

Latest results from T2K

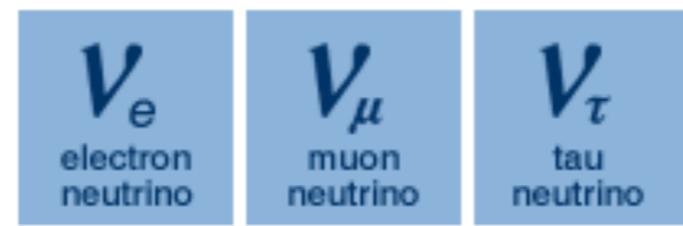


COMHEP2021
Nov 30th 2021

Kendall Mahn
Michigan State University
for the T2K collaboration

All about neutrinos

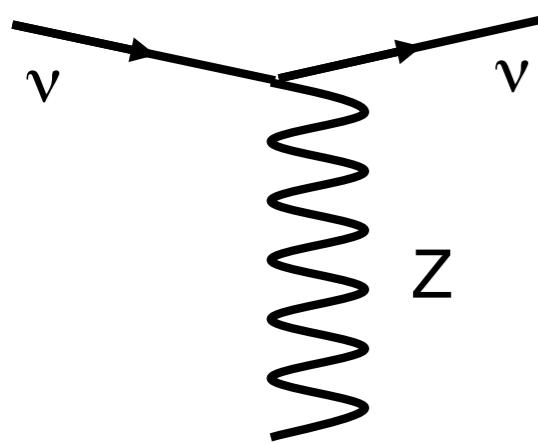
- Three flavors of neutrinos (ν) ... and antineutrinos ($\bar{\nu}$)



All about neutrinos

- Three flavors of neutrinos (ν) ... and antineutrinos ($\bar{\nu}$)
- Interact via the weak force

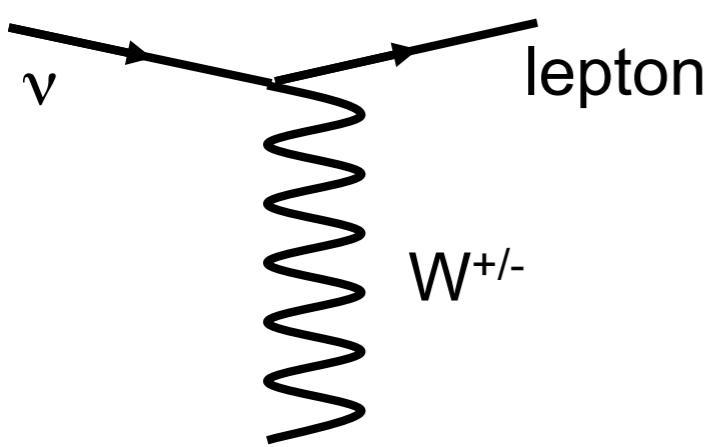
Neutral Current (NC)



Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
	e electron	μ muon	τ tau



Charged Current (CC)



$$\nu_e \rightarrow e$$

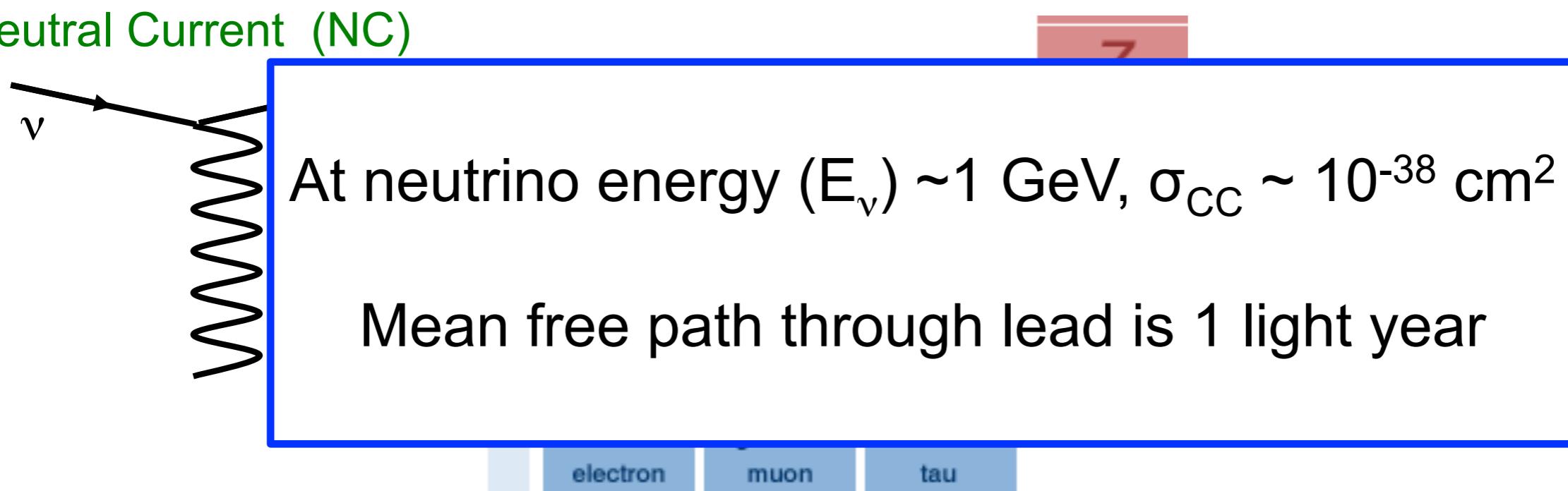
$$\nu_\mu \rightarrow \mu$$

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

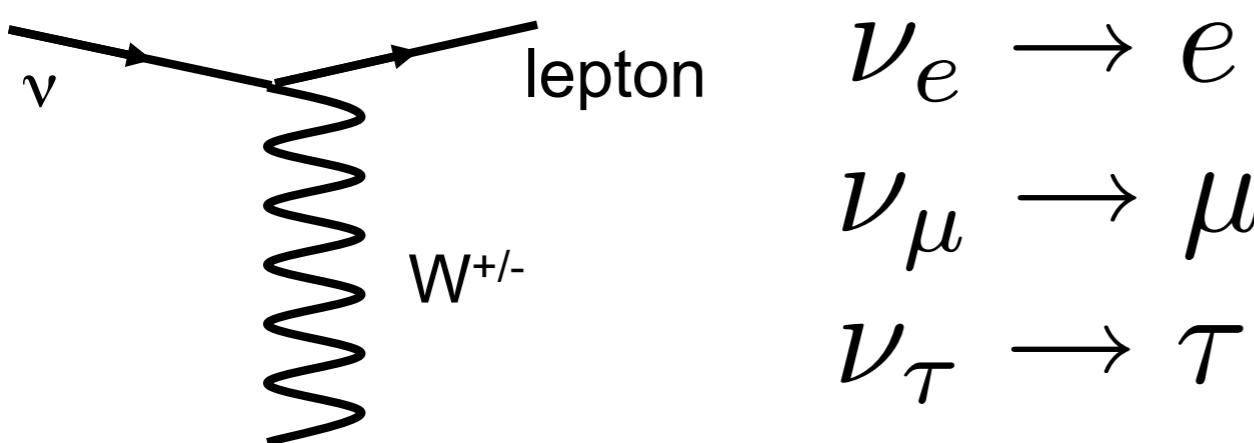
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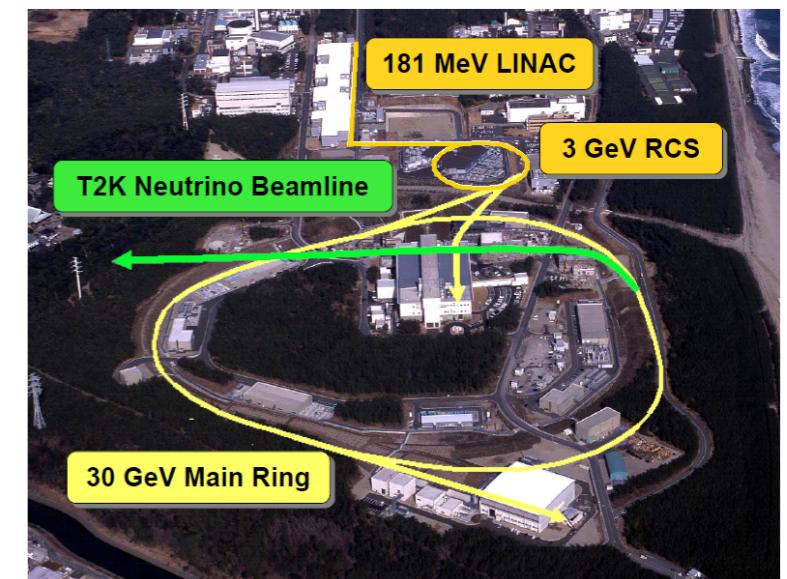
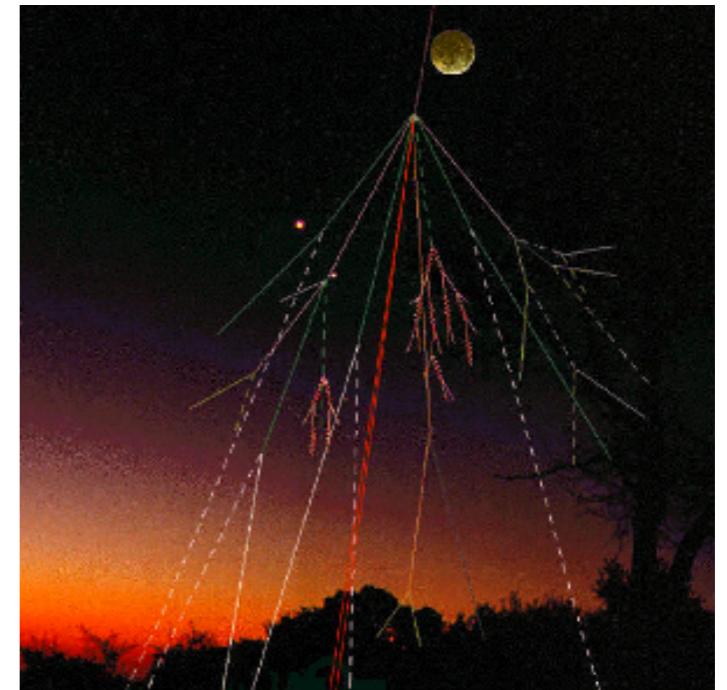
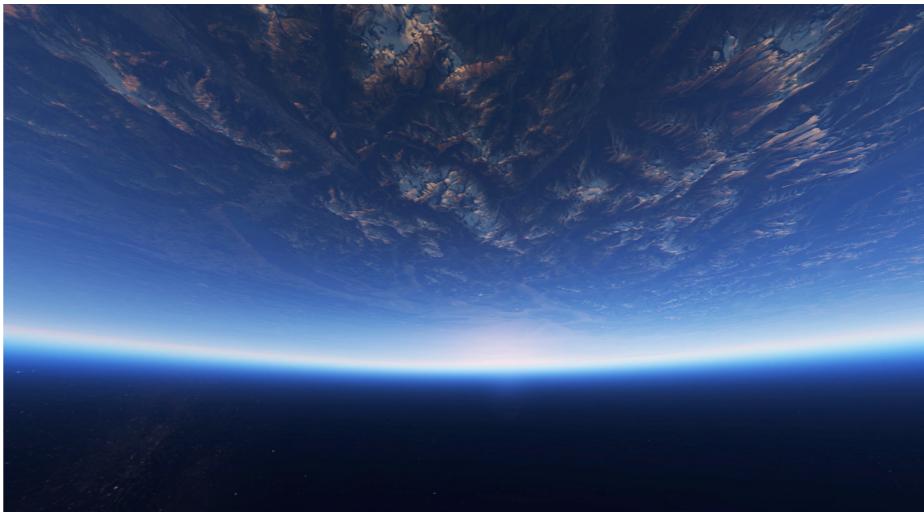
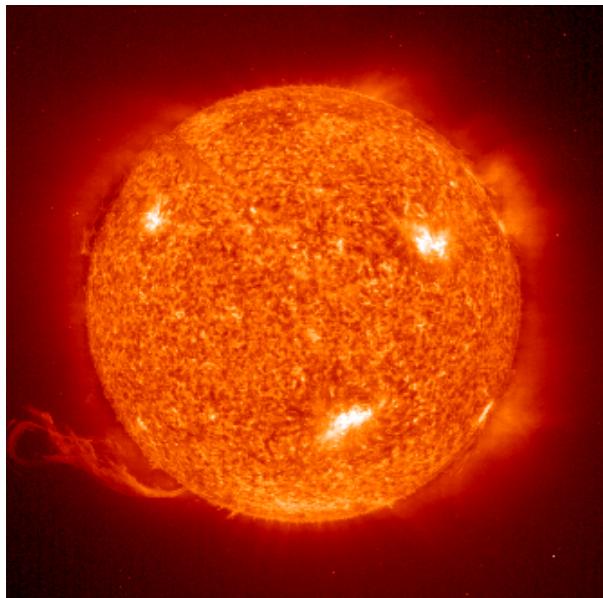


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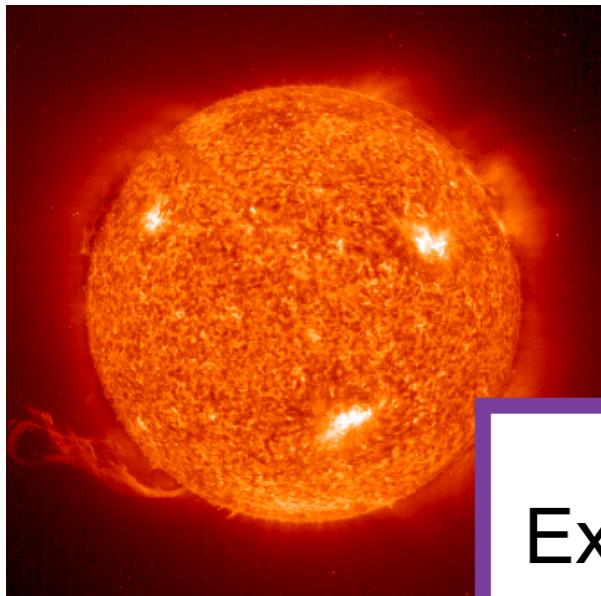
All about neutrinos

- Three flavors of neutrinos (ν) ... and antineutrinos ($\bar{\nu}$)
- Interact via the weak force
- Abundant

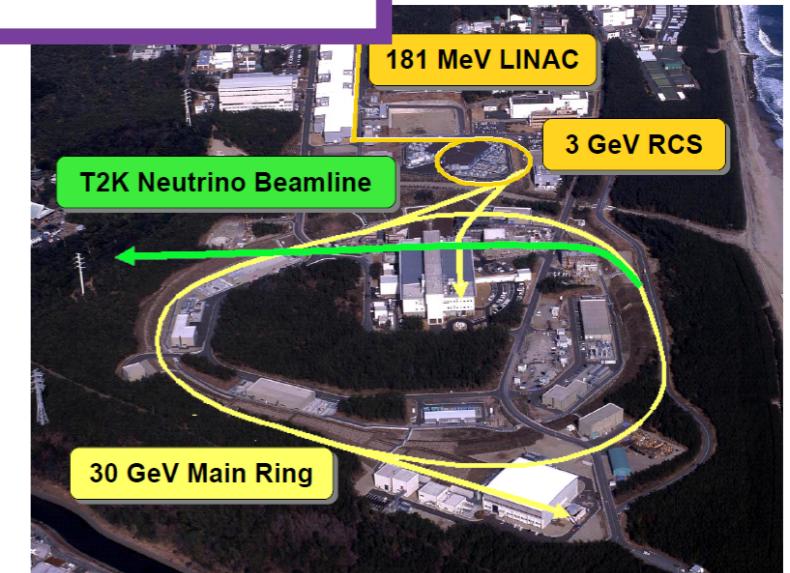
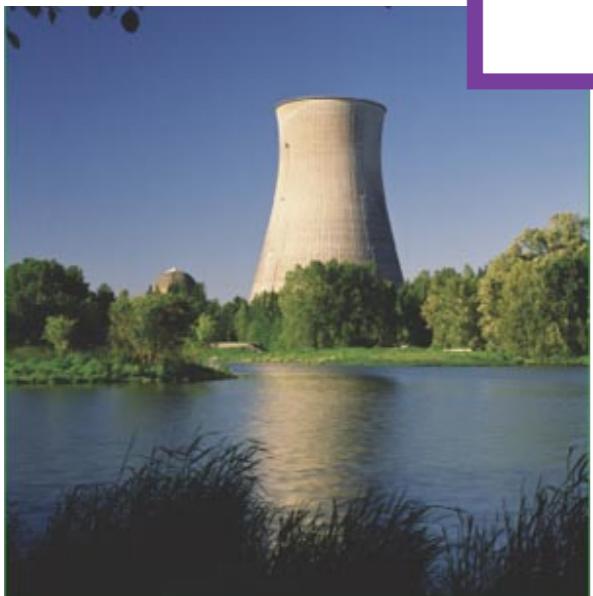


All about neutrinos

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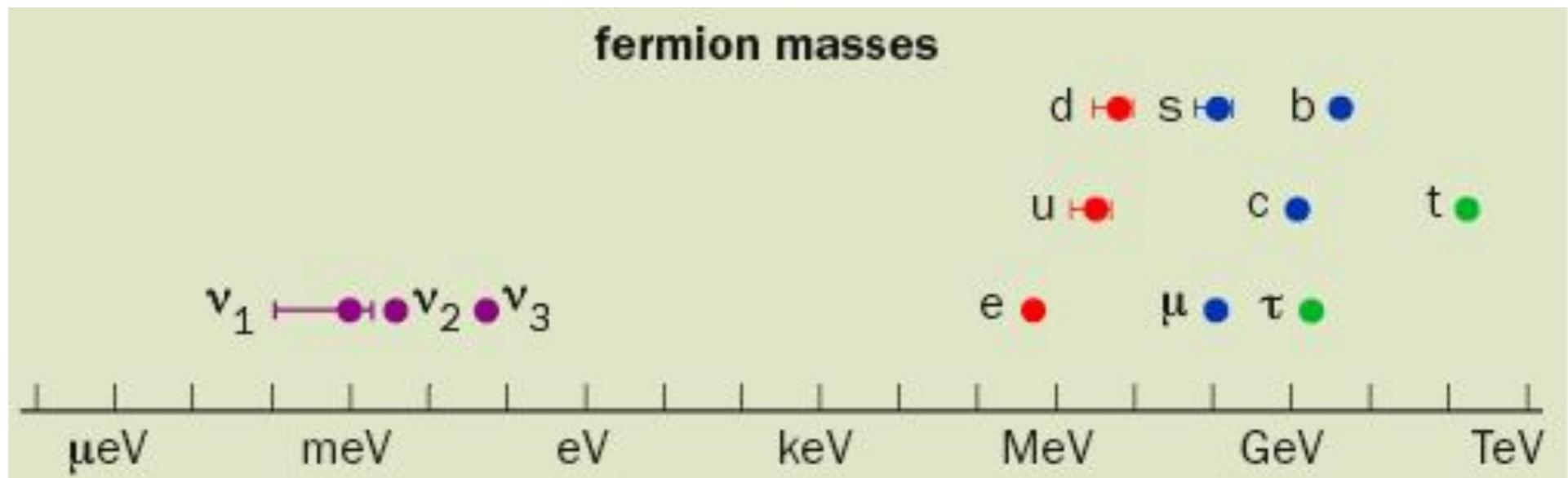
Except for the photon, neutrinos are the most plentiful particle in the universe



All about neutrinos

- Three flavors of neutrinos (ν) ... and antineutrinos ($\bar{\nu}$)
- Interact via the weak force
- Abundant
- Massive

Credit: H. Murayama



Credit: wikicommons

Neutrino mass is very small compared to other leptons

We know neutrinos have mass due to neutrino oscillation (2015 Nobel Prize)

What is neutrino oscillation?

What is neutrino oscillation?

This is a purely quantum mechanical effect where the mass eigenstates (ν_1 , ν_2 , ν_3) are superpositions of the flavor eigenstates (ν_e , ν_μ , ν_τ)

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If I reached in a jar of ν_2 without looking,
I would have about a 1/3 chance to eat:

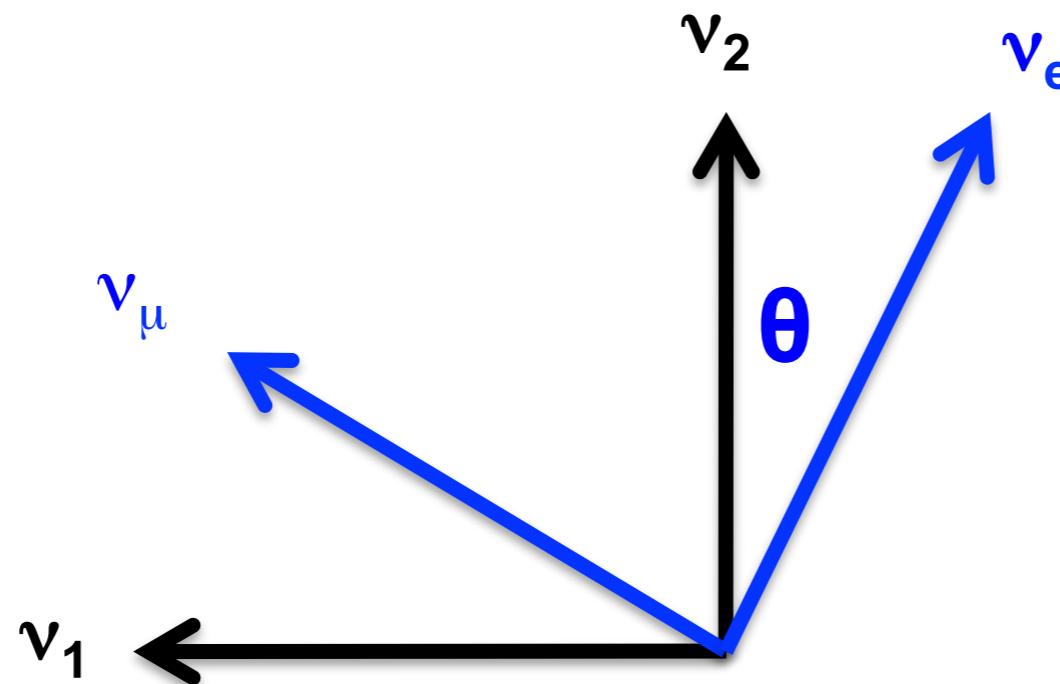
a green jelly bean (ν_e / lime)

or a yellow jelly bean (ν_μ / lemon)

or a blue jelly bean (ν_τ / berry)

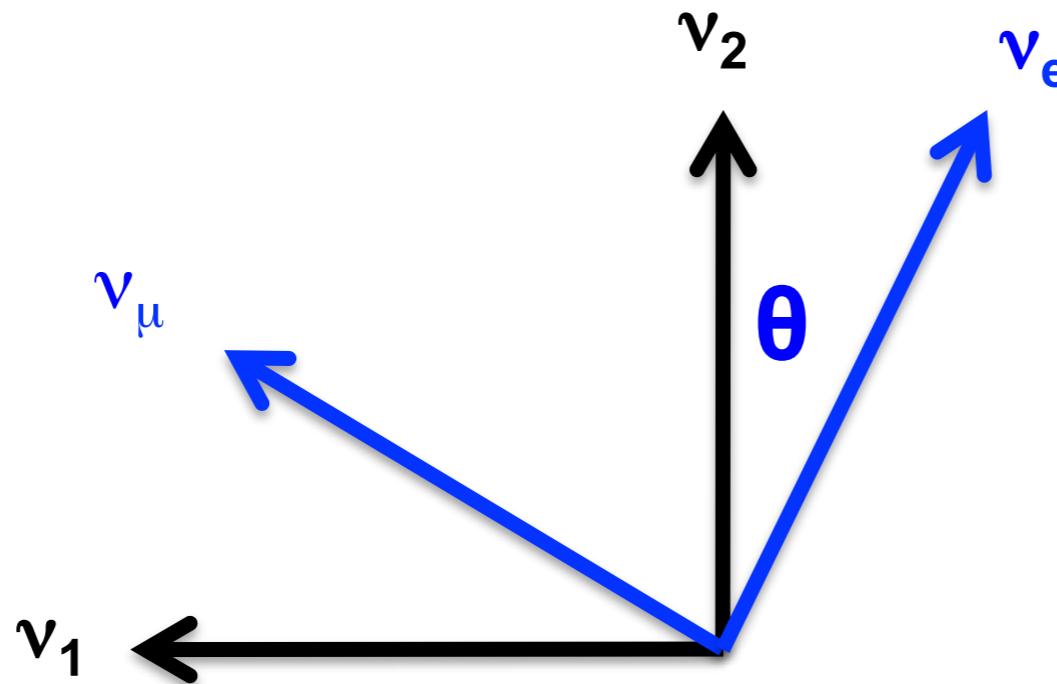
Neutrino oscillation with two flavors

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



Neutrino oscillation with two flavors

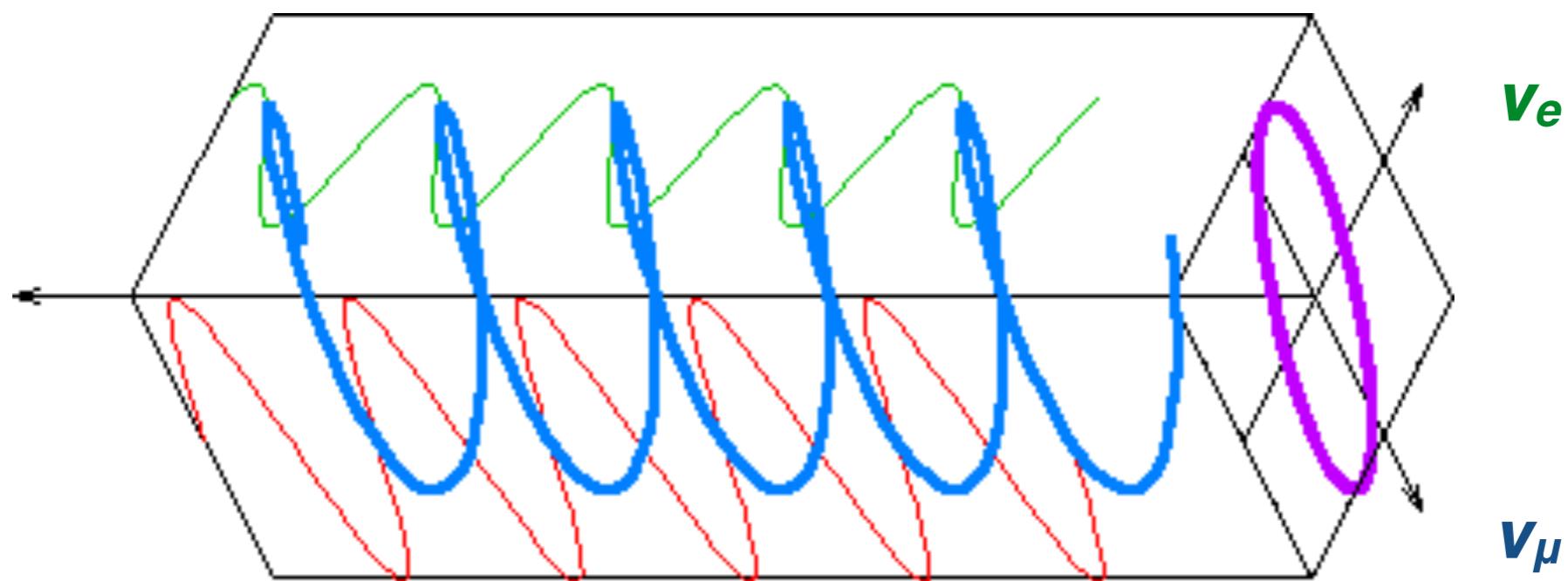
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$$|\nu_\mu(t)\rangle = -\sin \theta e^{-iE_1 t} |\nu_1\rangle + \cos \theta e^{-iE_2 t} |\nu_2\rangle$$

Neutrino oscillation with two flavors

Credit: wikipedia

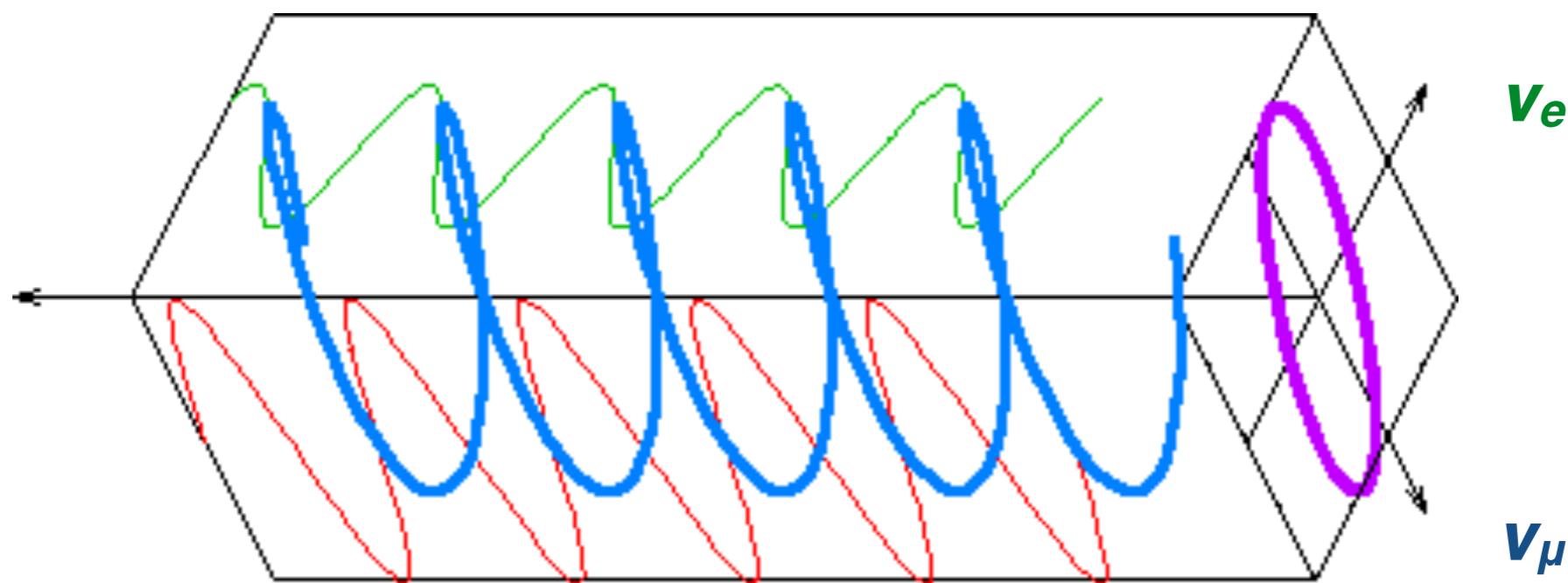


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Neutrino oscillation with two flavors

$$P_{\mu e} = \langle \nu_e | \nu_\mu(t) \rangle = \sin^2(2\theta) \sin^2(1.27\Delta m_{ij}^2 L/E)$$

Credit: wikipedia



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Credit: wikipedia

Experimental setup determines:

L (distance travelled, km) and E (GeV)

Experiments measure:

The mixing angle (θ) and Δm^2 (difference of the masses squared)

Fundamental particles, but much is unknown

What we still don't know about neutrinos:

- Neutrino oscillation
- Can we find new physics in the neutrino sector (neutrino CP violation?)

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 - Related: Are there non-standard interactions in neutrinos?

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

Pontecorvo-Maki-Nakagawa-Sakata matrix (PMNS)

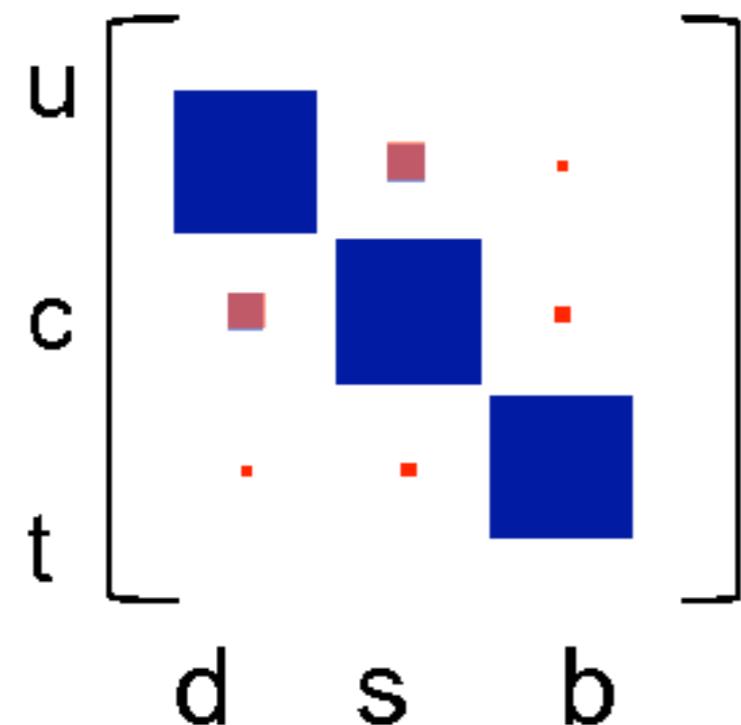
Elements of U are accessible with neutrino oscillation experiments

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 Mass states

Quarks

Cabbibo-Kobayashi-Maskawa (CKM)



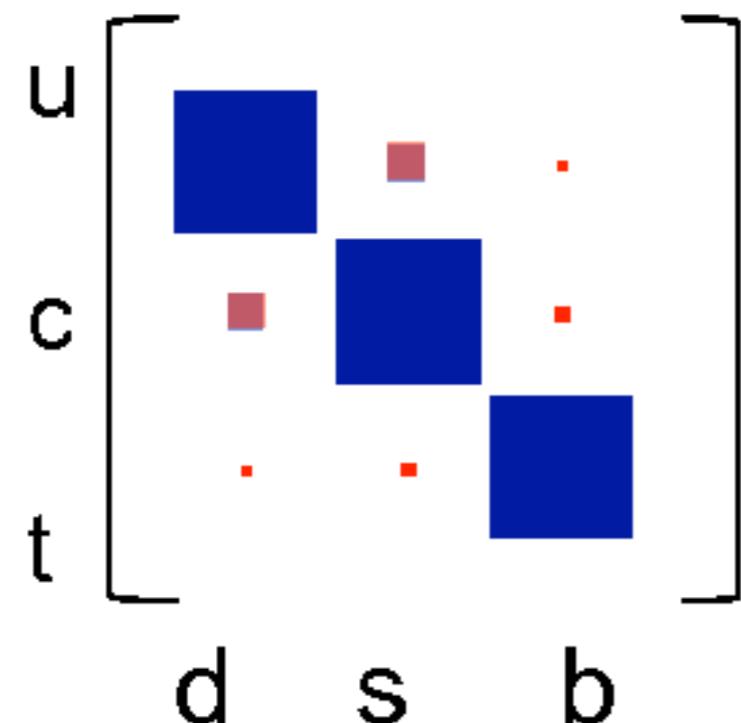
Measurements also allow to test unitarity of the mixing matrix

What do we know about neutrino oscillation?

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 Mass states

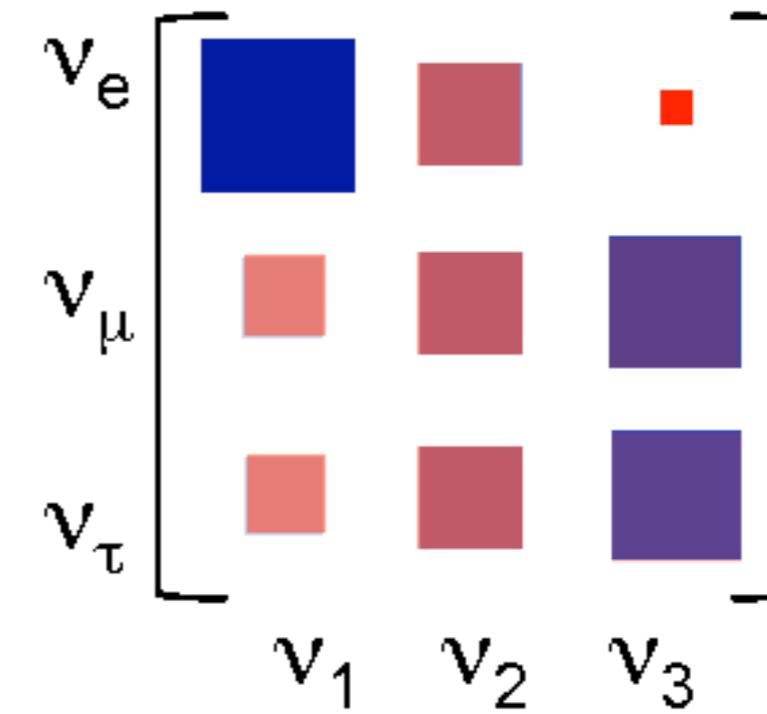
Quarks

CKM



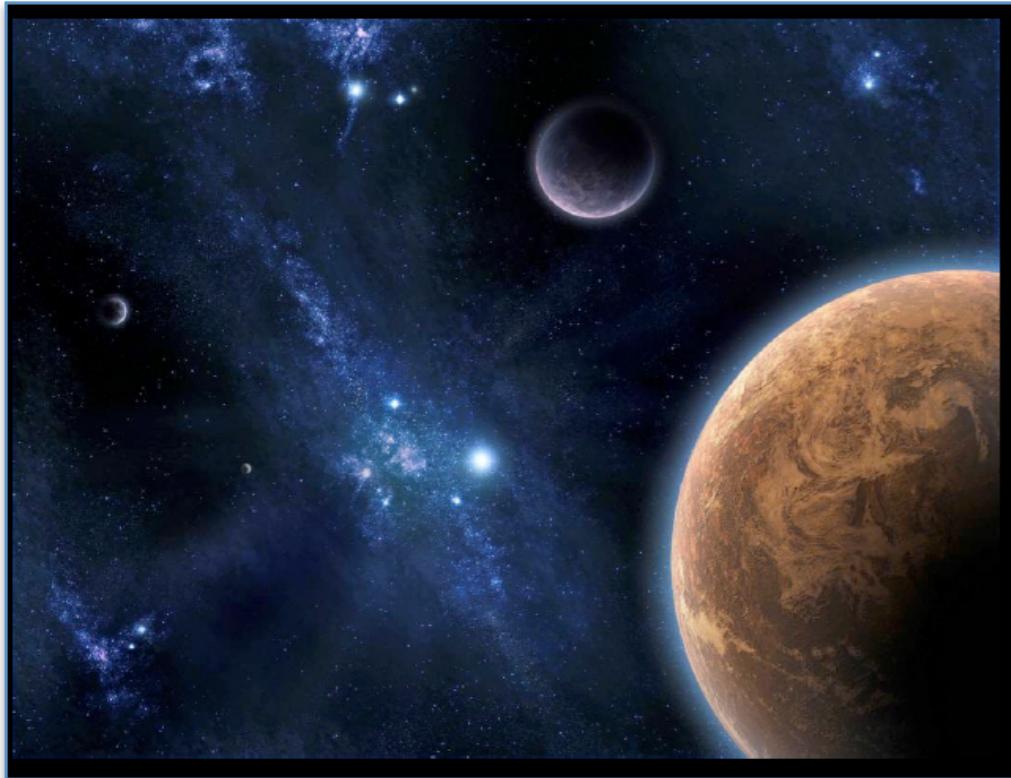
Leptons

PMNS

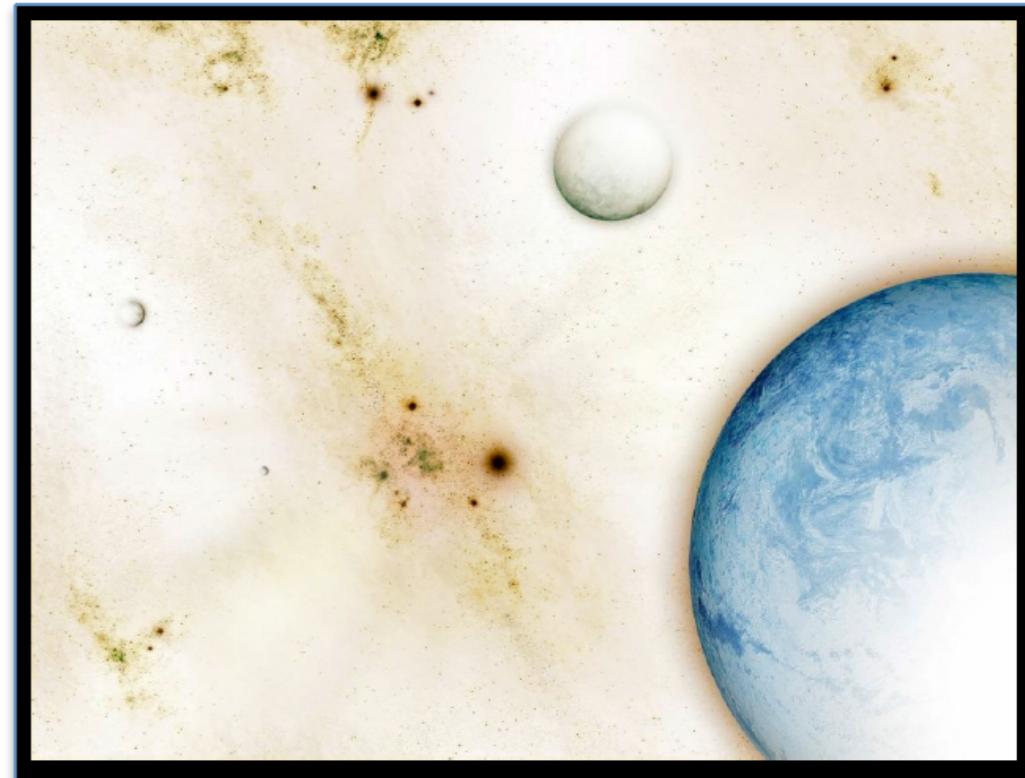


Is there new physics in the leptonic sector?

Why should we search for CP violation?



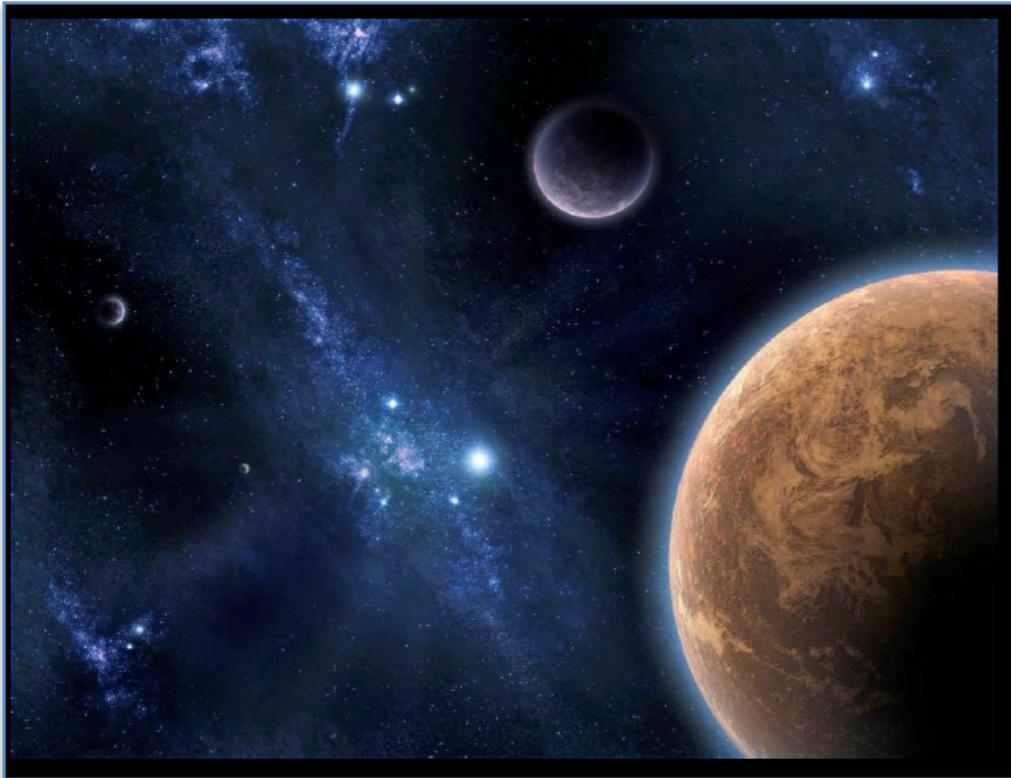
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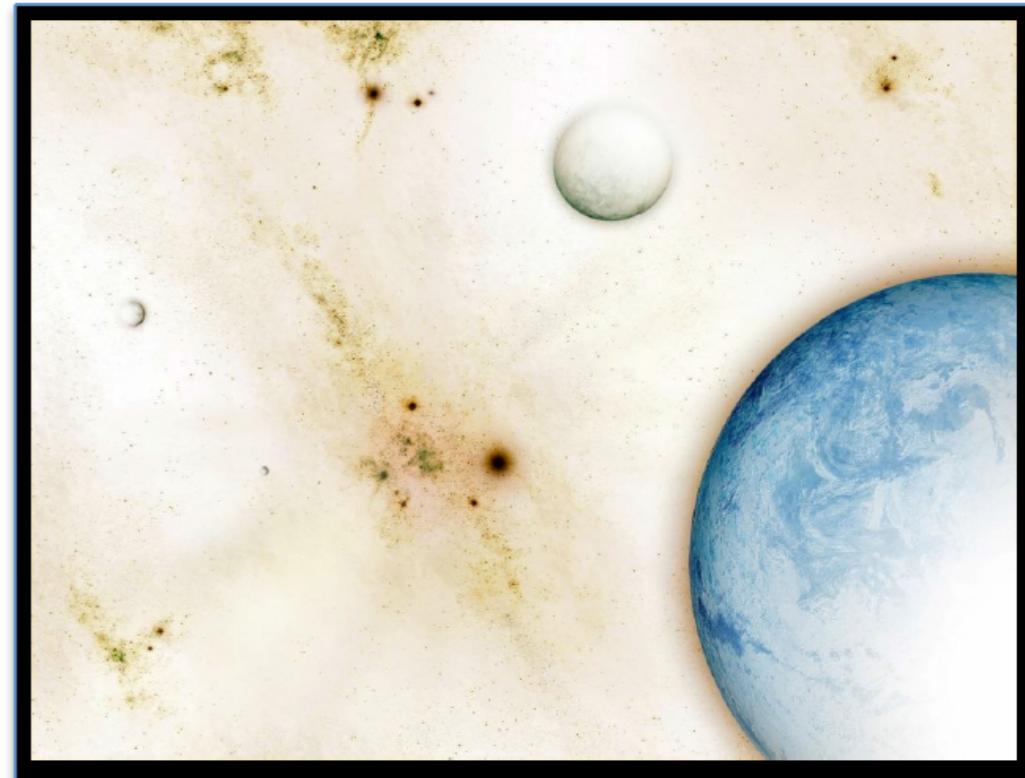
Observed matter/antimatter asymmetry requires Sakharov's conditions:

- **CP violation**
- Baryon number violation
- Non thermal equilibrium

Why should we search for CP violation?



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Observed matter/antimatter asymmetry requires Sakharov's conditions:

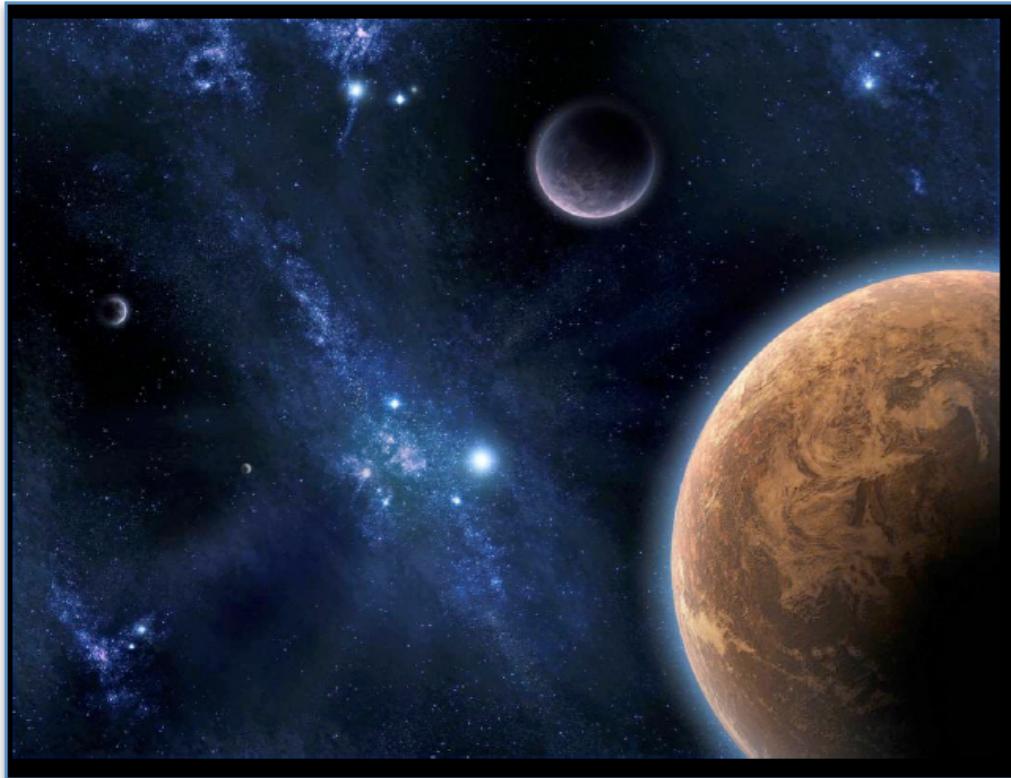
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CKM?

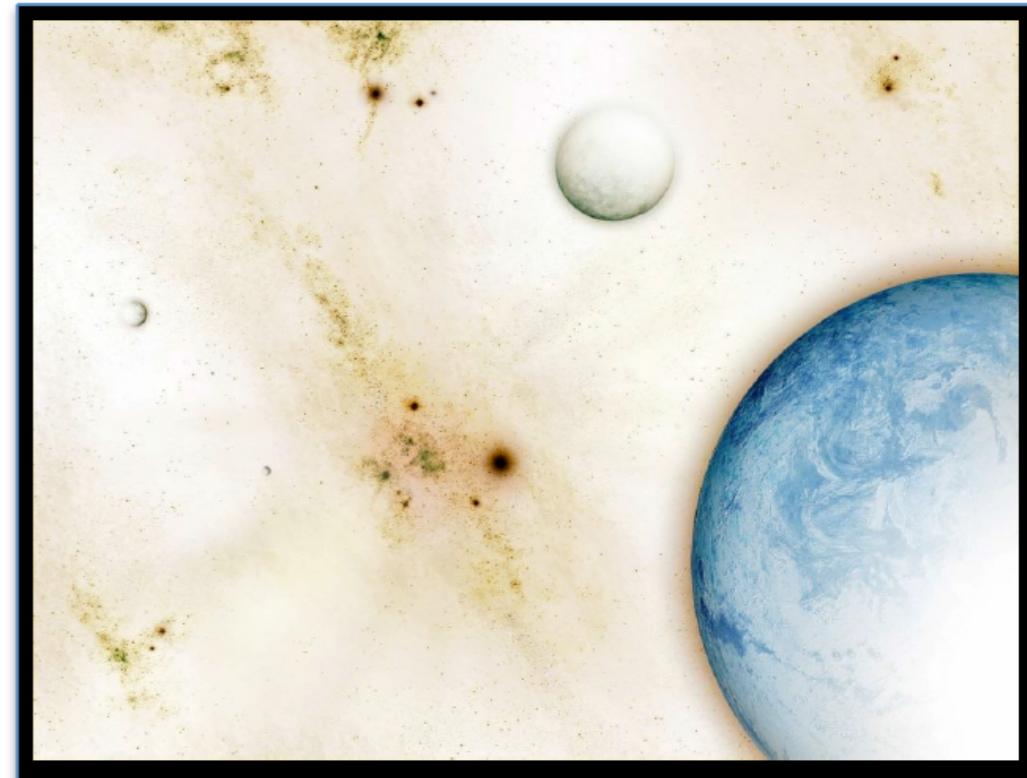
Neutrinos?

Strong CP violation?

Why should we search for CP violation?



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Observed matter/antimatter asymmetry requires Sakharov's conditions:

- **CP violation**

CKM?

Not large enough...

Neutrinos?

Strong CP violation?

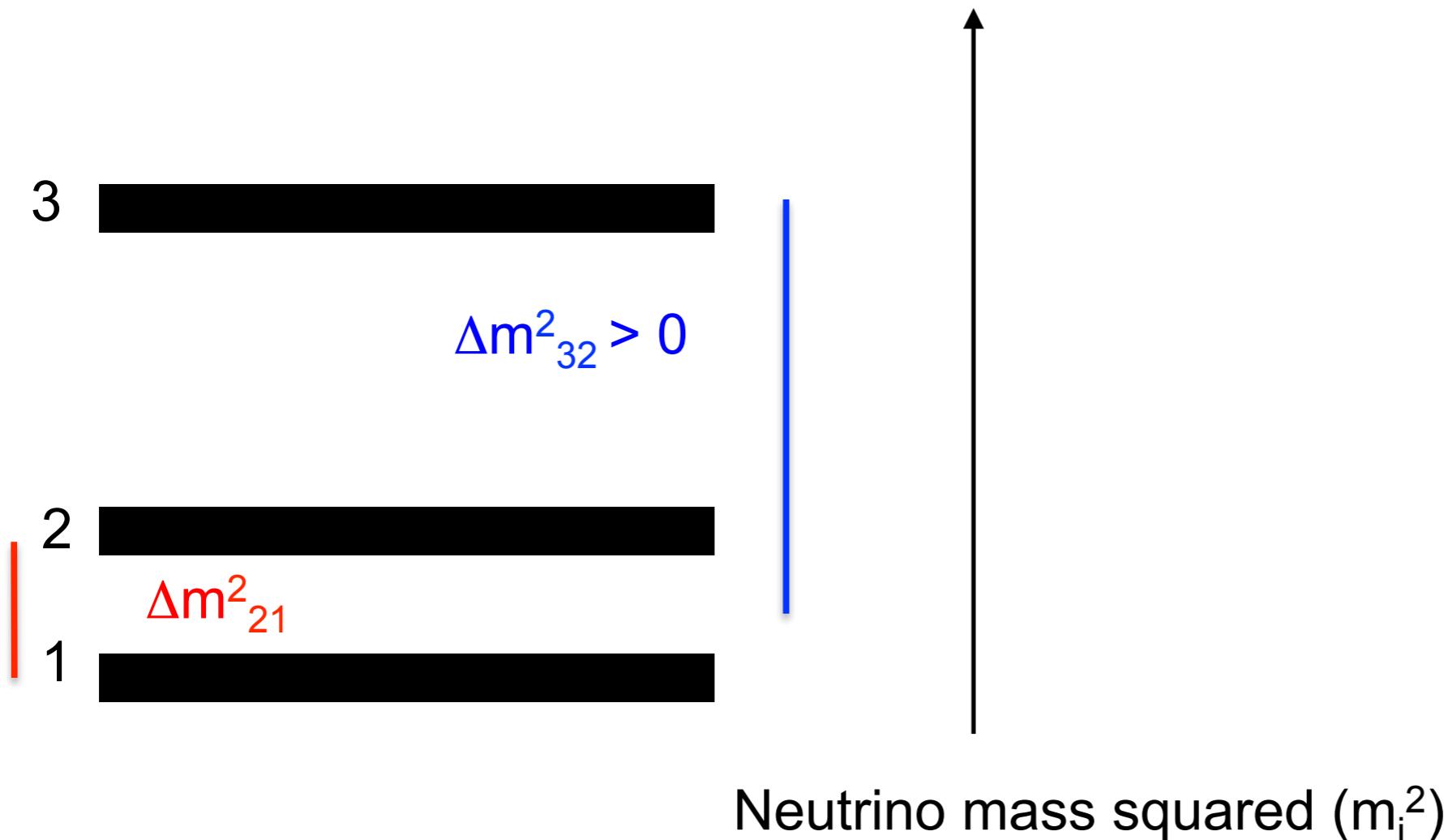
Not large enough...

Fundamental particles, but much is unknown

What we still don't know about neutrinos:

- Neutrino oscillation
 - Can we find new physics in the neutrino sector (neutrino CP violation?)
- **What is the origin of neutrino mass? What is the ordering of the masses of the neutrinos?**
 - Related: Are there non-standard interactions in neutrinos?

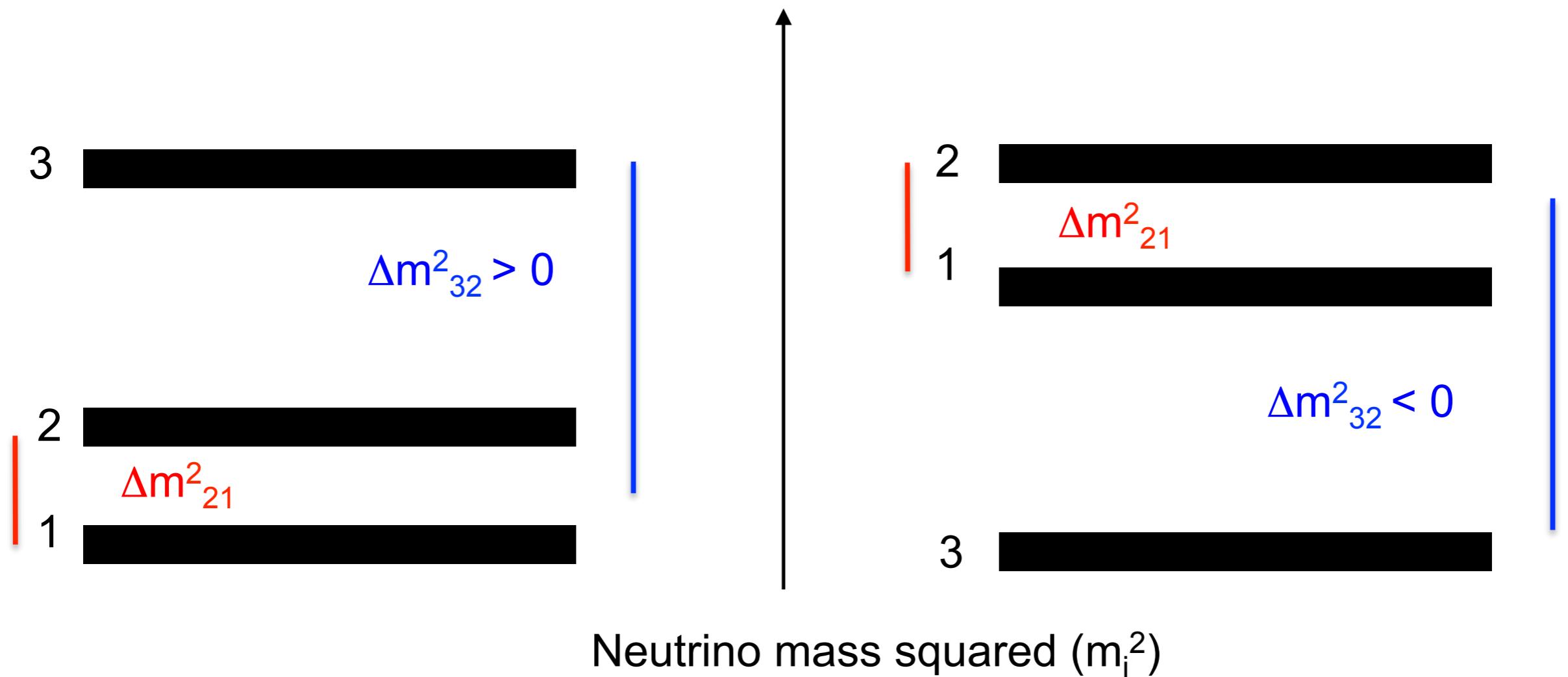
What do we know about neutrino oscillation?



- **Mass splitting: $|\Delta m_{32}^2|, \Delta m_{21}^2$**

Δm_{21}^2 mass splitting is known to be positive from solar neutrino oscillation experiments

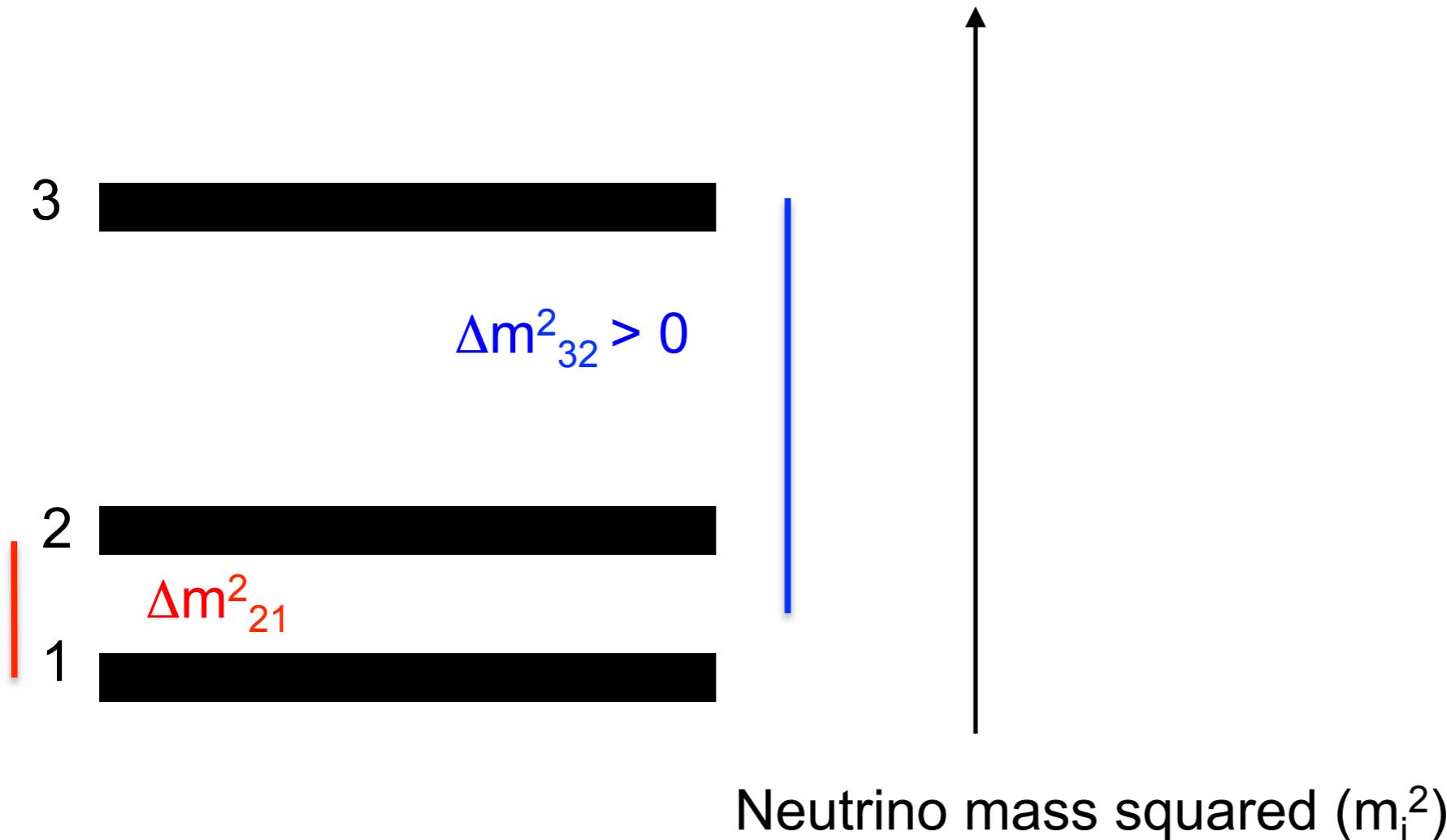
What do we know about neutrino oscillation?



- **Mass splitting:** $|\Delta m_{32}^2|, \Delta m_{21}^2$

We don't know if the 3rd or 1st mass eigenstate is heaviest ("mass hierarchy")

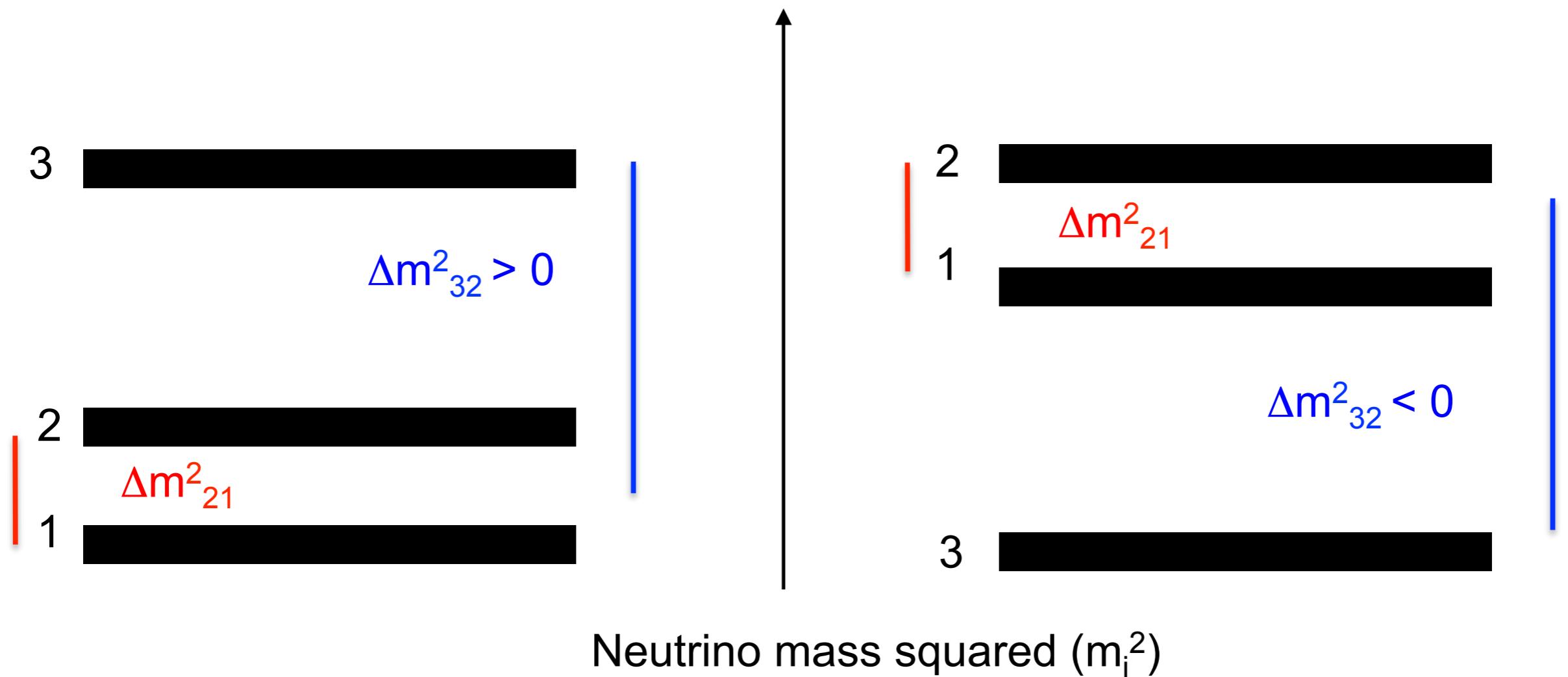
What do we know about neutrino oscillation?



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$\Delta m^2_{32} > 0$: “normal” hierarchy,

What do we know about neutrino oscillation?

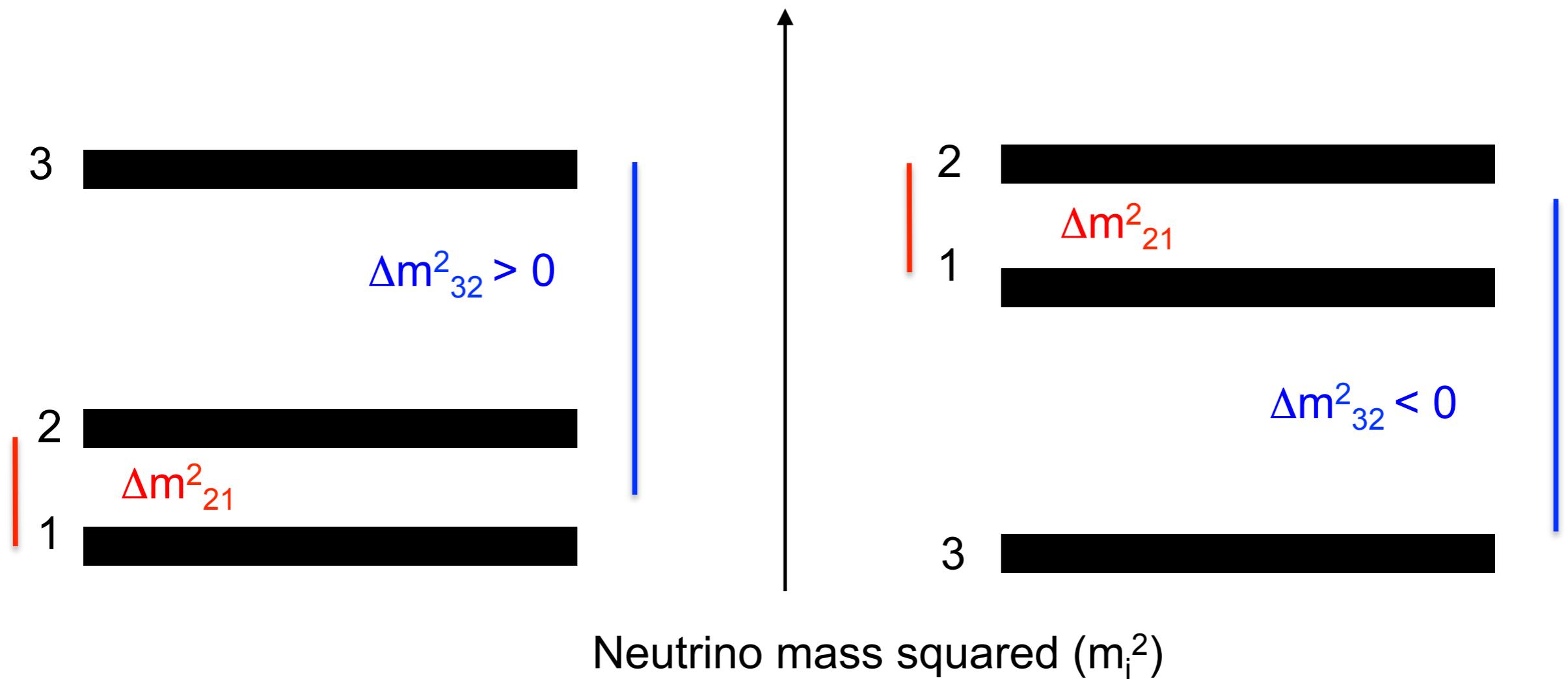


- **Mass splitting:** $|\Delta m^2_{32}|, \Delta m^2_{21}$

$\Delta m^2_{32} > 0$: “normal” hierarchy,

$\Delta m^2_{32} < 0$: “inverted” hierarchy

What do we know about neutrino oscillation?



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

$\Delta m^2_{32} > 0$: “normal” hierarchy,

$\Delta m^2_{32} < 0$: “inverted” hierarchy

Oscillation experiments are sensitive to the hierarchy due to interactions of ν_e (and electrons) in matter

Fundamental particles, but much is unknown

What we still don't know about neutrinos:

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Neutrino mass and oscillation are applicable to astrophysics

Supernova physics

Large scale structure

Cosmology

Accessing neutrino oscillation

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

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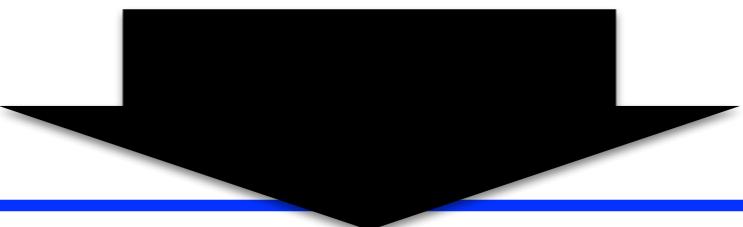
$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re} \left[U_{\beta i} U_{\alpha i}^* U_{\beta j}^* U_{\alpha j} \right] \sin^2 \left(\frac{1.27 \Delta m_{ij}^2 L}{E} \right) + 2 \sum_{i>j} \text{Im} \left[U_{\beta i} U_{\alpha i}^* U_{\beta j}^* U_{\alpha j} \right] \sin \left(\frac{2.54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

Probability to transition from flavor α to flavor β

Accessing neutrino oscillation

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$$\Delta m^2_{32} \gg \Delta m^2_{21}$$



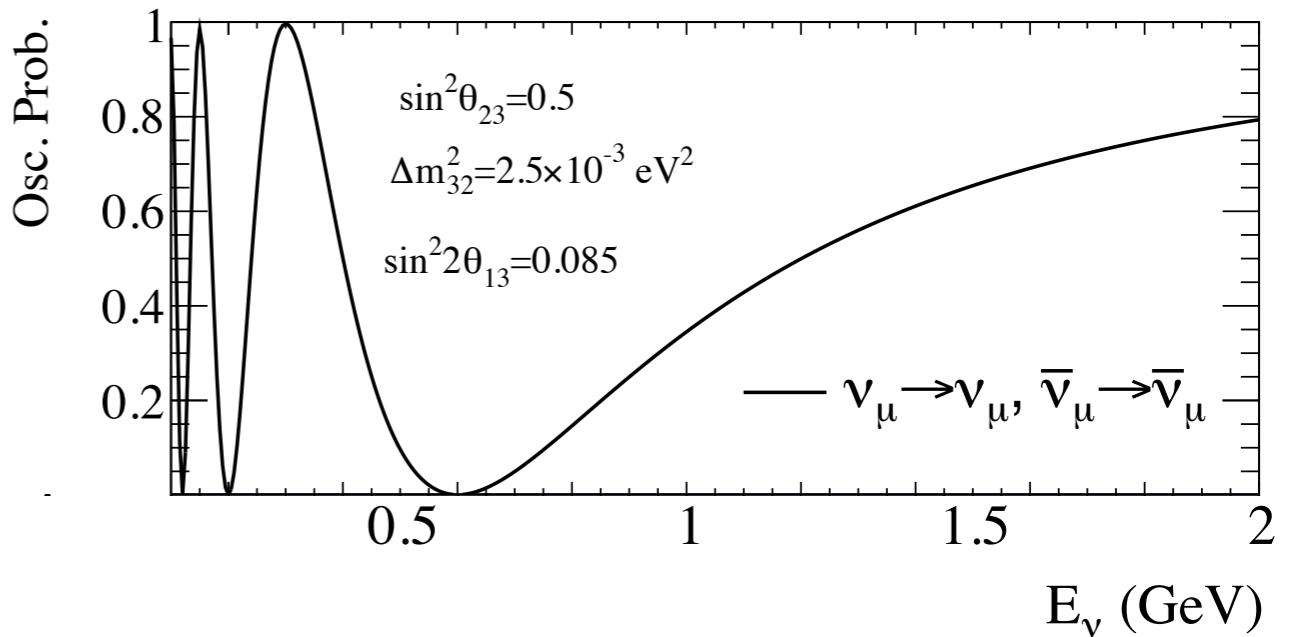
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{1.27 \Delta m_{32}^2 L}{E} \right) + \dots$$

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

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

Accessing neutrino oscillation



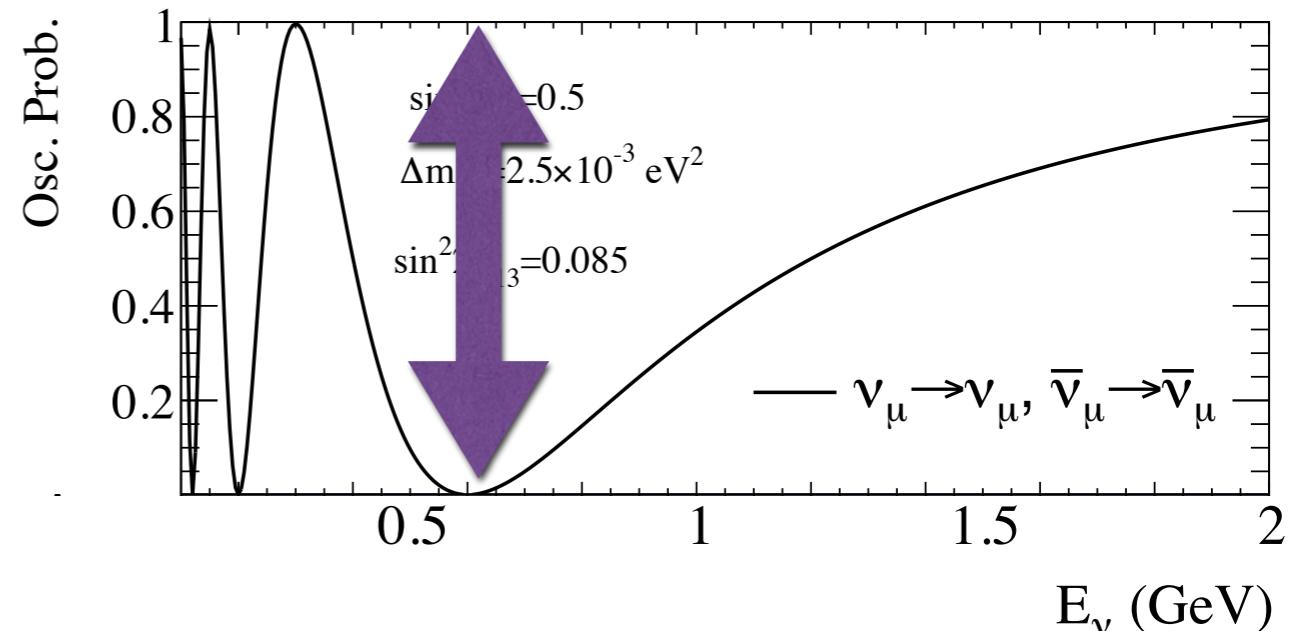
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ν_μ and $\bar{\nu}_\mu$ disappearance channel

Accessing neutrino oscillation

Oscillation depends on:

- **Amplitude** determined by mixing angles: θ_{12} , θ_{23} , θ_{13}



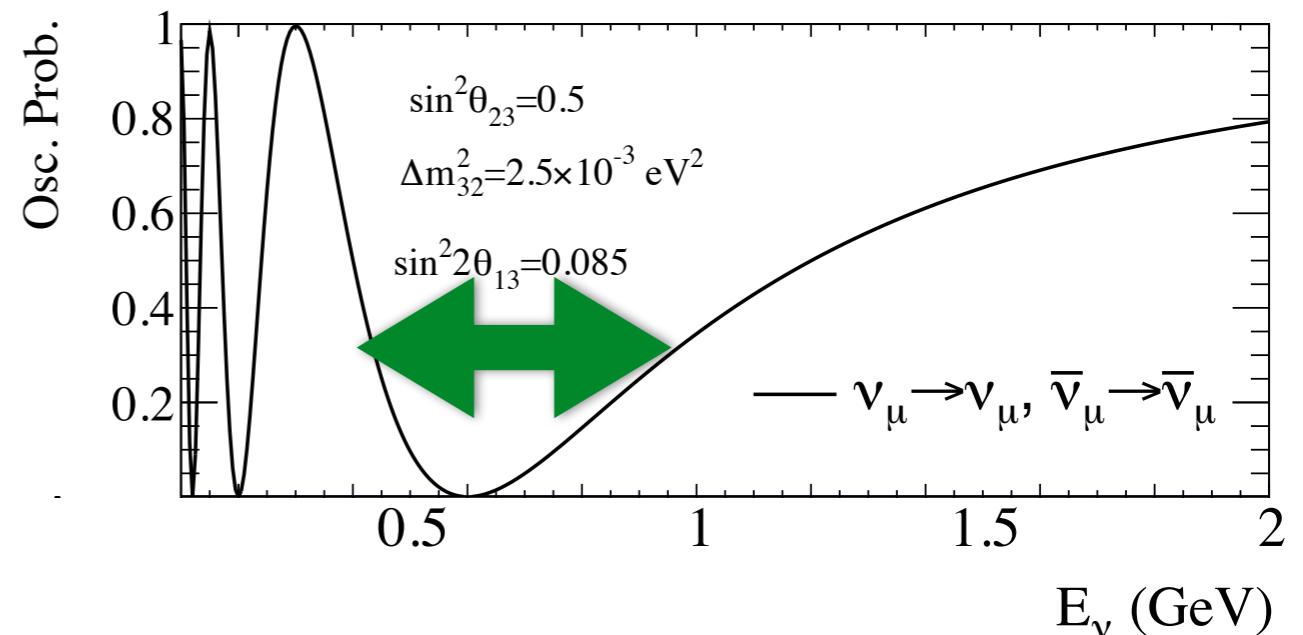
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Accessing neutrino oscillation

Oscillation depends on:

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



$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{1 - 27 \Delta m^2_{32} L}{E} \right) + \dots$$

ν_μ and ν̄_μ disappearance channel

Accessing neutrino oscillation

- Amplitude determined by mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$
- Frequency determined by mass splittings: $|\Delta m^2_{32}|, \Delta m^2_{21}$
- Mass ordering (hierarchy)
- CP violating phase (CPV): δ_{CP}

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

*Sensitive to all
oscillation parameters*

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

Accessing neutrino oscillation

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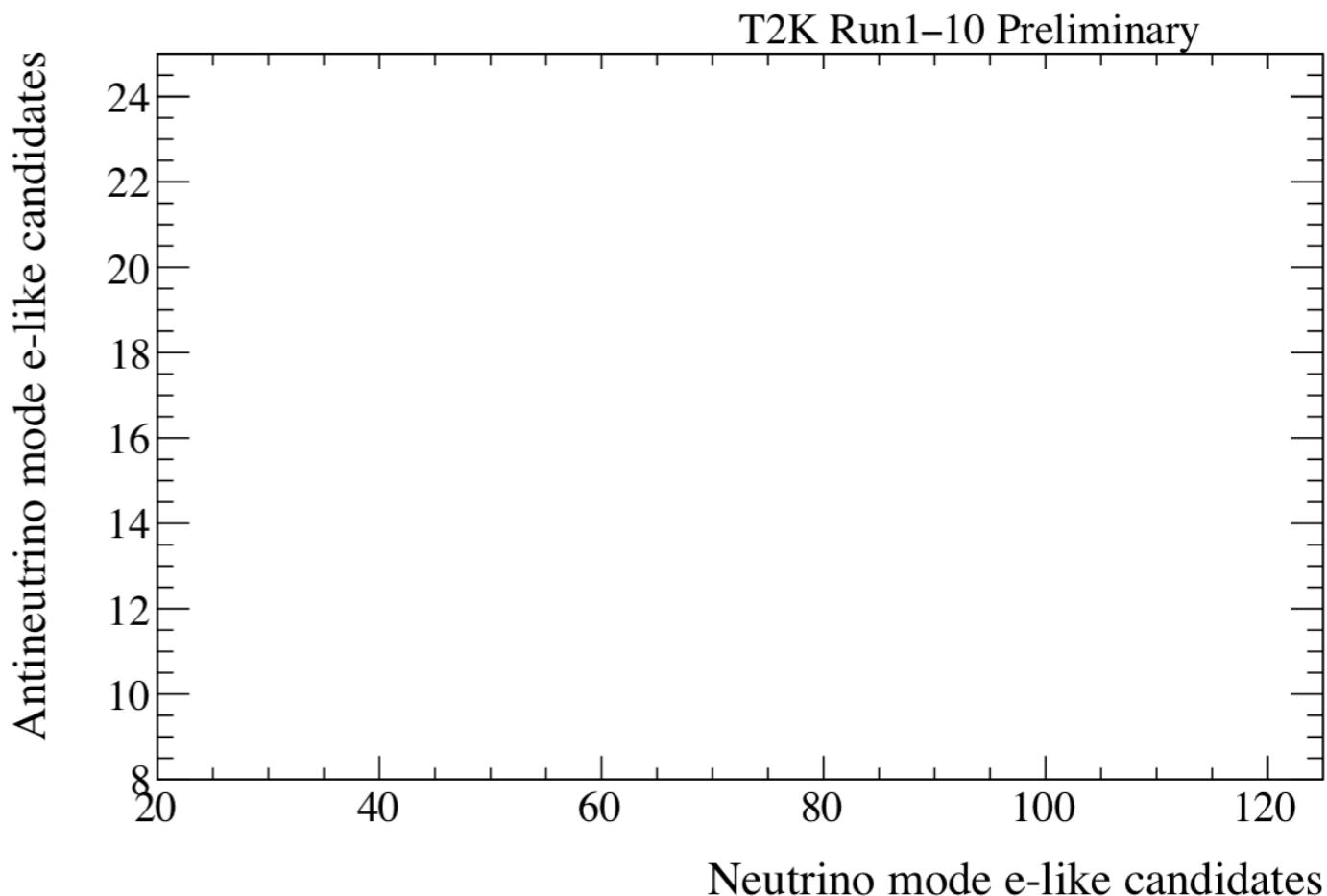
v_e and \bar{v}_e appearance channel

SAMPLE	PREDICTED		
	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
v_e appearance	97.6	82.4	67.6
\bar{v}_e appearance	16.7	19.0	20.9

δ_{CP} changes the v_e and \bar{v}_e appearance in opposite directions

Accessing neutrino oscillation

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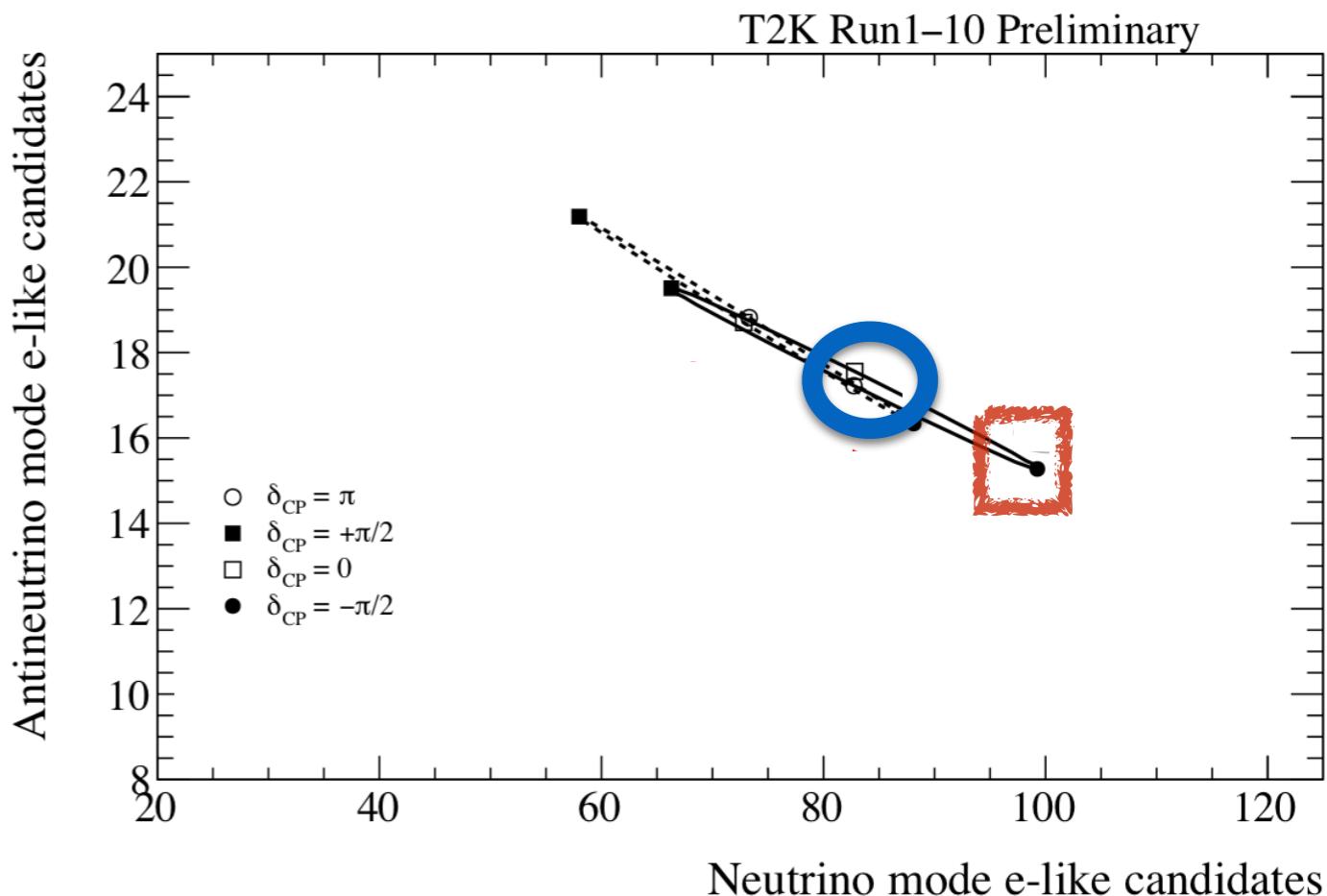
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2D plot of neutrino appearance rate vs. antineutrino appearance rate

Accessing neutrino oscillation

- Amplitude determined by mixing angles: θ_{12} , θ_{23} , θ_{13}
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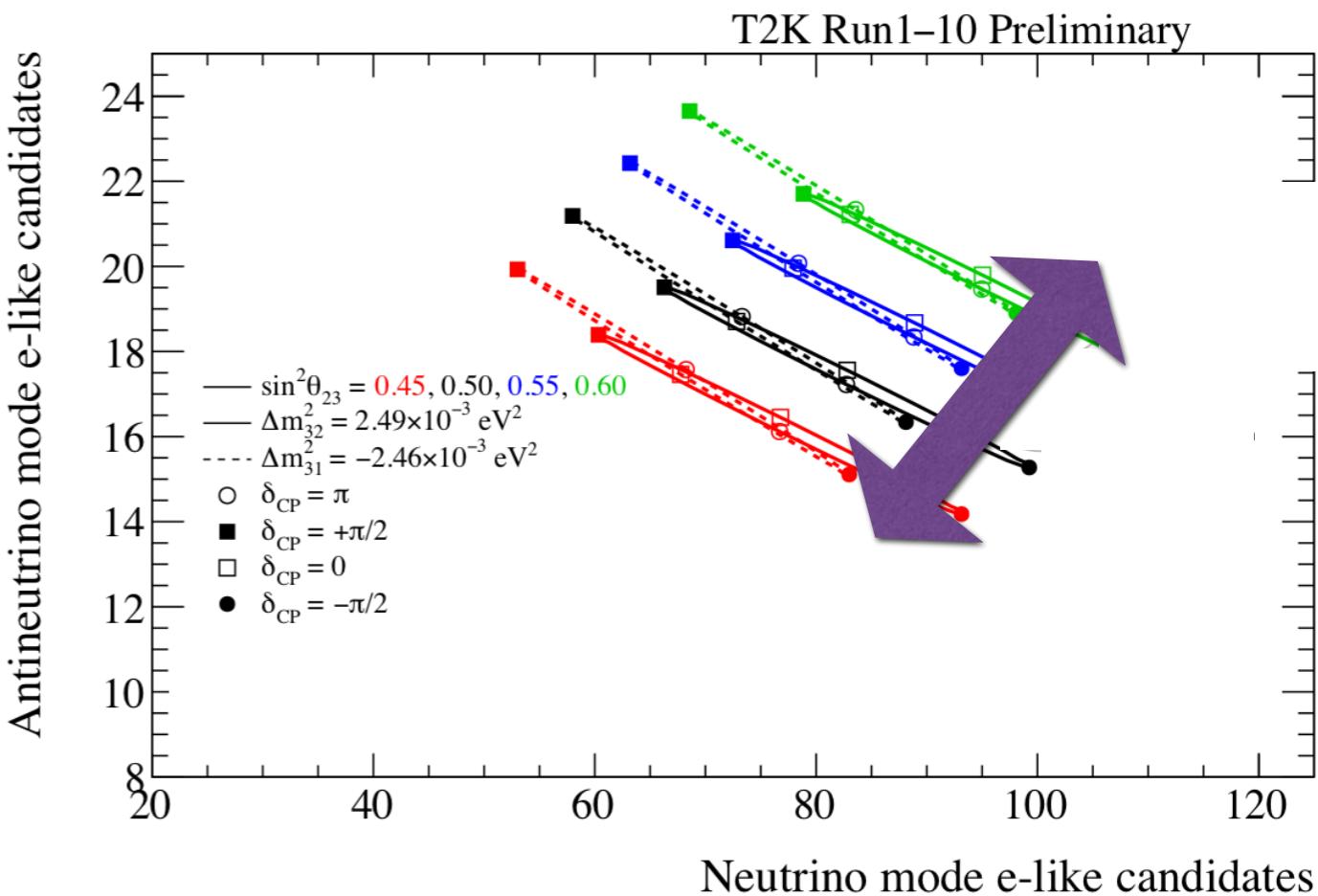
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Accessing neutrino oscillation

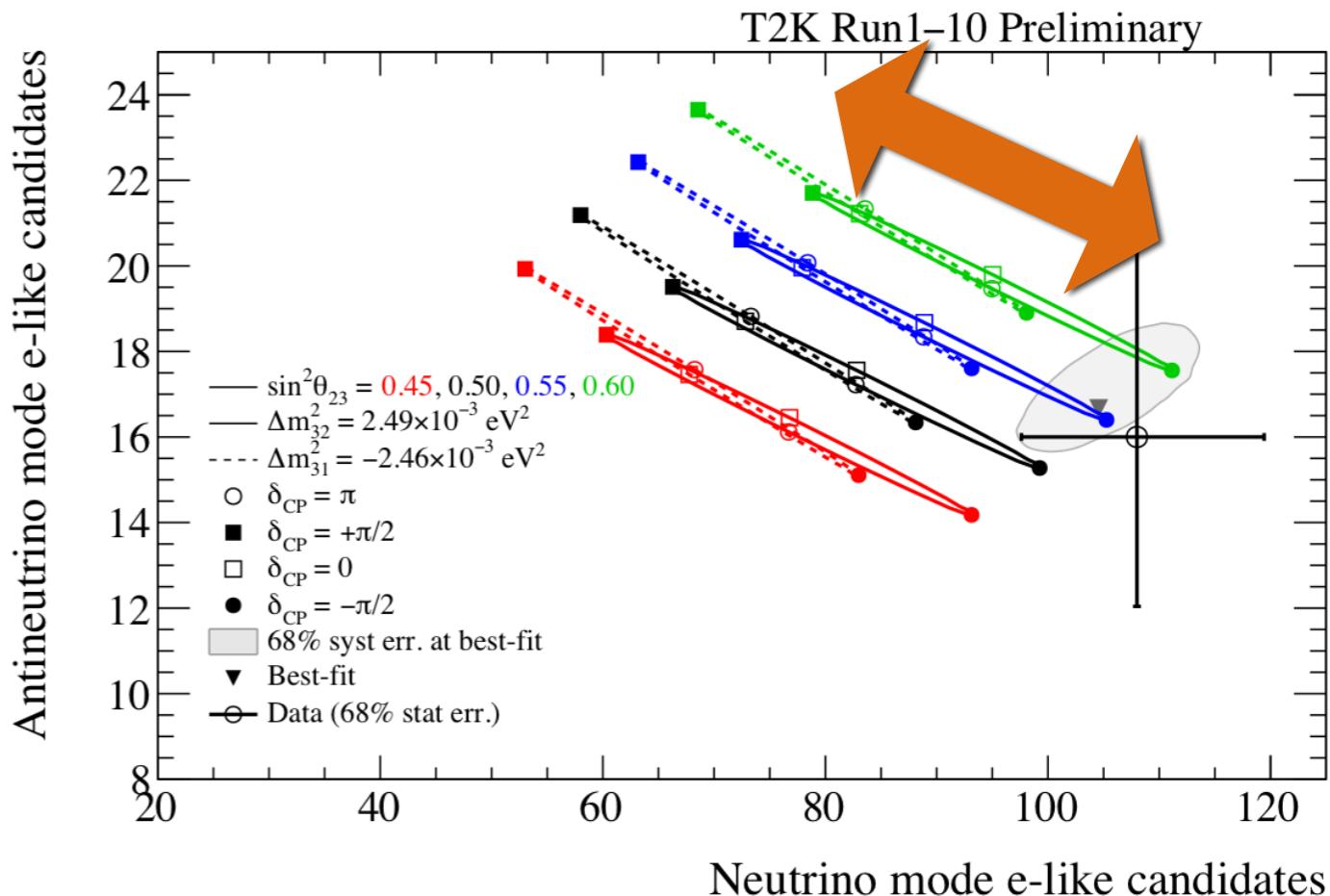
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For increasing θ_{23} enhance both ν_e and $\bar{\nu}_e$ appearance

Accessing neutrino oscillation

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



Normal to inverted hierarchy suppresses ν_e appearance, enhances $\bar{\nu}_e$ appearance

The following is the hard work
of many people on the
Tokai-to-Kamioka (T2K)
neutrino oscillation
experiment

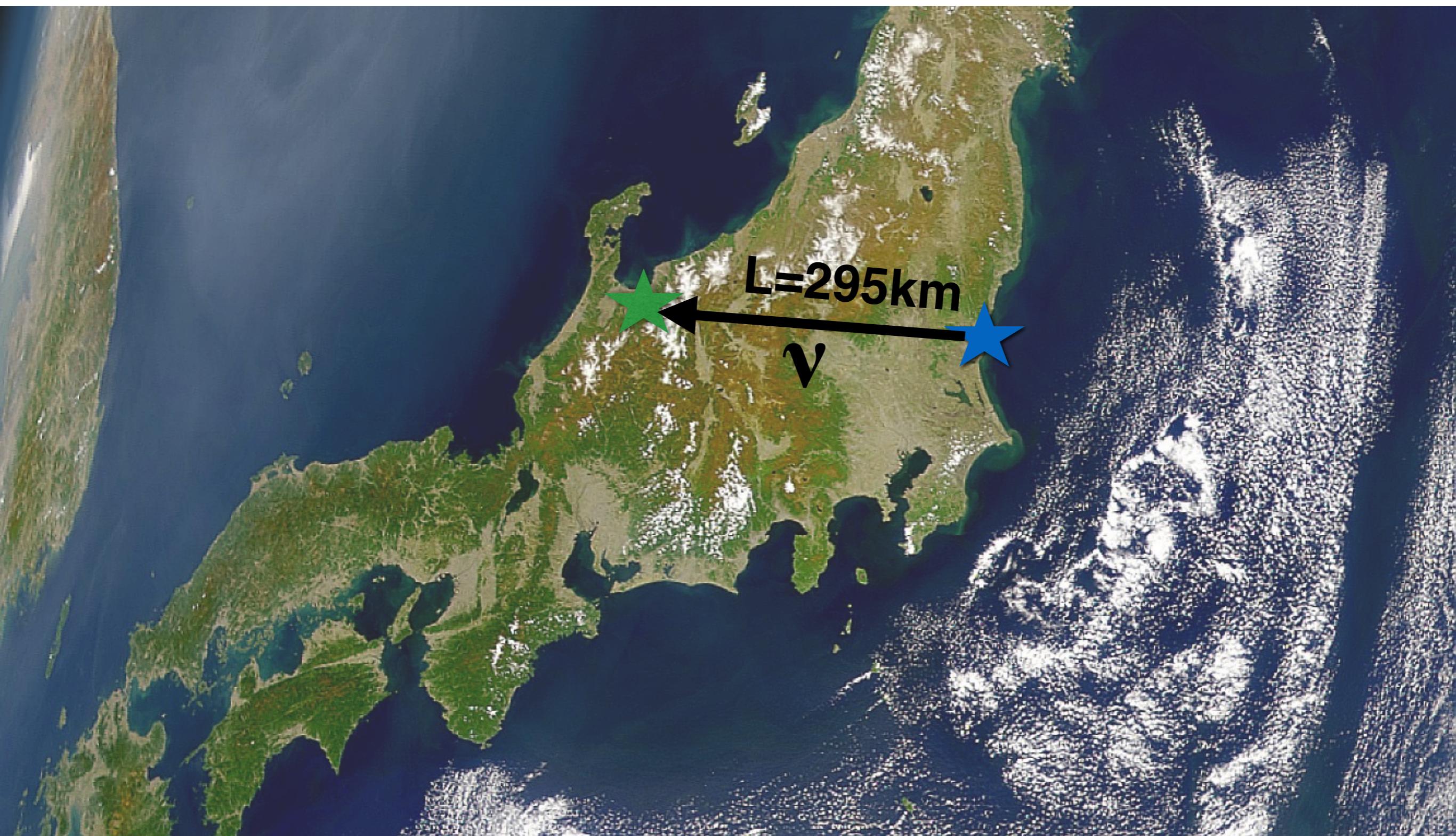


T2K collaboration: ~500 members, from institutions in 12 countries

Long baseline experiments

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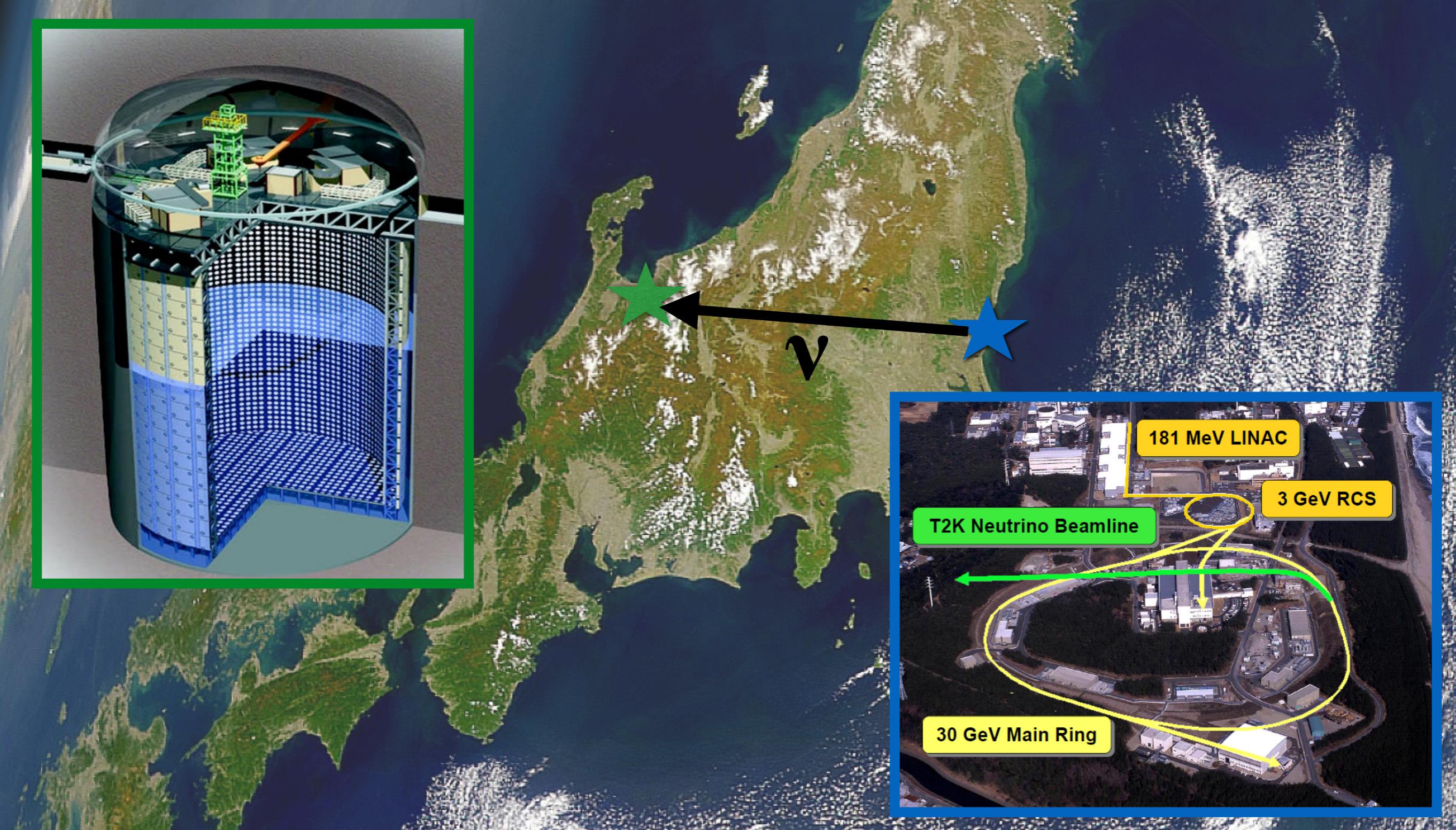


$$P(\nu_\mu \rightarrow \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{1.27 \Delta m_{32}^2 L}{E} \right) + \dots$$



Tokai-to-Kamioka is an accelerator-based neutrino experiment

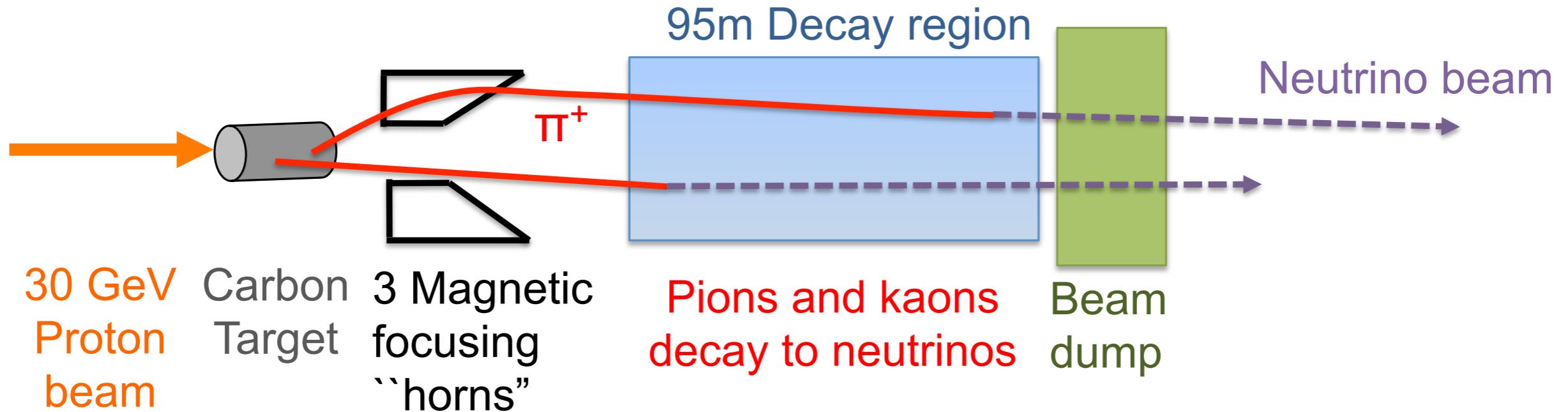
- Broad physics program includes measurements of $\nu_\mu, \bar{\nu}_\mu$ disappearance, $\nu_e, \bar{\nu}_e$ appearance, exotica and neutrino interactions



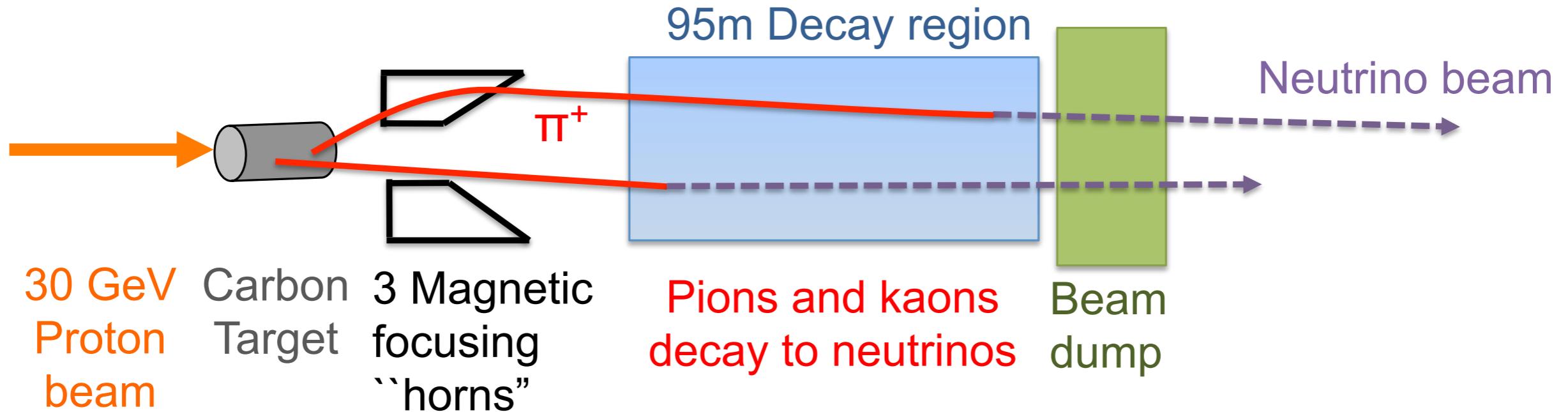
Main ingredients:

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

Accelerator-produced neutrino beams



Accelerator-produced neutrino beams



Tunable energy!

Can be neutrino or antineutrino!

99% pure muon neutrino beam!

T2K oscillation analysis strategy

Δm^2_{32} , θ_{13} , θ_{23} , δ_{CP} , mass hierarchy

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

Determine oscillation parameters from **event rates** with data taken over the last 10 years.

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ν_e event rate

$\bar{\nu}_e$ event rate

ν_μ event rate

$\bar{\nu}_\mu$ event rate

Determine oscillation parameters from **event rates** with data taken over the last 10 years.

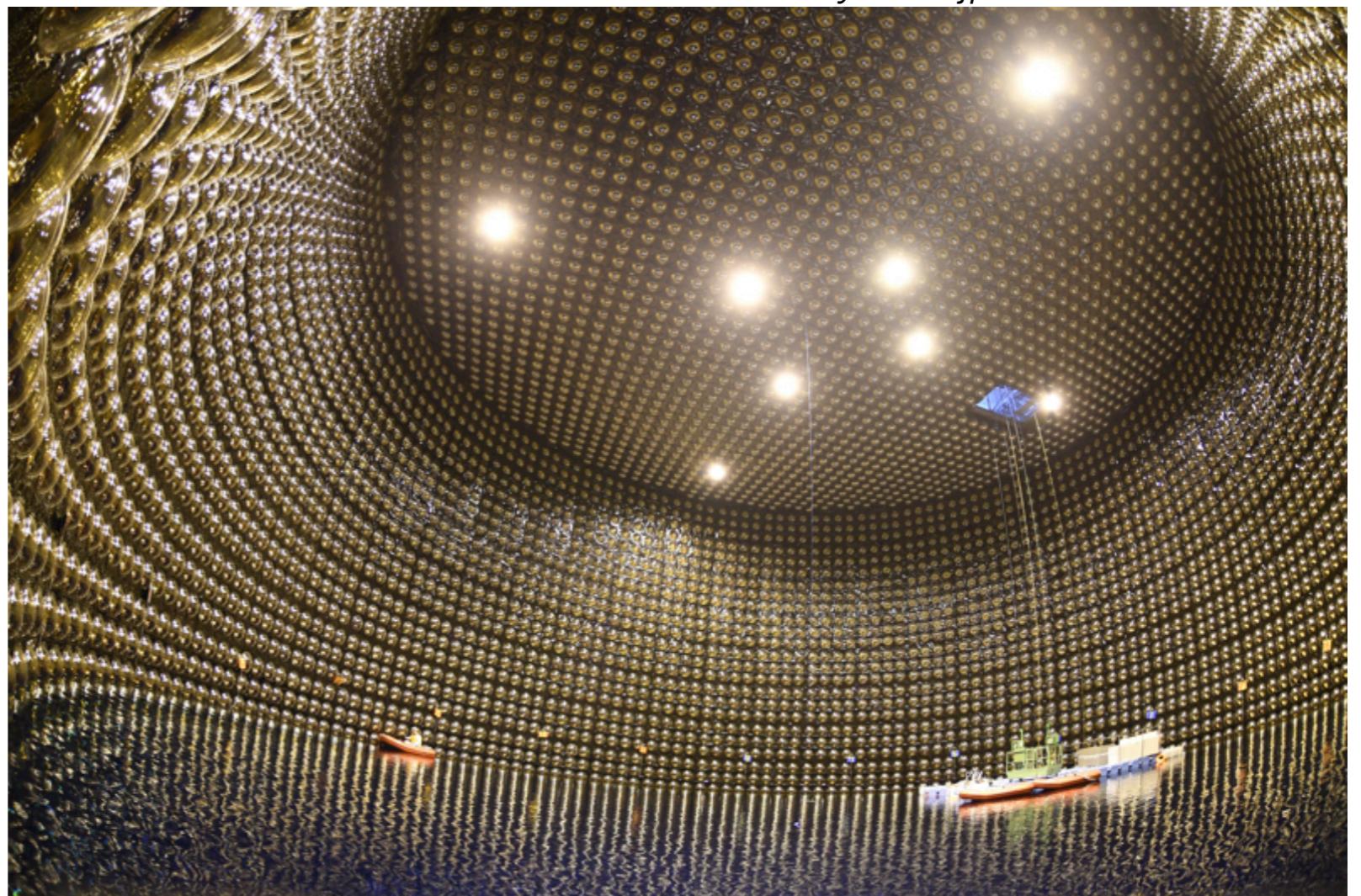
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ν_e event rate

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



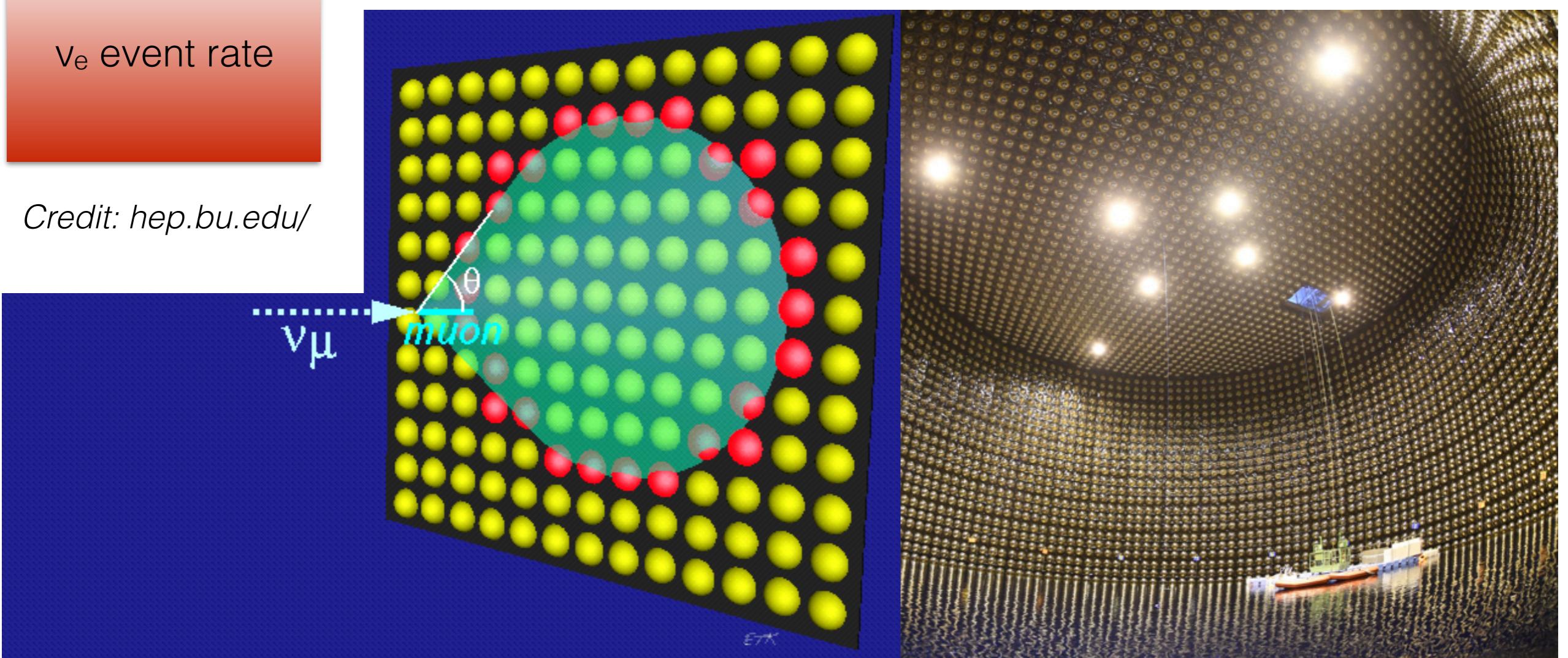
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ν_e event rate

Credit: hep.bu.edu/



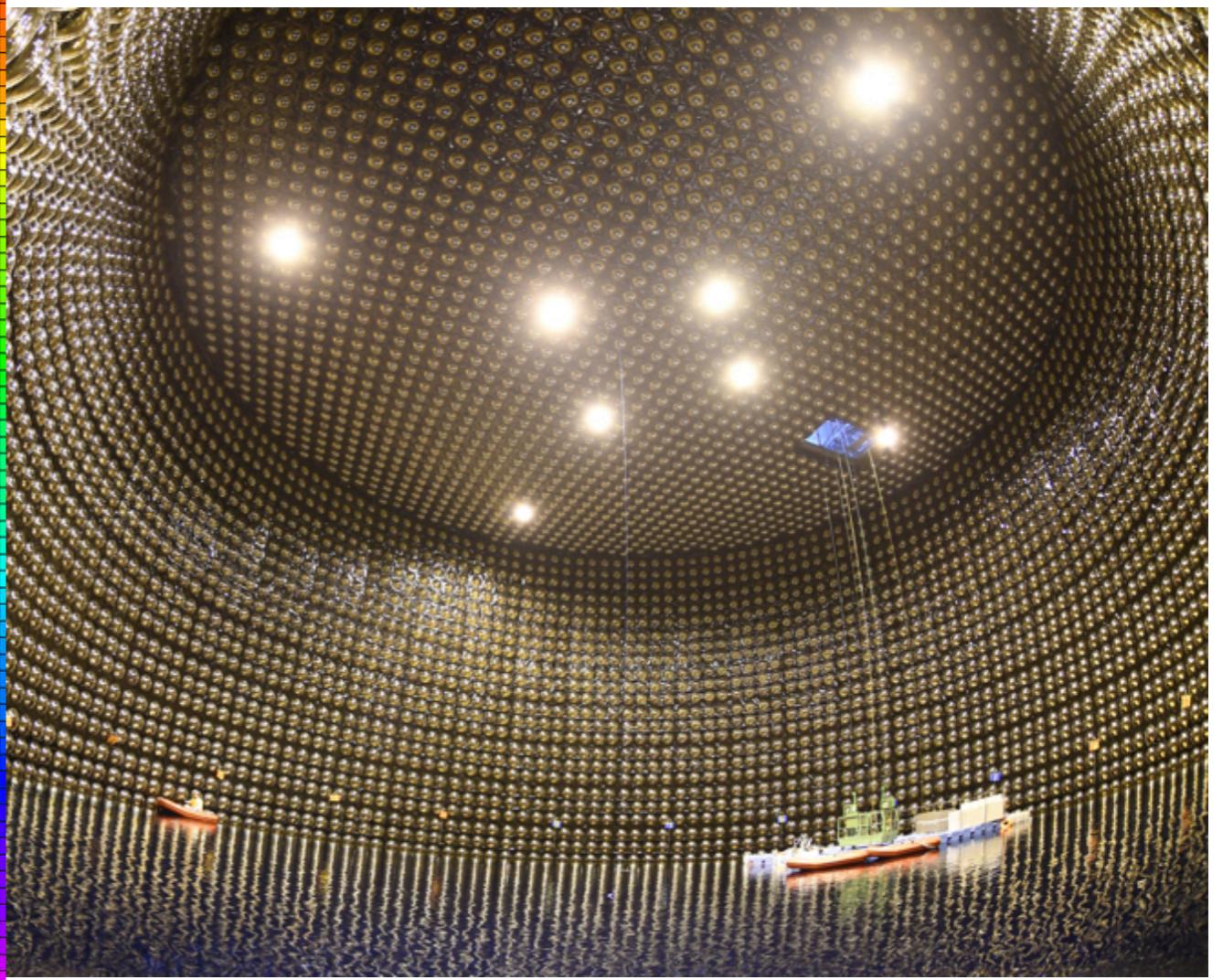
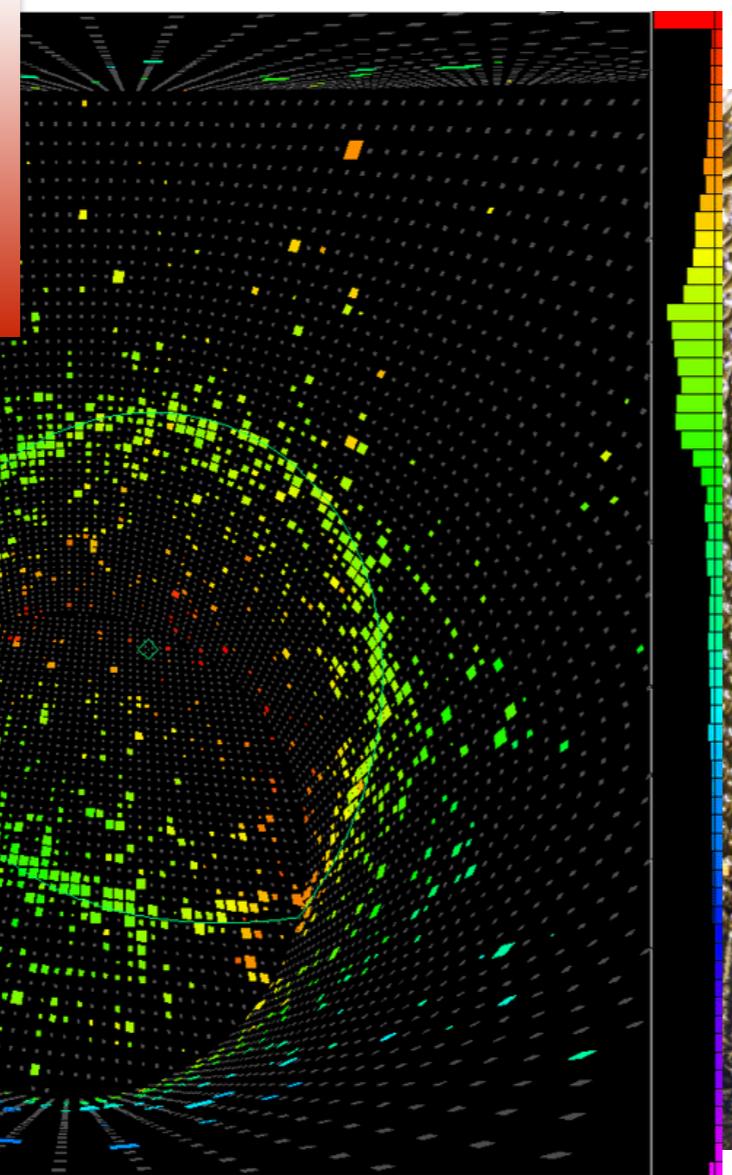
T2K oscillation analysis strategy

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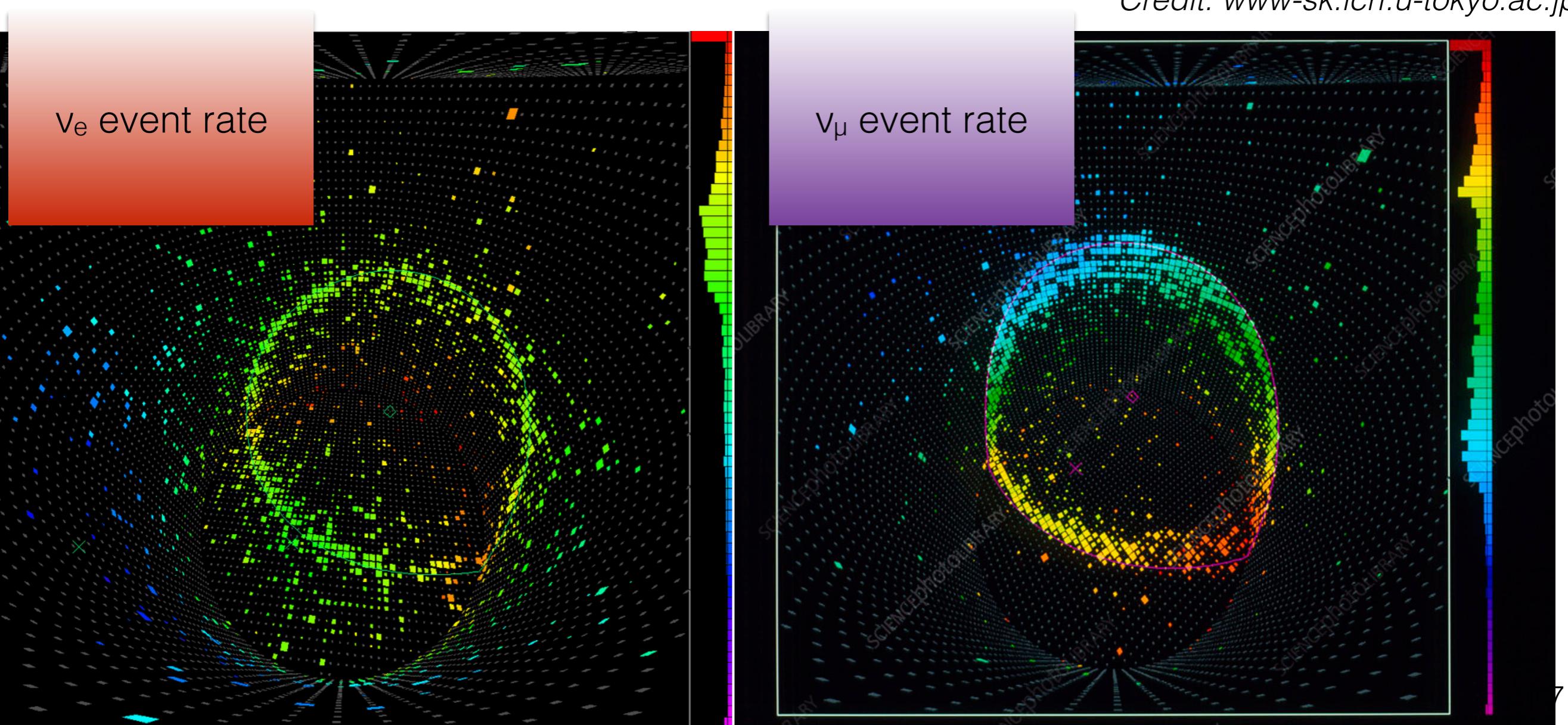
Credit: www-sk.icrr.u-tokyo.ac.jp/



T2K oscillation analysis strategy

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T2K oscillation analysis strategy

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<i>Flux (Φ)</i>	<i>Interaction model (cross between truth and section, σ)</i>	<i>Relationship observables (R)</i>	<i>Efficiency (ϵ)</i>
---------------------------------	---	-------------------------------------	---

Predicted event rate built from neutrino source, interaction, detector models

T2K oscillation analysis strategy

Δm^2_{32} , θ_{13} , θ_{23} , δ_{CP} , mass hierarchy

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

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

Model is tested with **near detector information**

- Time dependent effects (beamline stability)
- Reduces shared systematic uncertainty on source (flux), interaction model

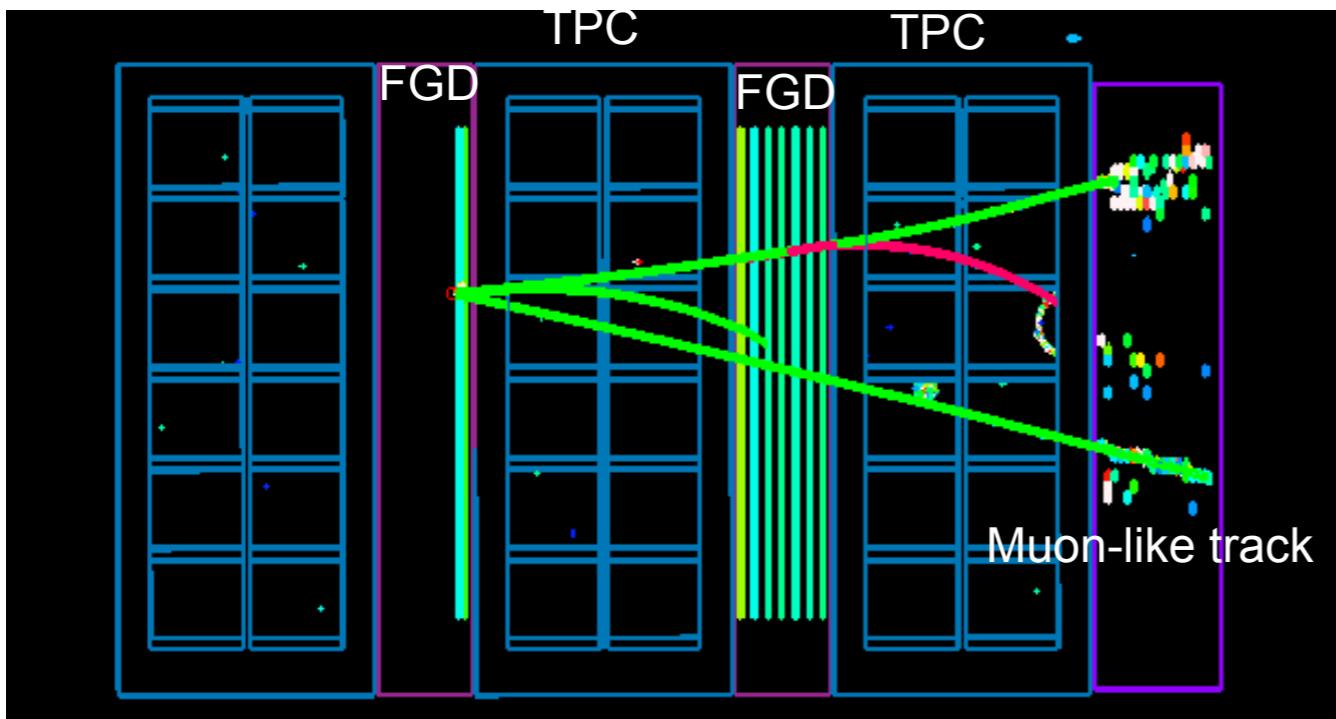
T2K oscillation analysis strategy

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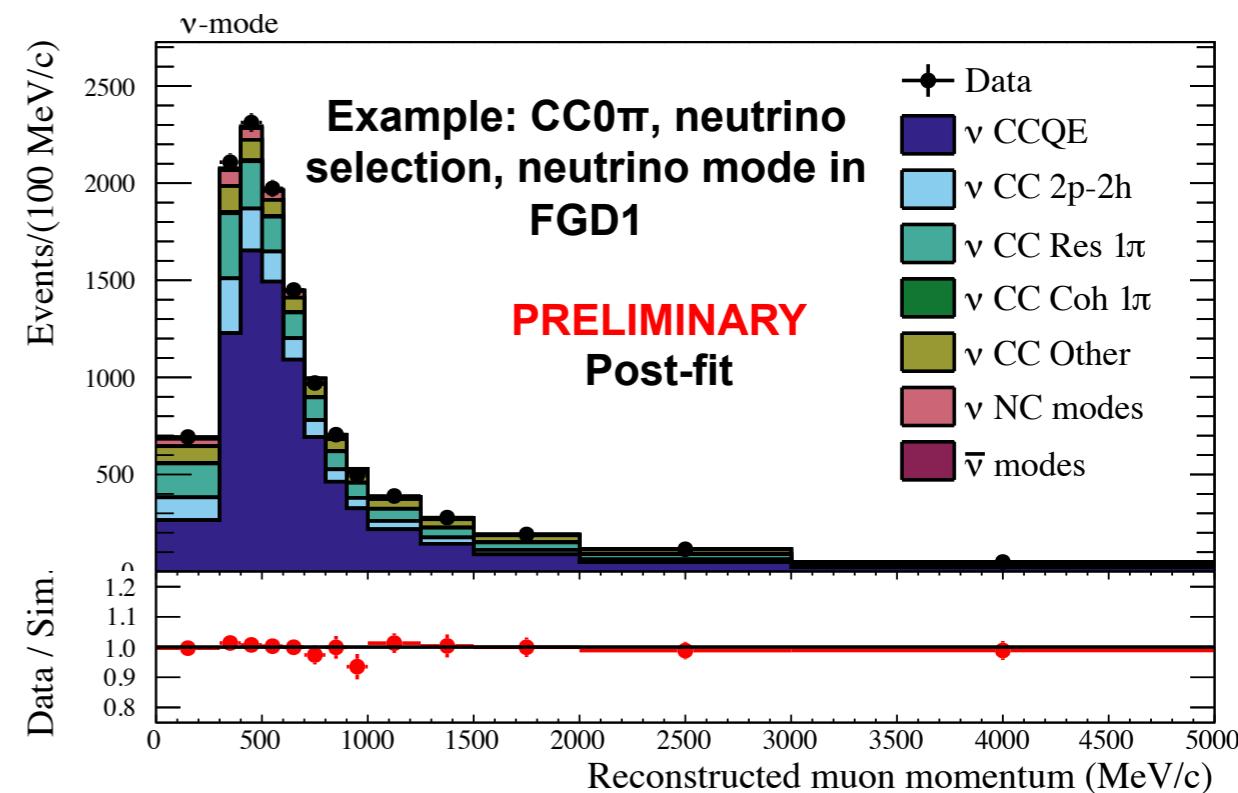
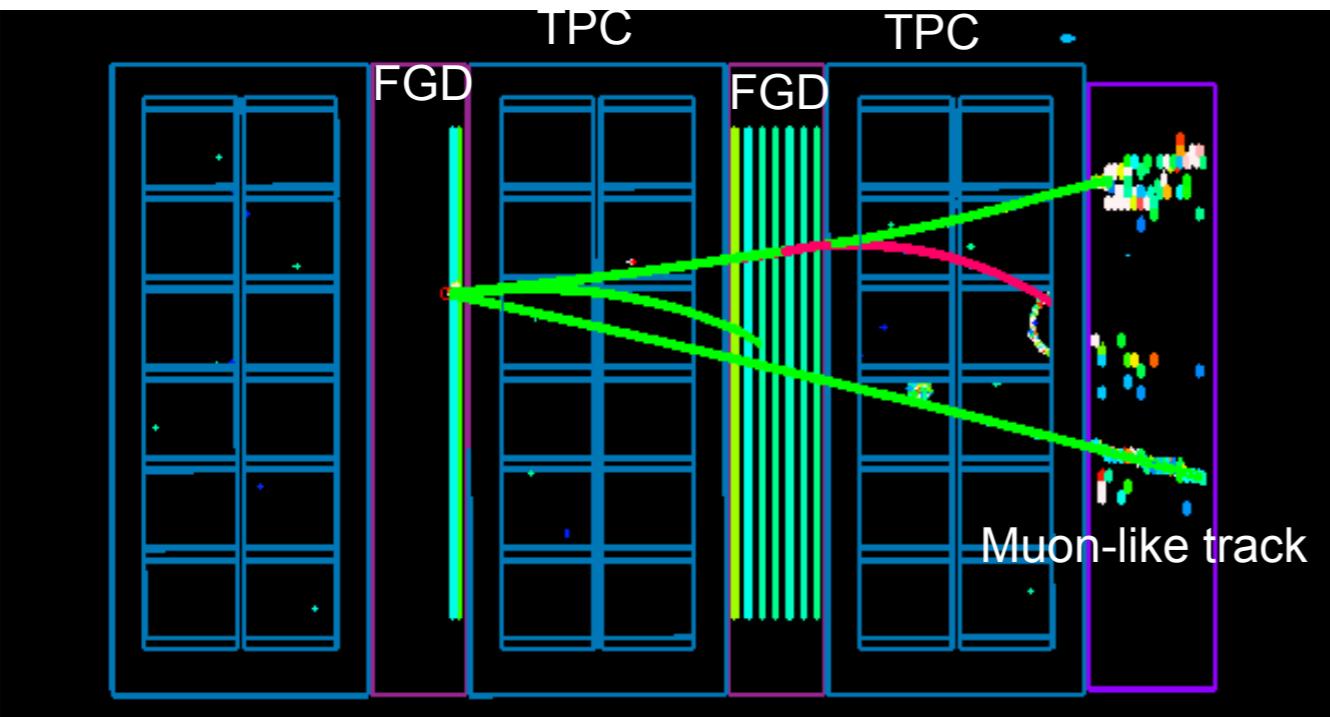
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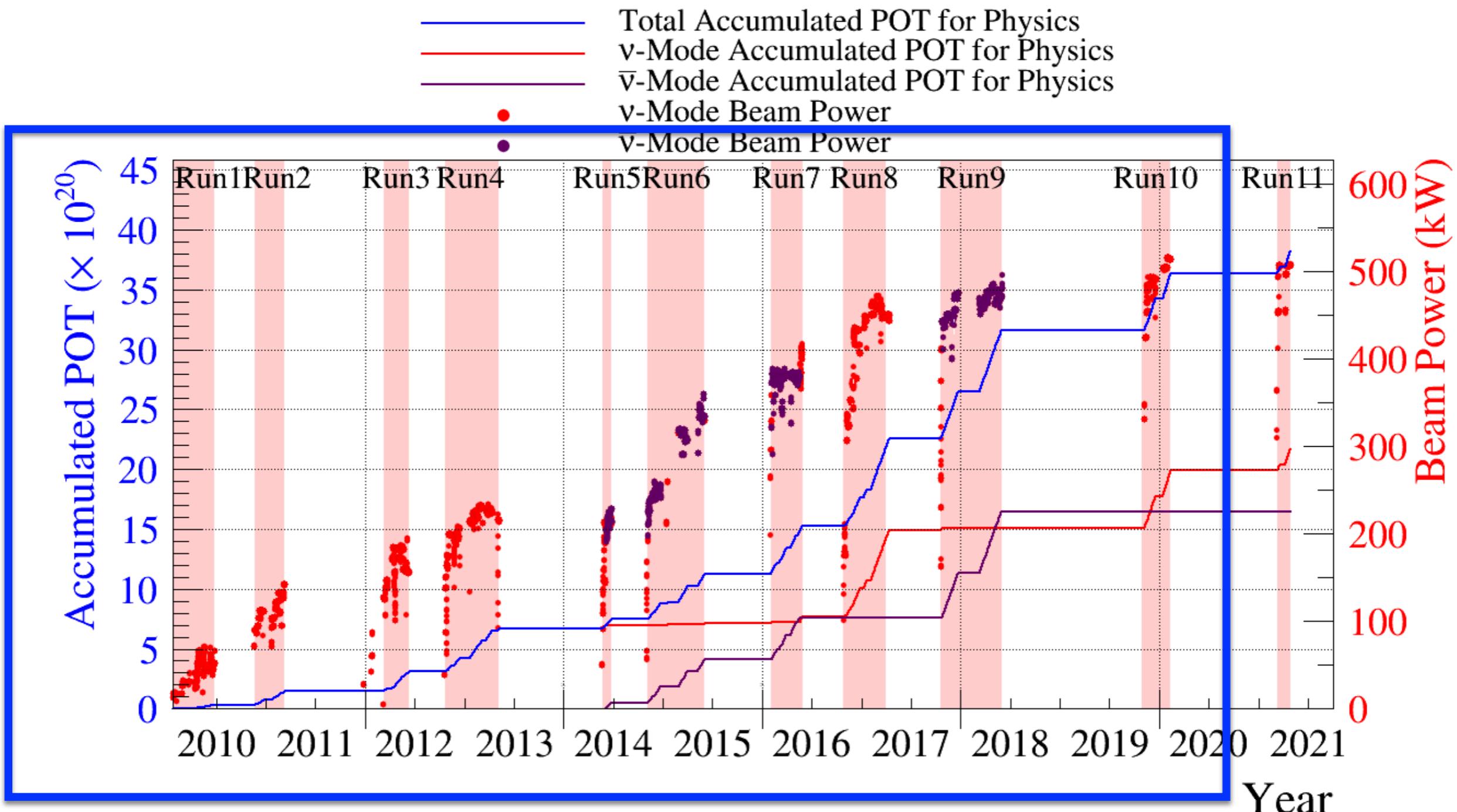
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Model is tested with near detector information



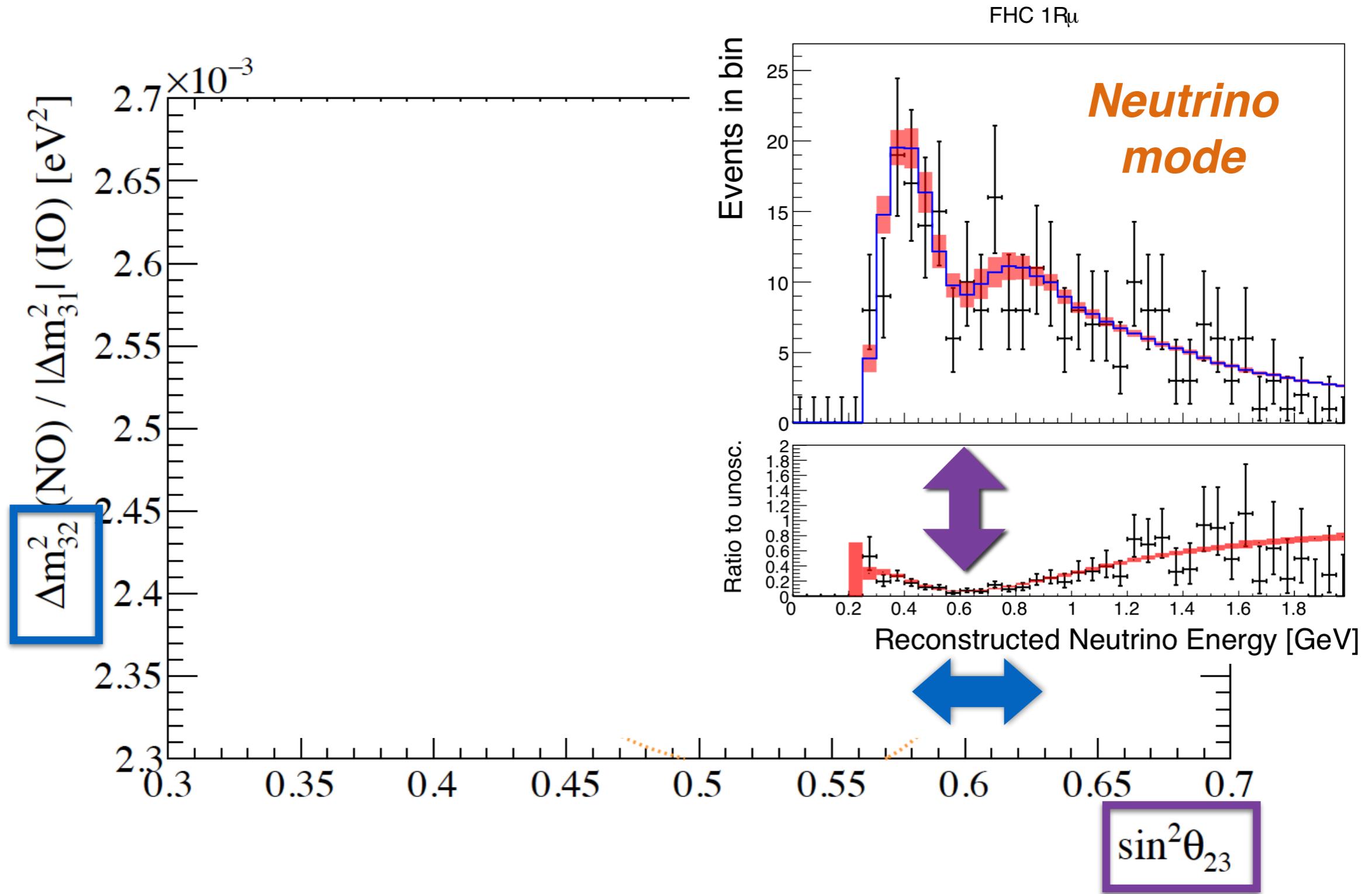
T2K: Data collection summary



OA2020 results: Run 1-10
v-mode POT (FHC) : 1.851×10^{21}
v-bar-mode POT (RHC) : 1.651×10^{21}

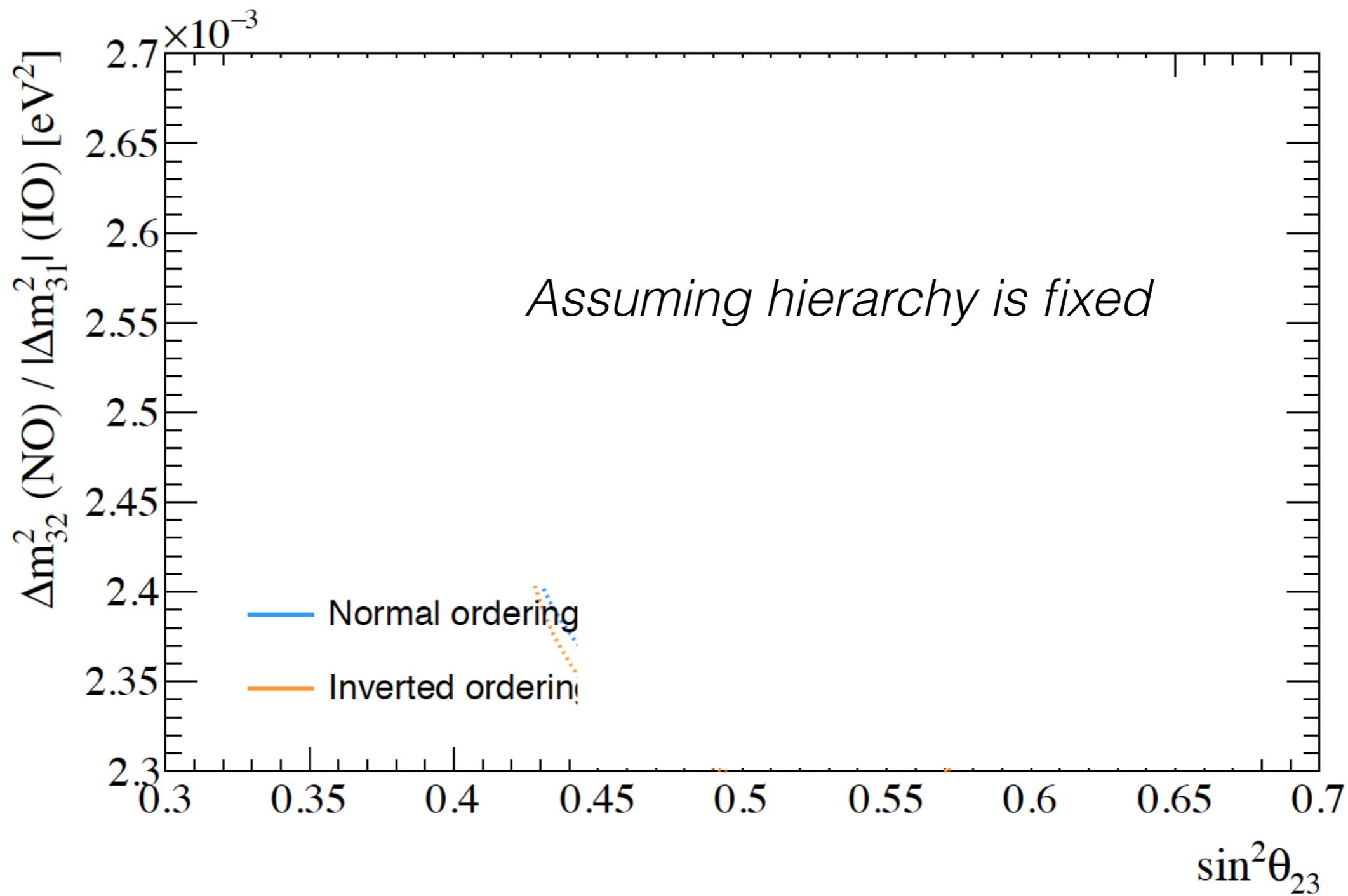
Data taken with SK Gd: Run 11:
v-mode POT (FHC) : 2.116×10^{21}
v-bar-mode (RHC) POT : 1.651×10^{21}
Total delivered: 3.818×10^{21}

T2K: Precision disappearance results



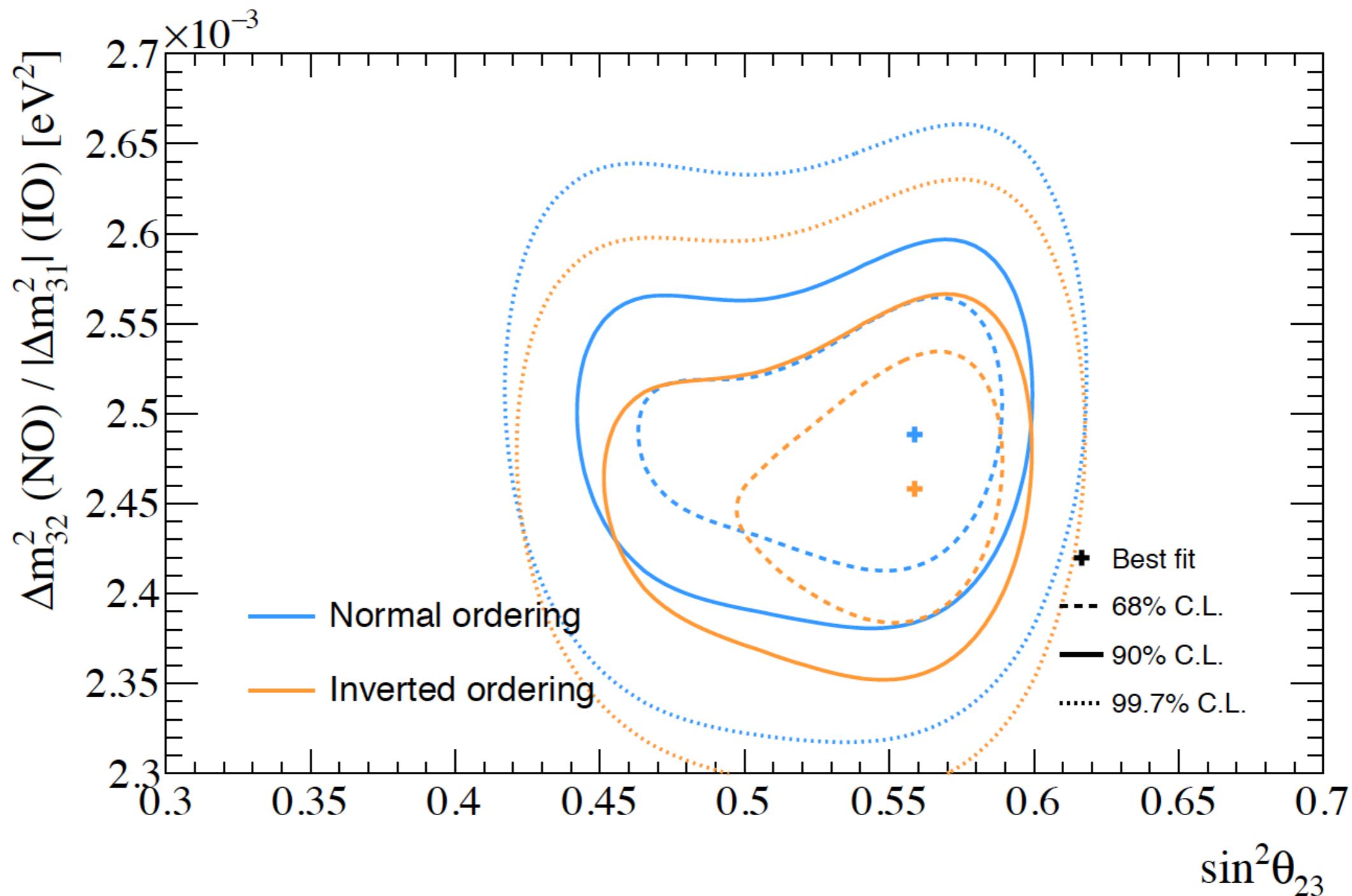
*T2K data produces “allowed” regions (closed contours)
which are parameter values consistent with our data*

T2K: Precision disappearance results



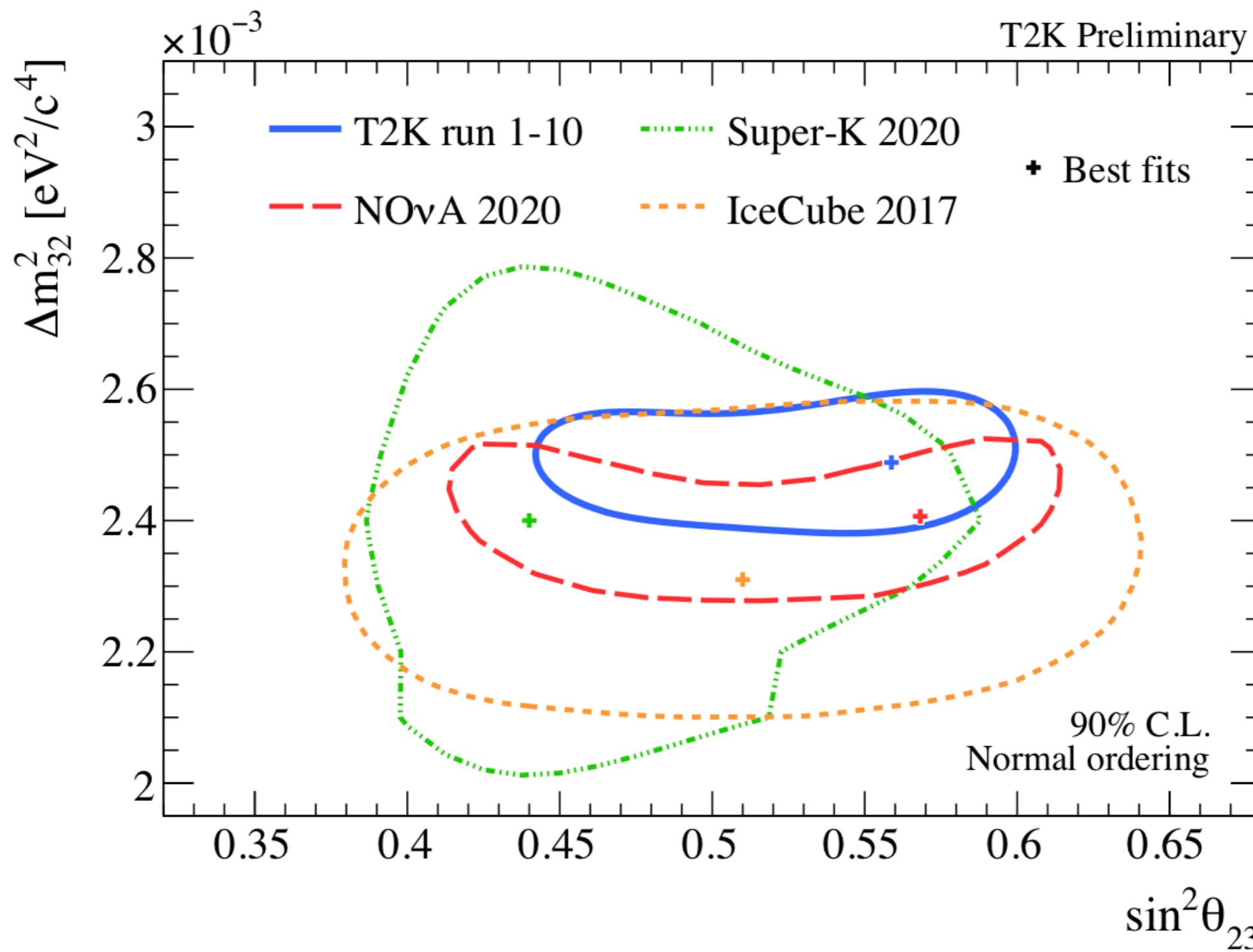
*T2K data produces “allowed” regions (closed contours)
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T2K: Precision disappearance results



T2K data is consistent with maximal mixing ($\theta_{23}=45\text{deg}$)

The current global picture, part 1



*Comparisons with other experiments (reactors, atmospheric neutrinos, accelerator-based) allow us to test if the three flavor picture is complete
[See talk on NOvA by P. Vahle, and JUNO talk by B. Hu]*

T2K: Window on CPV

	$\delta_{\text{CP}} = -\pi/2$	$\delta_{\text{CP}} = 0$	$\delta_{\text{CP}} = \pi/2$	$\delta_{\text{CP}} = \pi$	Data
FHC 1R μ	356.48	355.76	356.44	357.27	318
RHC 1R μ	138.34	137.98	138.34	138.73	137
FHC 1Re	97.62	82.44	67.56	82.74	94
RHC 1Re	16.69	18.96	20.90	18.63	16
FHC 1R ν_e CC1 π^+	9.20	8.01	6.51	7.71	14
FHC 1R μ ($E_{\text{rec}} < 1.2 \text{ GeV}$)	213.40	213.06	213.36	213.81	191
RHC 1R μ ($E_{\text{rec}} < 1.2 \text{ GeV}$)	68.53	68.34	68.53	68.74	71

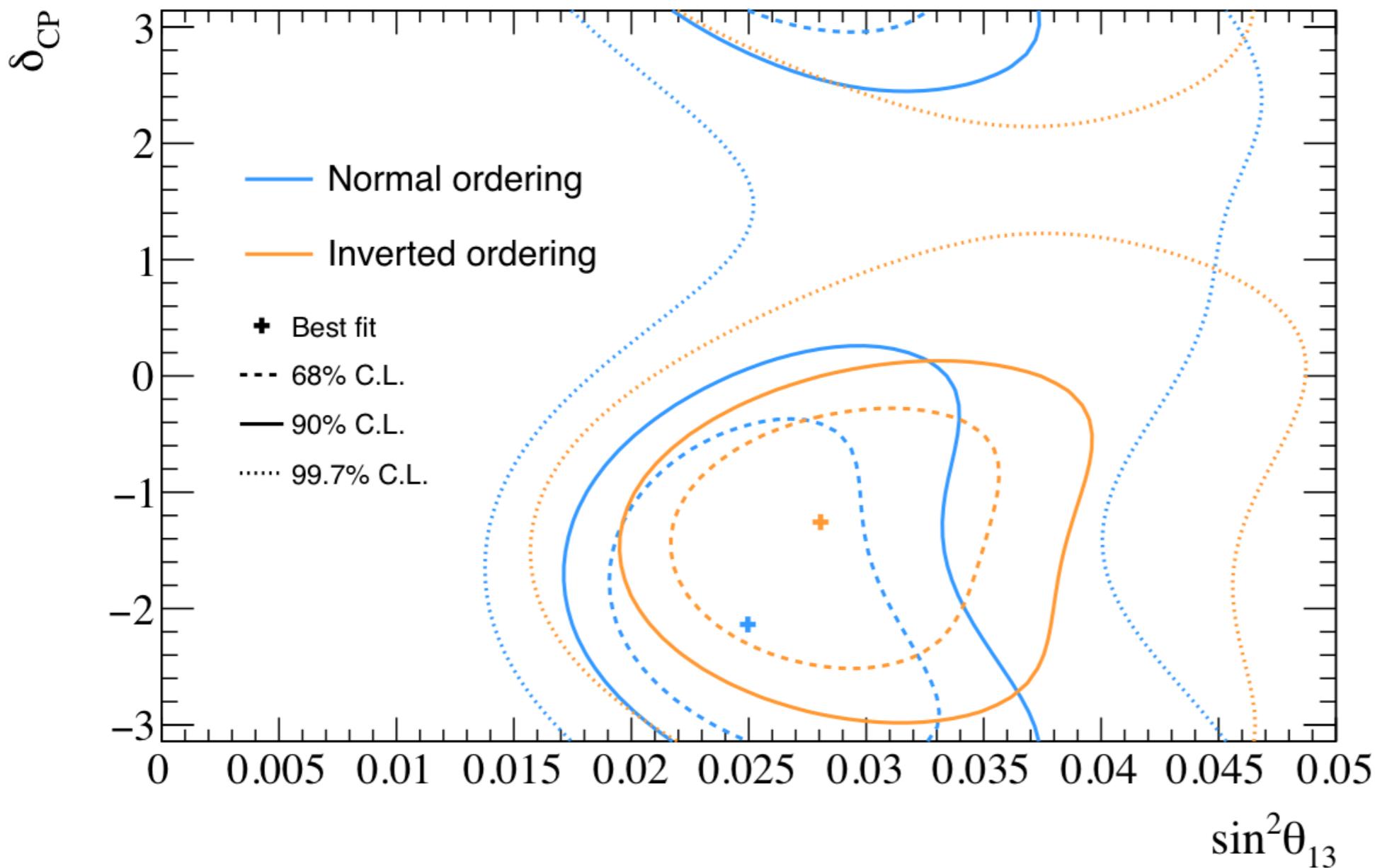
Data currently has an excess of electron neutrino events,

T2K: Window on CPV

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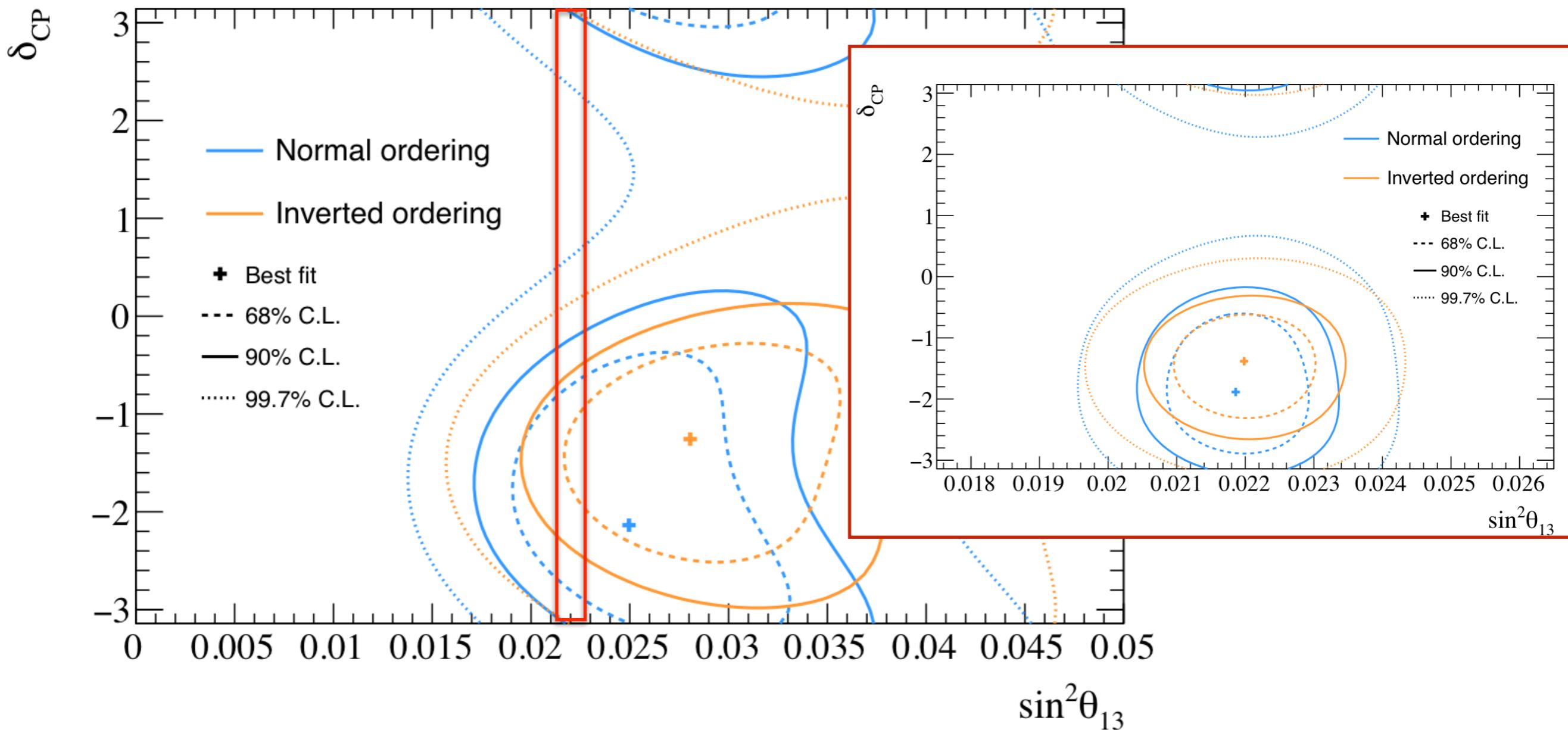
Data currently has an excess of electron neutrino events, and a deficit of electron antineutrino events...

T2K: Window on CPV



*CP phase vs. oscillation
parameter (θ_{13})*

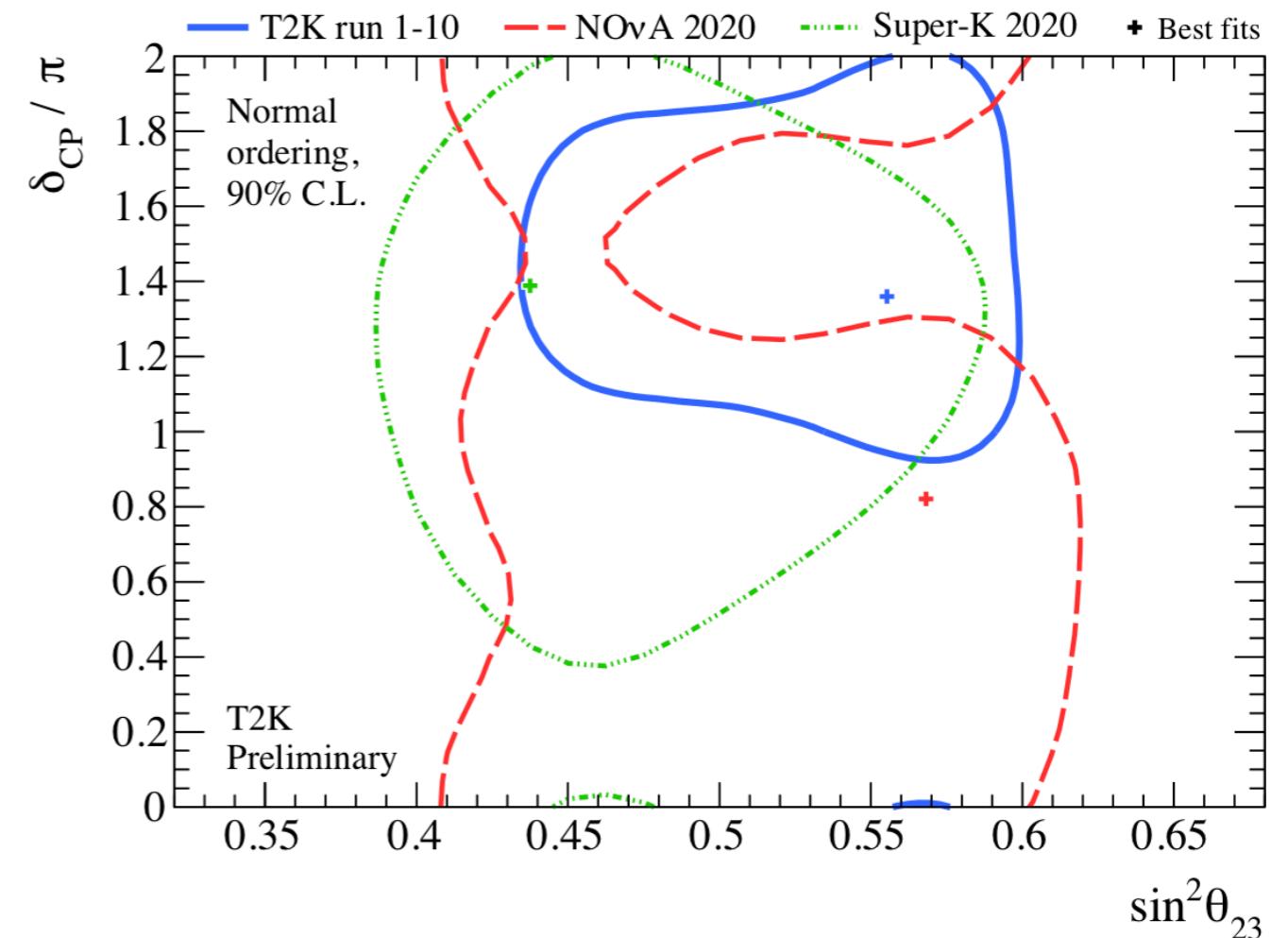
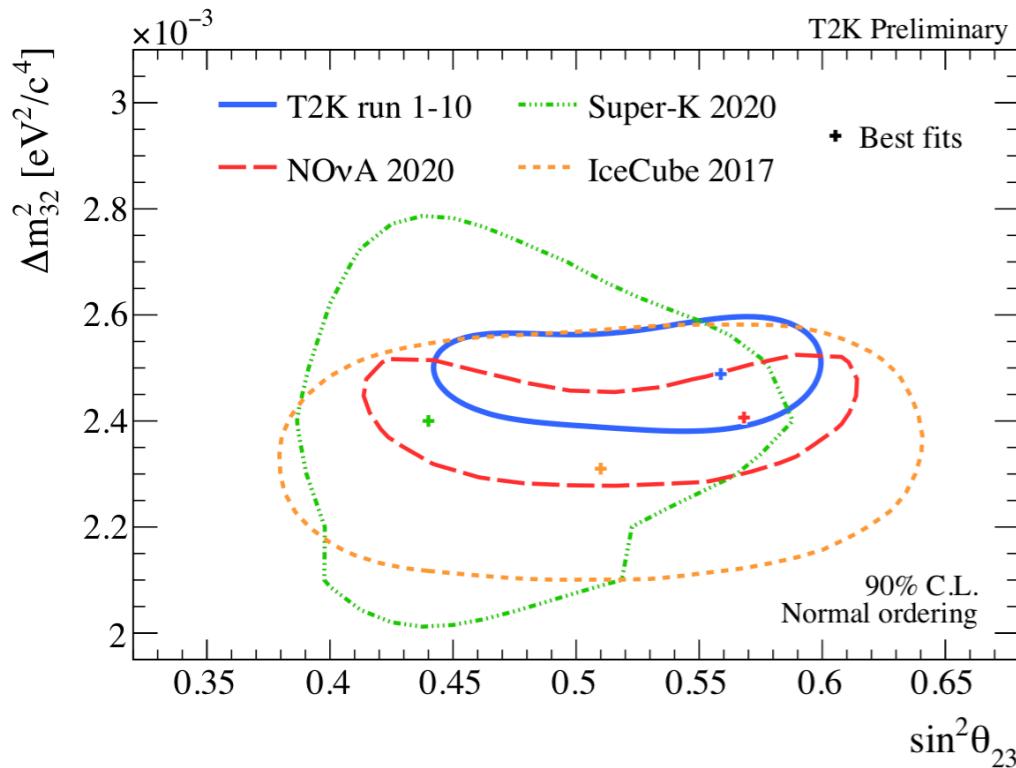
T2K: Window on CPV



Our data is also consistent with independent results (reactor measurements of θ_{13} only)

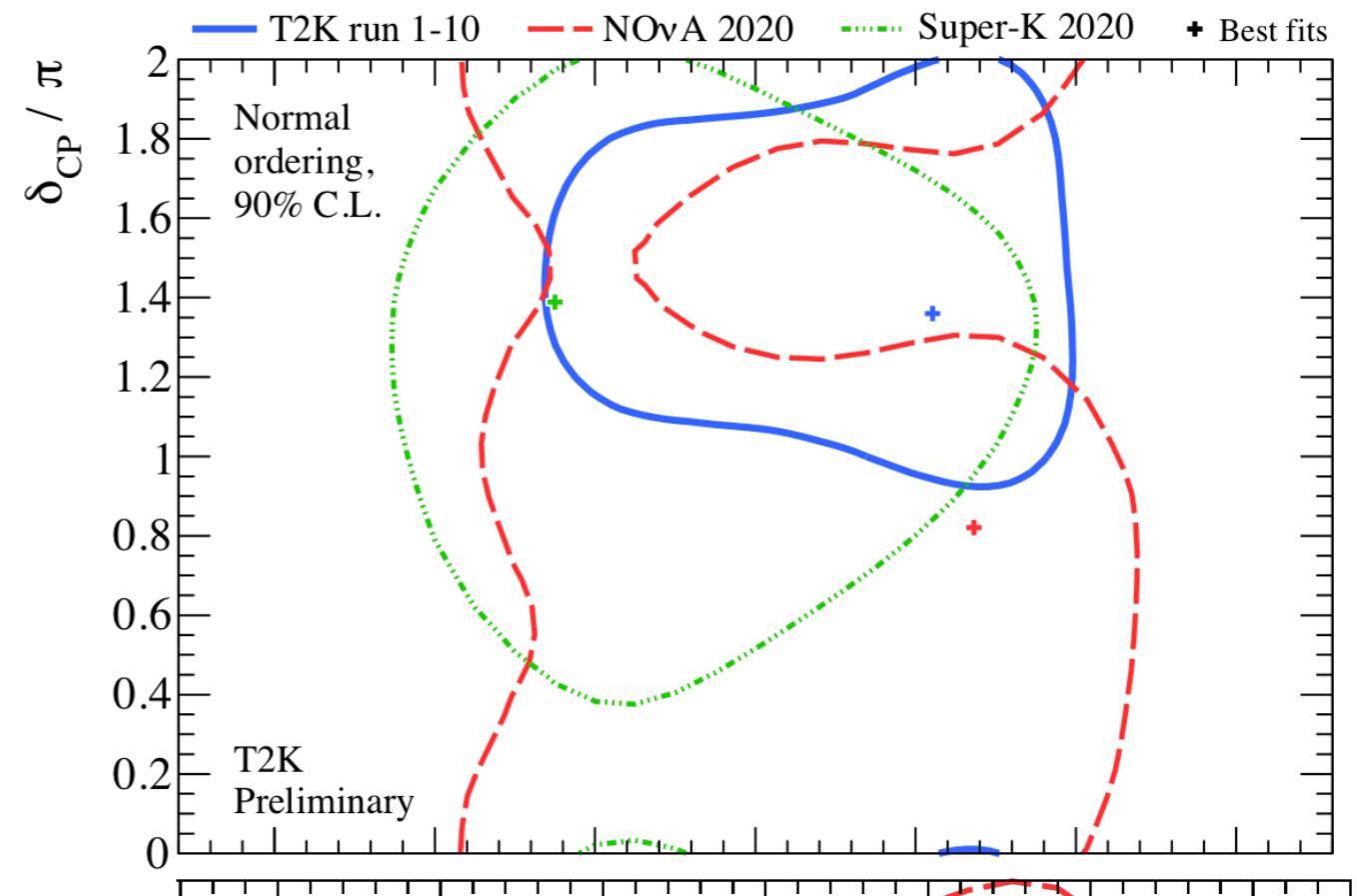
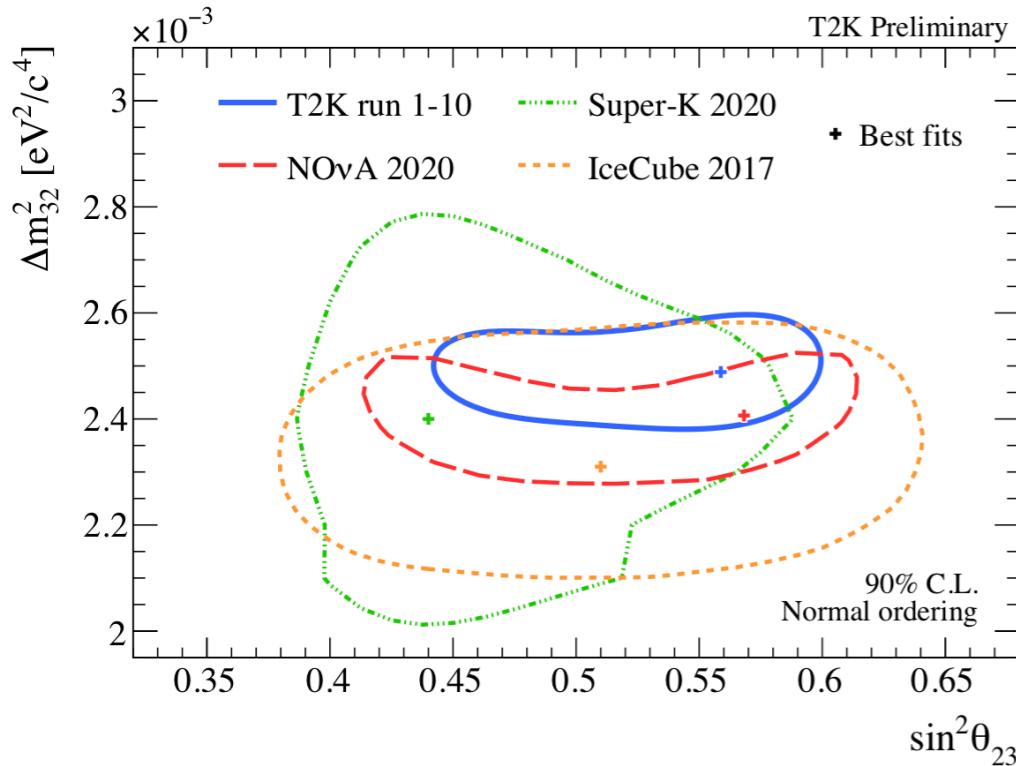
Combined, our data is inconsistent with some values of δ_{CP} - first significant constraint on CP violation in neutrinos

The current global picture, part 2

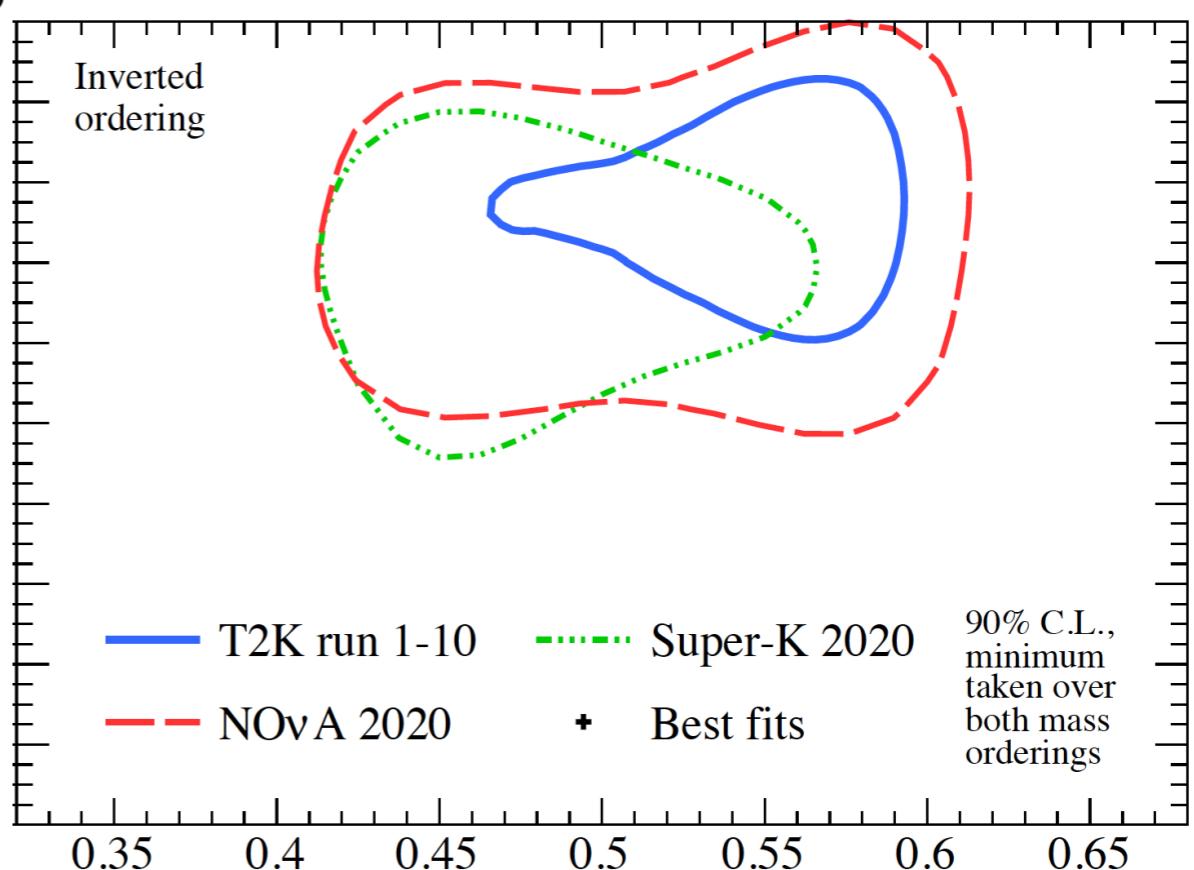


*Projection now in δ_{CP} vs.
 θ_{23} space*

The current global picture, part 2



*Work underway for joint analyses
with Super-Kamiokande and
NOvA experiments*

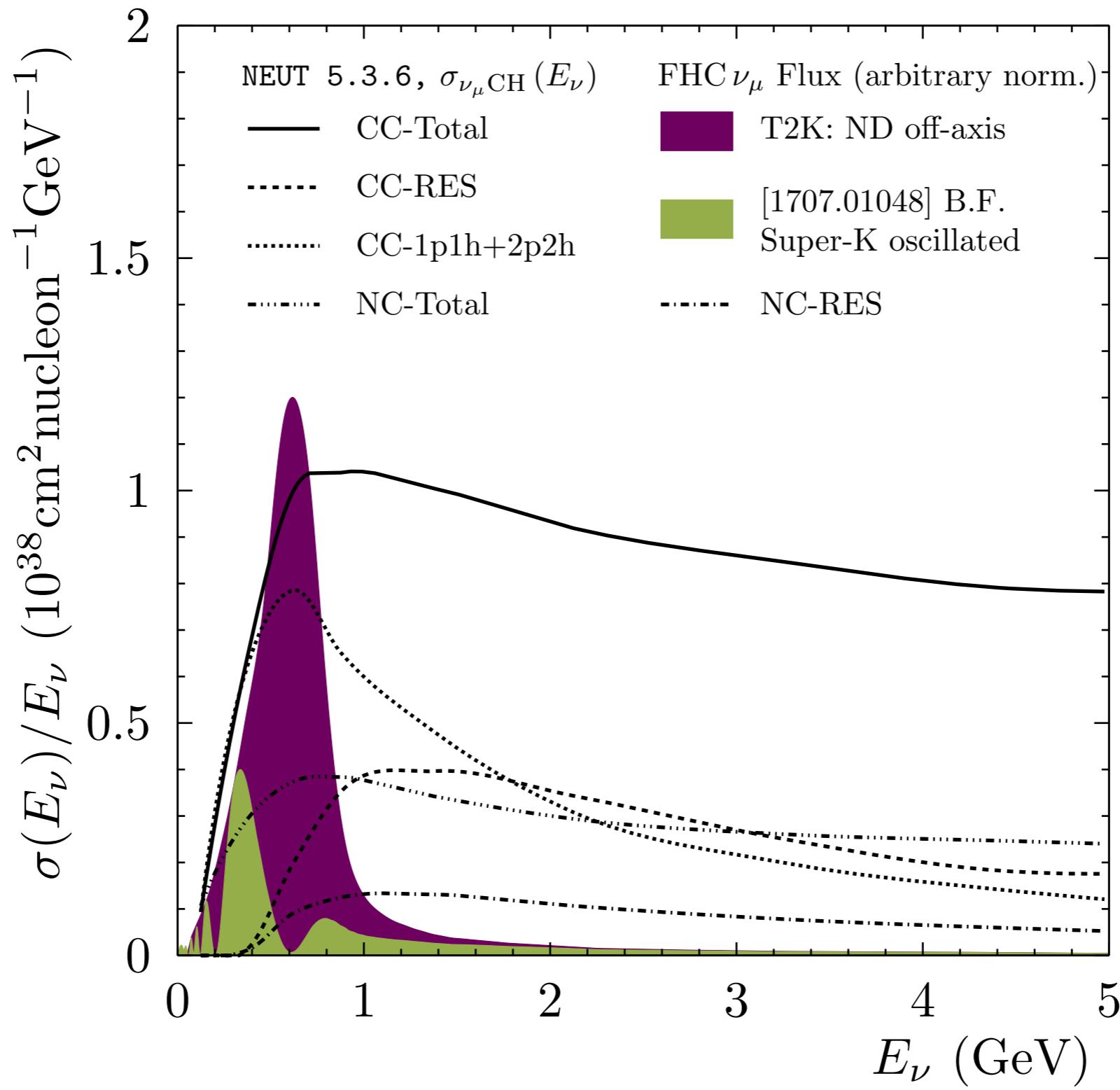




Tokai-to-Kamioka is an accelerator-based neutrino experiment

- Broad physics program includes measurements of $\nu_\mu, \bar{\nu}_\mu$ disappearance, $\nu_e, \bar{\nu}_e$ appearance, exotica and neutrino interactions

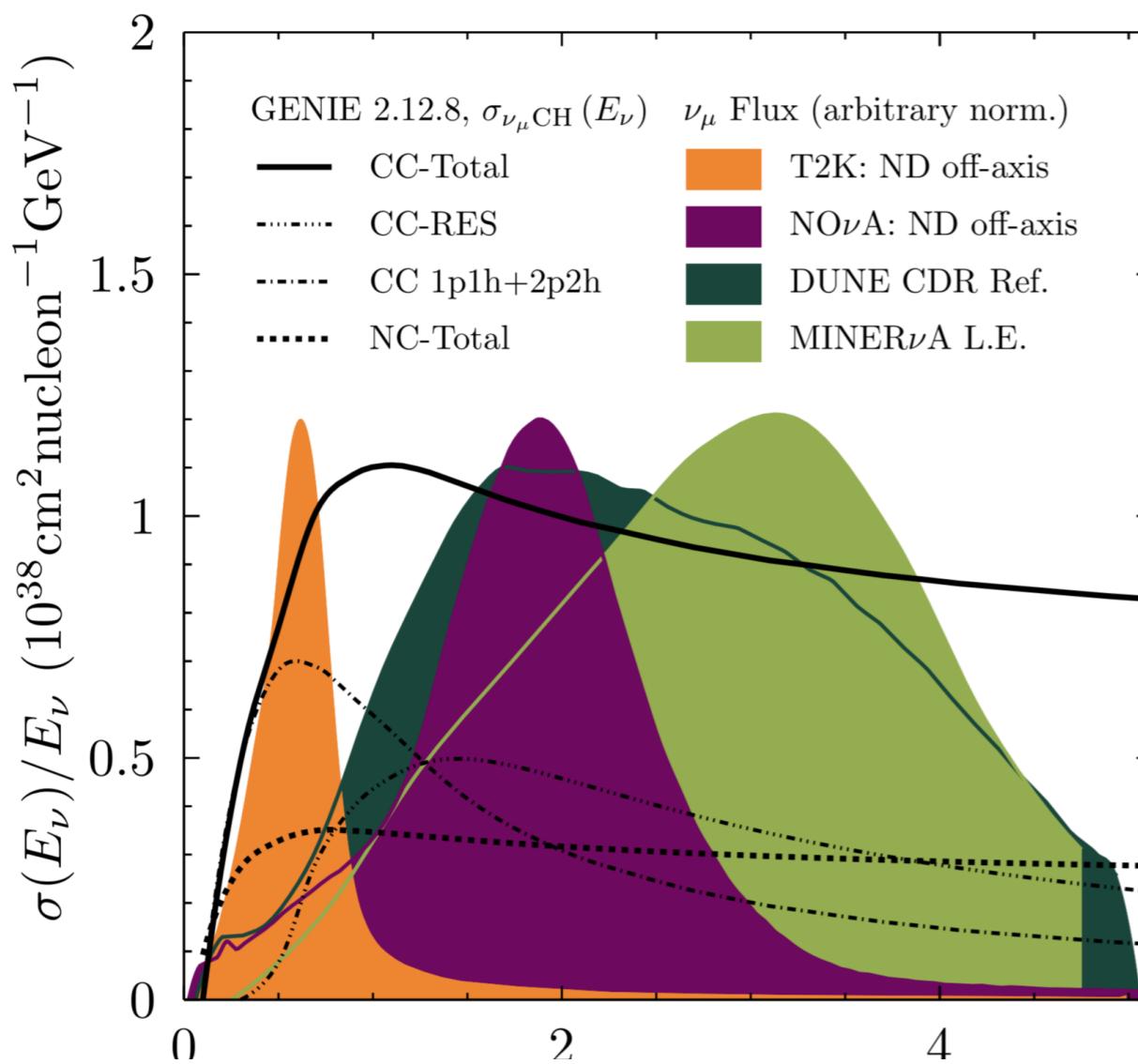
Why neutrino interactions matter *in one slide*



*Integral (**purple** vs. **green**) depends on **modeling** of energy dependance of many processes*

Global program requires multiple measurements

Osc experiment	Target	cross sections from
T2K, NOvA	Scintillator	T2K, NOvA ND, MINERvA LE, HE
T2K, SK, IceCube	Water	T2K (INGRID, WAGASCI, ND280), MINERvA
DUNE	Ar	T2K ND upgrade, MicroBooNE/SBN, MINERvA



Experiments test models using data at different energies and with a range of target material

[See talk on neutrino cross sections by J. Paley]

Cross section results in 2020-2021

First T2K measurement of transverse kinematic imbalance in the muon-neutrino charged-current single π^+ production channel containing at least one proton	<i>PRD</i> 103 (2021) 11, 112009
Measurements of ν_μ and $\bar{\nu}_\mu$ charged-current cross-sections without detected pions or protons on water and hydrocarbon at a mean anti-neutrino energy of 0.86 GeV	<i>PTEP</i> 2021 (2021) 4, 043C01
Simultaneous measurement of the muon neutrino charged-current cross section on oxygen and carbon without pions in the final state at T2K	<i>PRD</i> 101 (2020) 11, 112004
Measurement of the charged-current electron (anti-)neutrino inclusive cross-sections at the T2K off-axis near detector ND280	<i>JHEP</i> 10 (2020) 114
First combined measurement of the muon neutrino and antineutrino charged-current cross section without pions in the final state at T2K	<i>PRD</i> 101 (2020) 11, 112001

T2K exotic physics program

Intense neutrino source x multiple detectors = searches for new physics!

Phys. Rev. D 99, 071103 (2019)

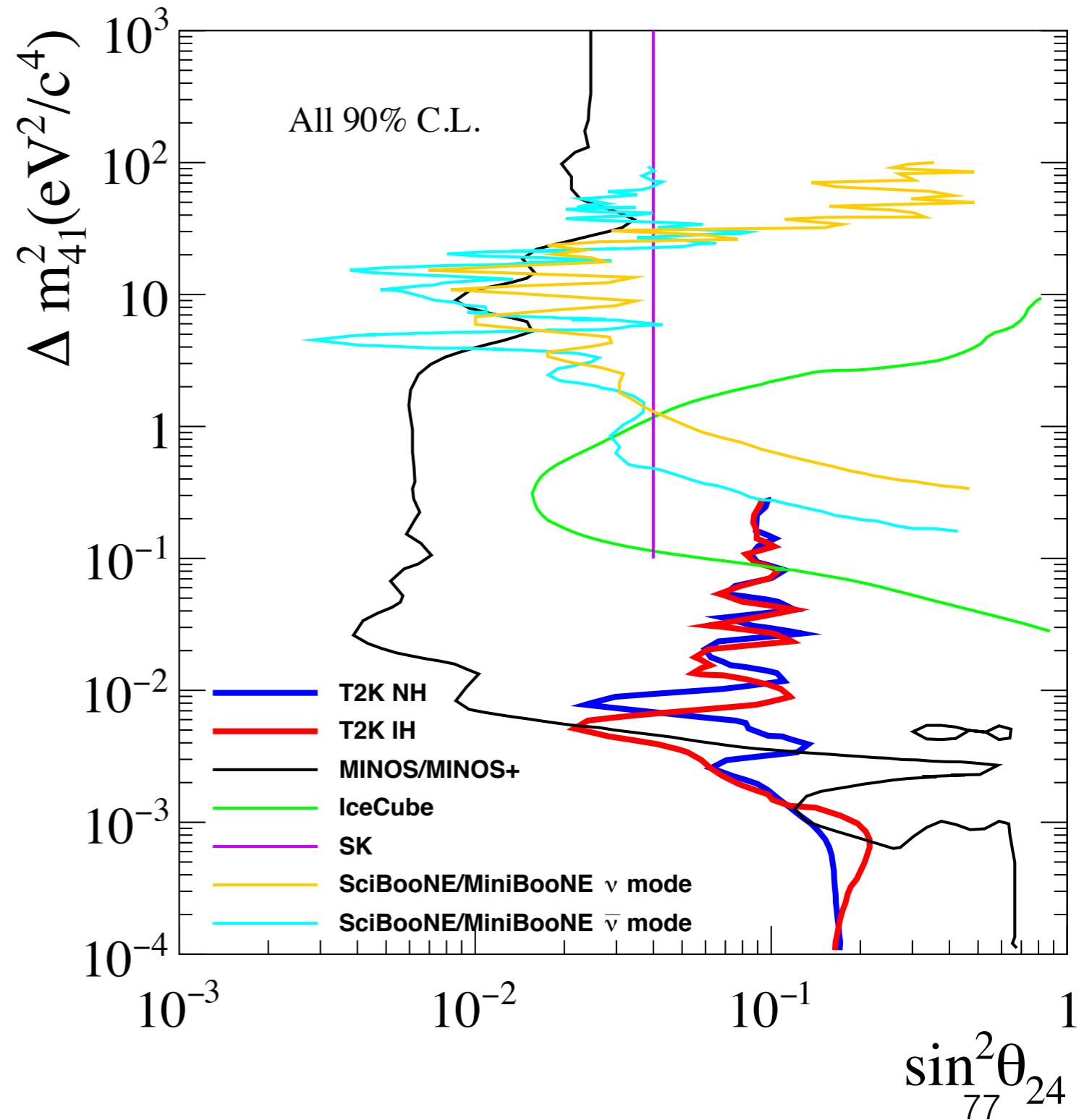
Sterile neutrino oscillation
search $\nu_\mu \rightarrow \nu_s$

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

ν_s

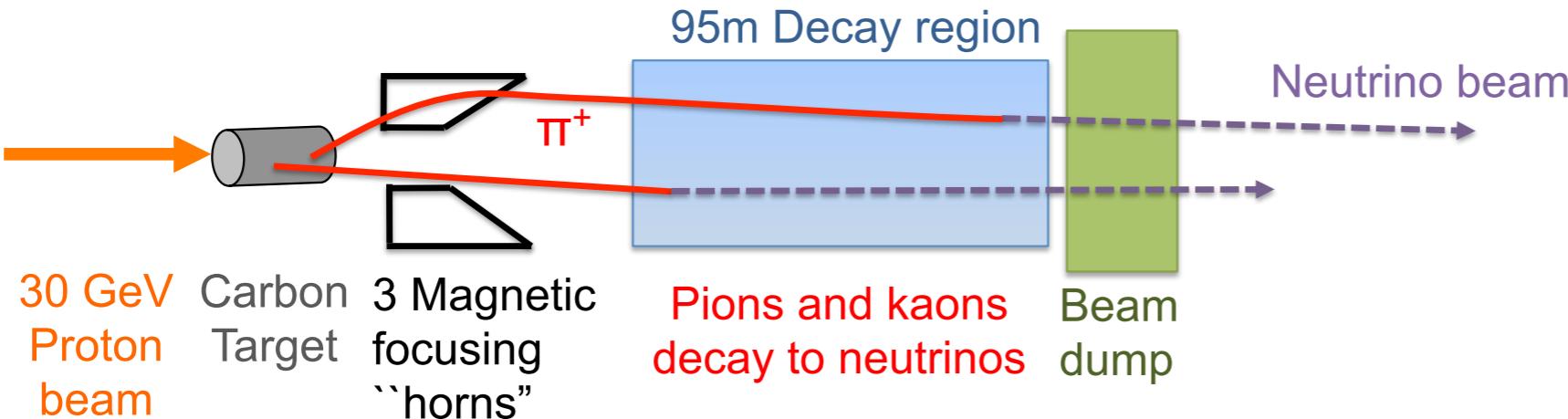
ν_4

[See talk on short baseline
physics by M. Betancourt]



T2K exotic physics program

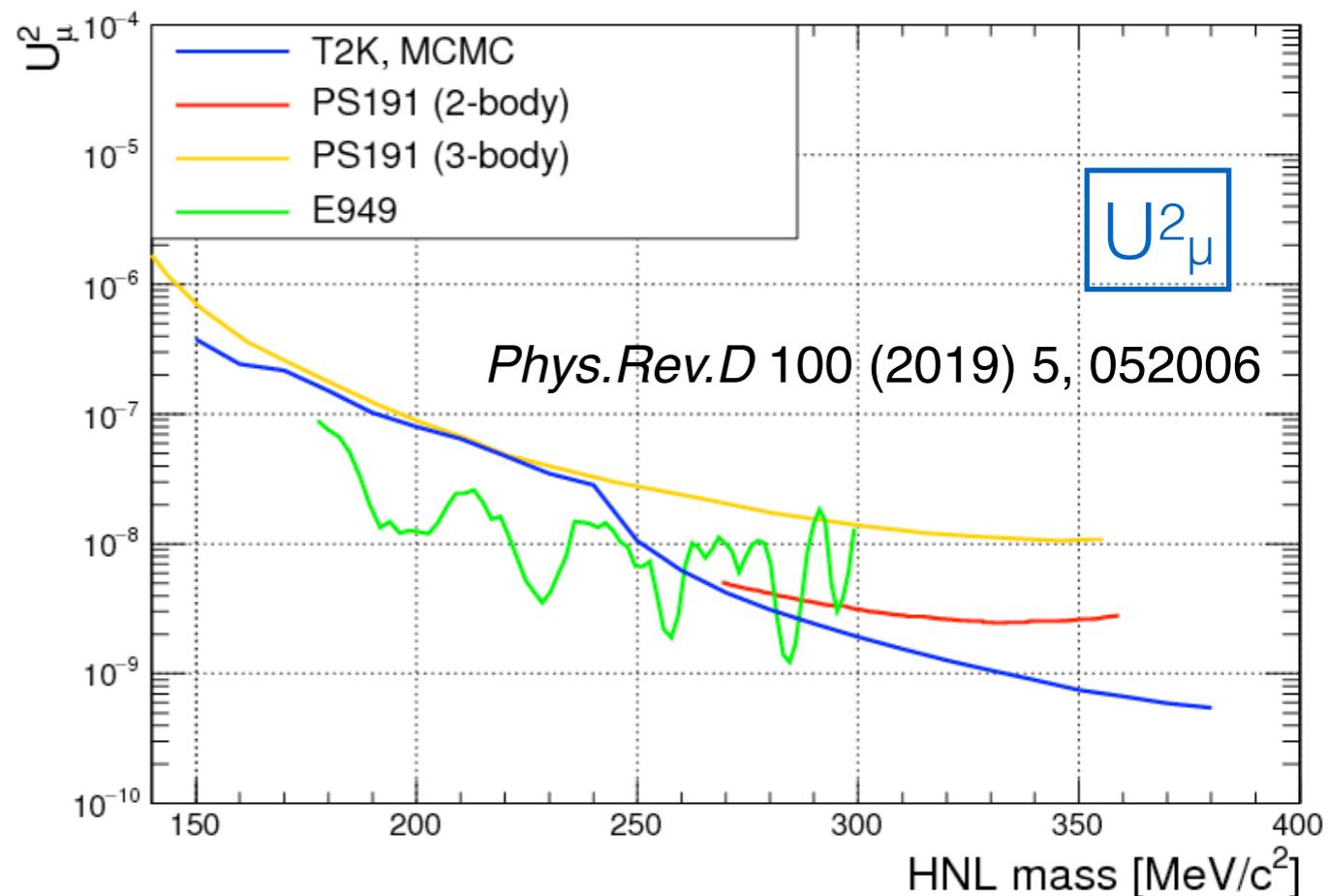
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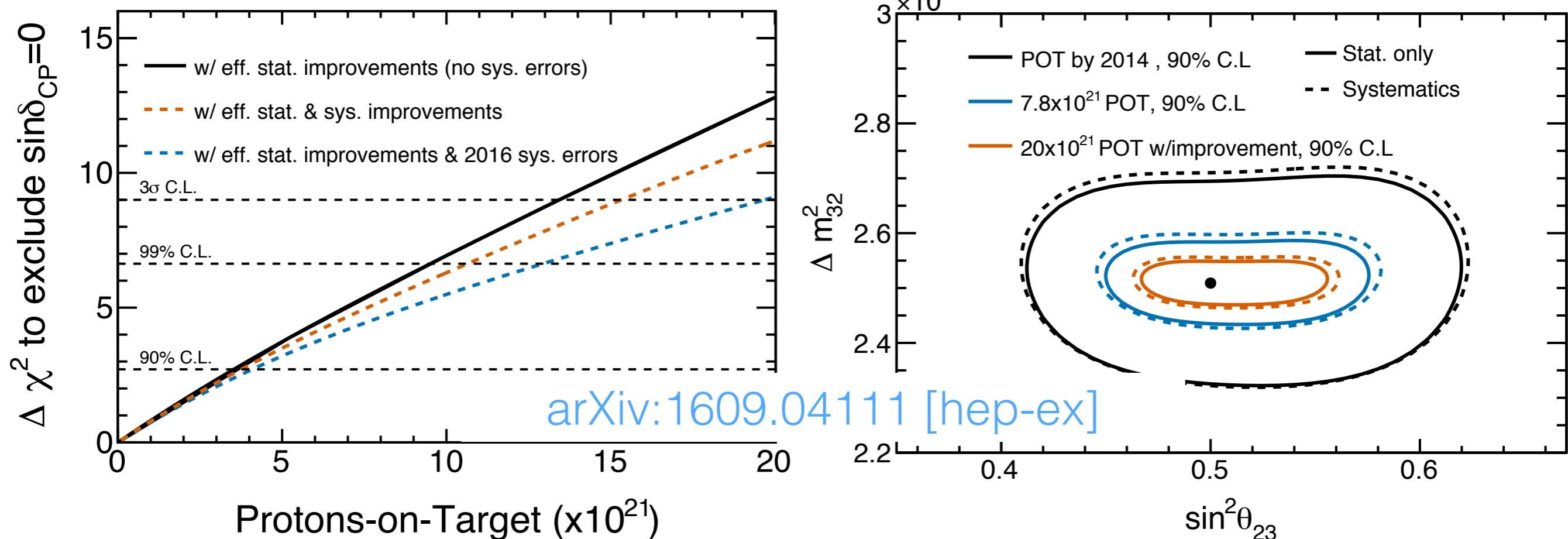
$$K^+ \rightarrow \ell^+ N \quad N \rightarrow \ell^\pm \pi^\mp, \ell^\pm \ell^\mp \nu$$

Production of heavy neutral leptons (N) from kaon decay

- Uses large volume, low mass TPCs for signal selection
- Best high-mass limits on coupling to N to μ , e

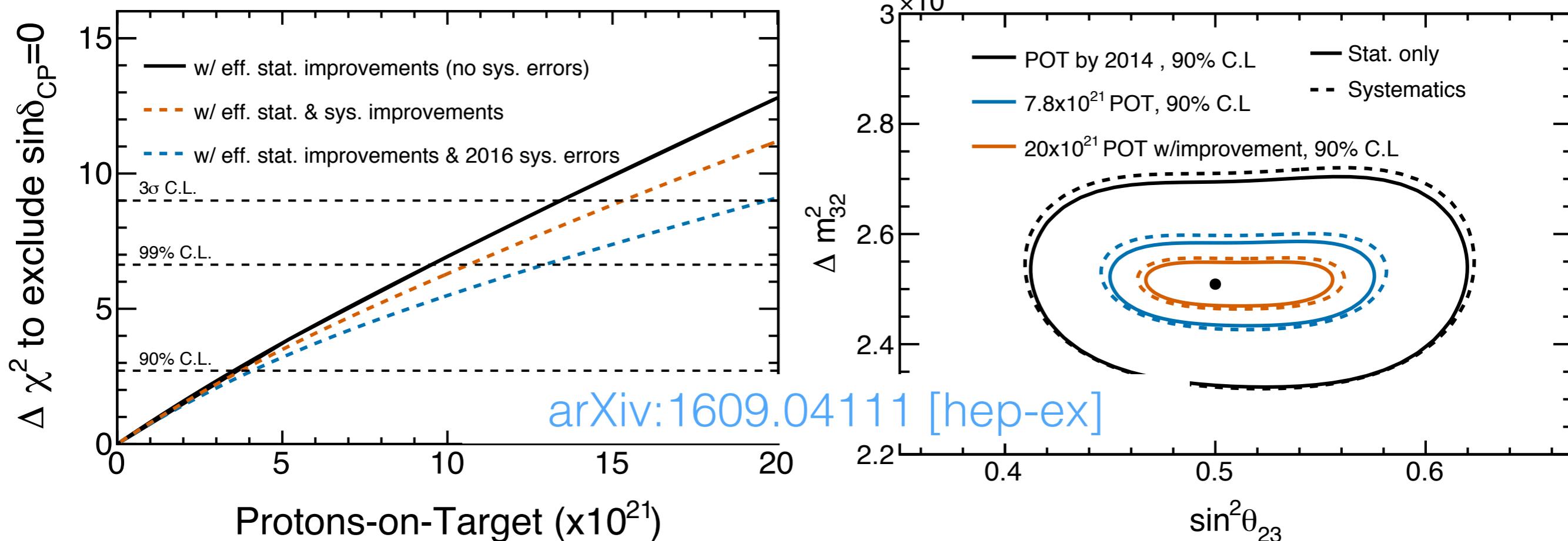


Continued run of T2K



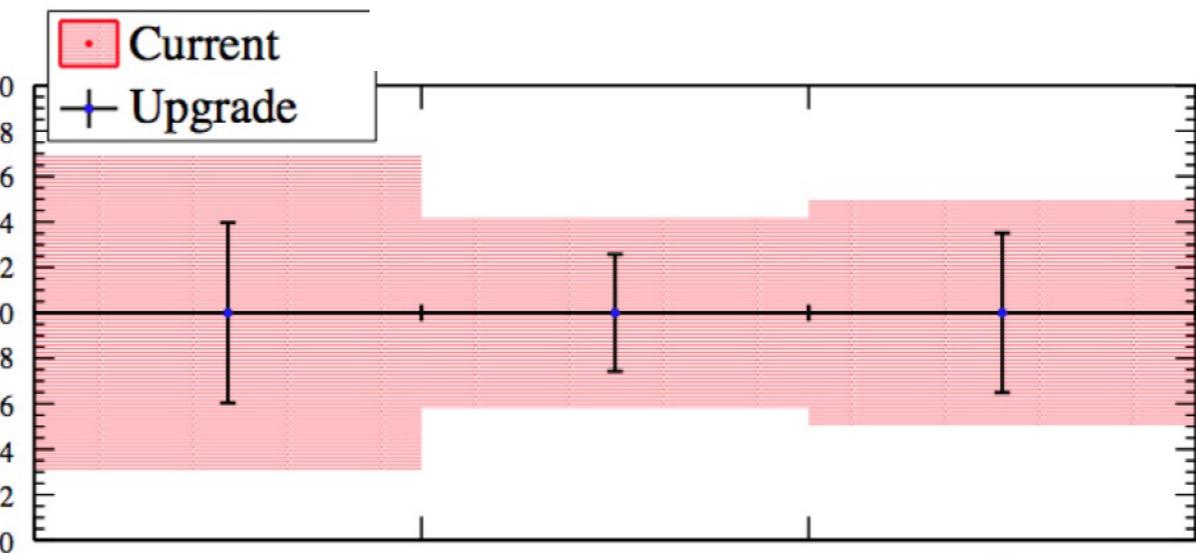
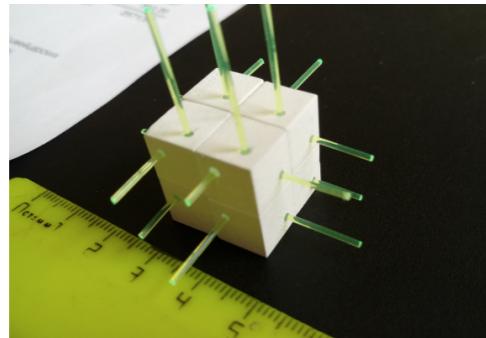
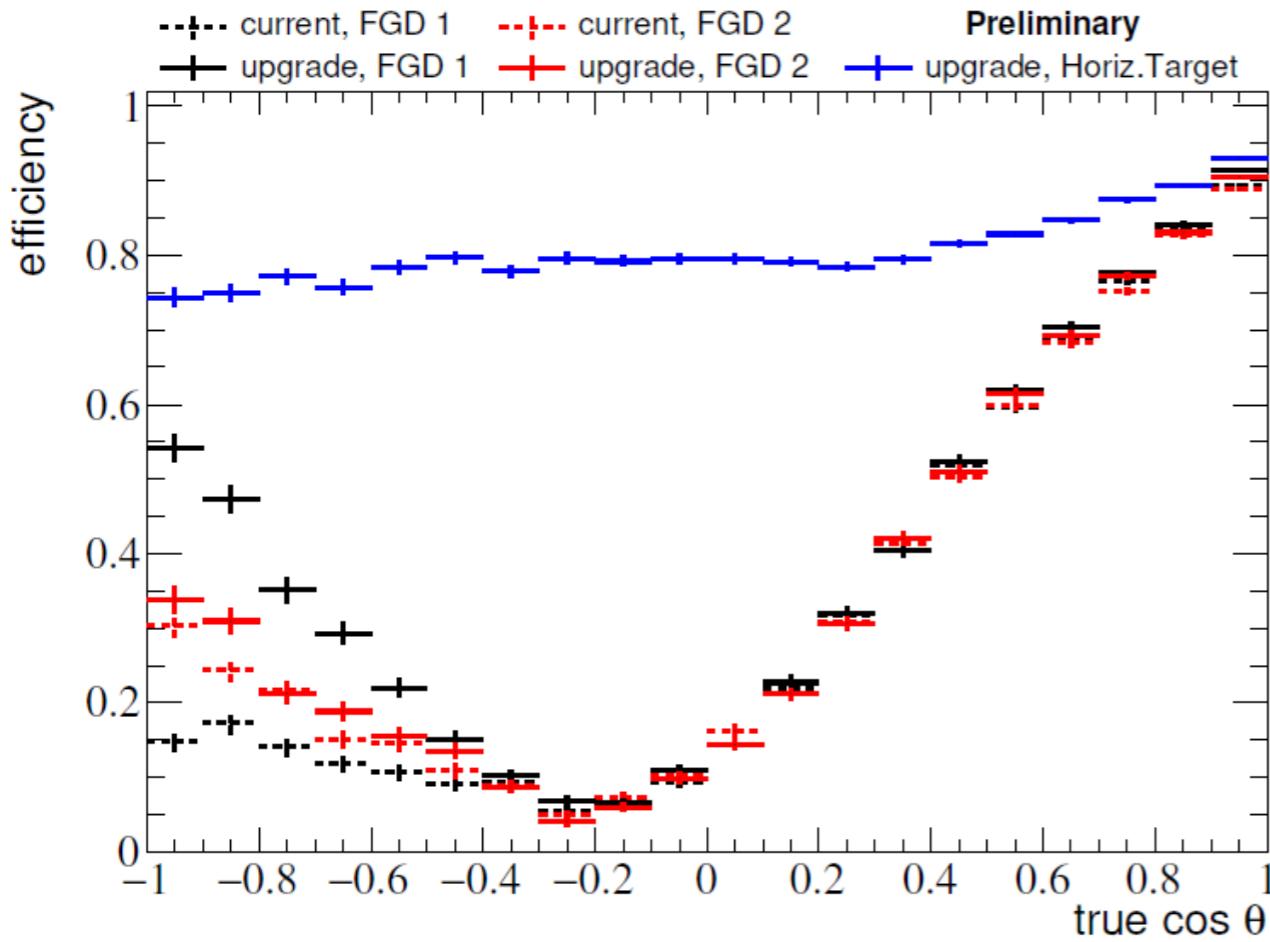
- Plan to collect at least 10×10^{21} POT by ~2026
- Accelerator upgrade (to 1.3 MW)
 - 50% effective statistical gain from operational and systematic improvements (30% achieved)

Continued run of T2K

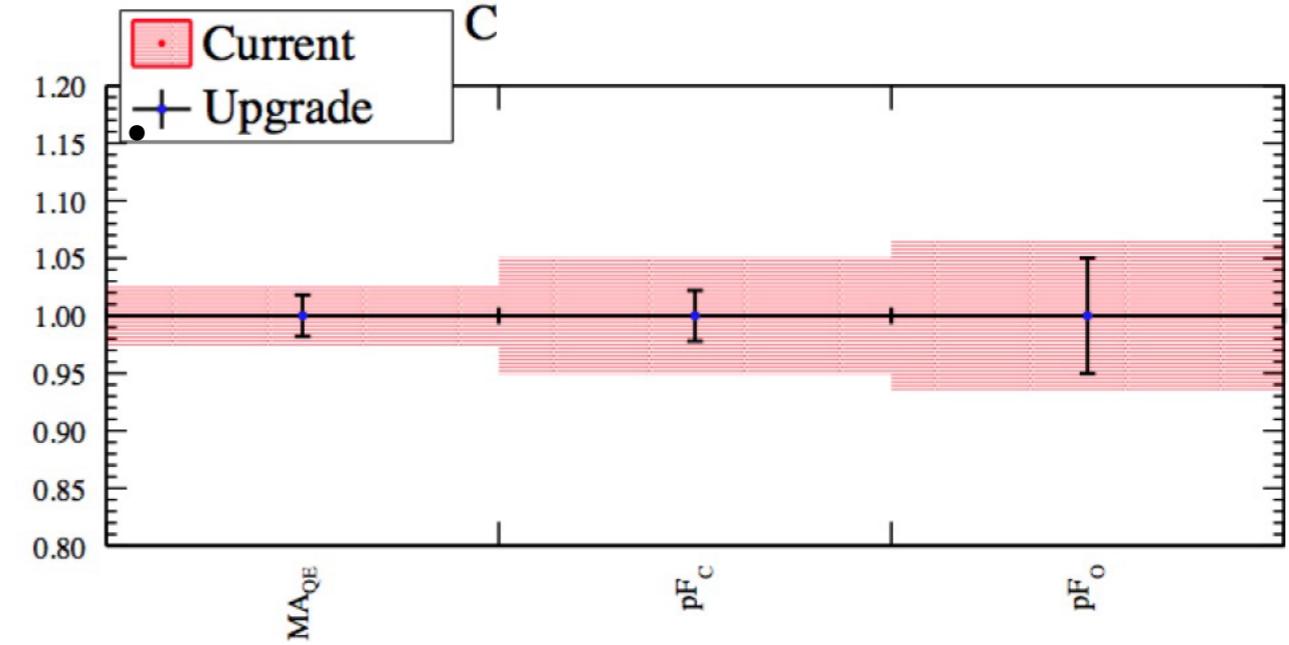


- Plan to collect at least 10×10^{21} POT by ~2026
- Accelerator upgrade (to 1.3 MW)
 - 50% effective statistical gain from operational and systematic improvements (30% achieved)
- **Upgrade to T2K beam line and near detectors (“ND upgrade”); incorporation of WAGASCI+ BabyMind into T2K**

Prospects for T2K: ND upgrade



CCQE model parameters



- ND upgrade will have improved acceptance compared to ND280
- Improved constraint of cross section models within oscillation analysis; improved statistics at high angle for cross section measurements

Summary

- T2K makes measurements of neutrino oscillation which have unique physics coverage with respect to, and complementary to, other experimental probes
 - Results presented for 2020 dataset, joint analyses ongoing
 - Improvements to the analysis and experimental set up underway
- T2K makes valuable measurements of neutrino interactions, and searches of exotic physics

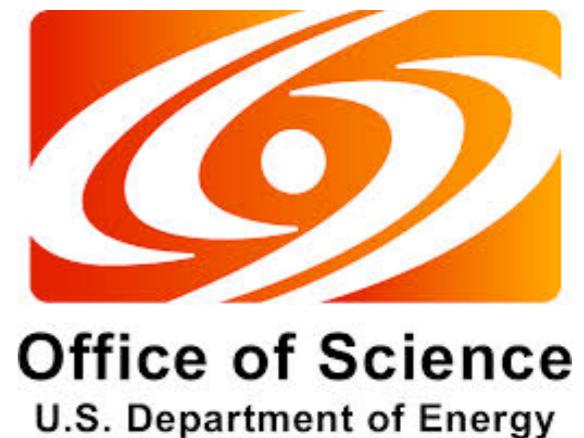
Thank you for the invitation to speak today!

I'm sorry I couldn't be there in person.



Support from:

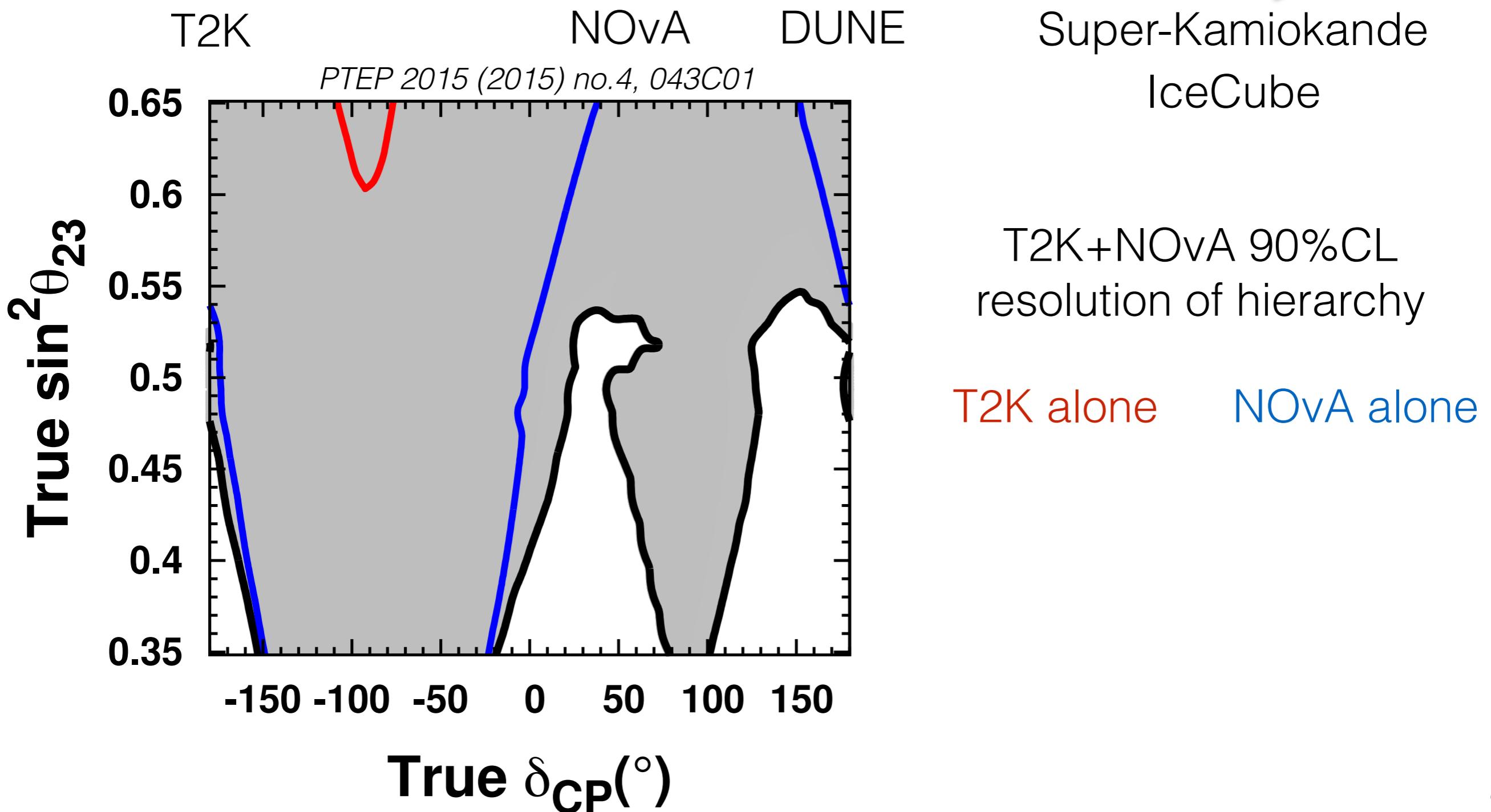
Department of Energy
award *DE-SC0015903, DUNE*
project



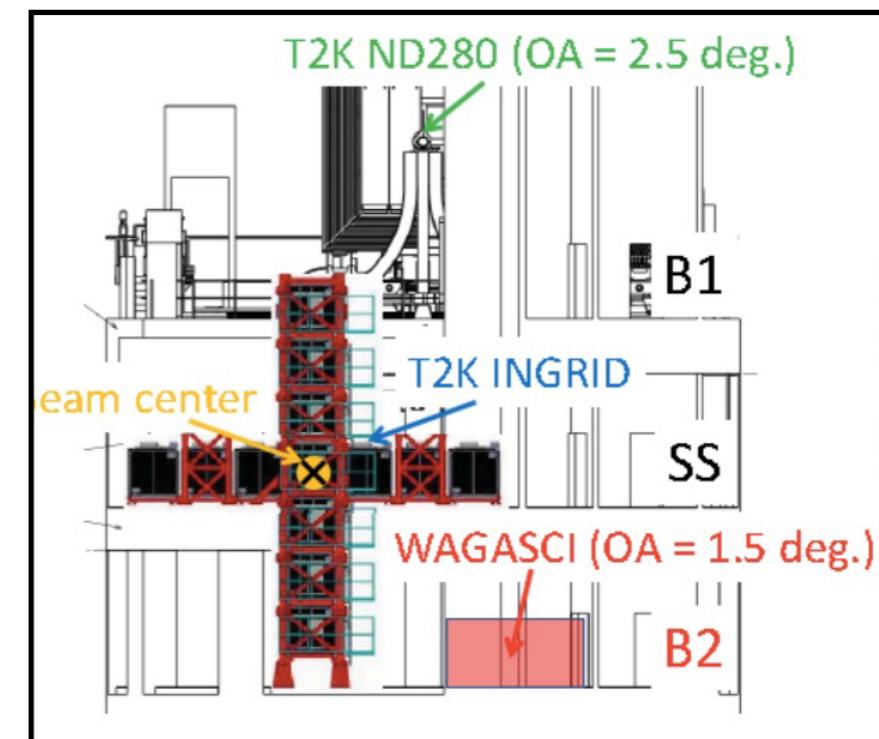
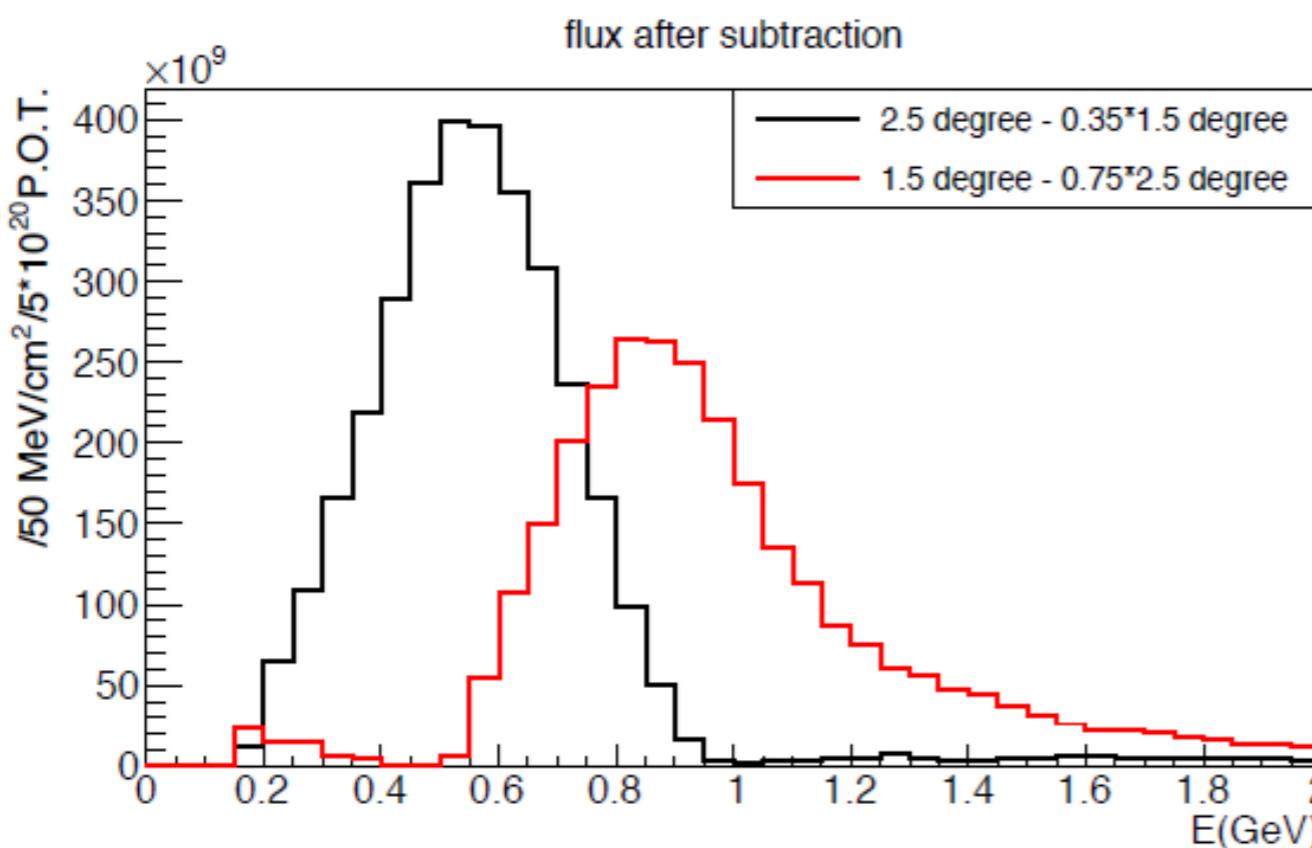
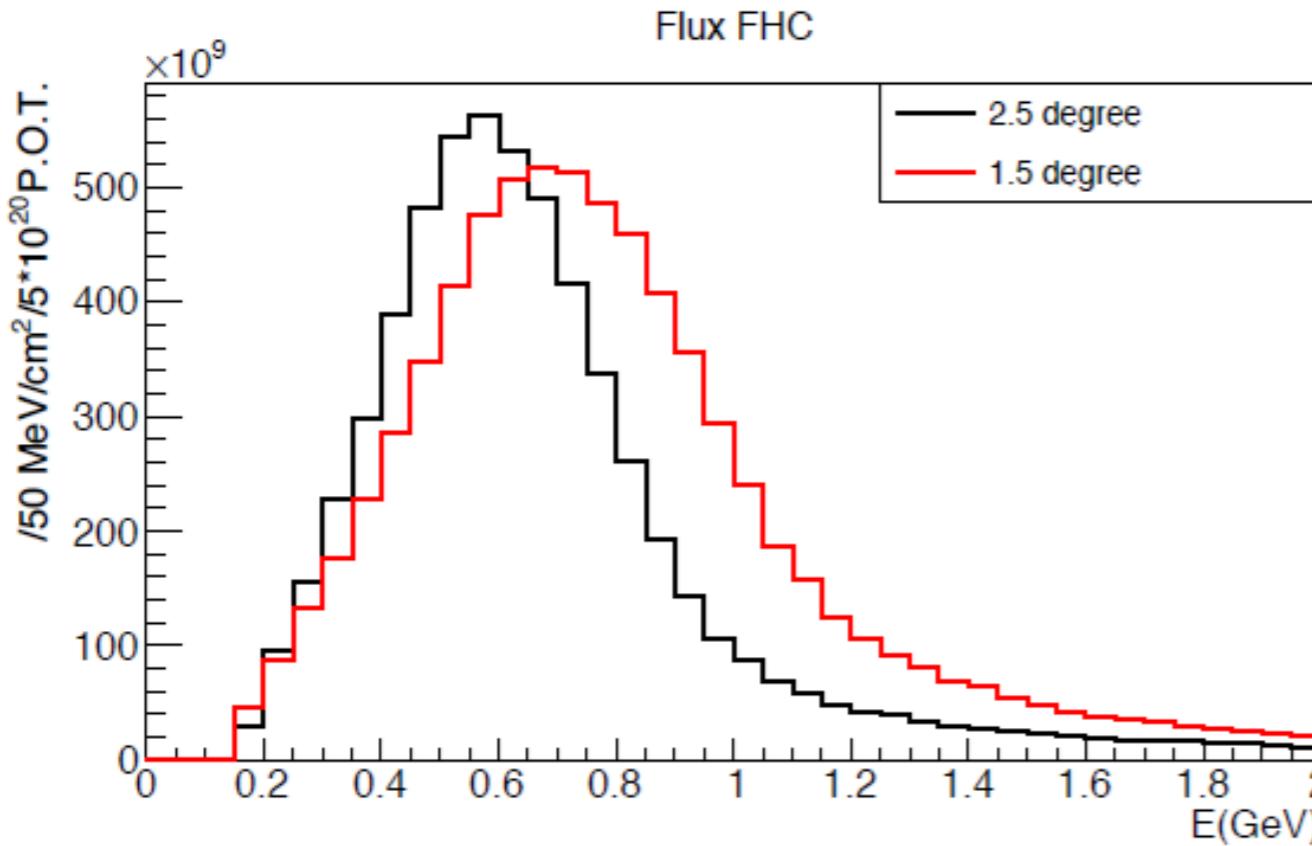
Backup

Complementary window: Matter effects

Strength of matter effect



Prospects for T2K: WAGASCI+BabyMIND



- WAGASCI+BabyMIND adds another off-axis point (1.5 deg) for water target
- Sign selection for neutrino, antineutrino separation

Maximum benefit to T2K for model independent selection and extraction machinery; differential measurements

T2K oscillation analysis strategy

$\Delta m^2_{32}, \theta_{13}, \theta_{23}, \delta_{CP}$, mass hierarchy

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Flux (Φ)

Interaction model (cross between truth and section, σ)

Relationship

Efficiency (ϵ)

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