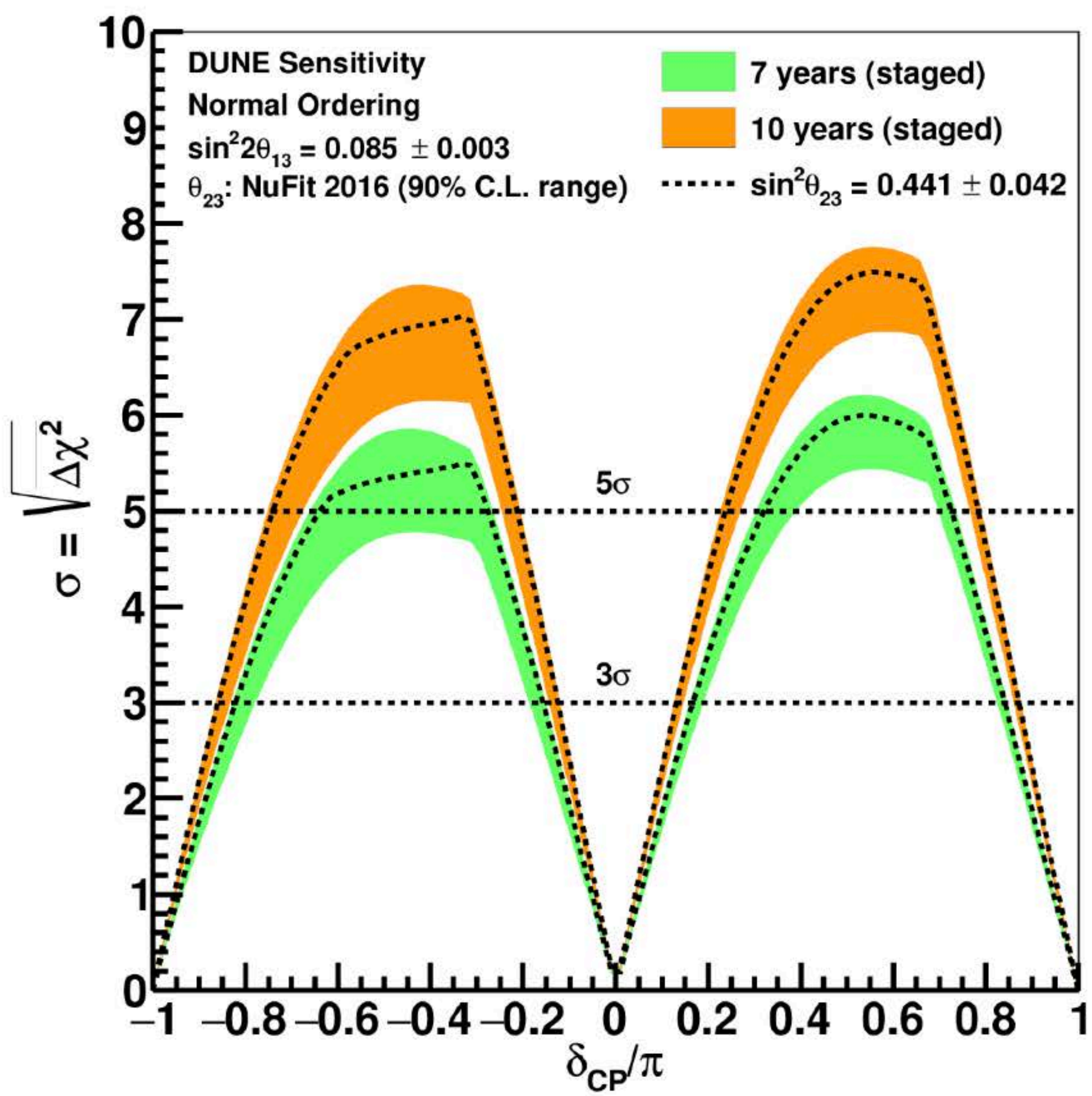


sinδCP=0 exclusion
Normal mass hierarchy
sin²2θ13=0.1
sin²θ23=0.5
HK 1tank 10years
σ=√χ²
5σ
3σ
δCP [degree]

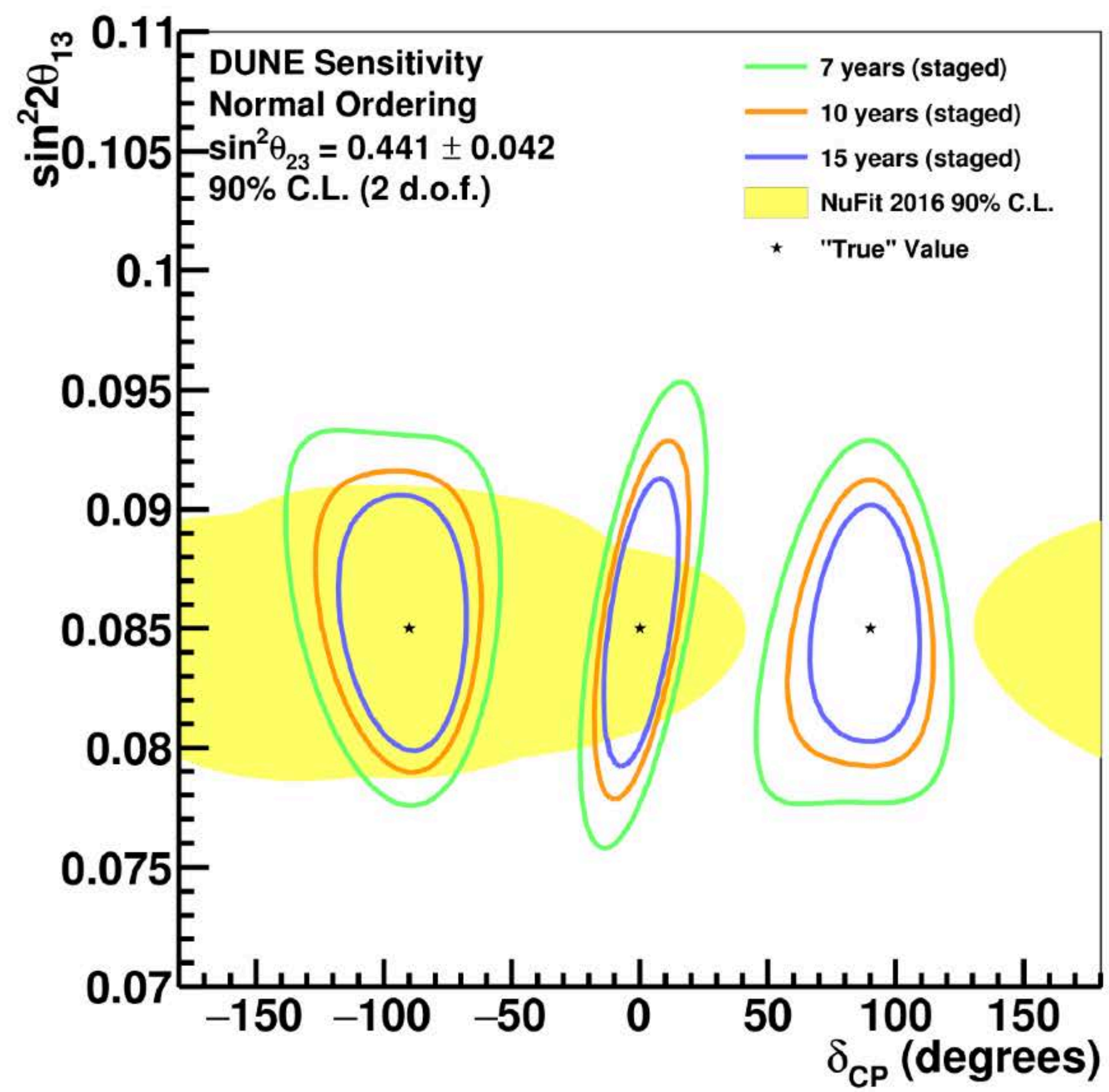


δCP 1σ error
1.3MW beam
1year = 10⁷s
δCP=90°
δCP=0°
Error of δ (degree)
Running time (year)

DUNE



DUNE Sensitivity
Normal Ordering
sin²2θ13 = 0.085 ± 0.003
θ23: NuFit 2016 (90% C.L. range)
7 years (staged)
10 years (staged)
sin²θ23 = 0.441 ± 0.042
σ = √Δχ²
5σ
3σ
δCP/π



DUNE Sensitivity
Normal Ordering
sin²θ23 = 0.441 ± 0.042
90% C.L. (2 d.o.f.)
7 years (staged)
10 years (staged)
15 years (staged)
NuFit 2016 90% C.L.
"True" Value
sin²2θ13
δCP (degrees)

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.