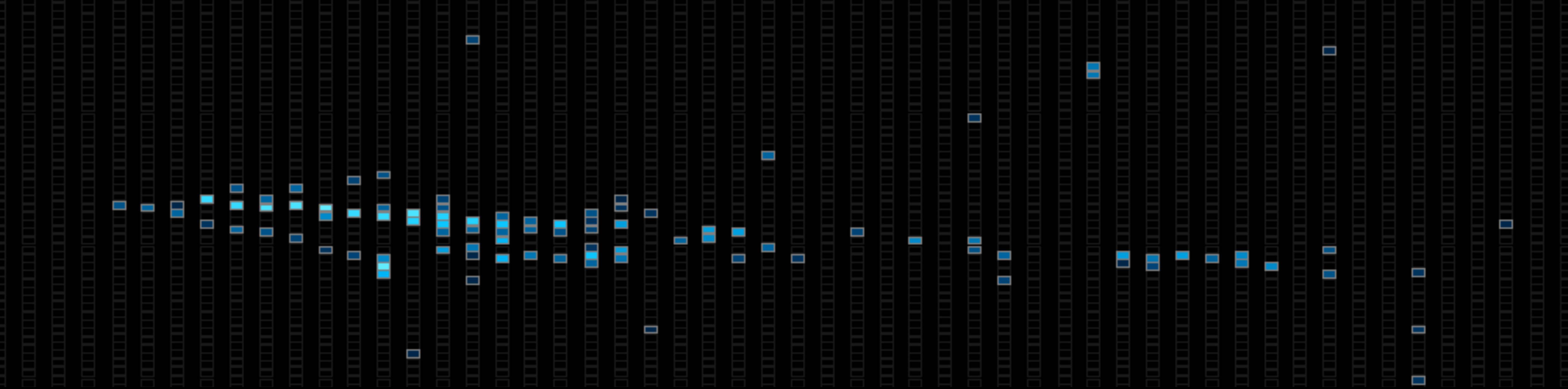
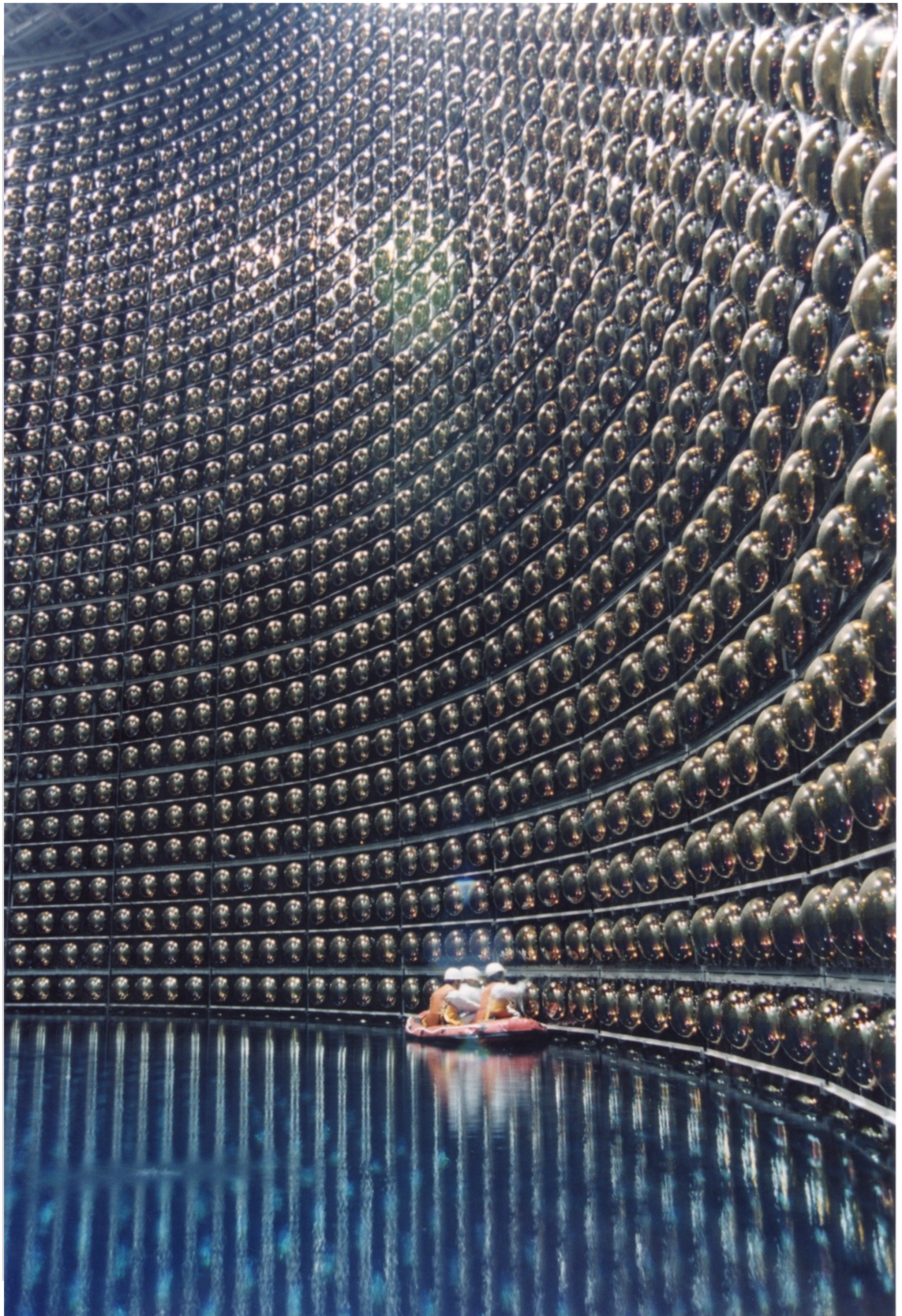


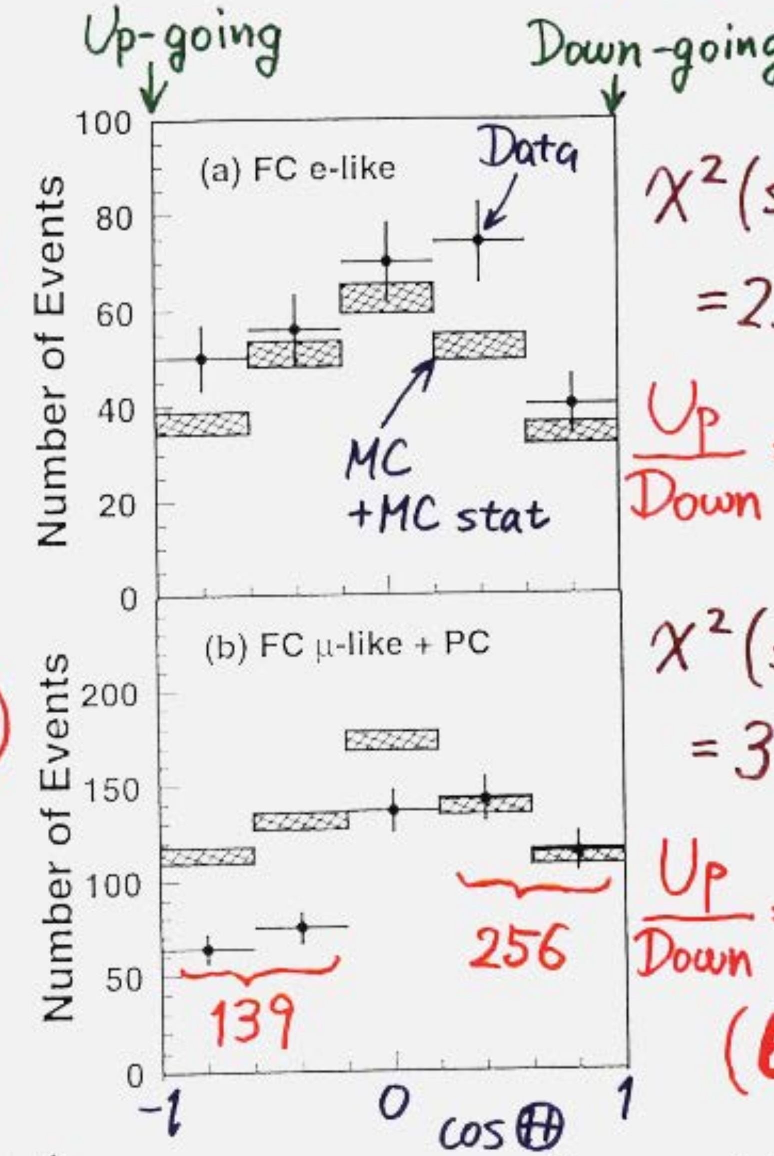
Experimental Overview of Neutrino Oscillations

Mark Messier
Indiana University

International Workshop On Next Generation Nucleon Decay and Neutrino Detectors (NNN18)
Vancouver, Canada
November 1, 2018



Zenith angle dependence (Multi-GeV)



ⓔ χ^2(shape) $= 2.8/4$ dof

$\frac{Up}{Down} = 0.93^{+0.13}_{-0.12}$

Ⓜ χ^2(shape) $= 30/4$ dof

$\frac{Up}{Down} = 0.54^{+0.06}_{-0.05}$

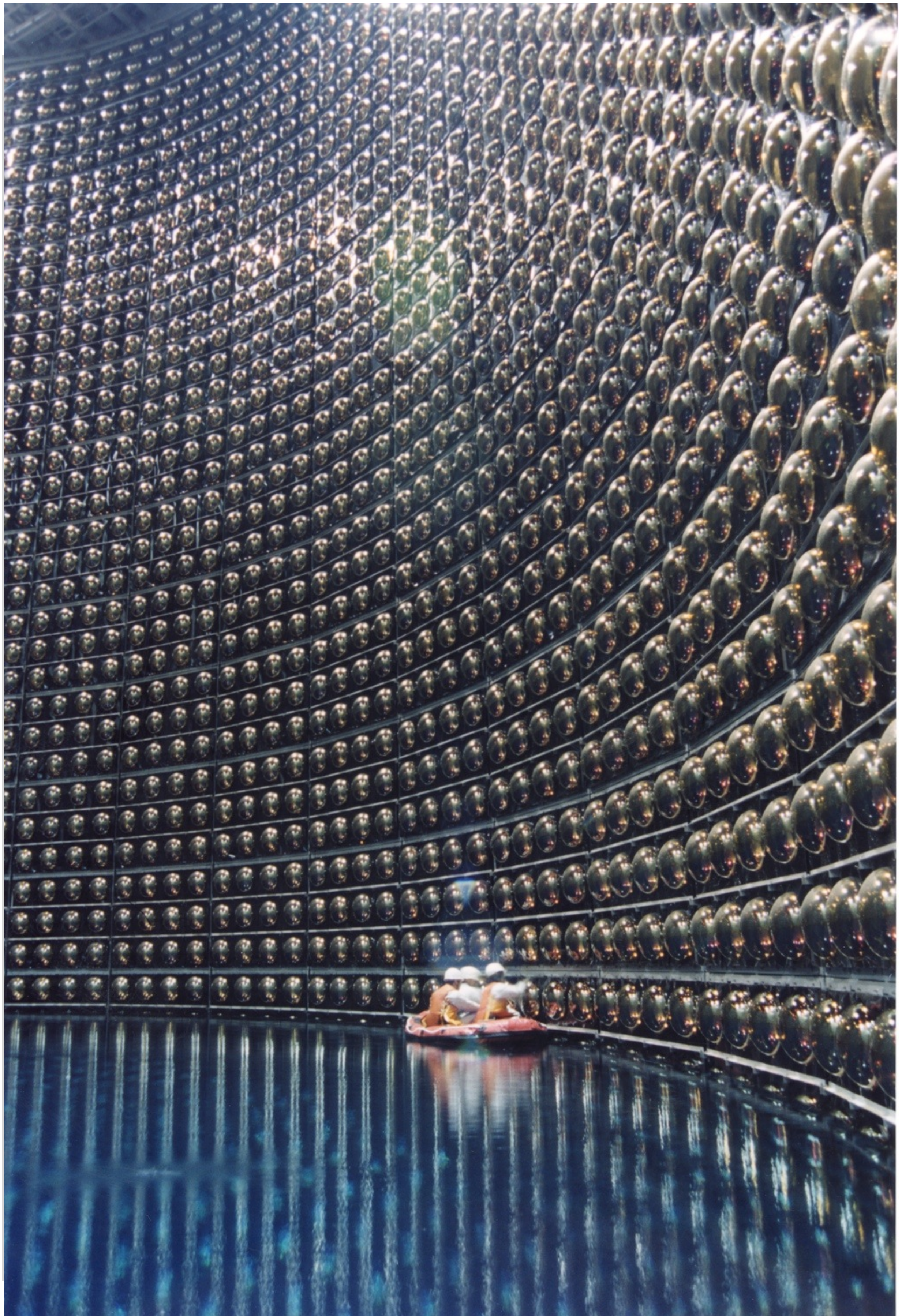
(6.2σ !!)

※ 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%

Super-Kamiokande



"All the News That's Fit to Print"

The New York Times

Late Edition

NEW YORK, FRIDAY, JUNE 5, 1998

40 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

Bajram Curri, in northern Albania, has received 4,500 refugees from Yugoslavia in three days. One group ate yesterday in a school building.

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

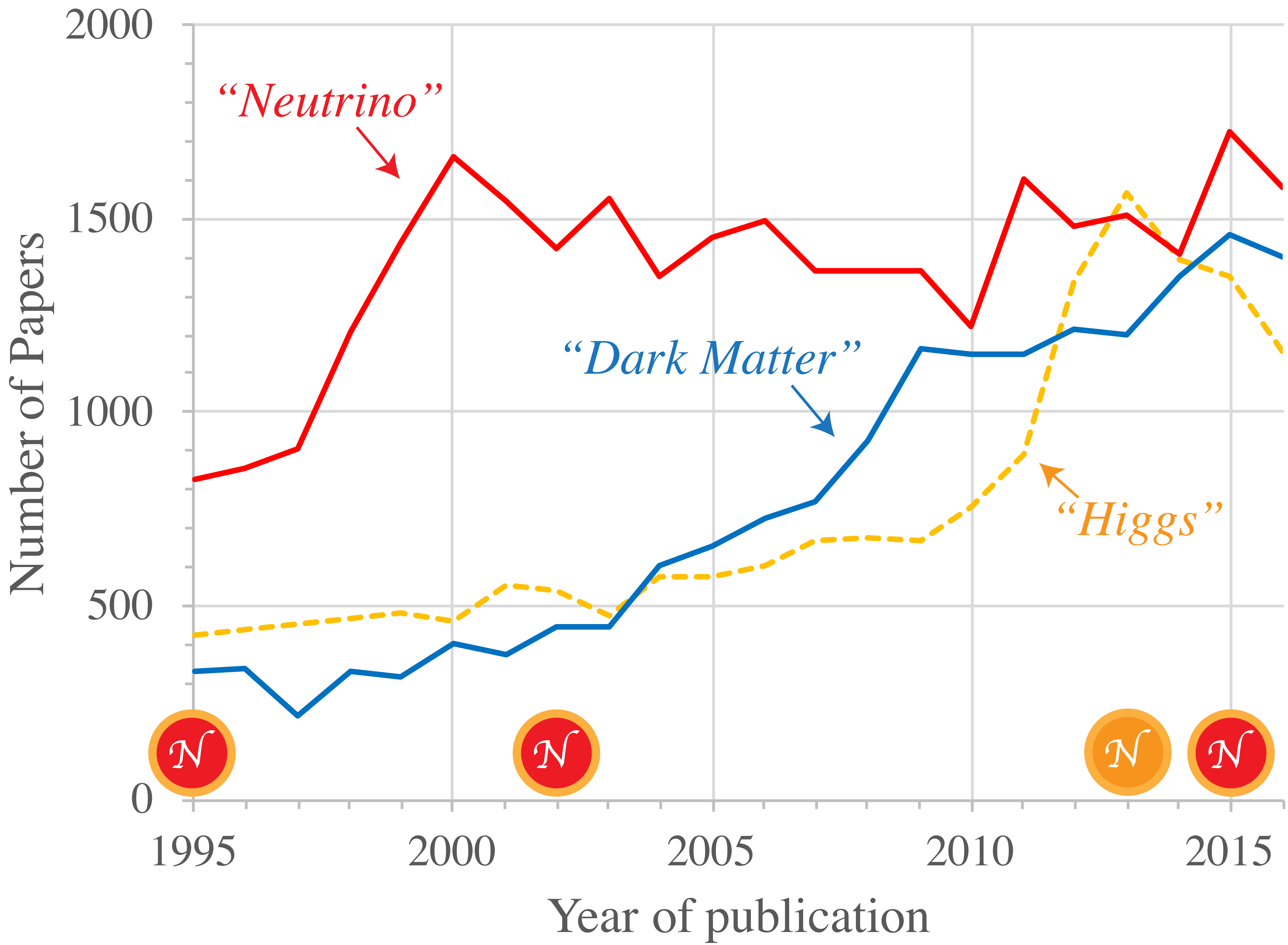
Seles Upsets Hingis in French Open

INSIDE

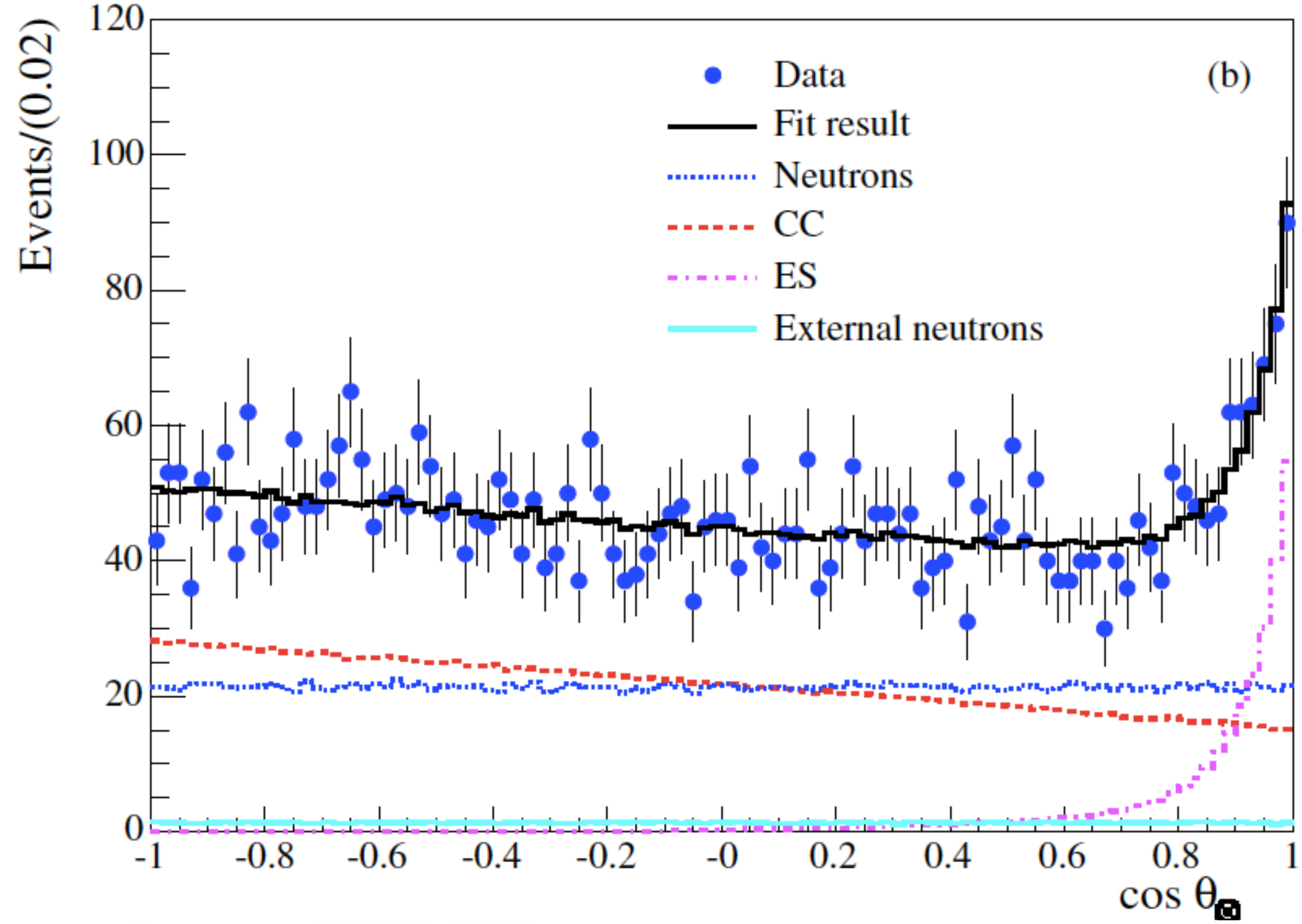
A Catalogue of Loss

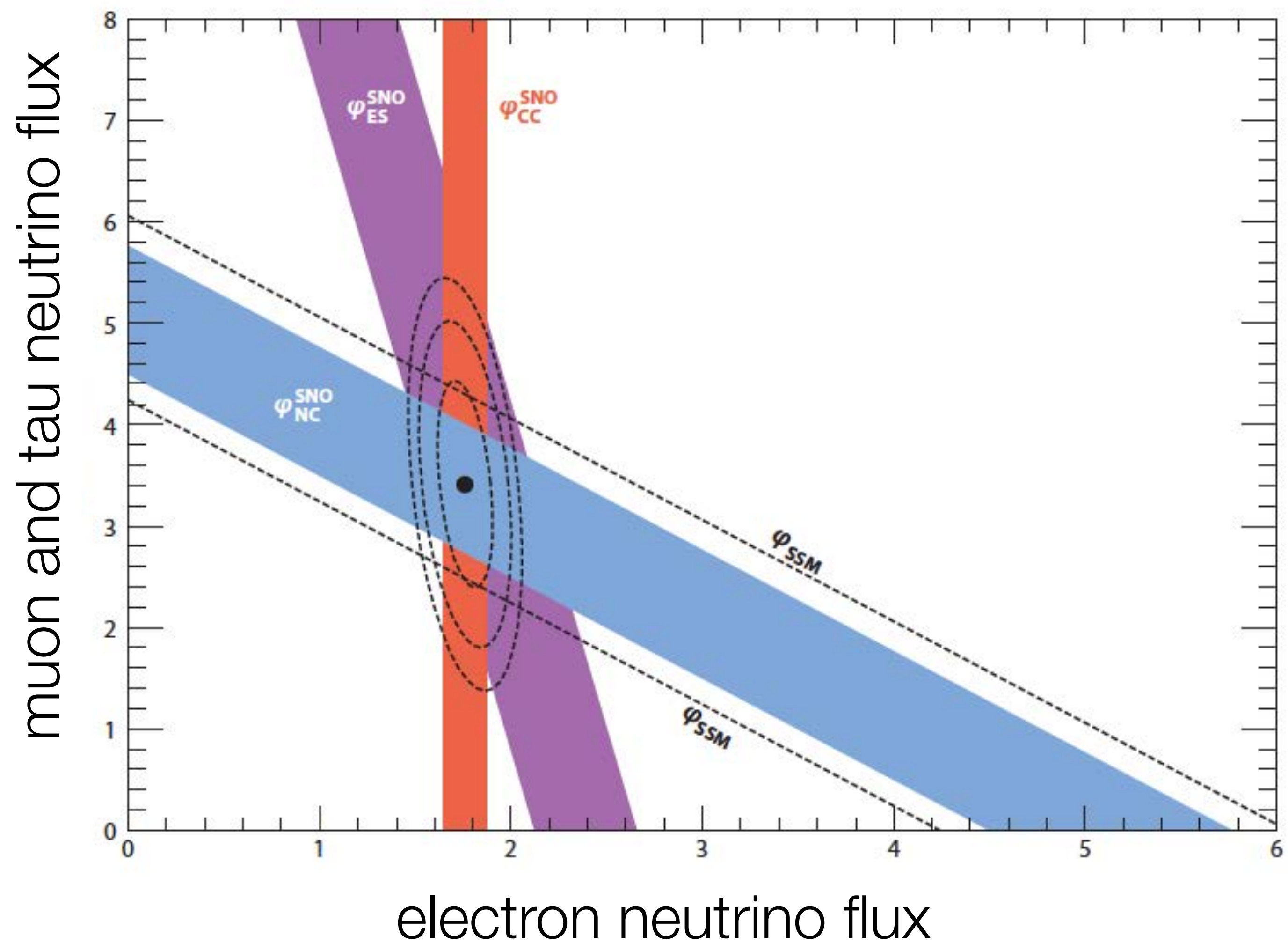
News Summary

Super-Kamiokande

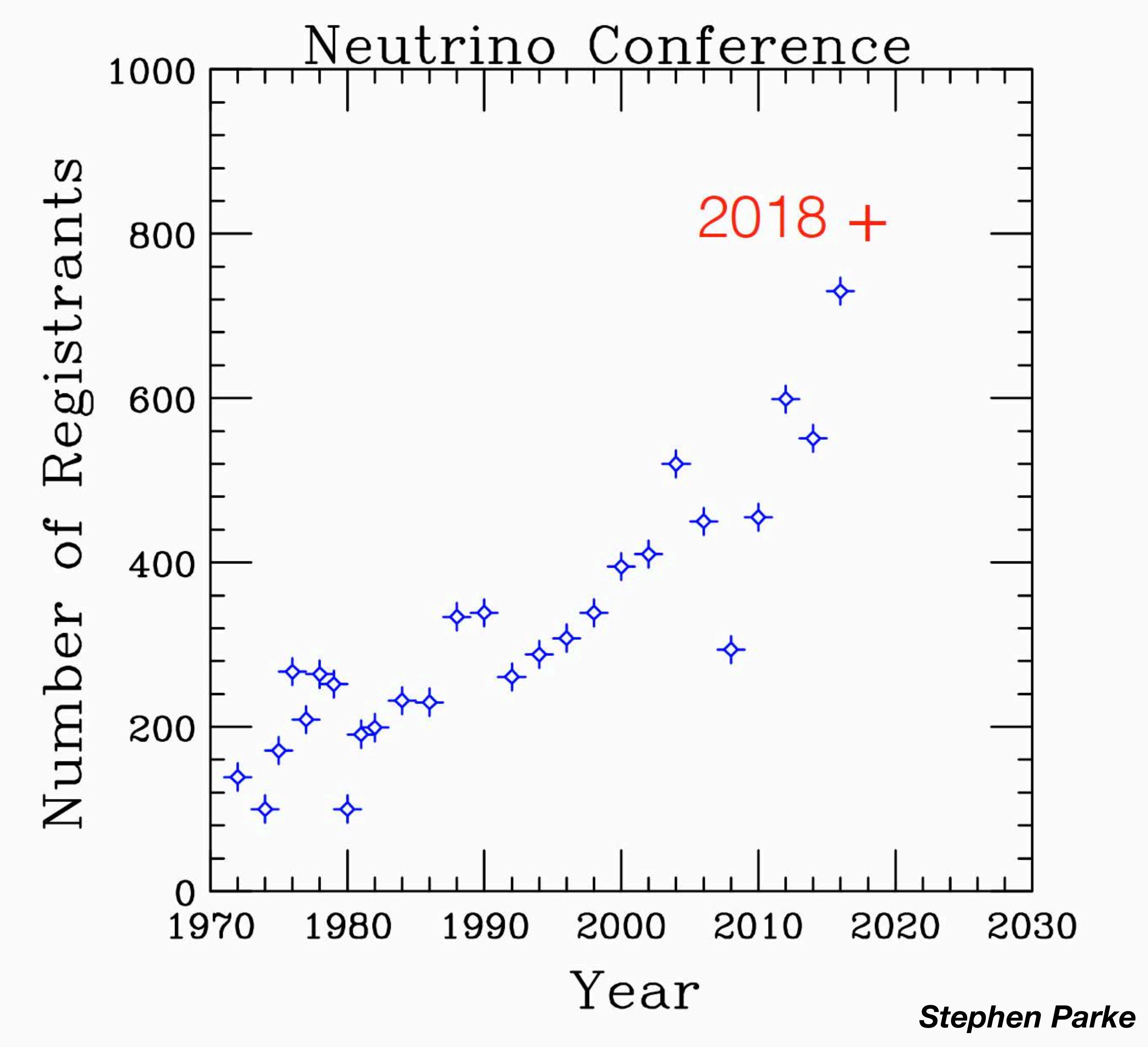


Data based on INSPIRES search "find ti Neutrino and date 2000", eg.


Events/(0.02)
(b)
Data
Fit result
Neutrons
CC
ES
External neutrons
0
20
40
60
80
100
120
-1
-0.8
-0.6
-0.4
-0.2
-0
0.2
0.4
0.6
0.8
1
cos θ☉


φ_{ES}^{SNO}
φ_{CC}^{SNO}
φ_{NC}^{SNO}
φ_{SSM}
φ_{SSM}
0
1
2
3
4
5
6
7
8
0
1
2
3
4
5
6
muon and tau neutrino flux
electron neutrino flux

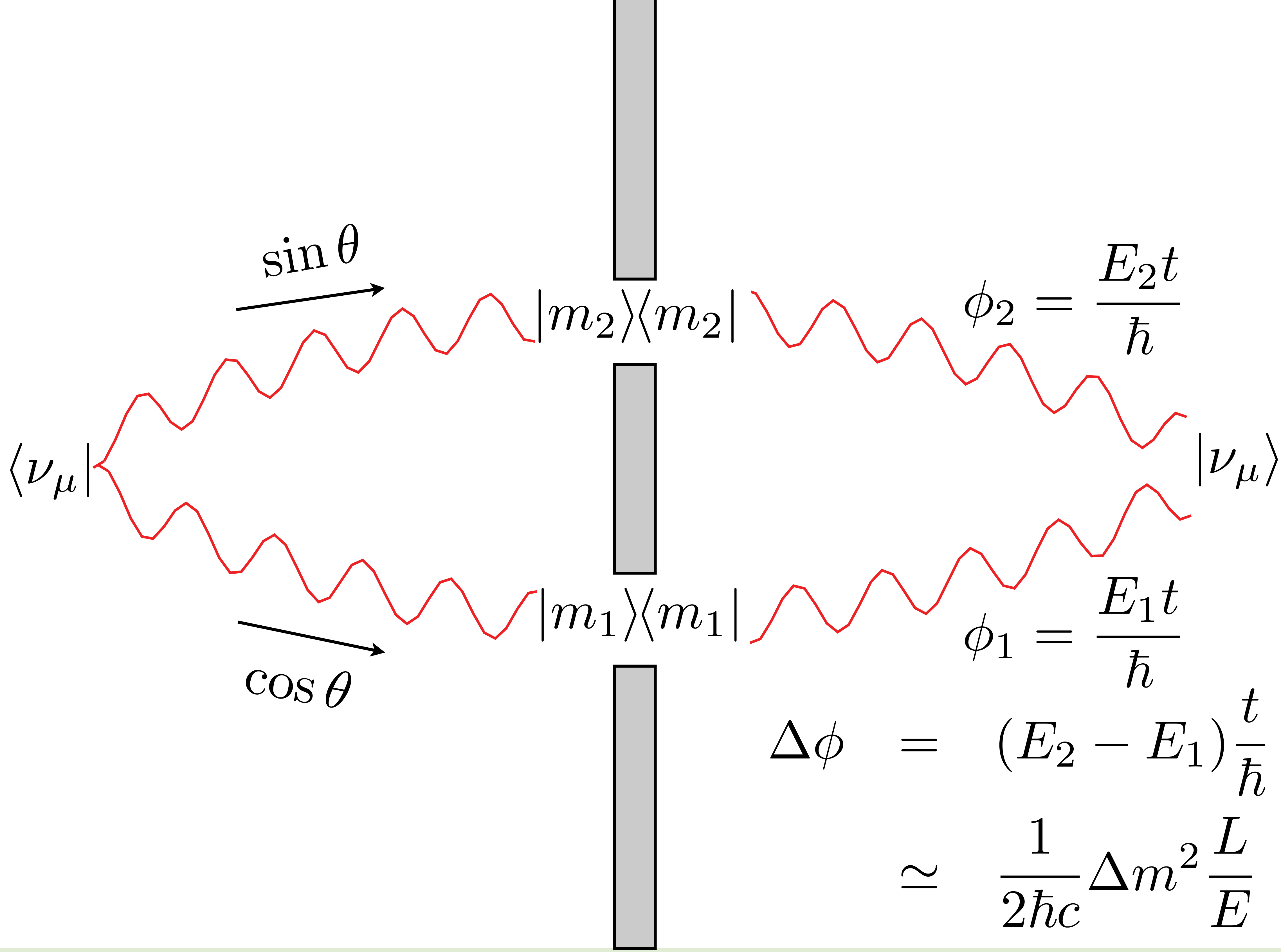
SNO



NEVTRINO 2018

XXVIII INTERNATIONAL CONFERENCE ON NEUTRINO PHYSICS AND ASTROPHYSICS

4–9 June
Heidelberg

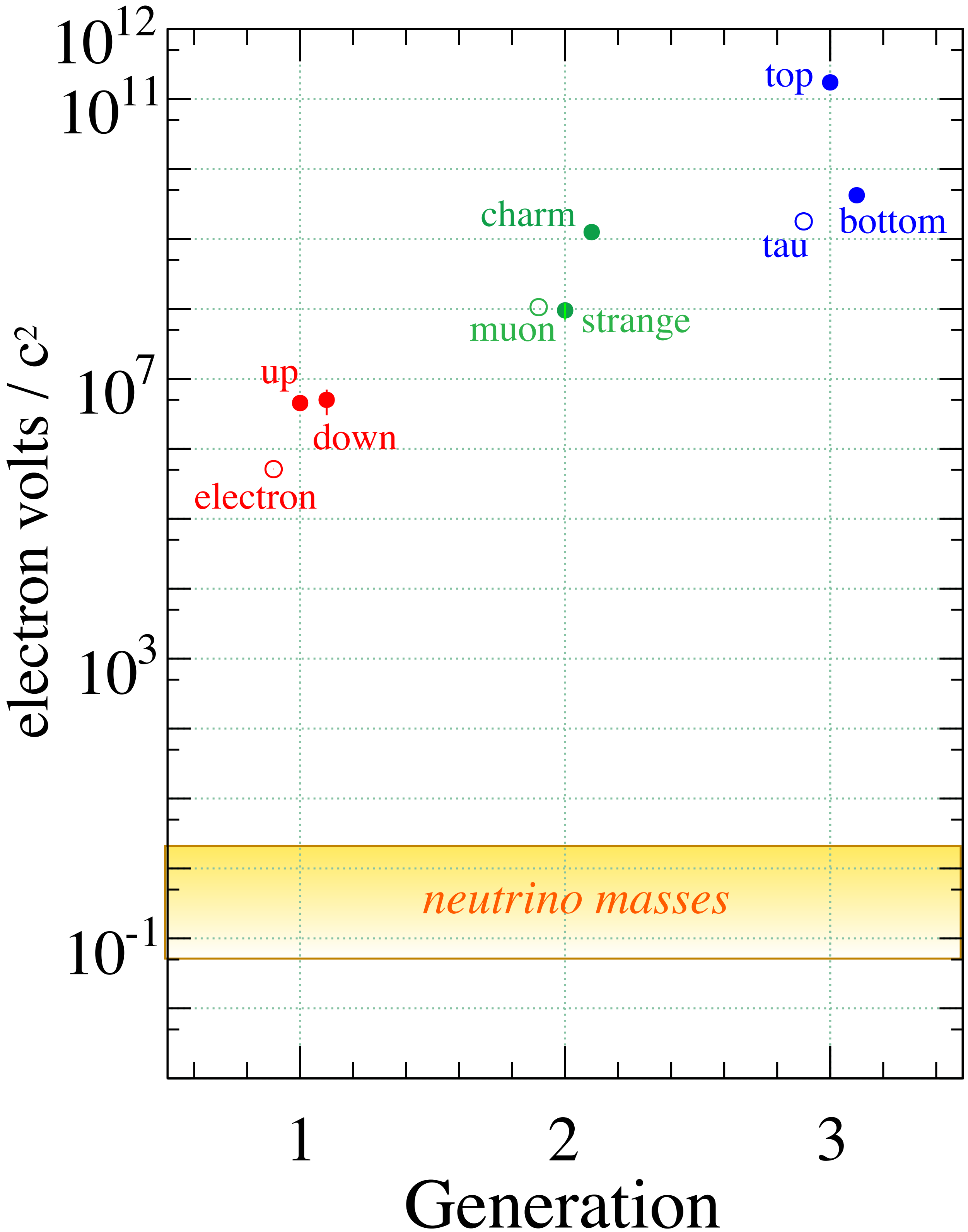


$$\phi_2 = \frac{E_2 t}{\hbar}$$

$$\phi_1 = \frac{E_1 t}{\hbar}$$

$$\begin{aligned} \Delta\phi &= (E_2 - E_1)\frac{t}{\hbar} \\ &\simeq \frac{1}{2\hbar c}\Delta m^2 \frac{L}{E} \end{aligned}$$

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(1.27\Delta m^2[\mathrm{eV}^2]\frac{L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$



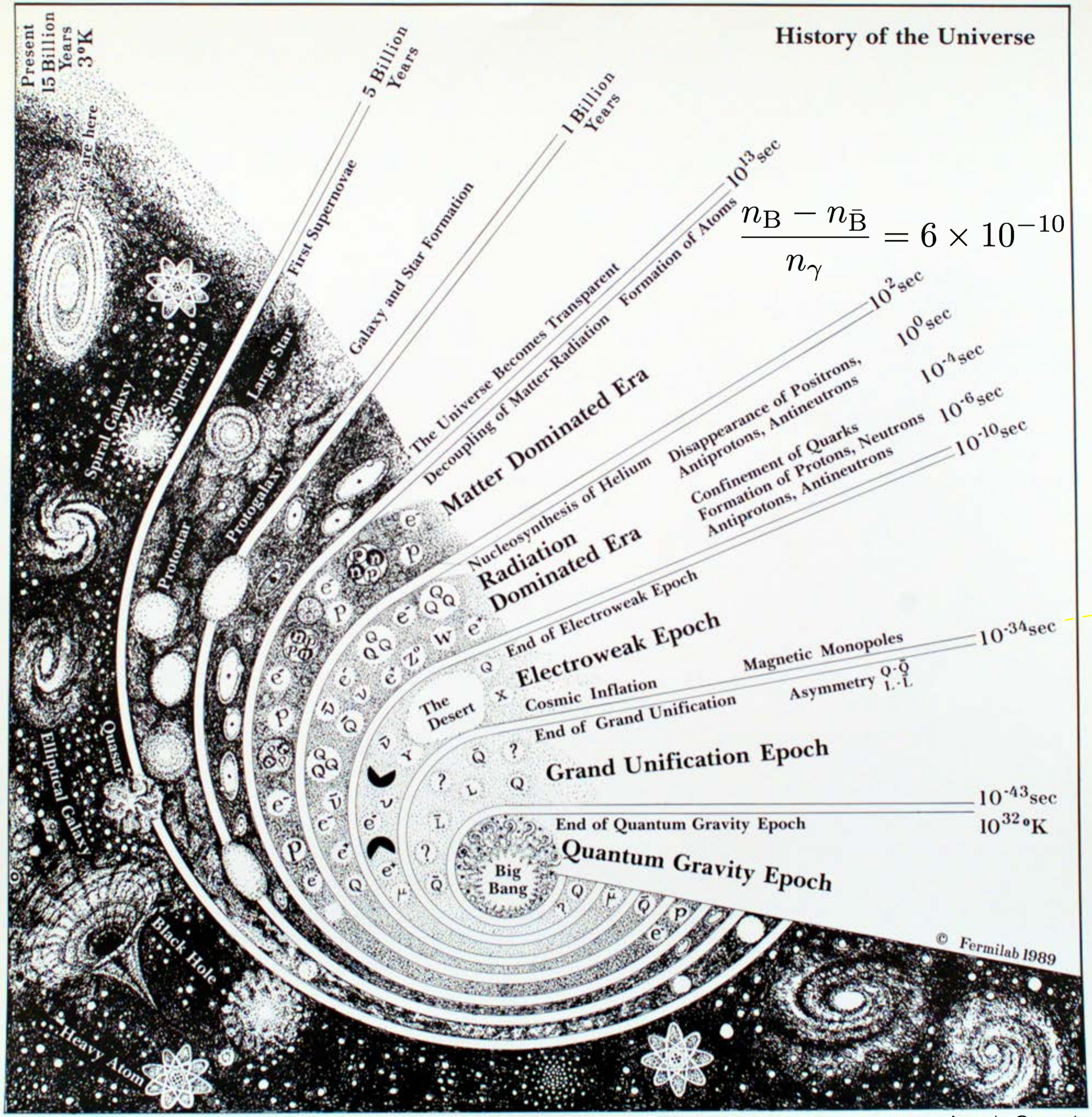
see-saw mechanism

$$\mathcal{L}_{\text{mass}} = \begin{bmatrix} \nu_L & \nu_R \end{bmatrix} \begin{bmatrix} 0 & m \\ m & M \end{bmatrix} \begin{bmatrix} \nu_L \\ \nu_R \end{bmatrix}$$

$$\lambda \simeq \frac{m^2}{M} \simeq \frac{(1\ \text{GeV})^2}{10^{11}\ \text{GeV}} = 0.01\ \text{eV}$$

Neutrino Mass

Neutrino masses and mixing are a window on physics approaching the GUT scale



$$\frac{n_{\mathrm{B}} - n_{\bar{\mathrm{B}}}}{n_\gamma} = 6 \times 10^{-10}$$

$$\frac{q - \bar{q}}{q + \bar{q}} \simeq 10^{-10}$$

$$\frac{q - \bar{q}}{q + \bar{q}} \simeq 0$$

Angela Gonzalez

Neutrino oscillations

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

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

Measurements

- θ_{12}
- θ_{13}
- θ_{23}
- δ_{CP}
- $\Delta m^2{}_{21}$
- $\Delta m^2{}_{31}$
- Mass ordering
- Dirac/Majorana

Neutrino mass textures

$$U_{e3} = \sqrt{\frac{\Delta m^2_{12}}{\Delta m^2_{13}}}$$

$$\frac{\sqrt{\Delta m^2_{31}}}{2}\begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{bmatrix}$$

normal mass ordering

$$\sqrt{\Delta m^2_{31}}\begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{1}{2} & \frac{1}{2} \end{bmatrix} \qquad \sqrt{\Delta m^2_{31}}\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

$$U_{e3} = \frac{\Delta m^2_{12}}{\Delta m^2_{13}}$$

inverted mass ordering

$$\sqrt{\frac{\Delta m^2_{31}}{2}}\begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

follows hep-ph/0510213

Extrapolate to GUT scale

$$|Y_{\rm B}| \simeq 2.4 \times 10^{-11} |\sin\delta| \left(\frac{\sin\theta_{13}}{0.15}\right)\left(\frac{M_1}{10^{11}\ \mathrm{GeV}}\right)$$

for example Pascoli, Petcov & Riotto PRD2007

Neutrino Oscillations at Reactors

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

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

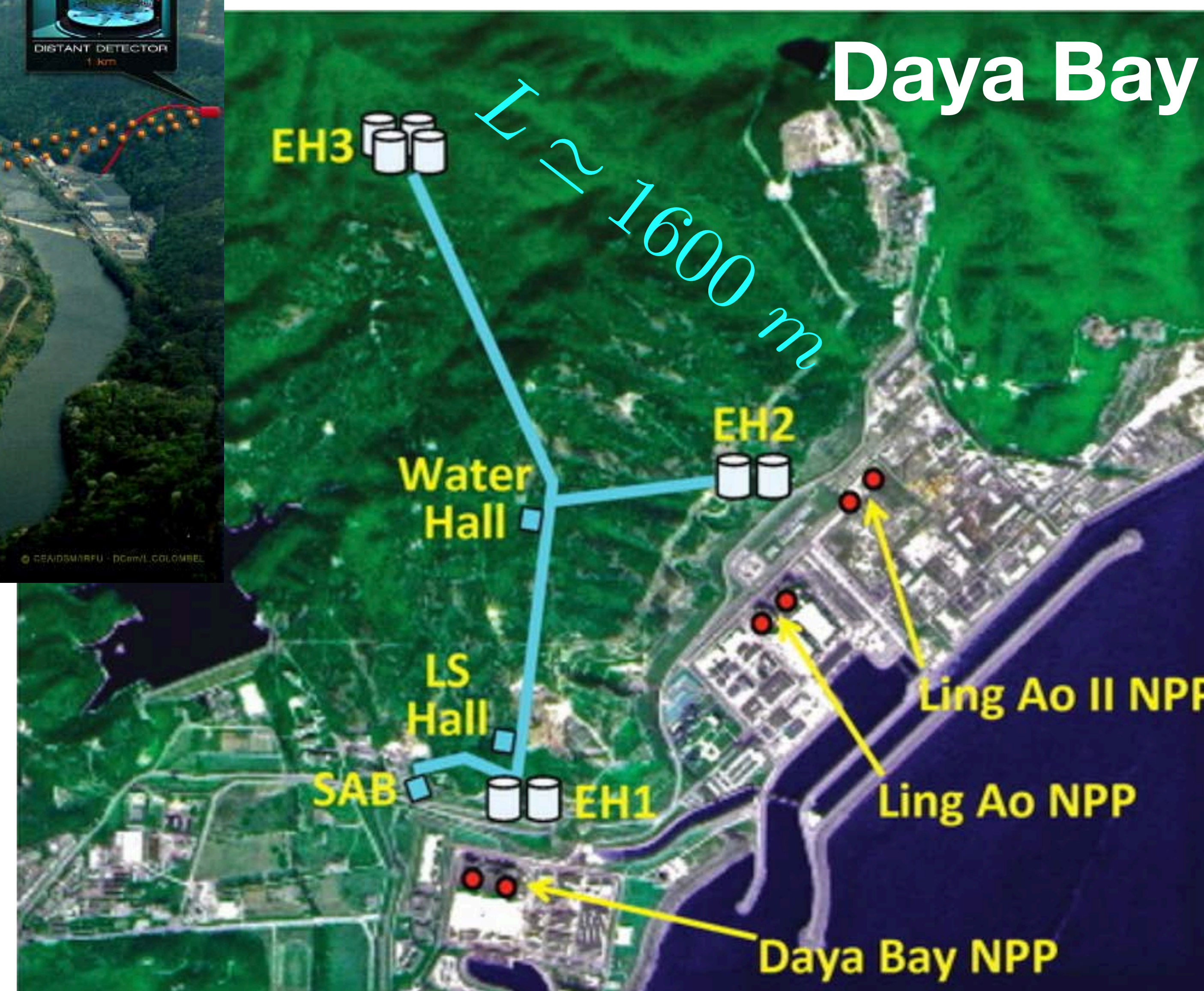
$\lvert\Delta m^2_{32}\rvert \equiv \lvert m^2_3 - m^2_2\rvert \simeq 2\times 10^{-3}\ \mathrm{eV}^2$	$\Delta m^2_{31} \simeq \Delta m^2_{32}$	$\Delta m^2_{21} \simeq 8\times 10^{-5}\ \mathrm{eV}^2$
$\nu_\mu \longrightarrow \nu_\mu$ $\nu_\mu \longrightarrow \nu_\tau$	$\nu_e \longrightarrow \nu_e$ $\nu_\mu \longrightarrow \nu_e$	$\nu_e \longrightarrow \nu_e$ $\nu_e \longrightarrow \nu_\mu + \nu_\tau$
atmospheric and long baseline	reactor and long baseline	solar and reactor

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

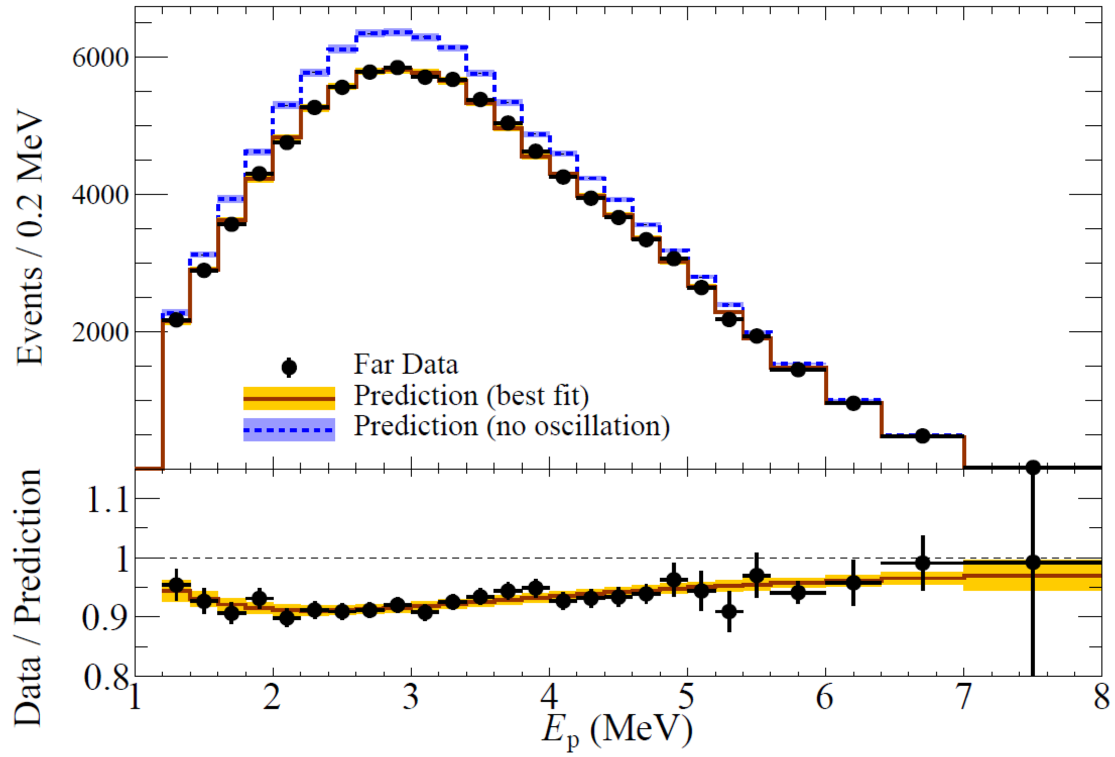
$$\Delta = \frac{1.27 \cdot 0.0025 \text{ eV}^2 \cdot 1600 \text{ m}}{4 \text{ MeV}} \simeq \frac{\pi}{2}$$

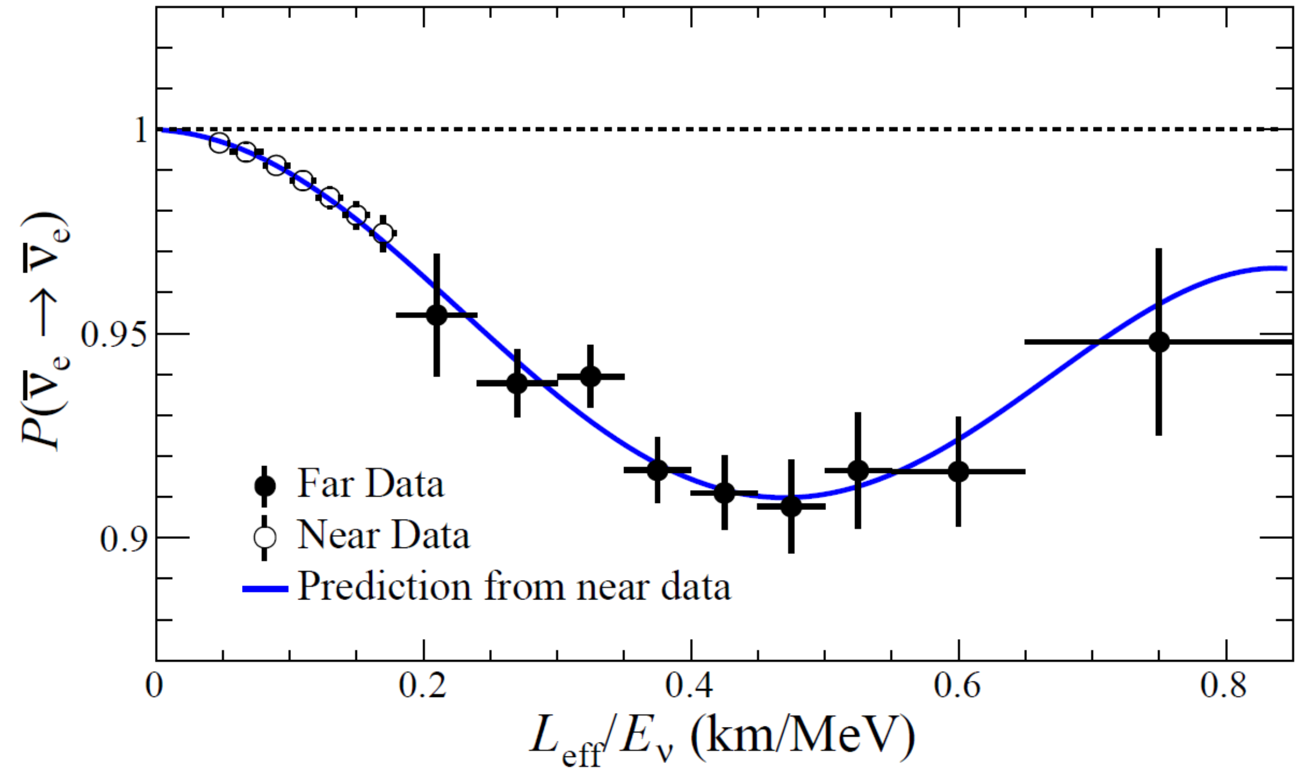
$\bar{\nu}_e \to \bar{\nu}_e$ at atmospheric mass scale

$E \simeq 4$ MeV

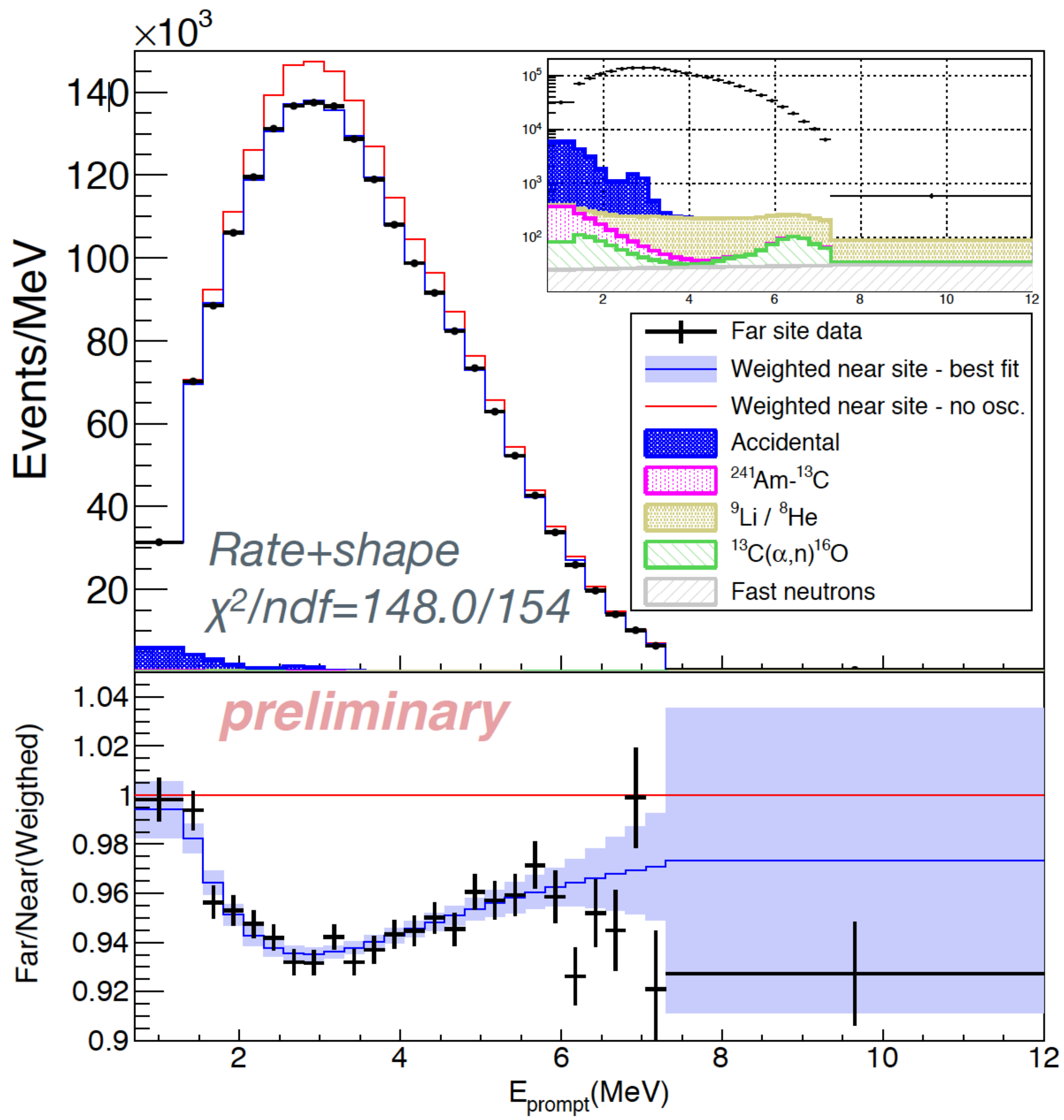


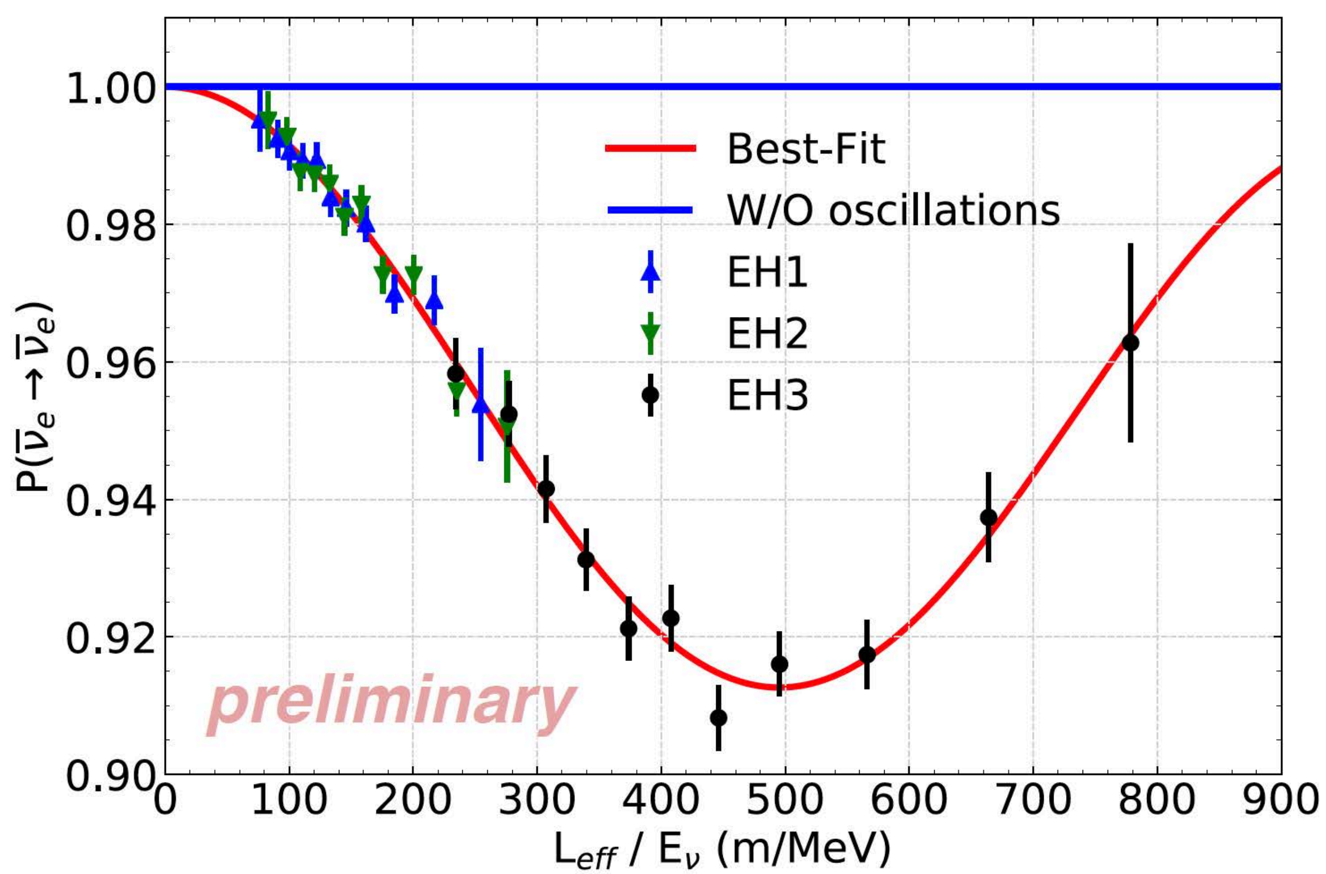
RENO





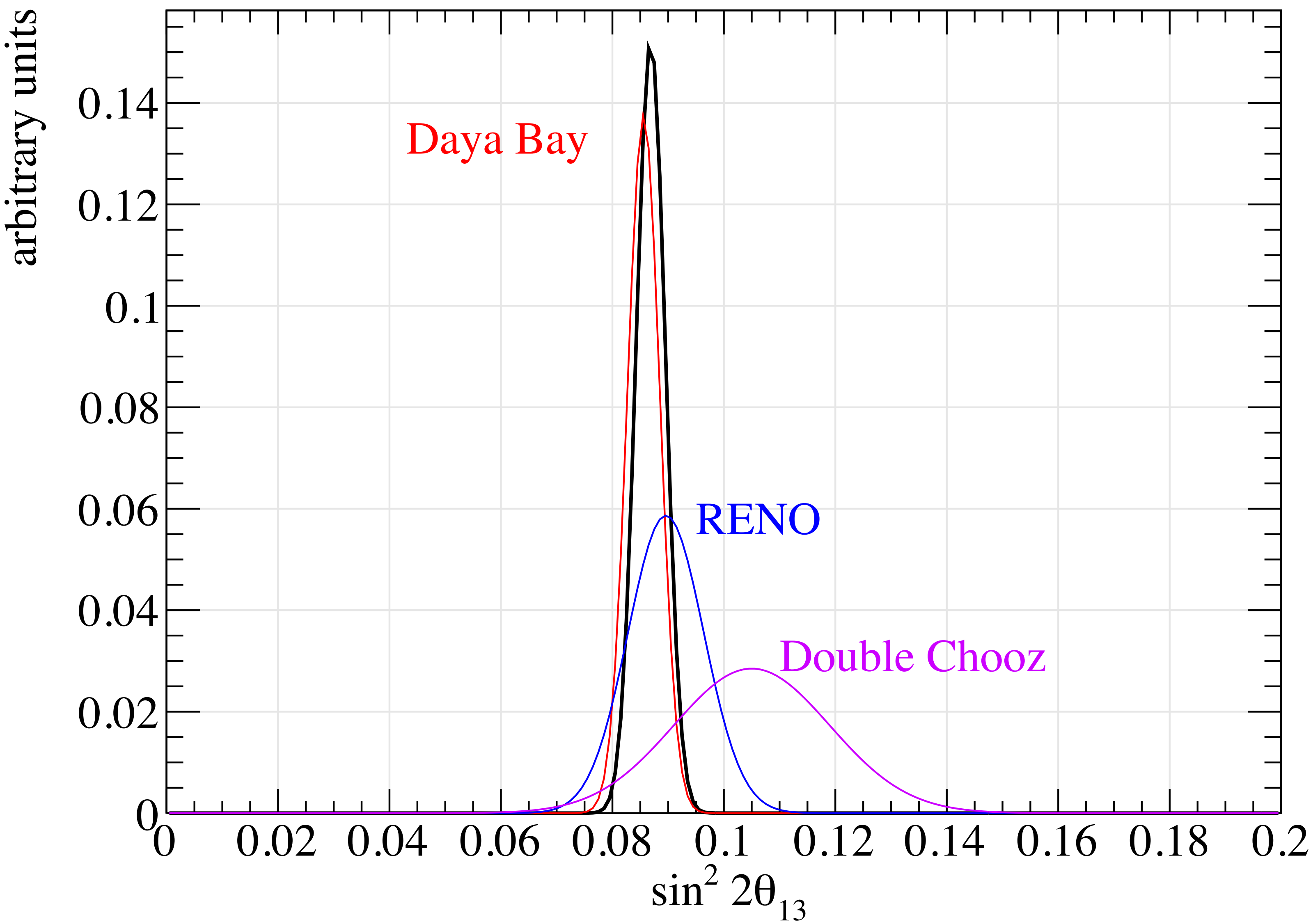
Daya Bay



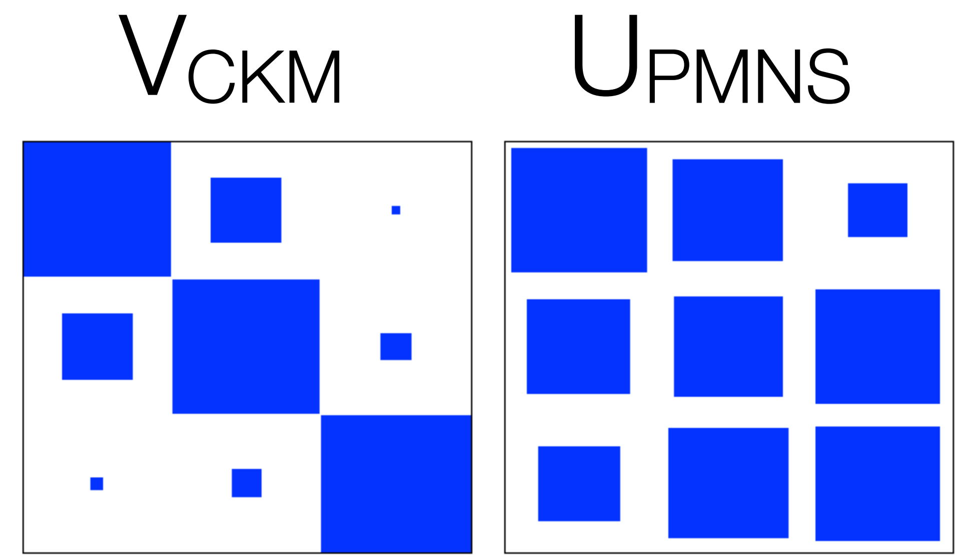


$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{1.267\Delta m^2 L}{E} - P_{\text{solar}}$$

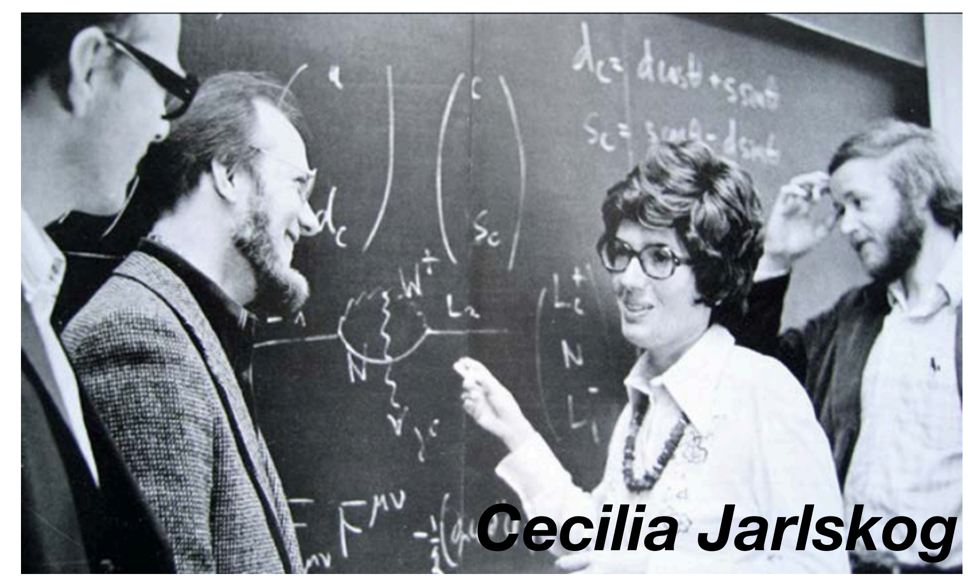
$$\sin^2 2\theta_{13} = 0.0869 \pm 0.0026$$



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



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

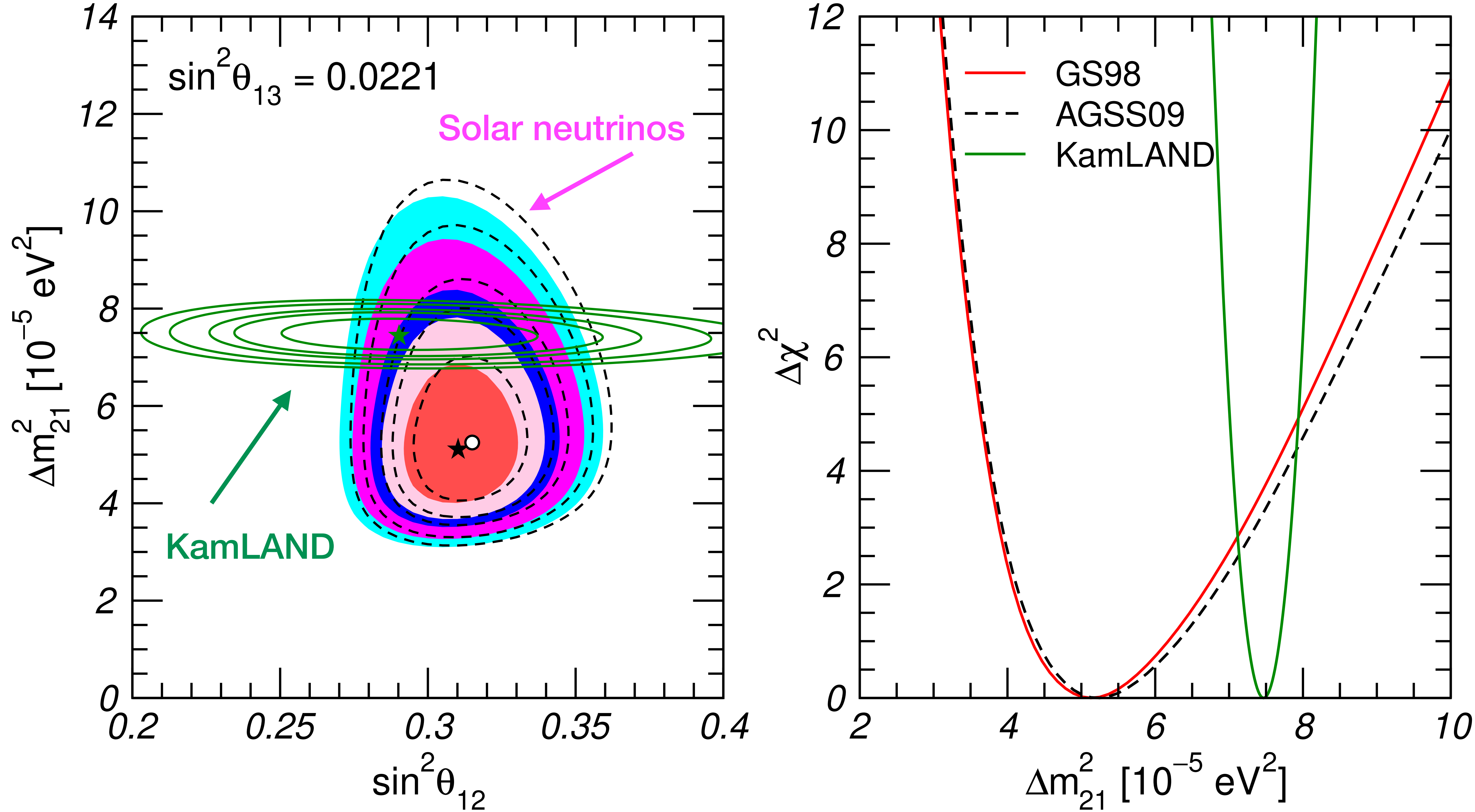


CP violation in leptons

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

JHEP 01 (2017) 087 [arXiv:1611.01514]

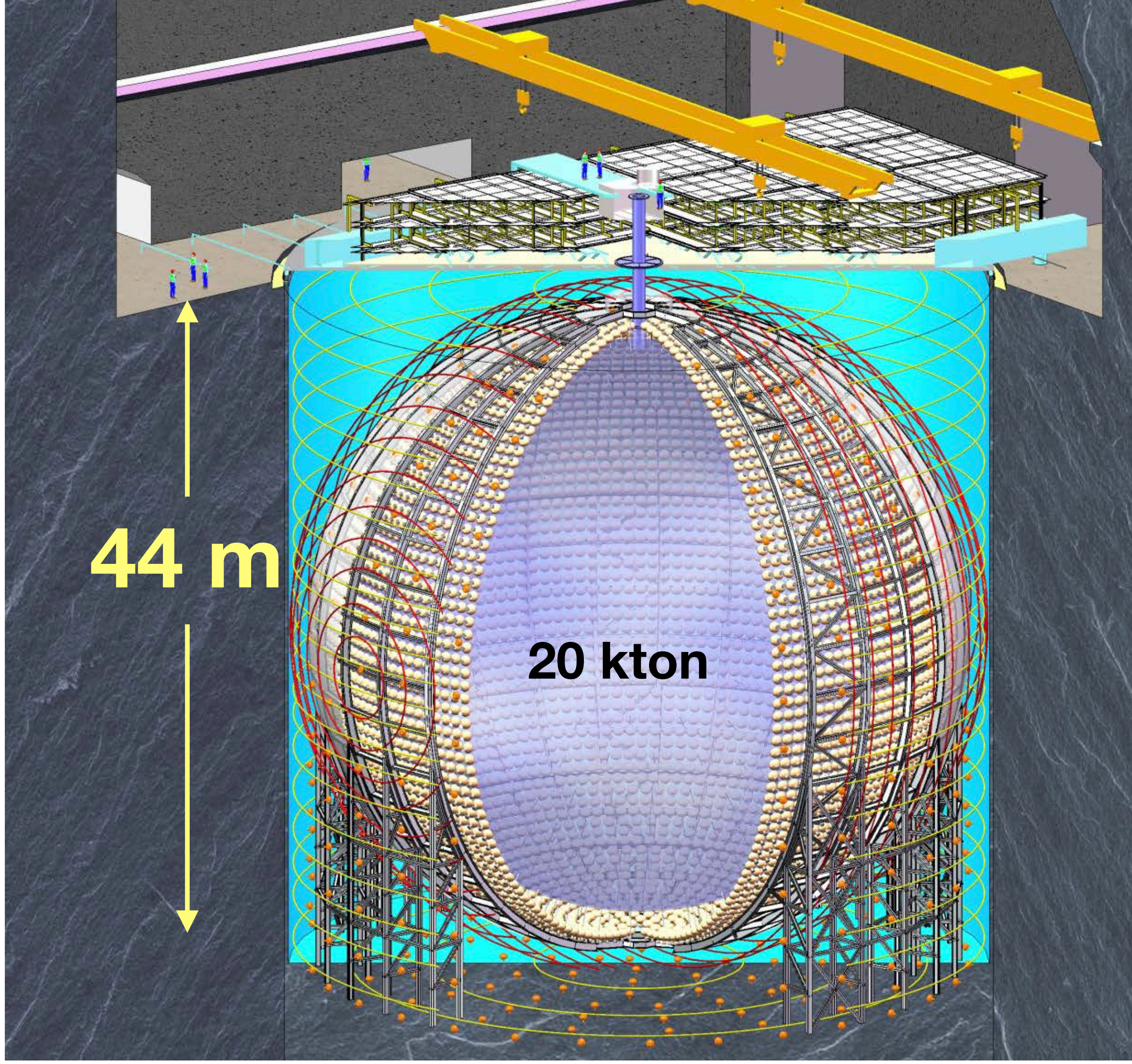
NuFIT 3.2 (2018)



Solar Neutrinos and KamLAND

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}

Neutrino Oscillations at Accelerators

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

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

$|\Delta m^2_{32}| \equiv |m^2_3 - m^2_2|$
$\simeq 2 \times 10^{-3}\ \mathrm{eV}^2$

$\nu_\mu \longrightarrow \nu_\mu$
$\nu_\mu \longrightarrow \nu_\tau$

atmospheric and
long baseline

$\Delta m^2_{31} \simeq \Delta m^2_{32}$

$\nu_e \longrightarrow \nu_e$
$\nu_\mu \longrightarrow \nu_e$

reactor and
long baseline

$\Delta m^2_{21} \simeq 8 \times 10^{-5}\ \mathrm{eV}^2$

$\nu_e \longrightarrow \nu_e$
$\nu_e \longrightarrow \nu_\mu + \nu_\tau$

solar and
reactor

T2K

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

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

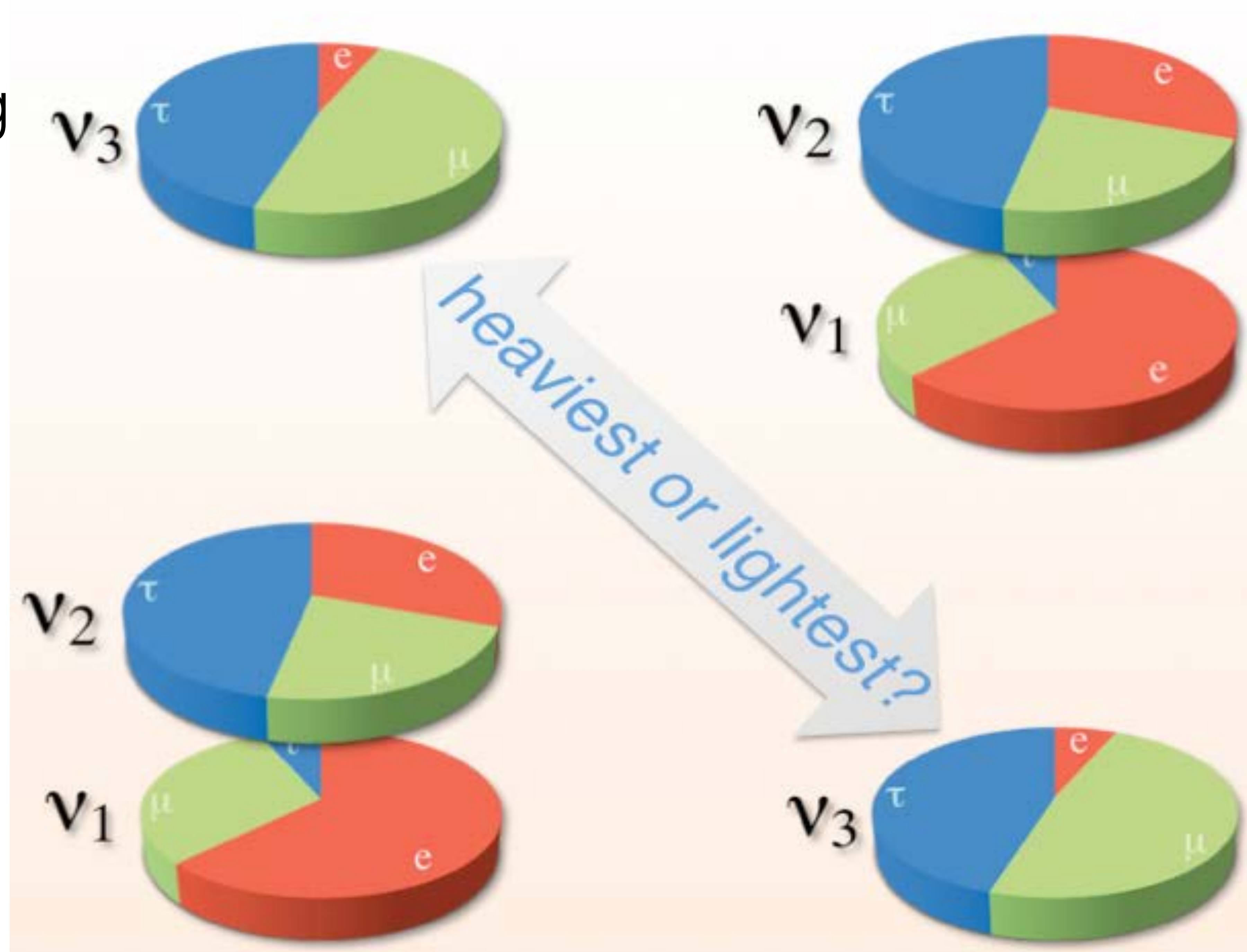
NOvA

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

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

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]

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

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

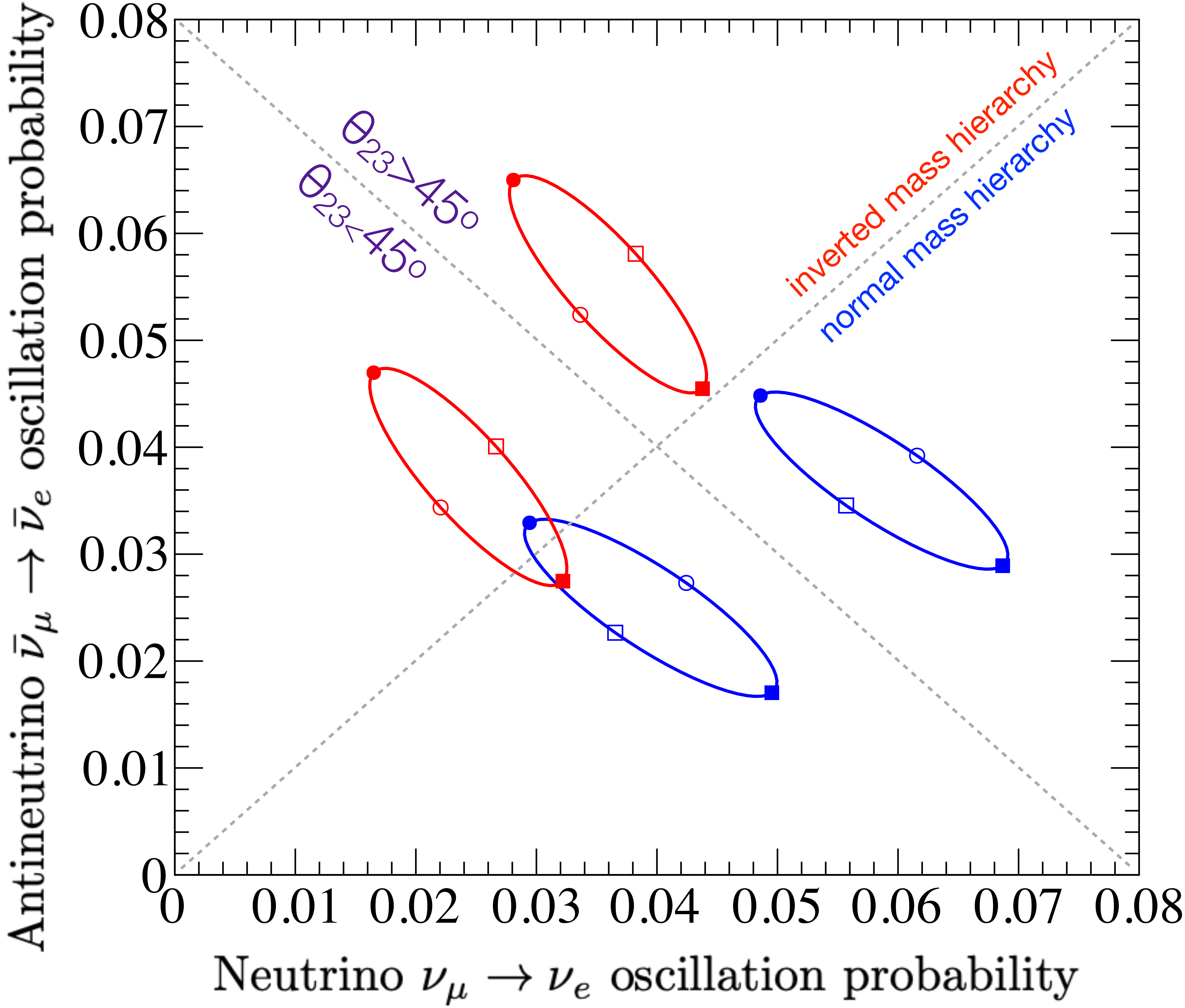
$$\sqrt{P_{\rm atm}} = \sin\theta_{23}\sin 2\theta_{13}\frac{\sin(\Delta_{31}\mp aL)}{\Delta_{31}\mp aL}\Delta_{31}$$

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

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

$aL = 0.08$ 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?



θ23>45o
θ23<45o
inverted mass hierarchy
normal mass hierarchy
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
Antineutrino $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probability
Neutrino $\nu_\mu \rightarrow \nu_e$ oscillation probability

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

Factor	Type	Inverts for $\overline{\nu}$?	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]%

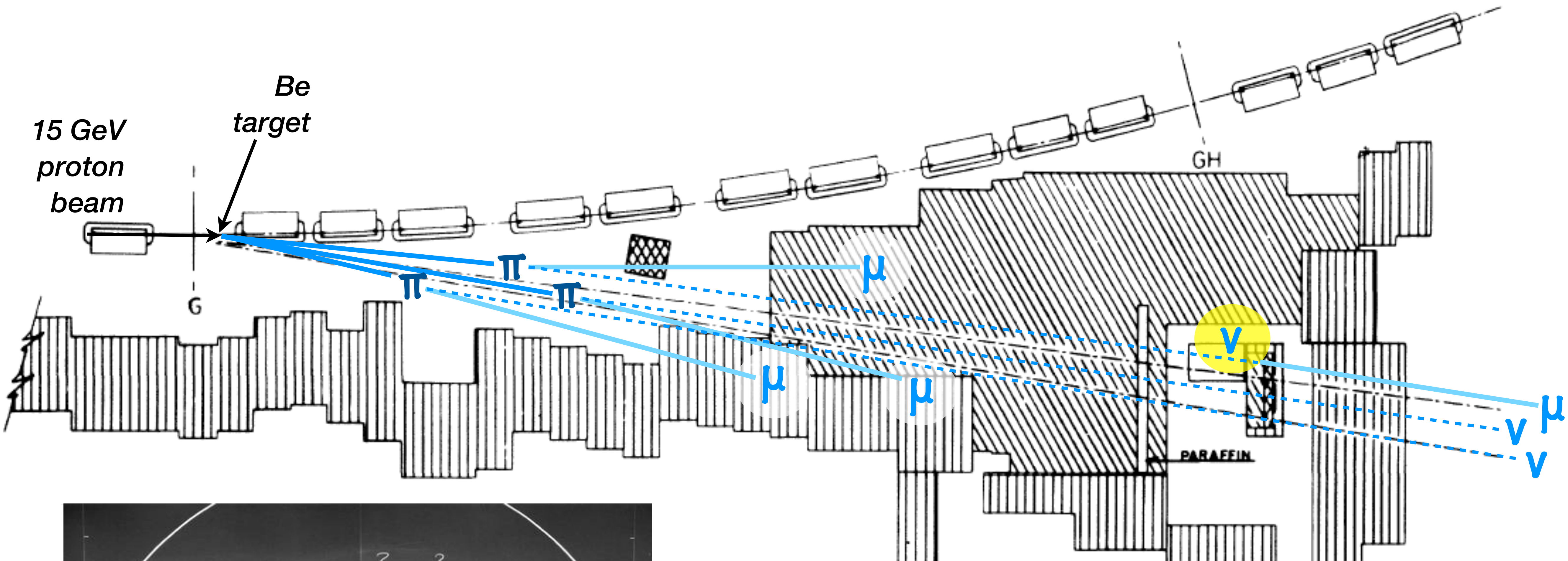
Nota bene:

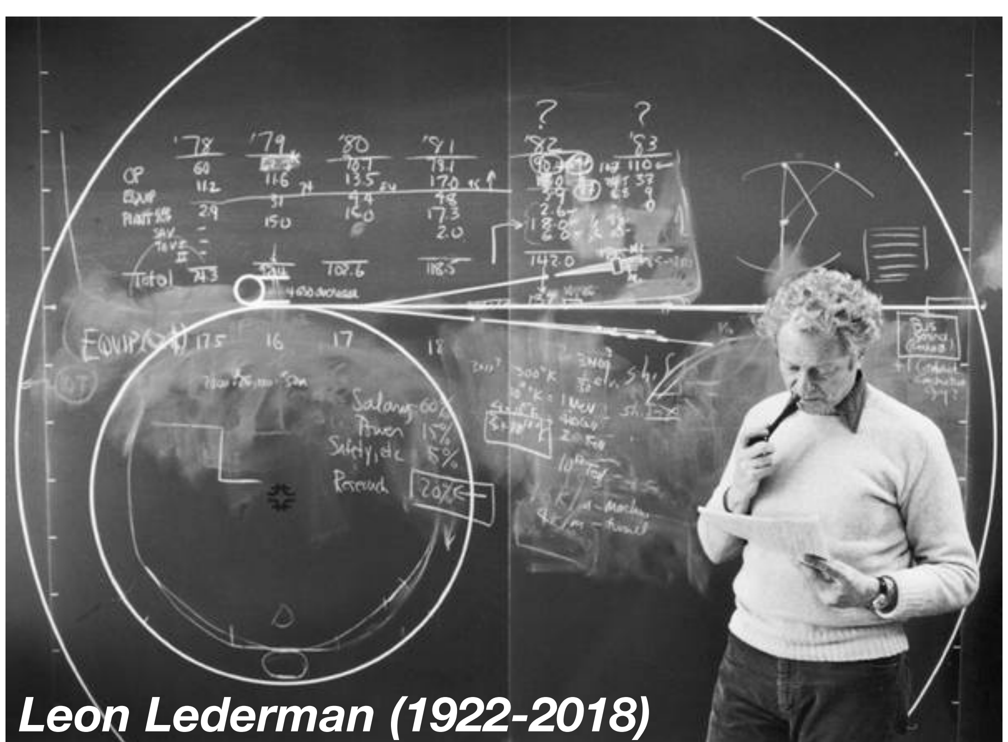
- Calculations are for rate only; there is some additional information in the energy spectrum
- These estimates neglect non-linearities in combining different effects
- In the calculation of the matter effect and CP violation effects the calculated values account for the fact that T2K runs at an energy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

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

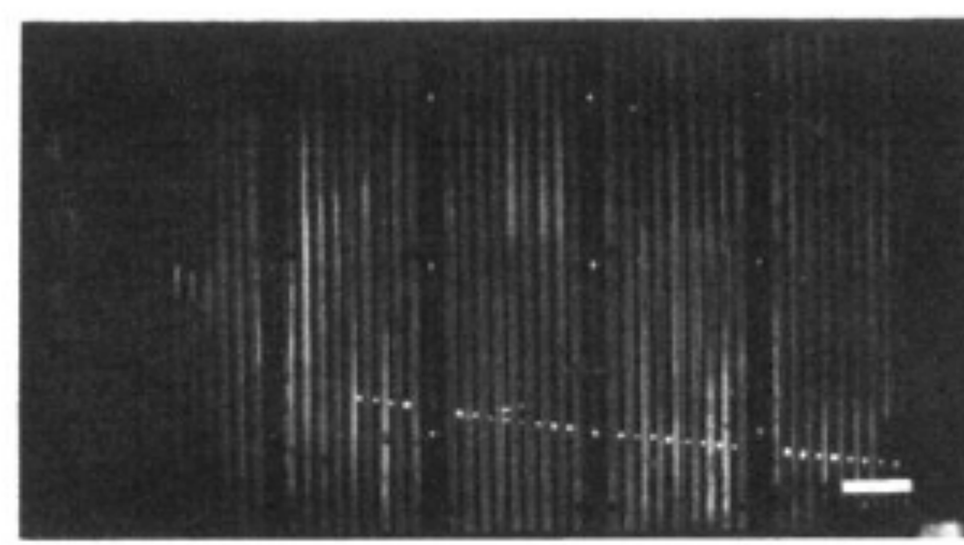
G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York
(Received June 15, 1962)

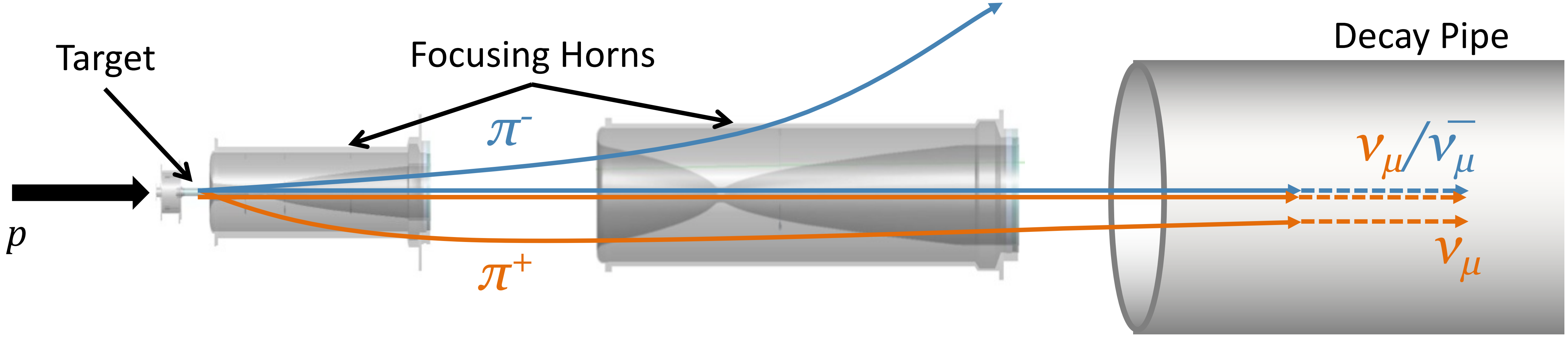




Leon Lederman (1922-2018)



A



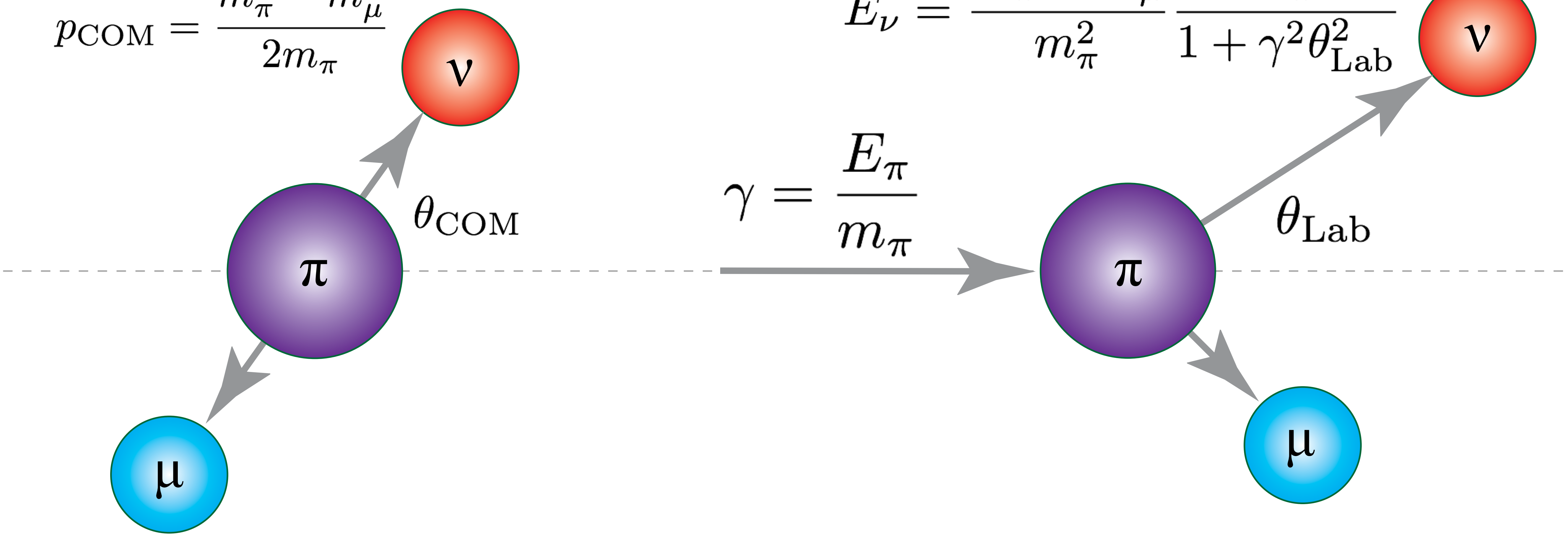
Center of mass frame

$$p_{\text{COM}} = \frac{m_\pi^2 - m_\mu^2}{2m_\pi}$$

Boosted frame

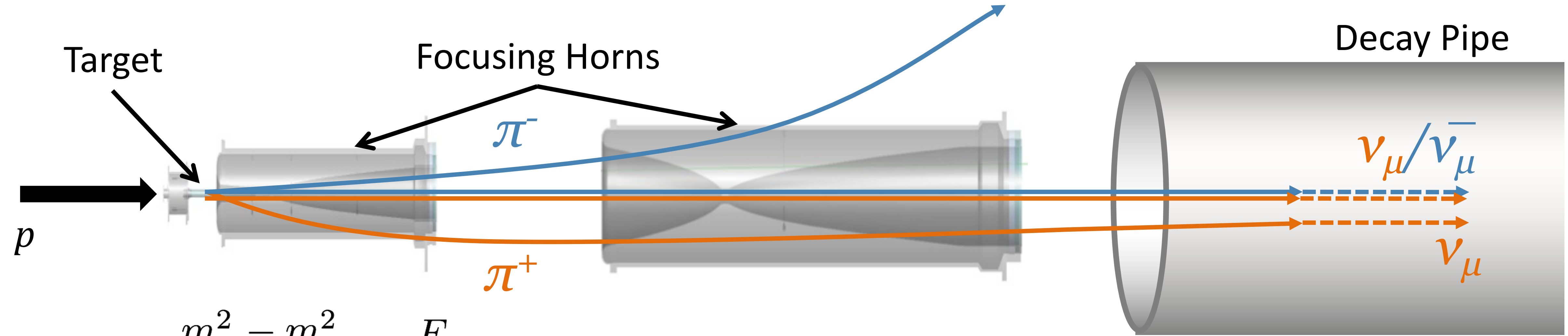
$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{m_\pi^2} \frac{E_\pi}{1 + \gamma^2 \theta_{\text{Lab}}^2}$$

$$\gamma = \frac{E_\pi}{m_\pi}$$

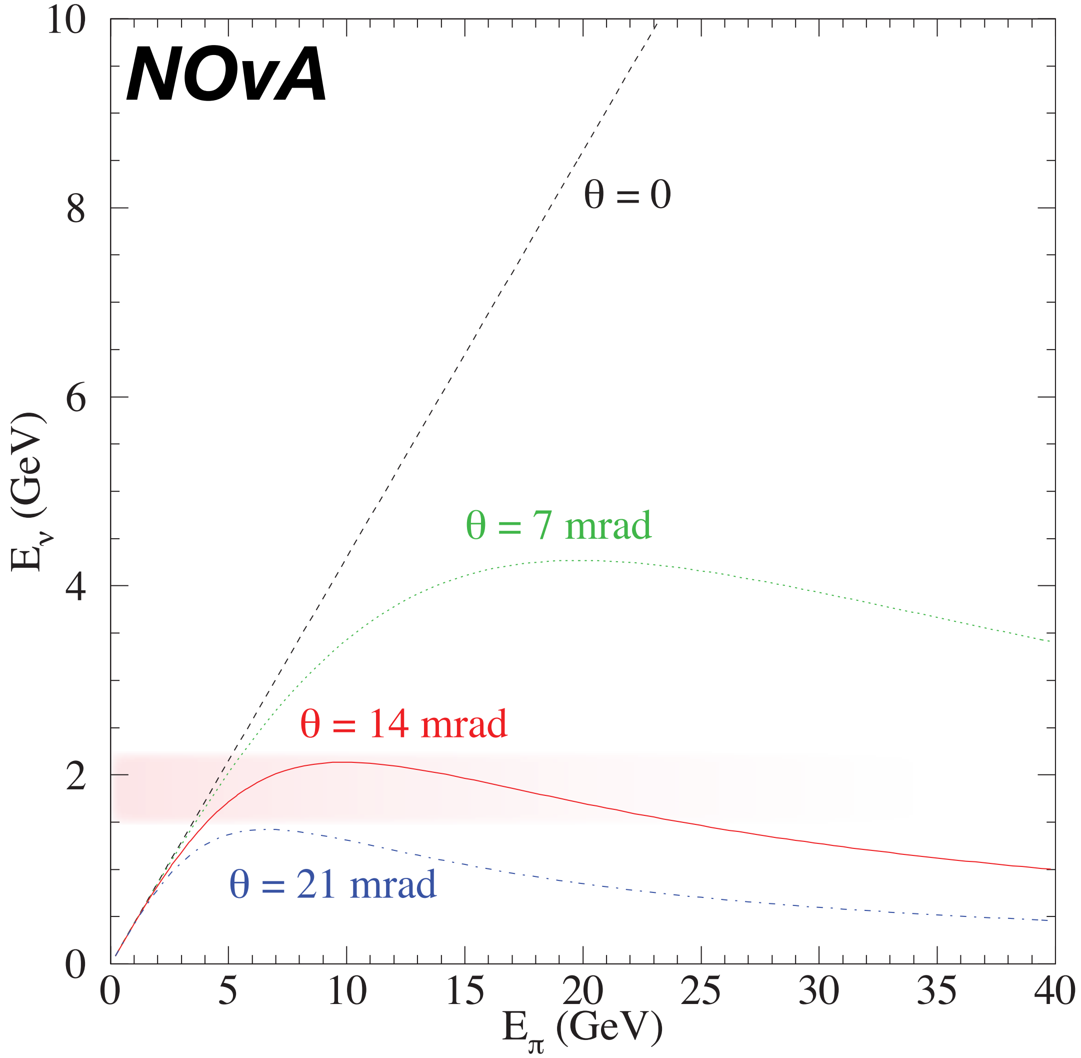


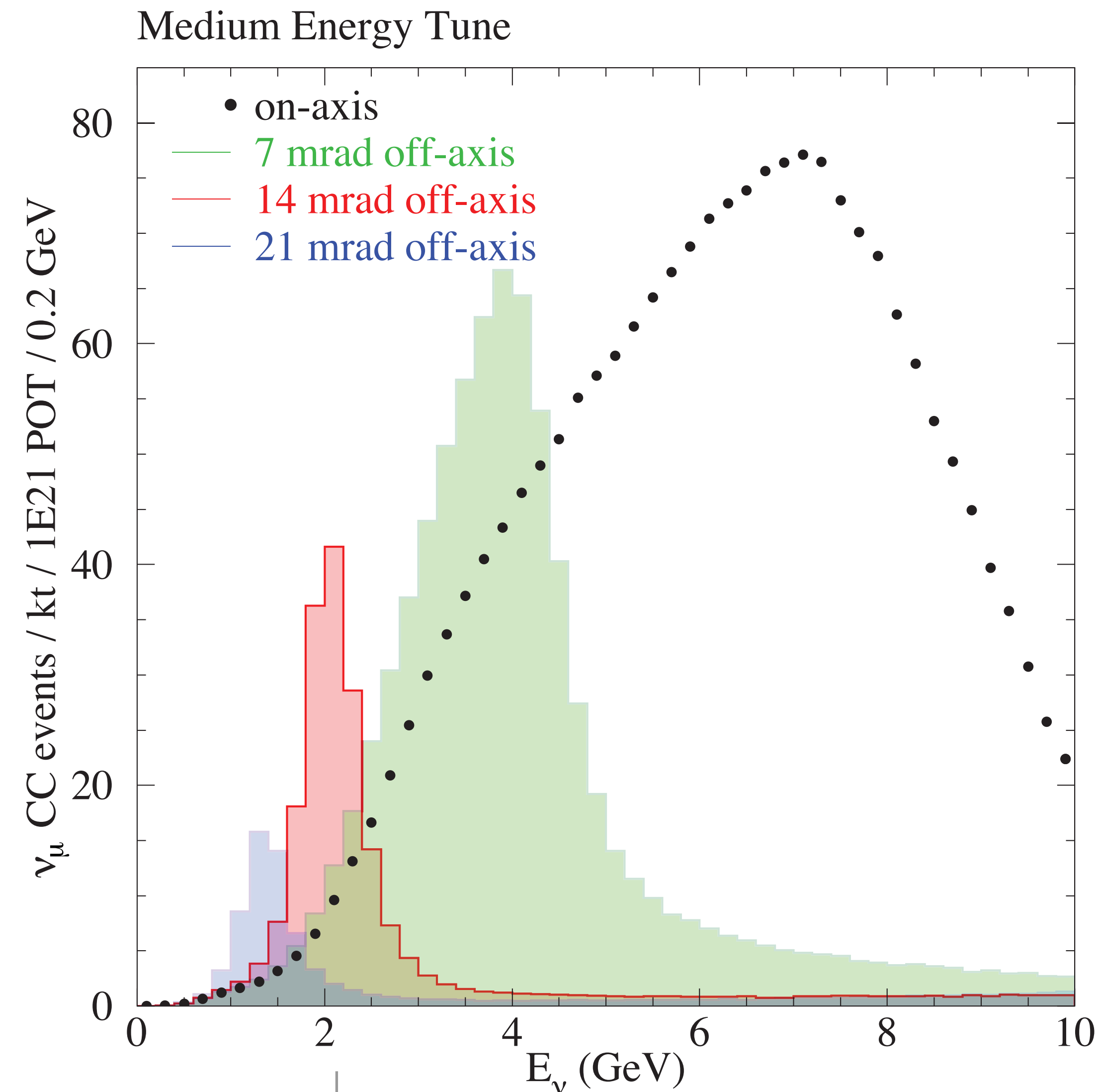
Making a neutrino beam

Angle is energy



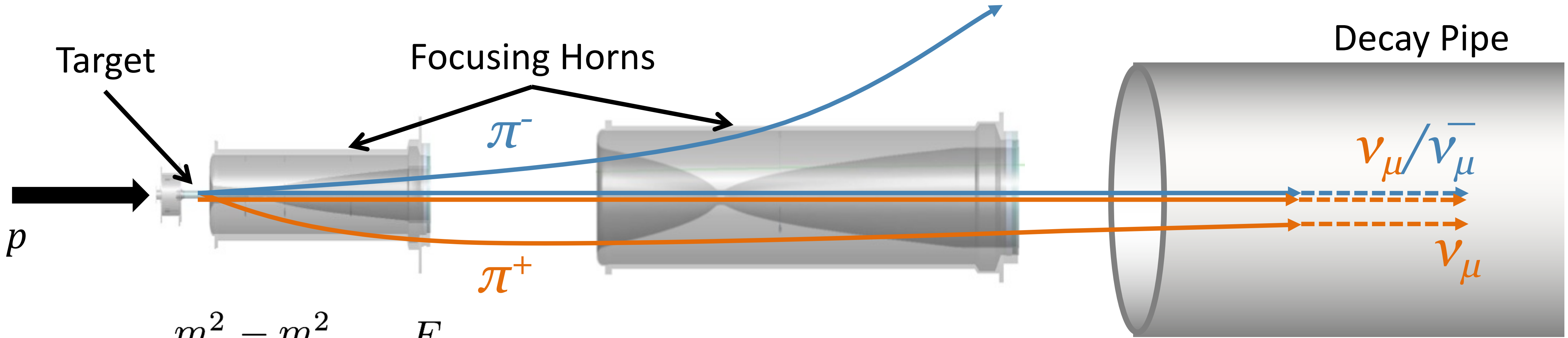
$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{m_\pi^2}\,\frac{E_\pi}{1+\gamma^2\theta_{\mathrm{Lab}}^2}$$



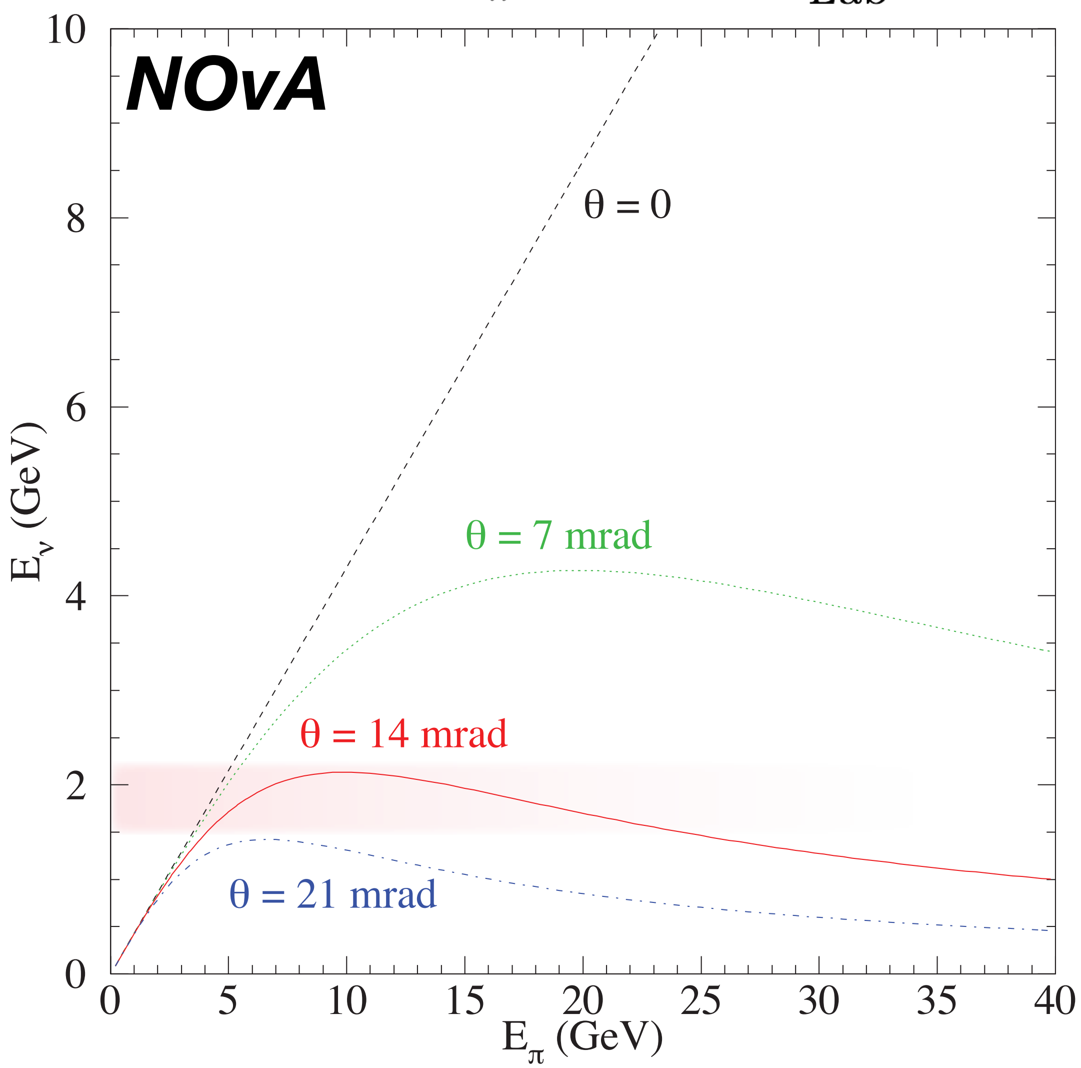


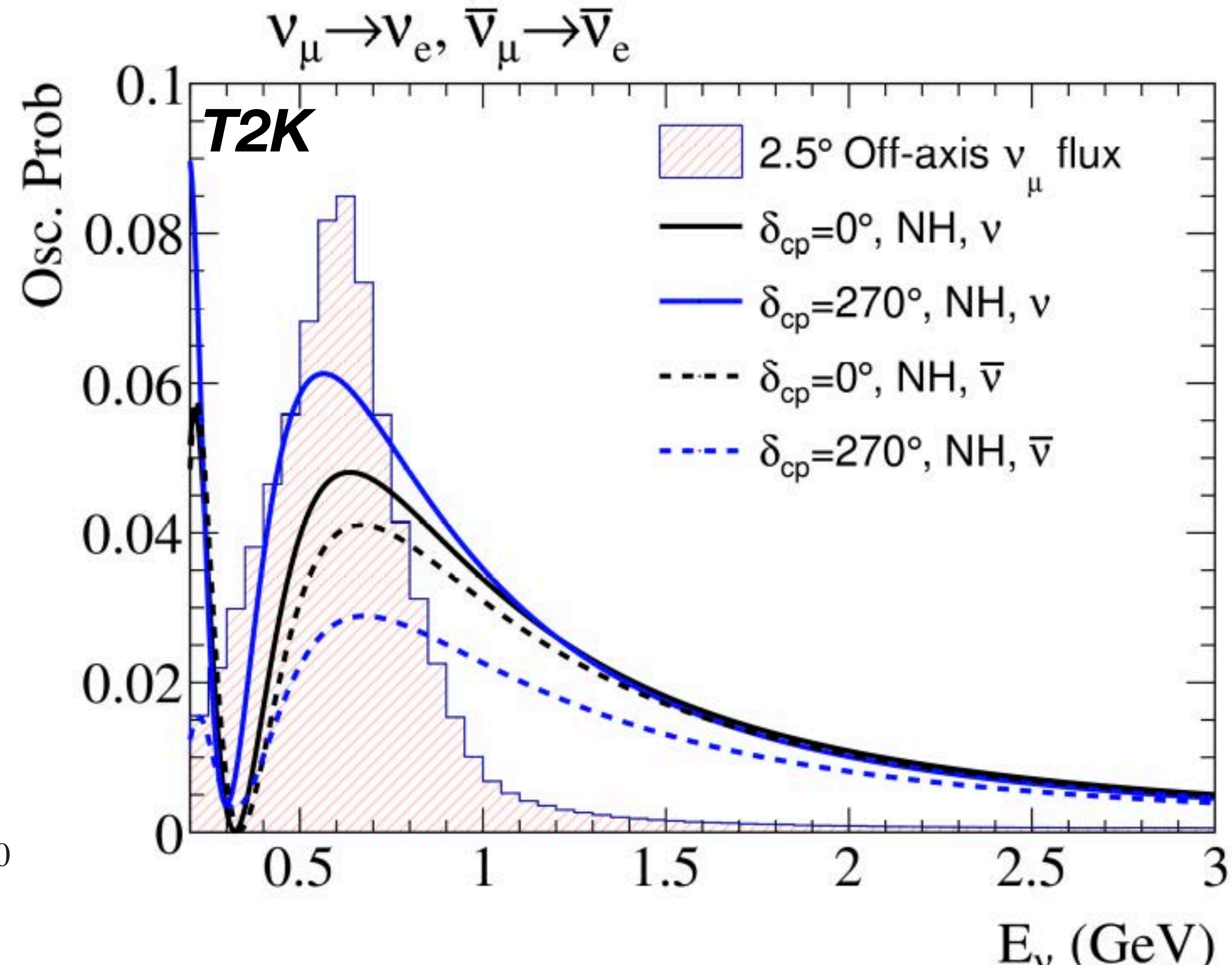
Making a neutrino beam

Angle is energy



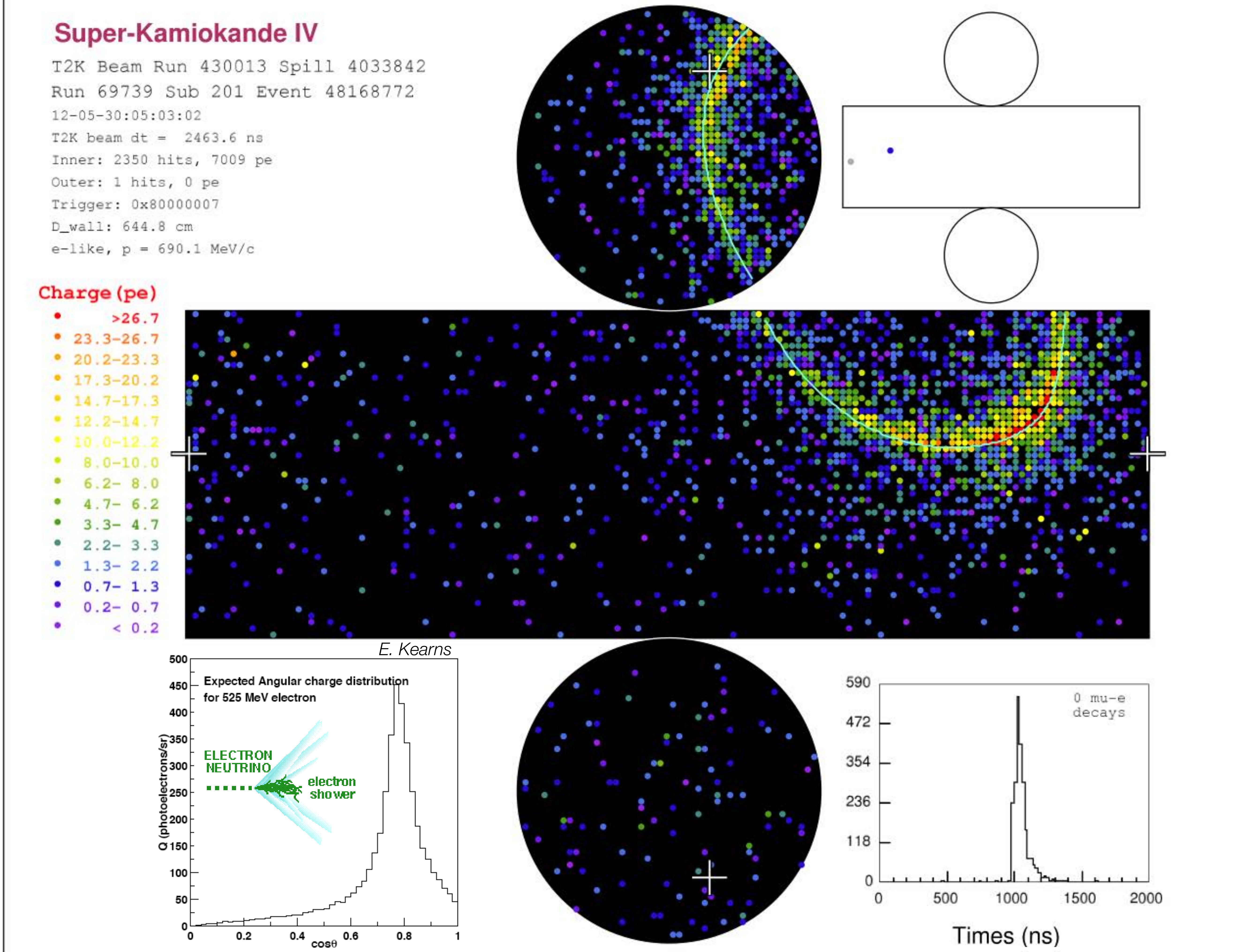
$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{m_\pi^2} \frac{E_\pi}{1 + \gamma^2\theta_{\text{Lab}}^2}$$



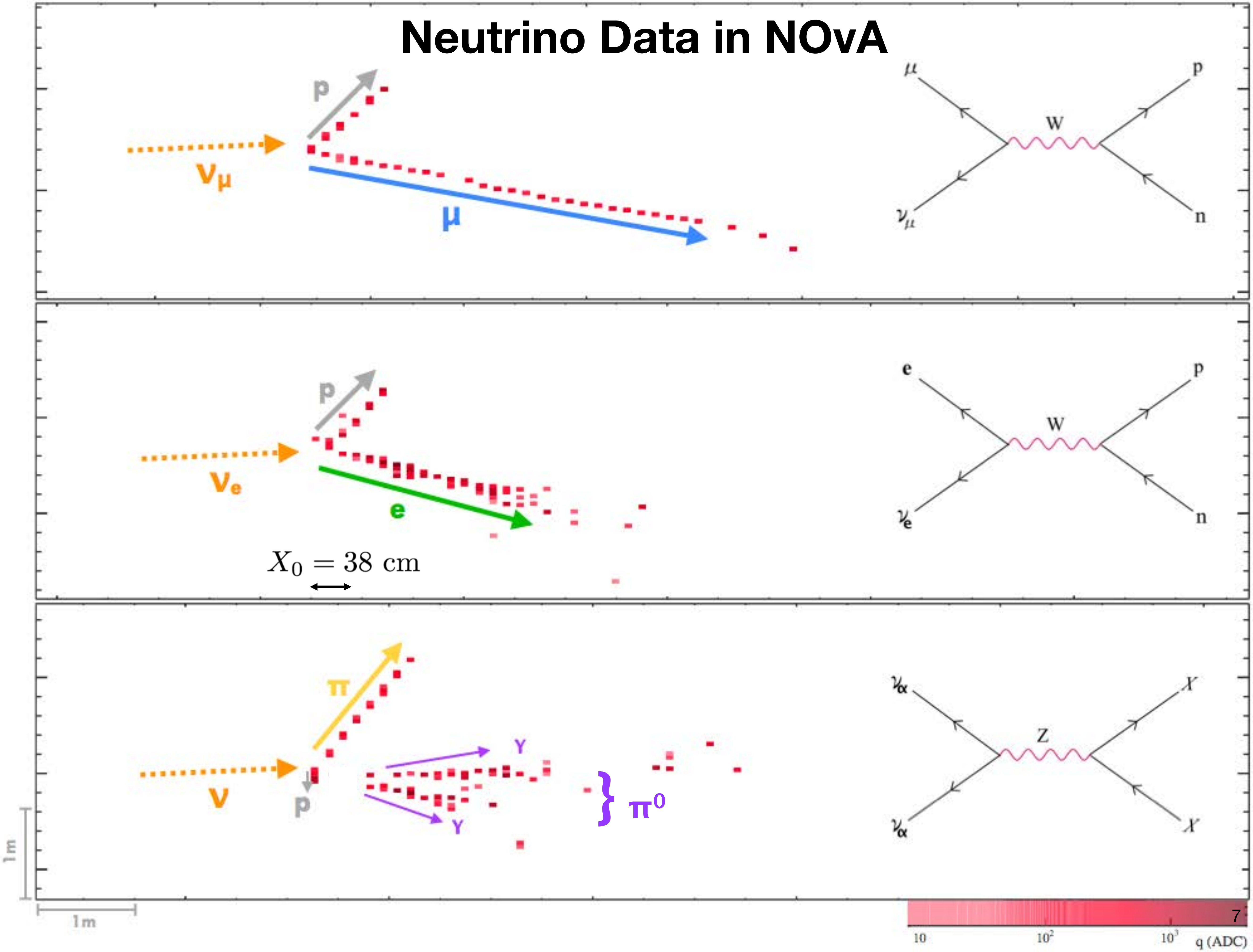


Making a neutrino beam

Angle is energy

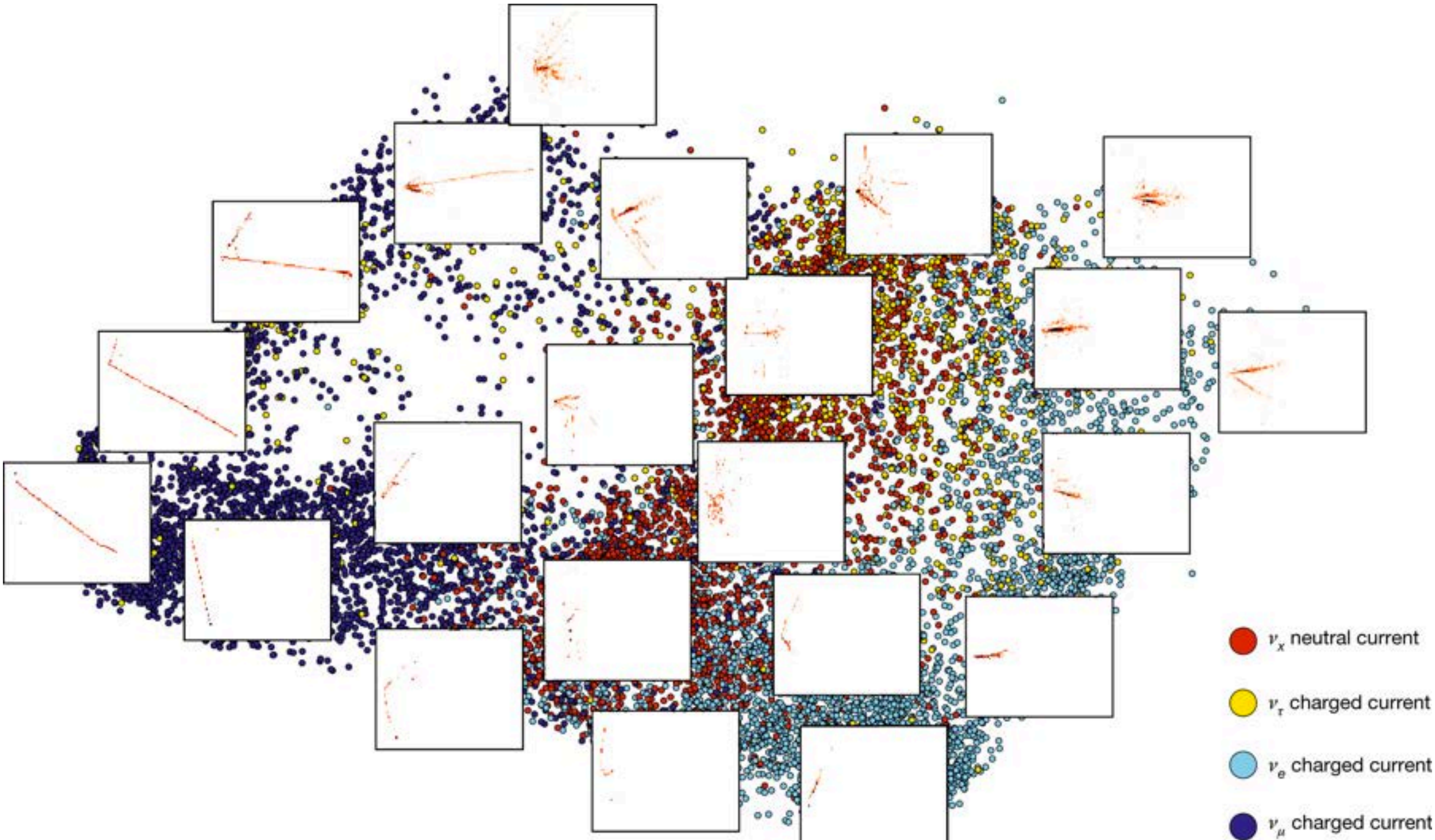

Super-Kamiokande IV
T2K Beam Run 430013 Spill 4033842
Run 69739 Sub 201 Event 48168772
12-05-30:05:03:02
T2K beam dt = 2463.6 ns
Inner: 2350 hits, 7009 pe
Outer: 1 hits, 0 pe
Trigger: 0x80000007
D_wall: 644.8 cm
e-like, p = 690.1 MeV/c
Charge (pe)
>26.7
23.3-26.7
20.2-23.3
17.3-20.2
14.7-17.3
12.2-14.7
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
E. Kearns
Expected Angular charge distribution
for 525 MeV electron
ELECTRON
NEUTRINO
electron
shower
Q (photoelectrons/sr)
cosθ
0 mu-e
decays
Times (ns)

Neutrino Data in NOvA

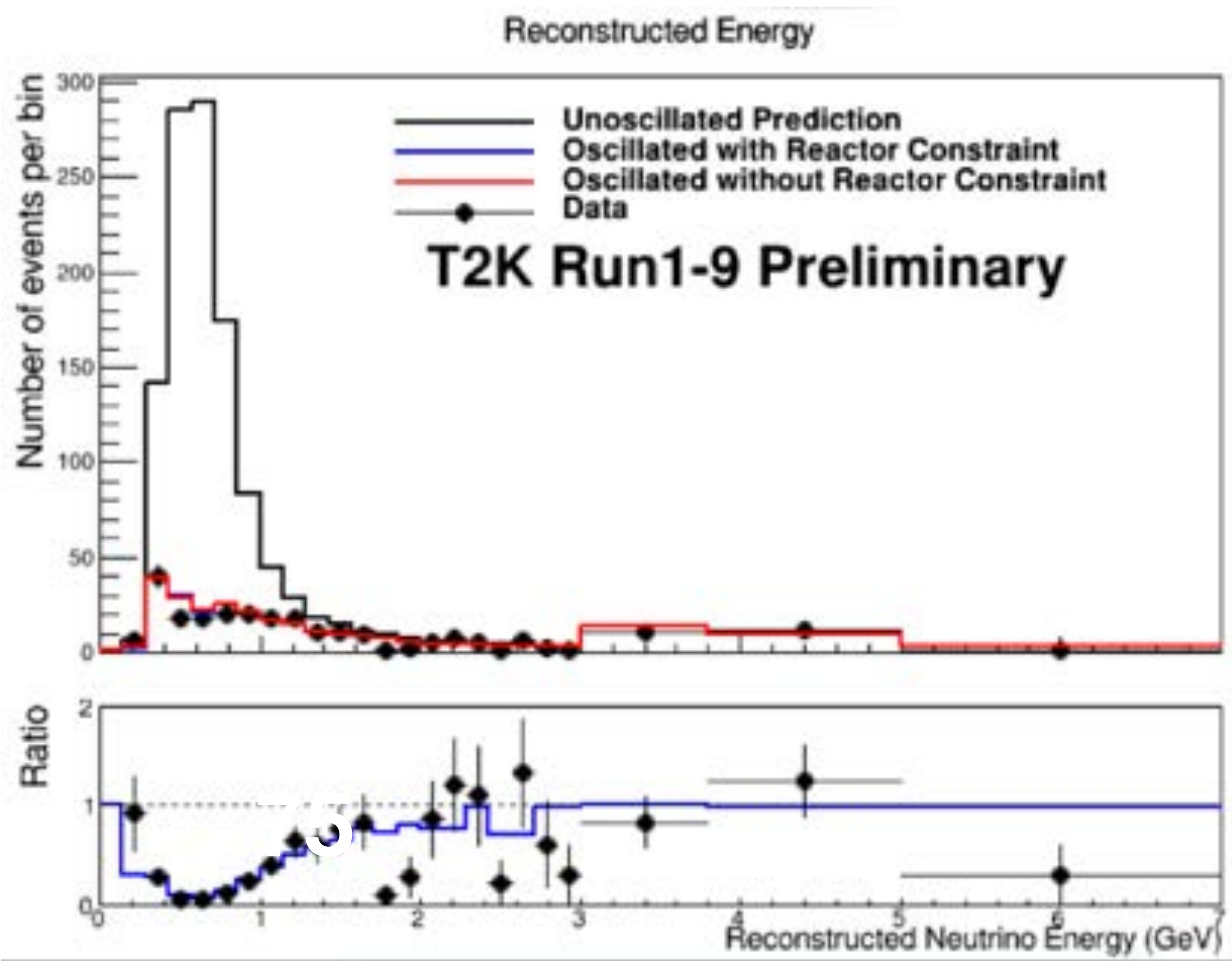


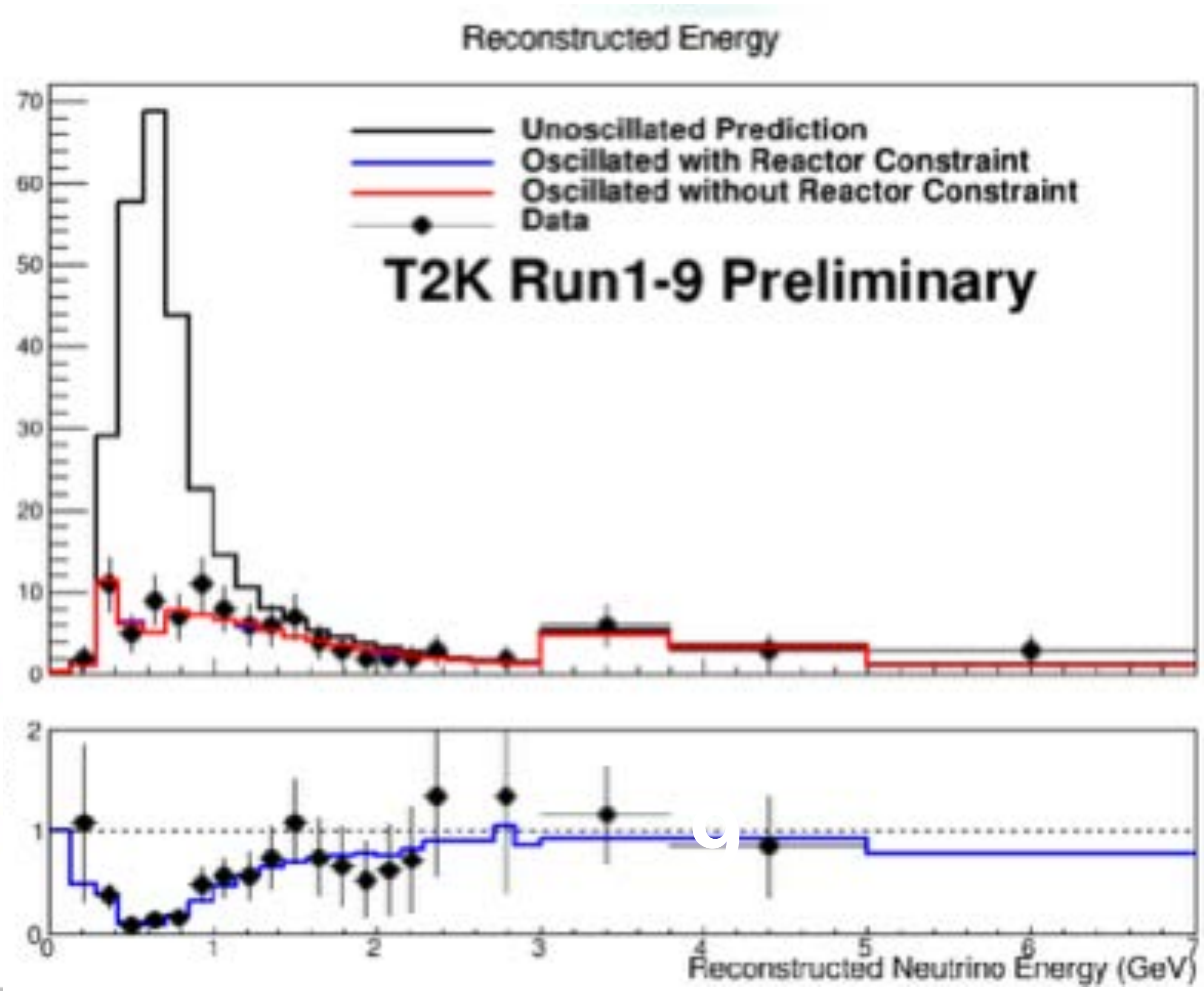
Machine learning at the energy and intensity frontiers of particle physics

Alexander Radovic[1]*, Mike Williams[2]*, David Rousseau[3], Michael Kagan[4], Daniele Bonacorsi[5,6], Alexander Himmel[7], Adam Aurisano[8], Kazuhiro Terao[4] & Taritree Wongjirad[9]



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

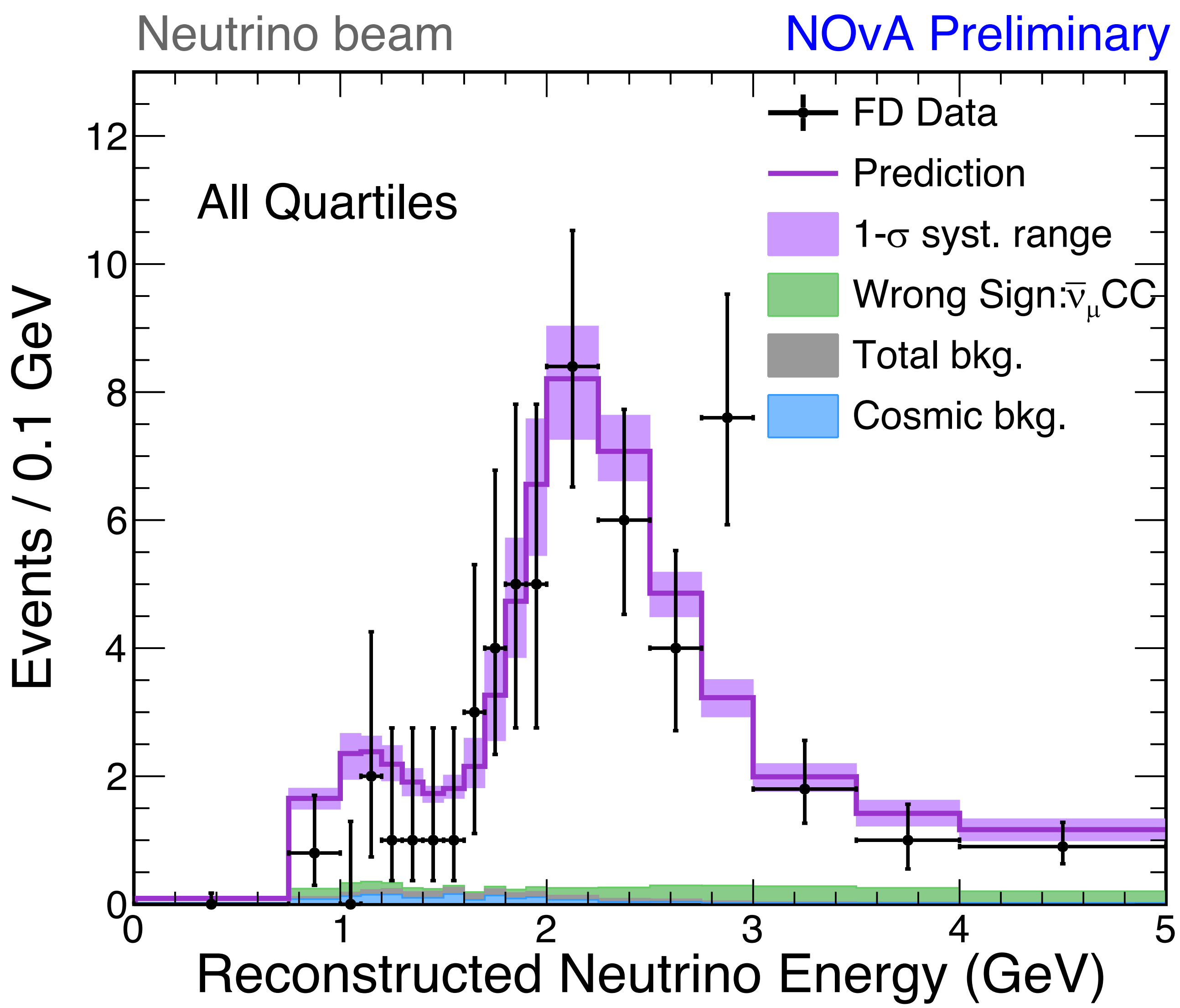




$243\ \nu_\mu - \mathrm{CC\ events}$ $\qquad$ $102\ \bar{\nu}_\mu - \mathrm{CC\ events}$

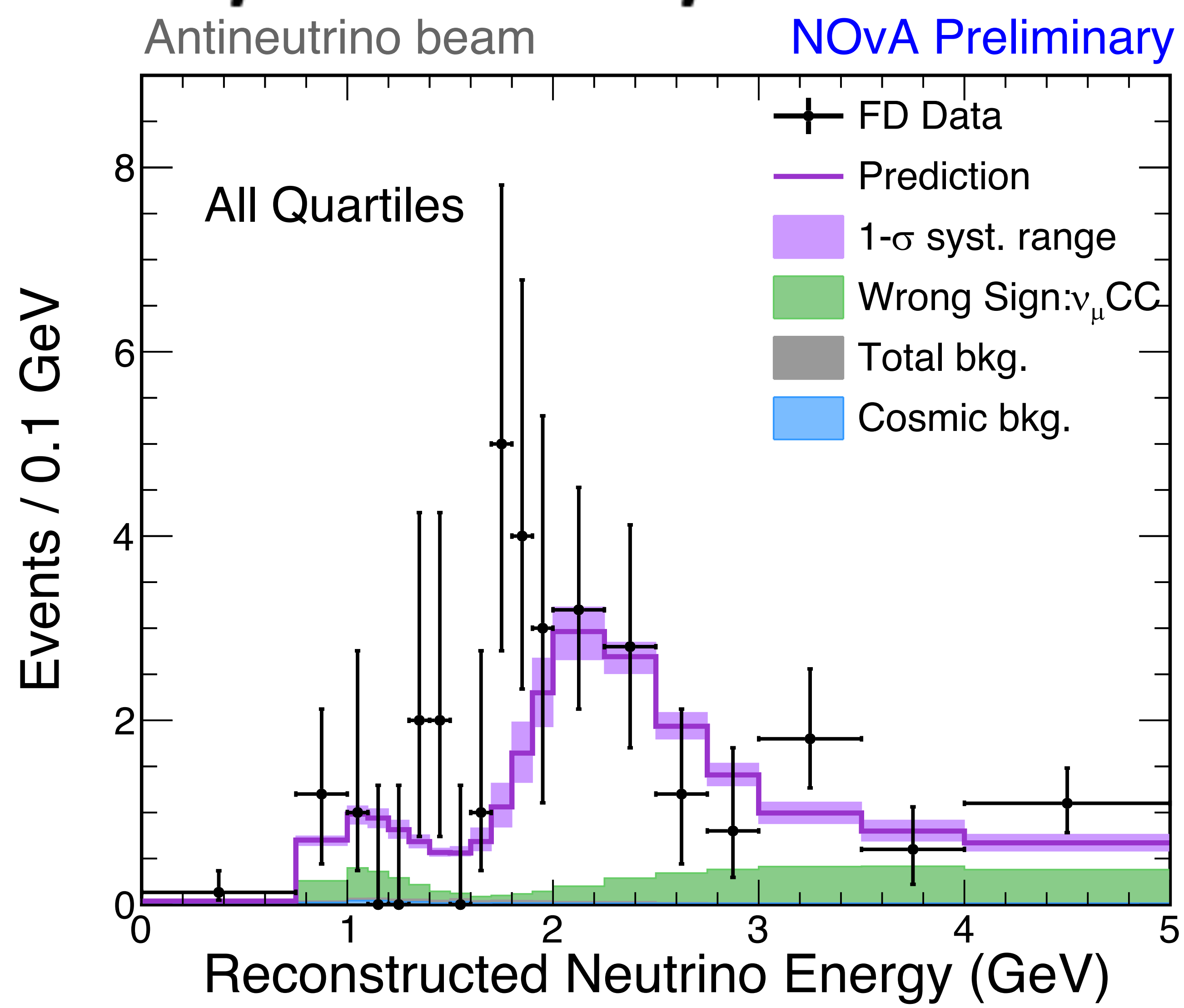
T2K event spectra

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



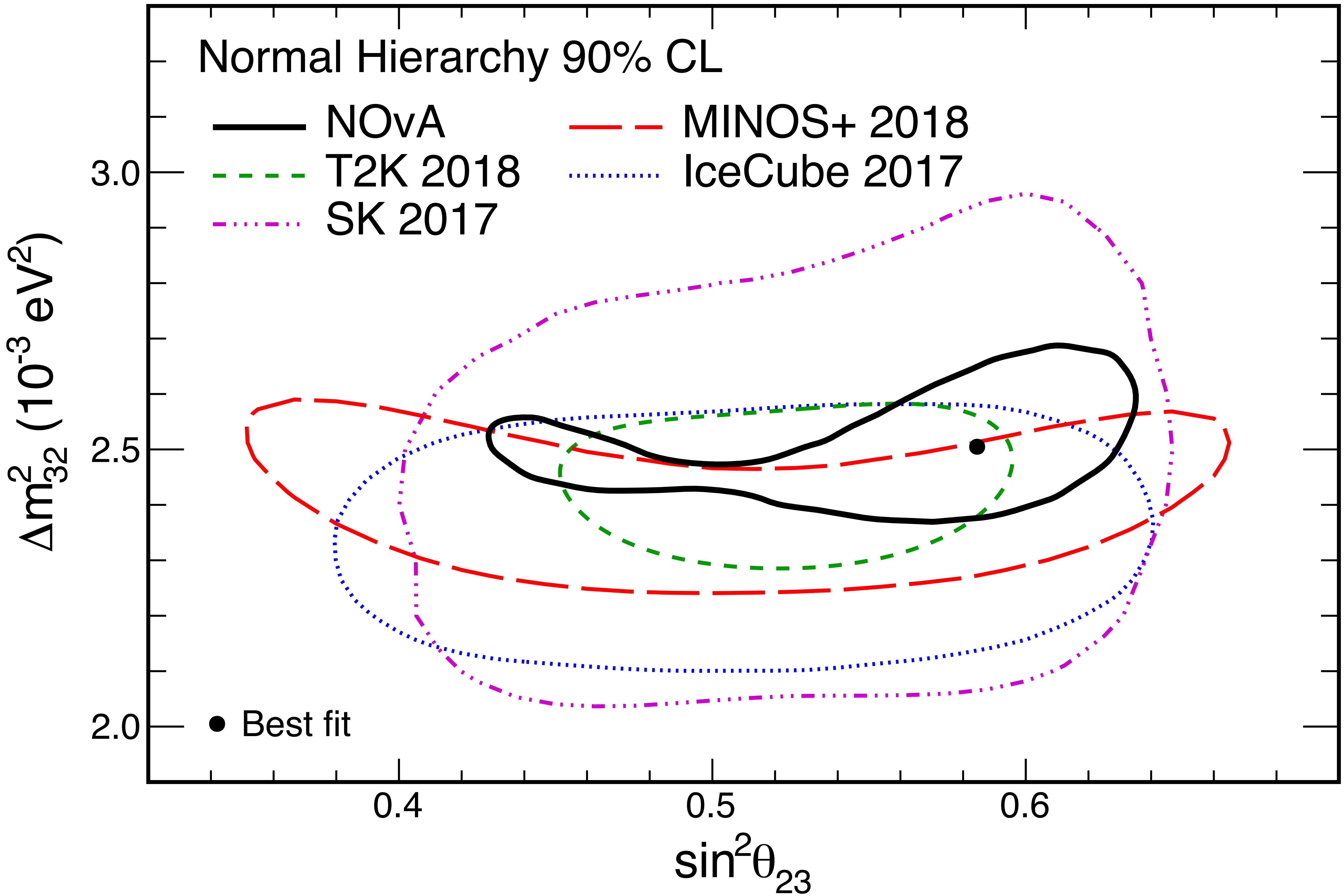
Total Observed	113
Unoscillated	730
Best fit prediction	121
Cosmic Bkgd.	2.1
Beam Bkgd.	1.2

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

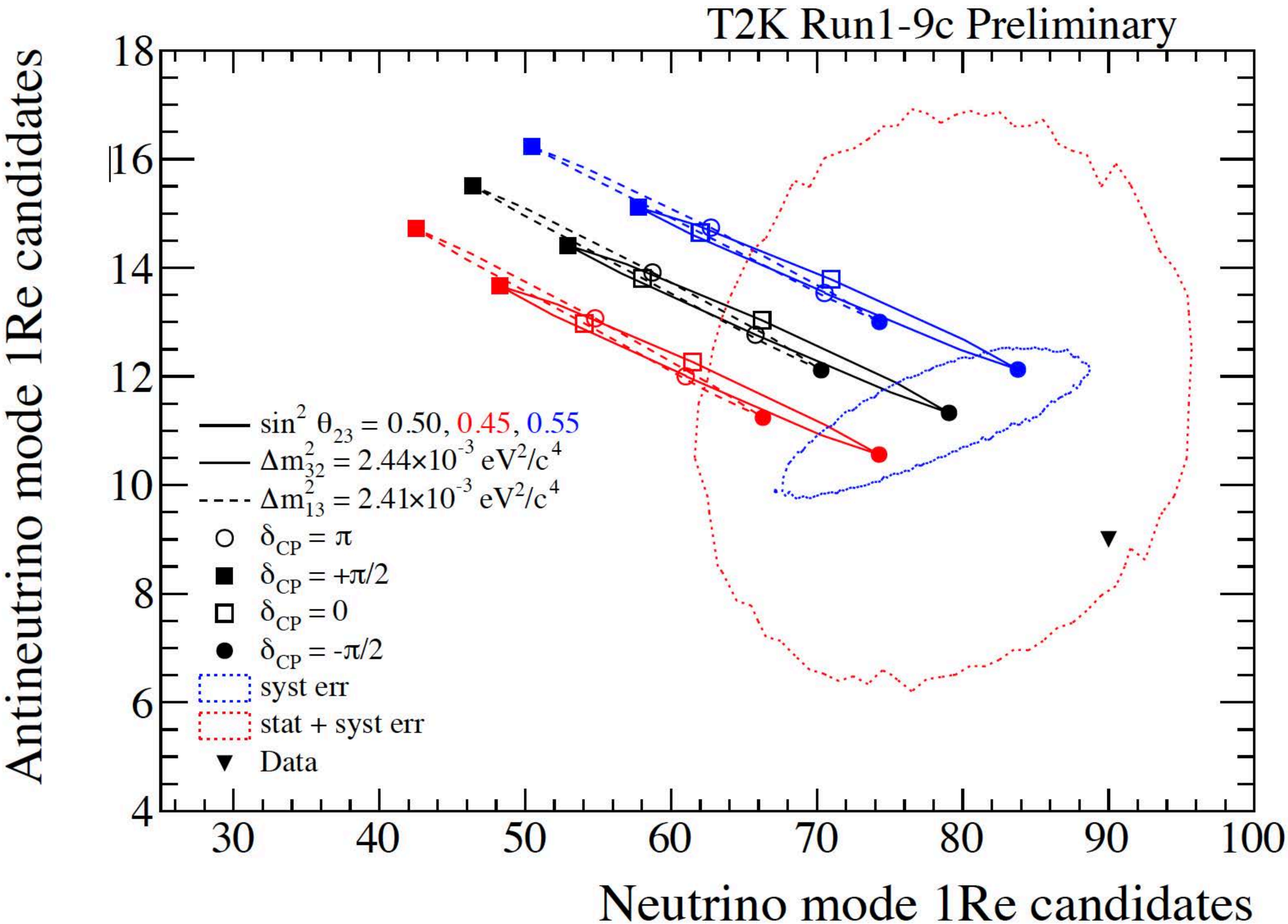


Total Observed	65
Unoscillated	266
Best fit prediction	50
Cosmic Bkgd.	0.5
Beam Bkgd.	0.6

NOvA Preliminary



Prefer non-maximal mixing in upper octant at 1.8σ (93% CL)

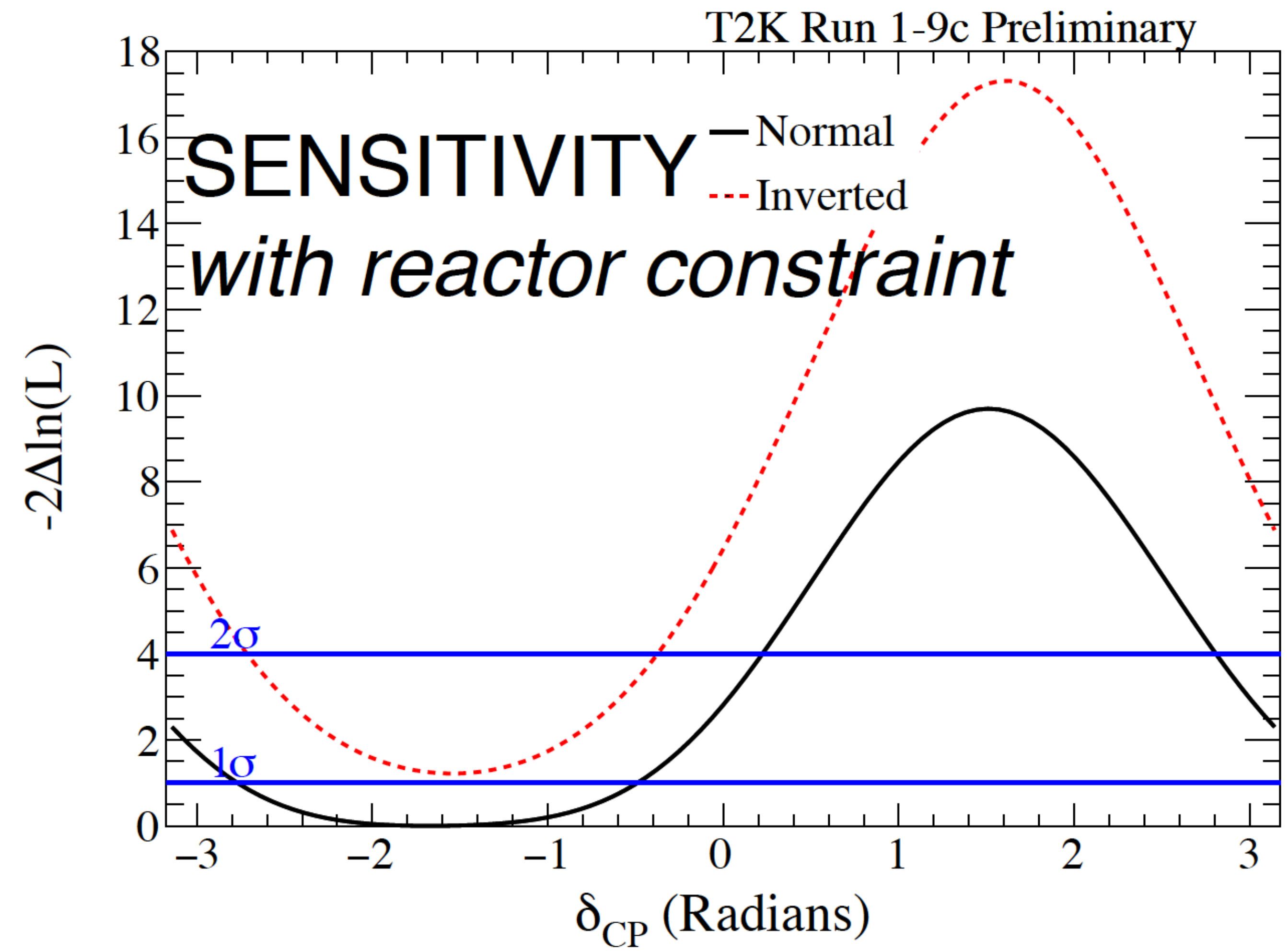


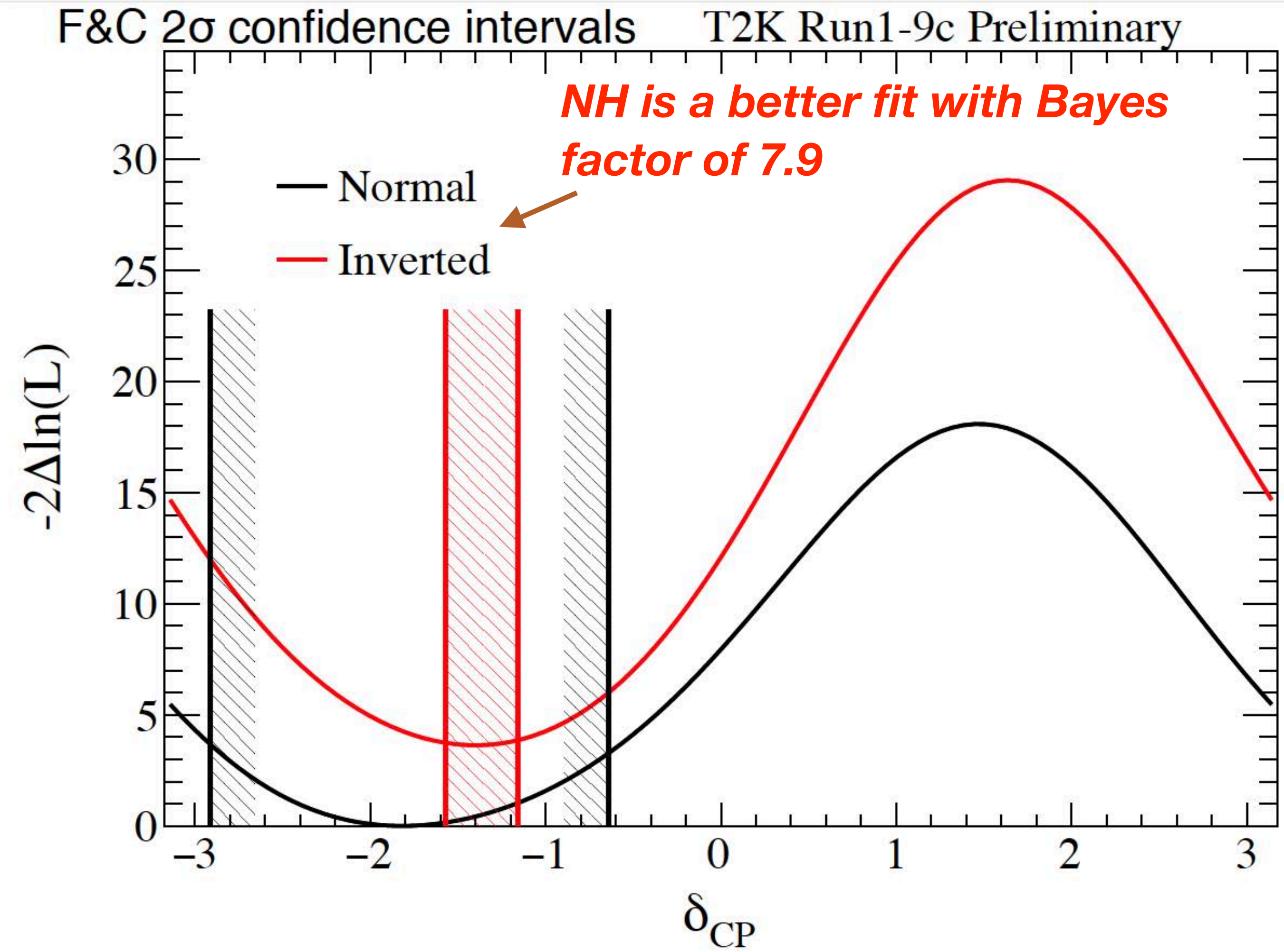
T2K neutrino and antineutrino event counts

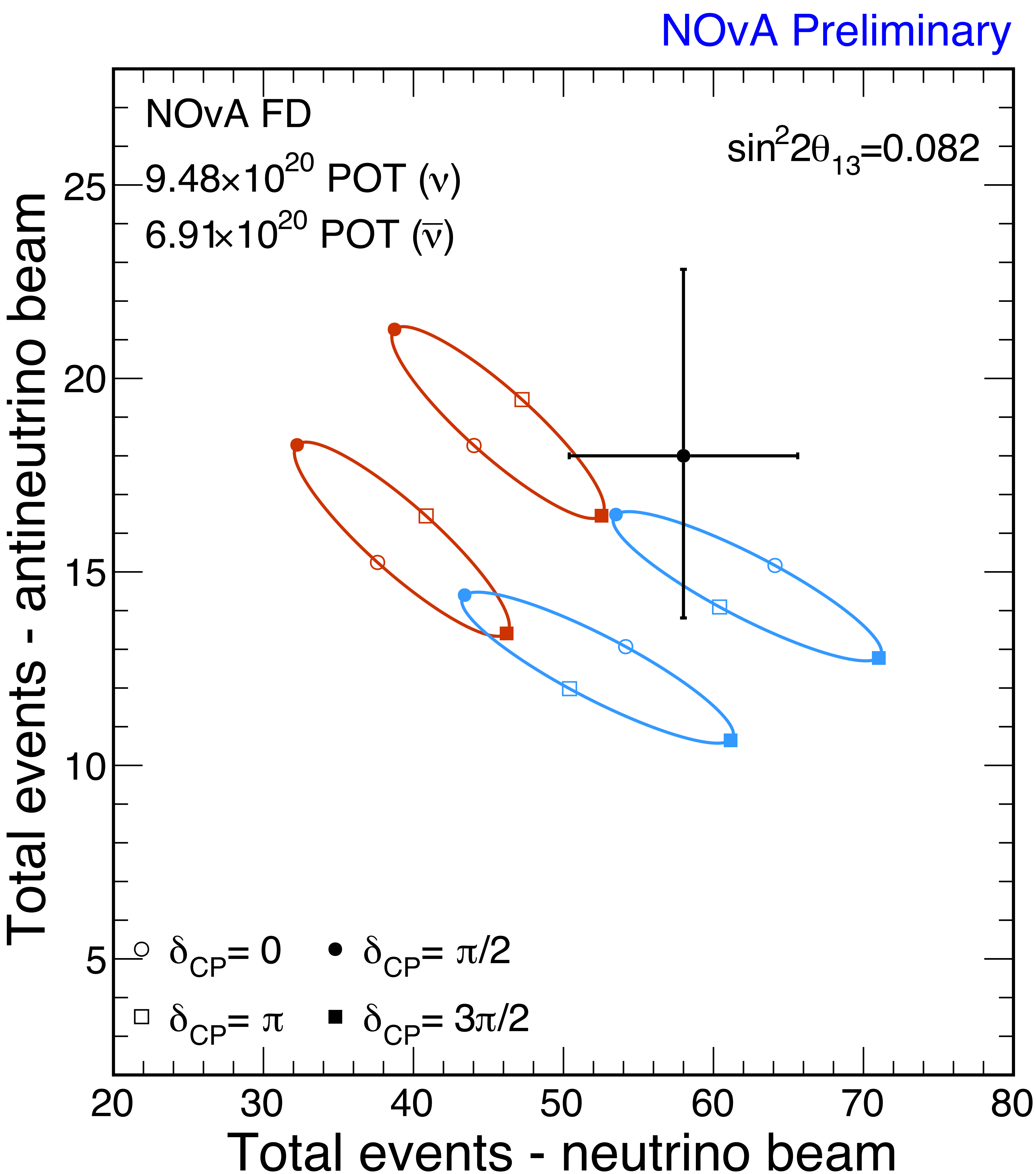
Relative to the best-fit parameters T2K has seen an upward fluctuation in neutrino events and a downward fluctuation in antineutrino events.

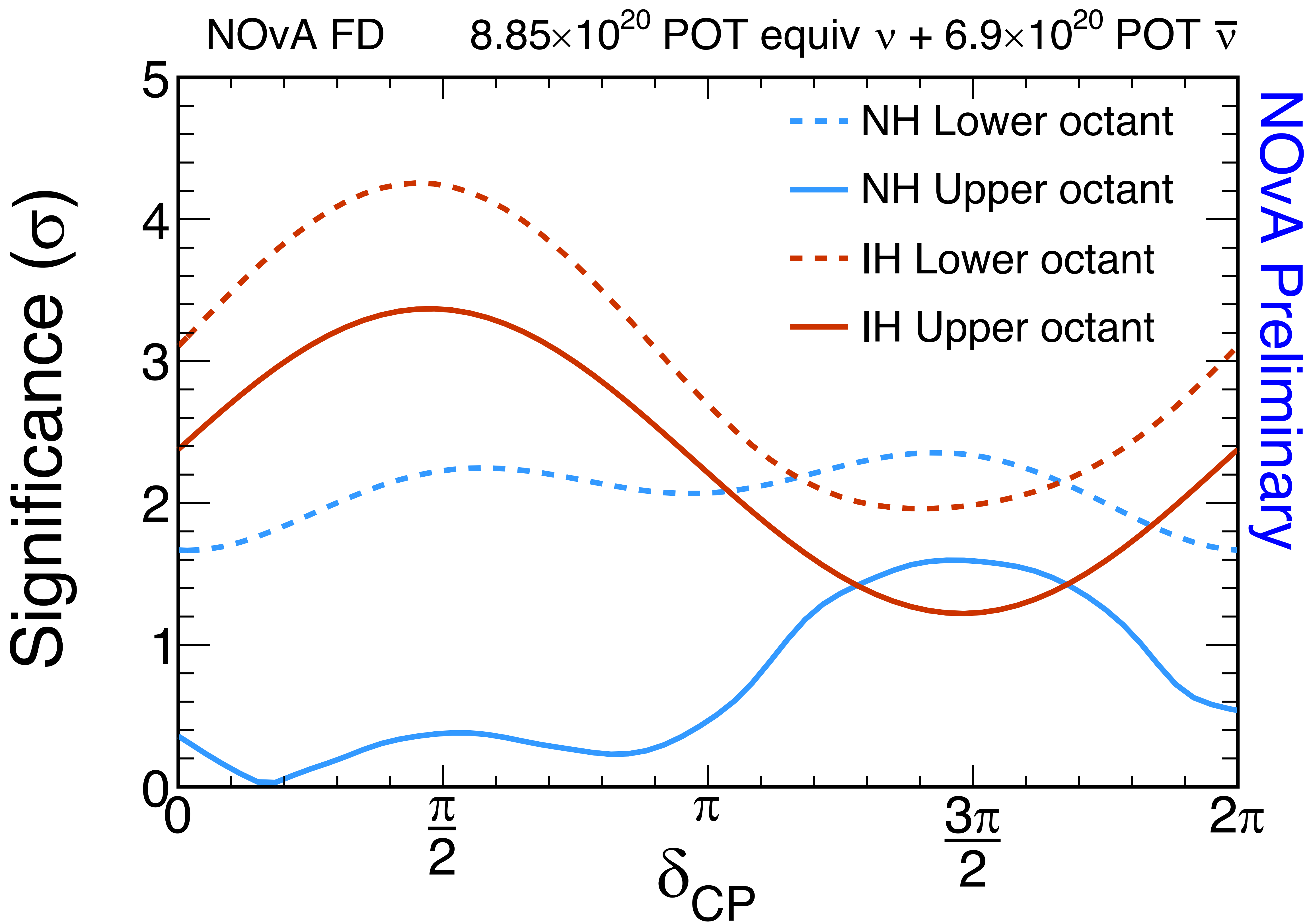
T2K measurement of CP phase δ

- 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.





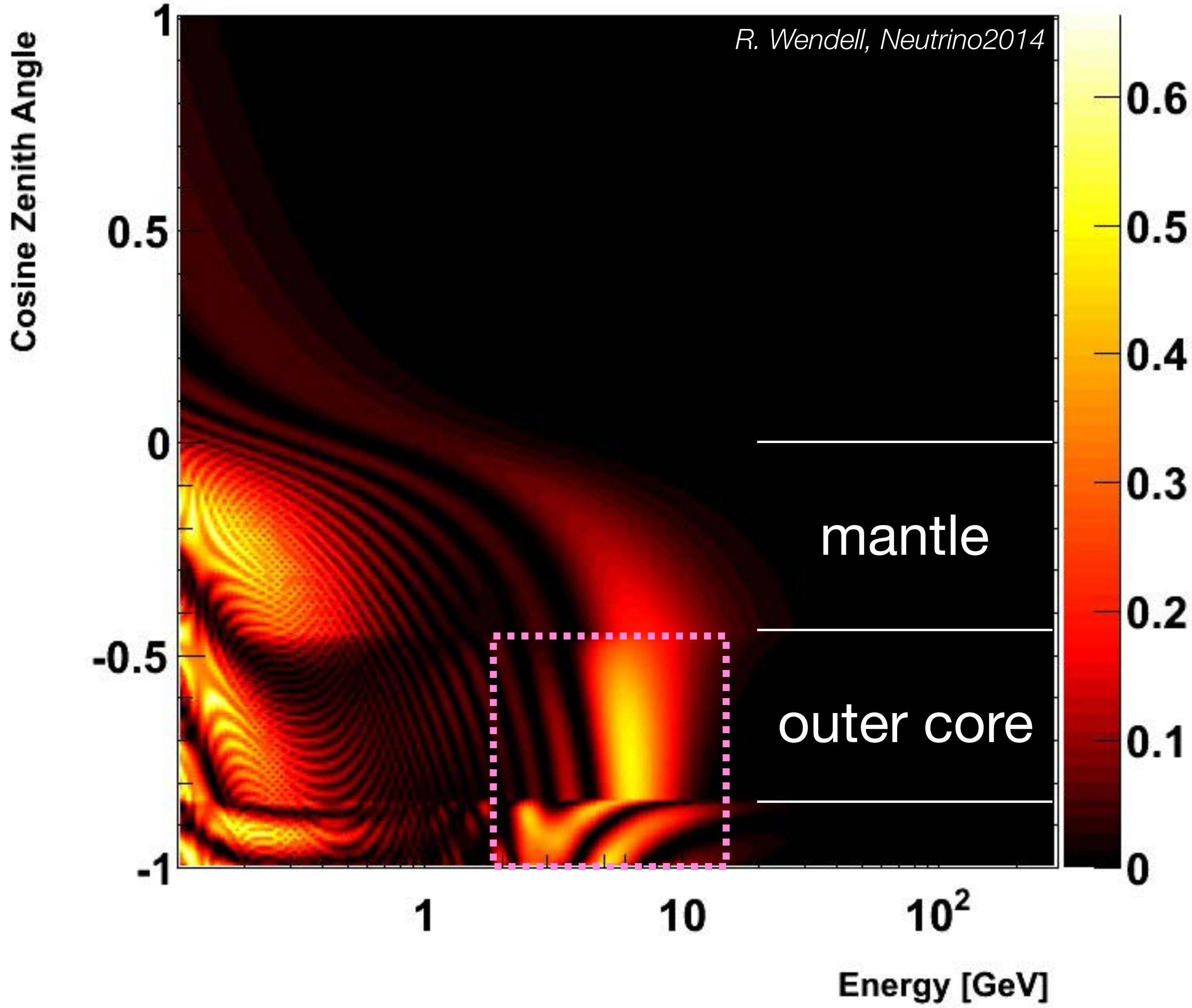

NOvA Preliminary
NOvA FD
9.48×10^20 POT (ν)
6.91×10^20 POT (ν̄)
sin²2θ13=0.082
Total events - antineutrino beam
Total events - neutrino beam
δCP= 0
δCP= π/2
δCP= π
δCP= 3π/2
5
10
15
20
25
20
30
40
50
60
70
80

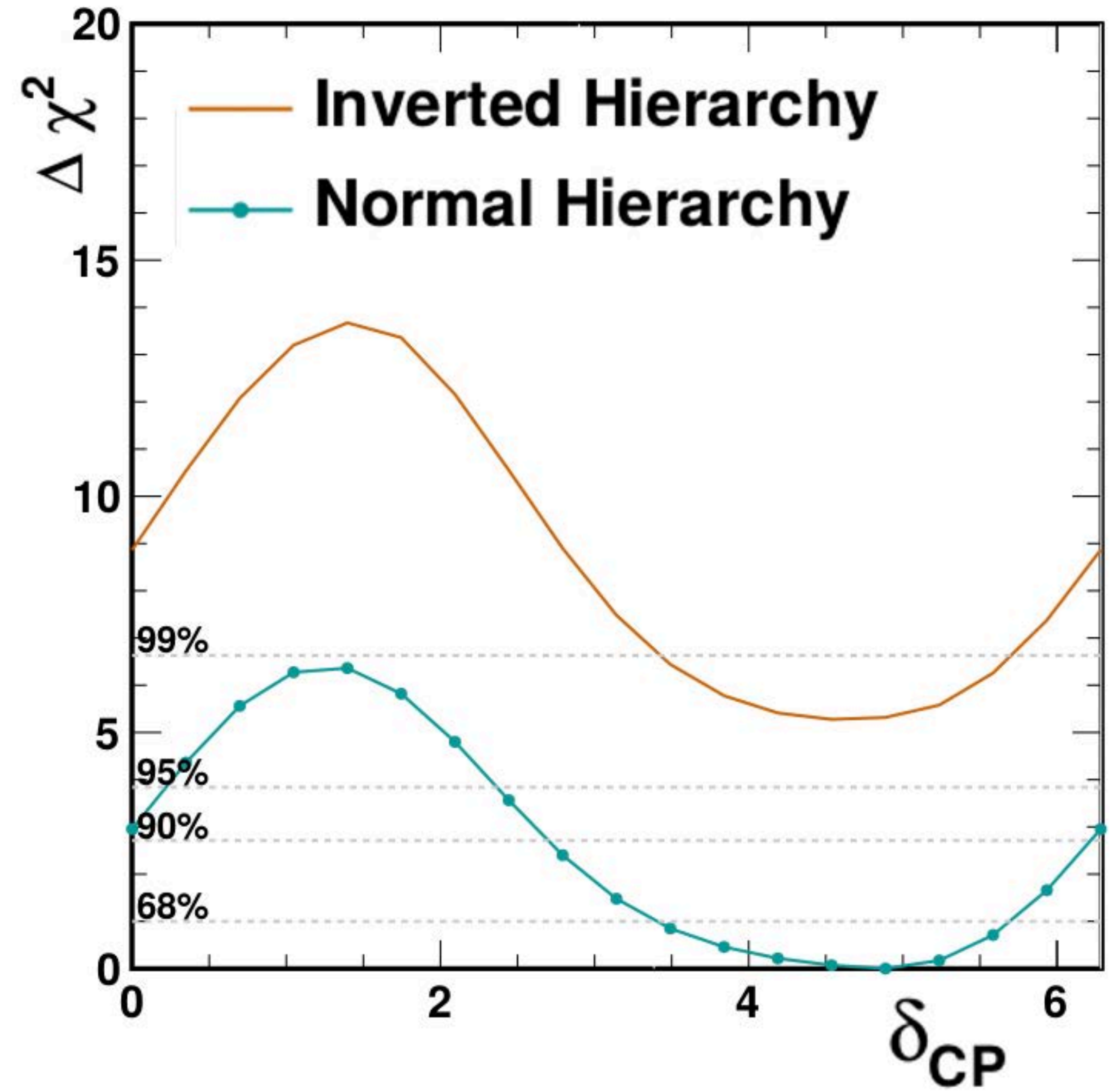


$$\chi^2_{\mathrm{IH}} - \chi^2_{\mathrm{NH}} = 2.47$$

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

$P(\nu_\mu \rightarrow \nu_e)$





	χ^2	$\lvert\Delta m^2_{32/31}\rvert$	$\sin^2(\theta_{23})$	δ_{CP}
Normal hierarchy	639.43	2.50×10^{-3}	0.550	4.88
Inverted hierarchy	644.70	2.40×10^{-3}	0.550	4.54

← 1.7σ

Super-Kamiokande Atmospheric Neutrinos

Includes constraints from 2015 T2K data release

Measurements

- θ_{12}
- θ_{13}
- θ_{23}
- δ_{CP}
- Δm^2_{21}
- Δm^2_{31}
- Mass ordering
- Dirac/Majorana

Neutrino mass textures

$$U_{e3} = \sqrt{\frac{\Delta m^2_{12}}{\Delta m^2_{13}}}$$

$$\frac{\sqrt{\Delta m^2_{31}}}{2}\begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{bmatrix}$$

normal mass ordering

$$\sqrt{\Delta m^2_{31}}\begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{1}{2} & \frac{1}{2} \end{bmatrix} \qquad \sqrt{\Delta m^2_{31}}\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

$$U_{e3} = \frac{\Delta m^2_{12}}{\Delta m^2_{13}}$$

inverted mass ordering

$$\sqrt{\frac{\Delta m^2_{31}}{2}}\begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

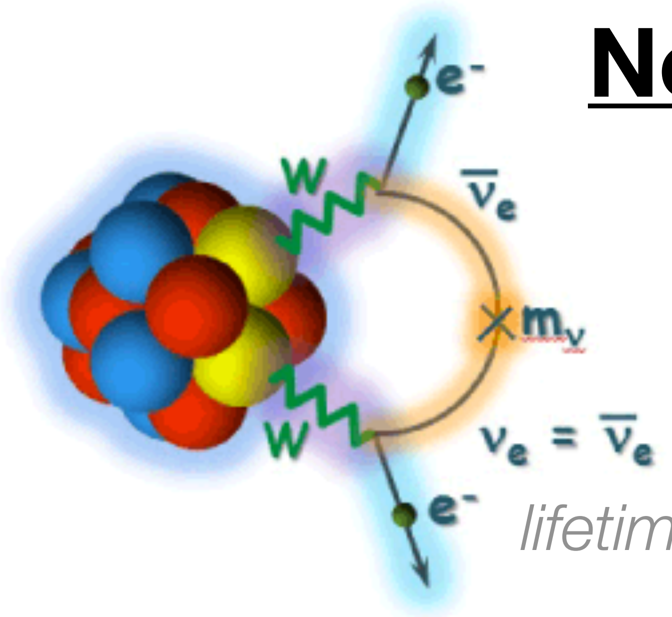
follows hep-ph/0510213

Extrapolate to GUT scale

$$|Y_{\mathrm{B}}| \simeq 2.4 \times 10^{-11} |\sin\delta| \left(\frac{\sin\theta_{13}}{0.15}\right)\left(\frac{M_1}{10^{11}\ \mathrm{GeV}}\right)$$

for example Pascoli, Petcov & Riotto PRD2007

Neutrino-less Double Beta Decay



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

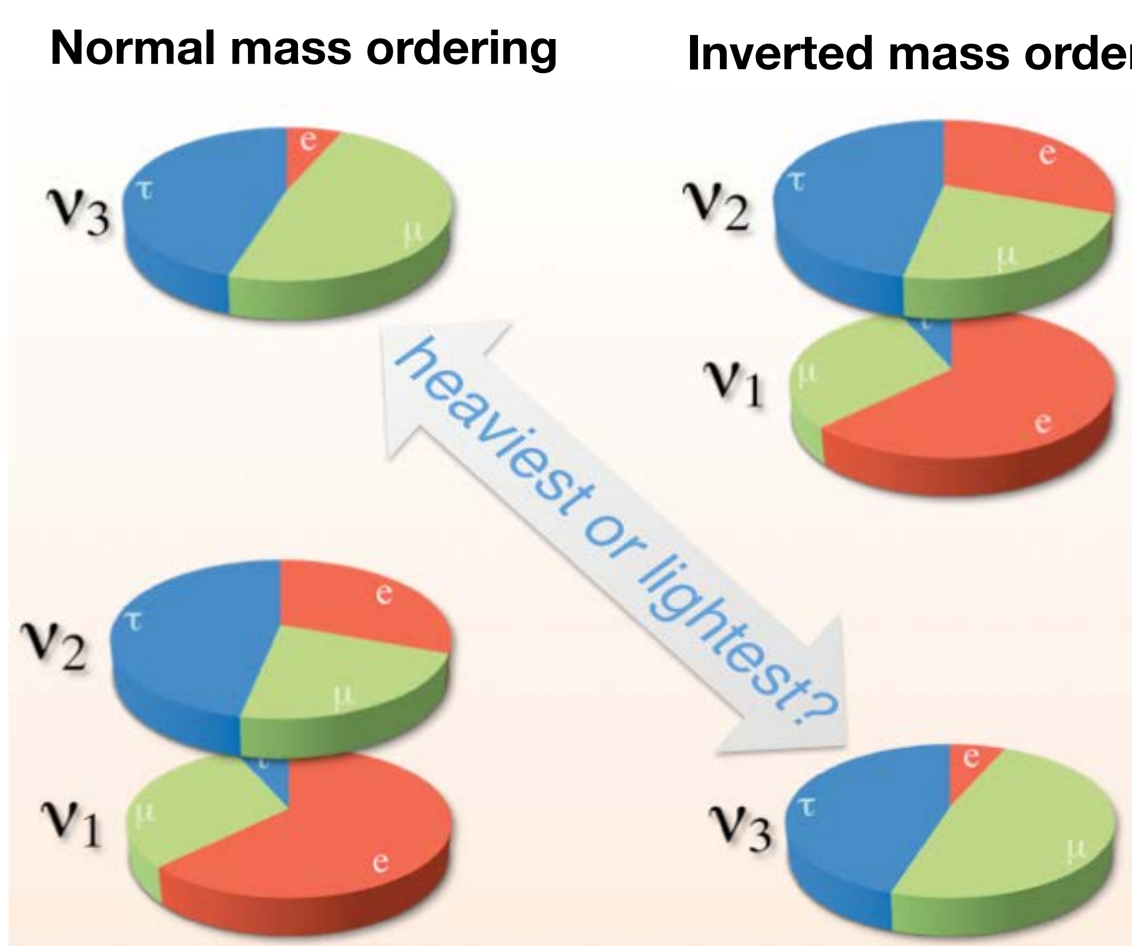
lifetime for 0νββ — *phase space* — *nuclear physics* — *effective neutrino mass*

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

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.

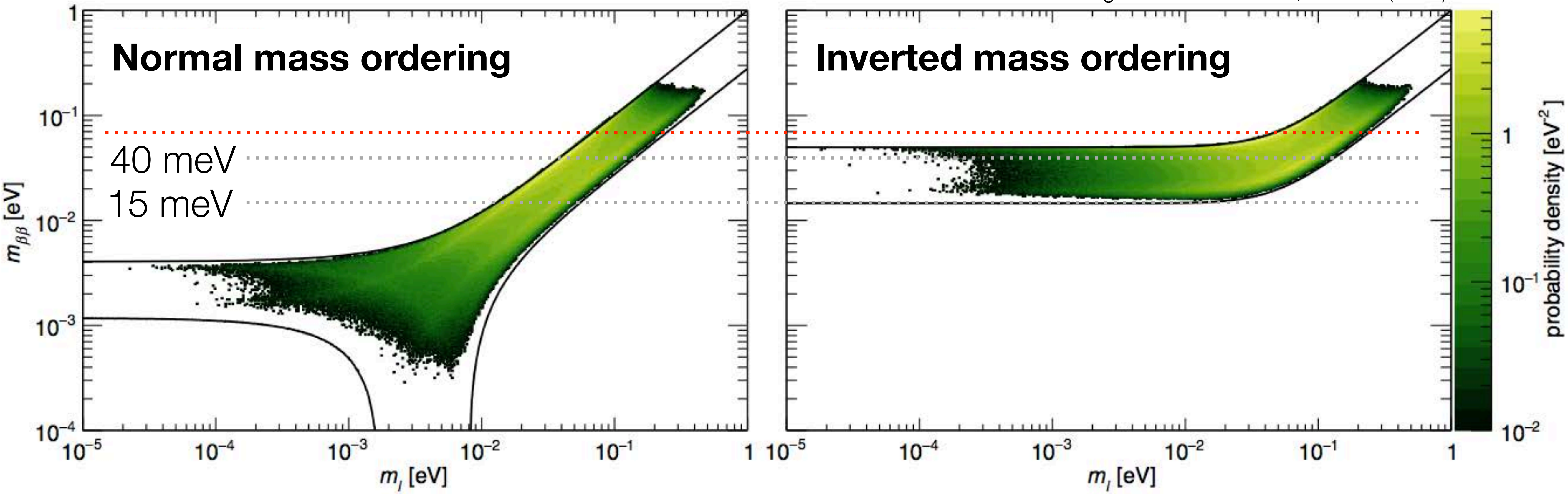
Accidental cancelations may result in $m_{\beta\beta} \rightarrow 0$.



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 ≈15-50 meV, $T_{1/2} \approx 10^{27\text{-}28}$ years

Agostini et al. PRD 96, 053001 (2017)

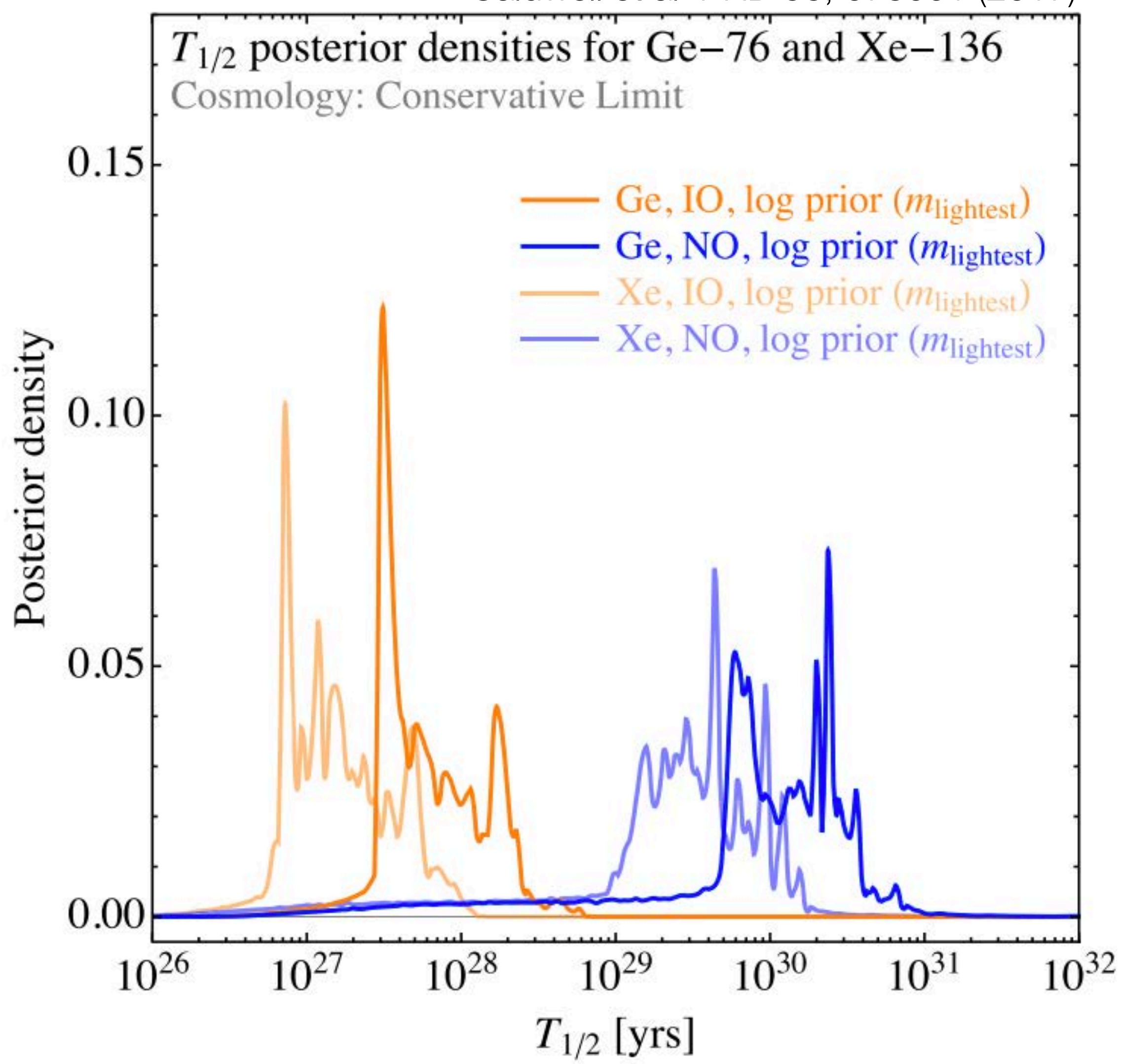


Using current oscillation, direct mass, and cosmological data as prior inputs, how likely is the next generation of experiments to discover 0νββ?

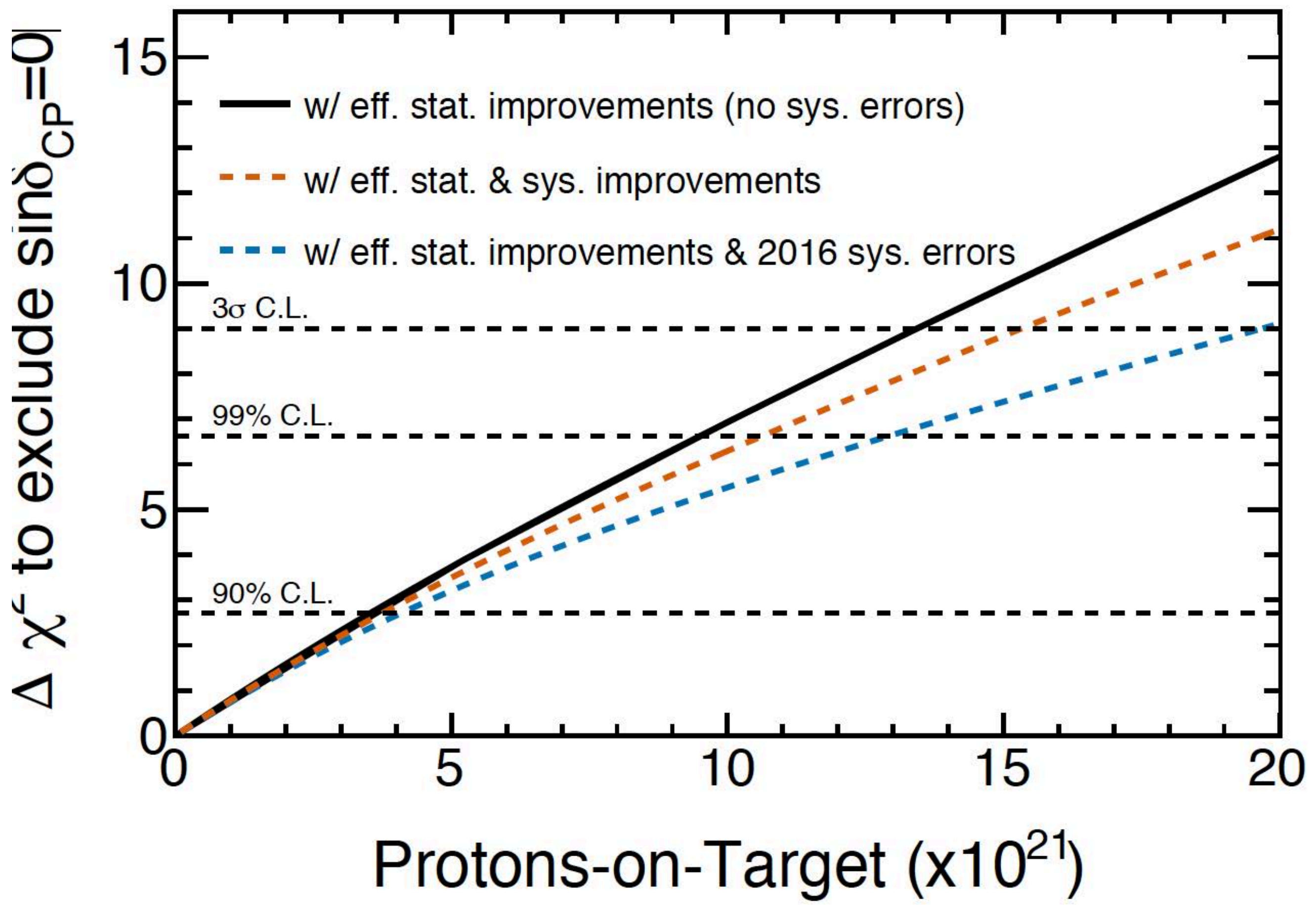
Turning that around, if 0νββ is discovered we will want to know the neutrino mass ordering and other oscillation parameters to interpret the observation.

Watch the assumptions! Caldwell et al. (right), for example, finds normal ordering harder to reach than does Agostini et al.

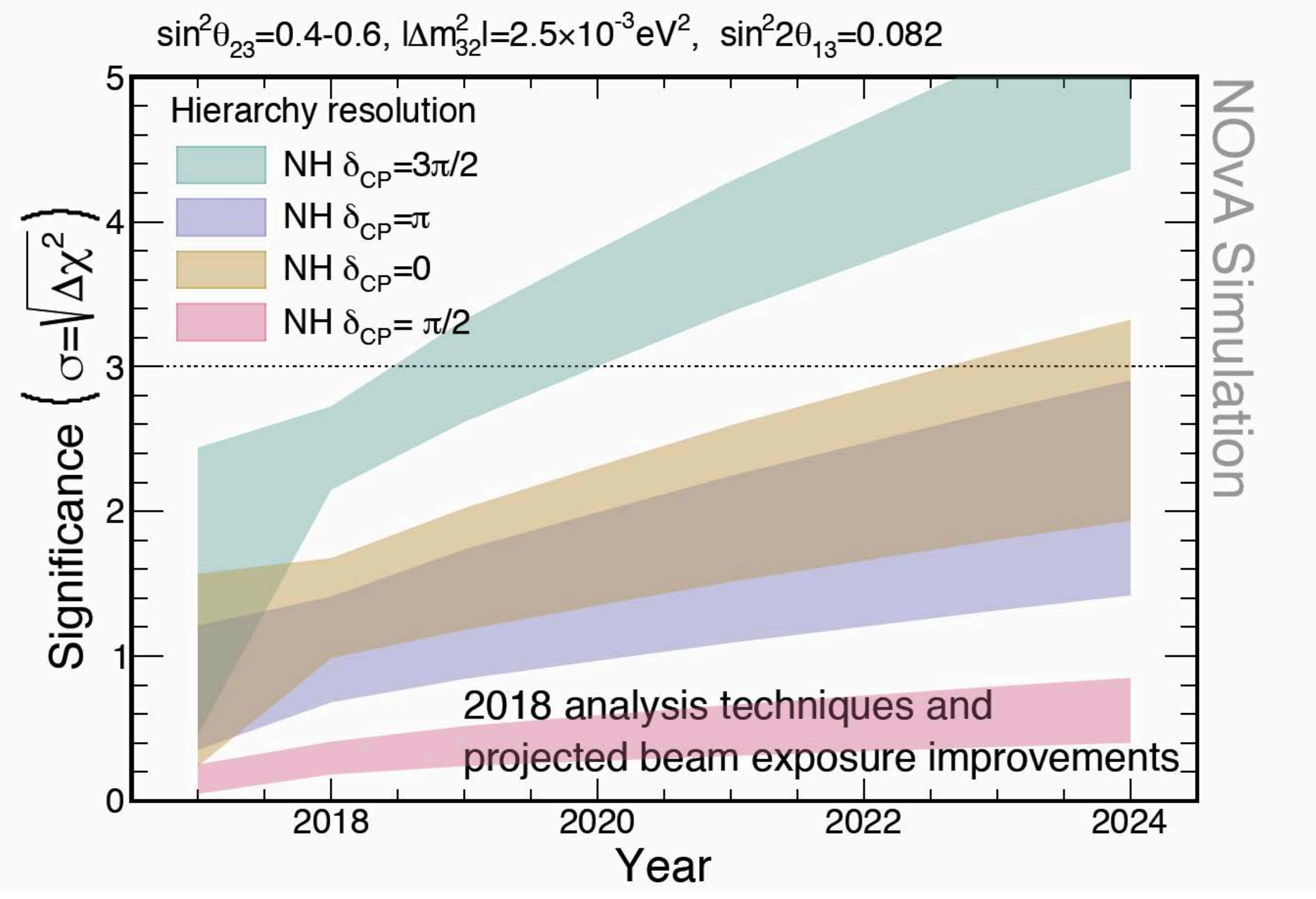
Caldwell et al. PRD 96, 073001 (2017)



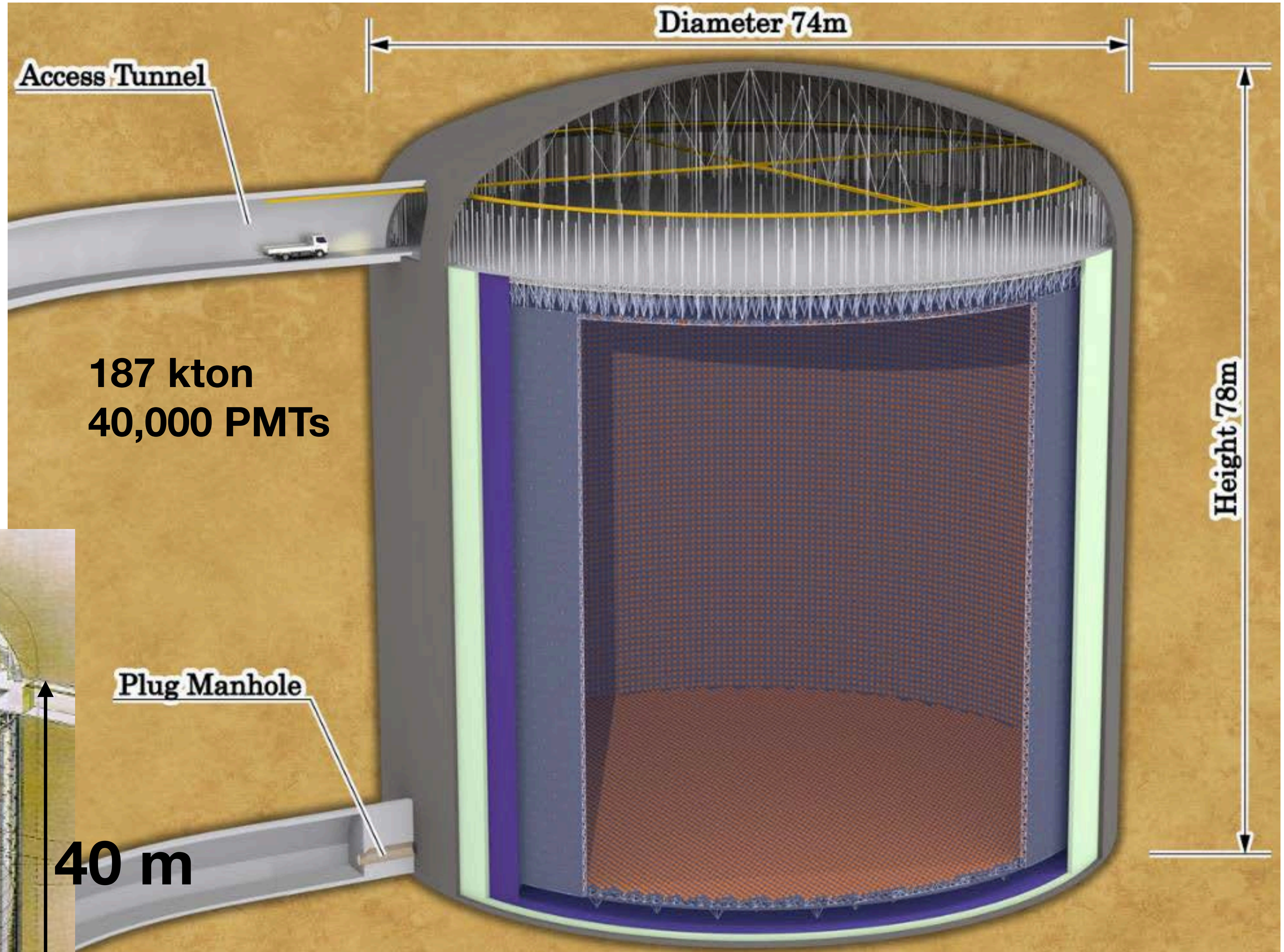
T2K and NOvA Extended Running



- 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 up to 5σ sensitivity to the mass hierarchy and up to 2σ sensitivity to CP violation

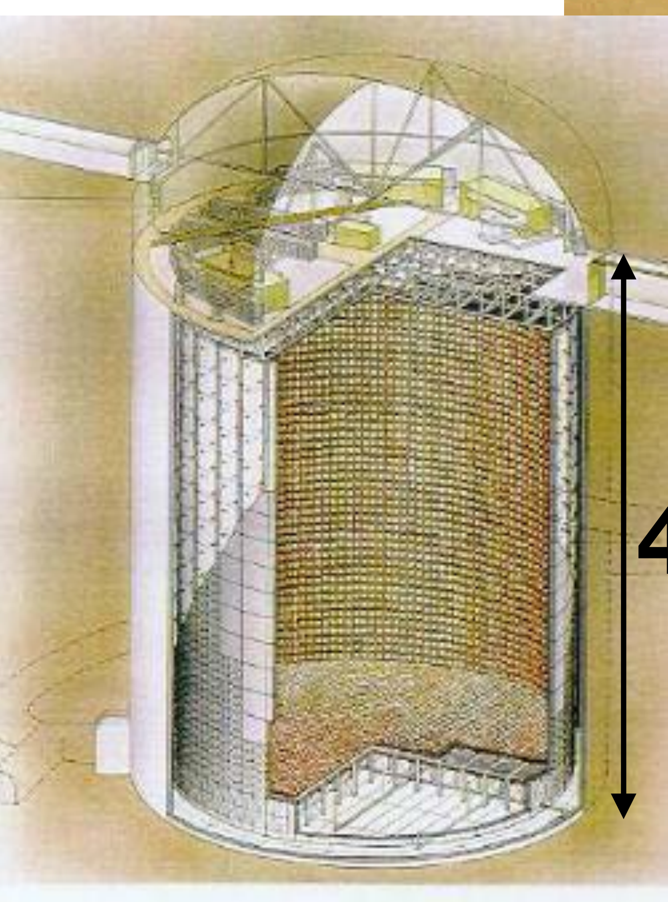


Hyper-Kamiokande



187 kton
40,000 PMTs

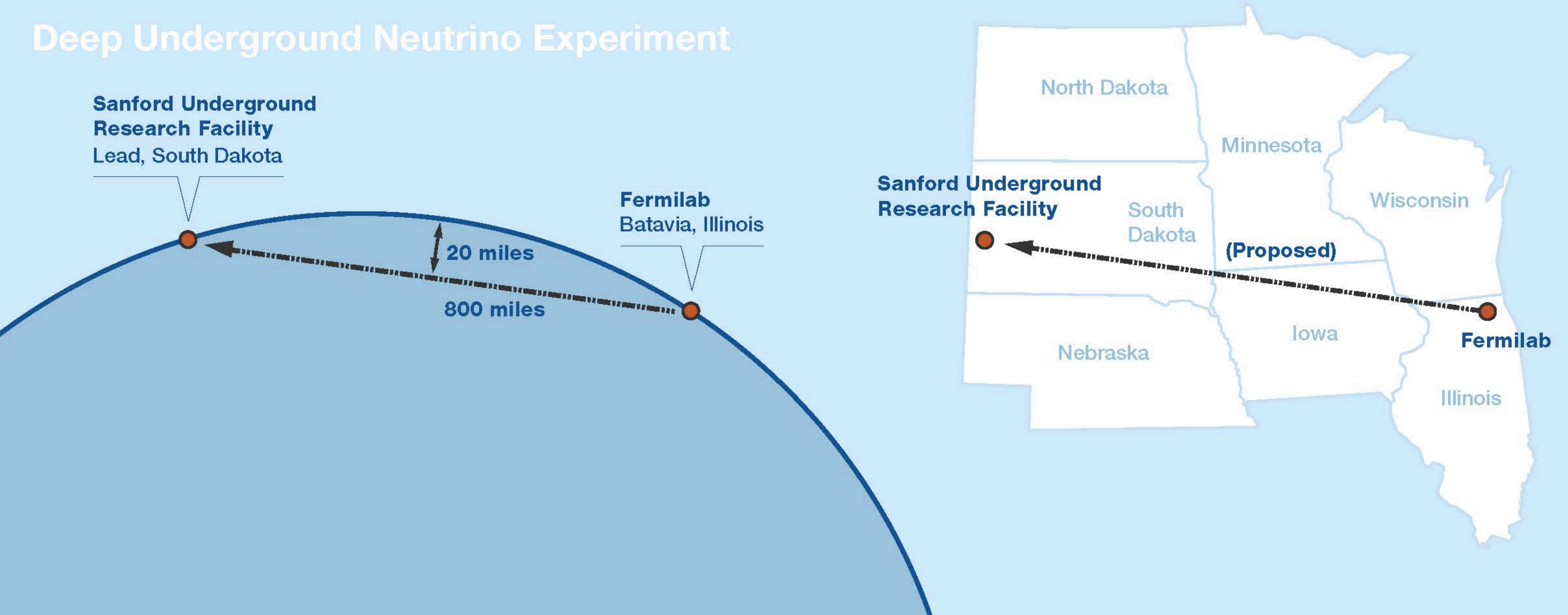
Super-K
22.5 kton
11,000 PMTs



40 m

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

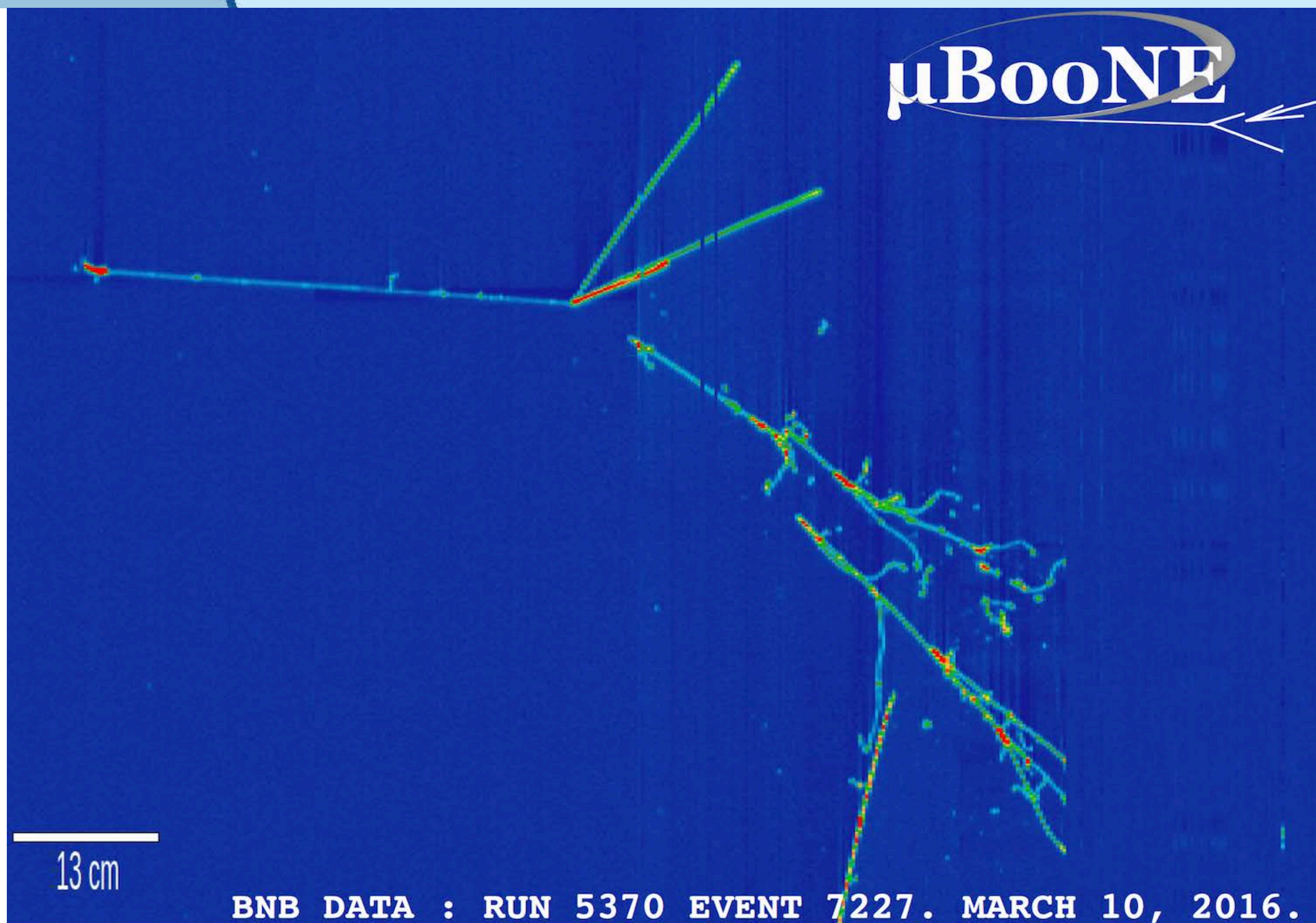
Deep Underground Neutrino Experiment



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

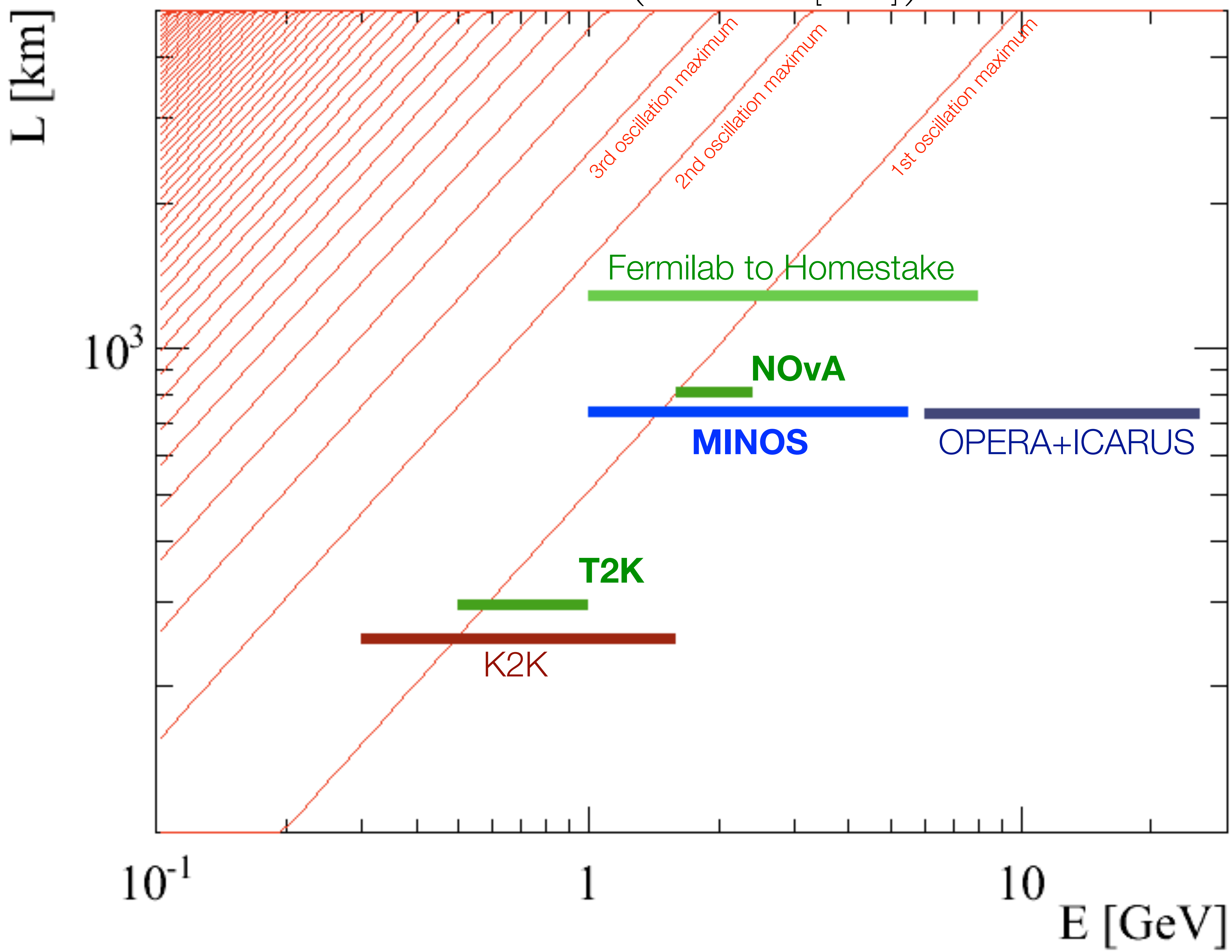
>5σ resolution of mass hierarchy
>5σ resolution of CP violation

2018 - Large scale prototype at CERN
2019 - Excavation begins
2022 - Installation
2026 - First neutrino beam

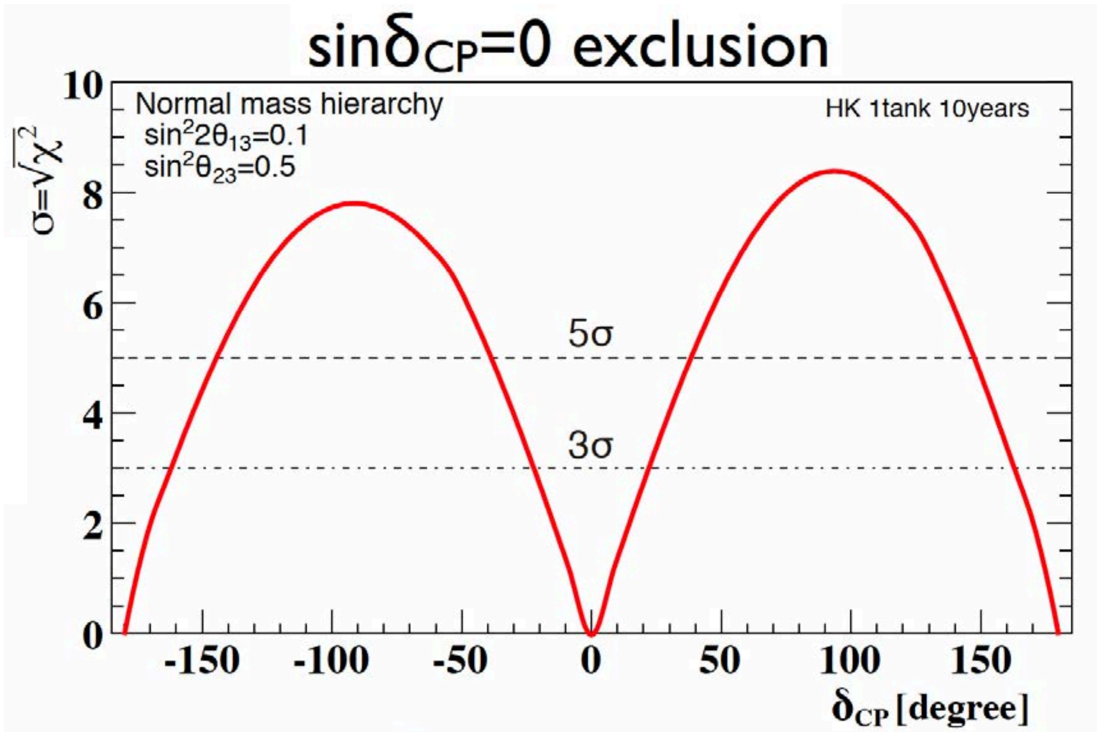


Long baseline experiments

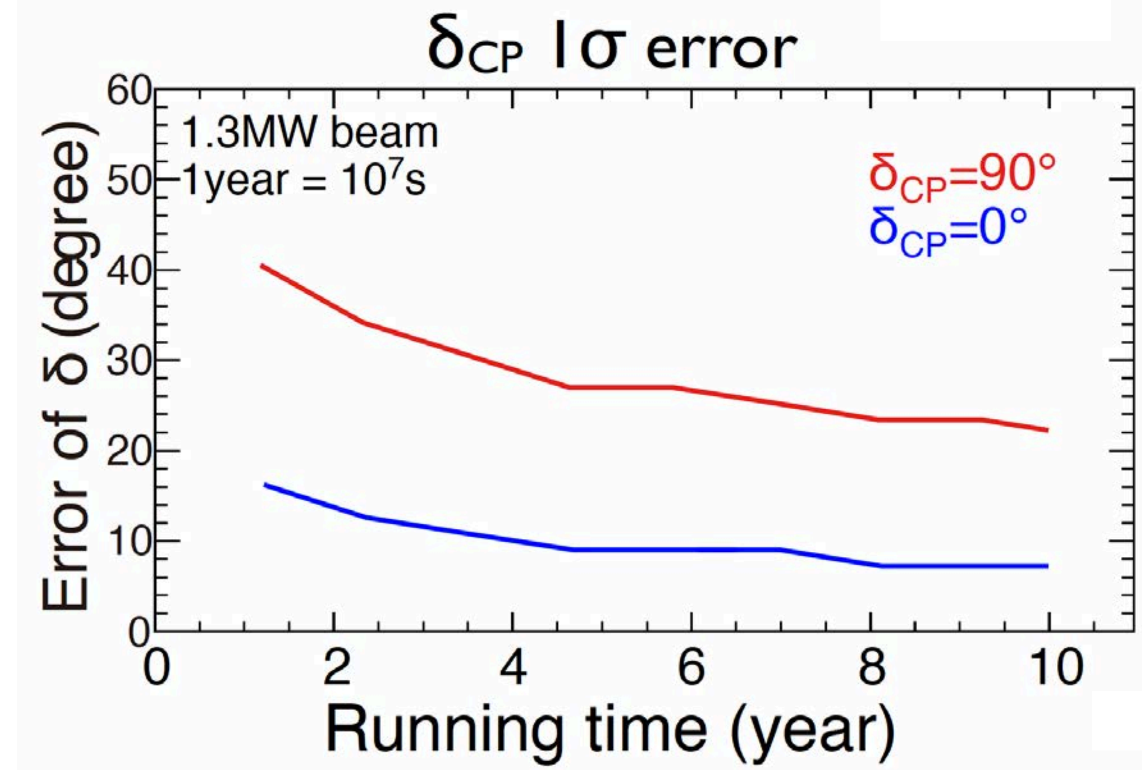
$$P = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2 \frac{L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$



Hyper-K

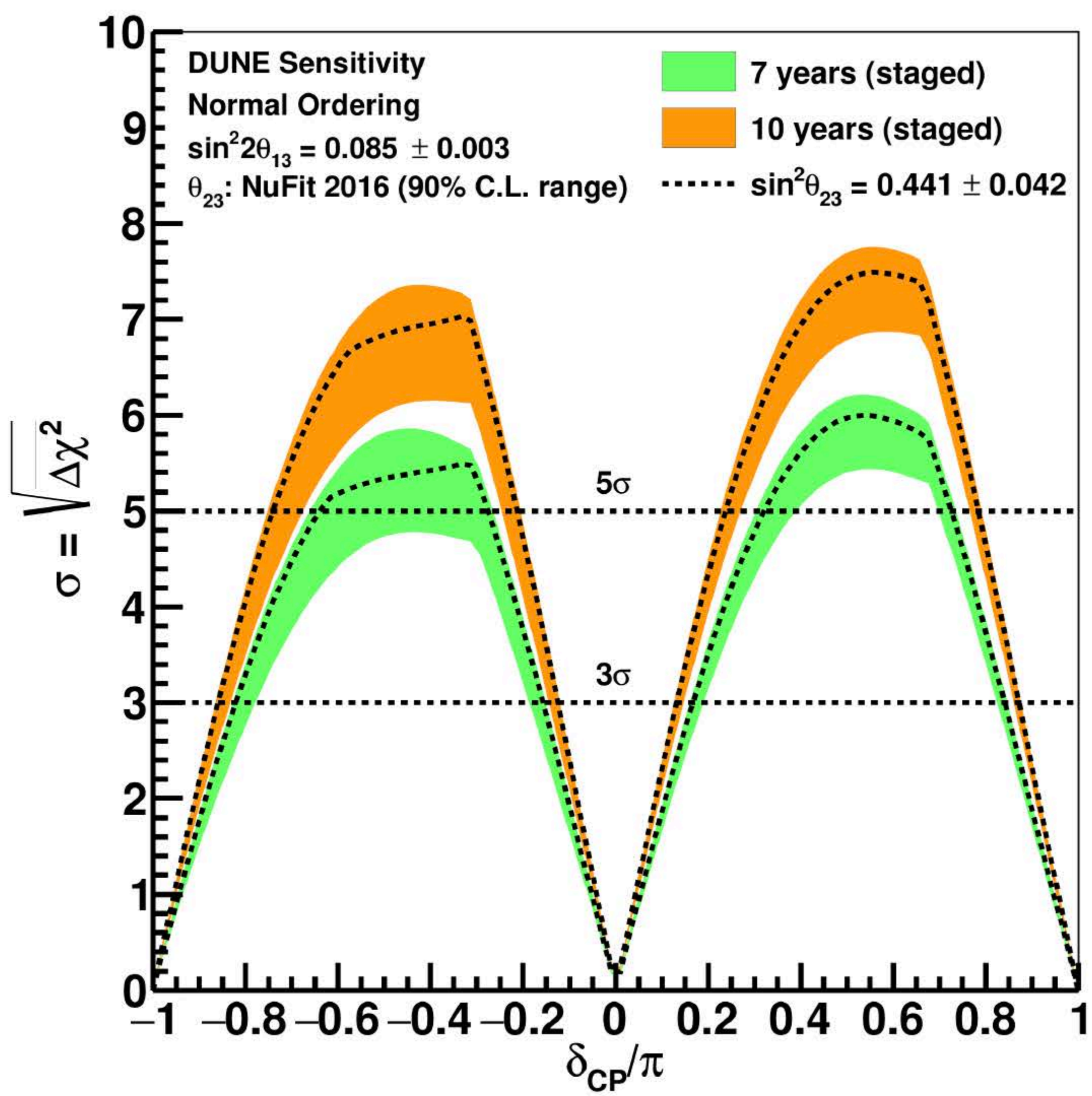


sinδCP=0 exclusion
Normal mass hierarchy
sin²2θ13=0.1
sin²θ23=0.5
HK 1tank 10years
5σ
3σ
σ=√χ²
δCP [degree]

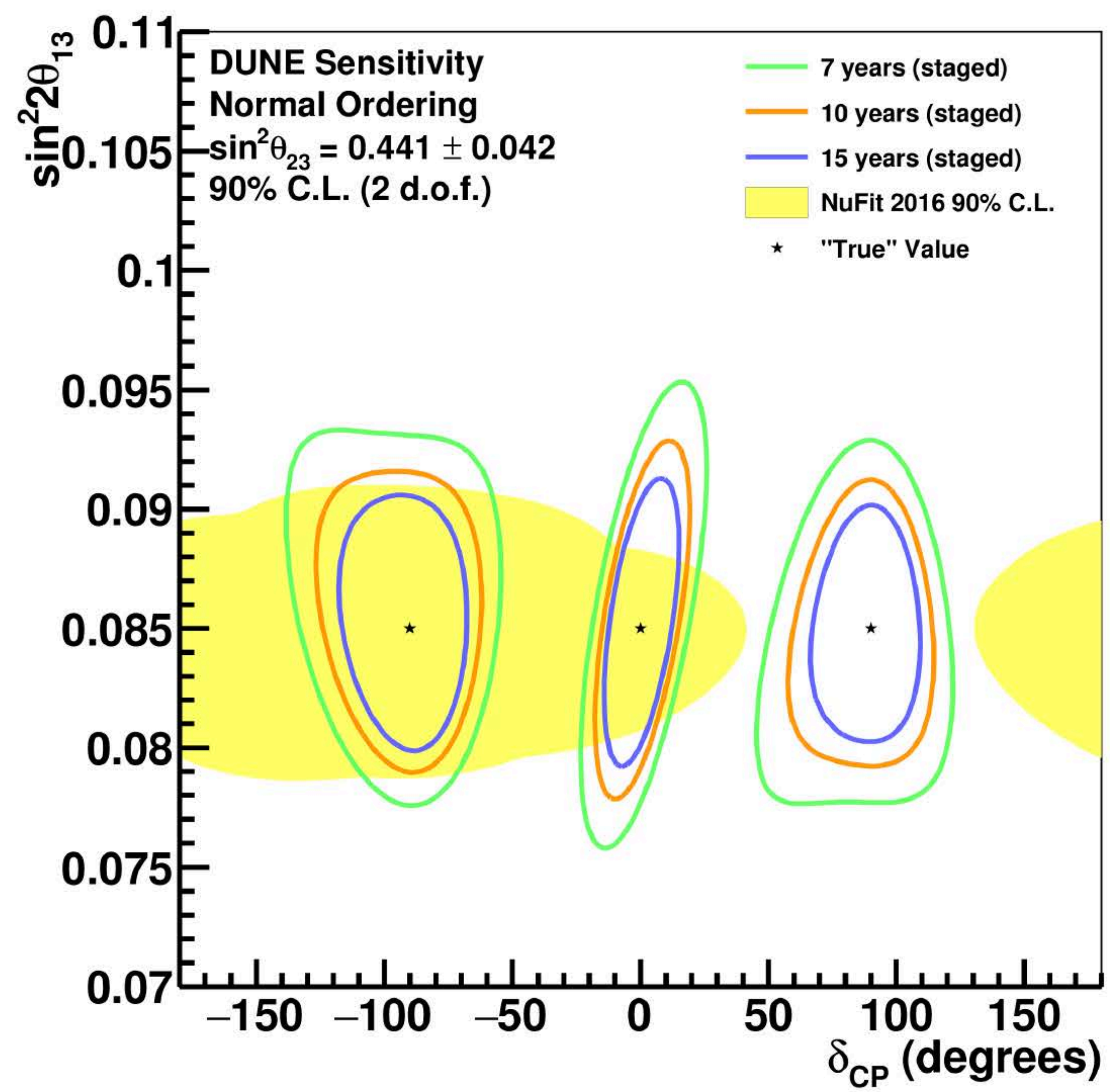


δCP 1σ error
1.3MW beam
1year = 10⁷s
δCP=90°
δCP=0°
Error of δ (degree)
Running time (year)

DUNE



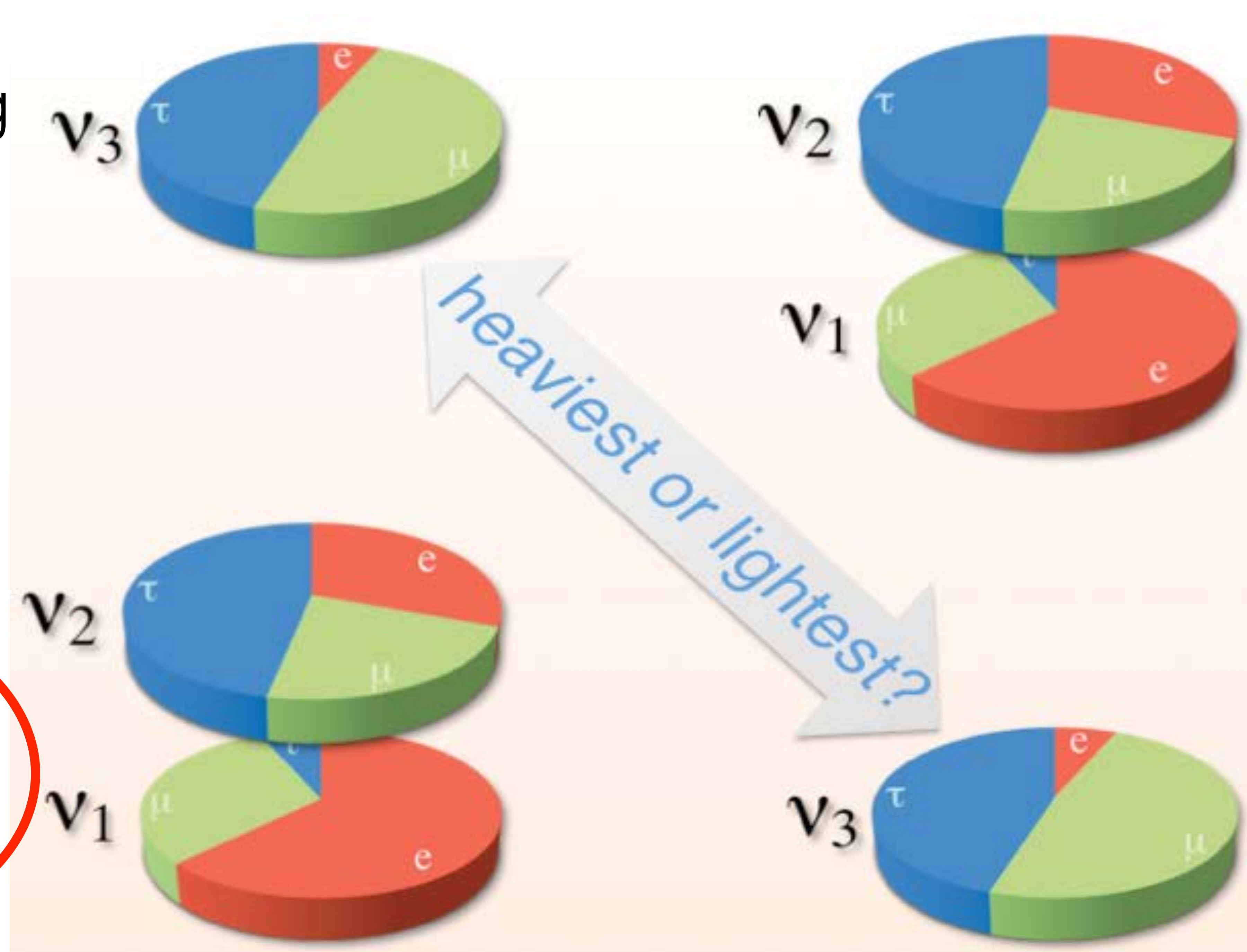
DUNE Sensitivity
Normal Ordering
sin²2θ13 = 0.085 ± 0.003
θ23: NuFit 2016 (90% C.L. range)
7 years (staged)
10 years (staged)
sin²θ23 = 0.441 ± 0.042
5σ
3σ
σ = √Δχ²
δCP/π



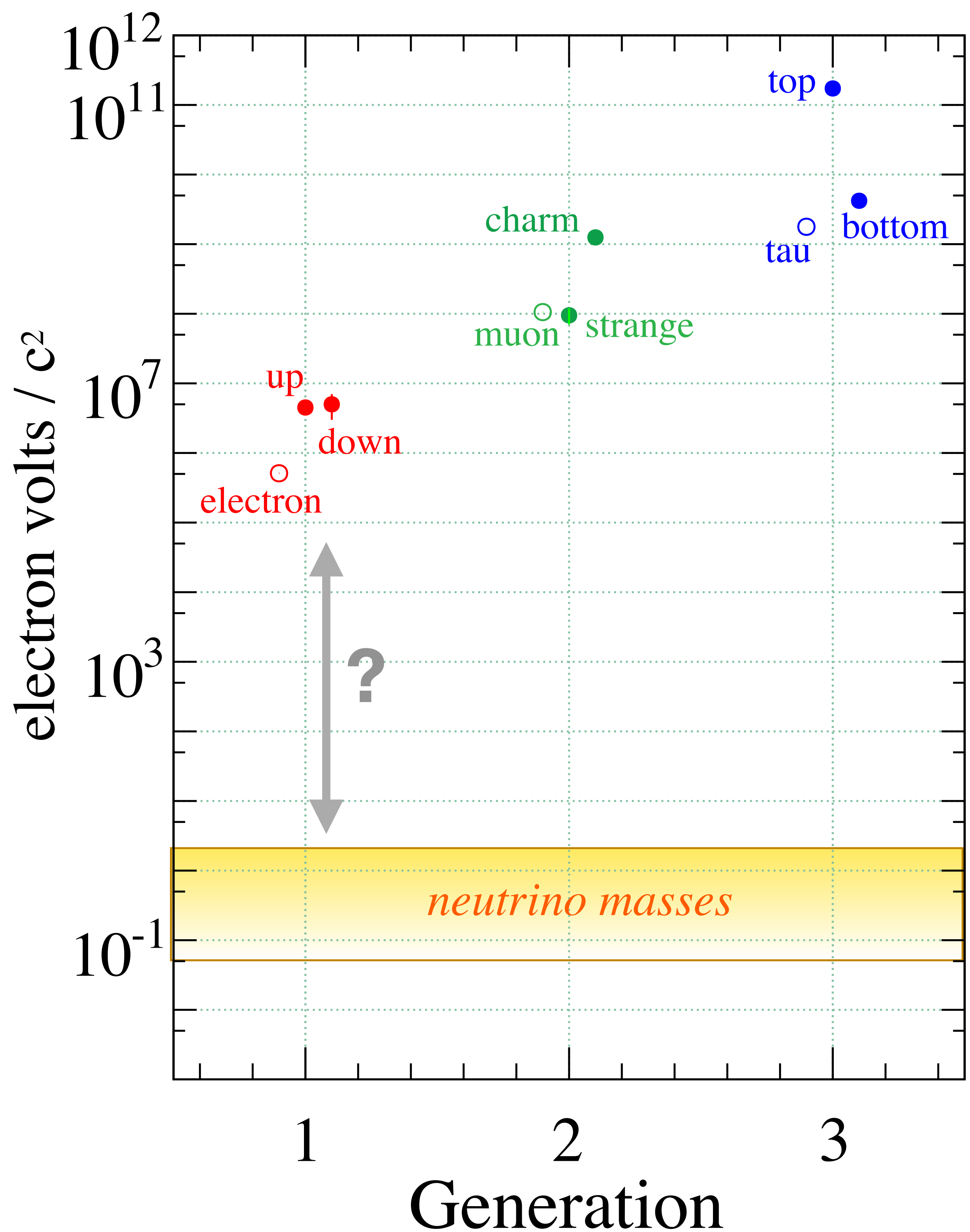
DUNE Sensitivity
Normal Ordering
sin²θ23 = 0.441 ± 0.042
90% C.L. (2 d.o.f.)
7 years (staged)
10 years (staged)
15 years (staged)
NuFit 2016 90% C.L.
"True" Value
sin²2θ13
δCP (degrees)

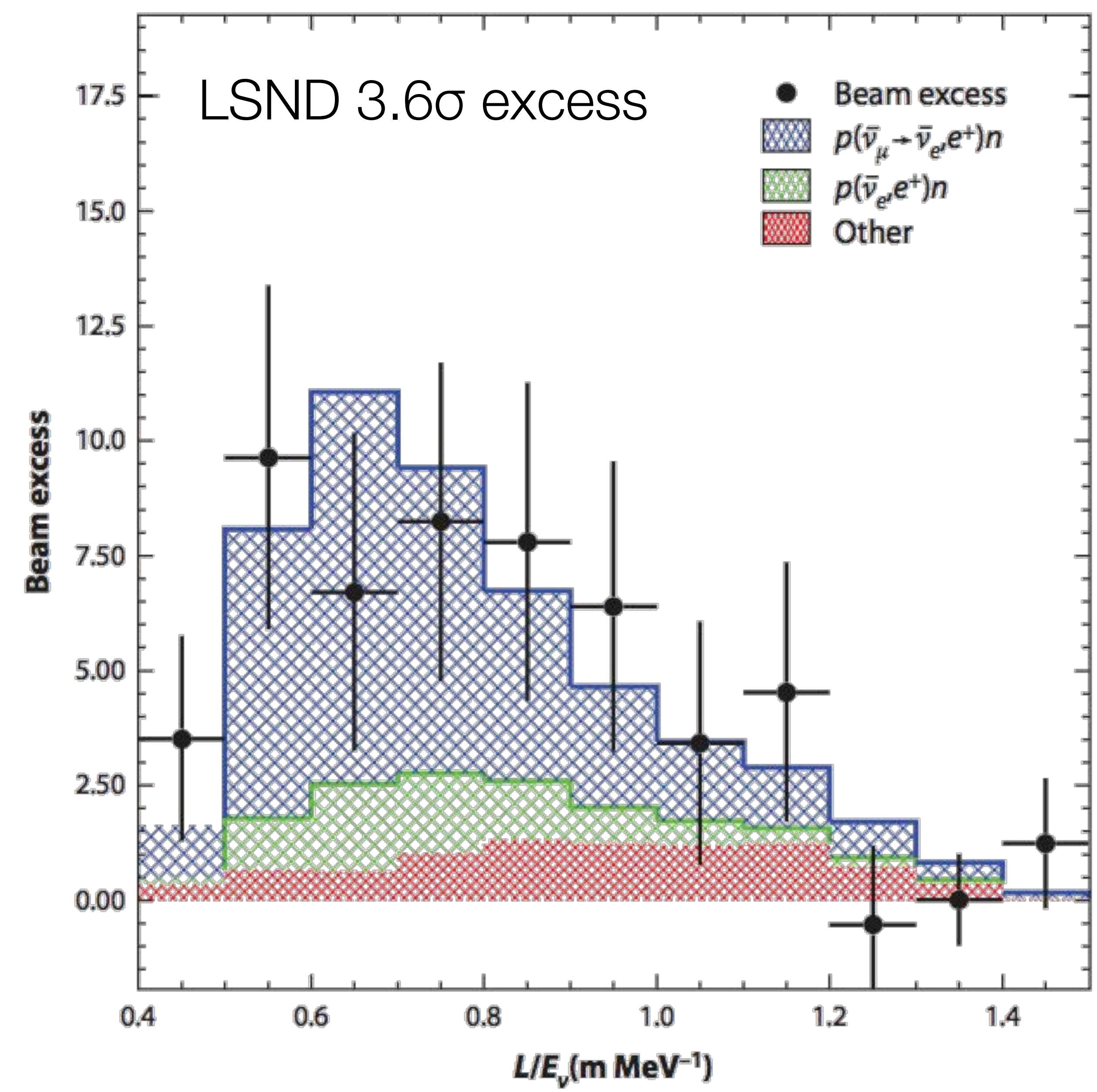
Next Questions In Neutrino Physics

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

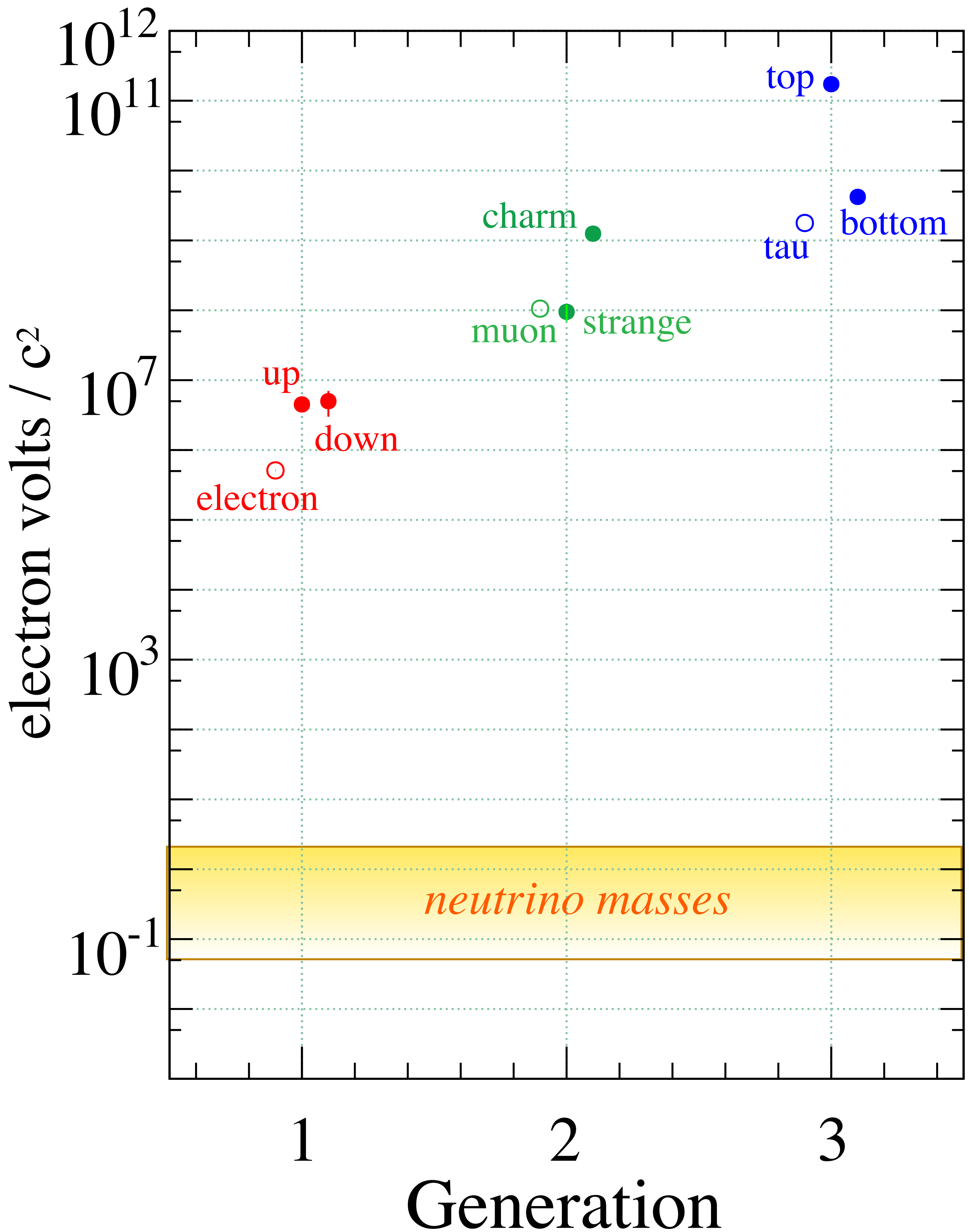


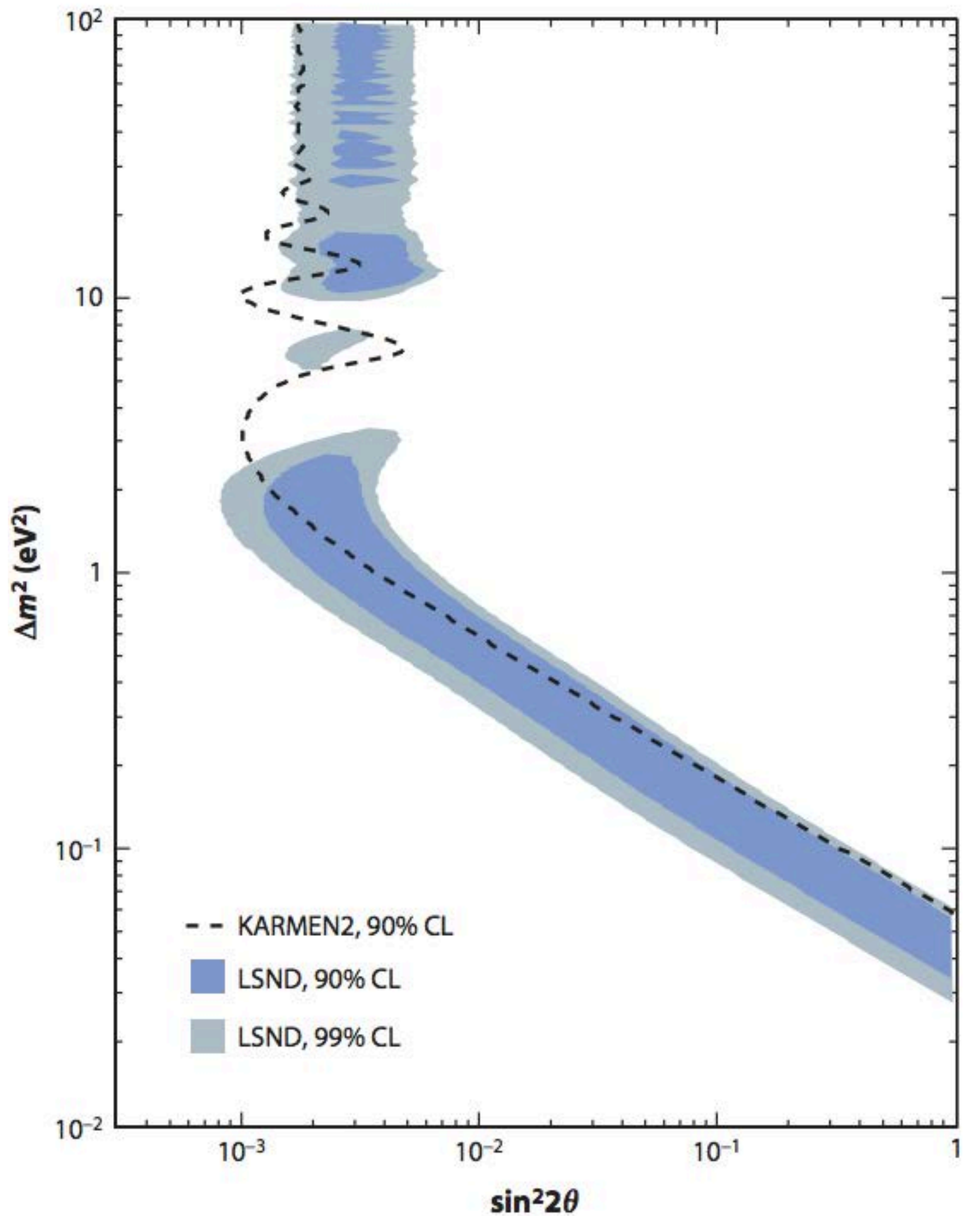
Motivation for sterile neutrino searches



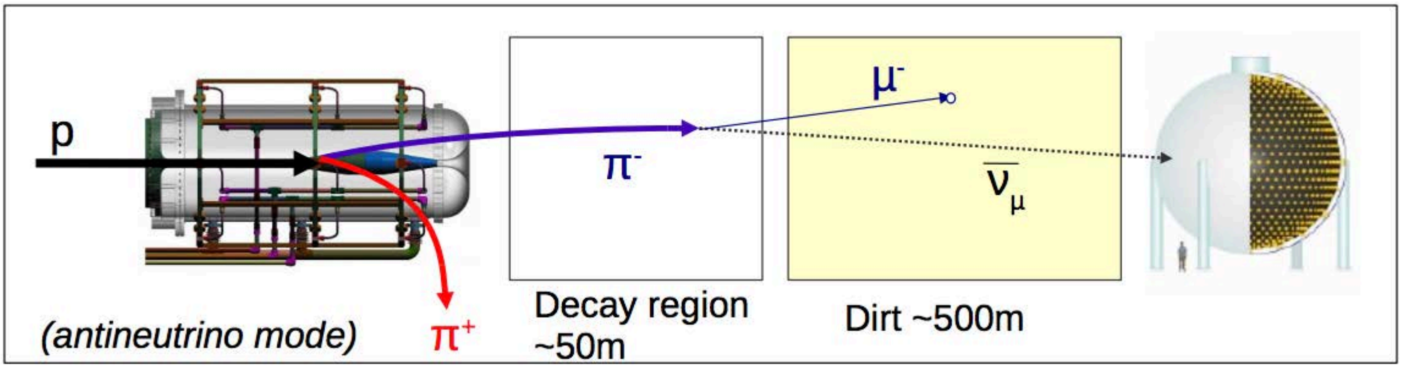


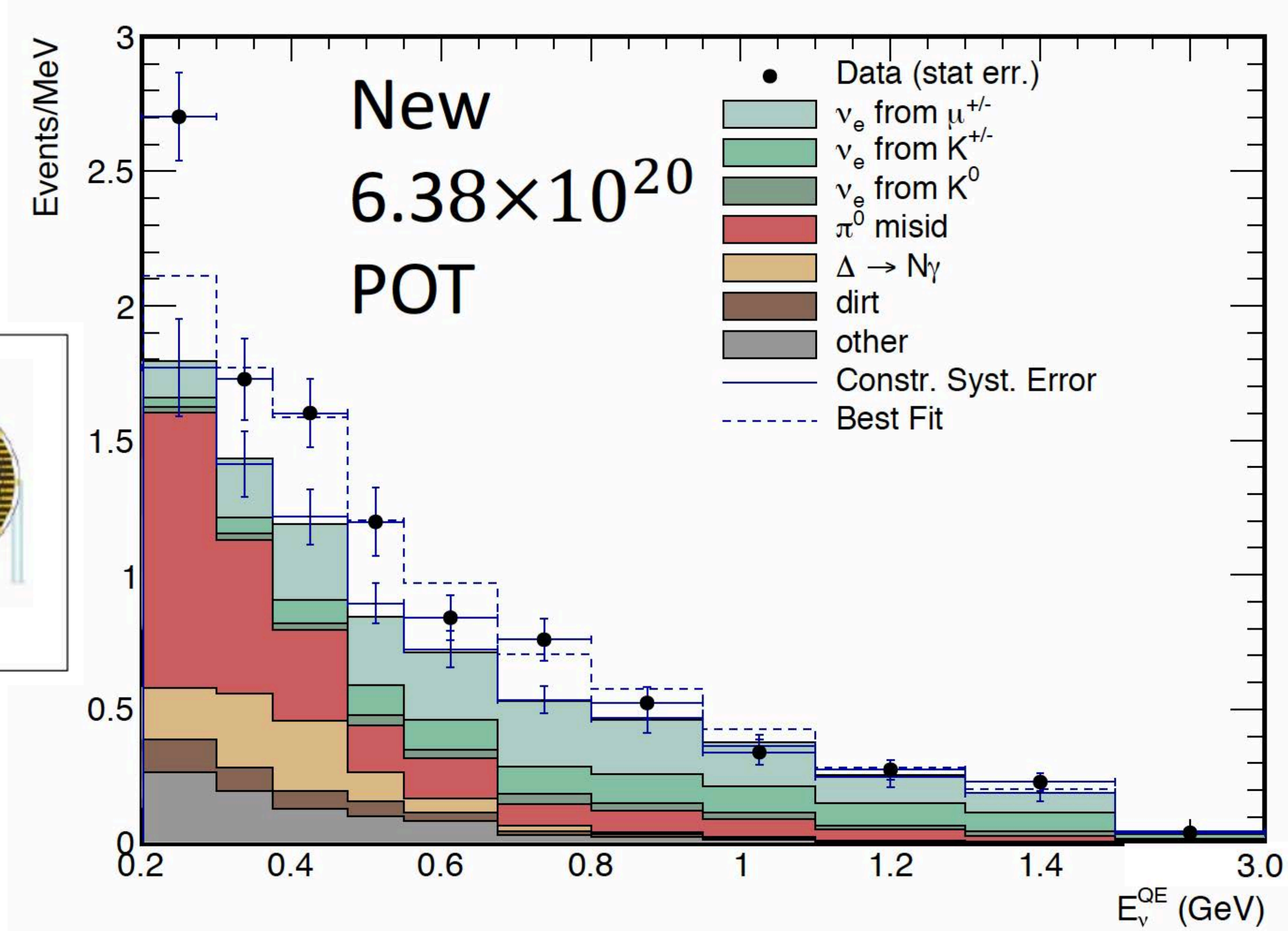
Motivation for sterile neutrino searches

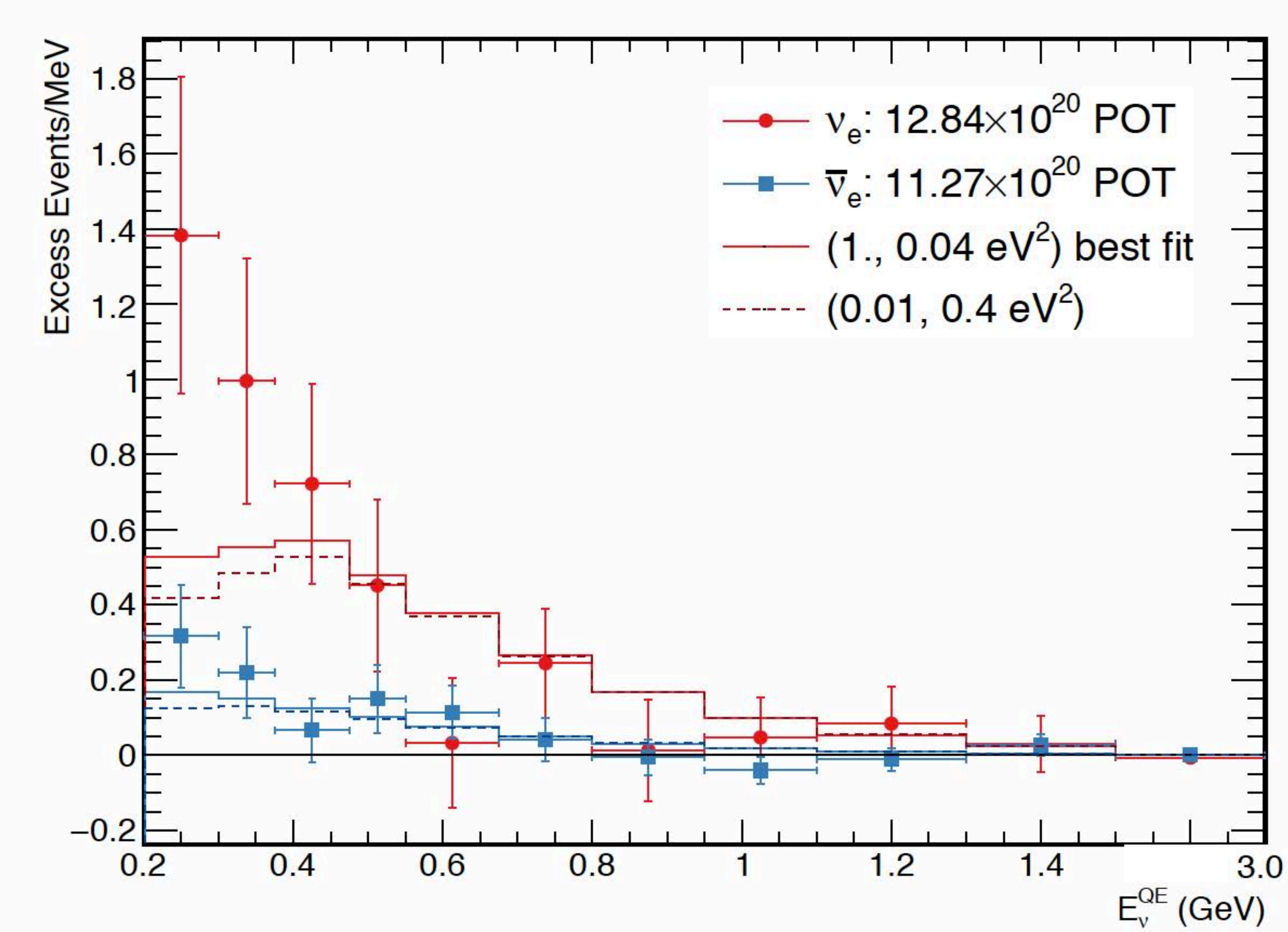




MiniBooNE excess

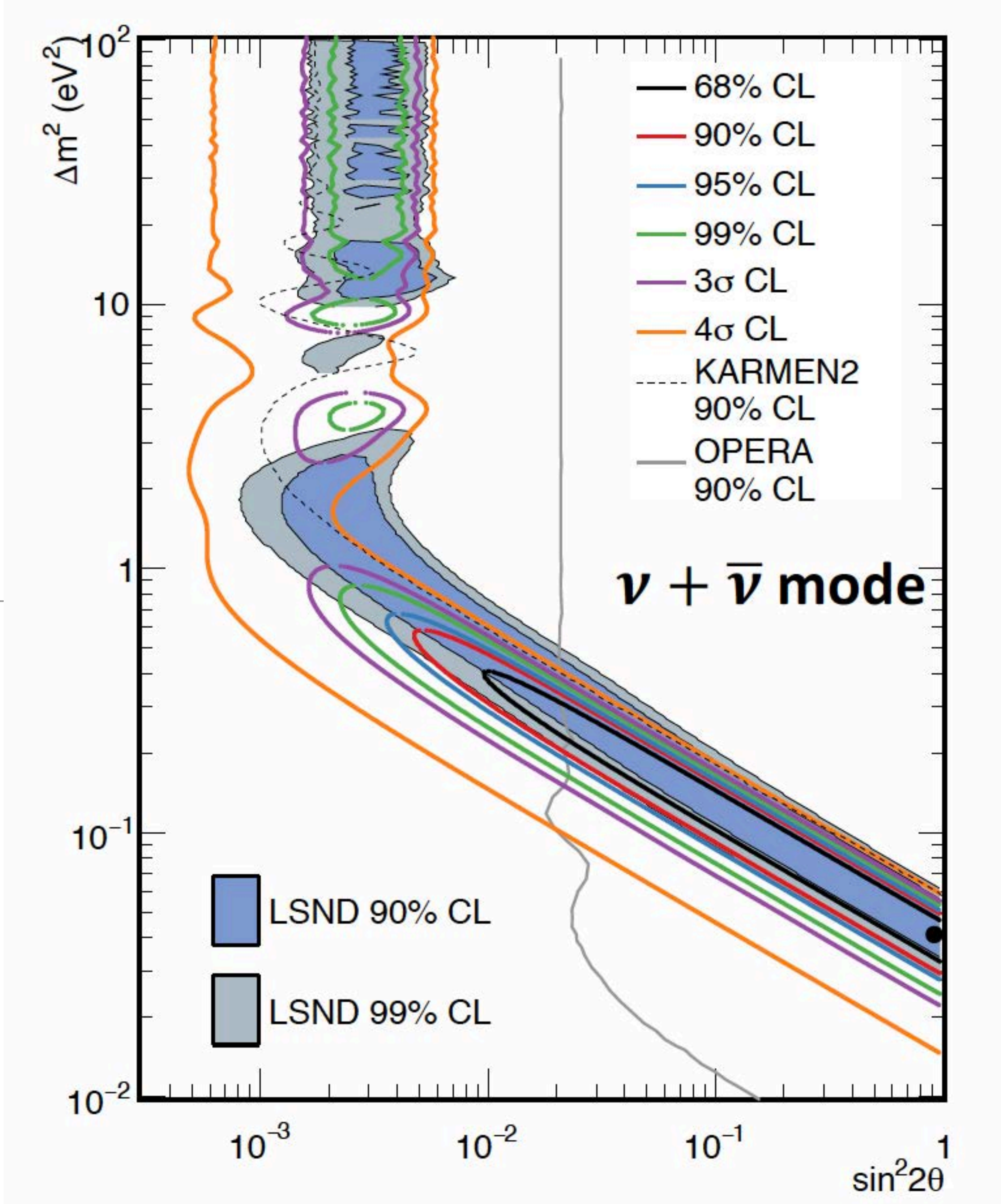






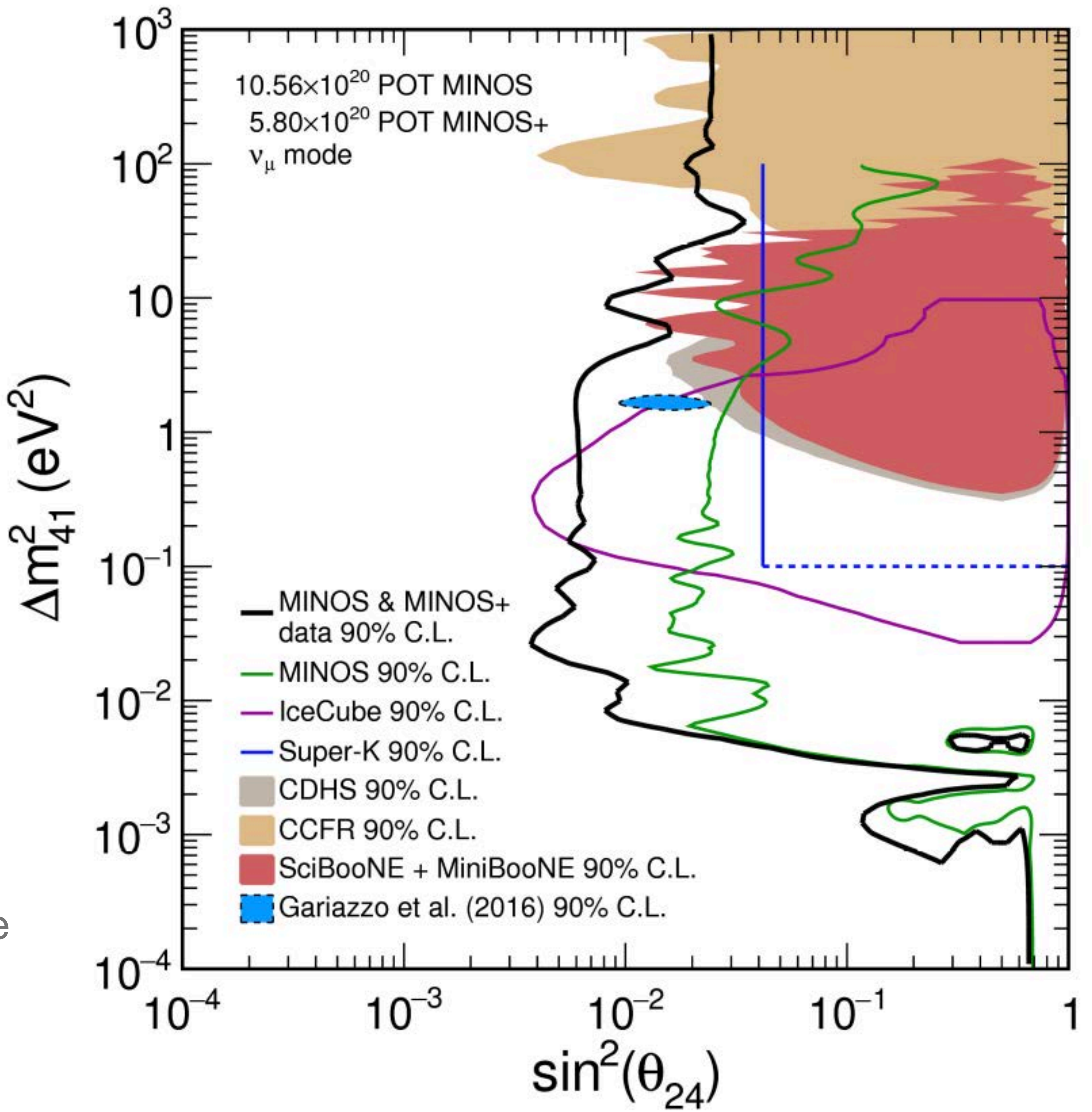
- MiniBooNE is a single-detector experiment on the Fermilab 8 GeV Booster neutrino beam line intended to explore the LSND reported excess.
- MiniBooNE sees an excess over backgrounds at low energies in both neutrino and antineutrino beams.

Interpretations of LSND and MiniBooNE in 3+1



Search for sterile neutrinos in disappearance channel

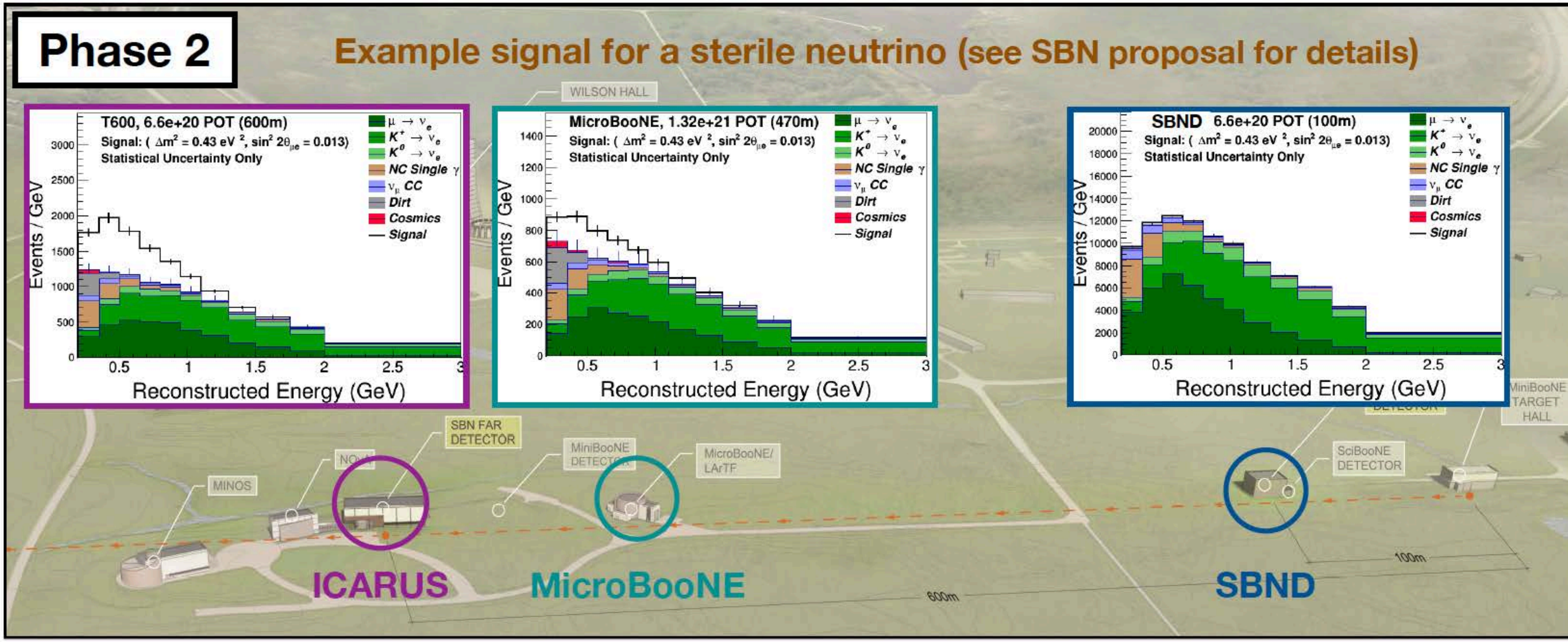
- Electron neutrino appearance through through $\nu_\mu \rightarrow \nu_e$ with eV-scale sterile neutrinos implies additional disappearance in $\nu_\mu \rightarrow \nu_\mu$
- This is not seen by a number of experiments, esp. MINOS and IceCUBE
- This creates a tension: there is no model involving sterile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

Summary

- **20 years on we know a lot about the parameters of neutrino oscillations and the door is open to measure CP violation.**
- **Current program will answer many outstanding questions and make progress on others**
  - Nature of ν_3 - θ_{23} octant
  - **Mass ordering**
  - **Are neutrinos Majoranna or Dirac?**
  - Is CP violated?
  - Is there more to neutrino oscillations than 3 flavors?
- Measurement of CP violation and its interpretation will require more intense beams, bigger and better detectors, better understanding of neutrino interactions, and better analysis techniques. All of these are topics for this workshop.