The wide world of **Neutrino Experiments**

TRISEP 2019 summer school

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TRIUMF
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Office of Science
U.S. Department of Energy

Disclaimer

- I speak (too) fast in English… sorry…
- Please! ask me to repeat or slow down
- It is OK to raise your hand or interrupt with a question

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Feedback? Comments? mahn@pa.msu.edu

Outline

Open questions

How do we study neutrino oscillation? Is our understanding of neutrino mixing complete?

What do we know about neutrino mass?

Neutrinos as probes: neutrino astrophysics, coherent neutrino scattering

Outline

Open questions

U.S. Strategic plan: “P5”

http://inspirehep.net/record/1299183

3.2: Pursue the Physics Associated with Neutrino Mass

Do neutrinos and antineutrinos oscillate differently? (CPV)

Are there additional neutrino types and interactions?

How are the neutrino masses ordered?

NEUTRINO OSCILLATION

What is the origin of neutrino mass?

What are the neutrino masses?

NEUTRINO-LESS DOUBLE BETA DECAY

Are neutrinos their own antiparticles?

DIRECT MASS

Why do I do this?

- Fundamental particle we know still SO little about
- Experimentally driven field
  - Incredible challenges to devise, operate and complete these experiments
- Field is complementary, competitive with other particle physics, nuclear physics

What do we know about neutrino oscillation?

Flavor states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass states

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Mass states

PDG review: Phys. Rev. D 98, 030001 (2018).

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Neutrino oscillation experiments measure mixing angles and mass splittings

Three mixing angles, one phase

What do we know about neutrino oscillation?

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Majorana phases accessible from neutrino-less double beta decay (more tomorrow)

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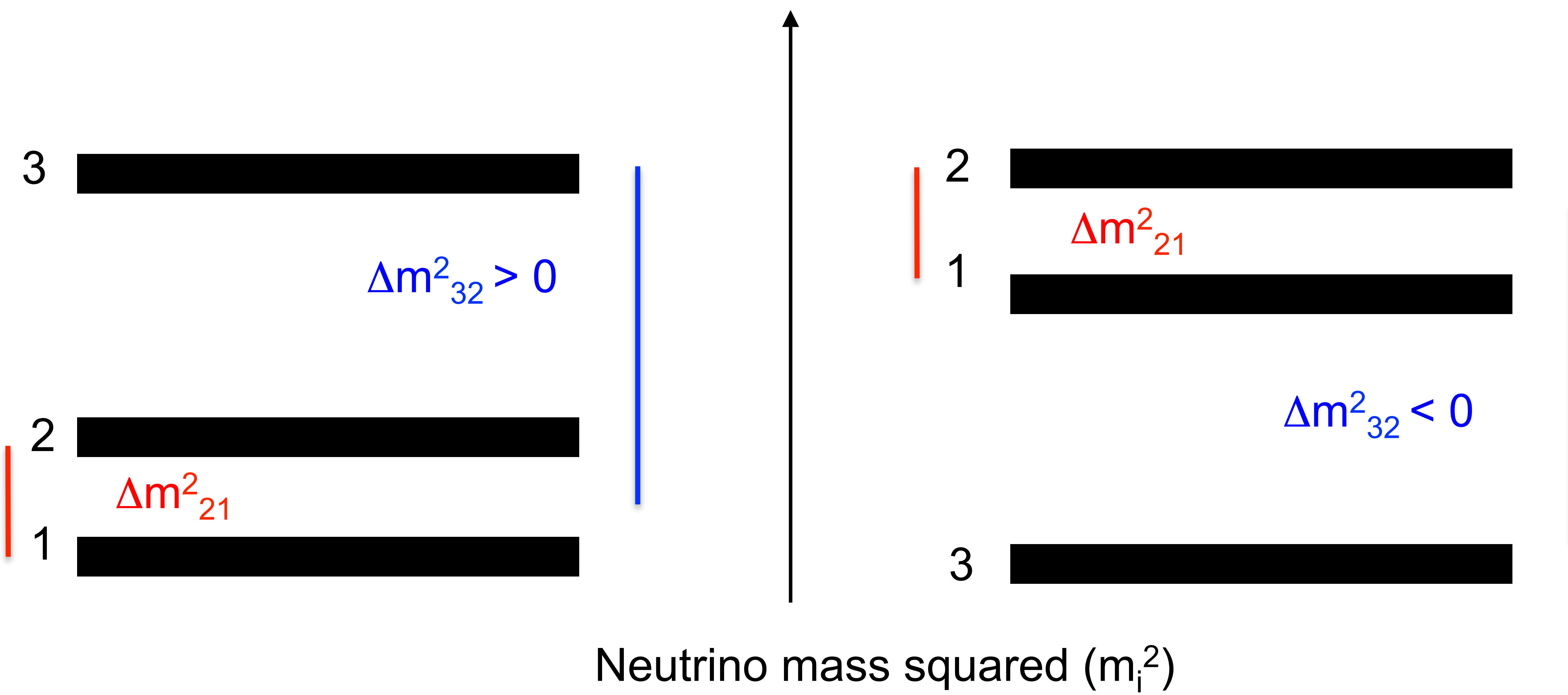
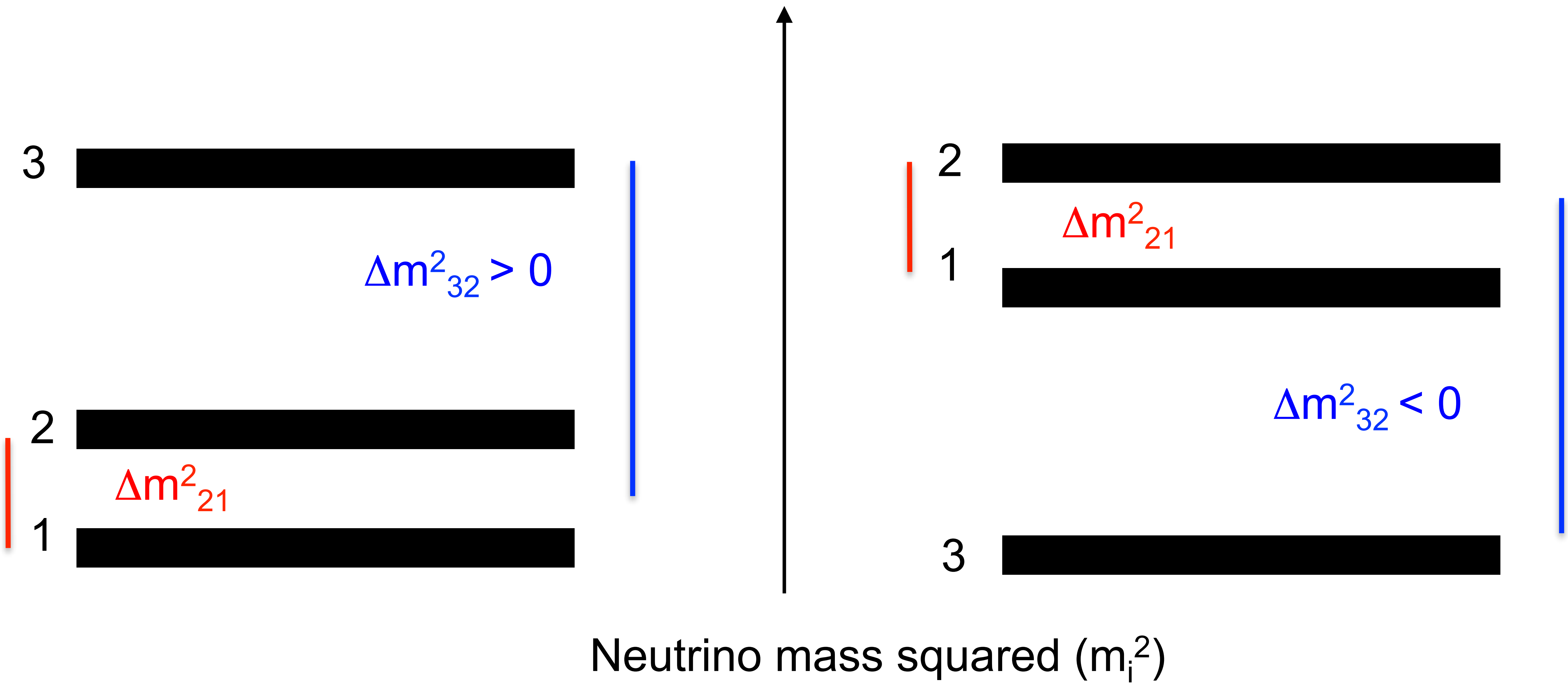


Mass splitting:$|\Delta m^2_{32/31}|, \Delta m^2_{21}$

What do we know about neutrino oscillation?

Flavor states
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$
Mass states



- $\Delta m^2_{32/31} > 0$: "normal" hierarchy, $\Delta m^2_{32/31} < 0$: "inverted" hierarchy

What do we know about neutrino oscillation?

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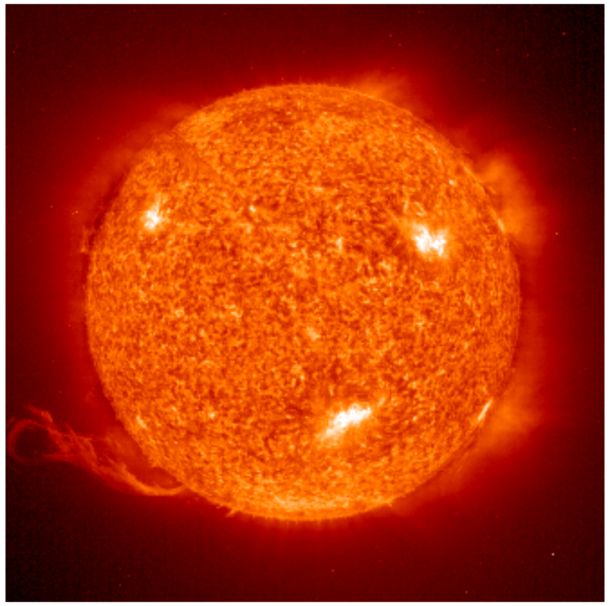
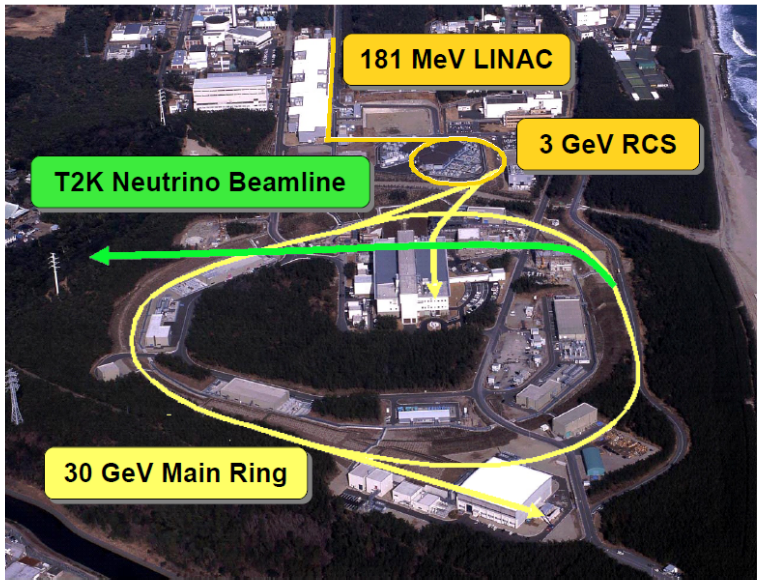
Is this matrix unitary? Are there 3 mass/flavor states?

“Flavors” of oscillation experiments

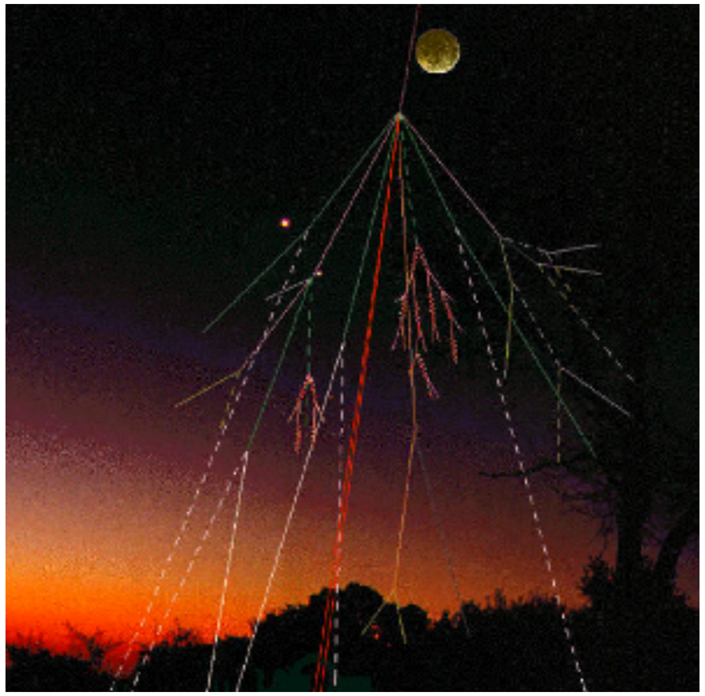


Solar

Reactor



Accelerator



Atmospheric

How neutrino oscillation experiments work: Two flavor case

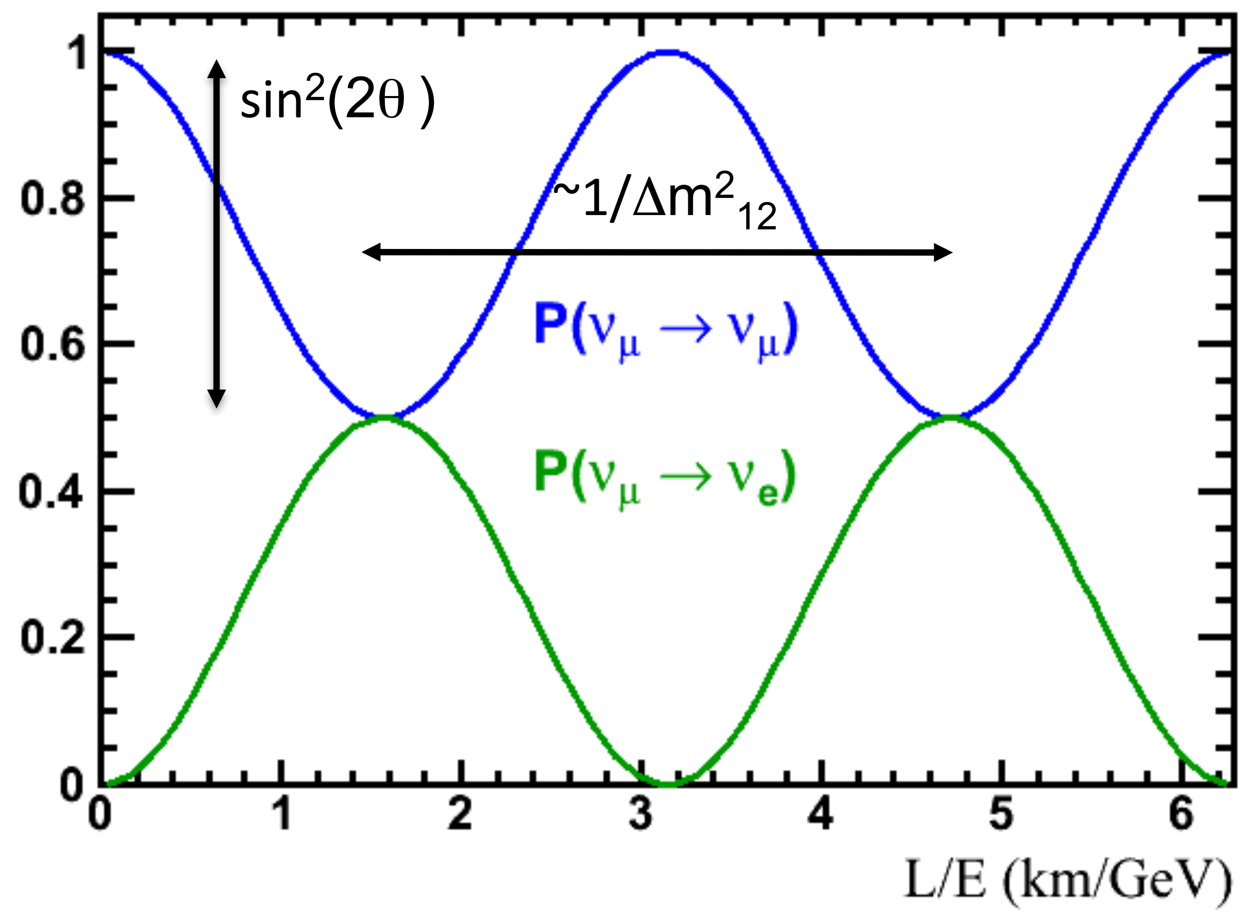
$$P_{\mu e} = \sin^2(2\theta)\ \sin^2(1.27\Delta m^2_{12} L/E)$$

Probability to observe ν_ε after starting in flavor state ν_μ depends on:

- θ: Mixing angle
- L (km): Distance the neutrino has travelled
- E (GeV): Energy of the neutrino
- Δm^2 (eV^2): mass splitting

  Difference of the square of the mass eigenvalues

$$\Delta m^2_{12} = m_1^2 - m_2^2$$



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Difference of the square of the mass eigenvalues

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Typically, an experiment has L and E determined from the neutrino source and detector setup

and measures Δm^2, θ

L/E (km/GeV)

What do we know about neutrino oscillation?

$|\Delta m^2_{32}| >> \Delta m^2_{21}$, producing high frequency and low frequency oscillation terms

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin^2\left(\frac{1.27\Delta m^2_{ij}L}{E}\right) + 2\sum_{i>j} \mathrm{Im}\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin\left(\frac{2.54\Delta m^2_{ij}L}{E}\right)$$

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If choose L, E, such that $\sin^2(\Delta m^2_{32}L/E)$ is of order 1, then Δm^2_{21} terms will be small. Then...

ν_μ "disappear" into ν_e, ν_τ

$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right)$$

A small amount of ν_e will "appear"

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

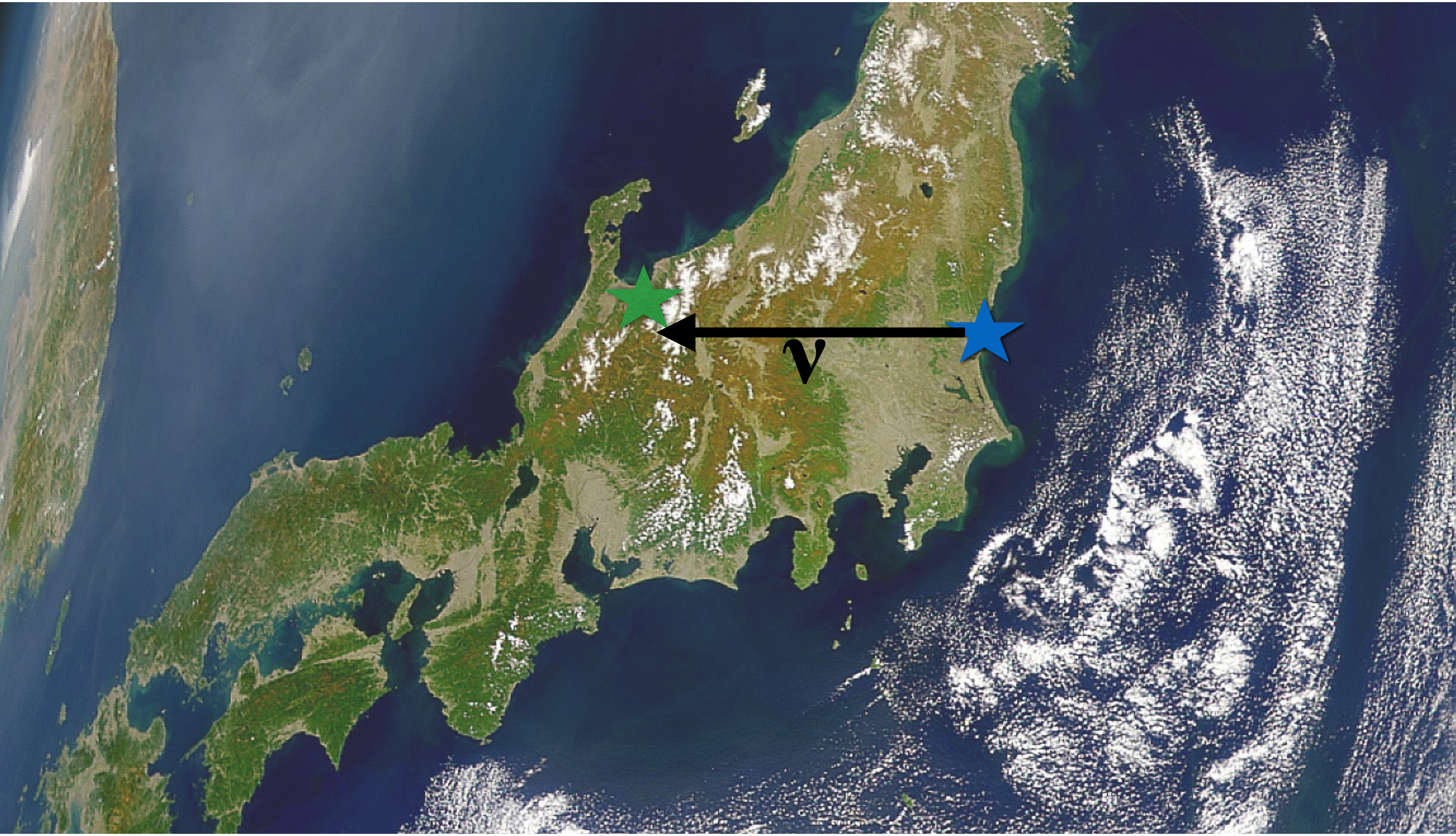
$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{31}L}{E}\right)$$

Only leading order terms shown

Long baseline experiments

$$P(\nu_\mu \rightarrow \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right) + \ldots$$

Long baseline experiments



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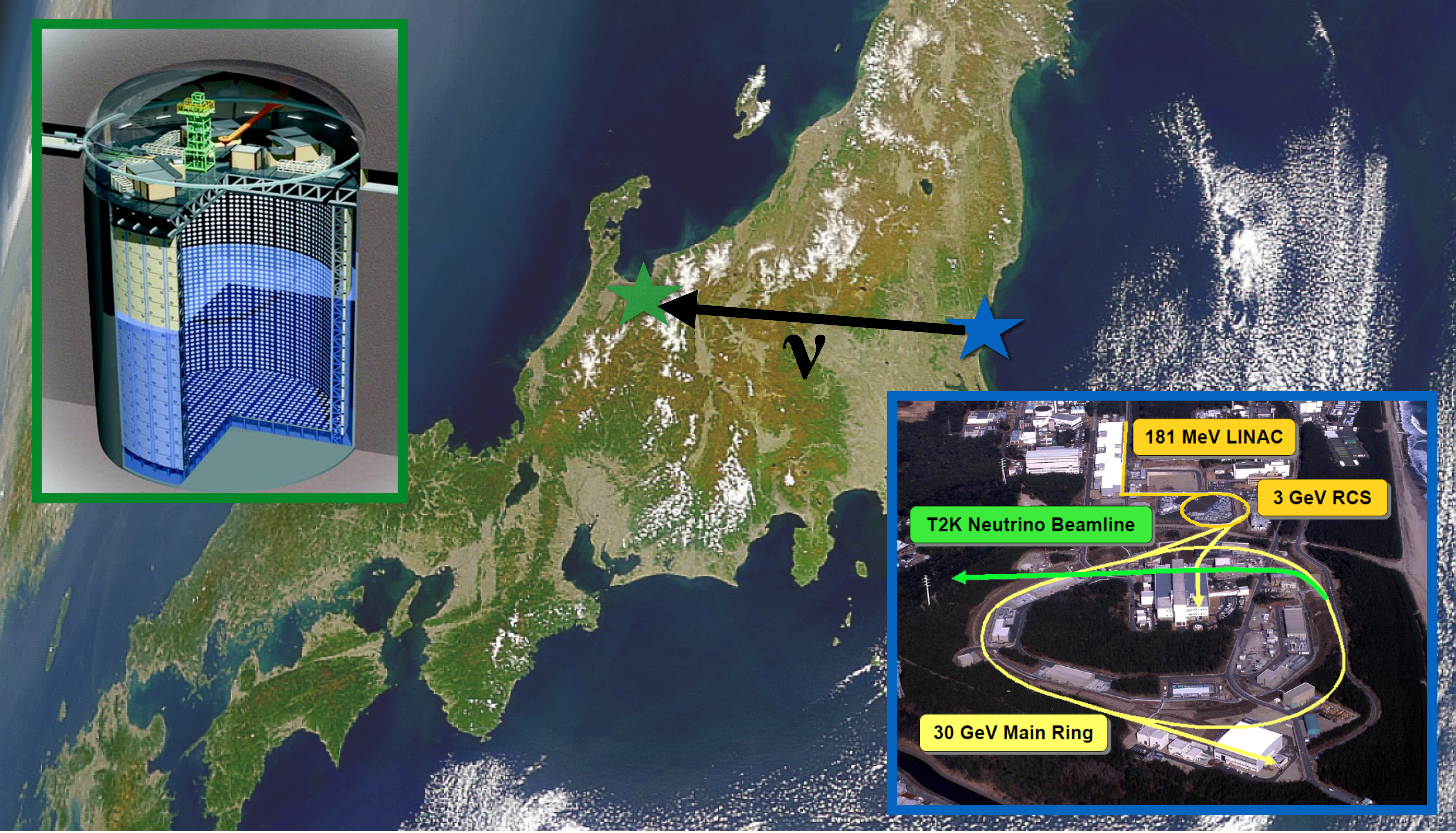


Example: Tokai-to-Kamioka experiment (~500 person collaboration)

- **Accelerator** produces an intense source
- Massive **far detector** (Super-Kamiokande)

Outline

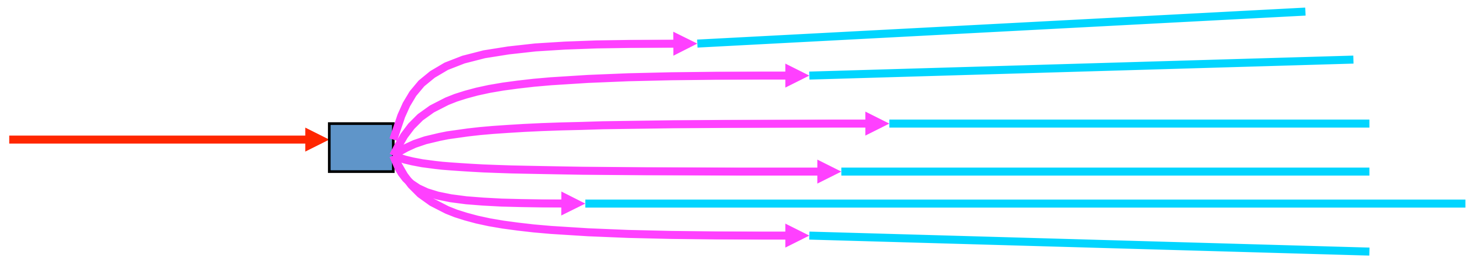
How do we study neutrino oscillation? Is our understanding of neutrino mixing complete?

Accelerator based neutrinos

Reactor and solar neutrinos

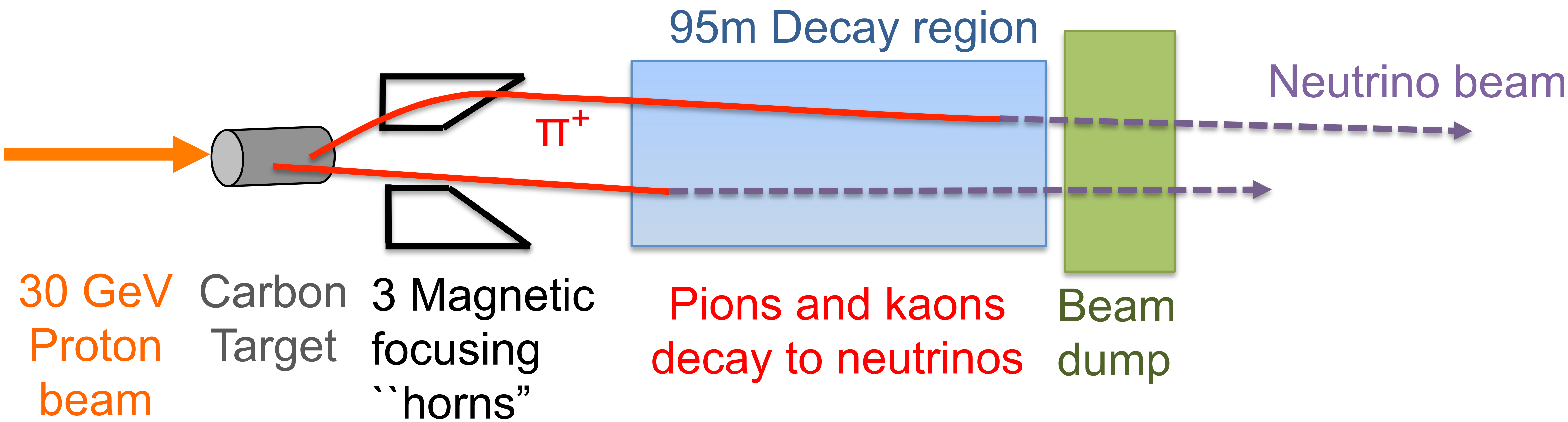
Accelerator-produced neutrino beams

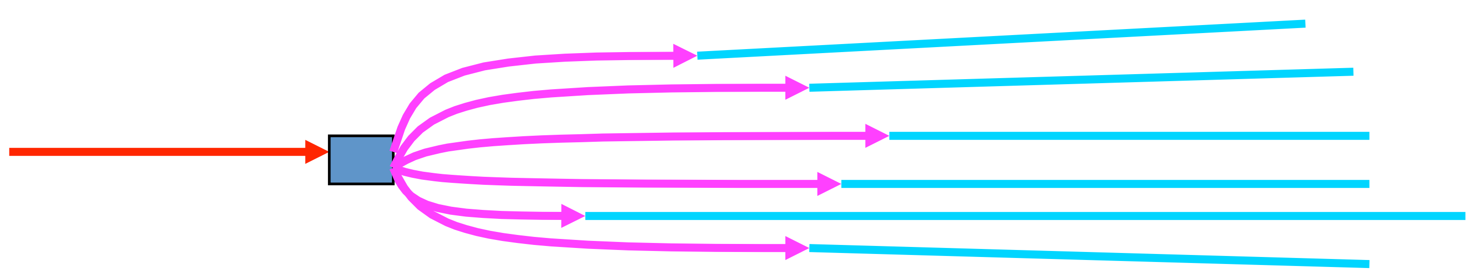
Electrical current hits a filament producing light focused into a beam



protons→carbon target→unstable particles→neutrinos

Accelerator-produced neutrino beams





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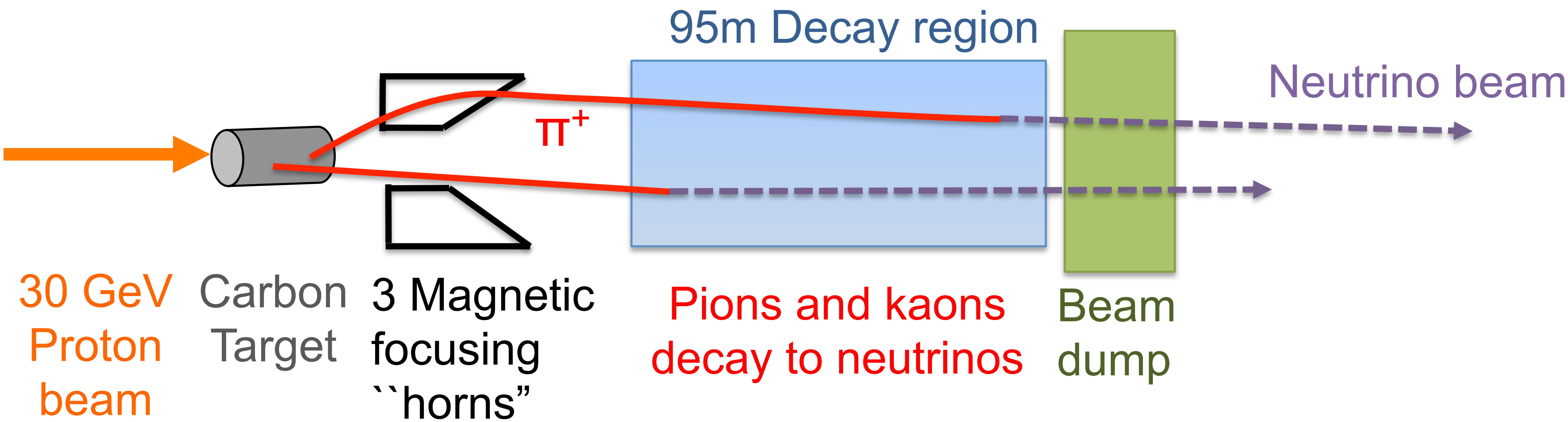

Tunable energy!

Can be neutrino or antineutrino!

99% pure muon neutrino beam!

Oscillation analysis strategy

$\Delta m^2_{32/31}$, θ_{13}, θ_{23}, δ_{CP}, mass hierarchy

$$N_{FD}^{\alpha\rightarrow\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true};E_{reco}) \times \boxed{P_{\alpha\beta}(E_{true})}$$

Determine oscillation parameters from **event rates**

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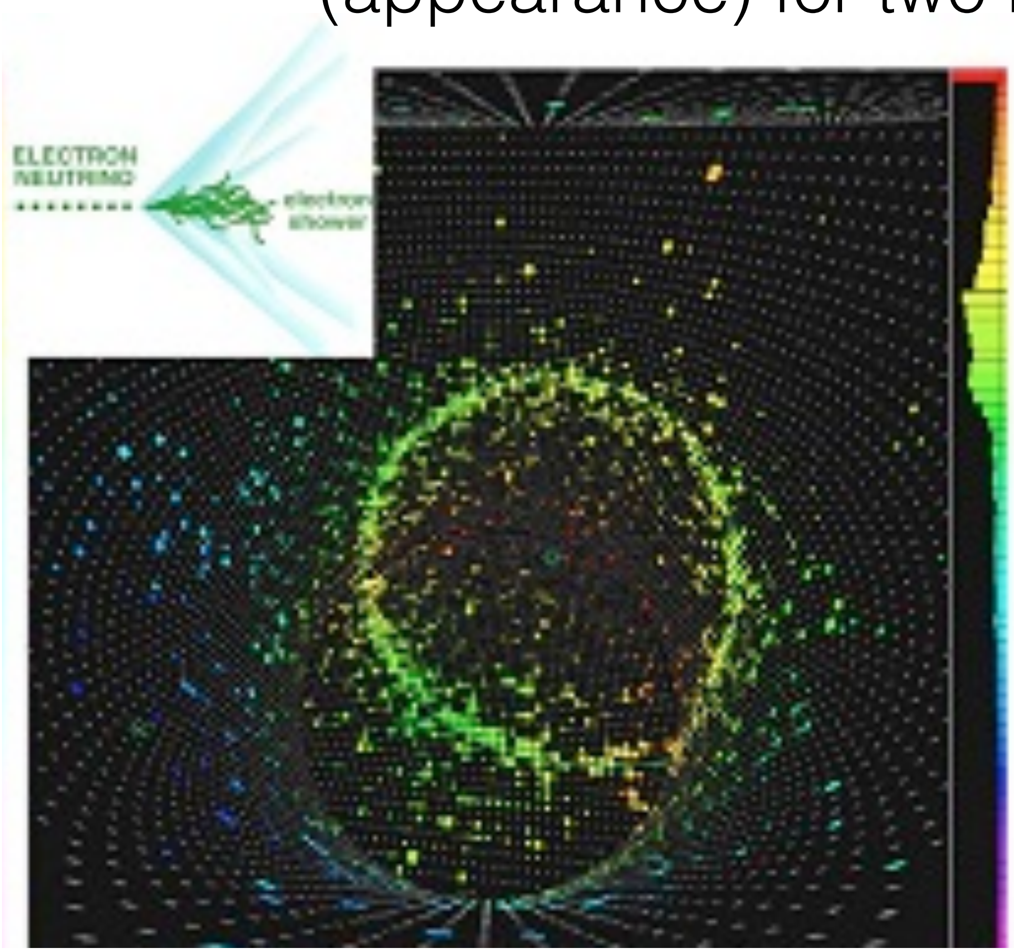
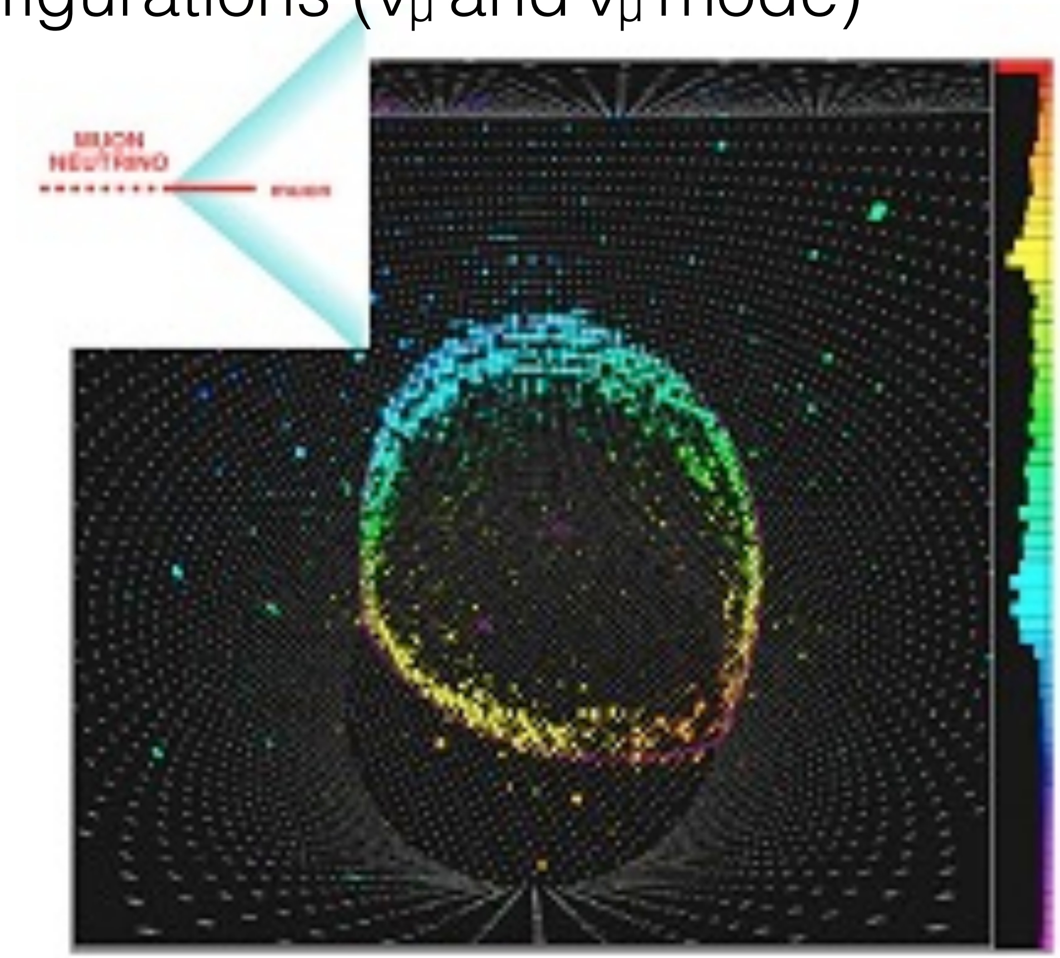
Cherenkov detectors separate flavor via ring toplogy

Four samples: ν_μ and $\bar{\nu}_\mu$ candidates (disappearance) and ν_e and $\bar{\nu}_e$ candidates (appearance) for two run configurations (ν_μ and $\bar{\nu}_\mu$ mode)





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Flux (Φ)

Interaction model (cross section, σ)

Relationship between truth and observables (R)

Efficiency (ϵ)

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Flux (Φ)

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Hadron production experiments

Accelerator R&D

Beamline monitoring

Electron scattering data

Neutrino scattering data

Theoretical modelling

Simulation and software development

Simulation development

Detector R&D

External measurements, including test beams

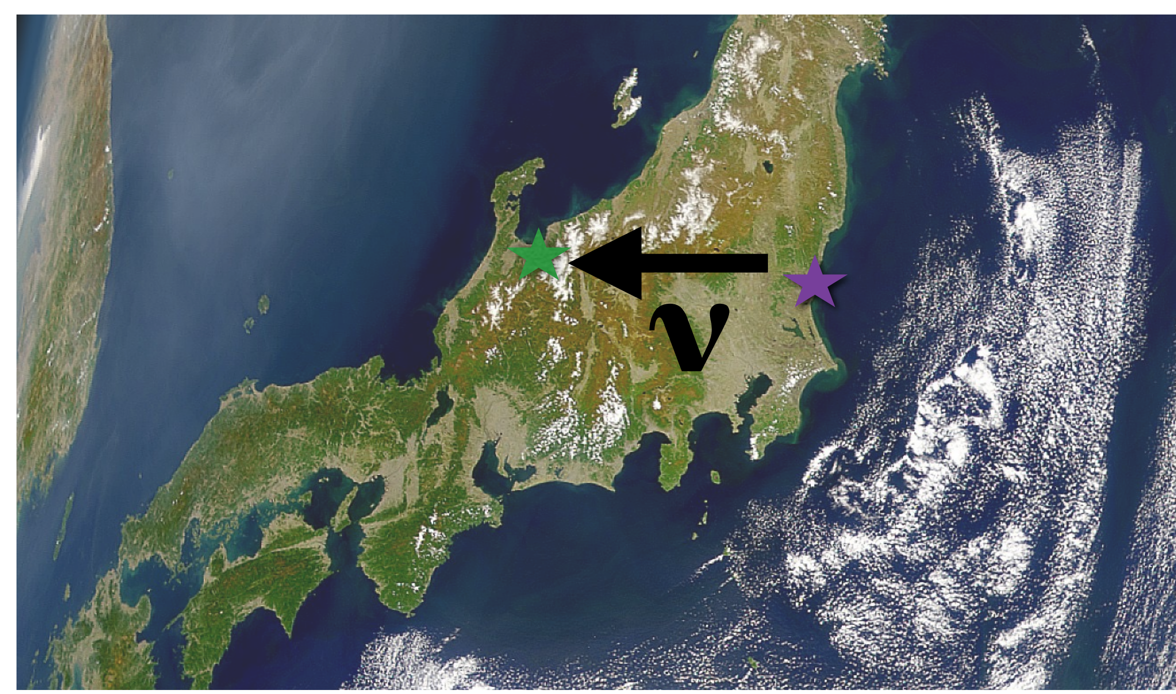
Oscillation analysis strategy

$\Delta m^2_{32/31}$, θ_{13}, θ_{23}, δ_{CP}, mass hierarchy

$$N_{FD}^{\alpha \to \beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco}) \times P_{\alpha\beta}(E_{true})$$

$$N_{ND}^{\alpha}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\alpha^i(E_{true}) \times \epsilon_\alpha(E_{true}) \times R_i(E_{true}; E_{reco})$$

- Near detector information provide stability monitoring, improved event rate prediction and reduces shared systematic uncertainty



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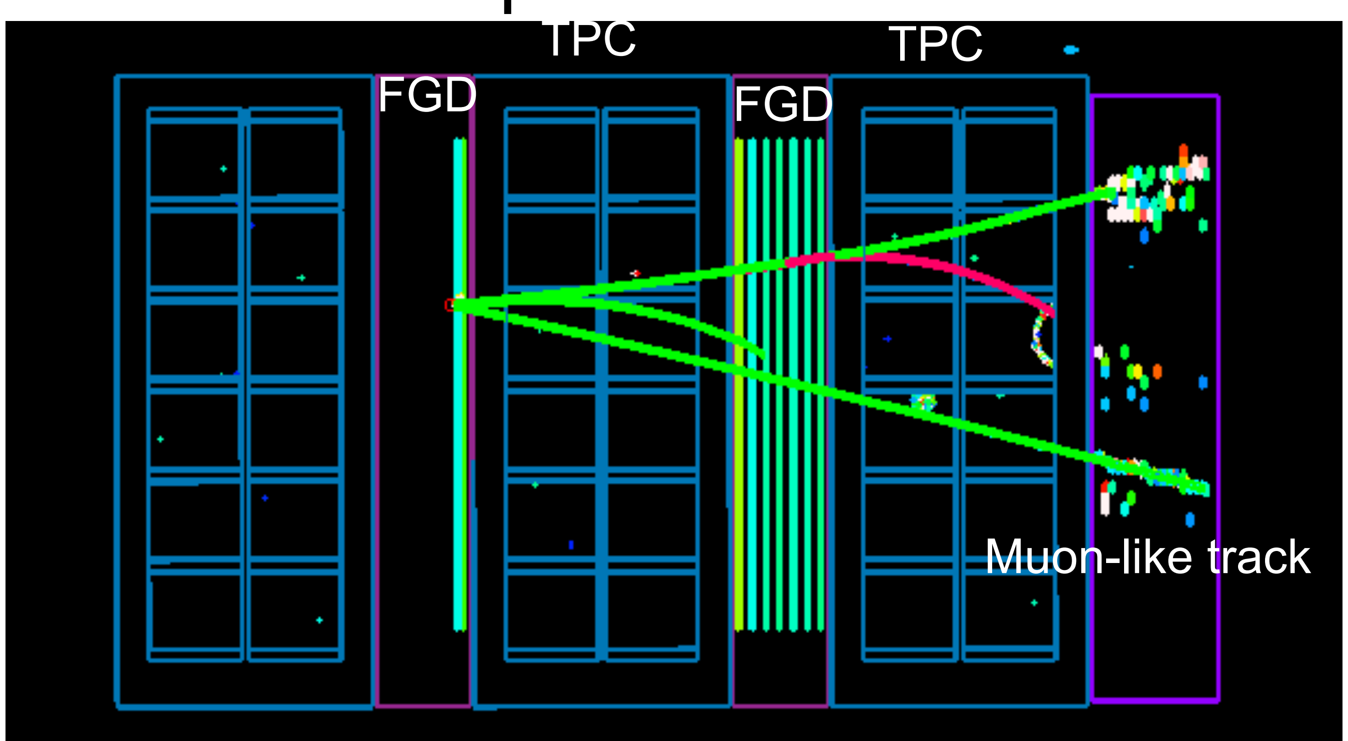
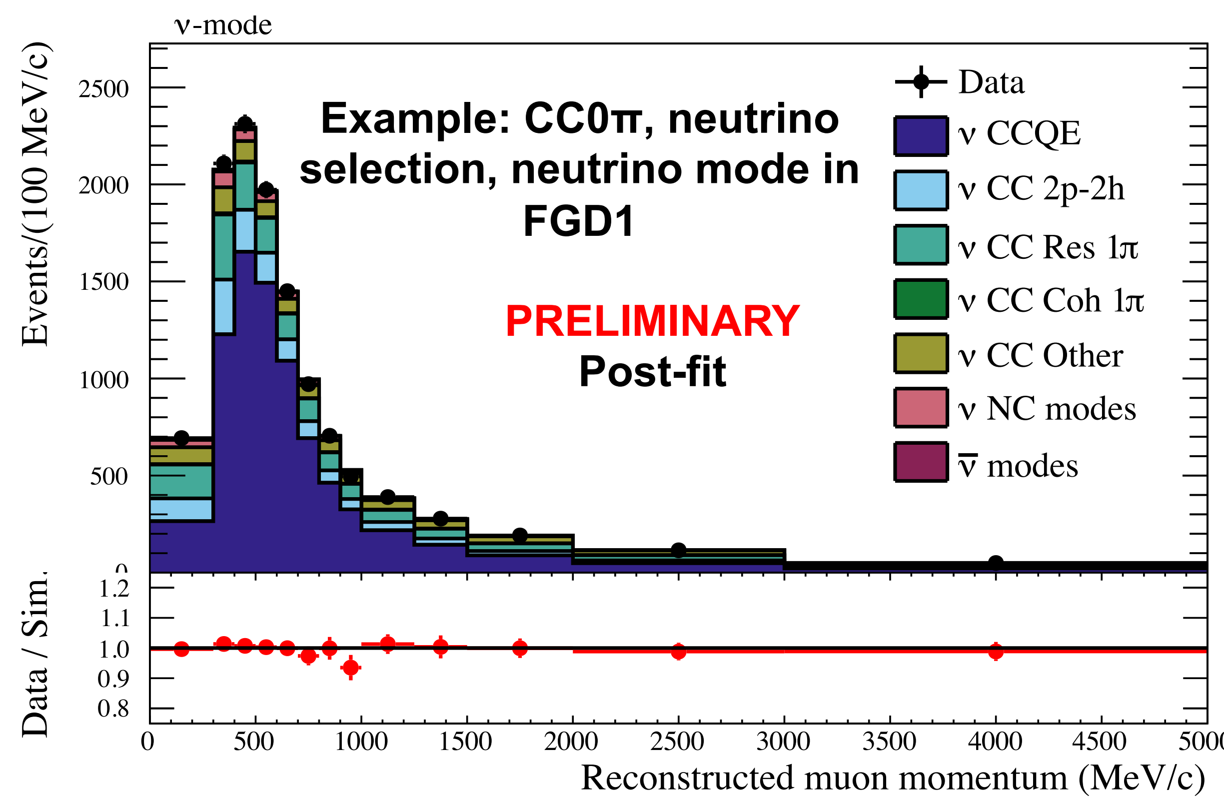


Example: neutrino candidate in antineutrino mode



Neutrino oscillation open questions

Oscillation depends on:

- Amplitude determined by mixing angles: θ_{12}, θ_{23}, θ_{13}
- Frequency determined by mass splittings: $|\Delta m^2_{32/31}|$,Δm^2_{21}
- CP violating phase (CPV)

Is $\sin^2(\theta_{23})=0.5$? (maximal mixing?)

What is the ordering of the masses (mass hierarchy, $\Delta m^2_{32/31} > 0$?)

Is there CPV in neutrinos?

Is this picture complete? Are there non-standard effects or sterile neutrinos?

Neutrino oscillation open questions

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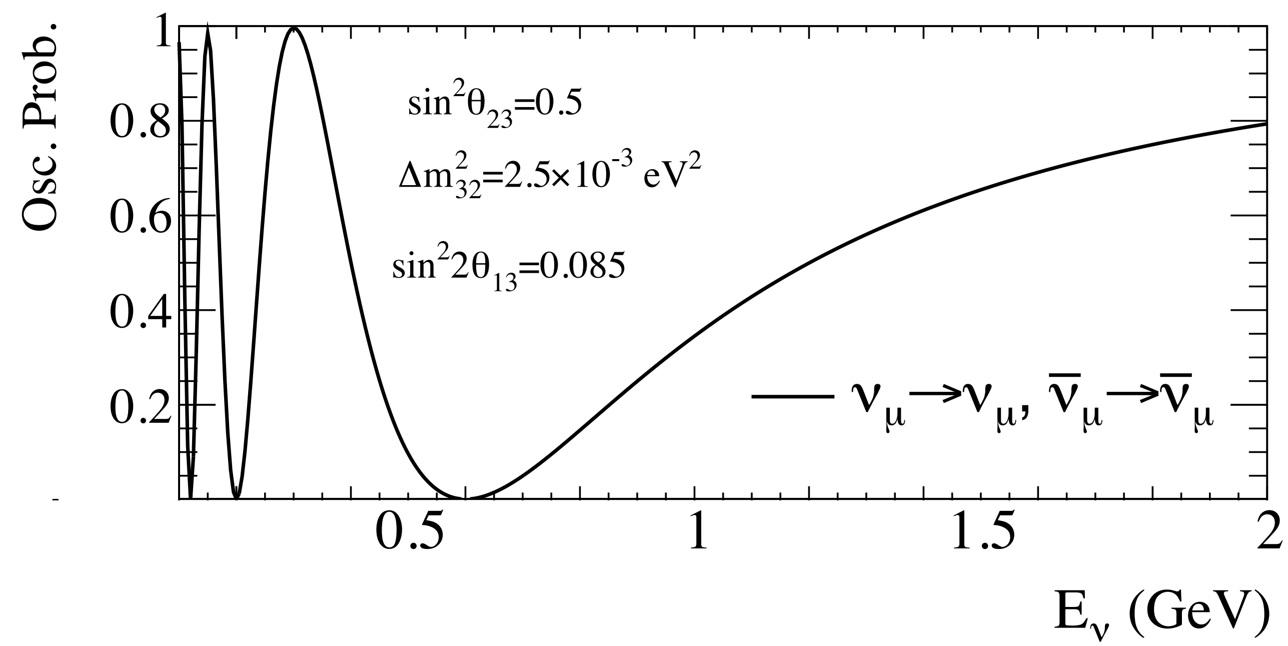
- **Amplitude** determined by mixing angles: θ_{12}, θ_{23}, θ_{13}
- **Frequency** determined by mass splittings: $|\Delta m^2_{32/31}|$, Δm^2_{21}

ν_μ and $\bar{\nu}_\mu$ disappearance channel



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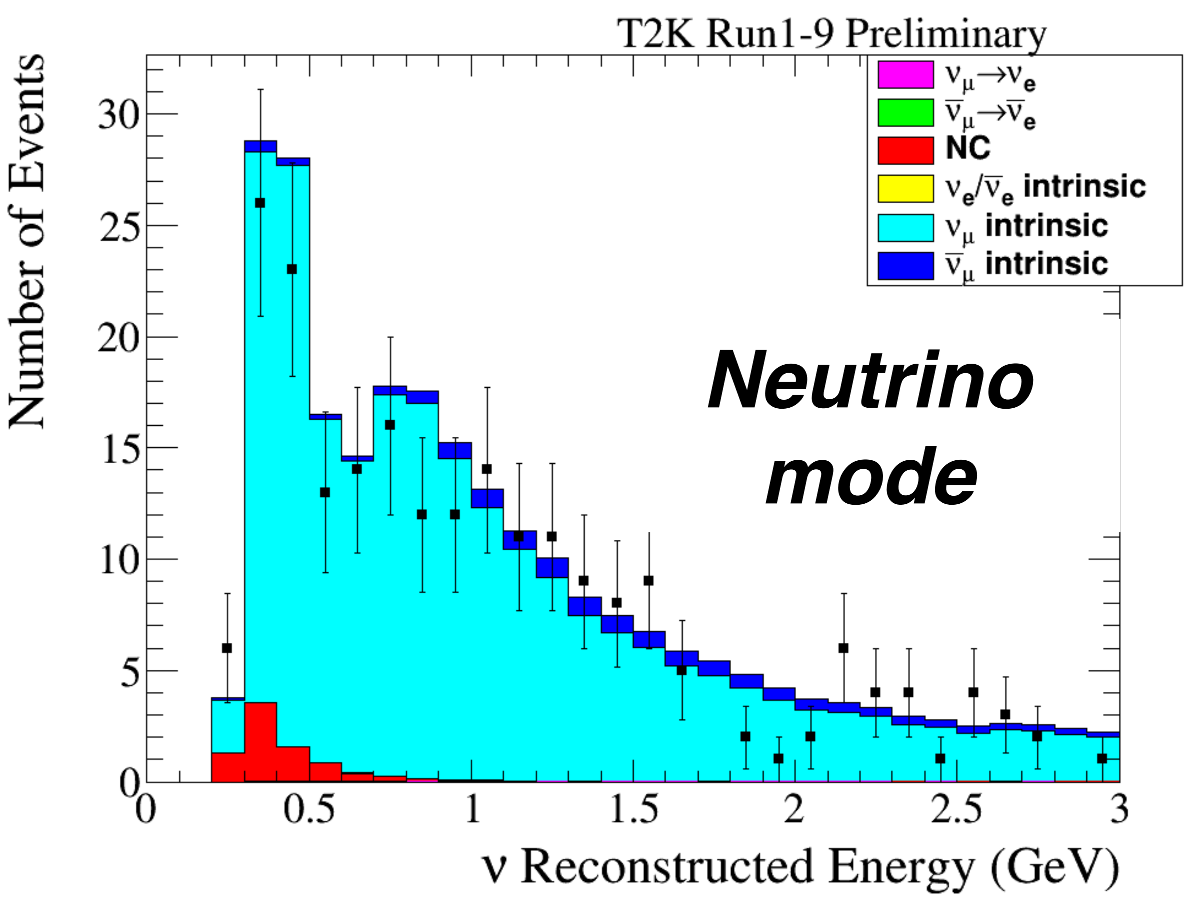
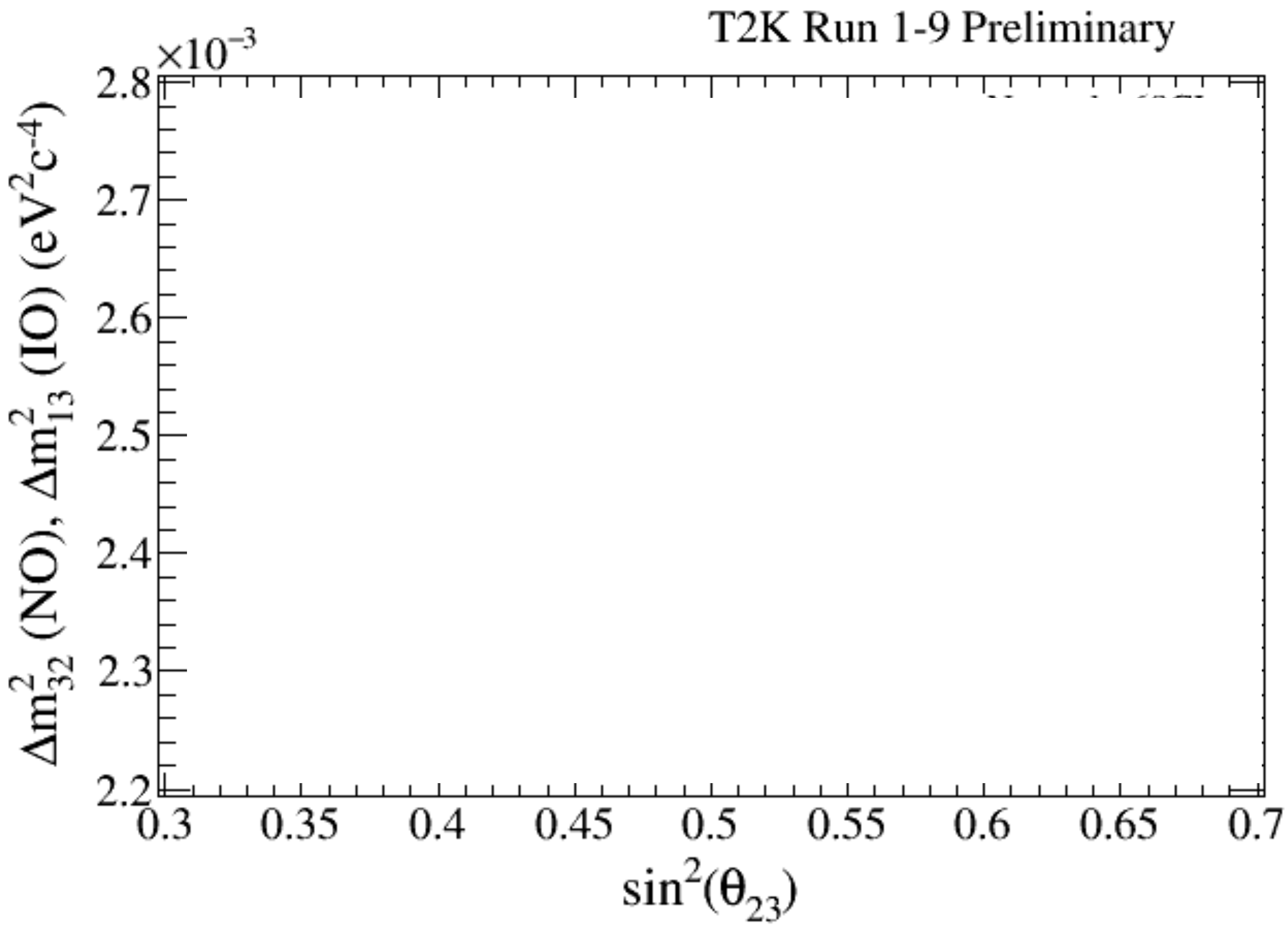
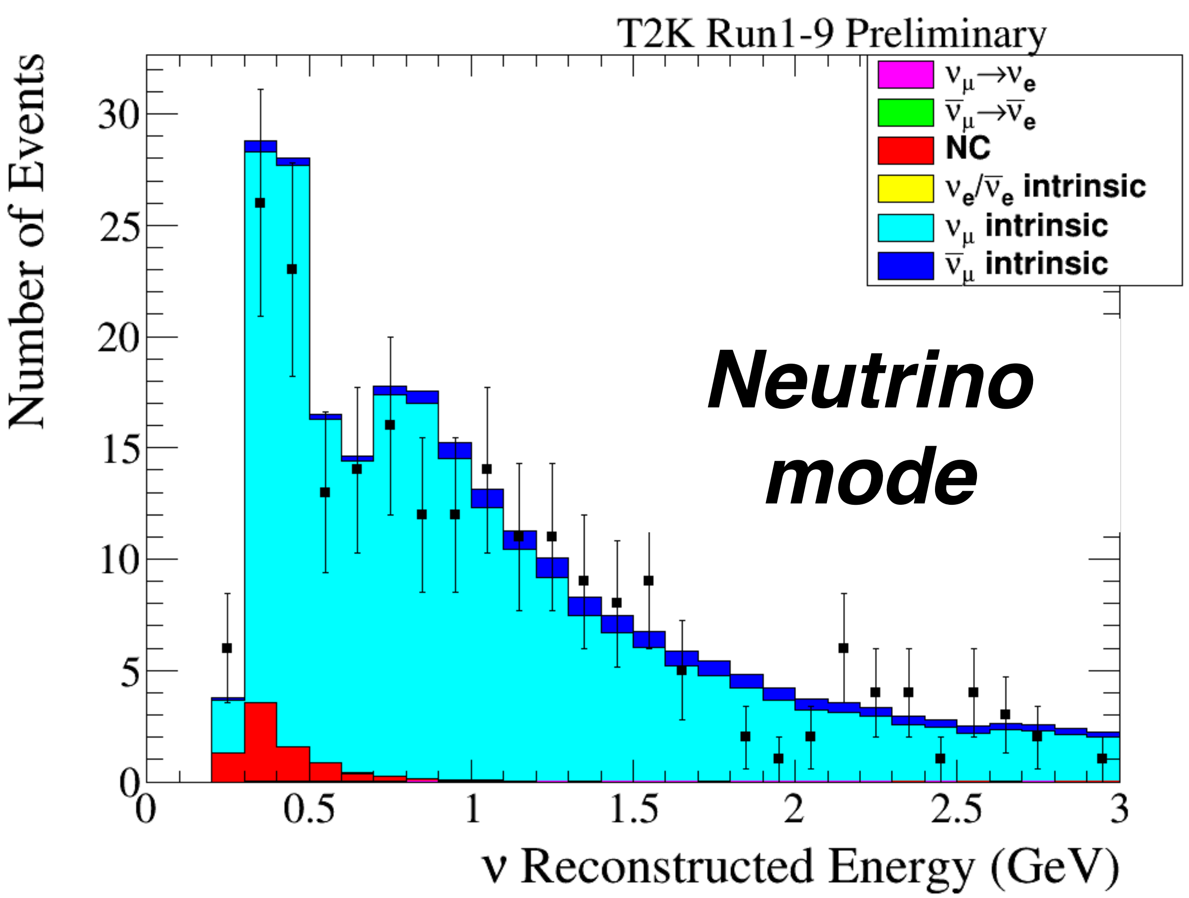
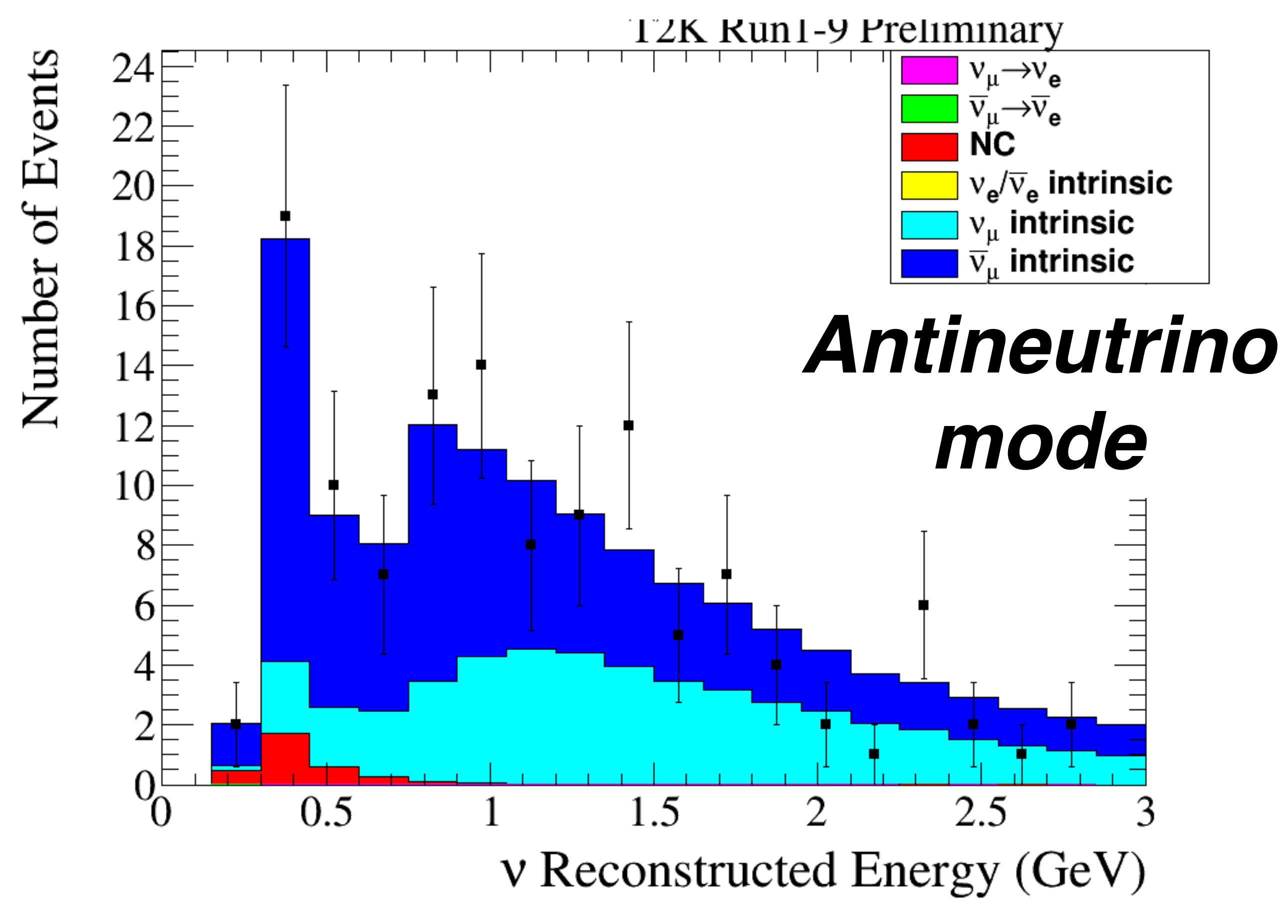


ν_μ and $\bar{\nu}_\mu$ candidates

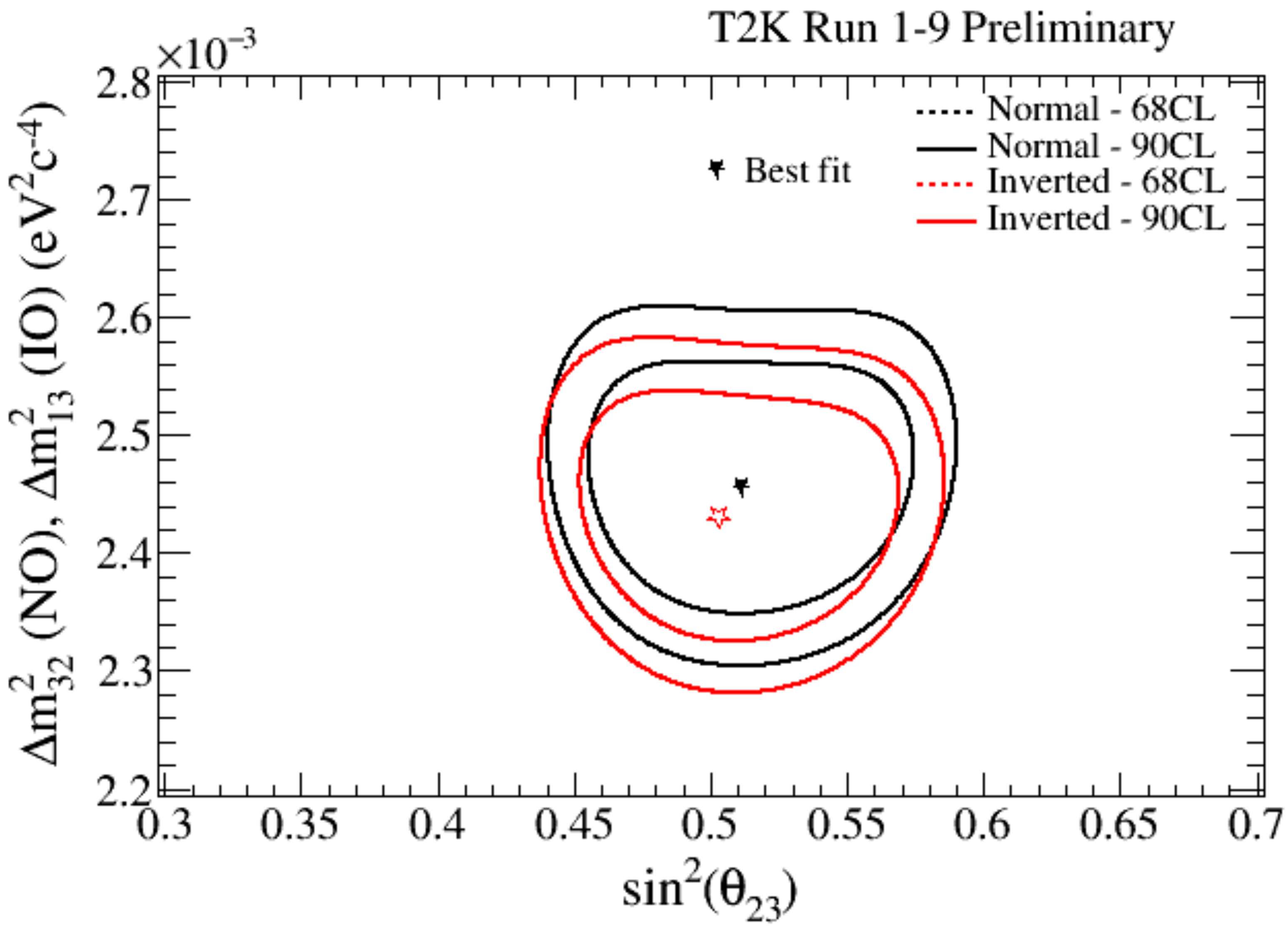
Closed regions are allowed values of oscillation parameters

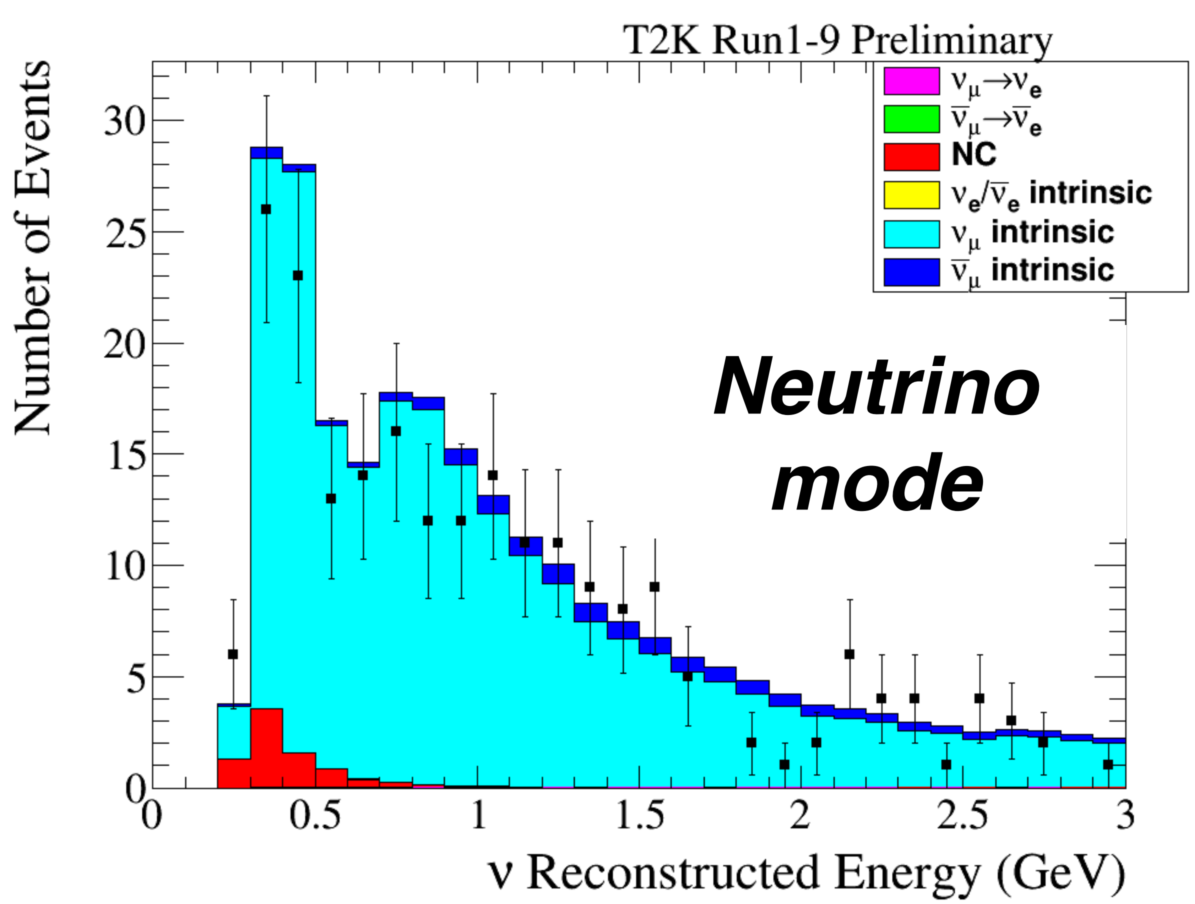


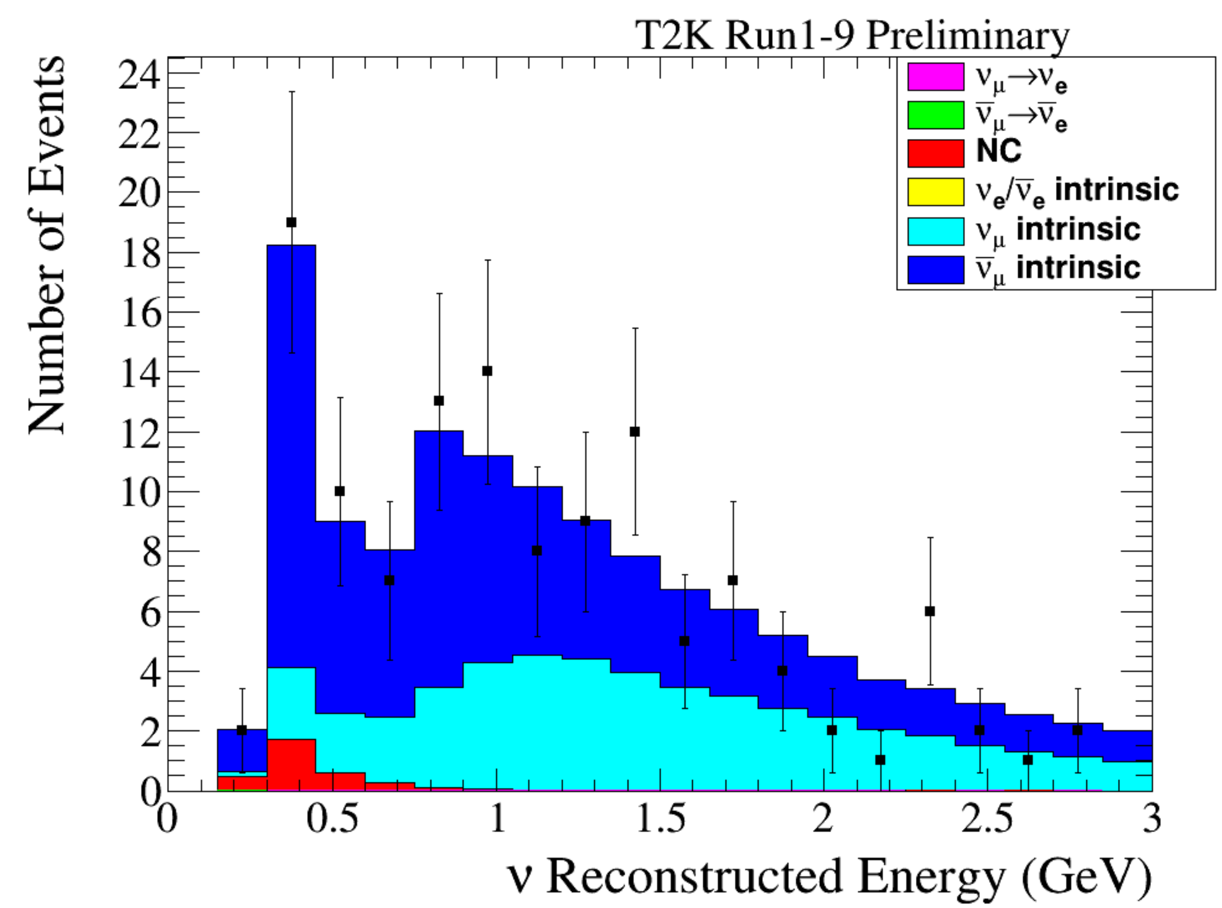




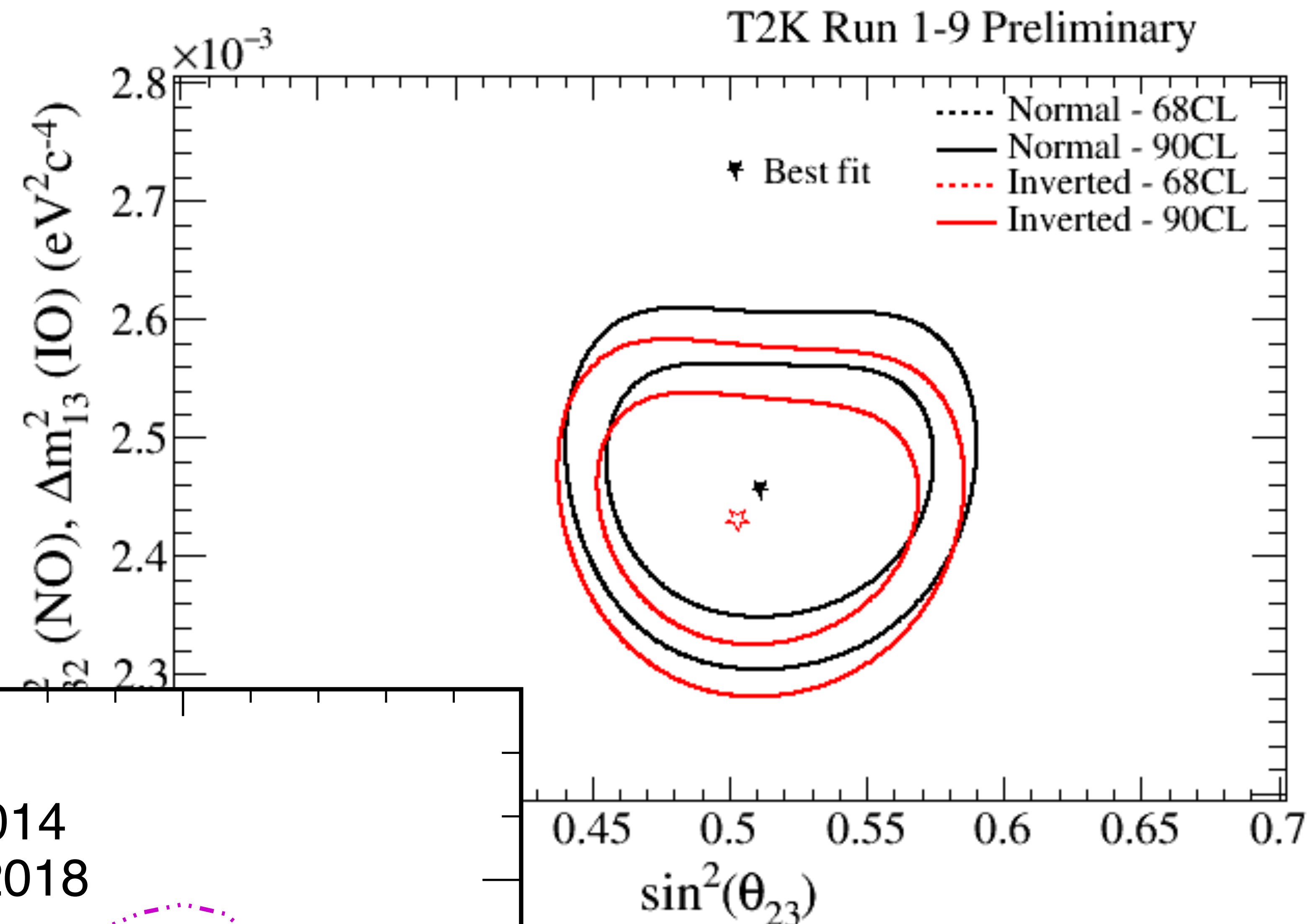
- T2K favors maximal mixing (θ_{23}=45deg)

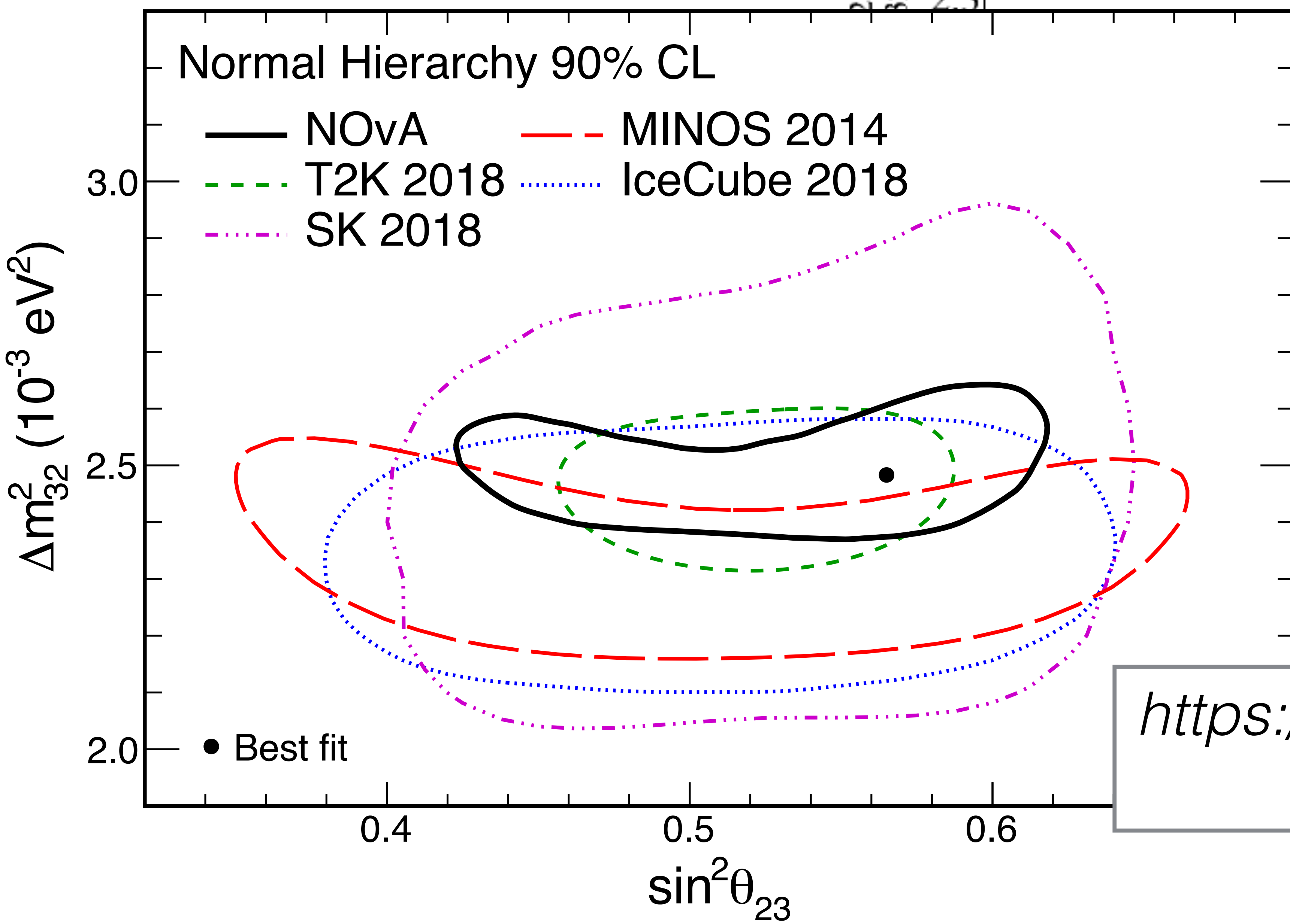






- T2K favors maximal mixing (θ_{23}=45deg)
- Global picture rapidly changing

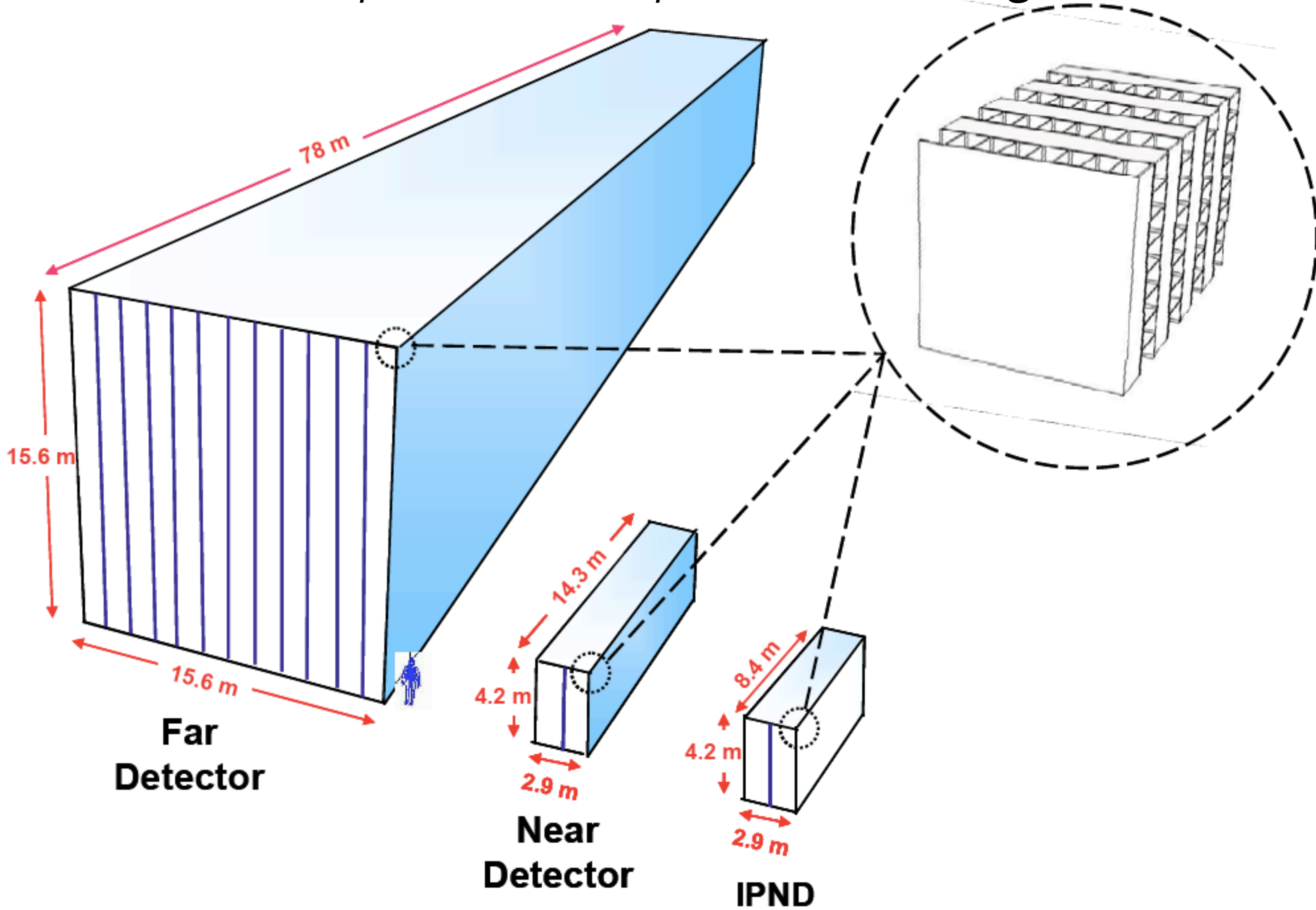




https://novaexperiment.fnal.gov/publications/

NuMI Off-axis ν_e Appearance (NOvA) Experiment

https://novaexperiment.fnal.gov/



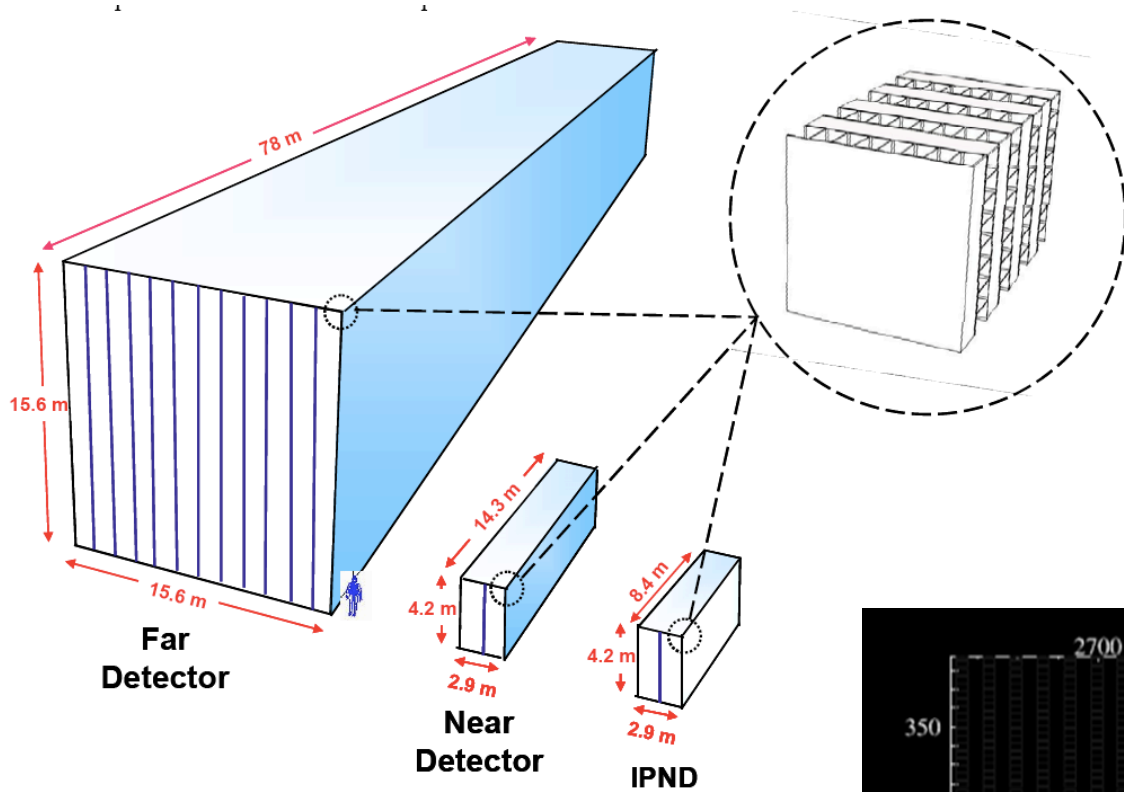
http://www.hep.umn.edu/

https://en.wikipedia.org/wiki/NOvA

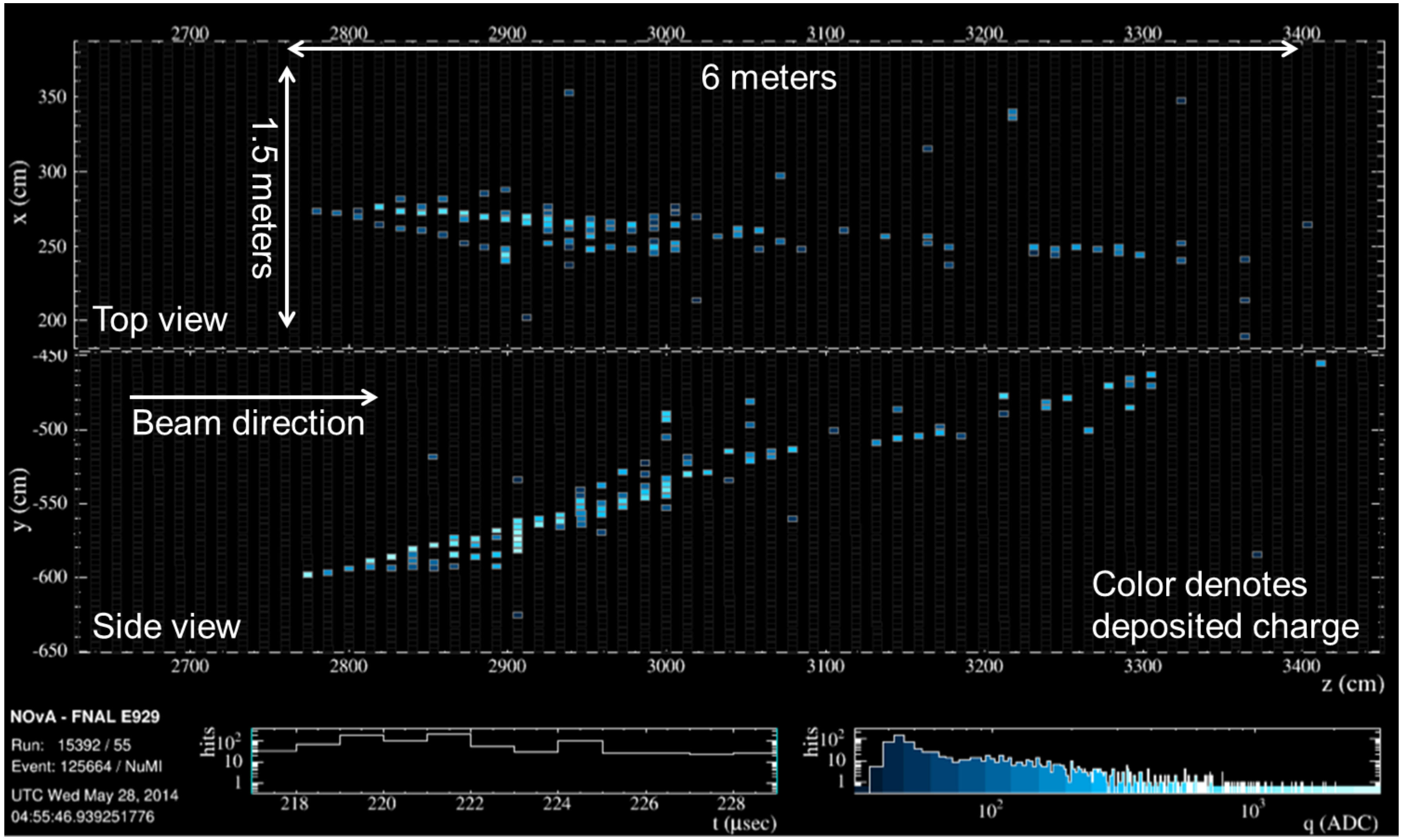
Accelerator driven experiment:

- ~2 GeV beam from Fermilab to Ash River, Minnesota (810km baseline)
- Identical near and far detector technology

NuMI Off-axis ν_e Appearance (NOvA) Experiment



ν_e candidate

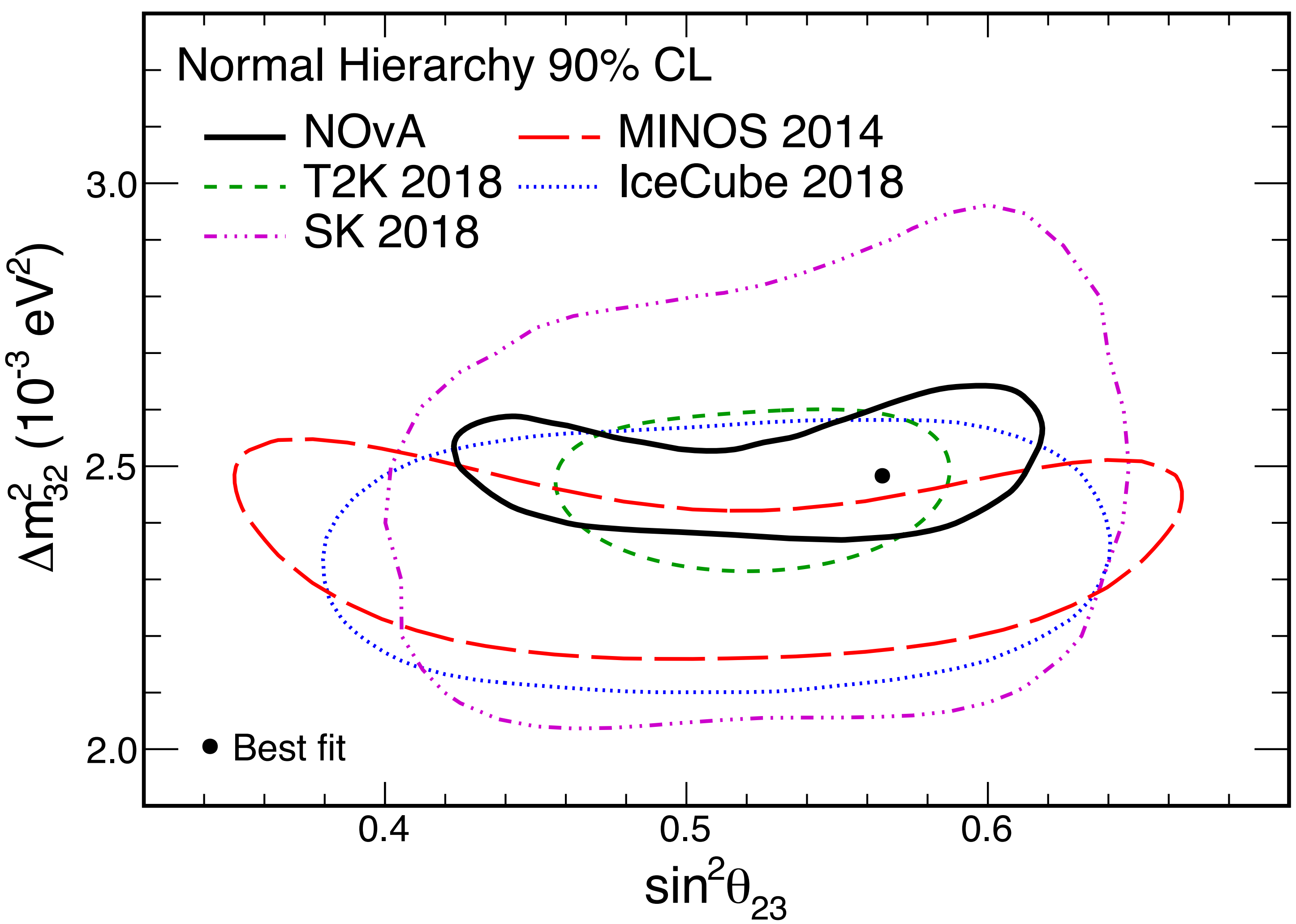


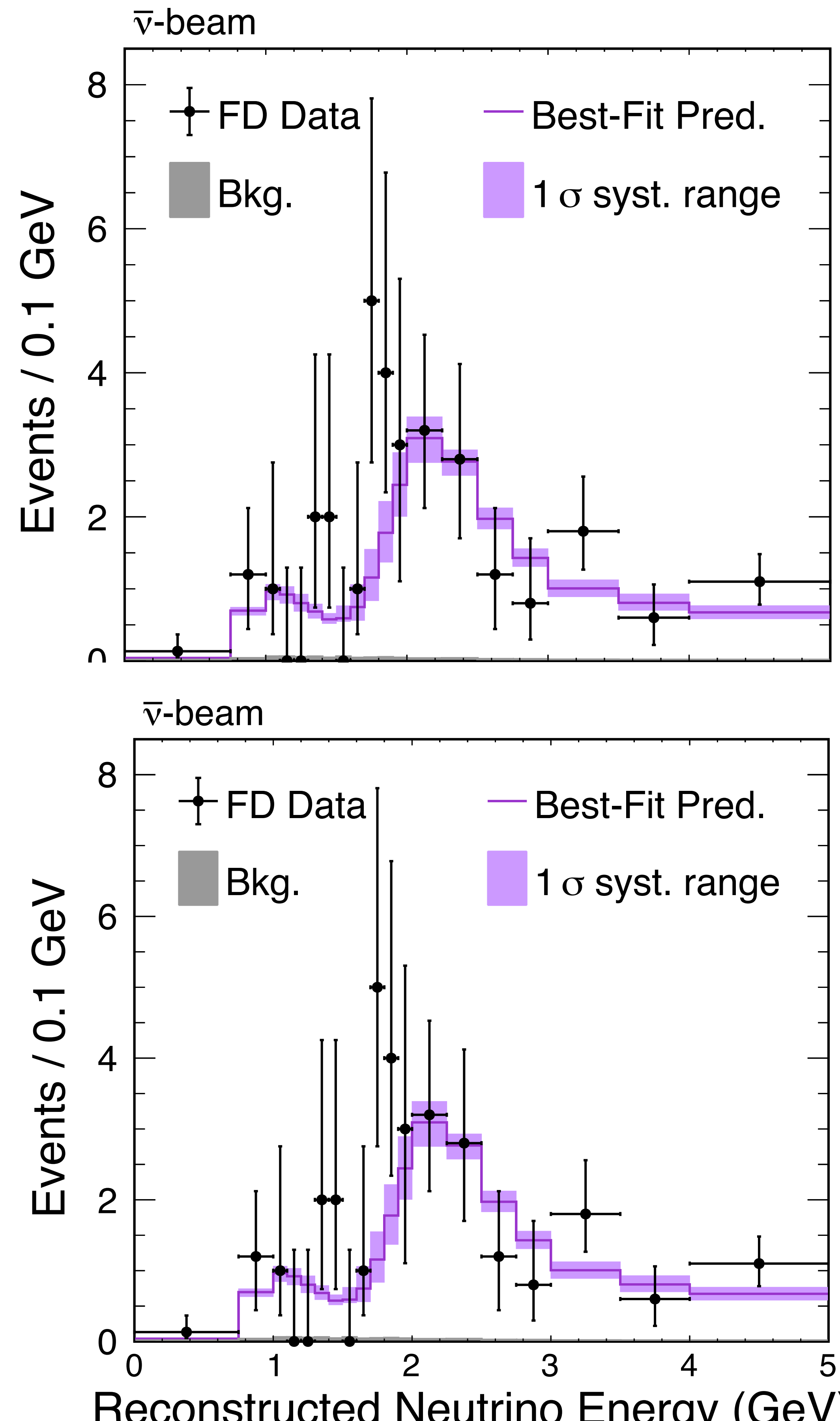
Challenge: data reduction https://youtu.be/V2rFVgvc41E

http://nusoft.fnal.gov/nova/

NuMI Off-axis ν_e Appearance (NOvA) Experiment

https://arxiv.org/abs/1906.04907



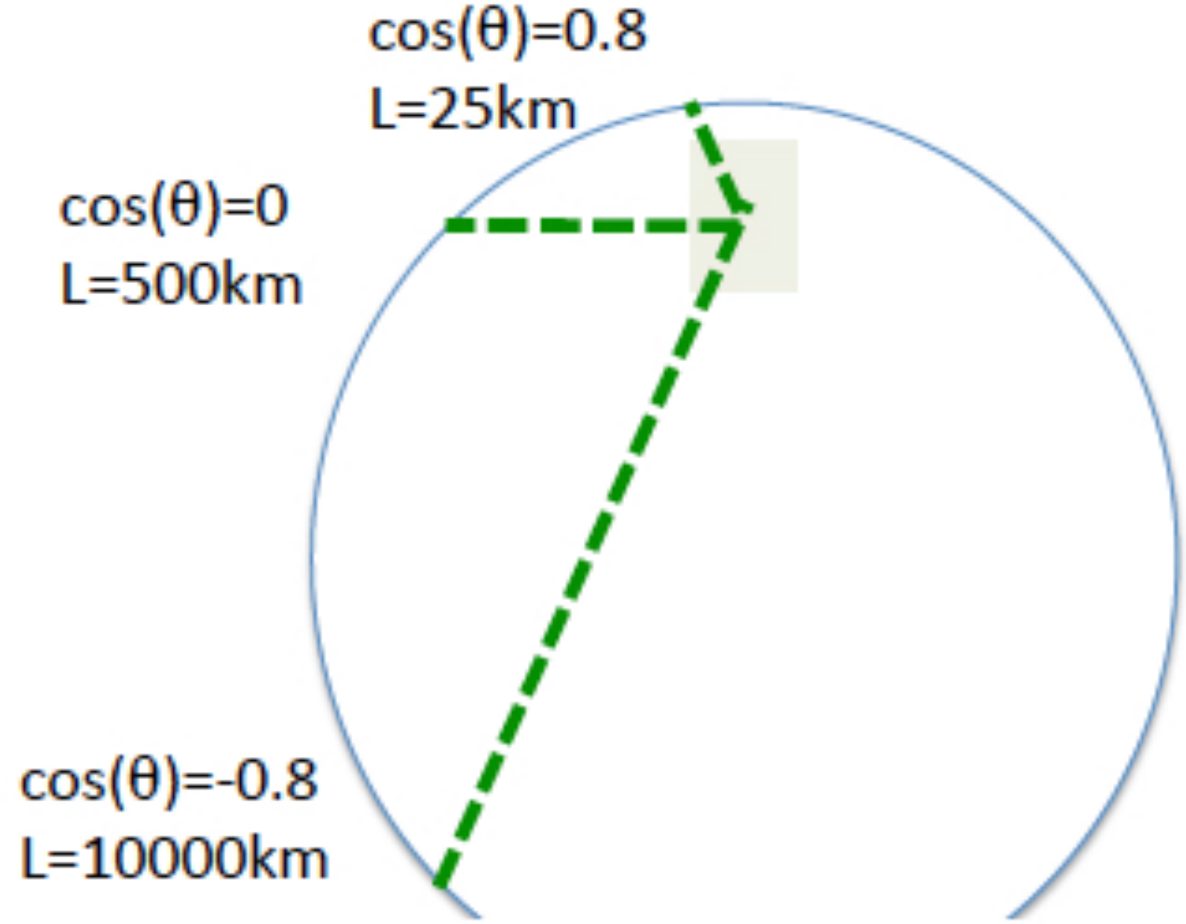


Super-Kamiokande and IceCube (atmospheric neutrinos)

Oscillation probability changes with L:

- Distance from production to detector
- As a function of angle from the zenith $\cos(\theta)$

$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\,\Delta m^2_{32} L}{E}\right)$$



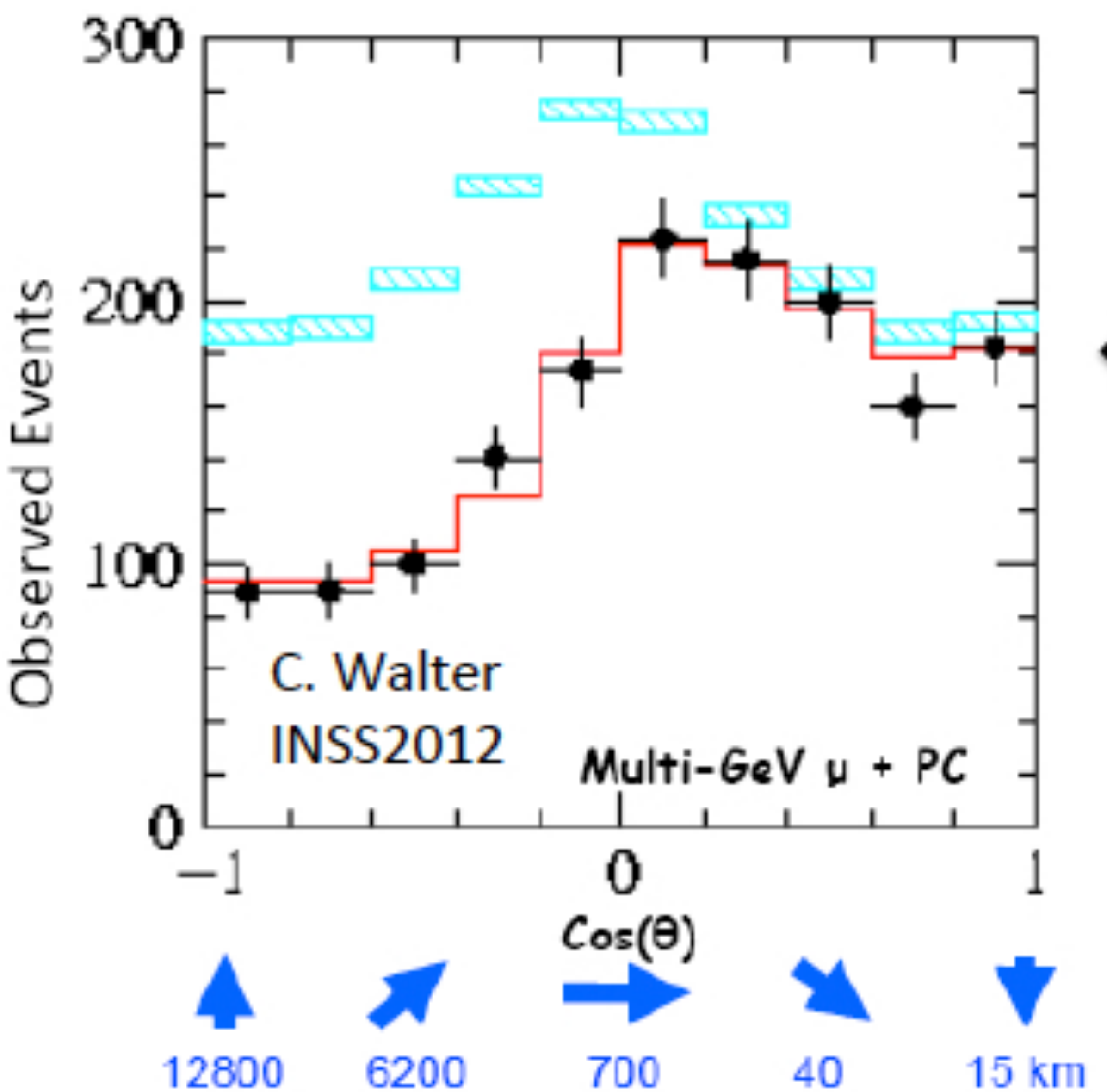
Determine $|\Delta m^2_{32}|$, θ_{23} from atmospheric and accelerator neutrinos:

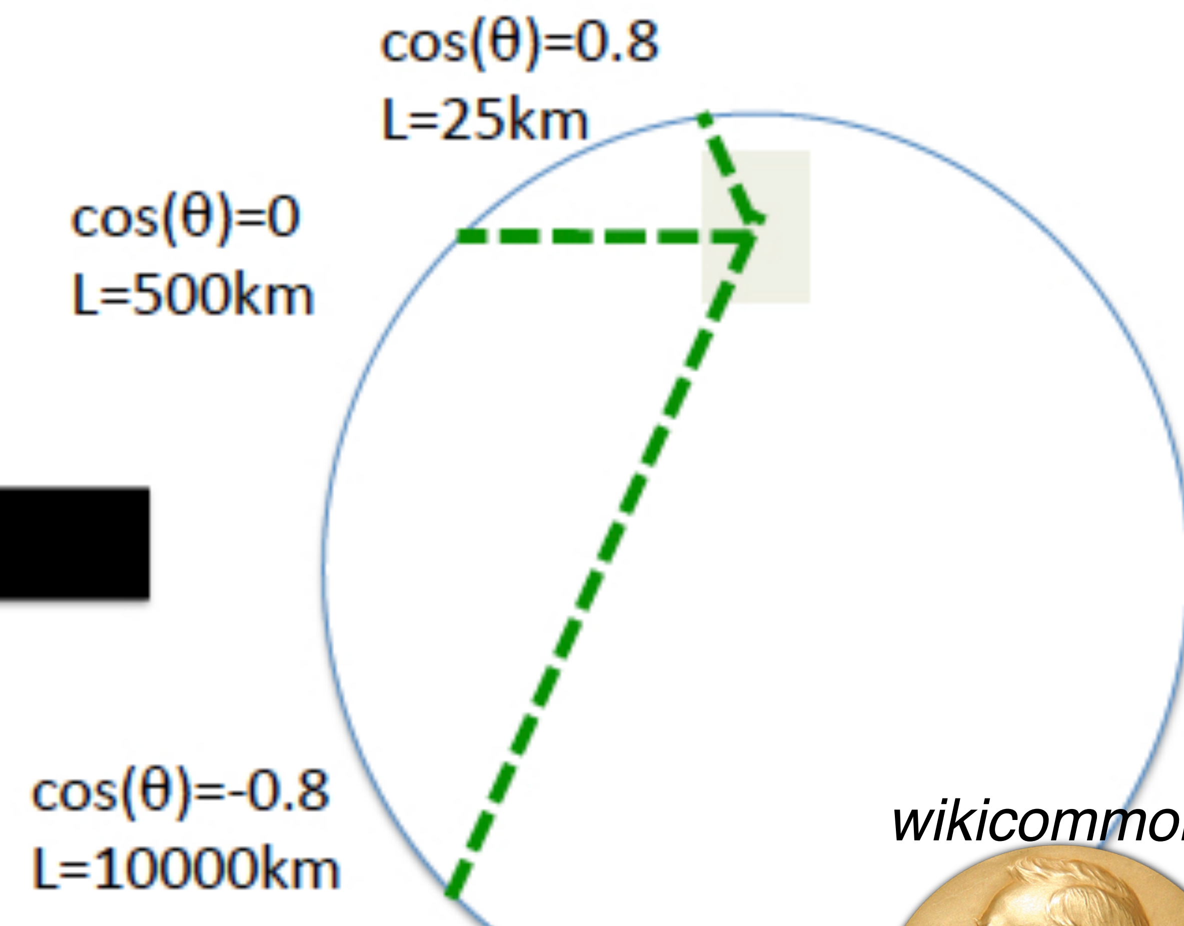
Super-Kamiokande and IceCube (atmospheric neutrinos)

Oscillation probability changes with L:

- Distance from production to detector
- As a function of angle from the zenith cos(θ)

$$P(\nu_\mu \rightarrow \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\,\Delta m_{32}^2 L}{E}\right)$$





wikicommons

Original: Phys.Rev.Lett. 81 (1998) 1562-1567

Latest: PTEP 2019 (2019) no.5, 053F01

Super-Kamiokande and **IceCube** (atmospheric neutrinos)

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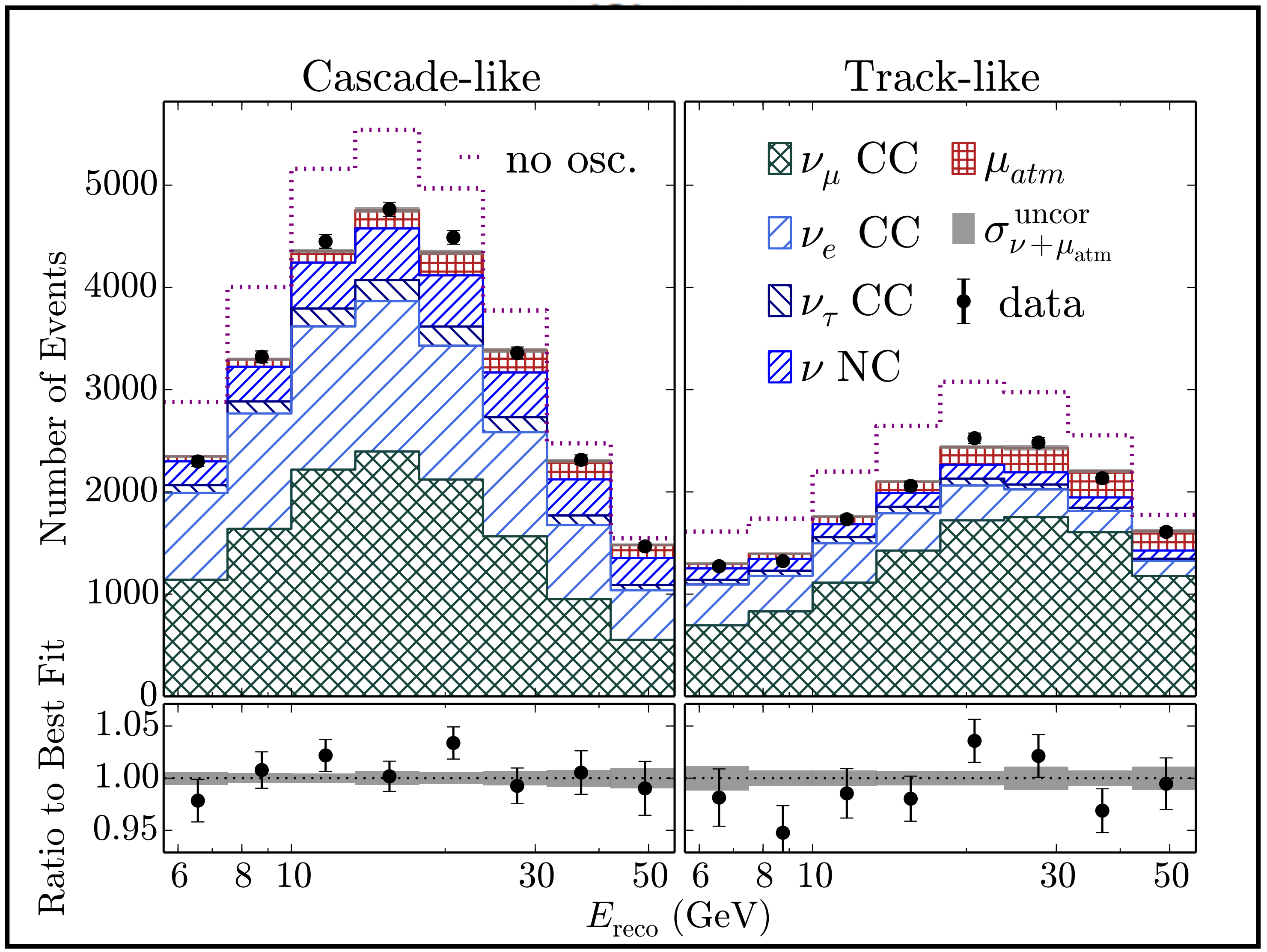
$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\,\Delta m_{32}^2 L}{E}\right)$$

Higher energy measurement also consistent



Phys. Rev. Lett. 120, 071801 (2018)

Neutrino oscillation open questions

Oscillation depends on:

- Amplitude determined by mixing angles: θ_{12}, θ_{23}, θ_{13}
- Frequency determined by mass splittings: $|\Delta m^2_{32/31}|$,Δm^2_{21}
- CP violating phase (CPV)

ν_e and $\bar{\nu}_e$ appearance channel

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

Depends on all the oscillation parameters simultaneously

Accessible from accelerators; important role of dedicated (reactor, solar) measurements

Neutrino oscillation open questions

Oscillation depends on:

- Amplitude determined by mixing angles: θ_{12}, θ_{23}, θ_{13}
- Frequency determined by mass splittings: $|\Delta m^2_{32/31}|$, Δm^2_{21}
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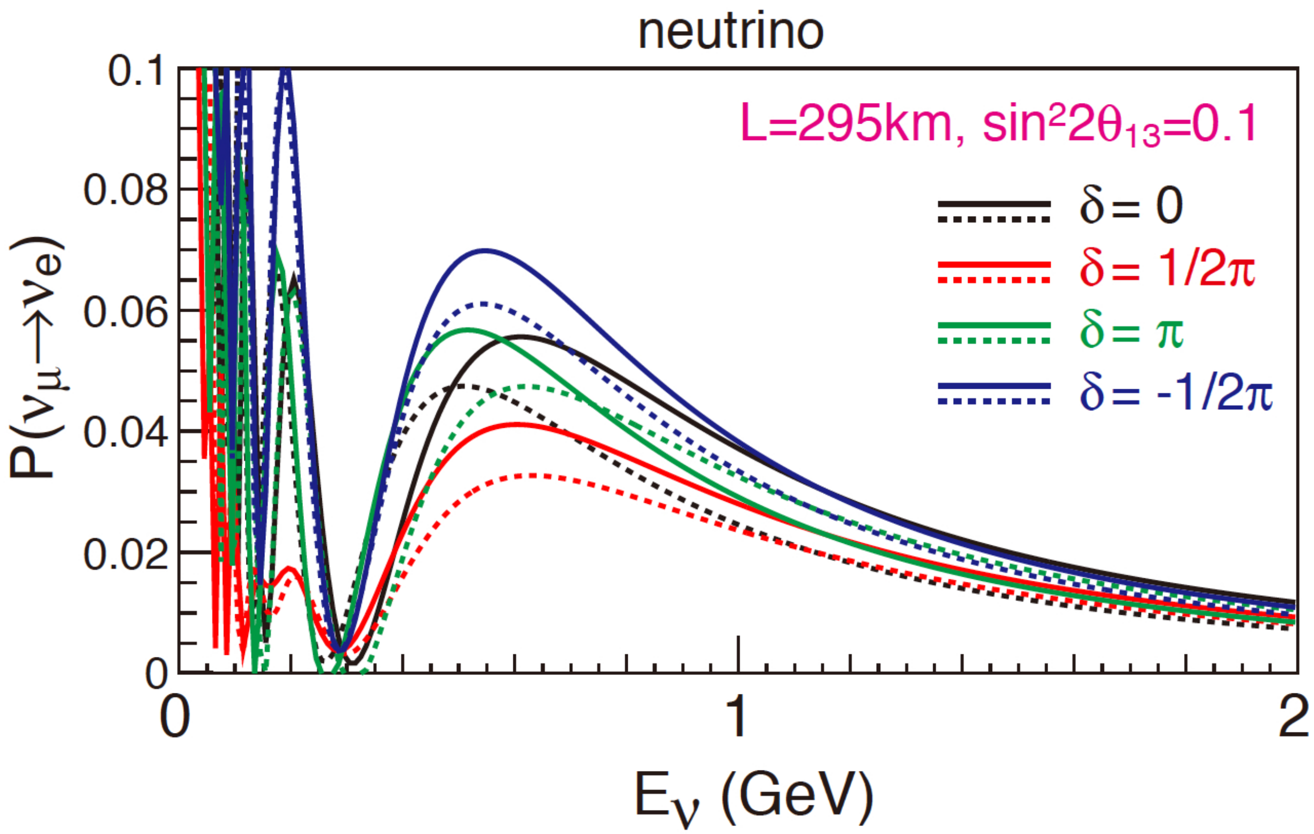


PTEP (2015) 053C02

Changing δ_{CP} or changing from inverted to normal hierarchy increases ν_e and decreases $\bar{\nu}_e$ appearance rates

Neutrino oscillation open questions

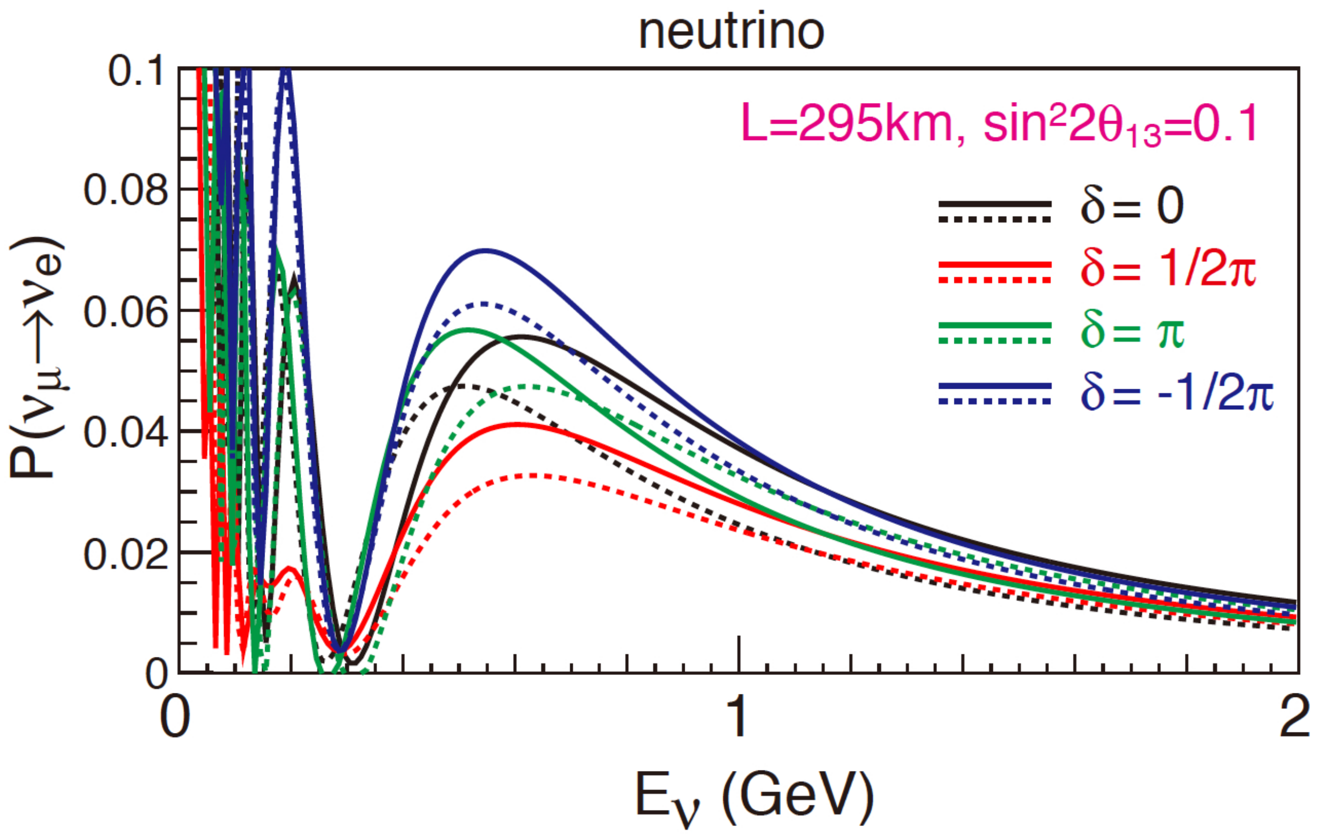
Oscillation depends on:

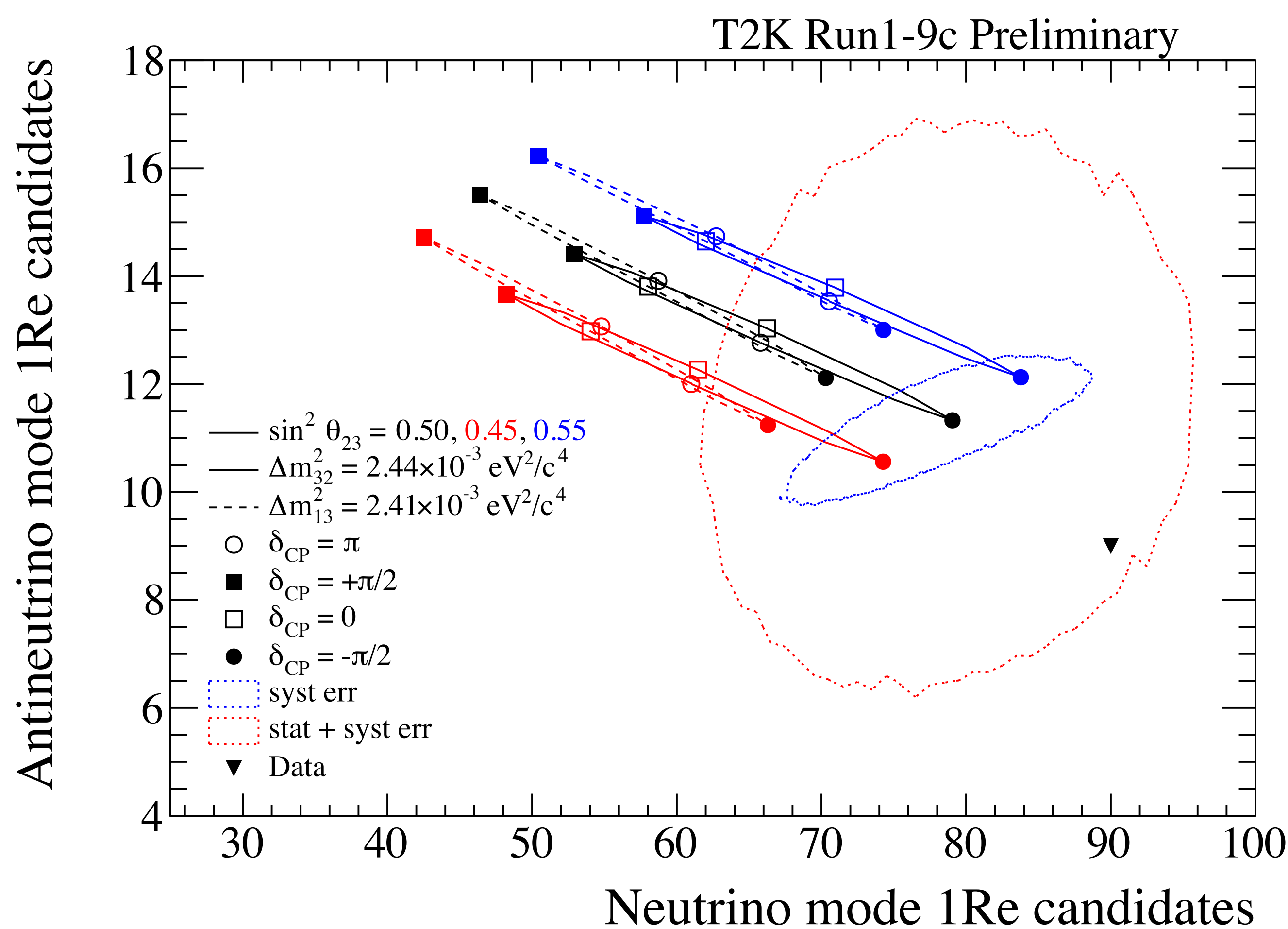
- Amplitude determined by mixing angles: θ_{12}, θ_{23}, θ_{13}
- Frequency determined by mass splittings: $|\Delta m^2_{32/31}|$, Δm^2_{21}
- CP violating phase (CPV)

ν_e and $\bar{\nu}_e$ appearance channel

Comparing ν_e to $\bar{\nu}_e$ appearance rates traces eclipses

"bi-probability plot"





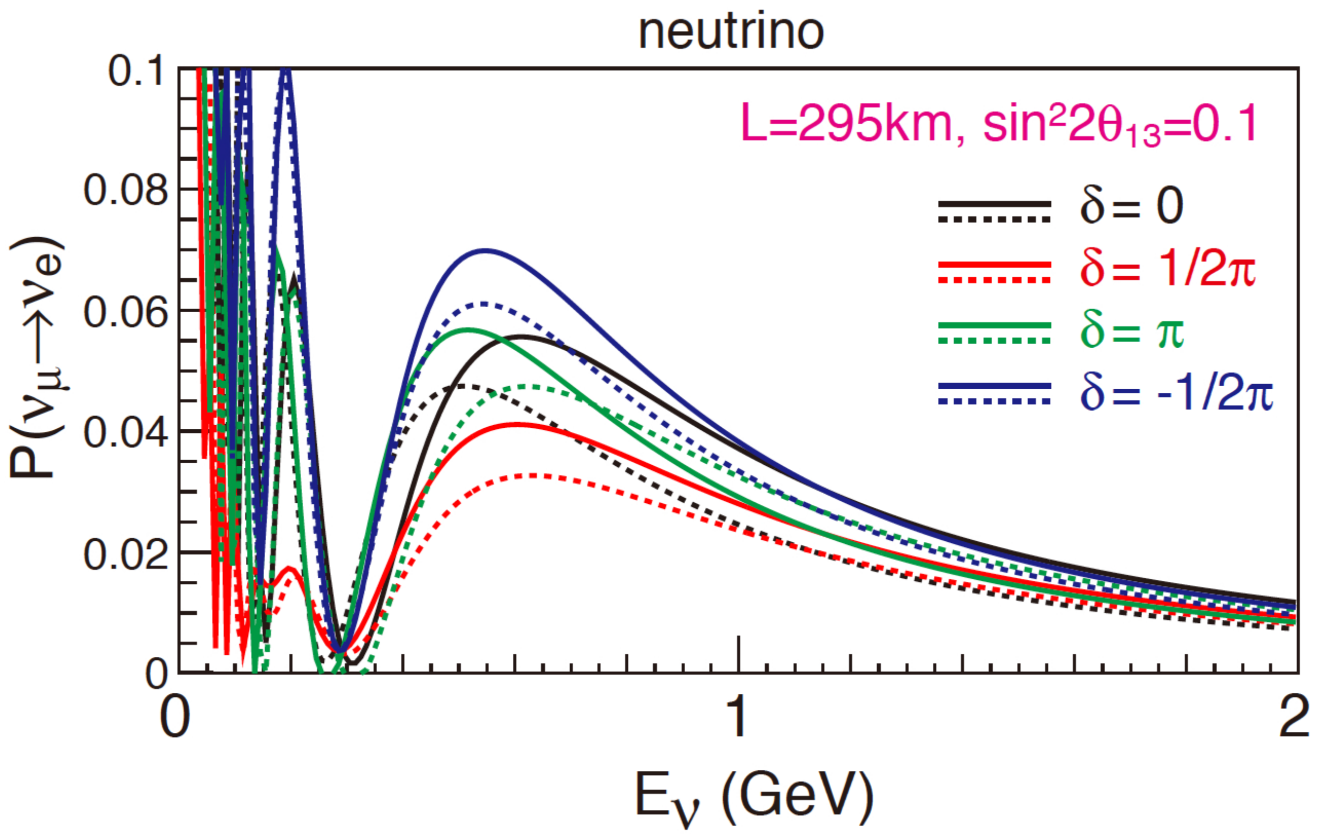
Neutrino oscillation open questions

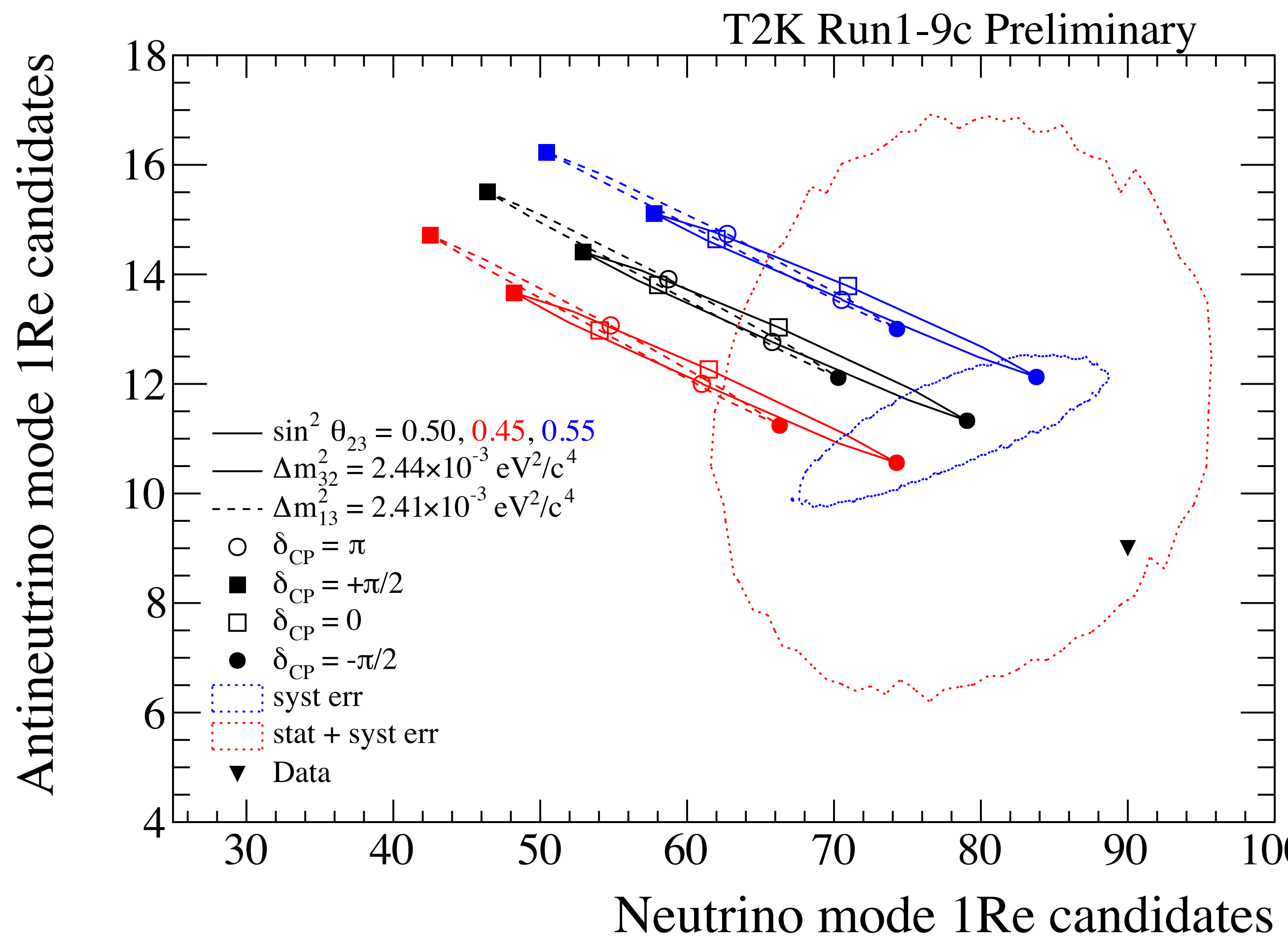
Oscillation depends on:

- Amplitude determined by mixing angles: θ_{12}, θ_{23}, θ_{13}
- Frequency determined by mass splittings: $|\Delta m^2_{32/31}|$, Δm^2_{21}
- CP violating phase (CPV)

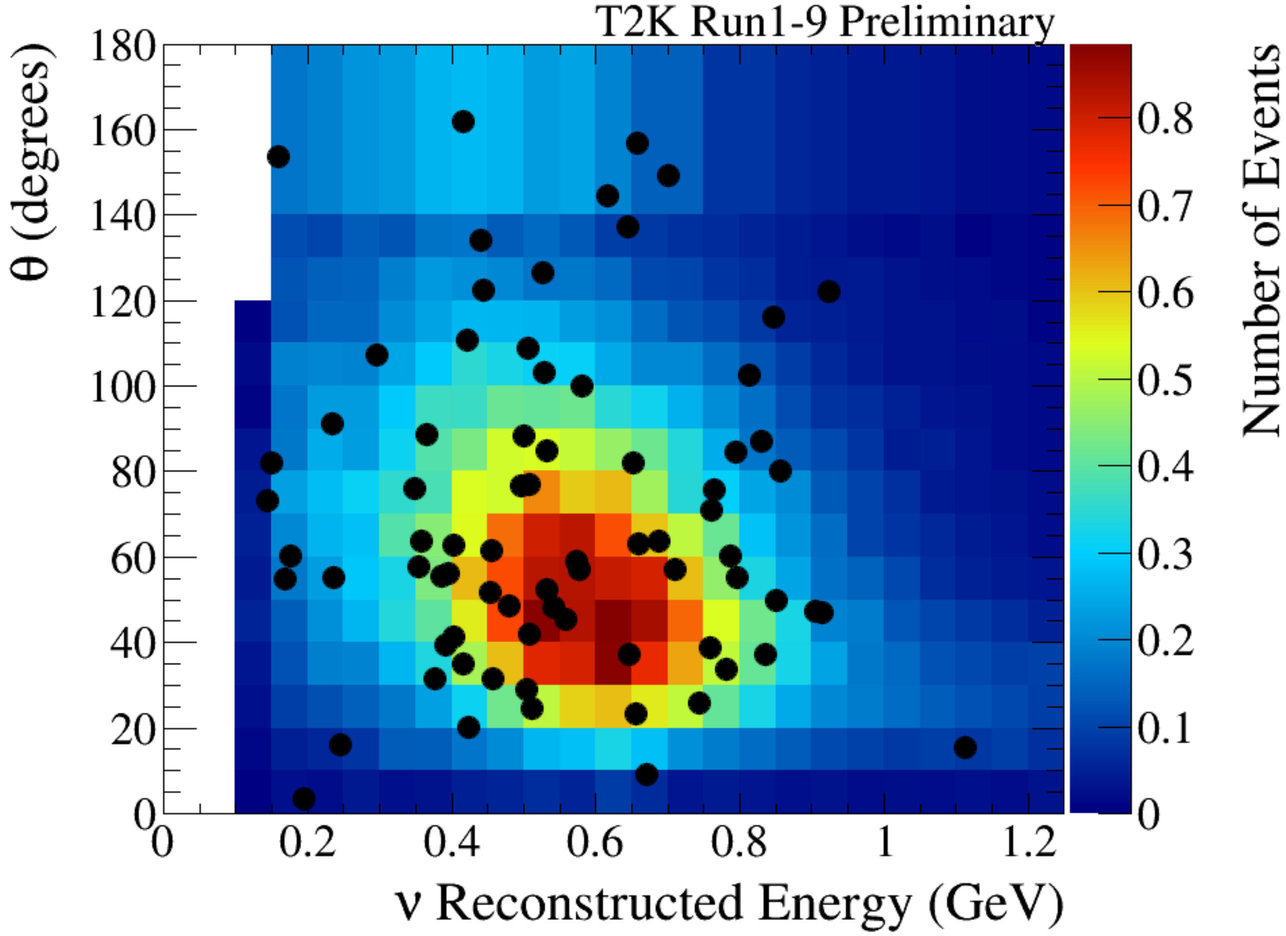
ν_e and $\bar{\nu}_e$ appearance channel

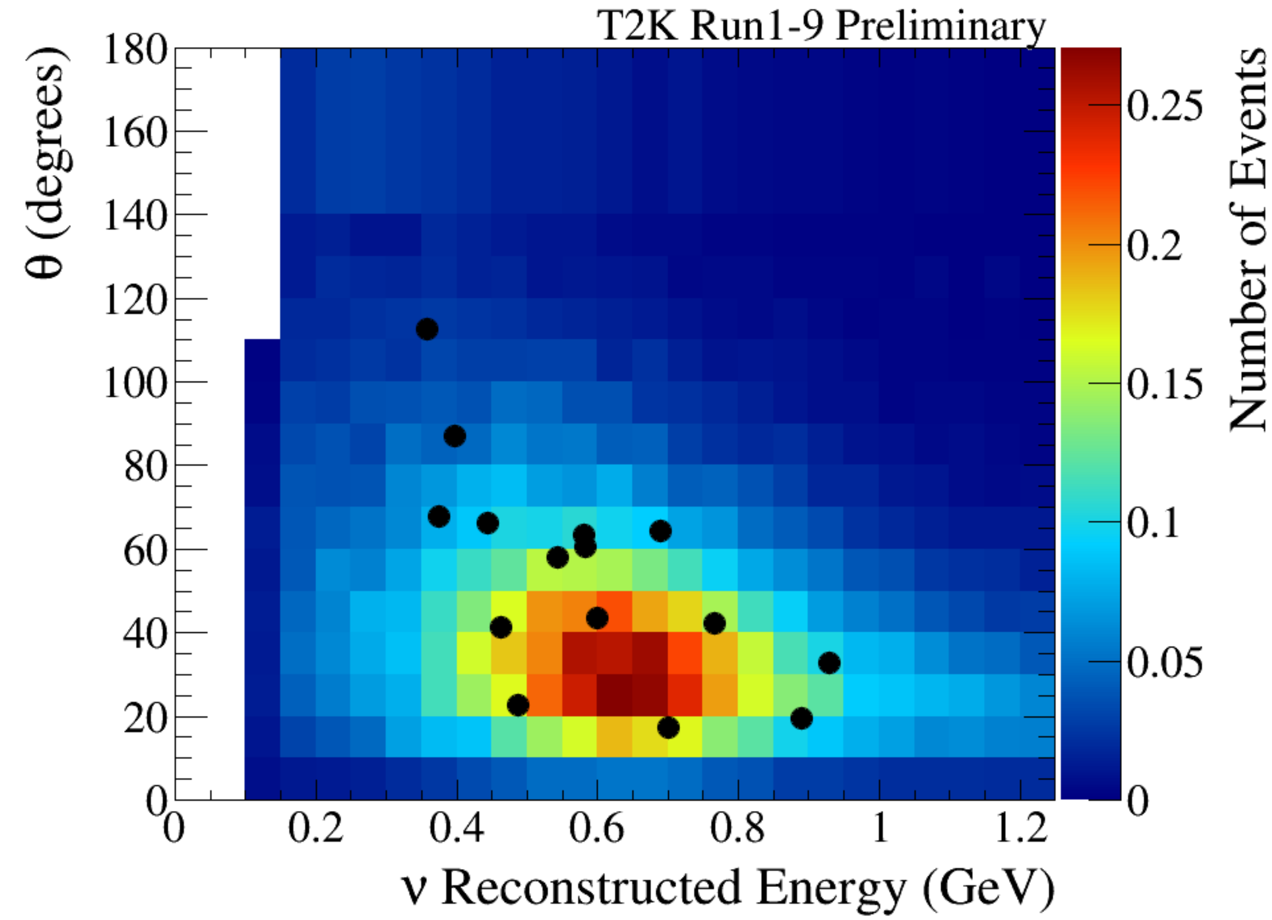
For increasing θ_{23} enhance both ν_e and $\bar{\nu}_e$ appearance





Appearance channel on T2K

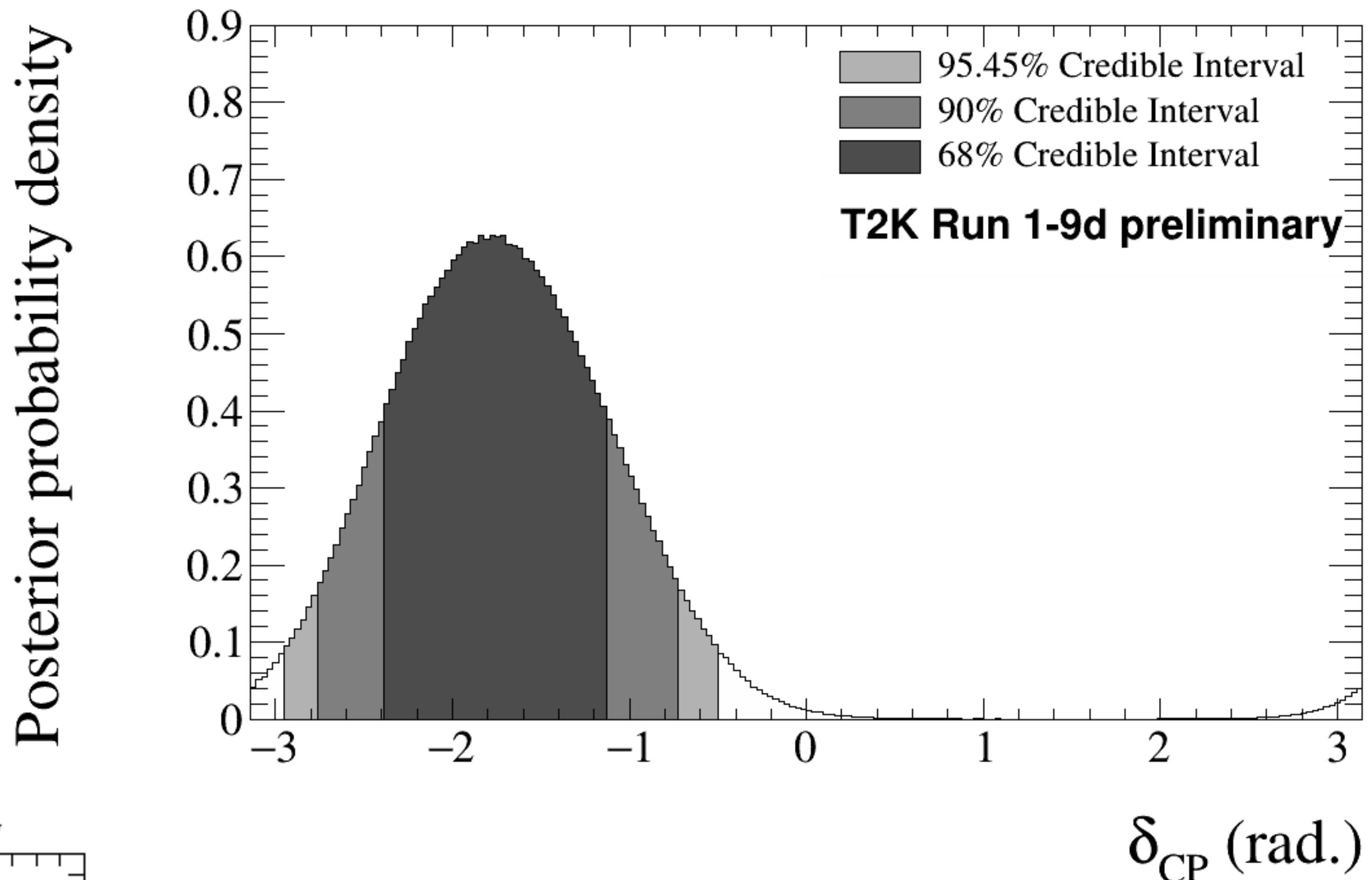


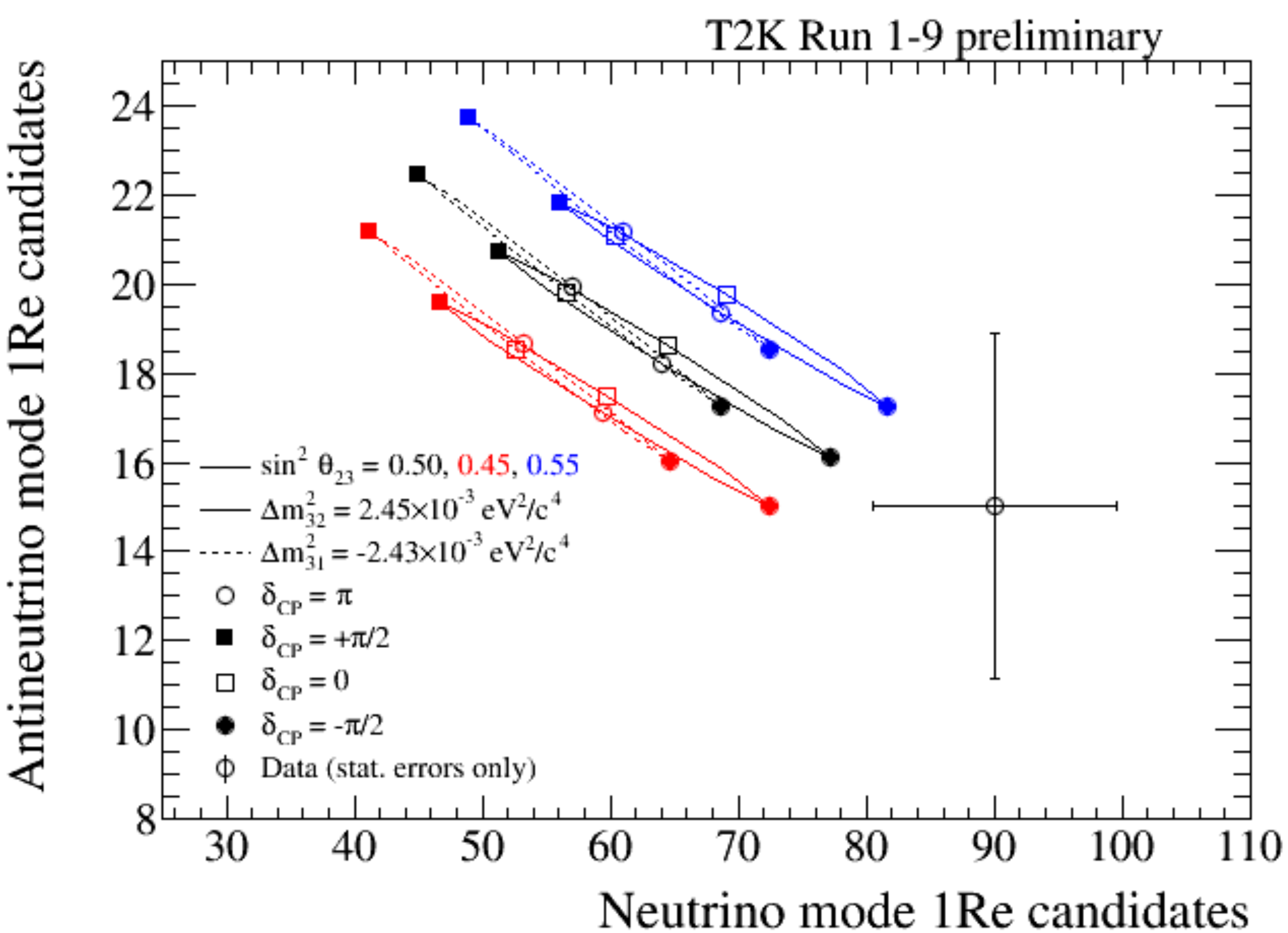


SAMPLE	PREDICTED				OBSERVED
	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$	
ν mode: ν_e (no pion)	74.4	62.2	50.6	62	75
ν mode: ν_e (1 pion)	7.0	6.1	4.9	5.8	15
$\bar{\nu}$ mode: $\bar{\nu}_e$ (no pion)	17.1	19.5	21.7	19.3	15

Appearance channel on T2K

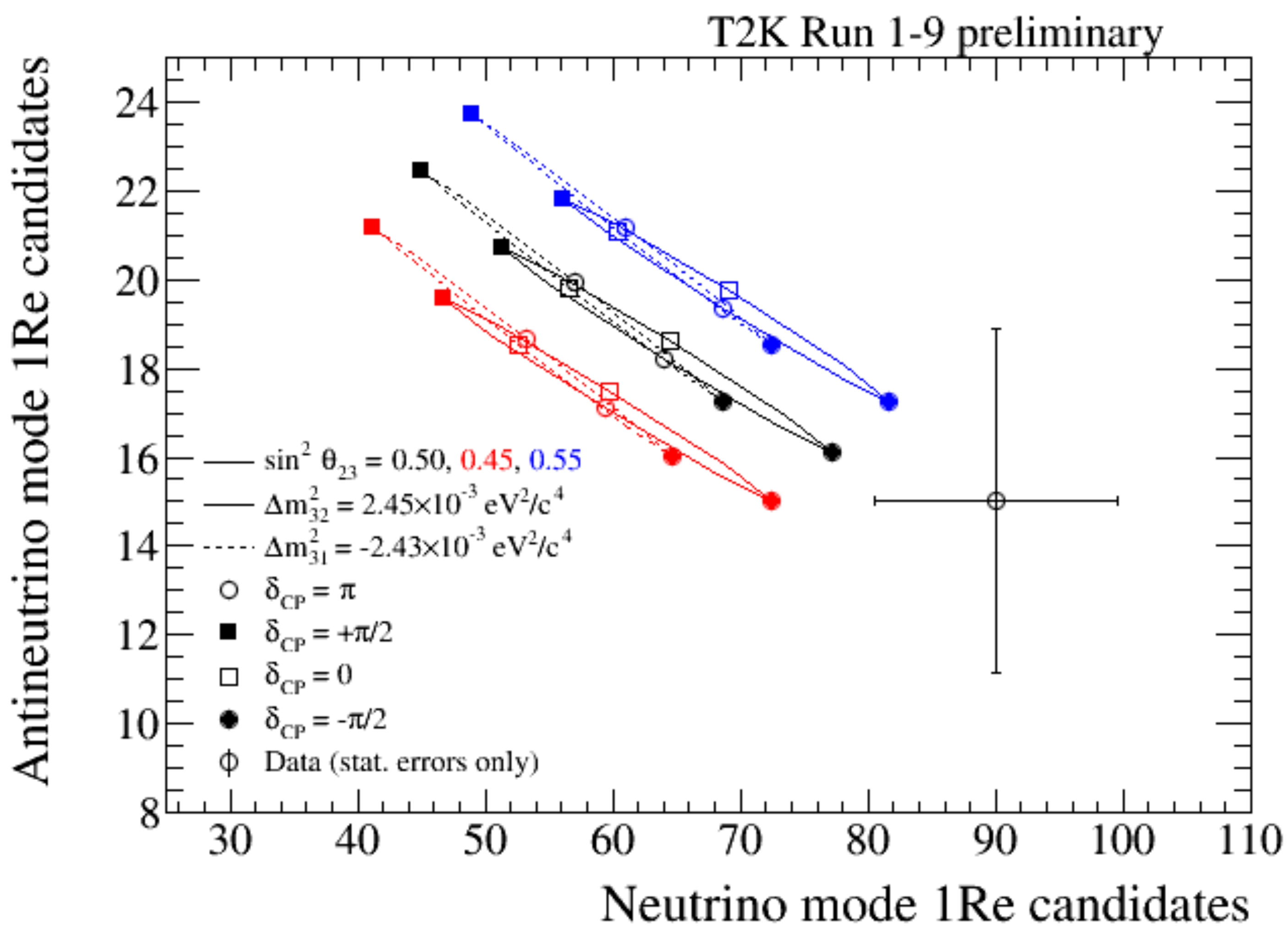
- CP conserving values outside of 2σ region for both hierarchies

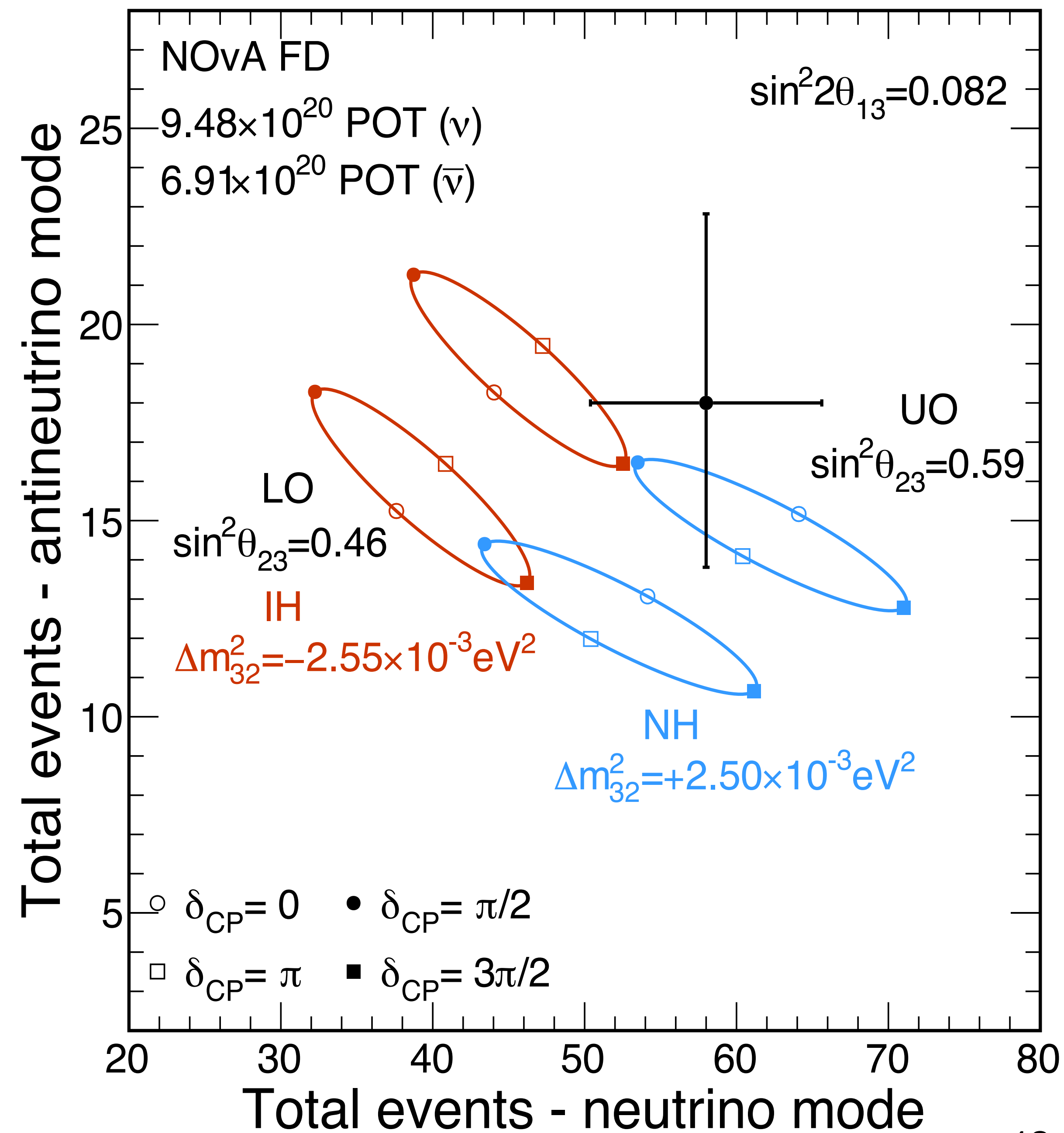




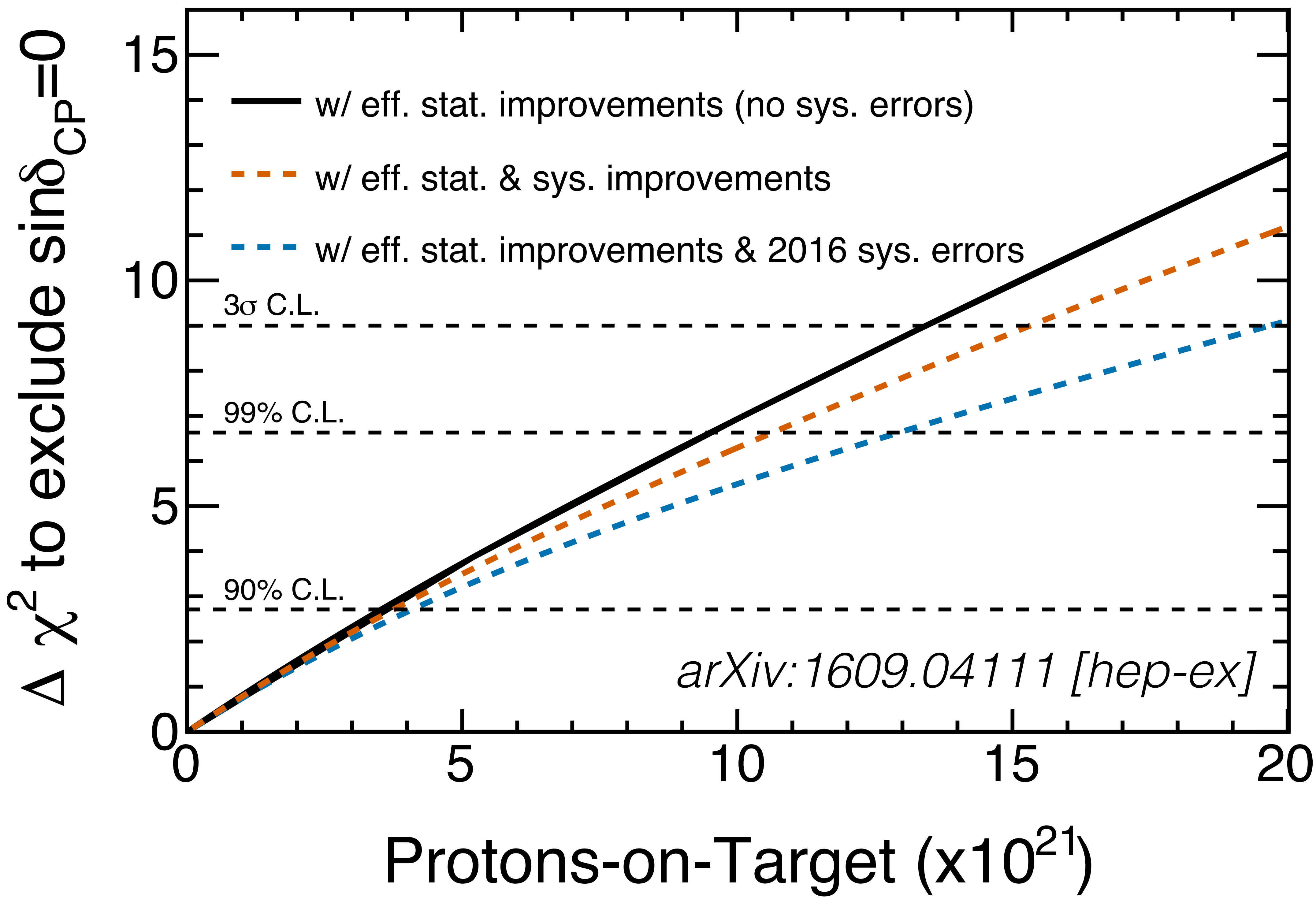
“Competition” with NOvA

- NOvA2018: prefers normal hierarchy, non-maximal θ_{23} and disfavors lower octant; exclude $\delta_{CP}=\pi/2$ in IH at >3σ
  - $\bar{\nu}_e$ appearance with 18 events (5.3 background expected)



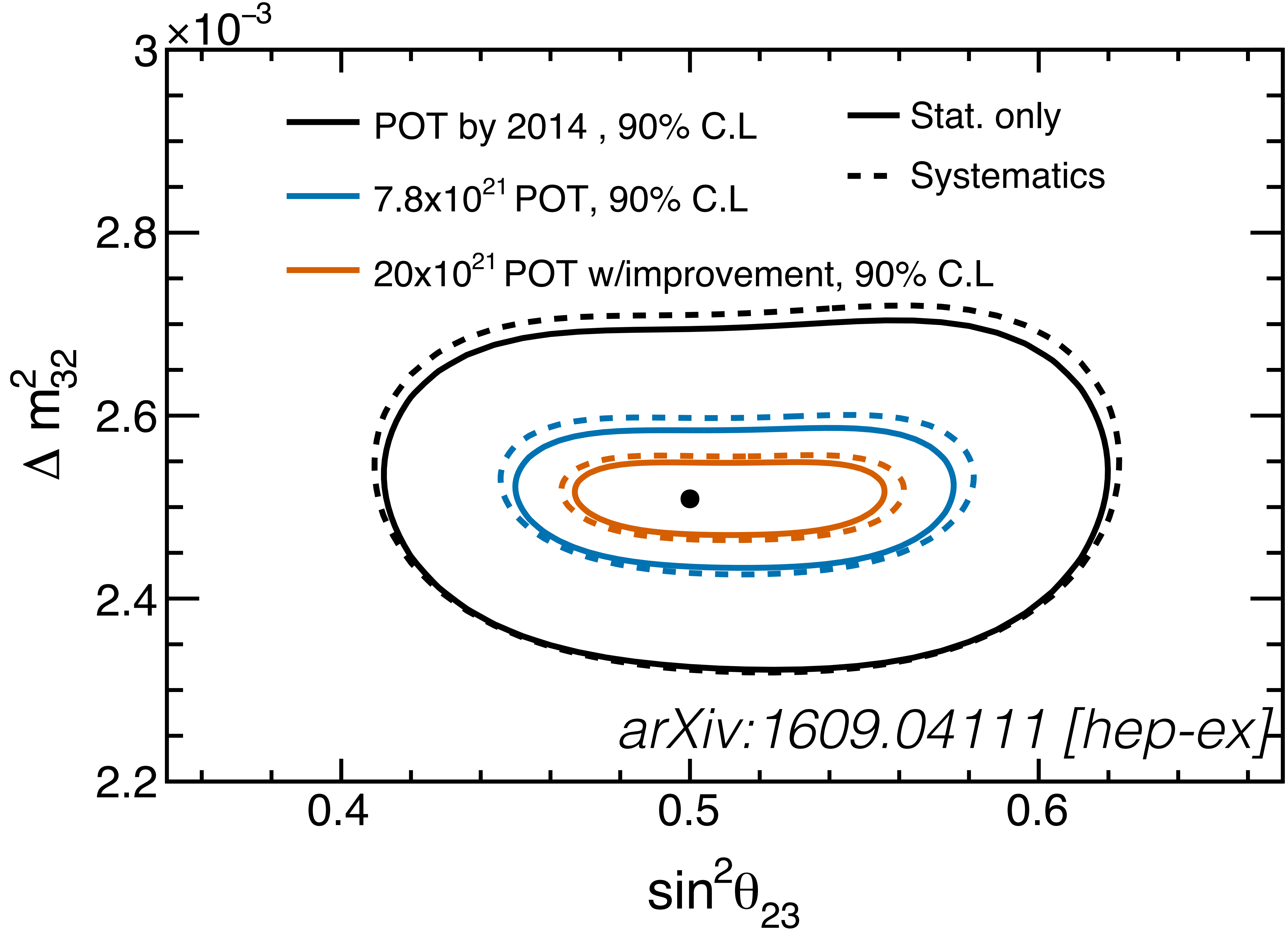


T2K future program



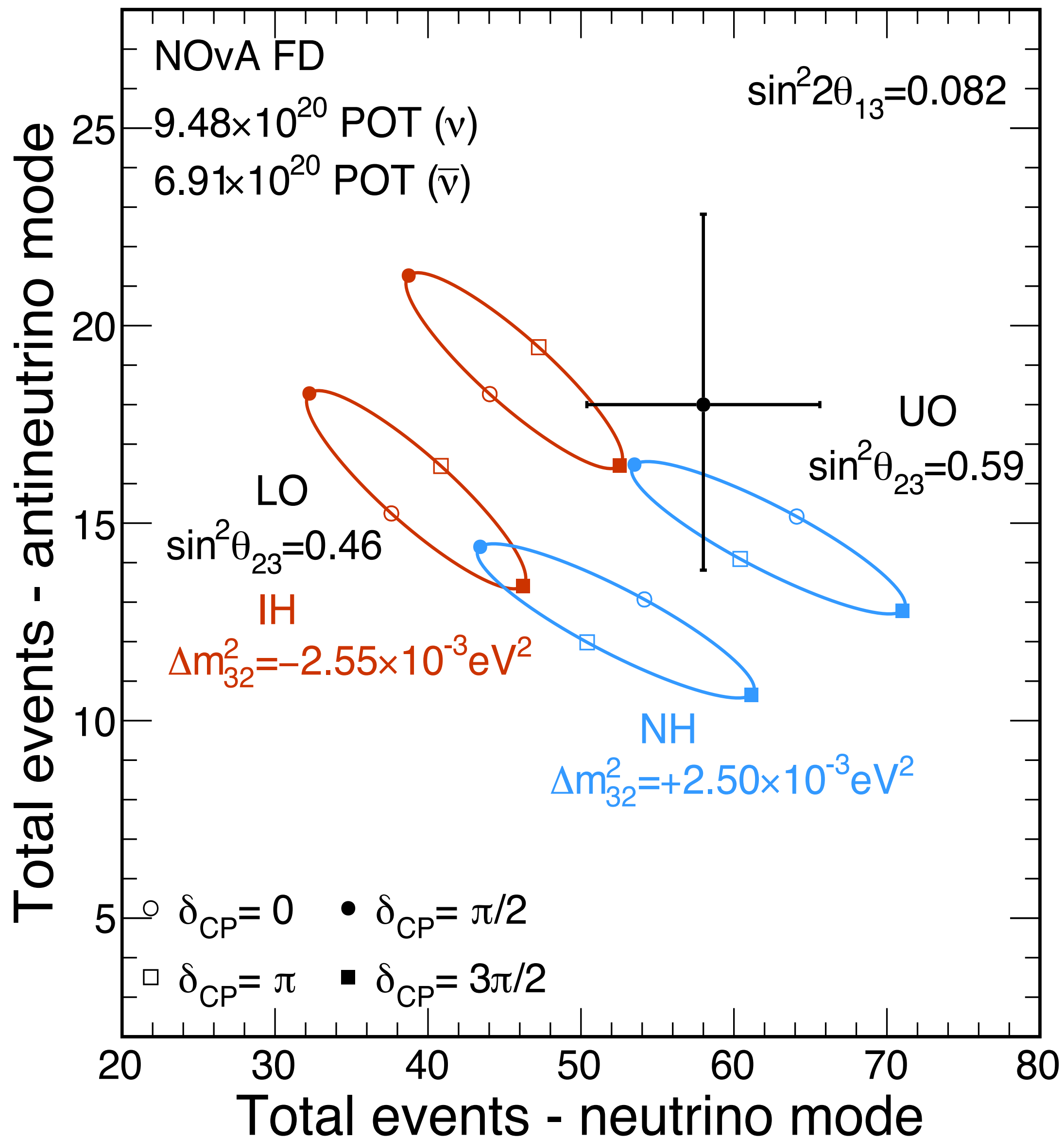
Sensitivity to evidence for CPV with beam time, analysis improvements and upgrades

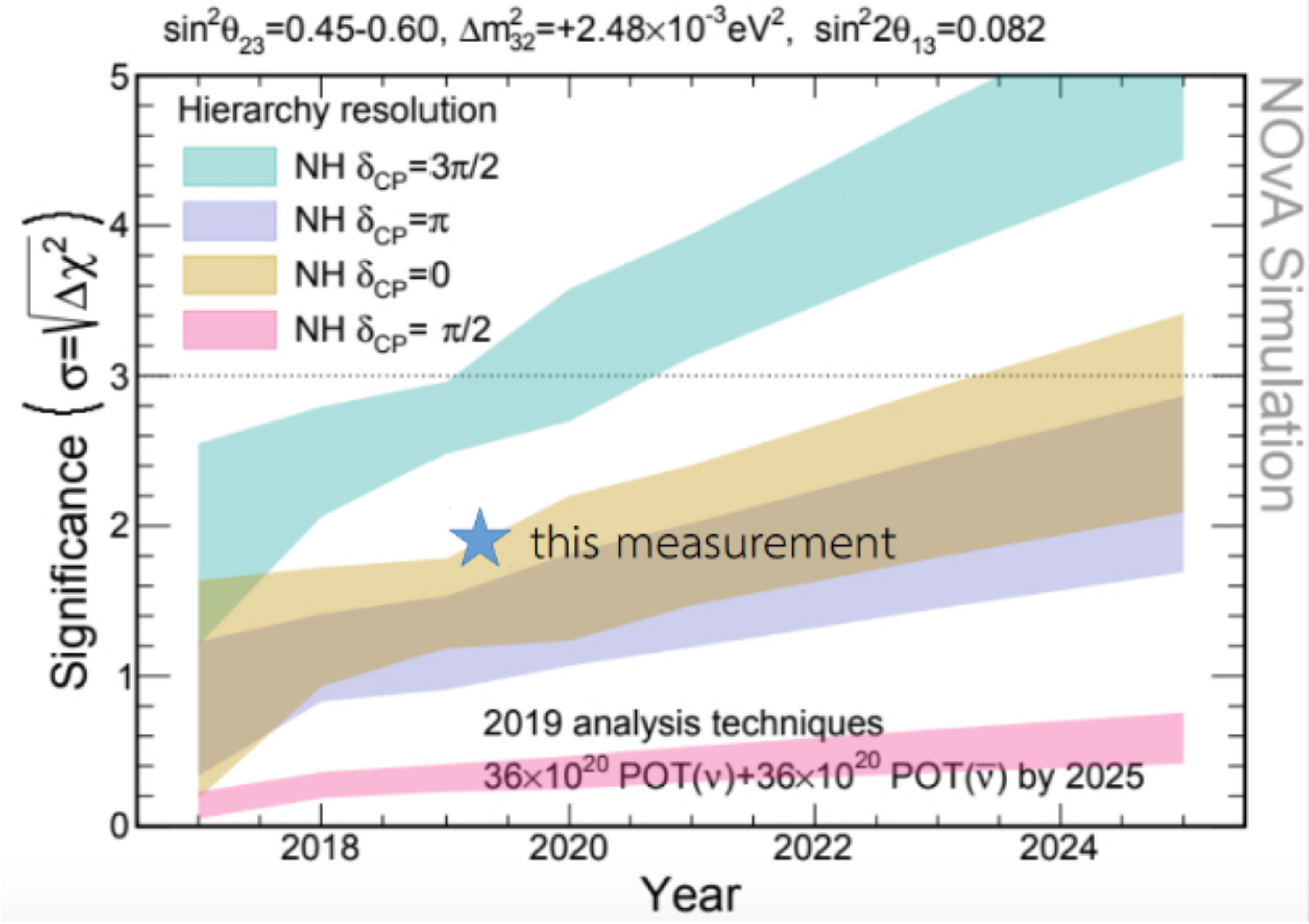
T2K future program



Improved precision on atmospheric mixing parameters (NOvA comperable)

NOvA future program

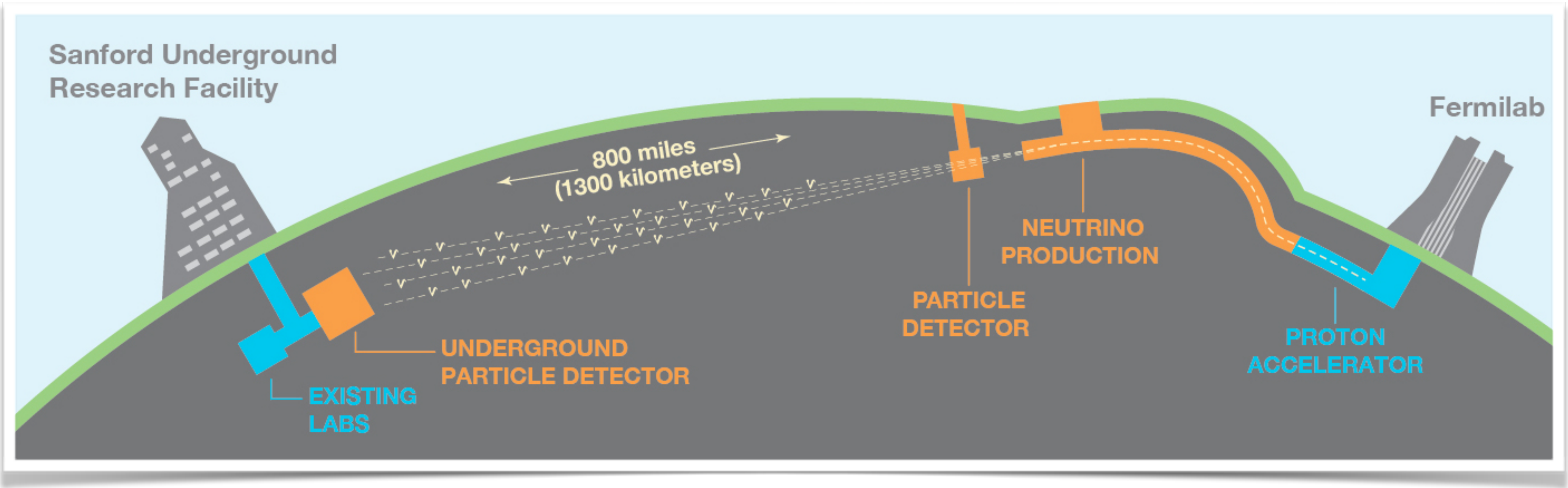


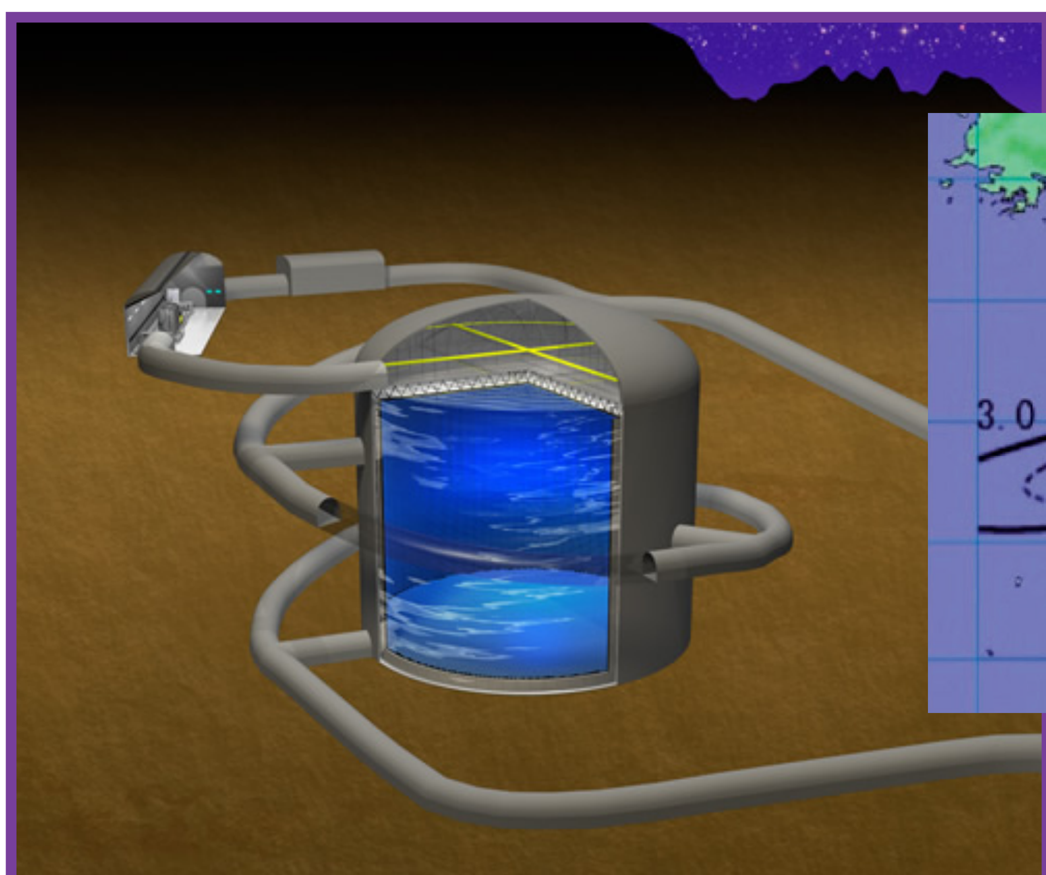


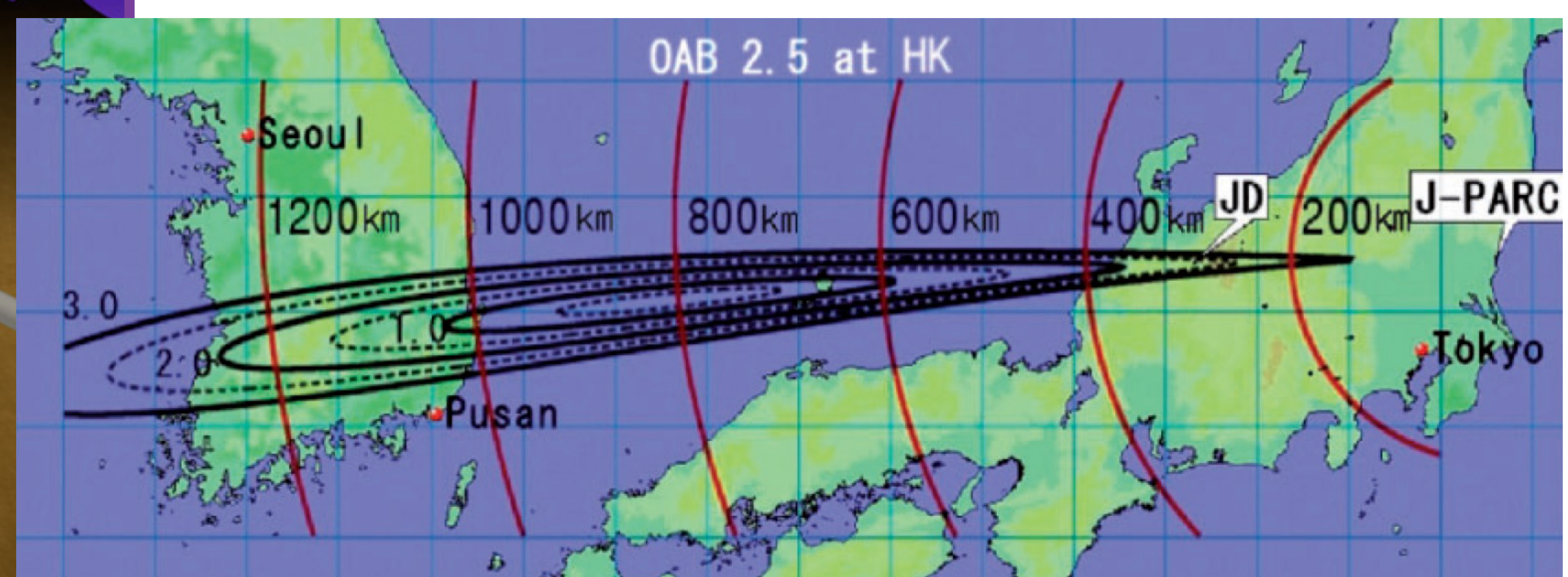
J. Wolcott, Jun 2019
http://nova-docdb.fnal.gov/cgi-bin/ShowDocument?docid=38391

- NOvA target: mass hierarchy
- Sensitivities of both experiments depend on true value of oscillation parameter

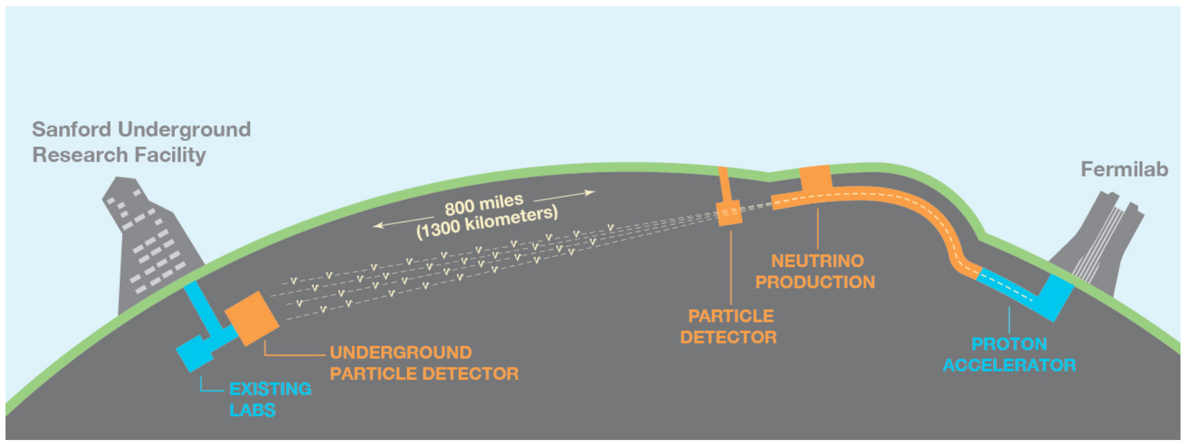
Next generation: DUNE and Hyper-Kamiokande

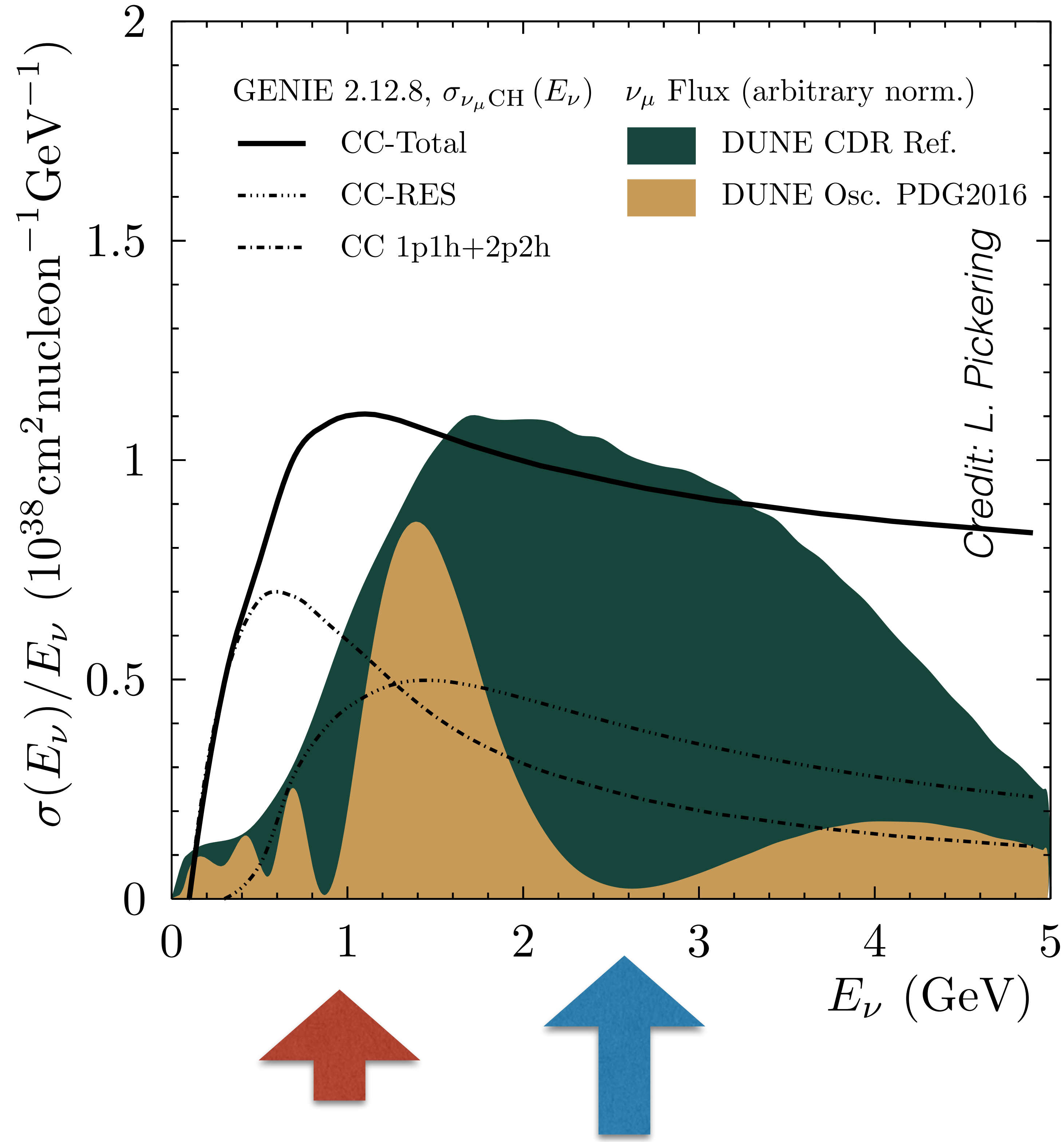






Deep Underground Neutrino Experiment (DUNE)

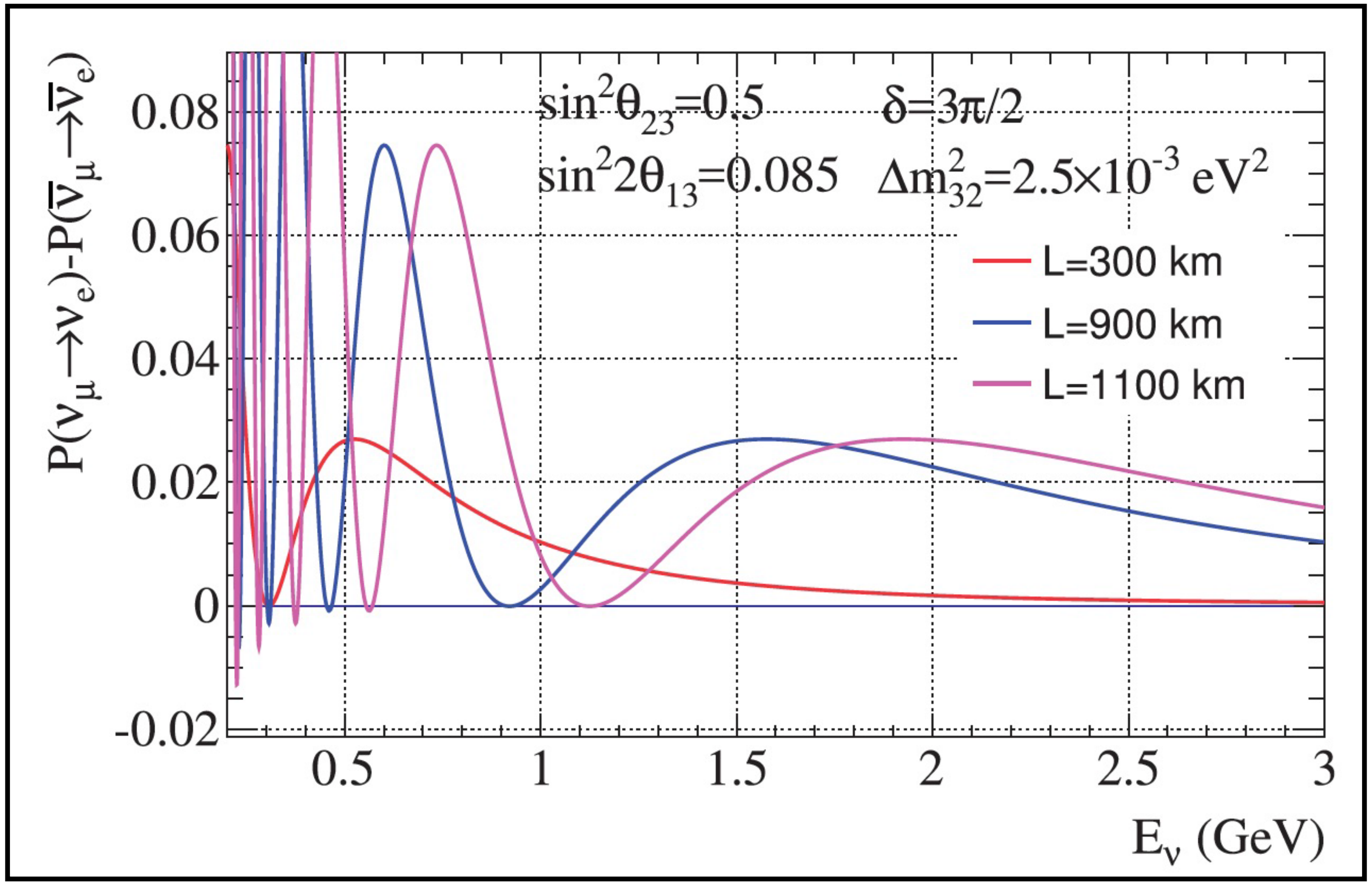




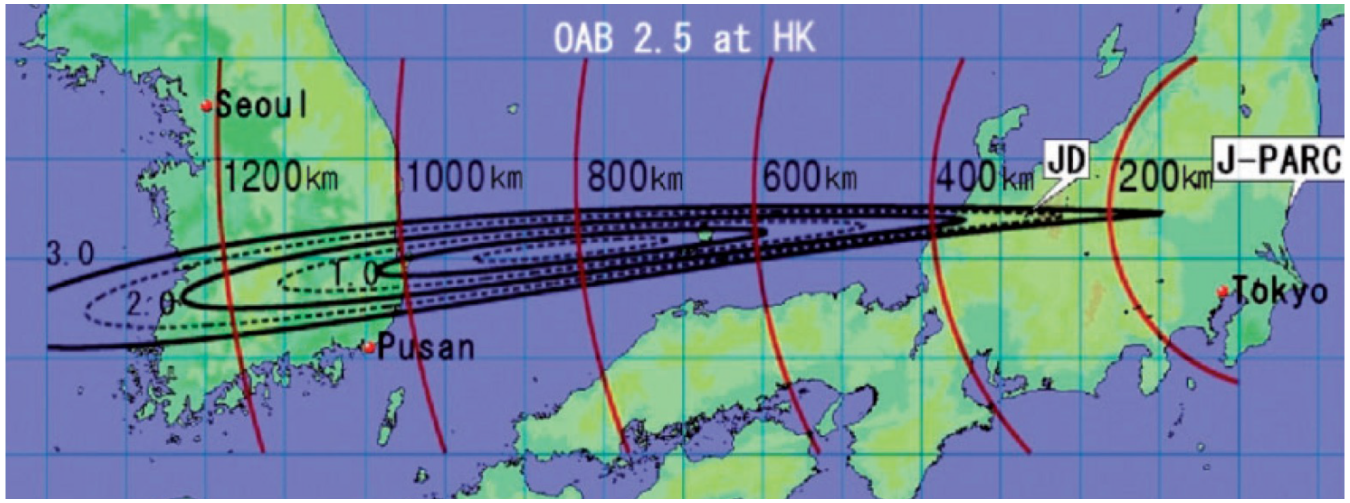
Second osc. max

First osc. max @ L=1300km

Tokai-to-Hyper-Kamiokande (T2HK)
(T2HKK?)

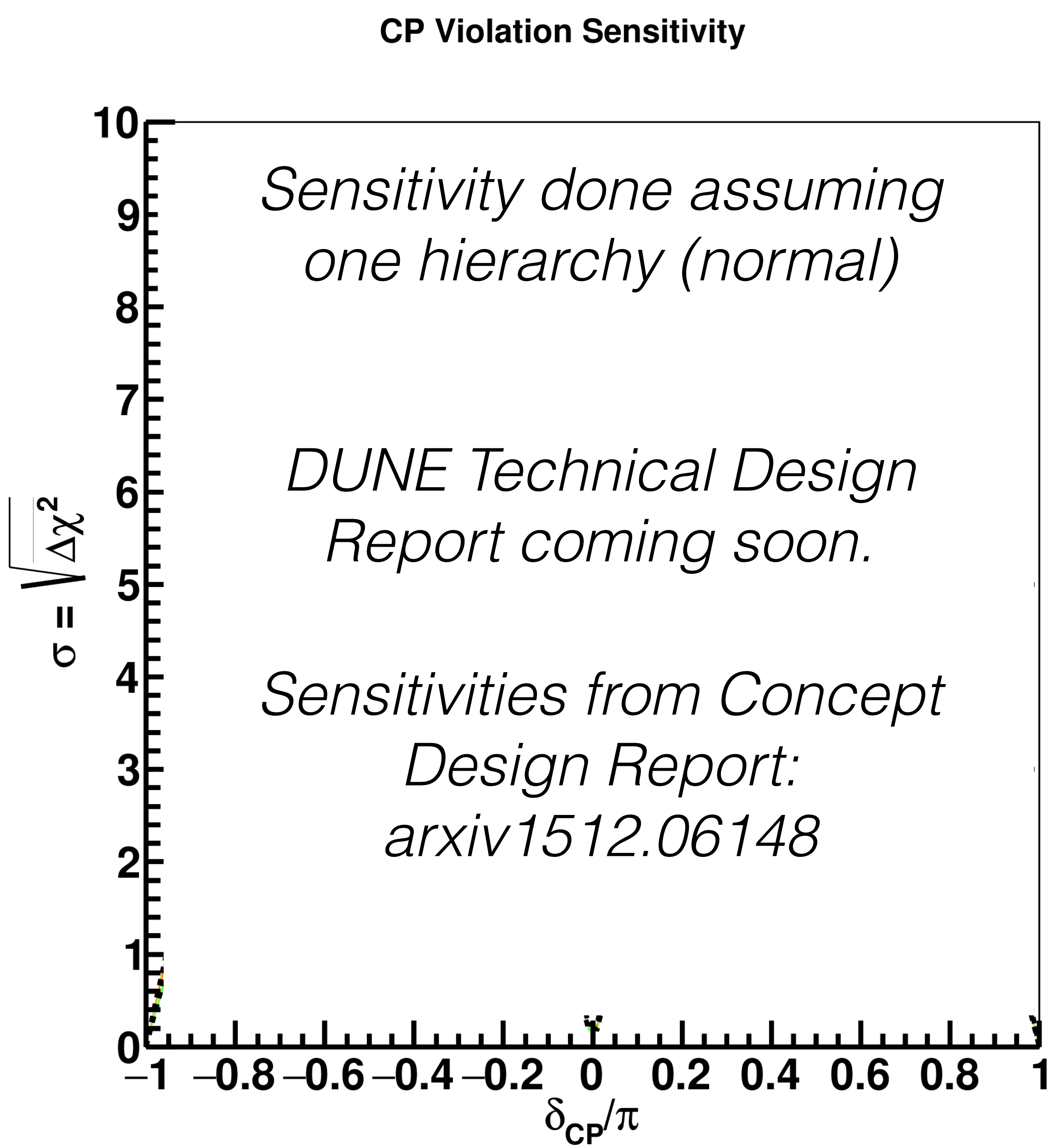


Prog. Theor. Exp. Phys. 2018 , 063C01



DUNE sensitivity to physics (CPV)

Significance



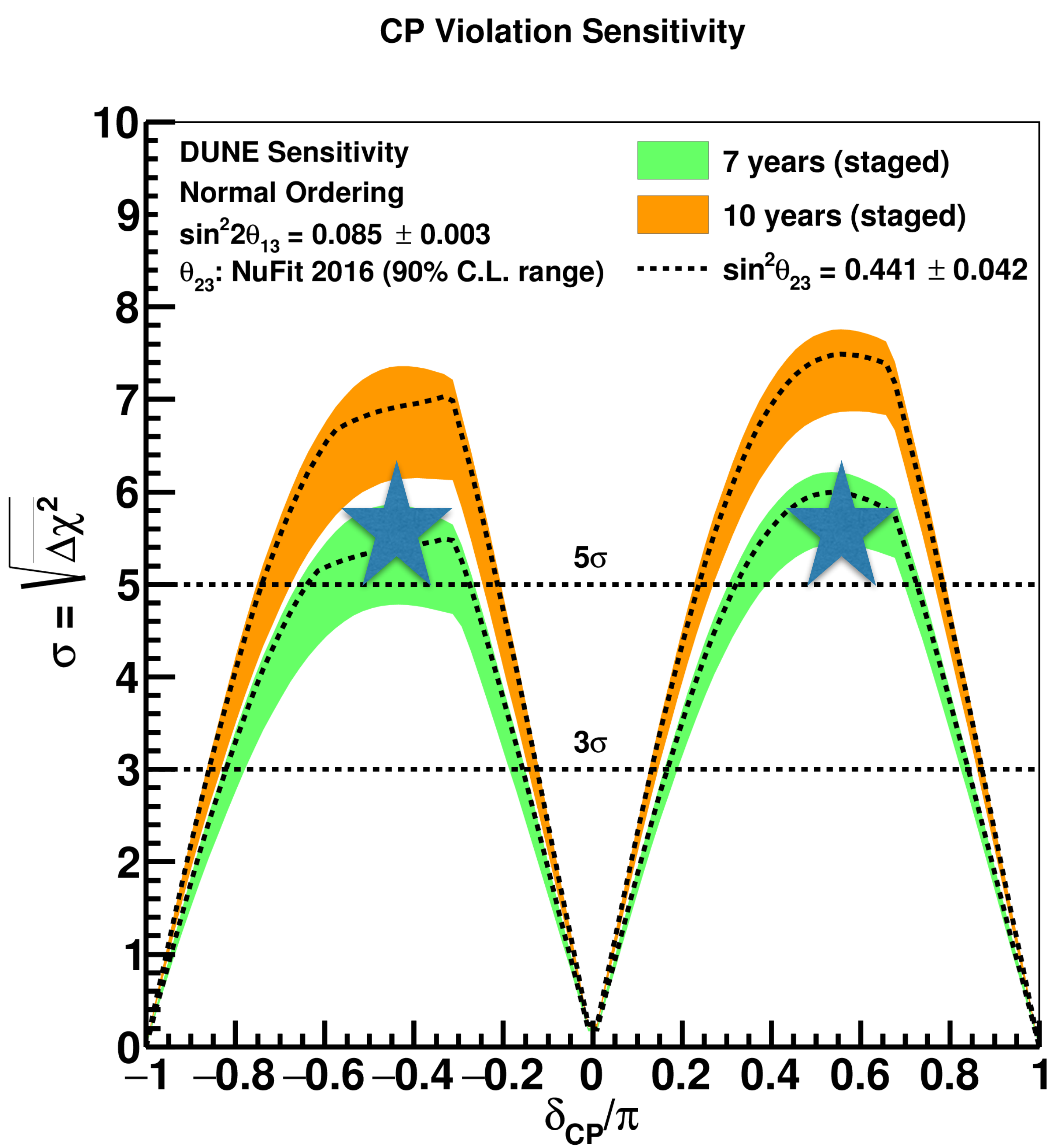
Sensitivity done assuming one hierarchy (normal)

DUNE Technical Design Report coming soon.

Sensitivities from Concept Design Report: arxiv1512.06148

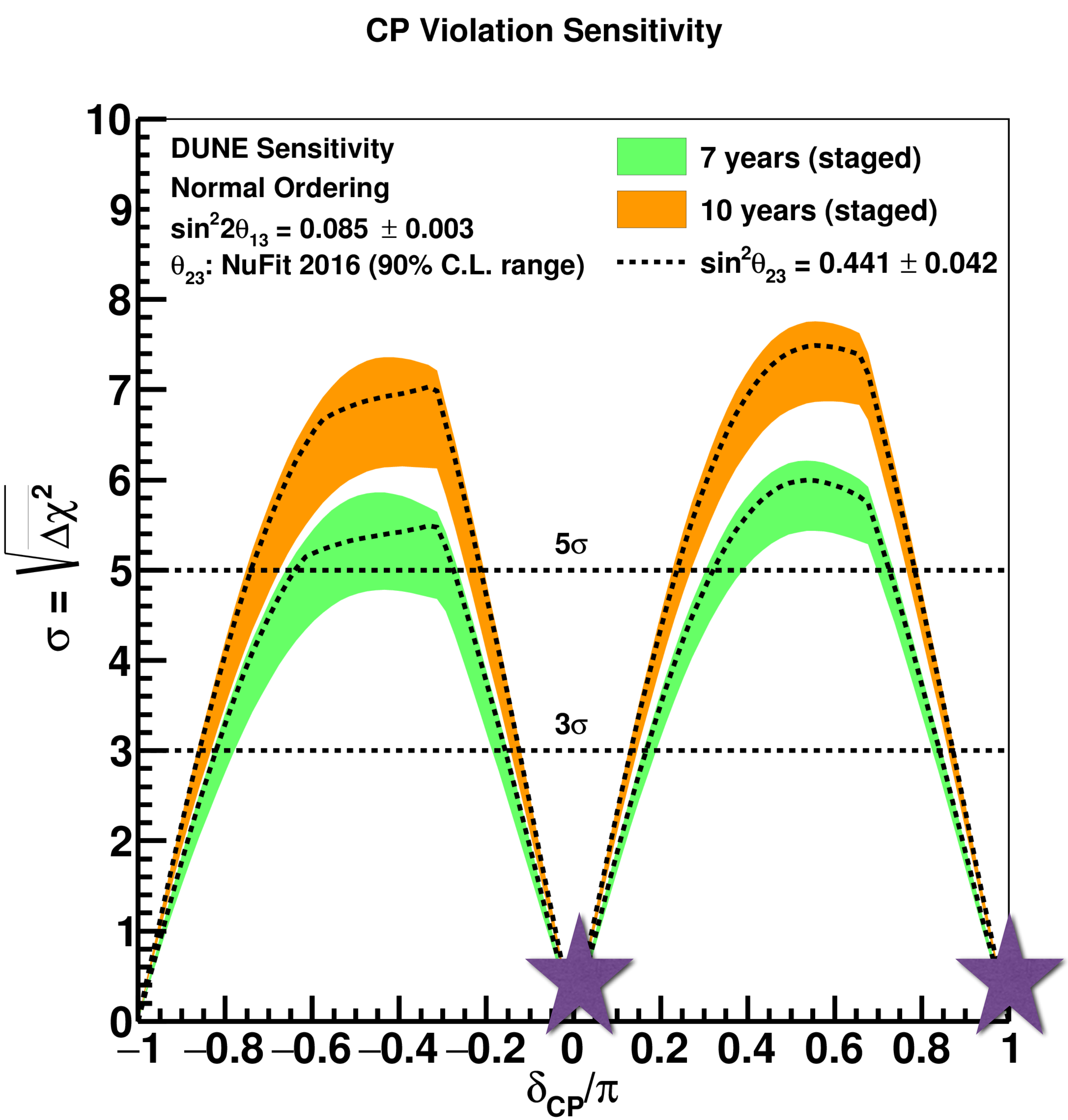
True value of δ_{CP}

DUNE sensitivity to physics (CPV)



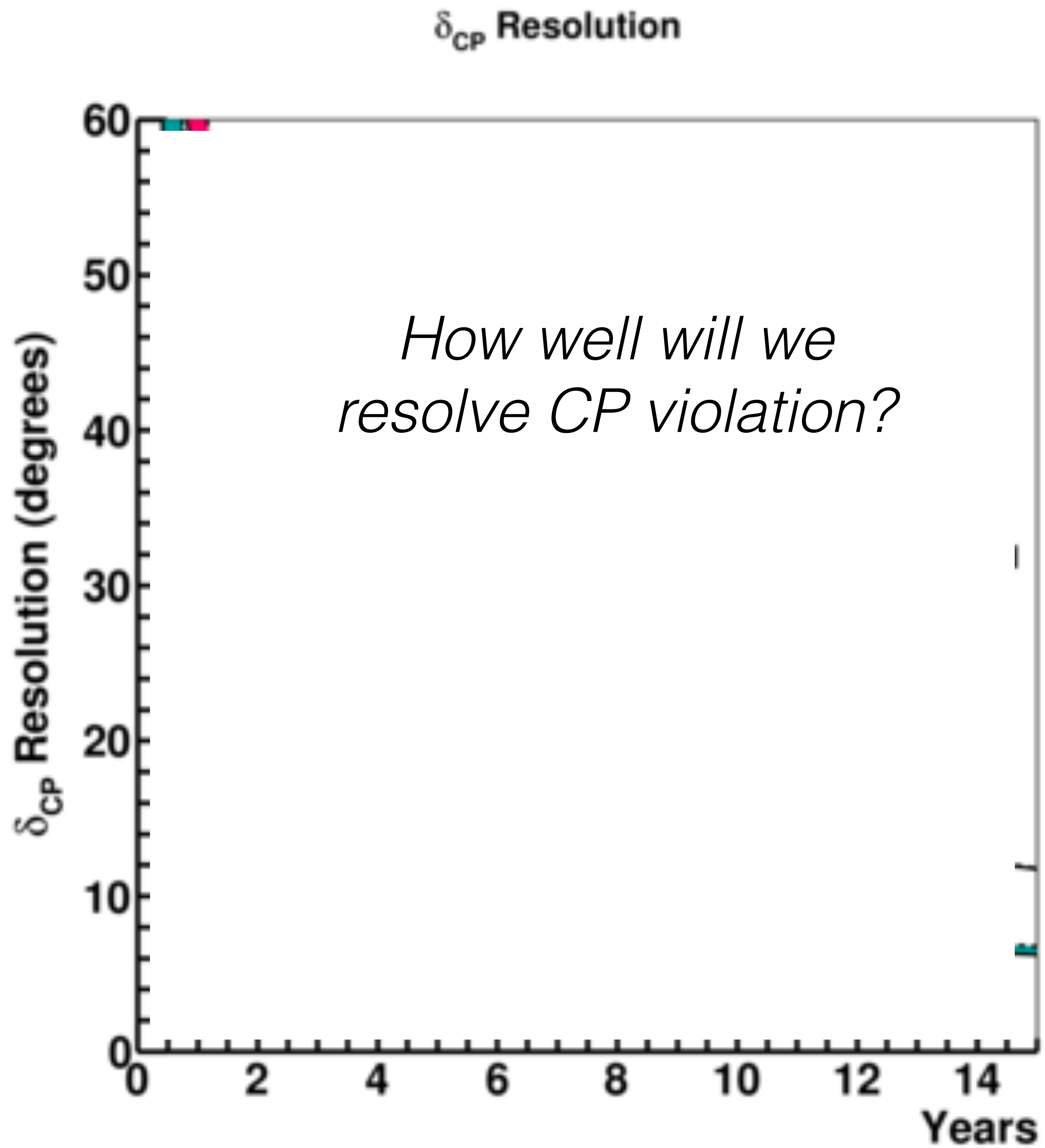
For large CP violating values, discovery of CPV with DUNE's staged run

DUNE sensitivity to physics (CPV)



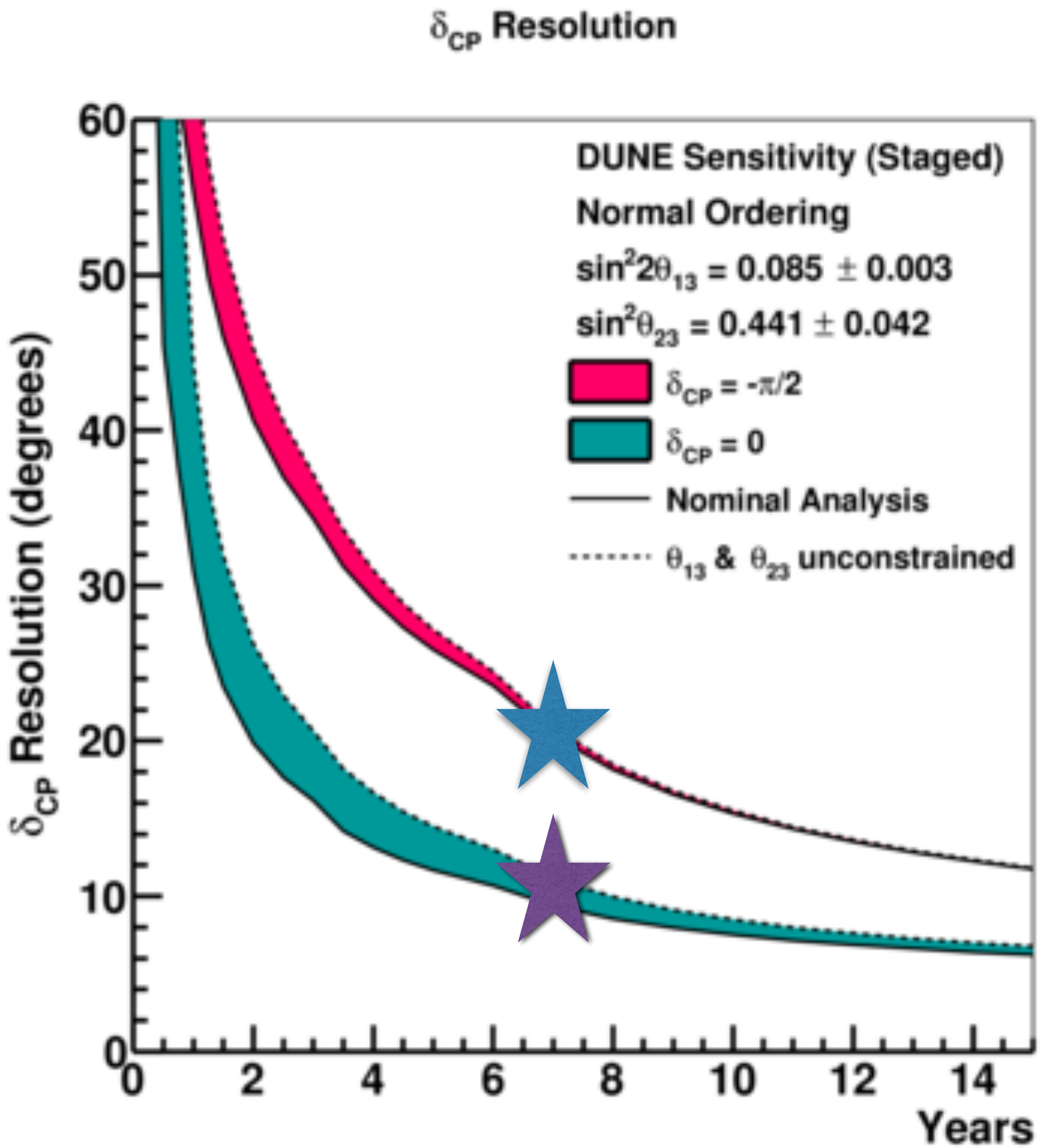
For small values (CP conserving), can't discover what's not there

DUNE sensitivity to physics (CPV)



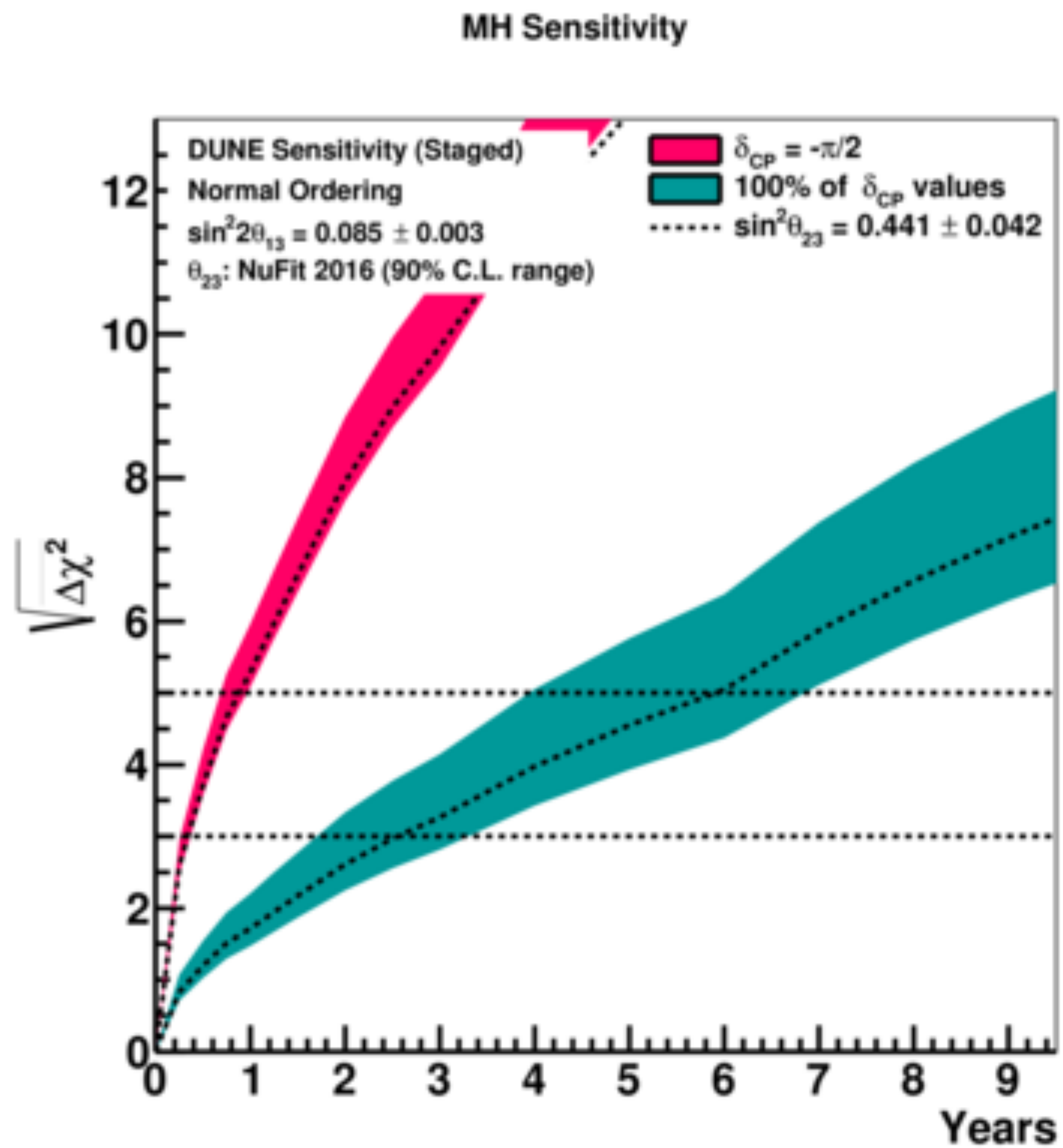
Time

DUNE sensitivity to physics (CPV)



For 7 years of running, DUNE resolves maximal (minimal) CPV to 20 (10) degrees

DUNE sensitivity to physics (Mass Hierarchy)



DUNE also can resolve the mass hierarchy

Complementary windows: HK sensitivity

Significant complementarity between the experiments given:

Systematic uncertainties

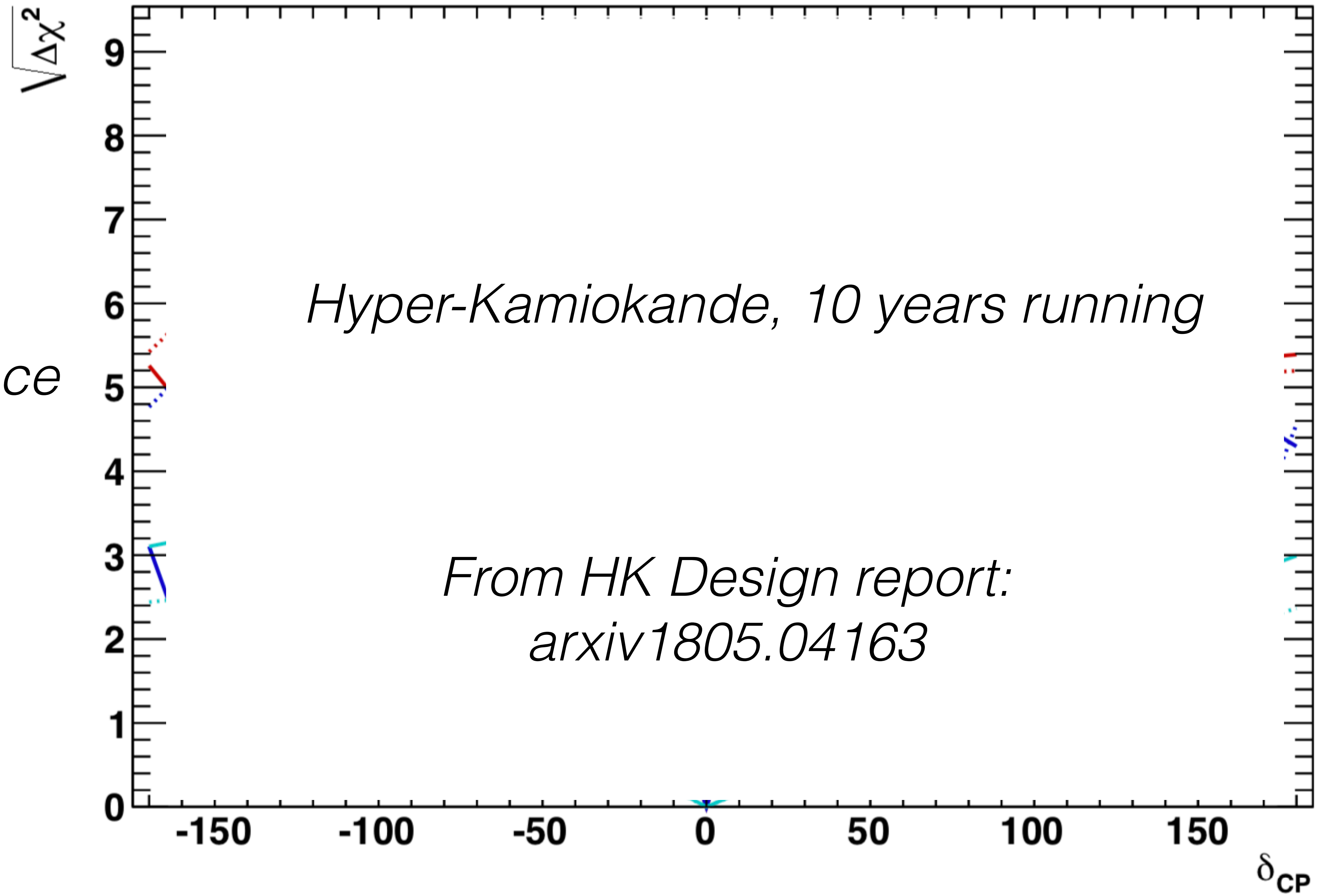
Degeneracy and complexity of oscillation parameter landscape

Beam energy

Baseline

Detector technology

Complementary windows: HK sensitivity



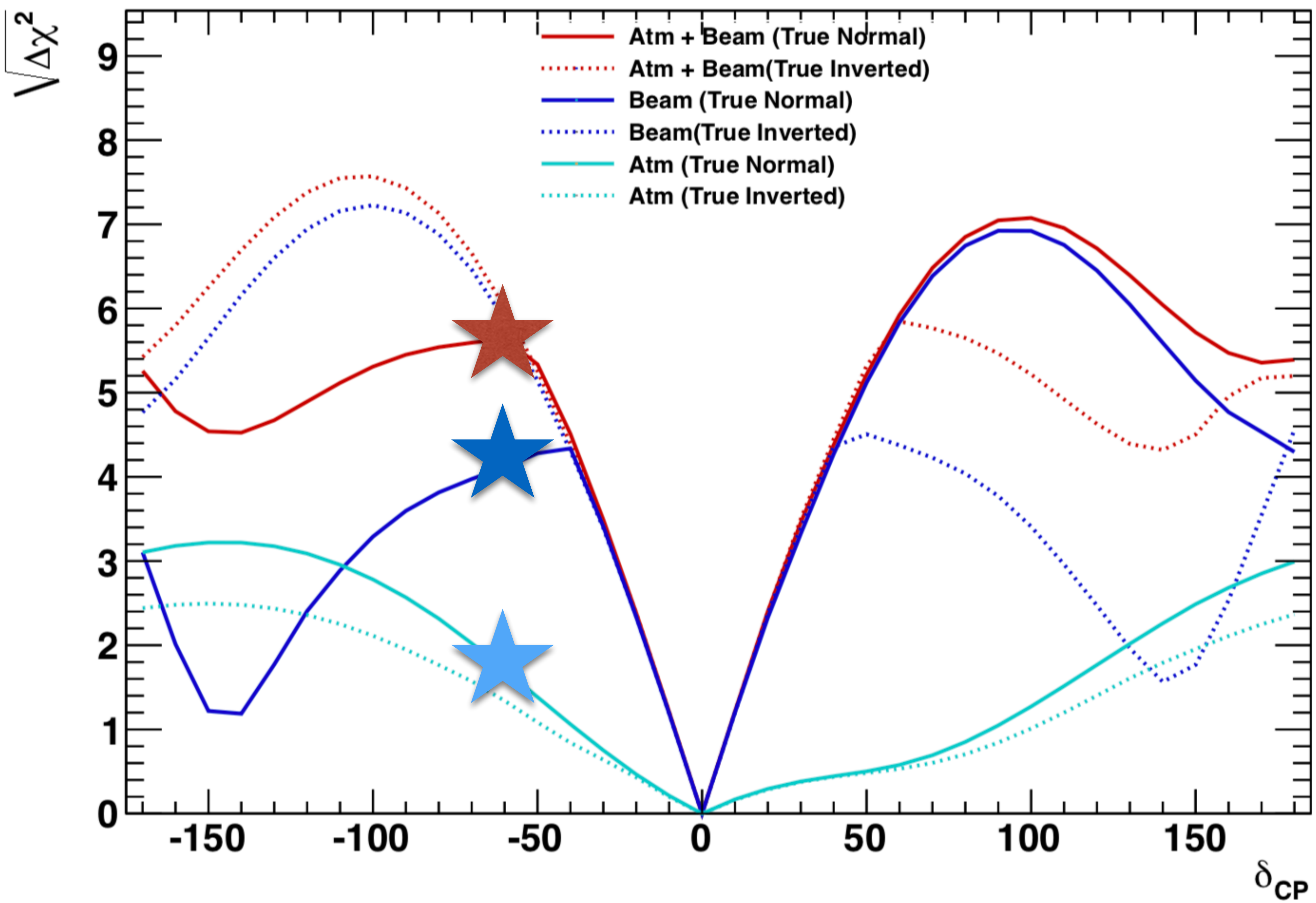
Hyper-Kamiokande, 10 years running

Significance

From HK Design report: arxiv1805.04163

True value of δ_{CP}

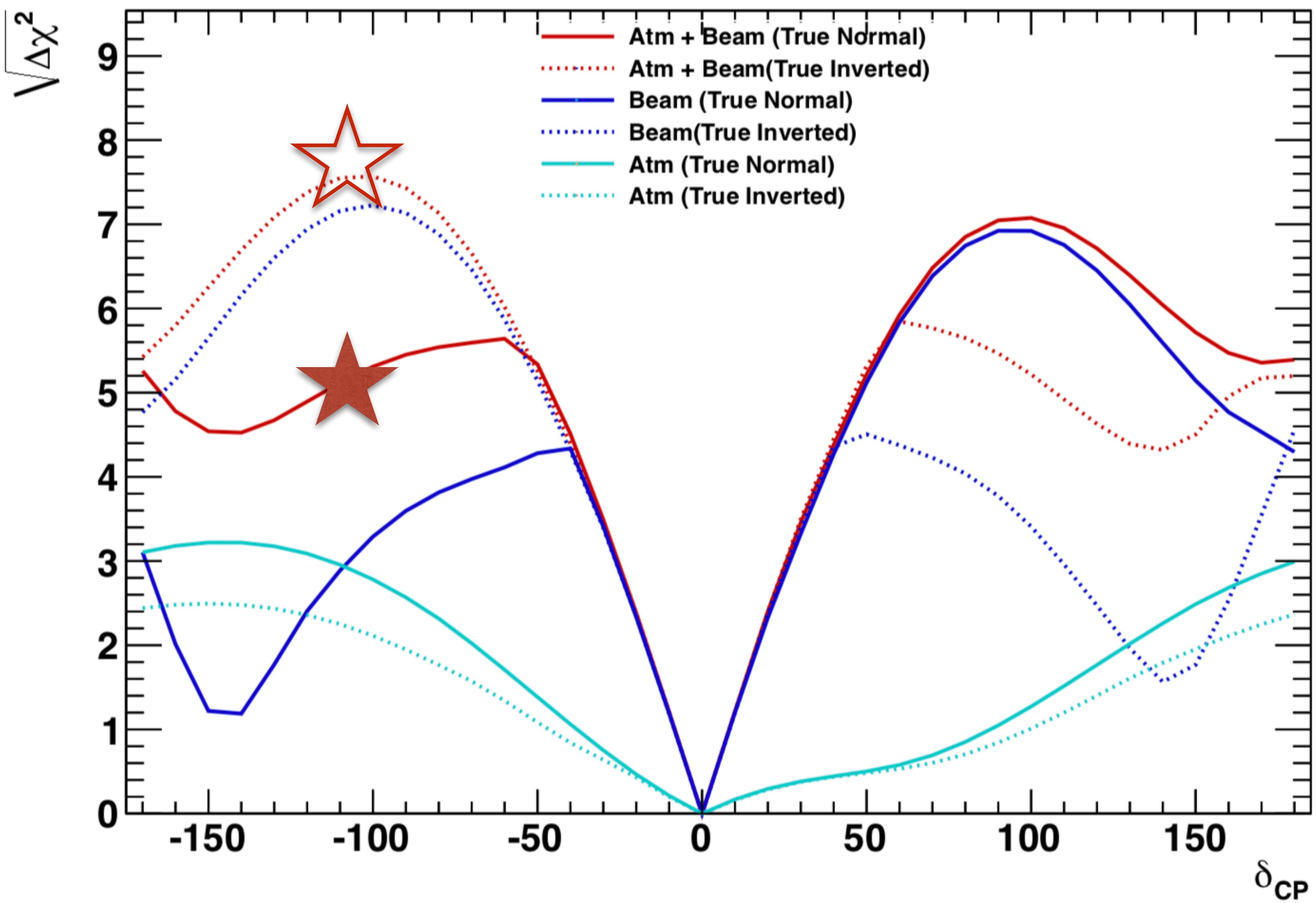
Complementary windows: HK sensitivity



HK Design report: arxiv1805.04163

Combination of atmospheric and beam interactions improves sensitivity

Complementary windows: HK sensitivity



HK Design report: arxiv1805.04163

Sensitivity depends on knowledge of hierarchy

(and other parameters, like θ_{23})

Complementary windows: beam, atmospheric

Strength of matter effect

HK beam | NOvA | DUNE | Atmospheric

Beam energy

Baseline

Detector technology

Degeneracy and complexity of oscillation parameter landscape

Systematic uncertainties

Questions on accelerator based experiments?

Outline

How do we study neutrino oscillation? Is our understanding of neutrino mixing complete?

Accelerator based neutrinos

Reactor and solar neutrinos

Reactor experiments

$$P\left(\nu_\mu \rightarrow \nu_e\right) \approx \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin\left(\frac{1.27\Delta m^2_{32} L}{E}\right)$$
$$\mp \frac{\Delta m^2_{21} L}{4E} J_{CP} \sin(\delta_{CP}) \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right) + ...$$

$$J_{CP} = \frac{1}{8} \cos\theta_{13} \sin(2\theta_{12}) \sin(2\theta_{23}) \sin(2\theta_{13}) \sin(\delta_{CP})$$

Depends on all the mixing parameters

Isolate θ_{13} with antineutrino disappearance from reactors

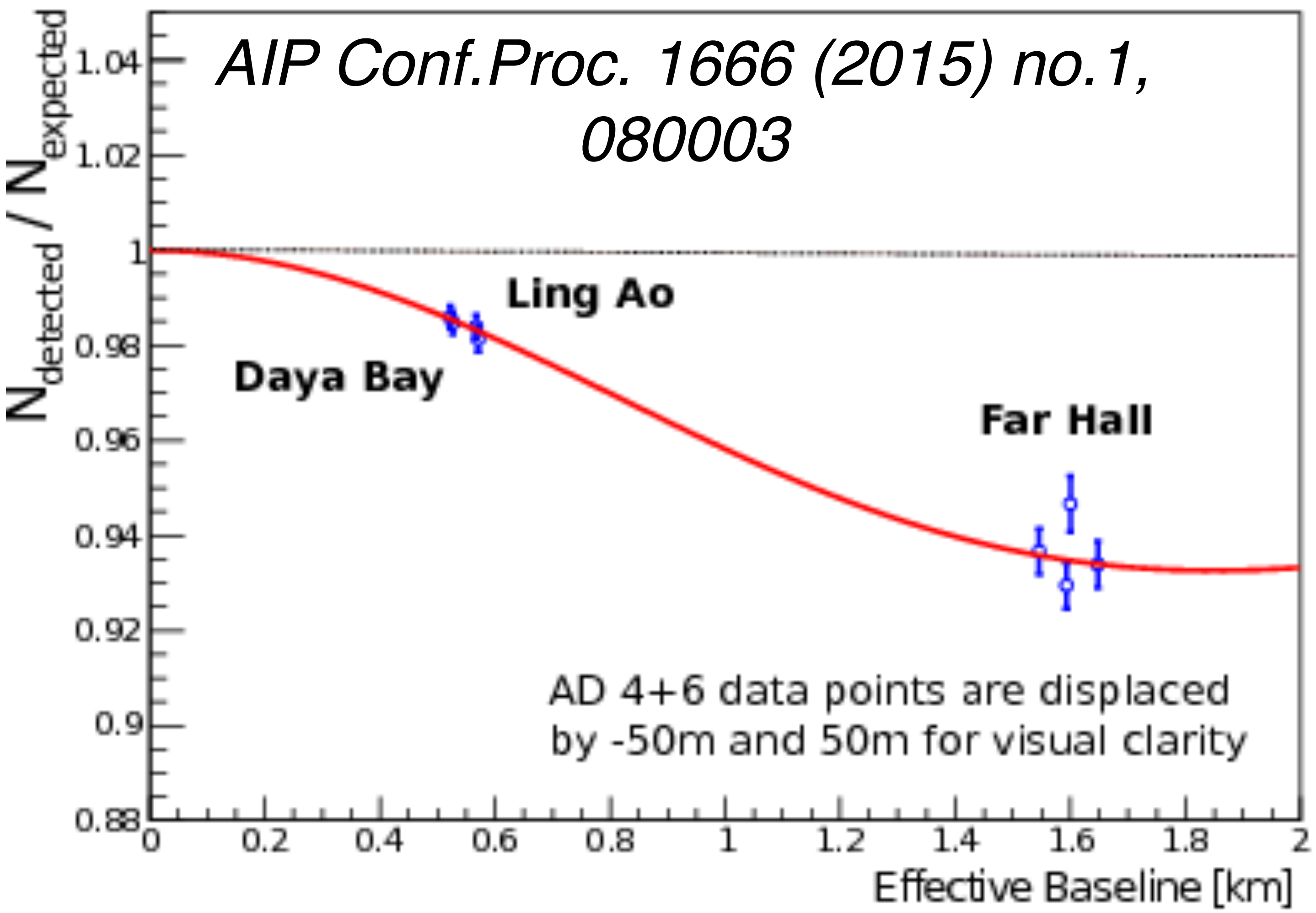
Reactor experiments

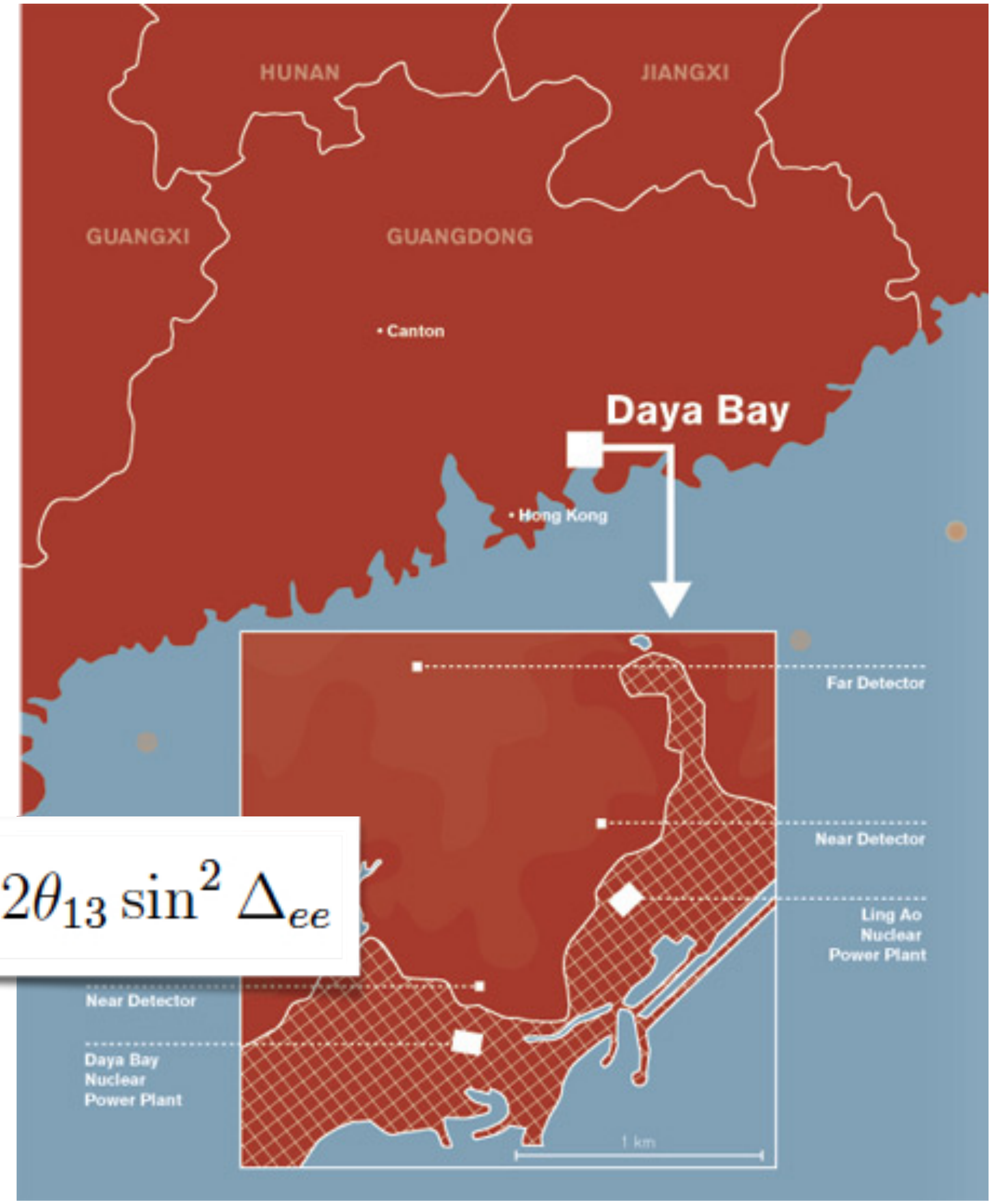
http://dayabay.ihep.ac.cn

http://doublechooz.in2p3.fr

https://en.wikipedia.org/wiki/Reactor_Experiment_for_Neutrino_Oscillation

Example: Daya Bay

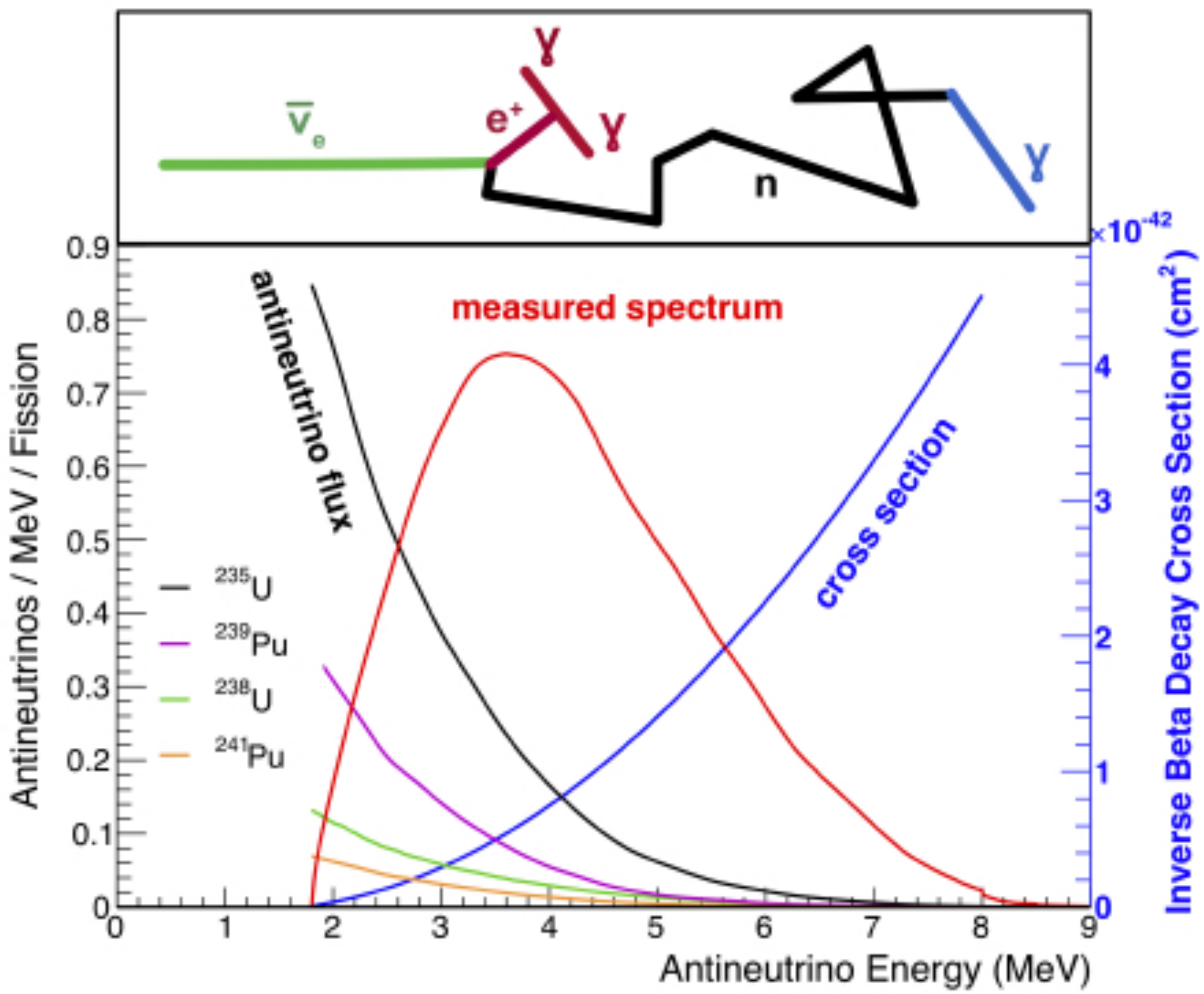




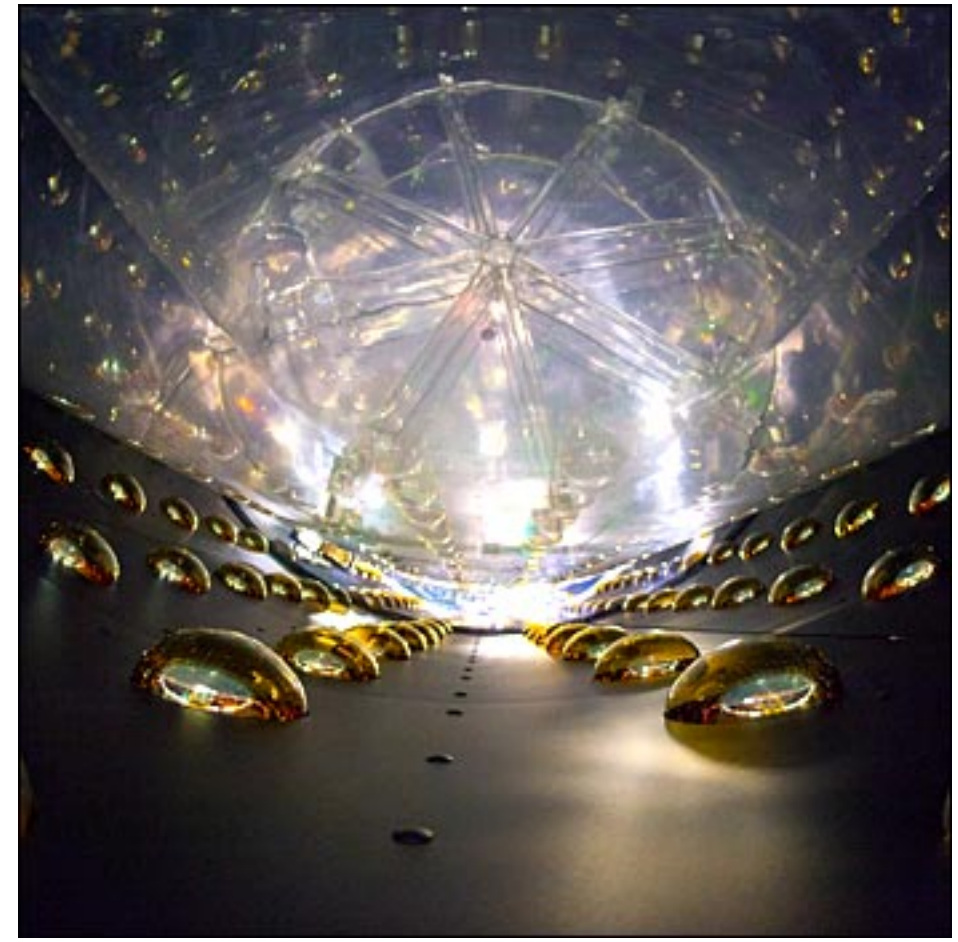
$$P = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{ee}$$

https://www.symmetrymagazine.org/article/octobernovember-2006/catching-neutrinos-in-china

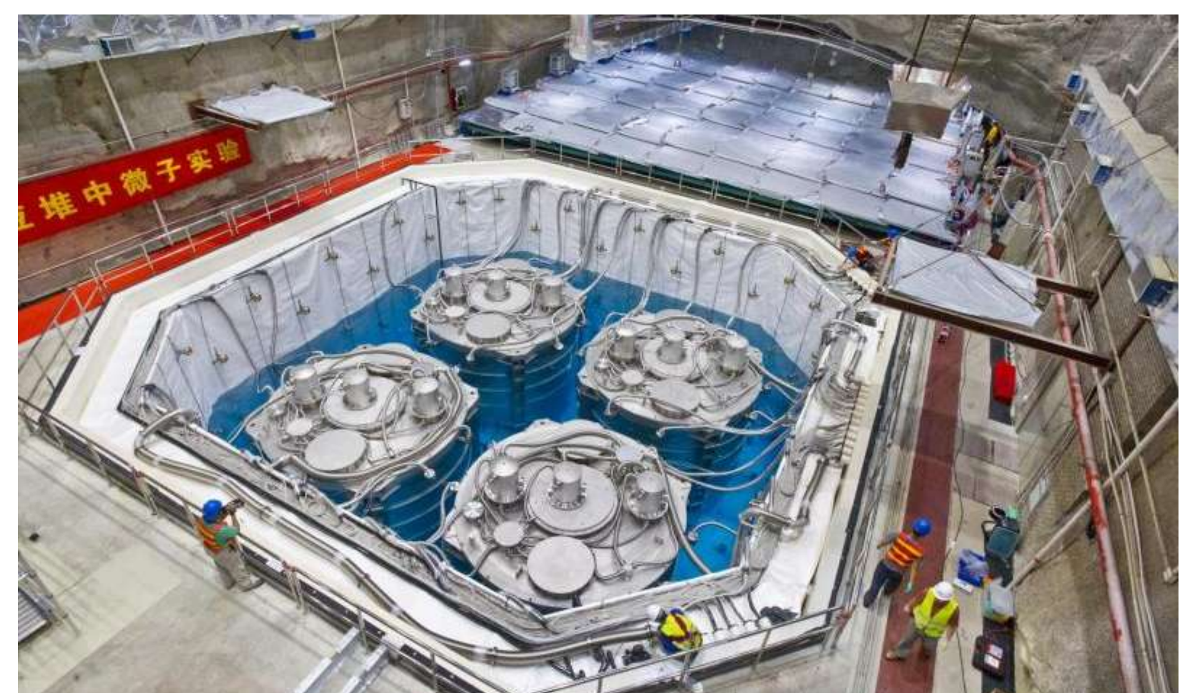
Example: Daya Bay



https://arxiv.org/abs/1902.03281

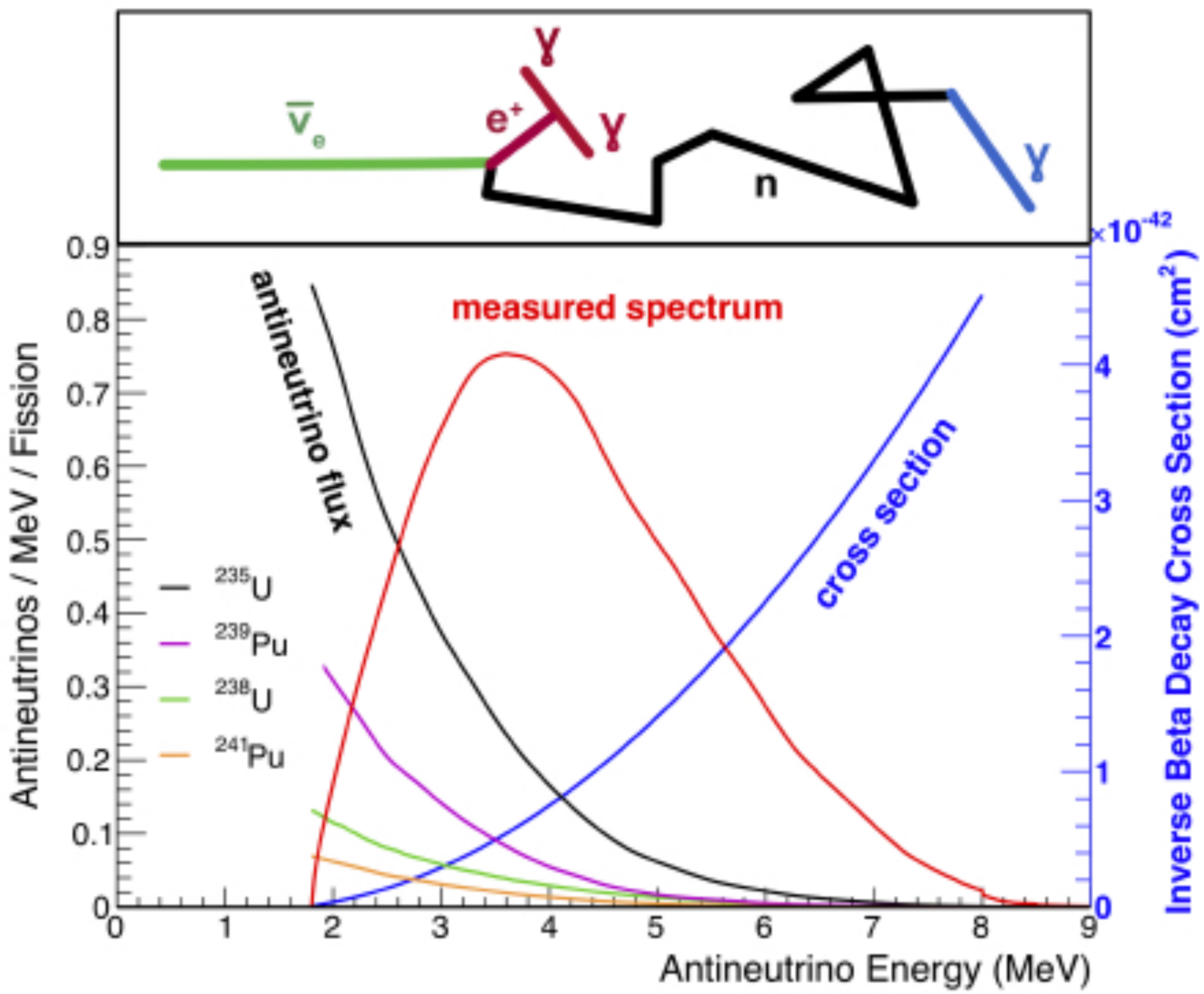


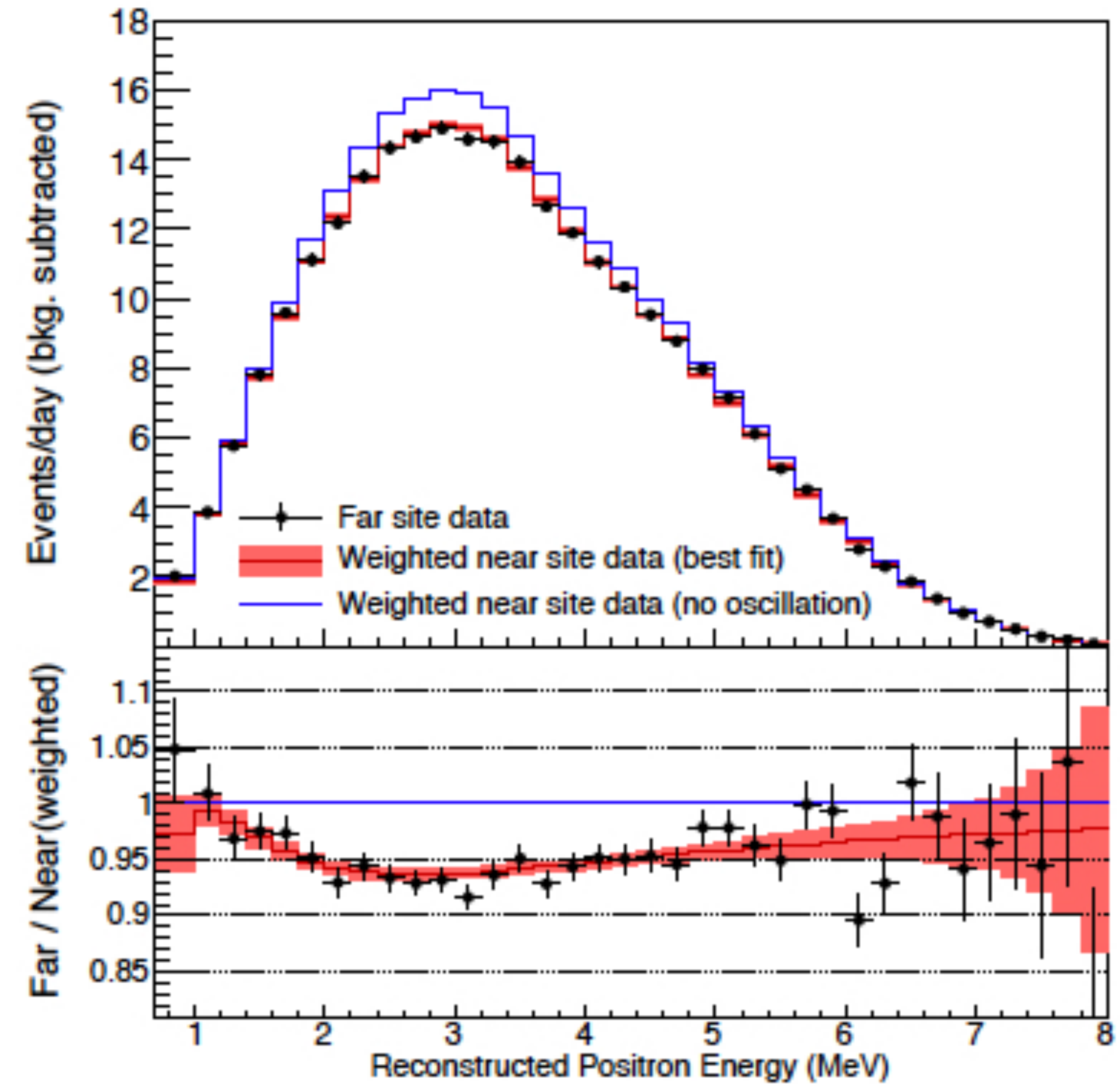
https://www.bnl.gov/newsroom/news.php?a=111395



https://phys.org/news/2015-09-precision-neutrino-daya-bay.html

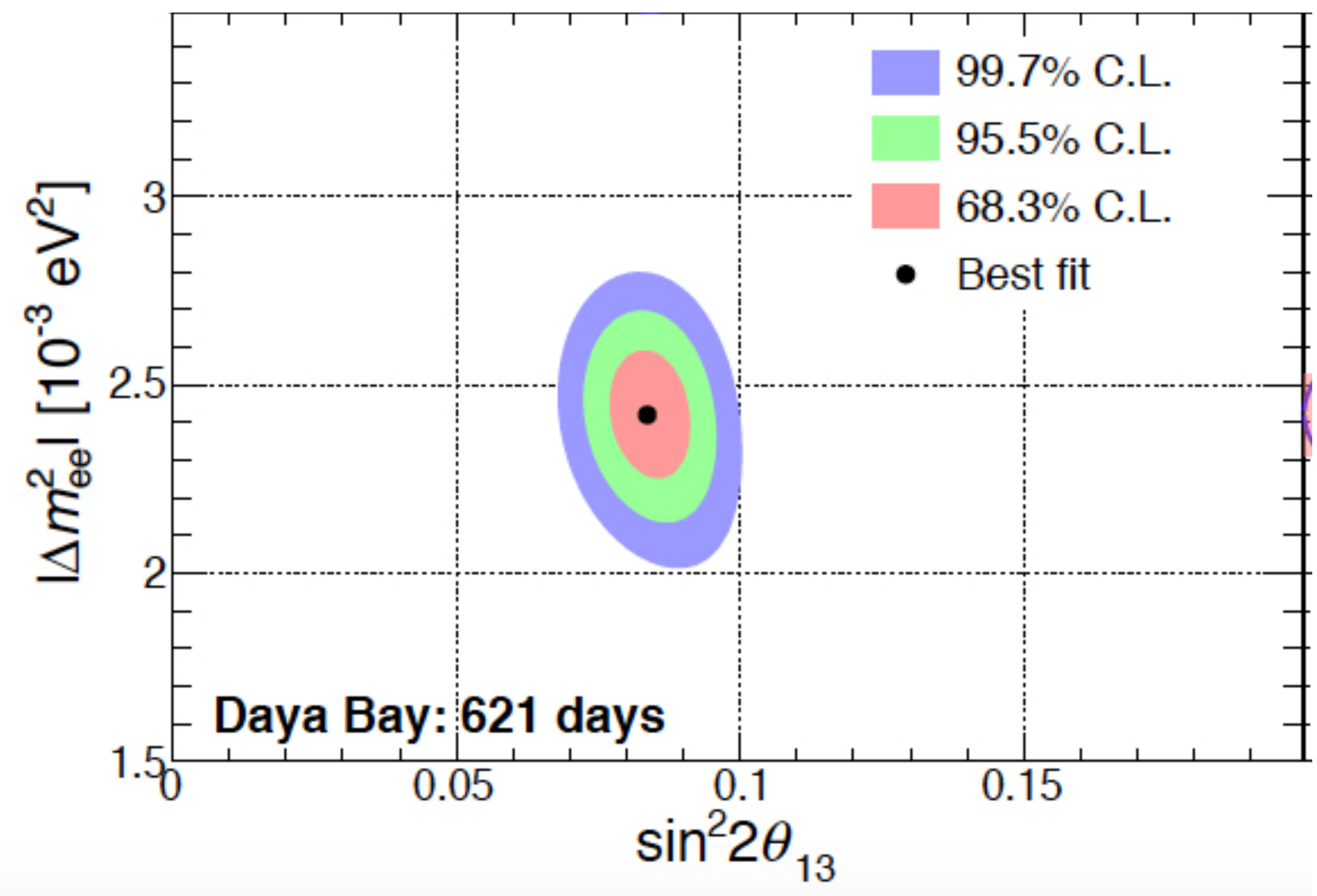
Example: Daya Bay

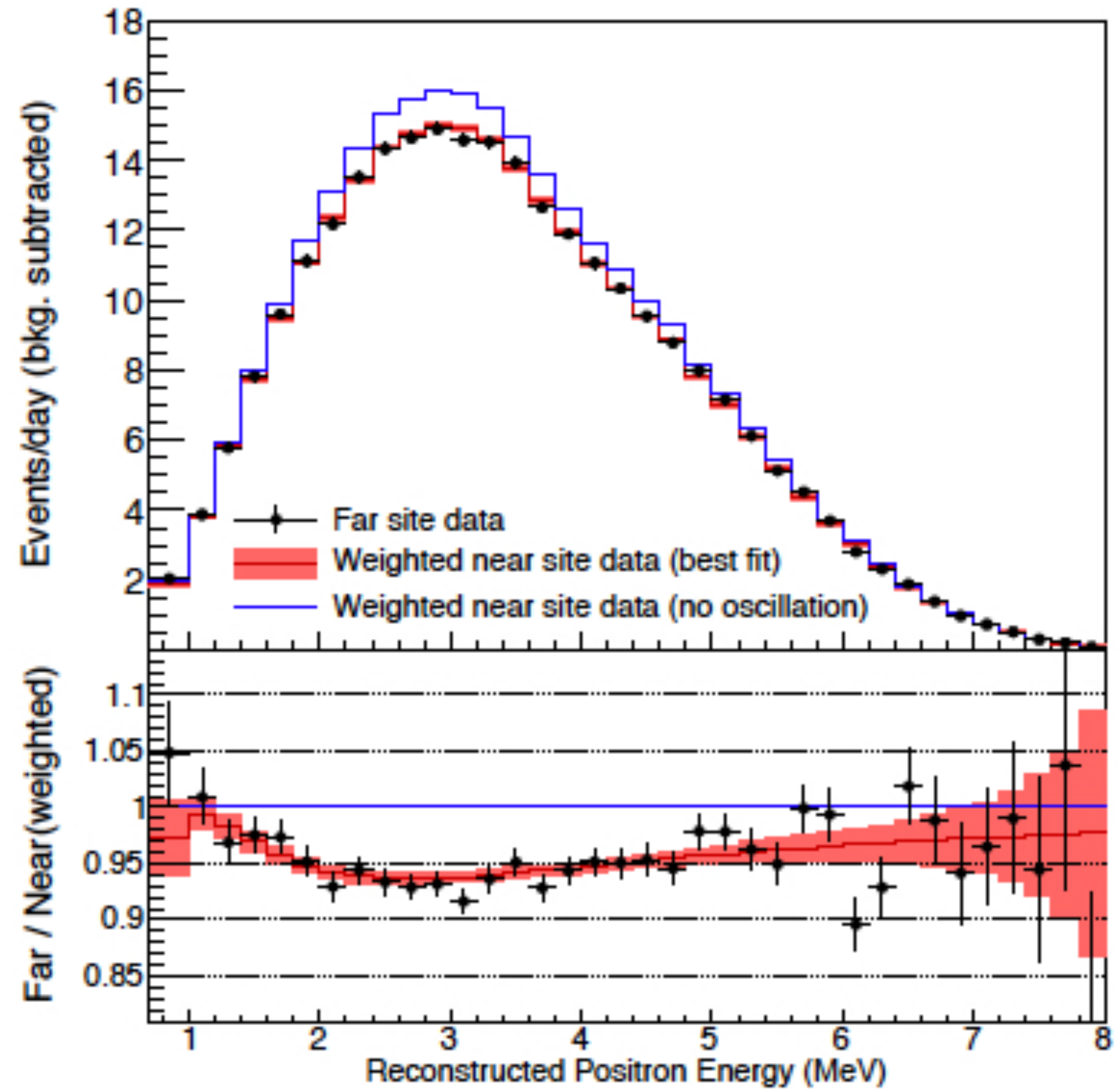




Phys. Rev. Lett. 115, 111802 (2015)

Example: Daya Bay



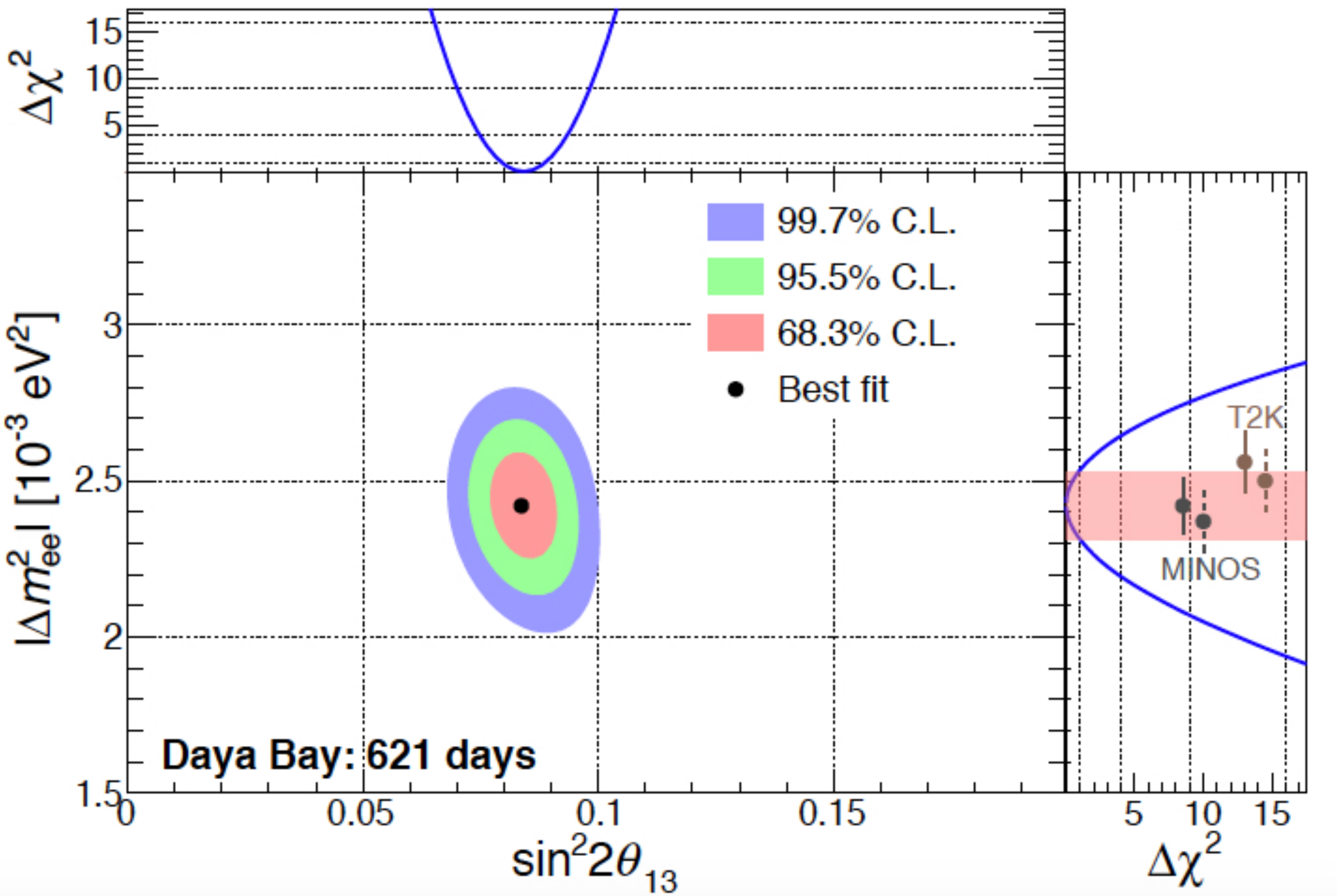


Phys. Rev. Lett. 115, 111802 (2015)

Challenge: Incredibly precise experiments

Recent paper is: Phys.Rev.Lett. 121 (2018) no.24, 241805
See PDG for global fits

Example: Daya Bay

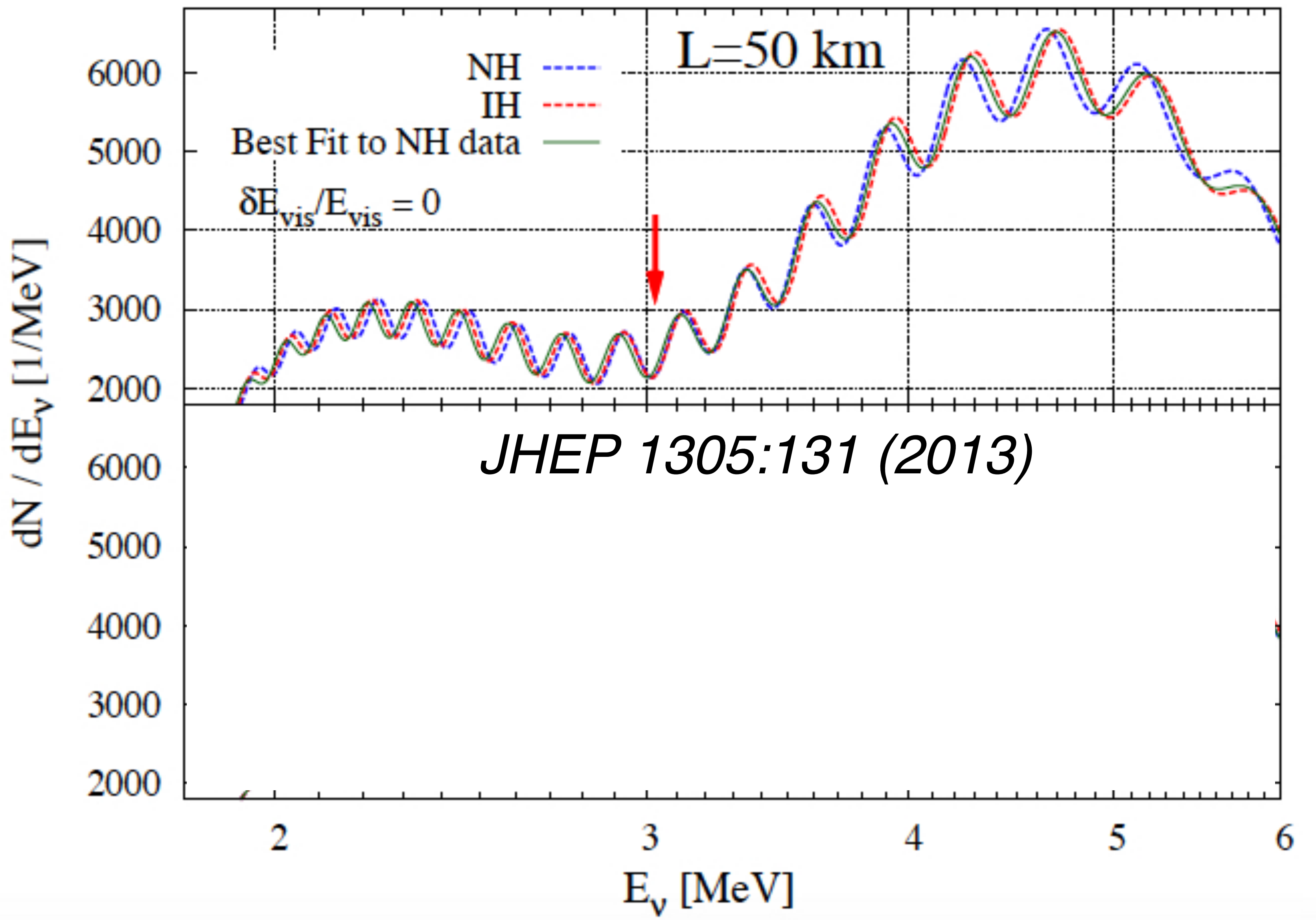


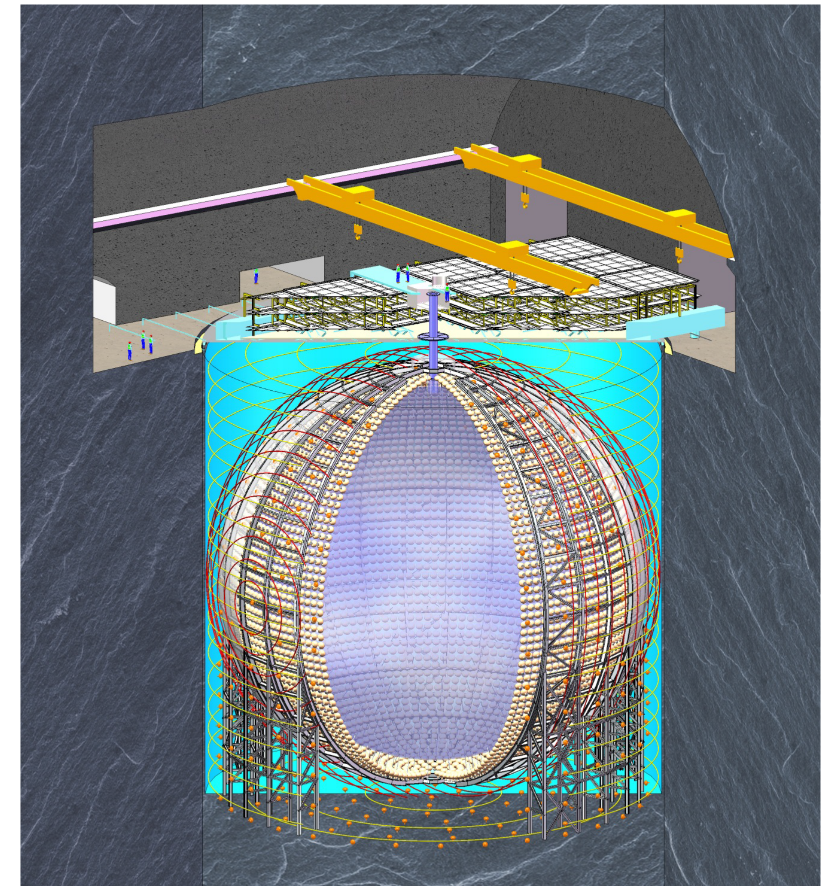
$$\Delta m^2_{\rm eff}|_e = \cos^2\theta_{12}|\Delta m^2_{31}| + \sin^2\theta_{12}|\Delta m^2_{32}|$$
$$= |\Delta m^2_{32}| \pm \cos^2\theta_{12}\Delta m^2_{21}.$$

Phys. Rev. Lett. 115, 111802 (2015)

Complementary to accelerator based; is the three flavor picture complete?

Future reactor experiments: JUNO

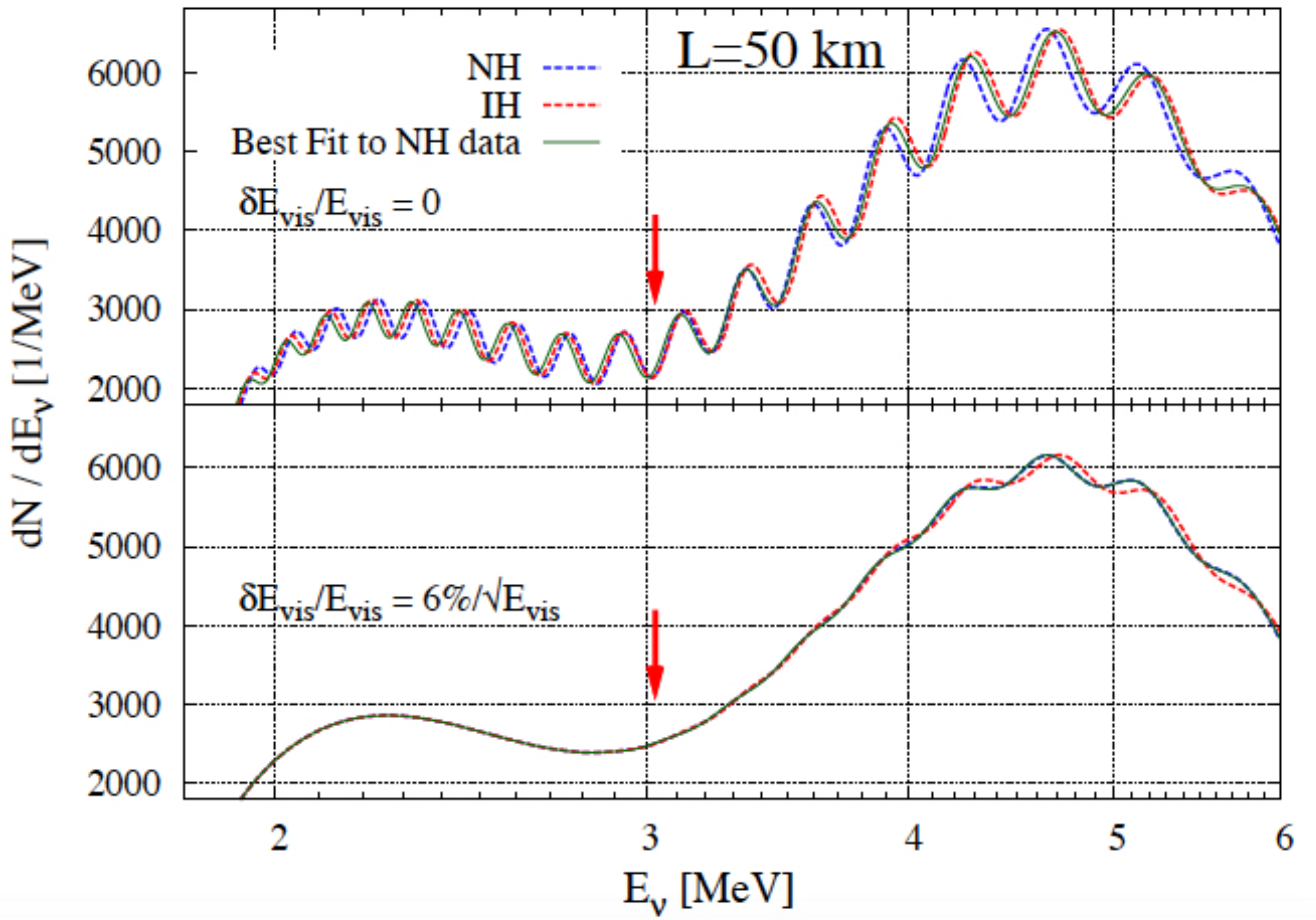


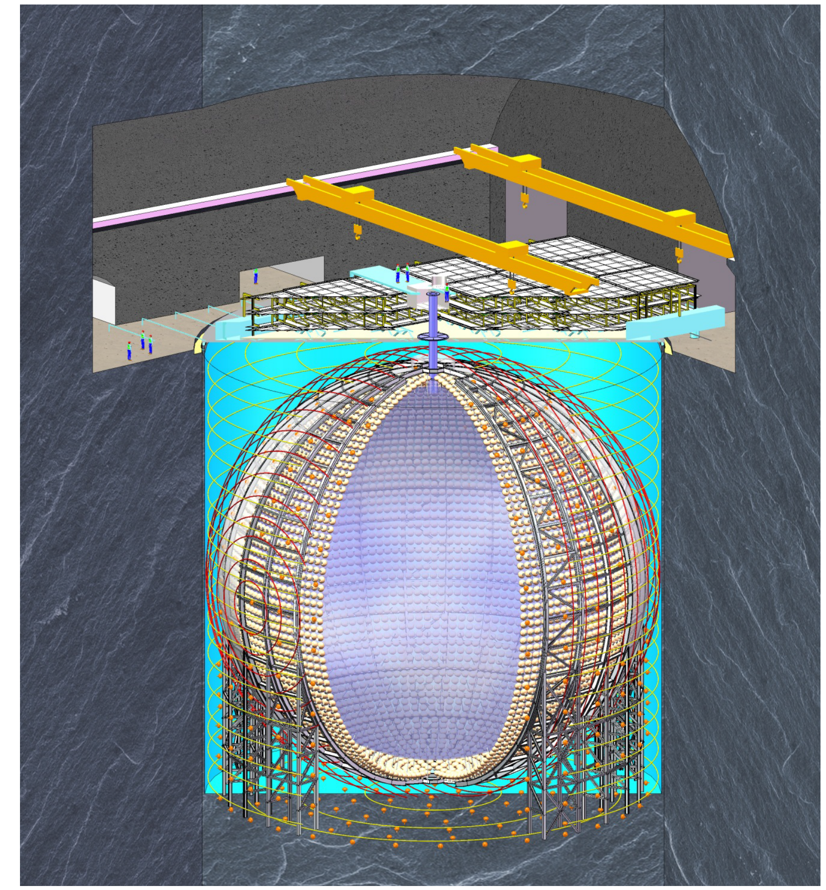


At baselines of 50km for reactor neutrino energies, novel sensitivity to hierarchy choice

Concept design report: arXiv:1508.07166

Future reactor experiments: JUNO





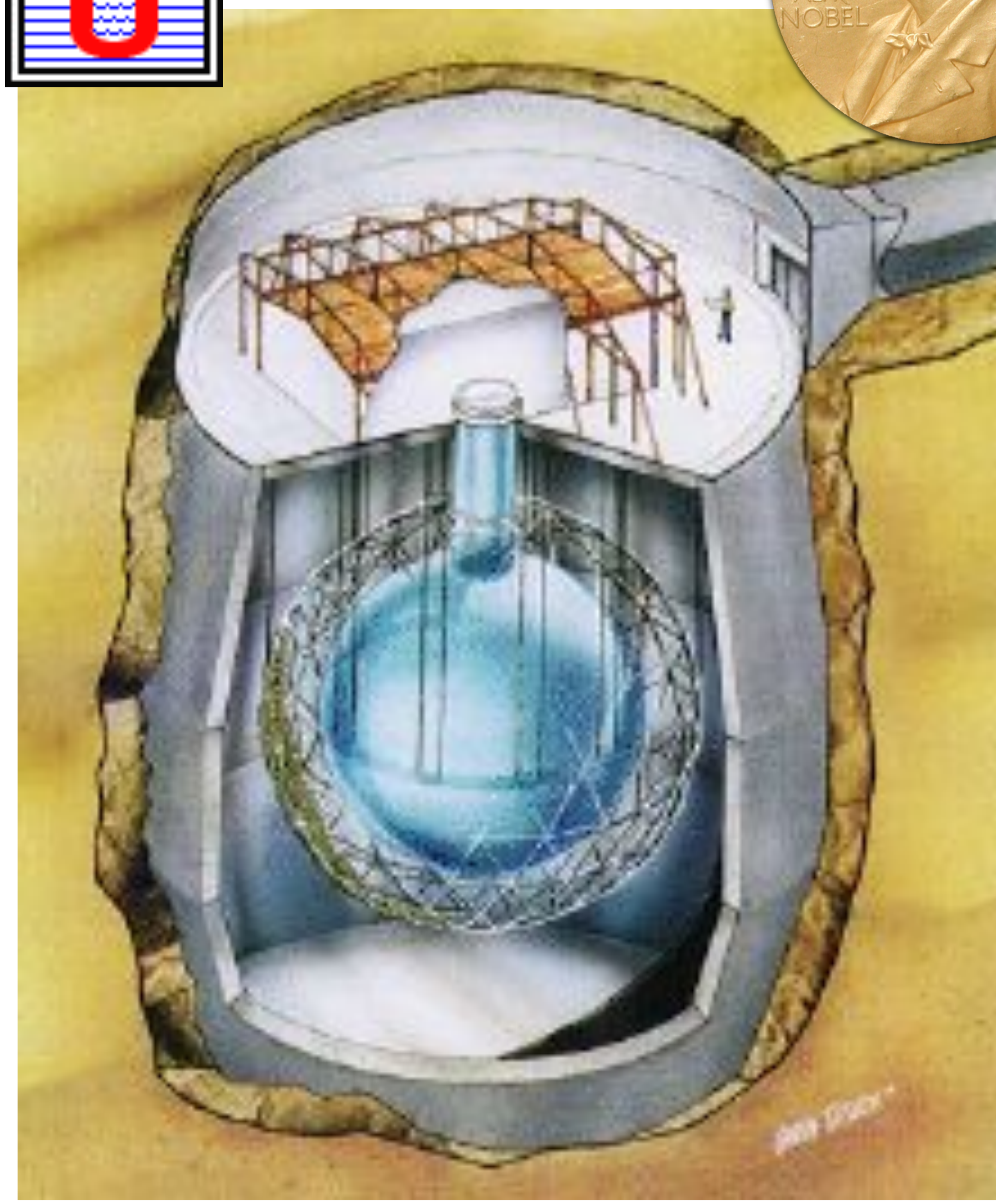
Challenge: Very sensitive to energy resolution; energy scale. Active R&D

Concept design report: arXiv:1508.07166

Solar neutrinos: Sudbury Neutrino Observatory

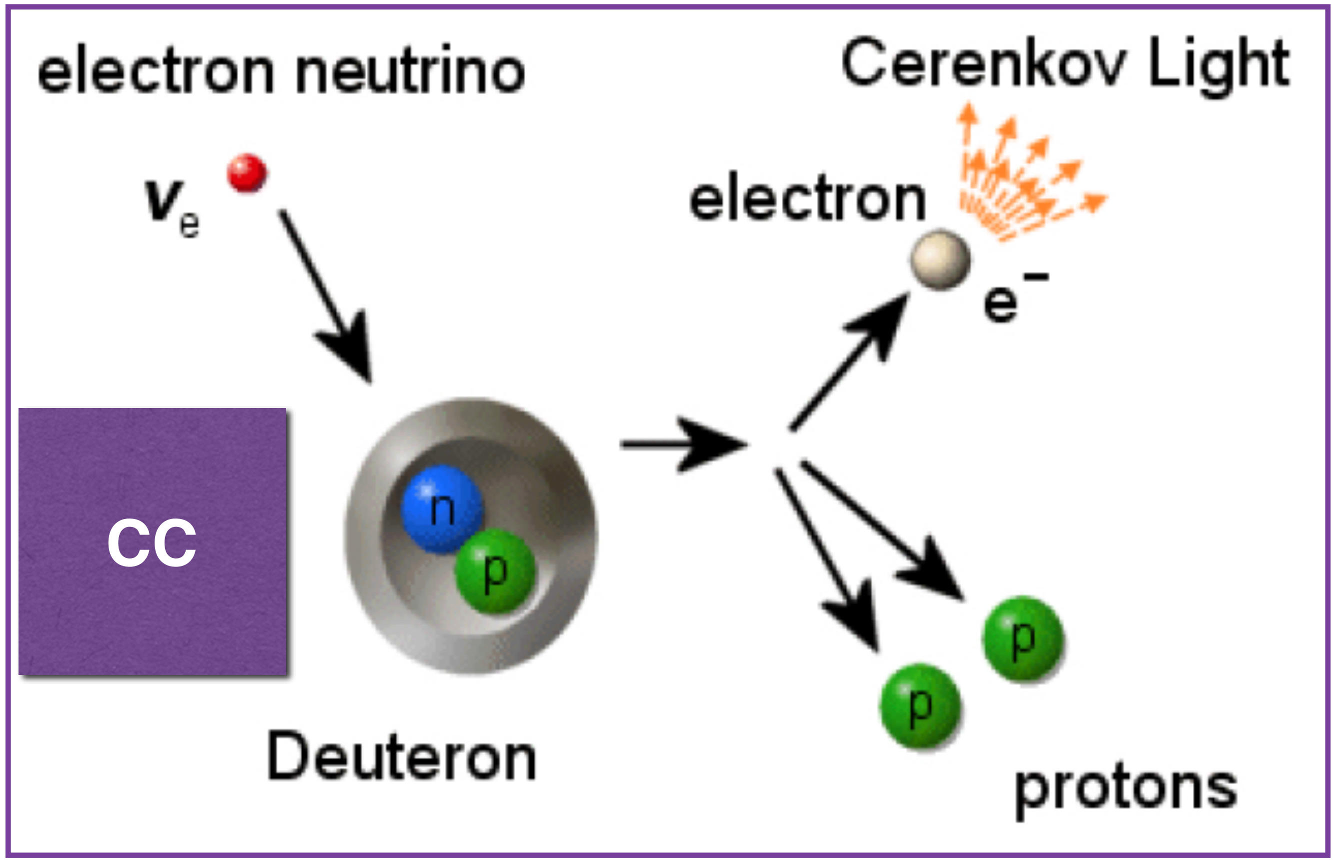
wikicommons

2km underground, filled with
$300M in heavy (deuterated) water

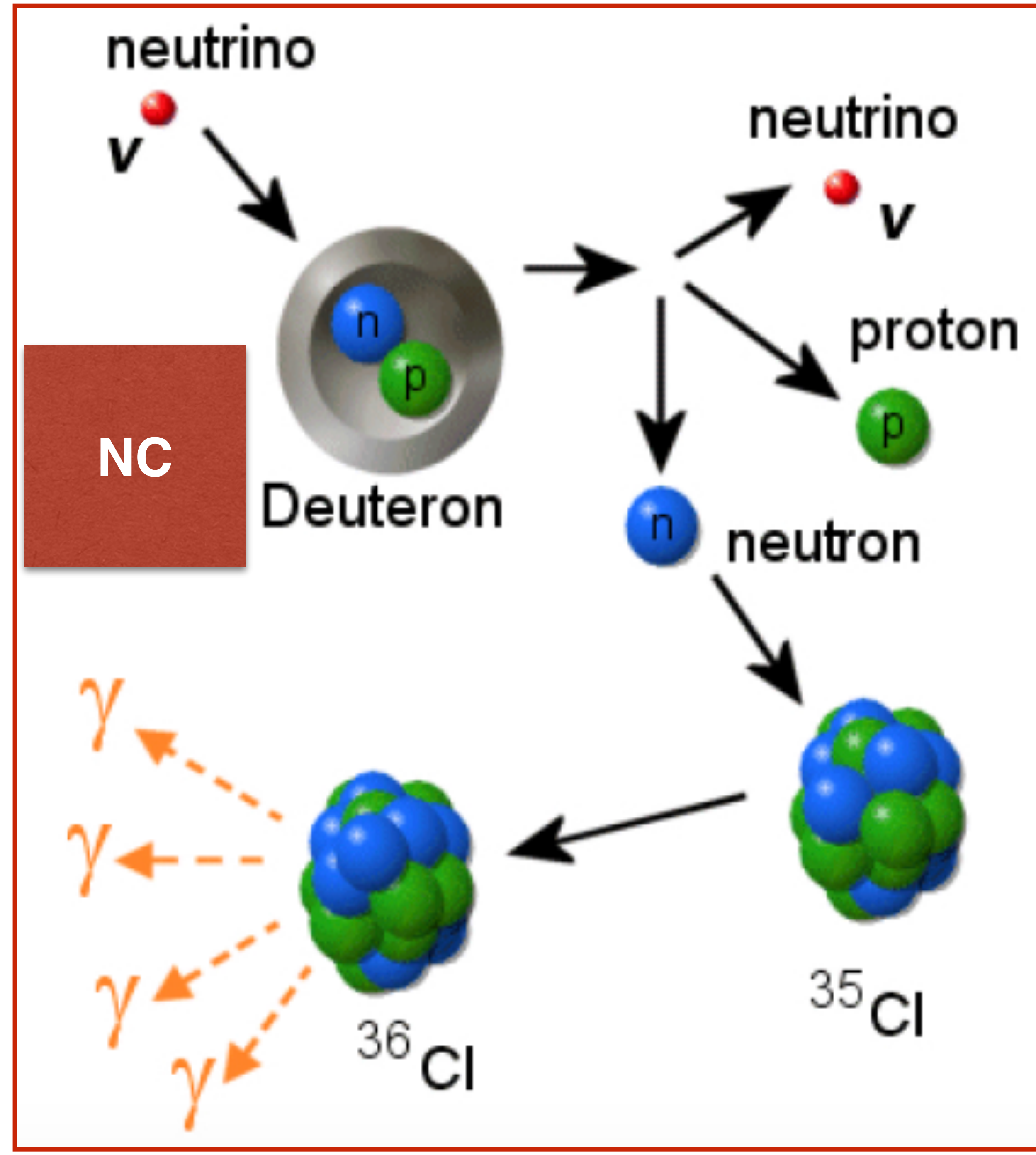


https://sno.phy.queensu.ca/

Solar neutrinos: Sudbury Neutrino Observatory



Credit: S. Oser

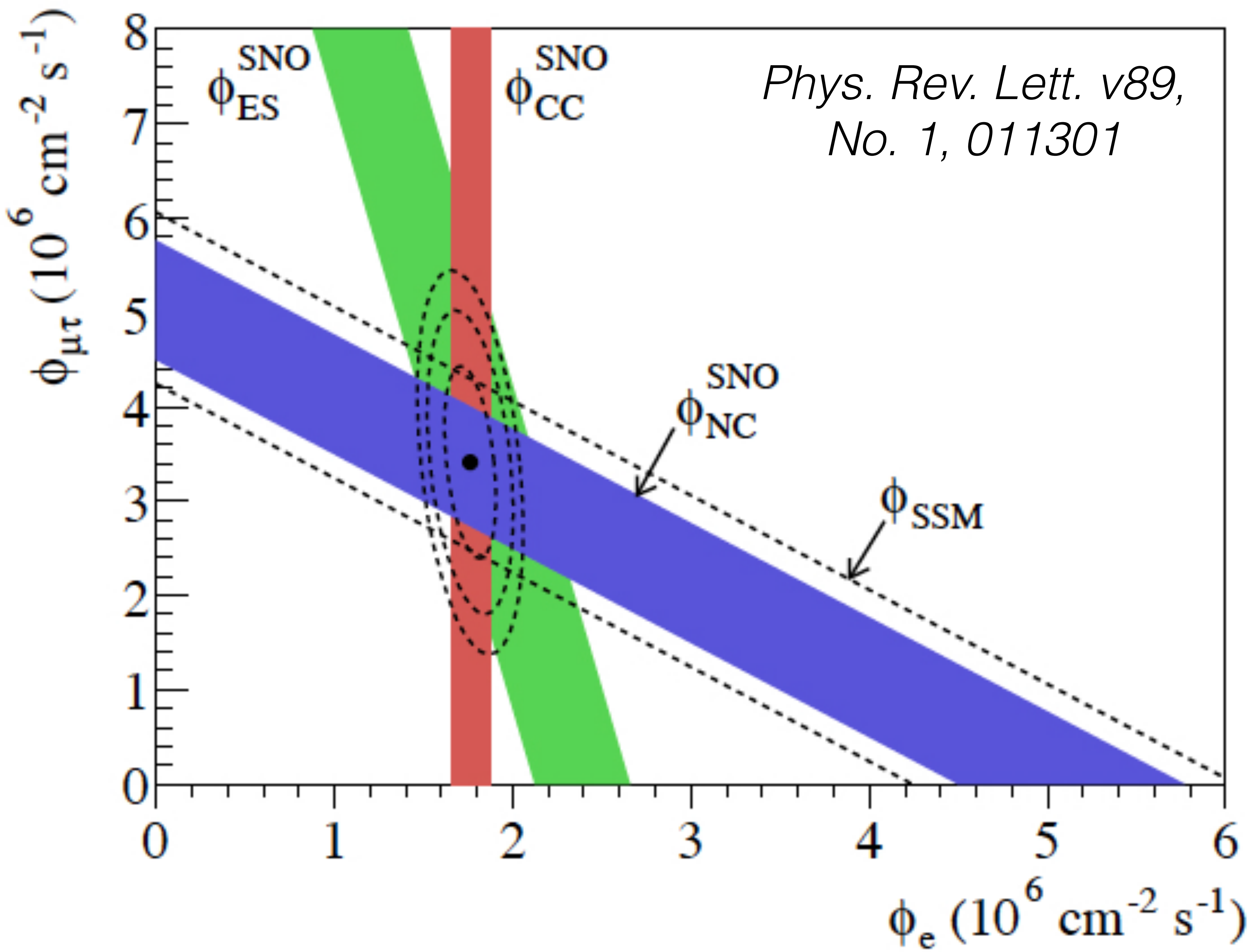


CC Charged Current Reaction	$\upsilon_e + d \rightarrow p + p + e^-$	$E_{threshold} = 1.4 MeV$
NC Neutral Current Reaction	$\upsilon_x + d \rightarrow \upsilon_x + p + n$	$E_{threshold} = 2.2 MeV$
ES Elastic Scattering Reaction	$\upsilon_x + e^- \rightarrow \upsilon_x + e^-$	$E_{threshold} \approx 0$

x denotes that this reaction will take place with any neutrino.

http://hyperphysics.phy-astr.gsu.edu/

SNO results



Consistency between CC (lack of nue flavor), NC (total neutrino flux) and Standard Solar Model (of neutrino production)

Solar experiments

http://www-sk.icrr.u-tokyo.ac.jp/

http://borex.lngs.infn.it/

Goals:
Non standard interactions?
Matter (MSW) effect understood?
Detection of new solar neutrino channels

Recent Super-Kamiokande solar results

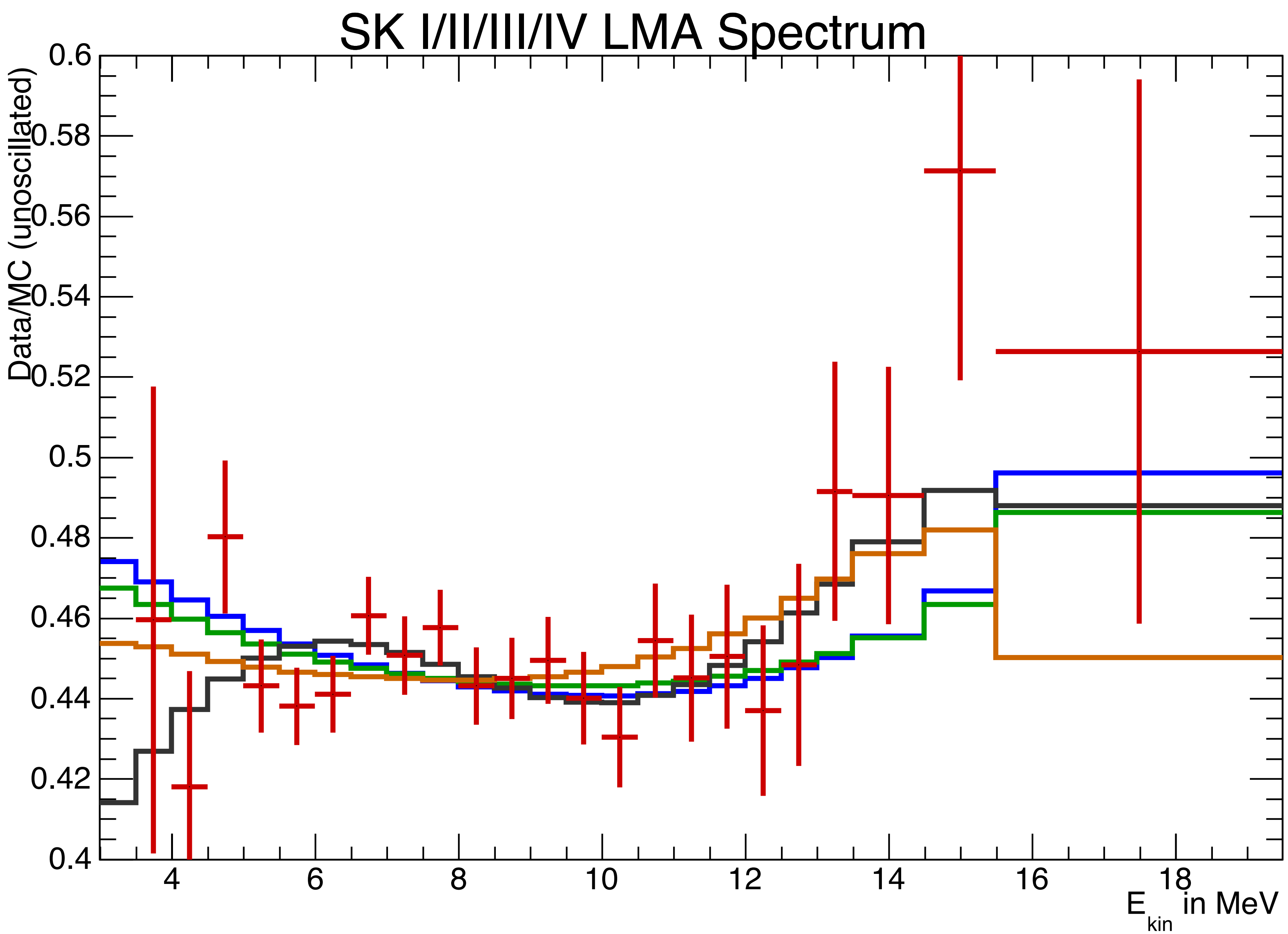
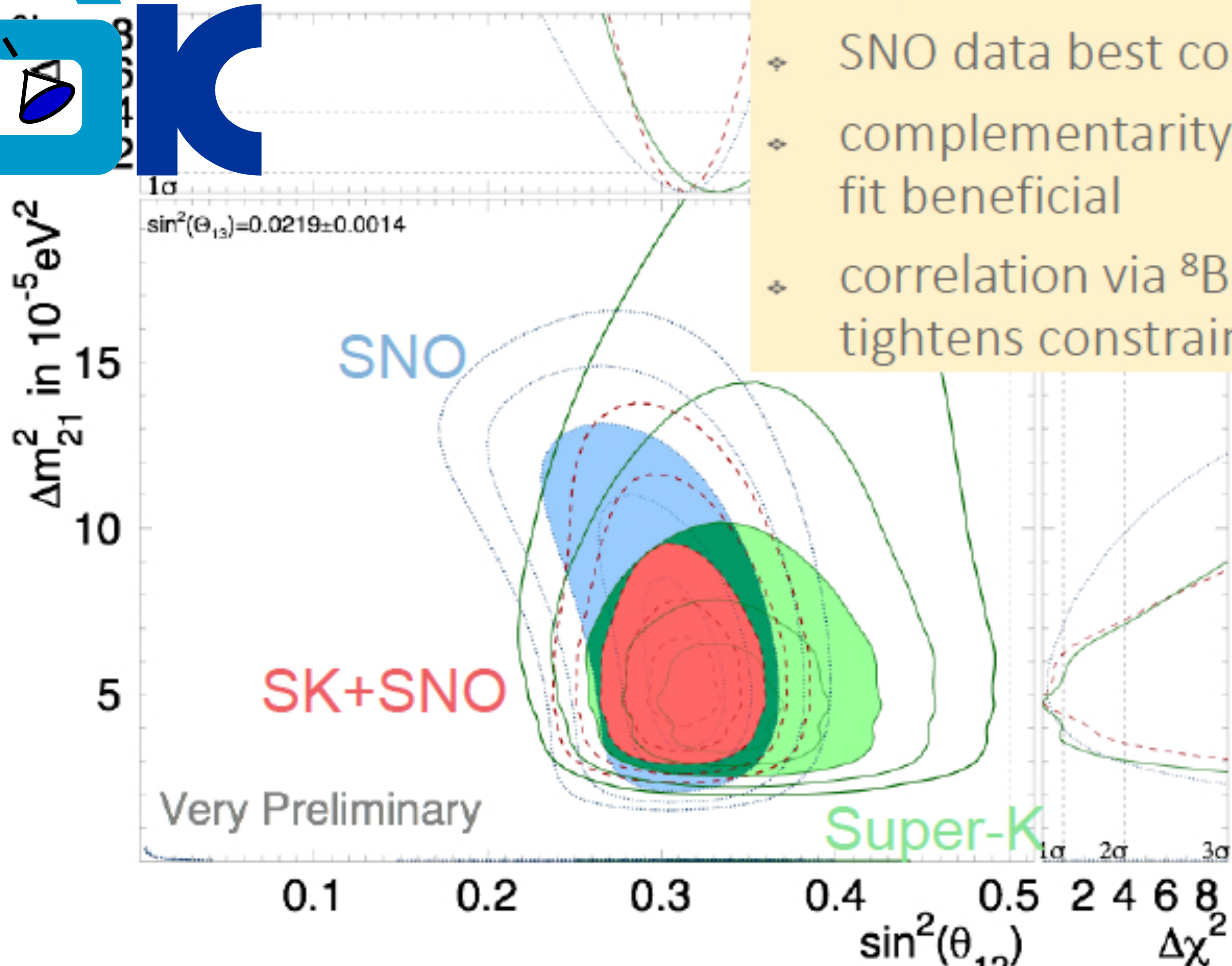


FIG. 26: SK-I+II+III+IV recoil electron spectrum compared to the no-oscillation expectation. The green (blue) shape is the MSW expectation using the SK (solar+KamLAND) best-fit oscillation parameters. The orange (black) line is the best fit to SK data with a general exponential/quadratic (cubic) P_{ee} survival probability.

Phys.Rev. D94 (2016) no.5, 052010

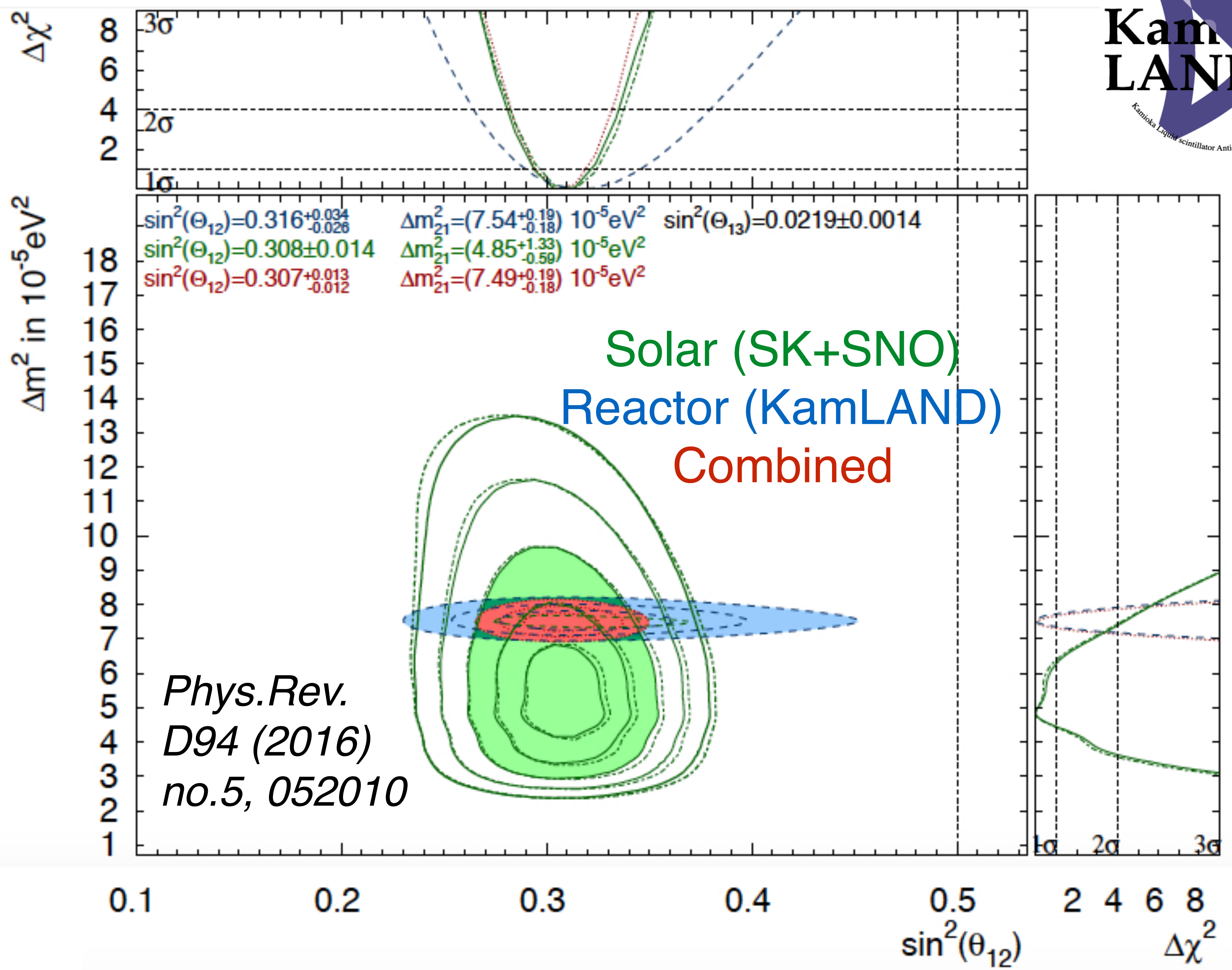
Recent Super-Kamiokande solar results



- Super-K data best constrains Δm^2_{21}
- SNO data best constrains $\sin^2\theta_{12}$
- complementarity makes combined fit beneficial
- correlation via ^8B flux further tightens constraints

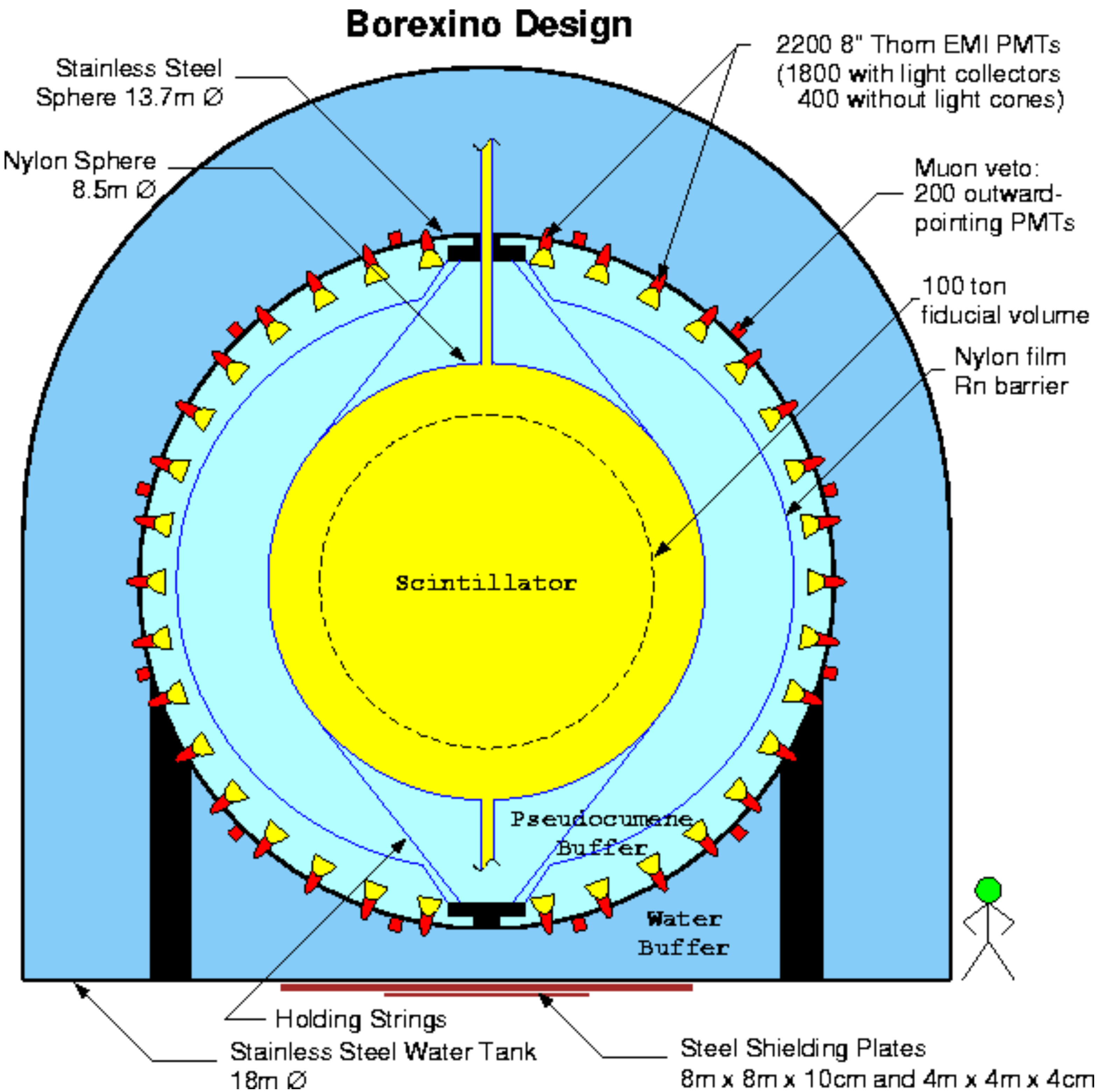
M. Ikeda, Talk at XXVIII International Conference on Neutrino Physics and Astrophysics, 4-9 June 2018 DOI: [10.5281/zenodo.1286857](https://doi.org/10.5281/zenodo.1286857)

Solar x Reactor



Reactor neutrinos, but longer baseline (avg 180km) so sensitive to solar osc.

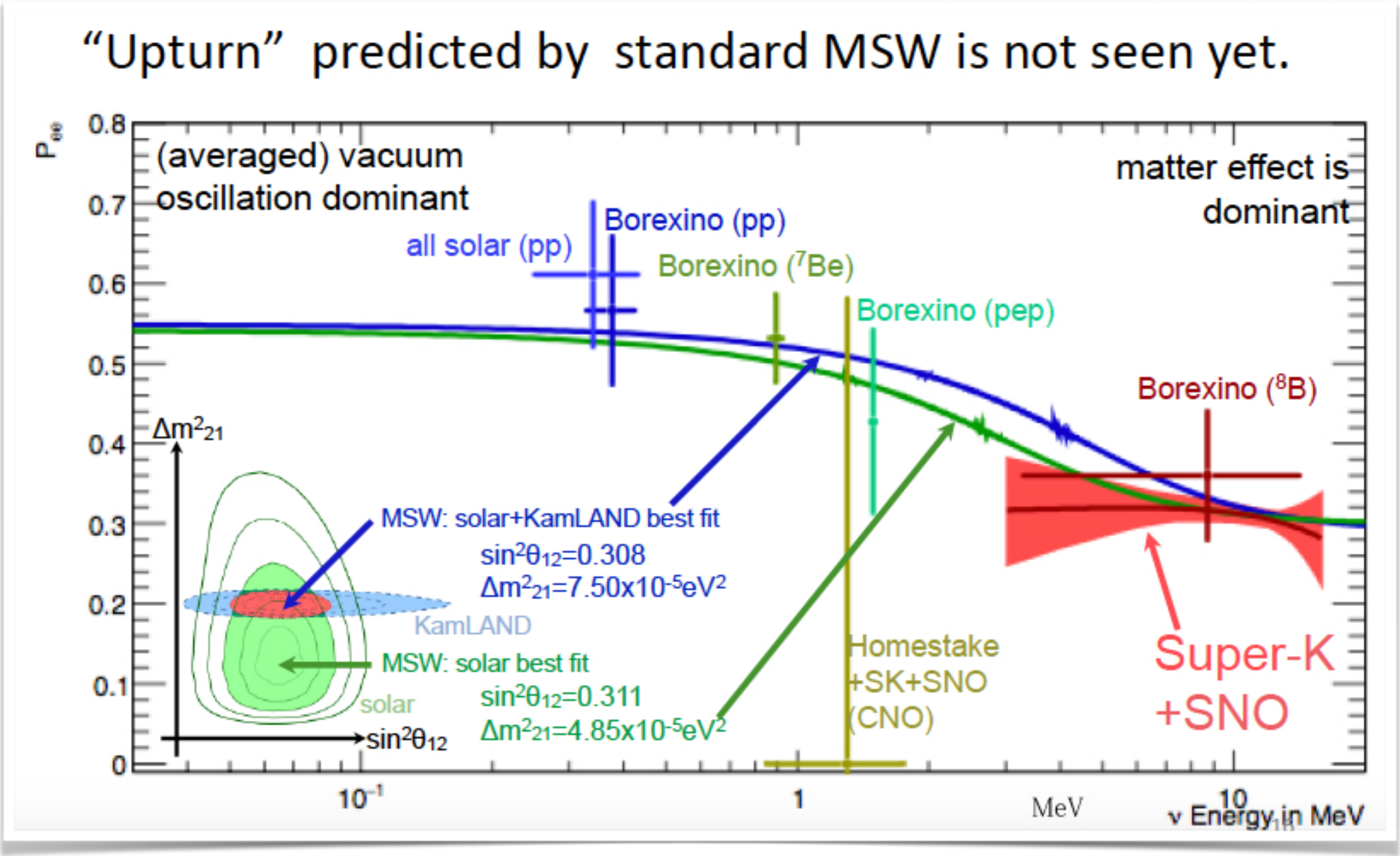
Borexino experiment



Precision liquid scintillator experiment

Sensitive to even lower energies of solar neutrinos; challenging analysis to achieve purity, reduction of backgrounds

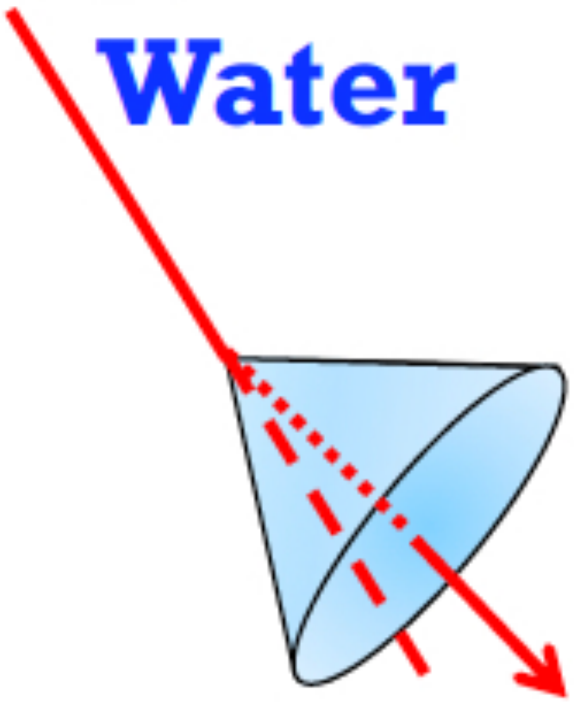
Solar neutrinos: Still puzzling



M. Ikeda, Talk at XXVIII International Conference on Neutrino Physics and Astrophysics, 4-9 June 2018 DOI: 10.5281/zenodo.1286857

Future solar experiments

SNO
SK
HK



Good directional information

Borexino
SNO+, JUNO
DUNE

Good energy resolution

Theia
Jinping

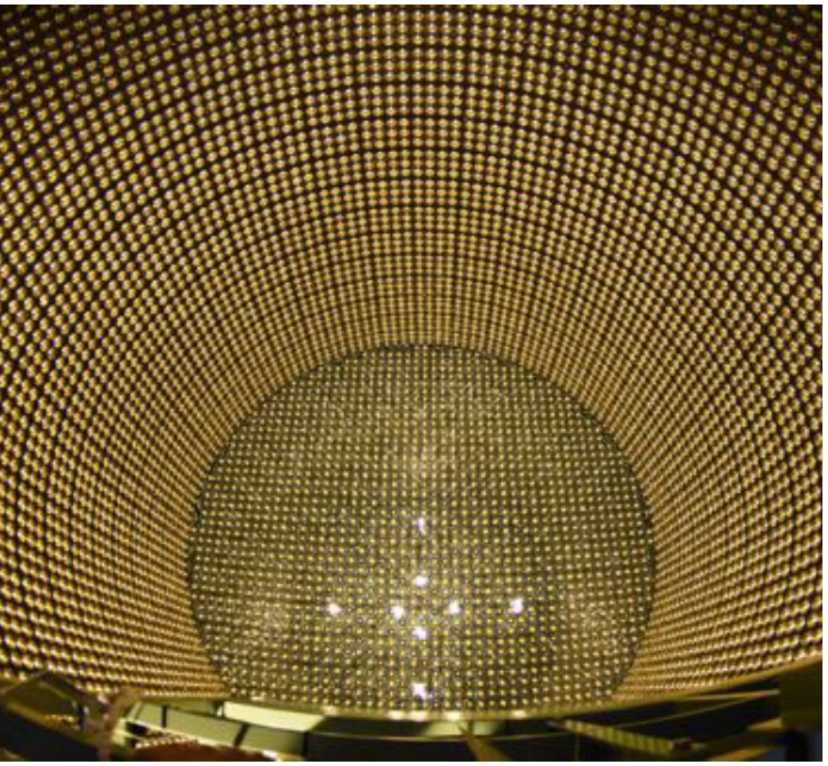
Directional + energy resolution

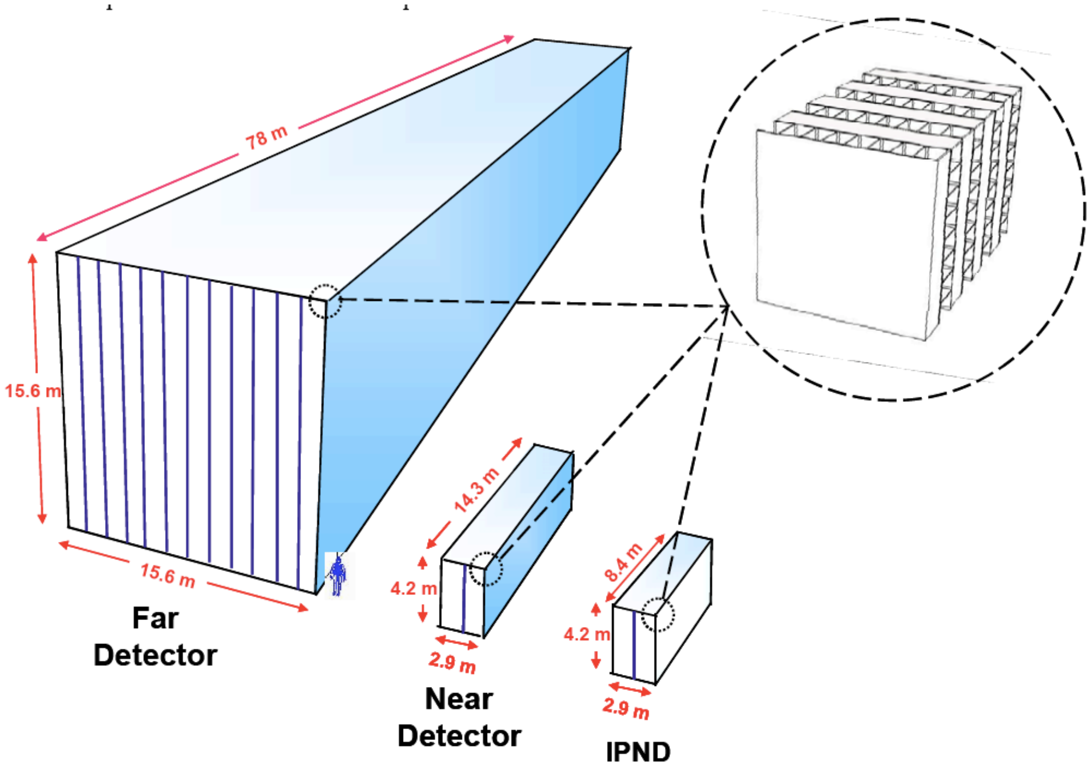
S. Chen, Talk at XXVIII International Conference on Neutrino Physics and Astrophysics, 4-9 June 2018 DOI: 10.5281/zenodo.1287063

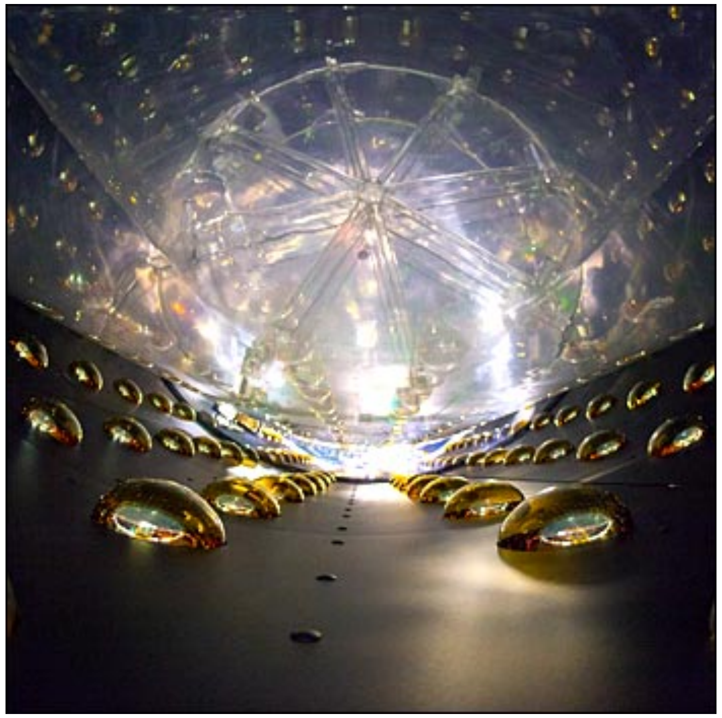
Questions on reactor, solar experiments?

Summary for lecture 1

Open questions!
are within reach of
accelerator, solar, and
reactor-based experiments



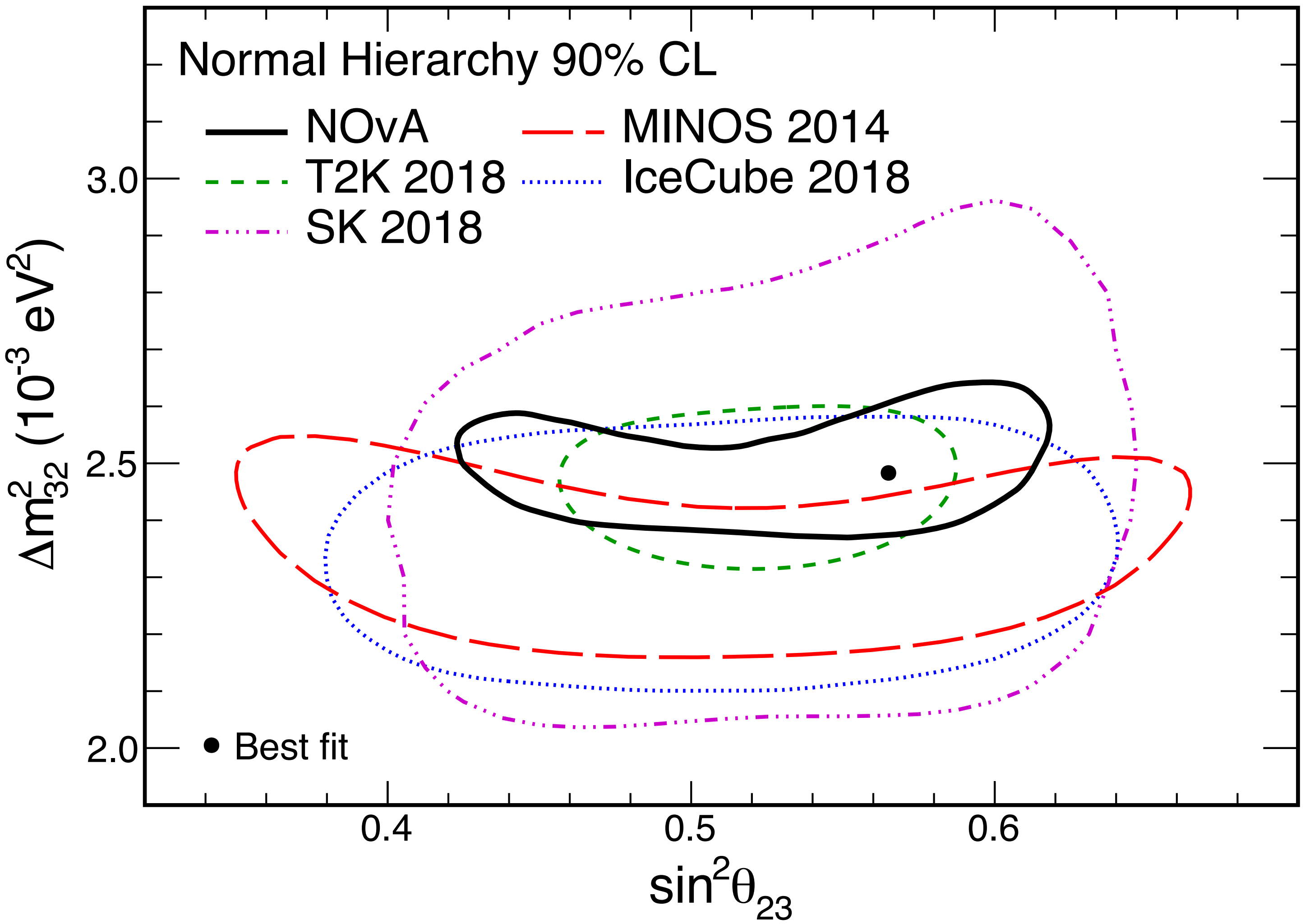




Summary for lecture 1

Open questions!
Are still being explored

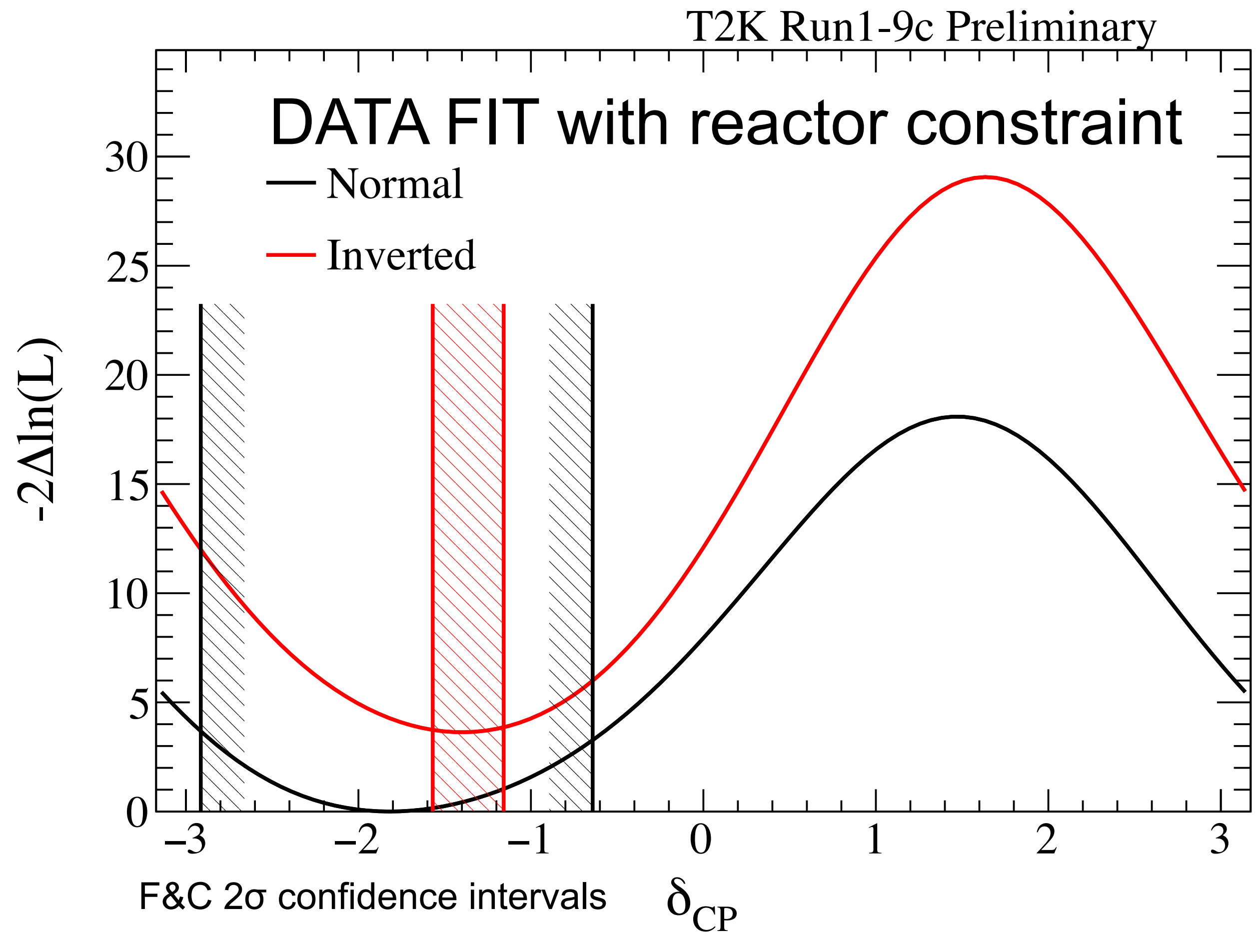
Is θ_{23} maximal or not?



Summary for lecture 1

Open questions!
have hints of new physics

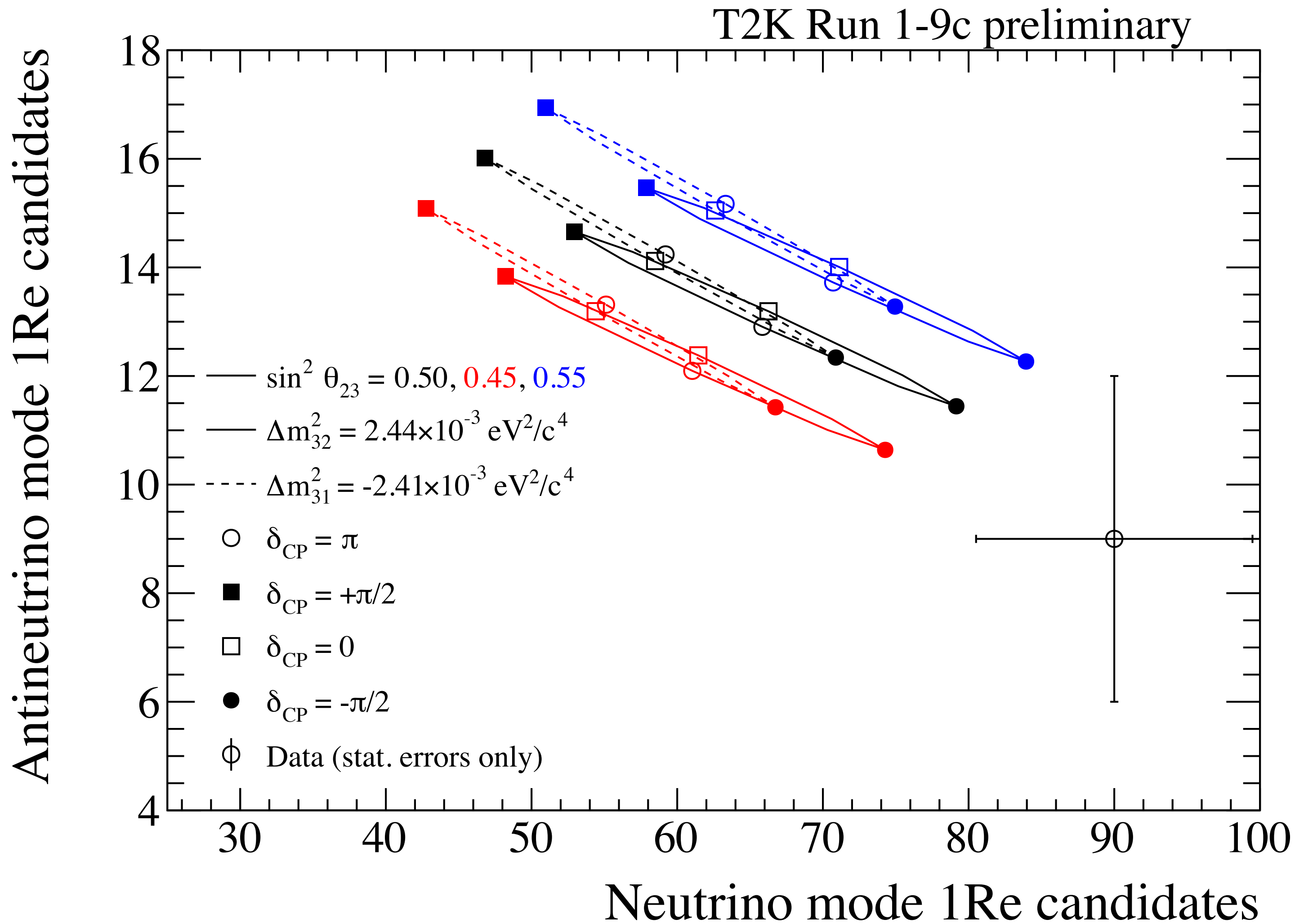
Is there CPV in neutrinos?

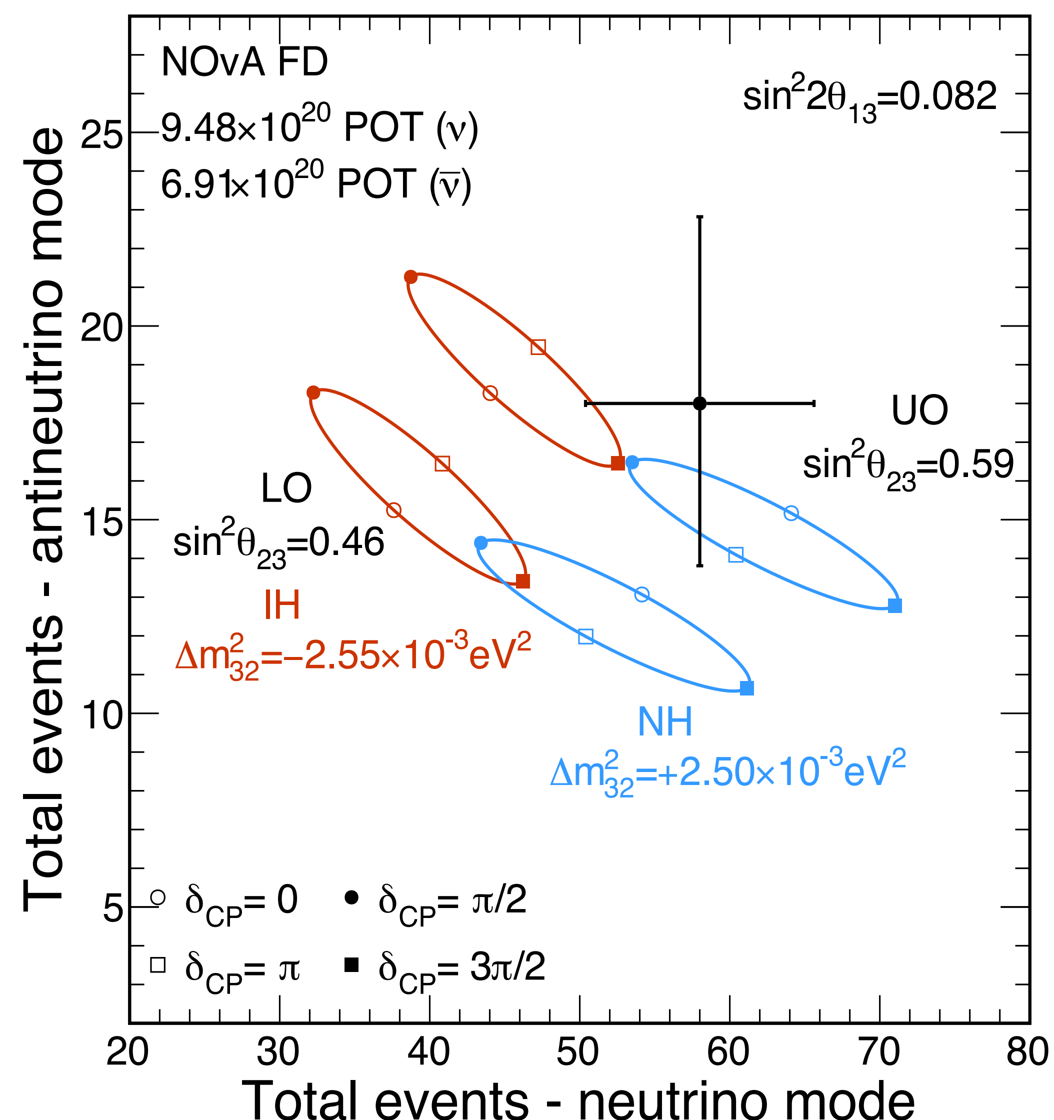


Summary for lecture 1

Open questions!
But we still have much to learn with current experiments

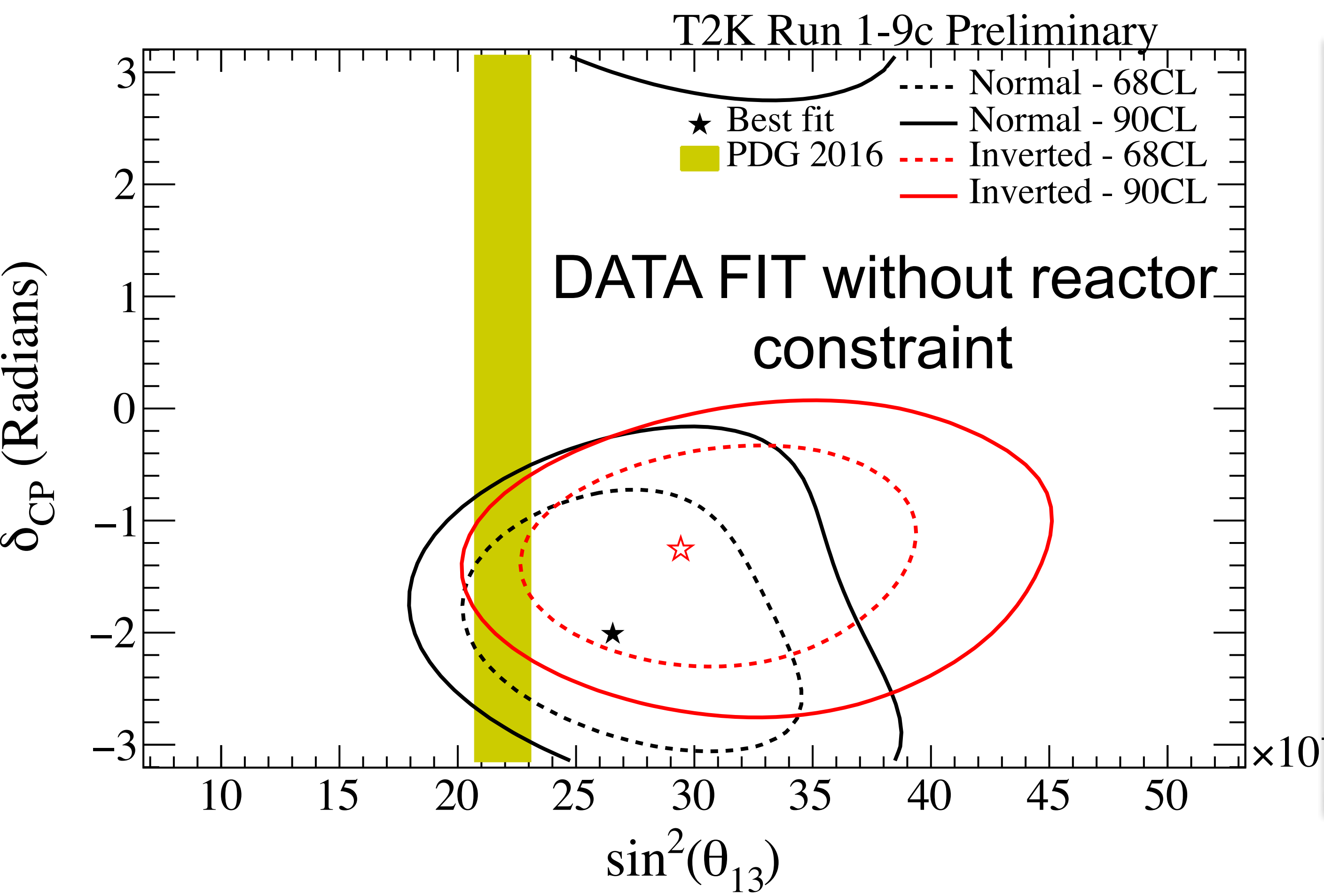
What is the mass hierarchy?

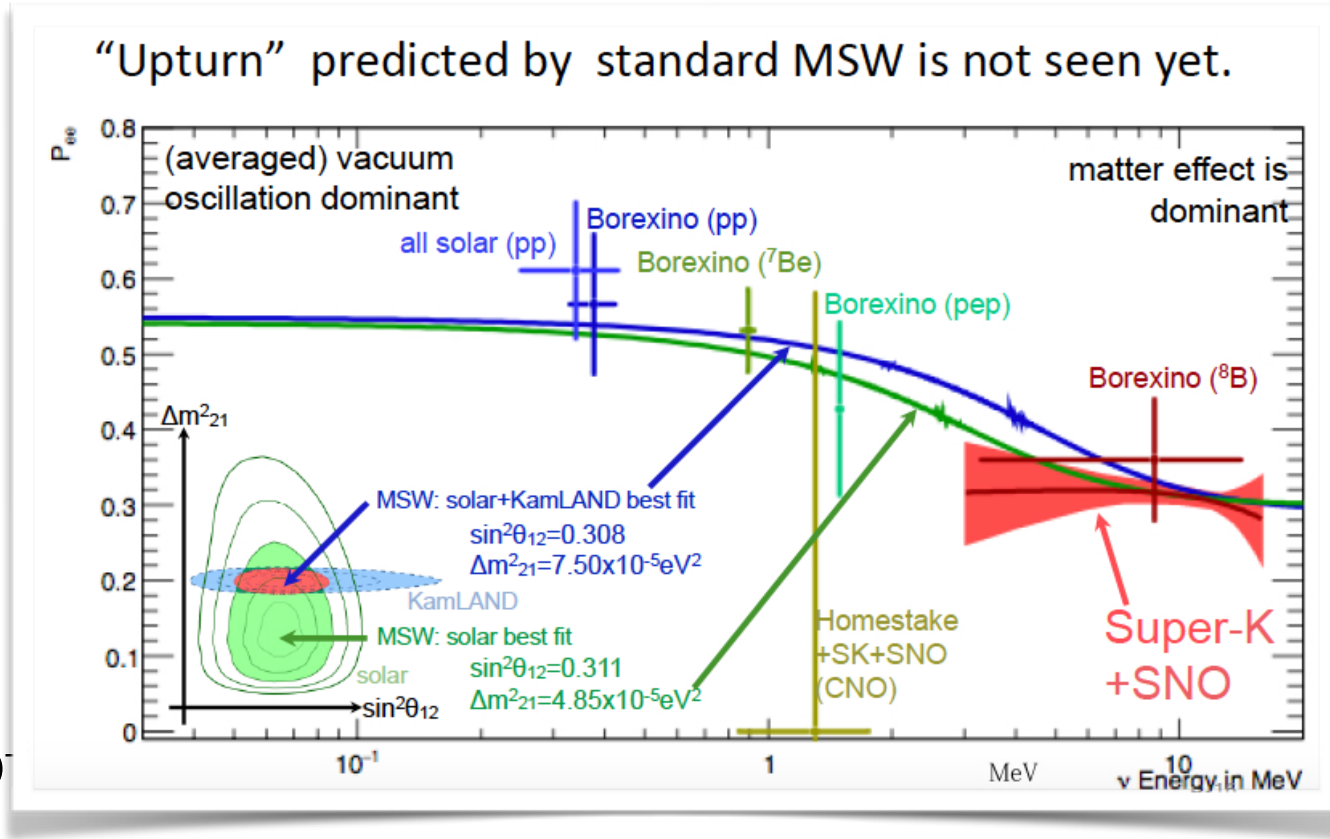




Summary for lecture 1

Open questions!
Some consistency… **but more tomorrow**





Is the three flavor picture complete?

Backup

What do we know about neutrino oscillation?

Flavor states
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$
Mass states

U terms include:

- **Mixing angles: θ_{12}, θ_{23}, θ_{13}**

Parameter	best-fit	3σ
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$	0.425	0.381 – 0.615
$\sin^2\theta_{13}$	0.0215	0.0190 – 0.0240

Credit: 2018 Particle Data Group

What do we know about neutrino oscillation?

Flavor states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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Is θ_{23} maximal or not?

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Mass states

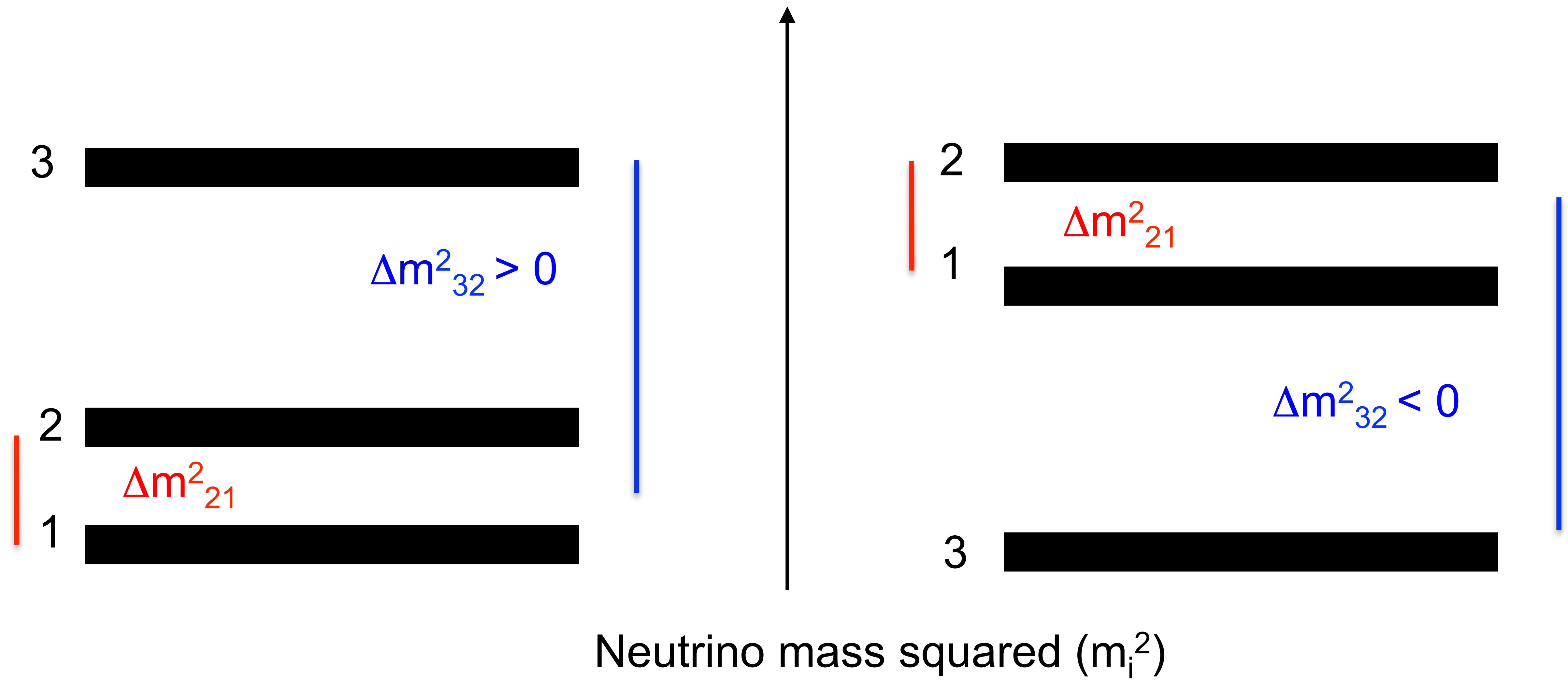
U terms include:

- Mixing angles: θ_{12}, θ_{23}, θ_{13}
- **CP violating phase (CPV)**

Is there CPV in neutrinos?

Parameter	best-fit	3σ
δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

What do we know about neutrino oscillation?



- **Mass splitting:$|\Delta m^2_{32/31}|$,Δm^2_{21}**

Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.96
$\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)