Results from T2K and the current landscape of neutrino oscillation

National Autonomous
University of Mexico
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for the T2K collaboration

Outline

Why are neutrinos interesting to study? Why is neutrino oscillation important?

Recent results from the Tokai-to-Kamioka (T2K) neutrino oscillation experiment

What is the future of accelerator-based oscillation experiments?

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

Feedback? Comments? *mahn@msu.edu*

Outline

Why are neutrinos interesting to study? Why is neutrino oscillation important?

All about neutrinos

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

All about neutrinos

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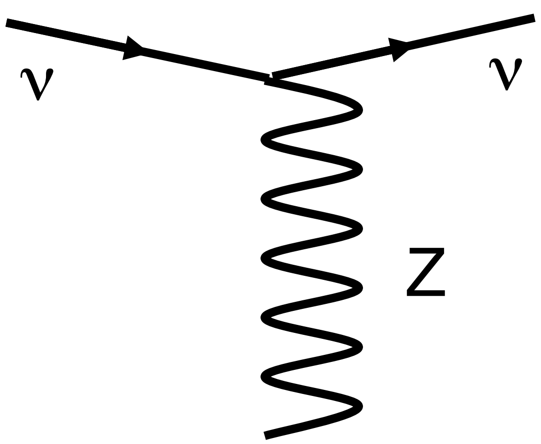
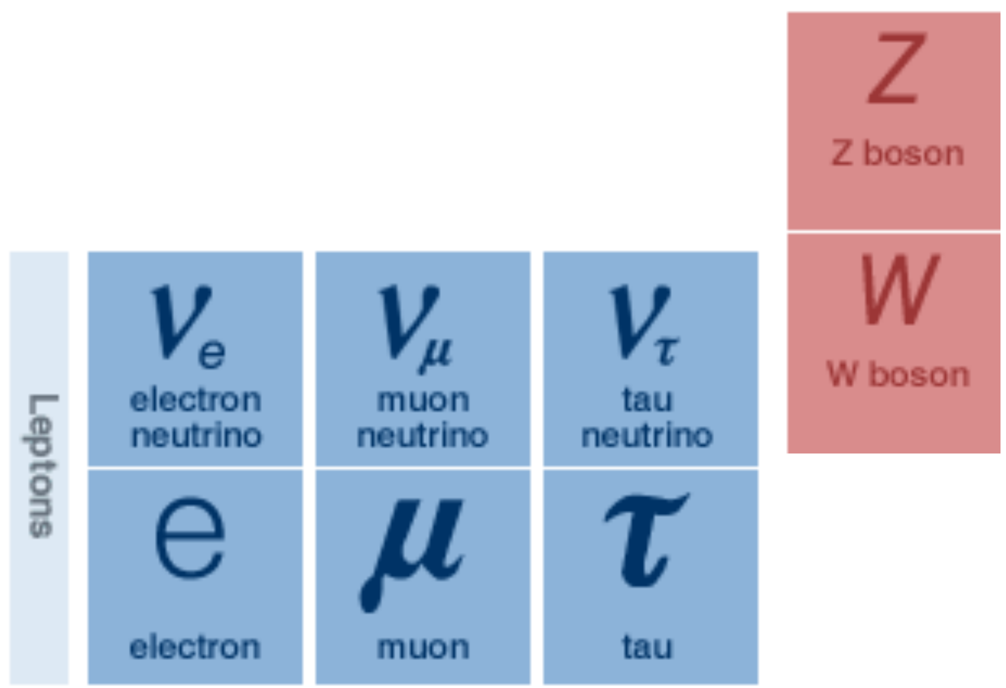
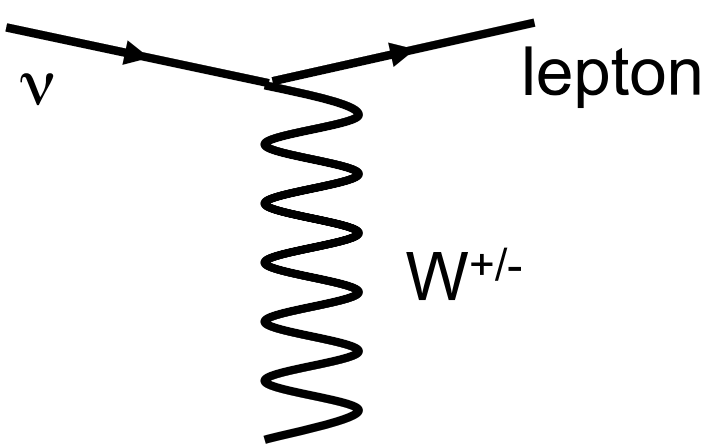
- Interact via the weak force

Neutral Current (NC)





Charged Current (CC)



$$\nu_e \longrightarrow e$$

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

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

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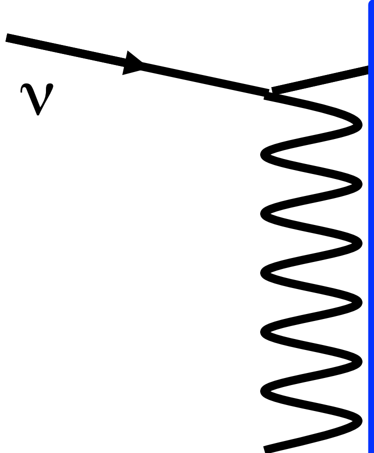
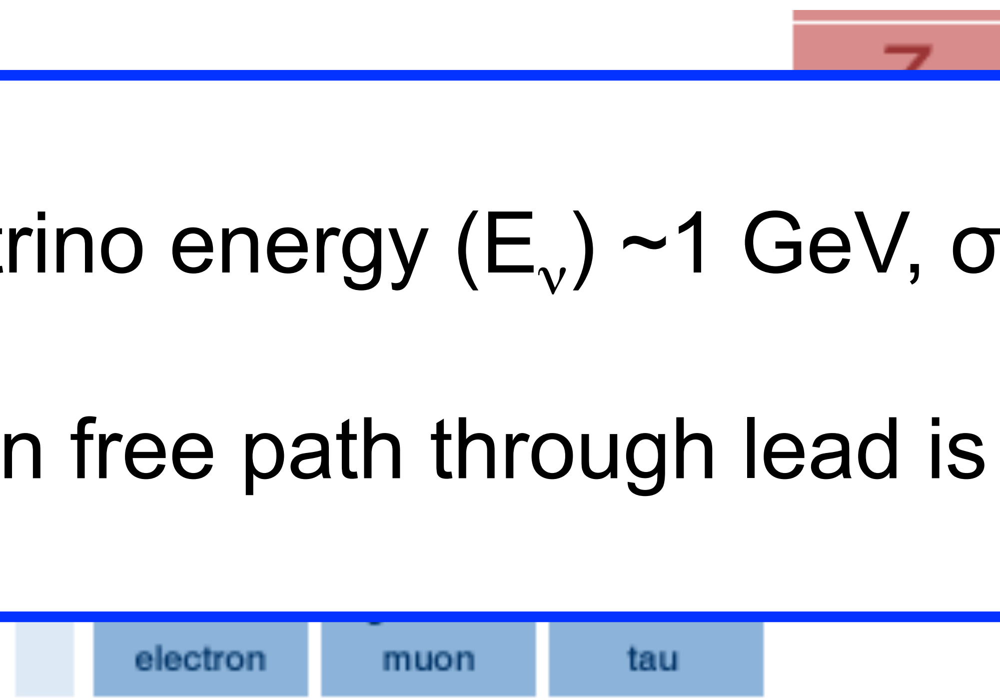
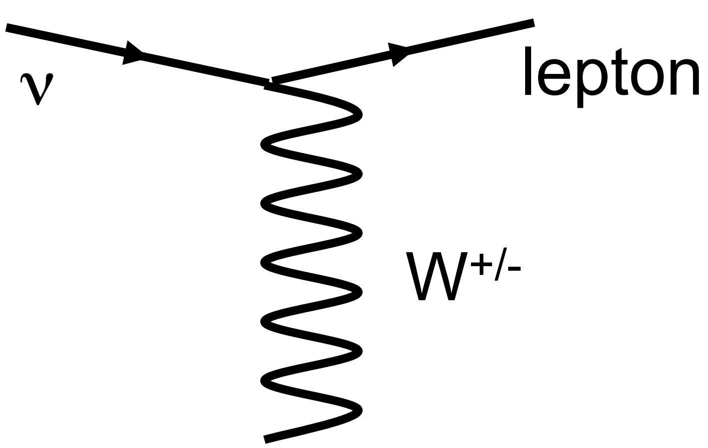




At neutrino energy (E_ν) ~1 GeV, σ_{CC} ~ 10^{-38} cm^2

Mean free path through lead is 1 light year

Charged Current (CC)



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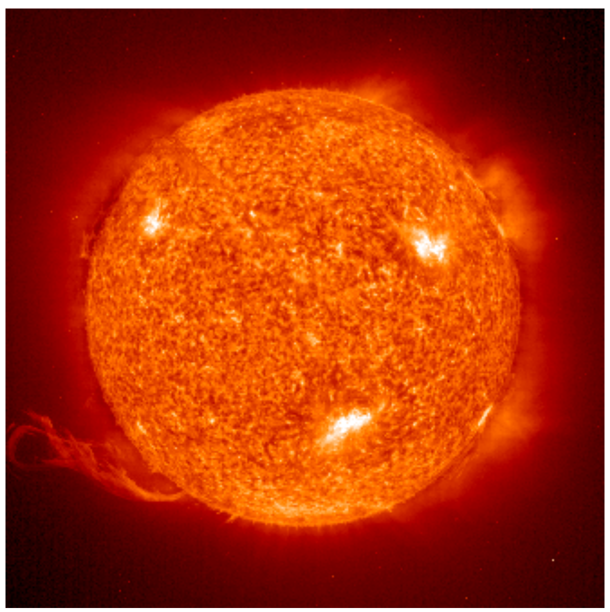

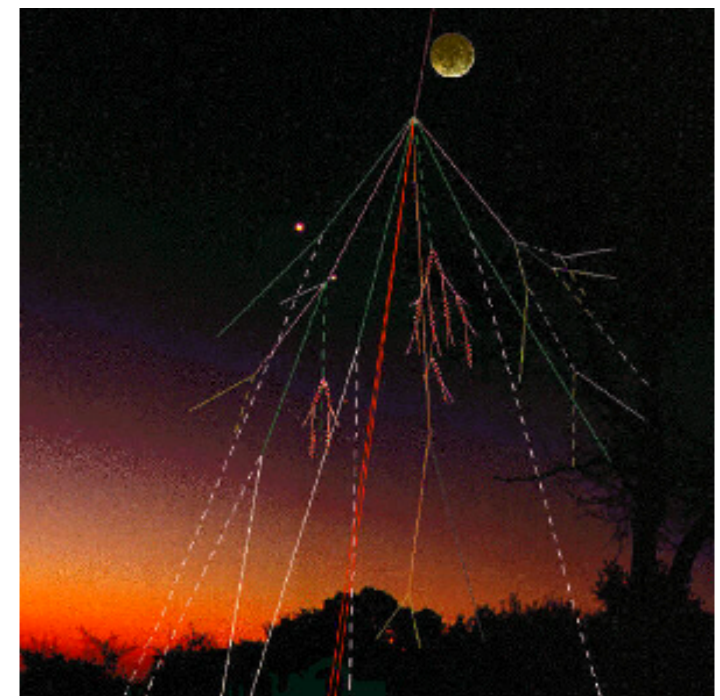
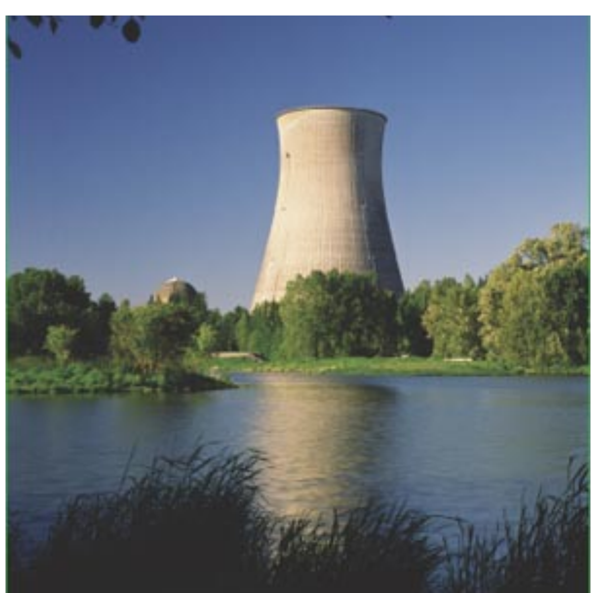

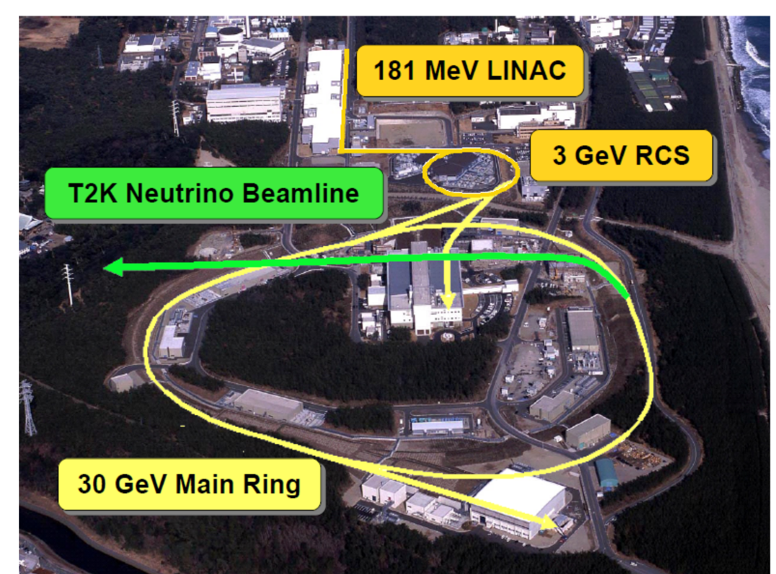

All about neutrinos

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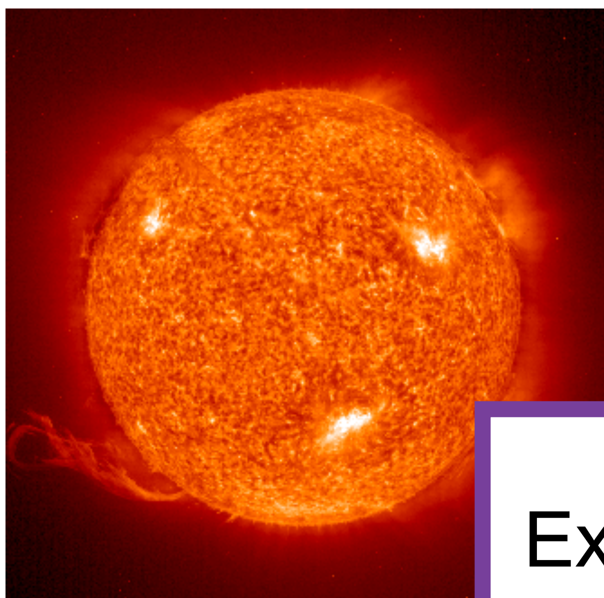
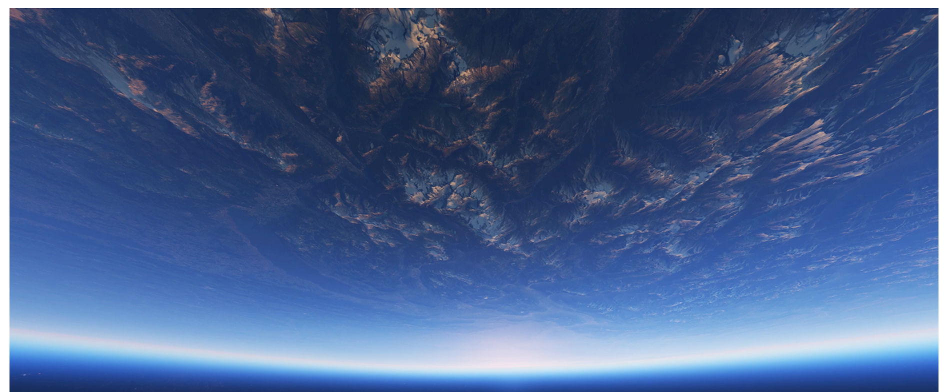
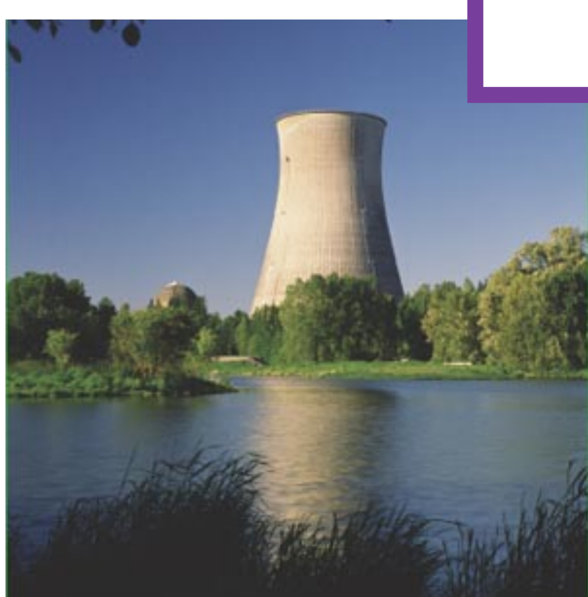
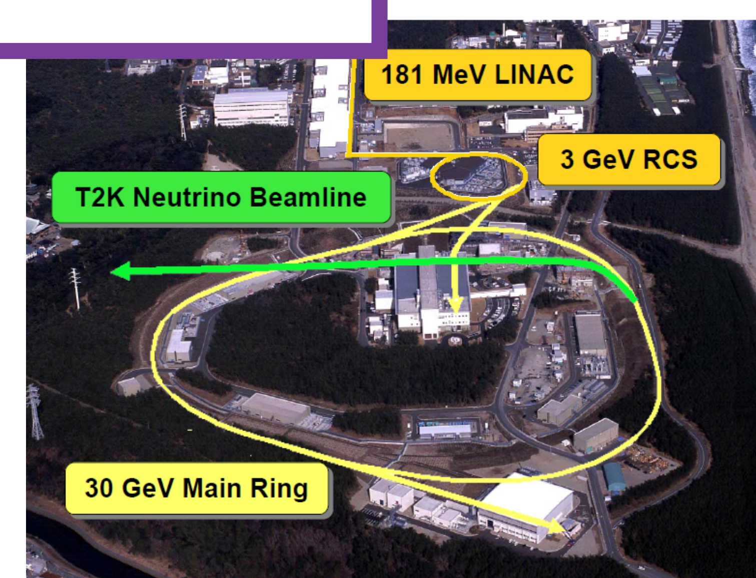




Except for the photon, neutrinos are the most plentiful particle in the universe

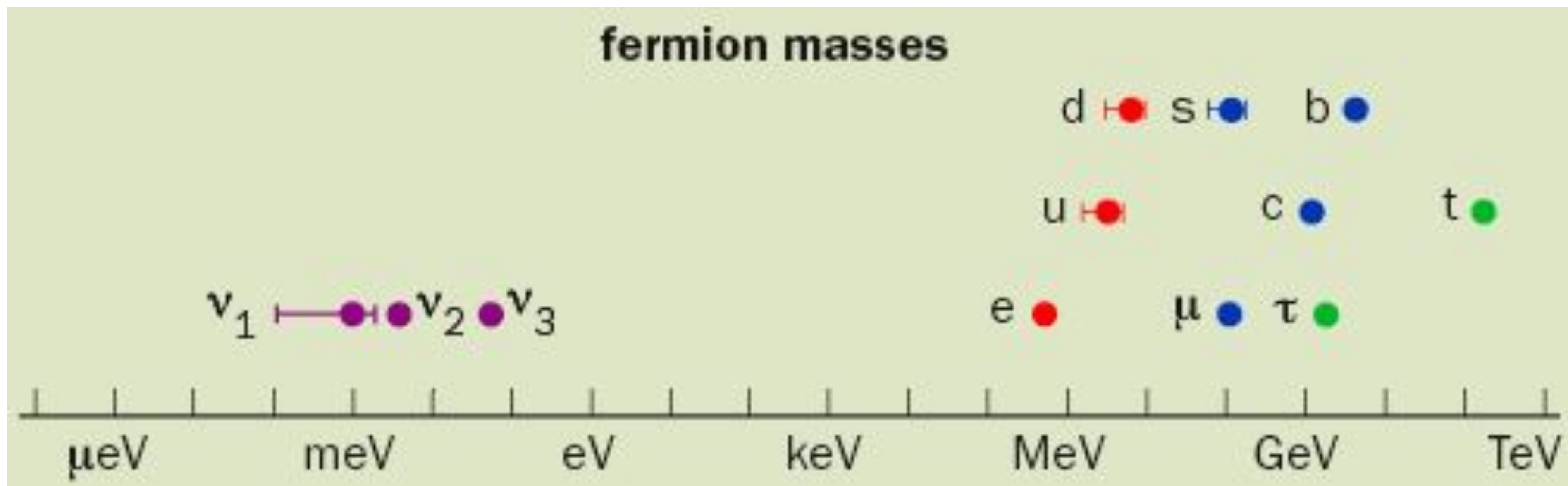




All about neutrinos

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

Credit: H. Murayama



Neutrino mass is very small compared to other leptons

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

Credit: wikicommons

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:

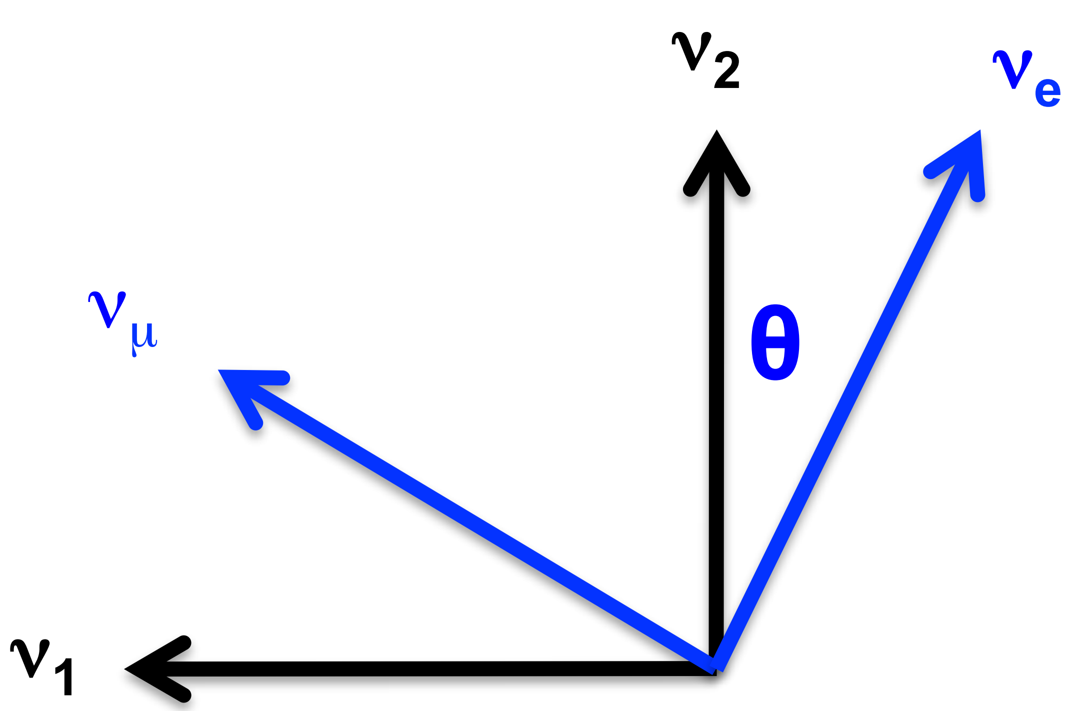
a green jelly bean (ν_e / lime)

or a yellow jelly bean (ν_μ / lemon)

or a blue jelly bean (ν_τ / berry)

Neutrino oscillation with two flavors

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



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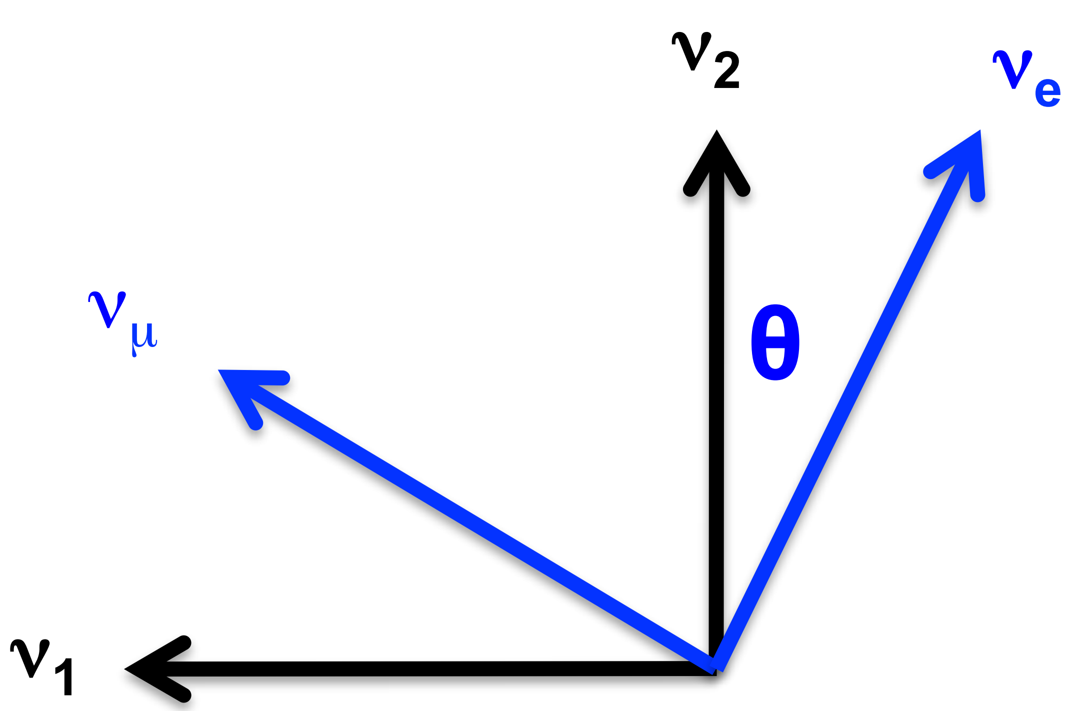
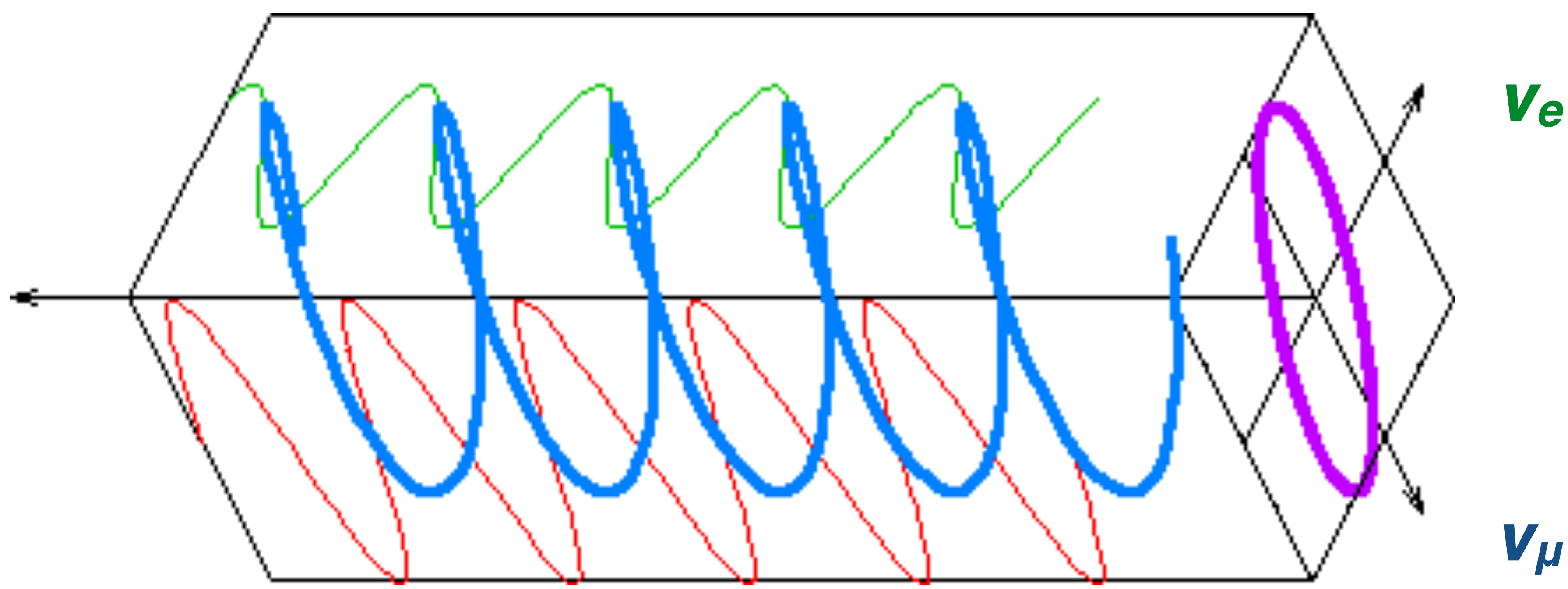


$$\boxed{|\nu_\mu(t)\rangle = -\sin\,\theta\;e^{-iE_1 t}\,|\nu_1\rangle + \cos\,\theta\;e^{-iE_2 t}\,|\nu_2\rangle}$$

Neutrino oscillation with two flavors

Credit: wikipedia



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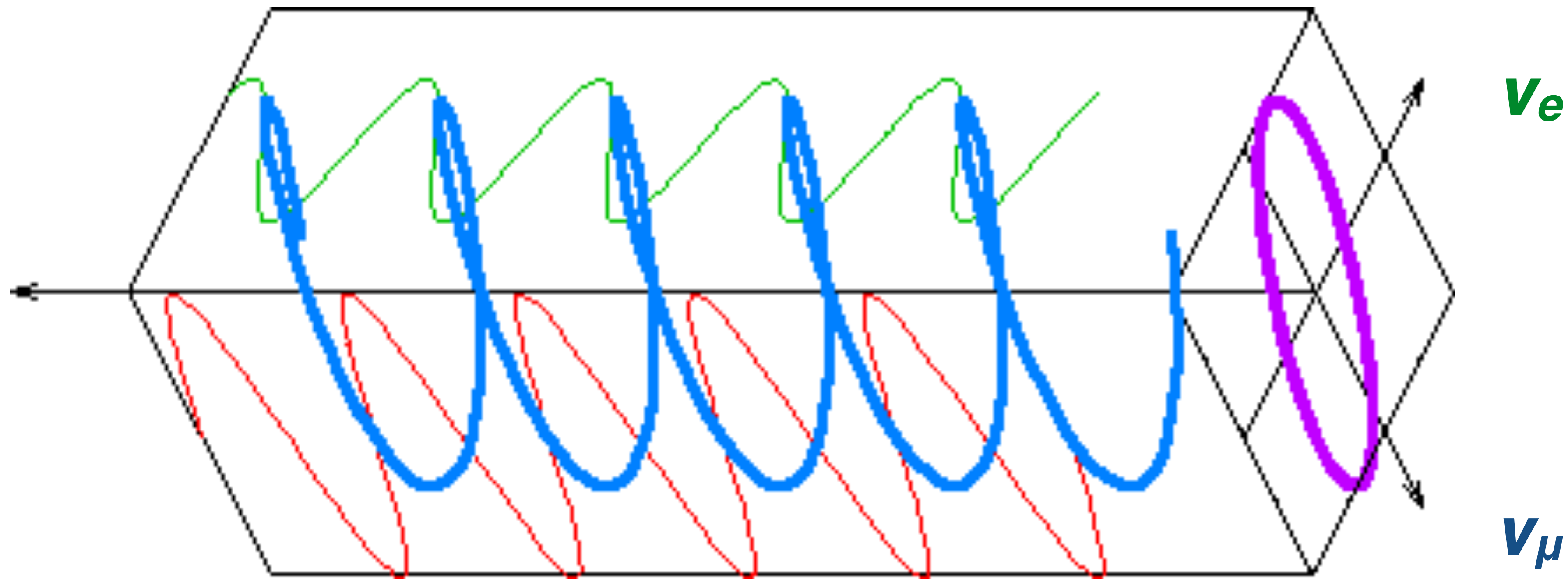
Neutrino oscillation with two flavors

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

Credit: wikipedia



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<u>Experimental setup determines:</u>

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

<u>Experiments measure:</u>

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

Outline

Why are neutrinos interesting to study? **Why is neutrino oscillation important?**

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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- 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?

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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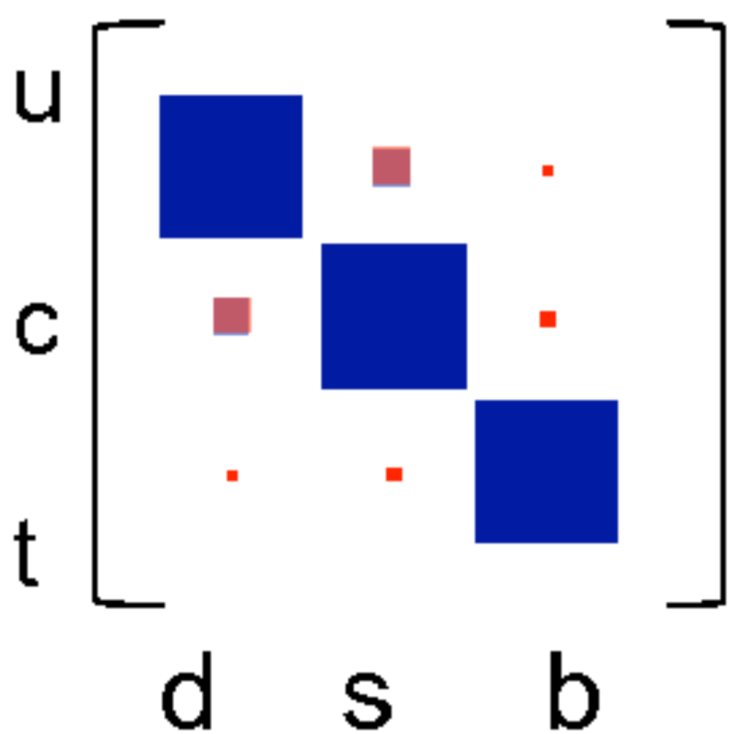
Mass states

Quarks

Cabbibo-Kobayashi-Maskawa (CKM)



Measurements also allow to test unitarity of the mixing matrix

Graphic: J.Phys. G45 (2018) no.1, 013001

What do we know about neutrino oscillation?

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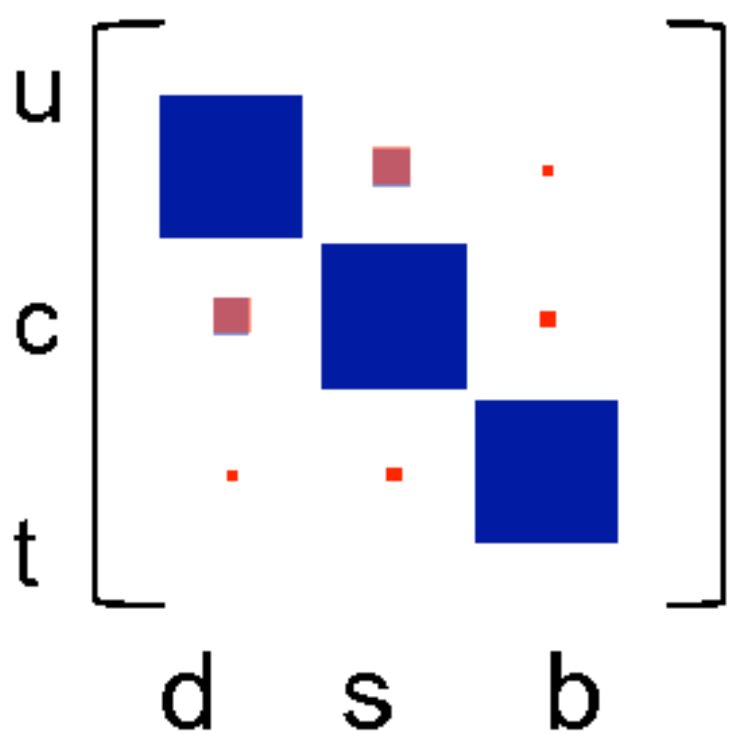
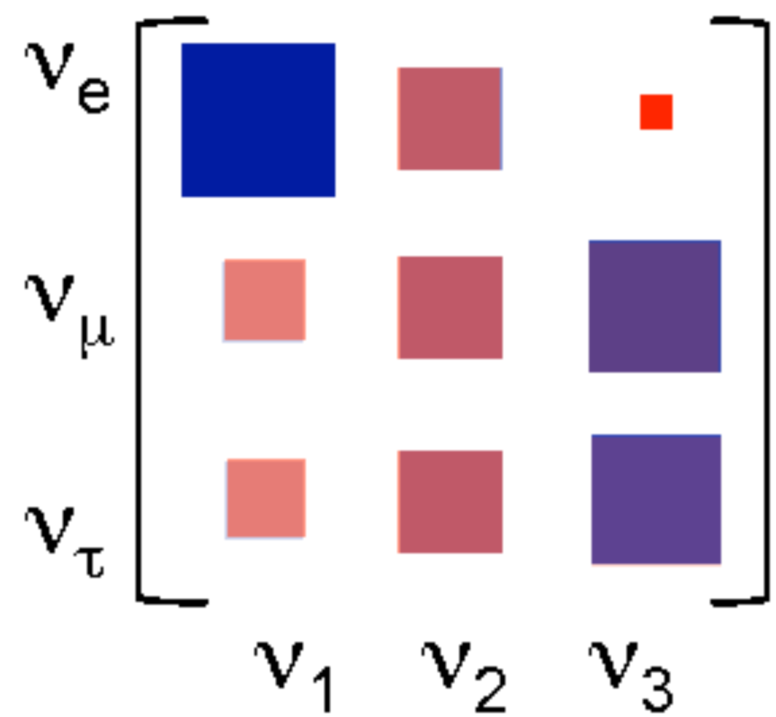
CKM



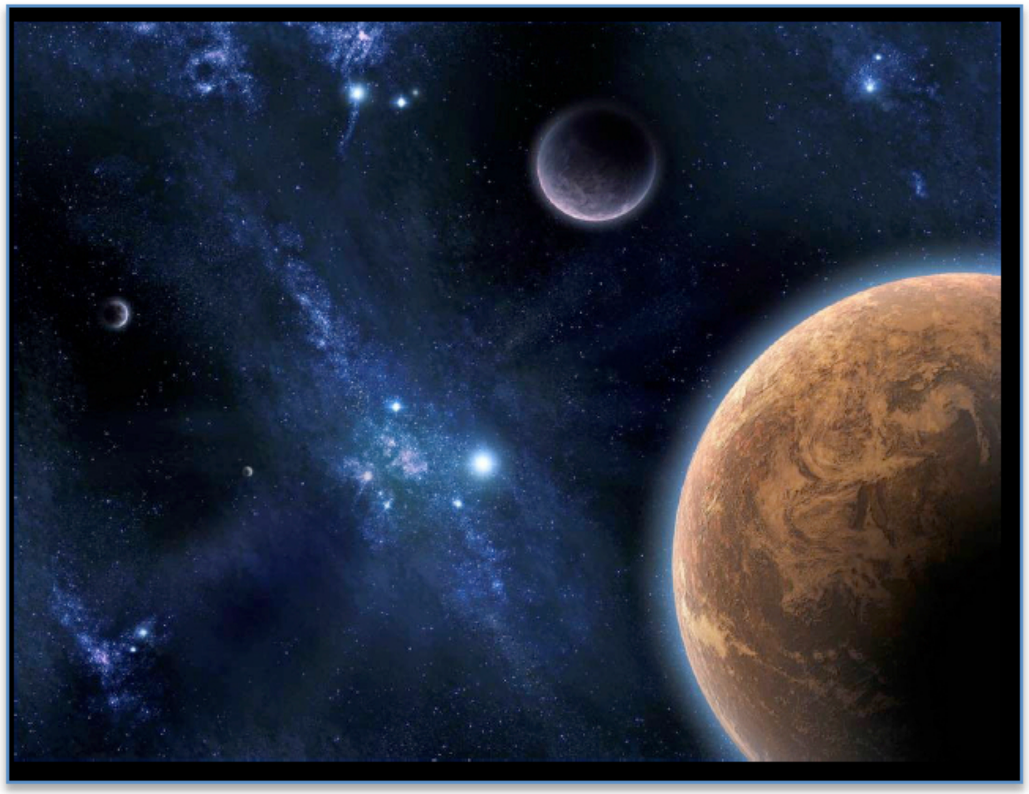
Leptons

PMNS



Is there new physics in the leptonic sector?

Why should we search for CP violation?



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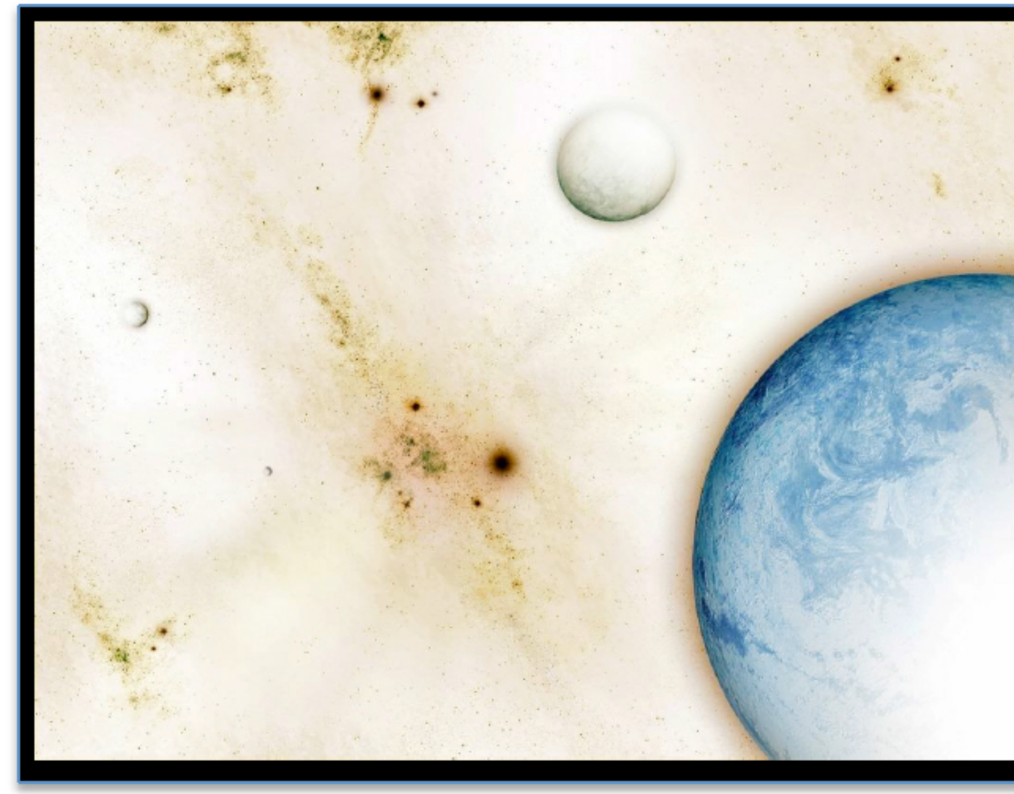
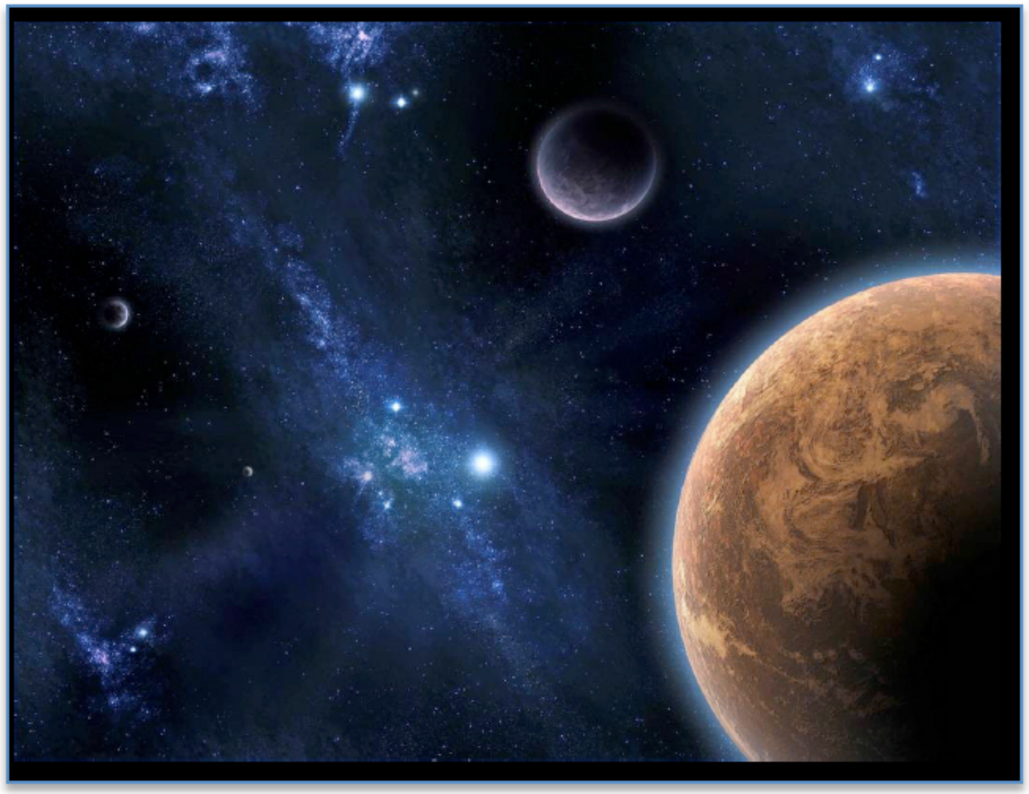


Observed matter/antimatter asymmetry requires Sakharov's conditions:

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

Why should we search for CP violation?



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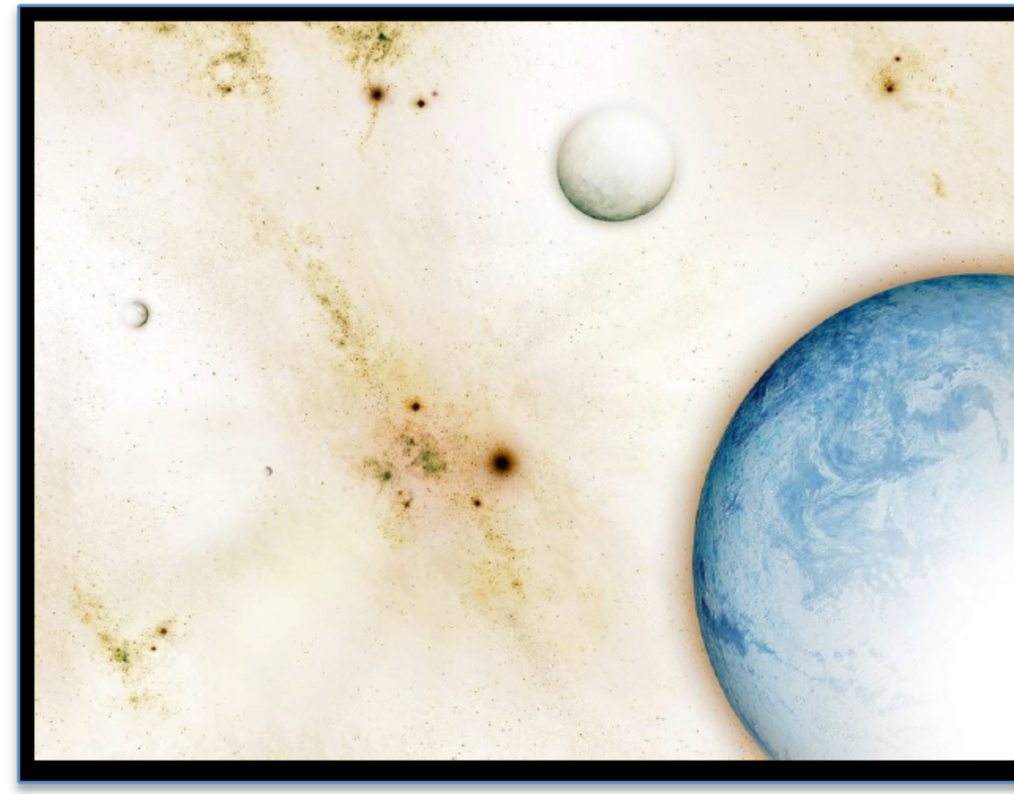

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CKM? Neutrinos? Strong CP violation?

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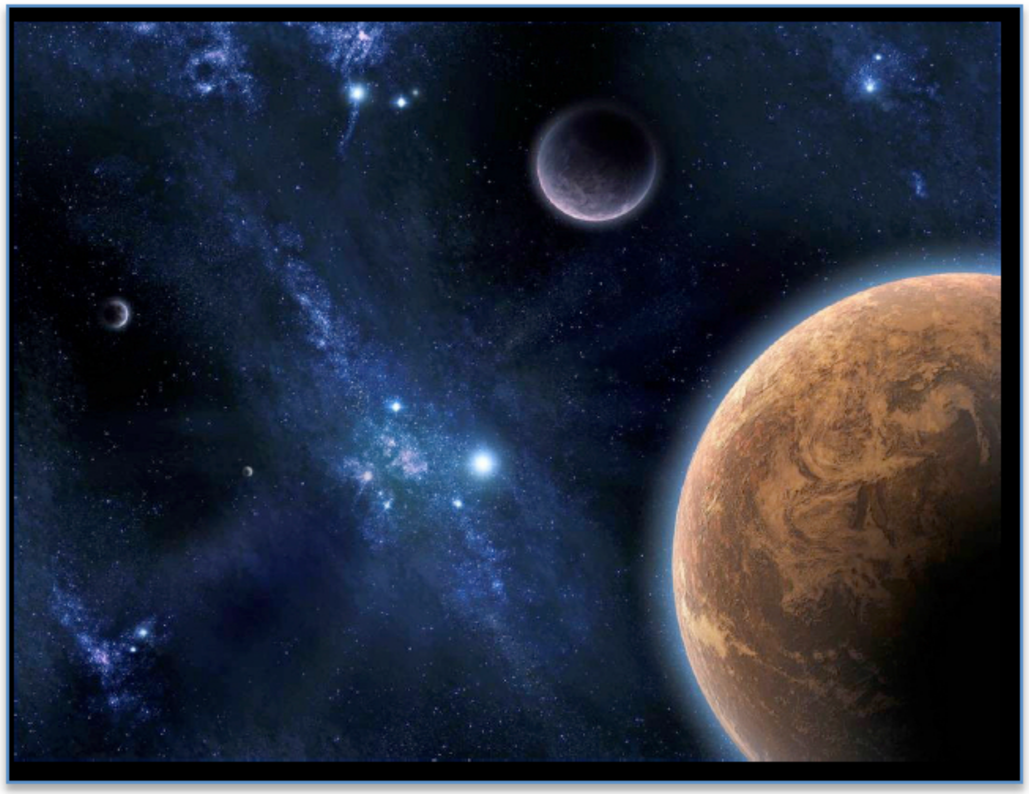

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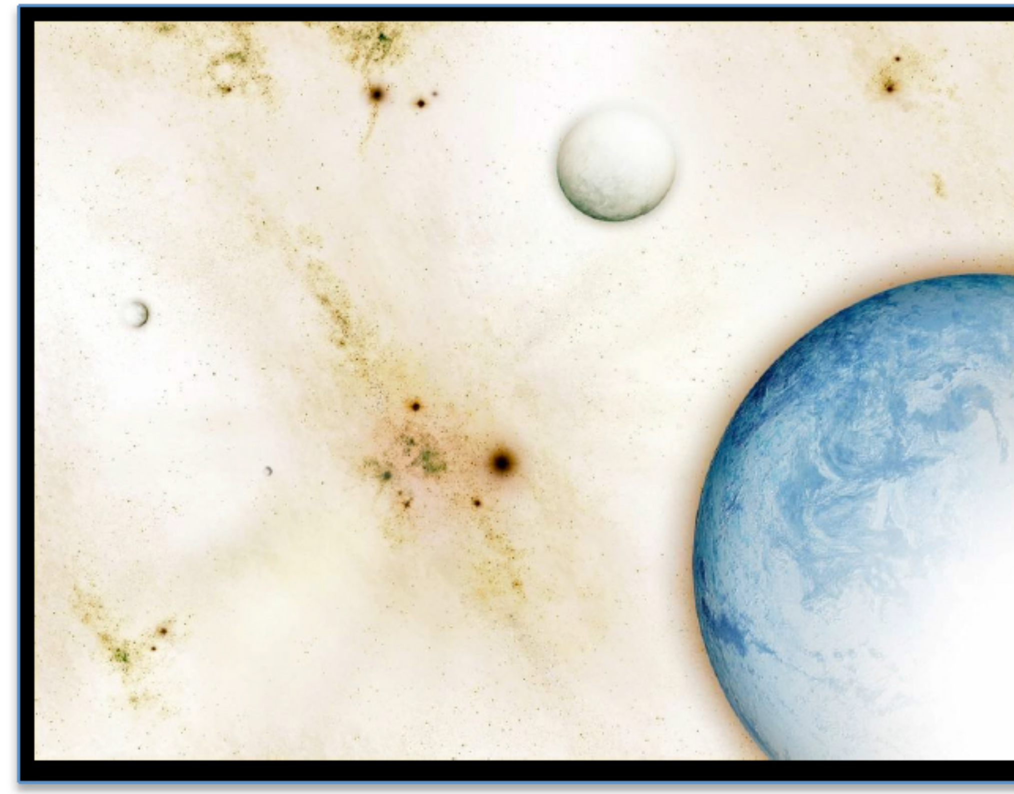

Observed matter/antimatter asymmetry requires Sakharov’s conditions:

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CKM? | Neutrinos? | Strong CP violation?

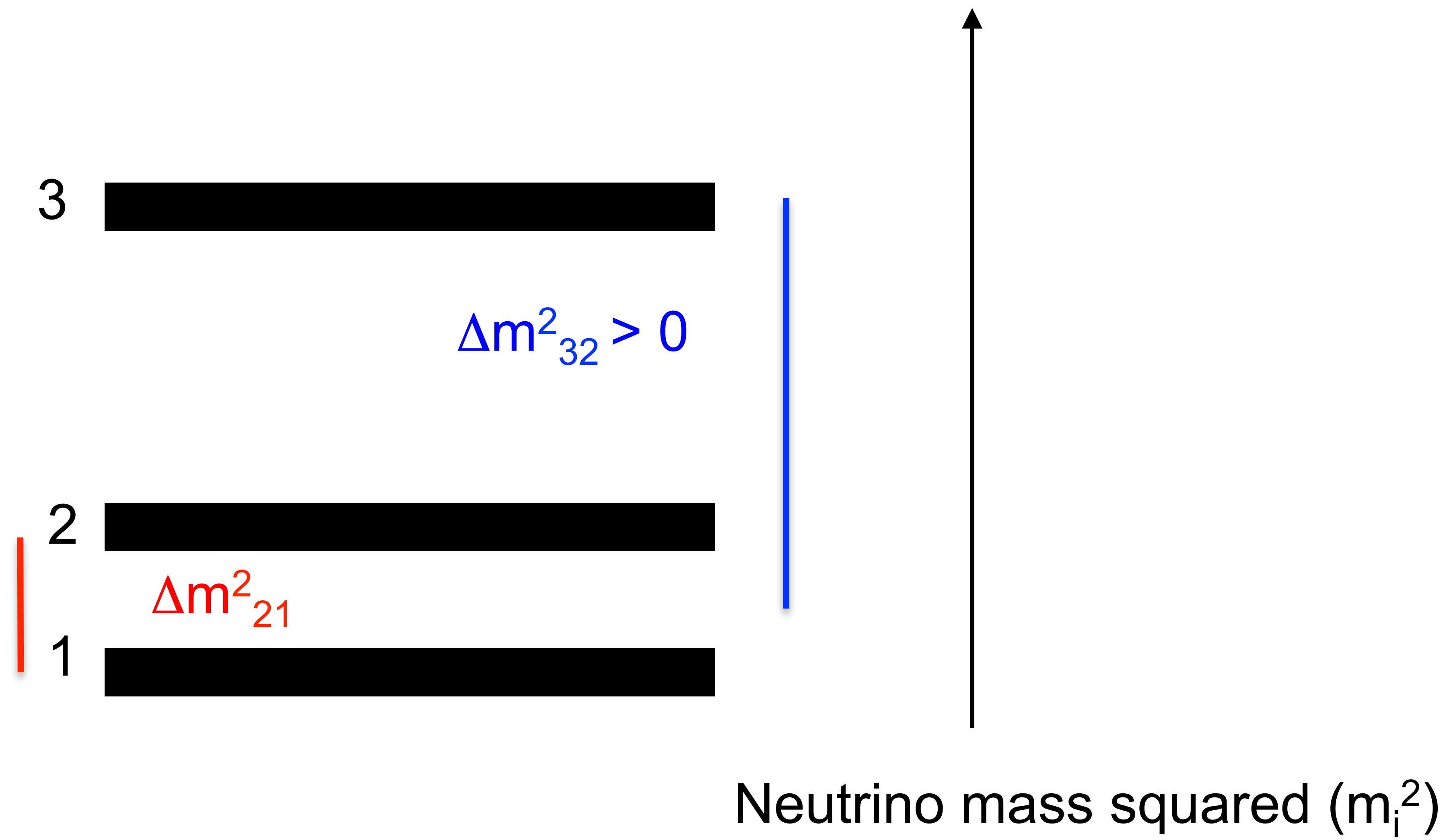
Not large enough… | | Not large enough…

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?

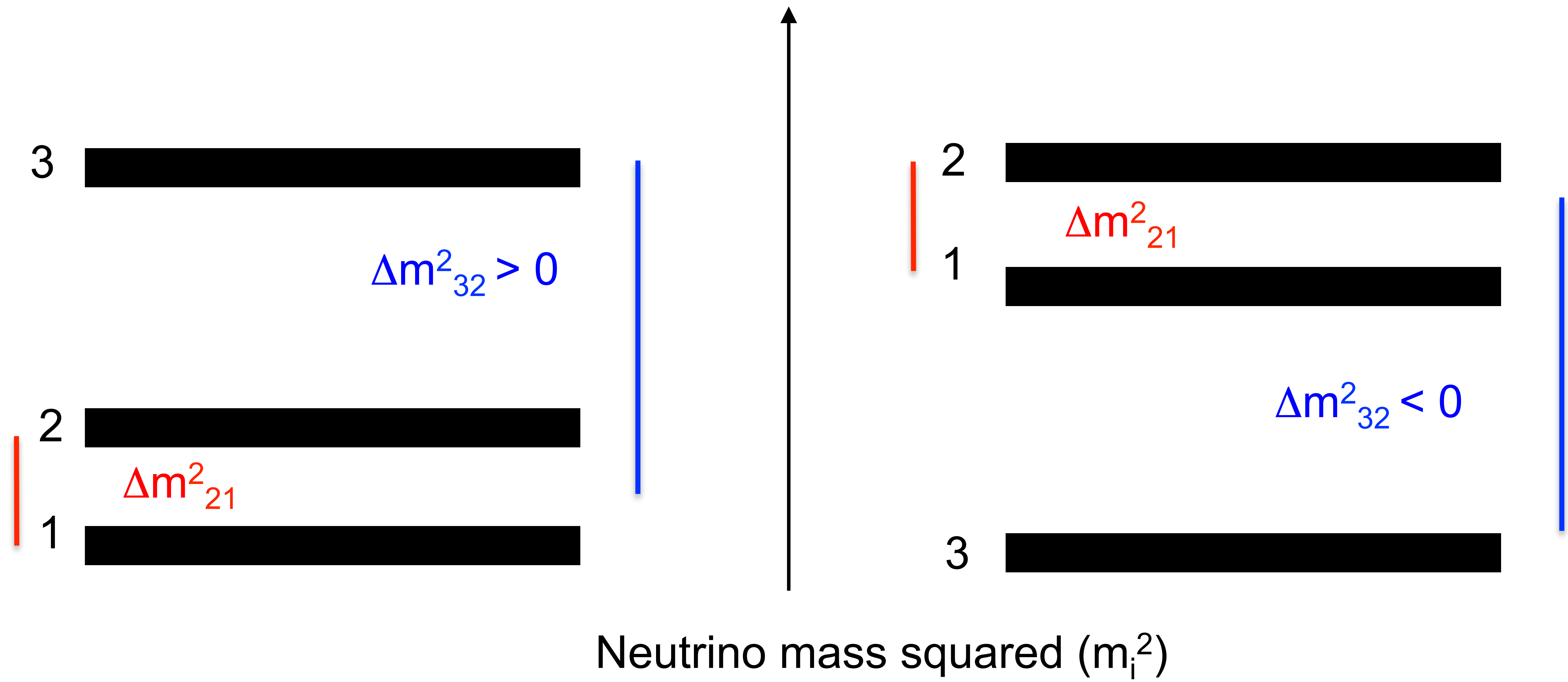
What do we know about neutrino oscillation?



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

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

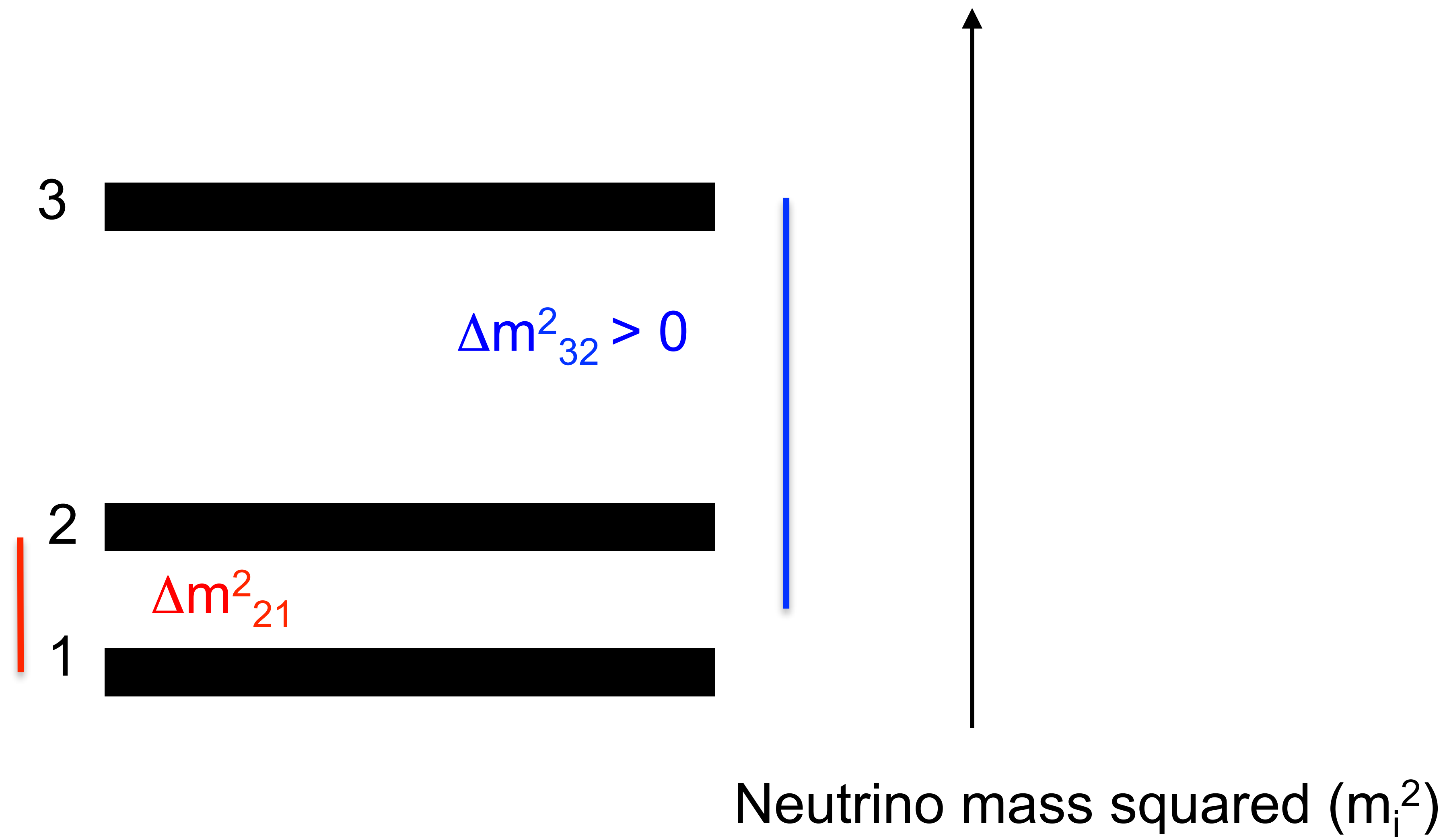
What do we know about neutrino oscillation?



- **Mass splitting:|Δm^2_{32}|,Δm^2_{21}**

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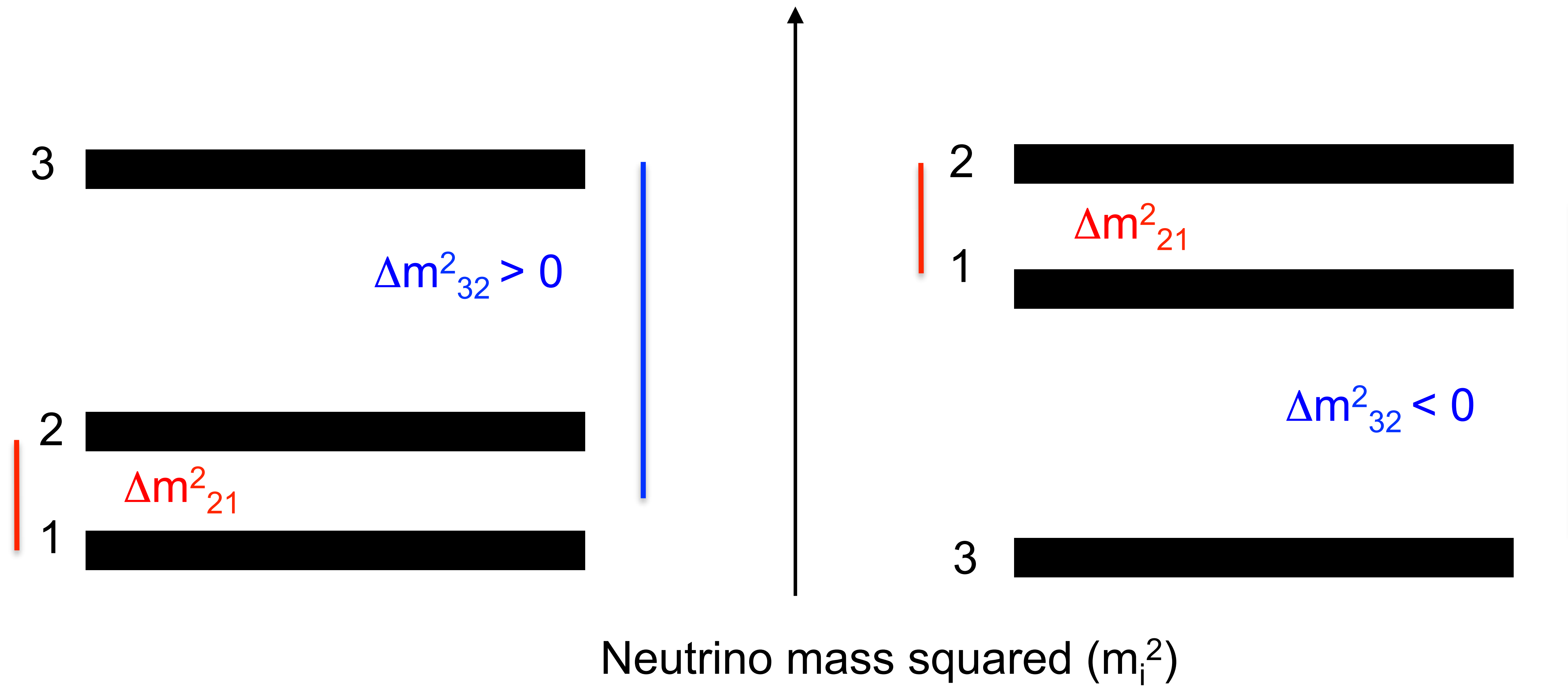
$\Delta m^2_{32} > 0$: "normal" hierarchy,

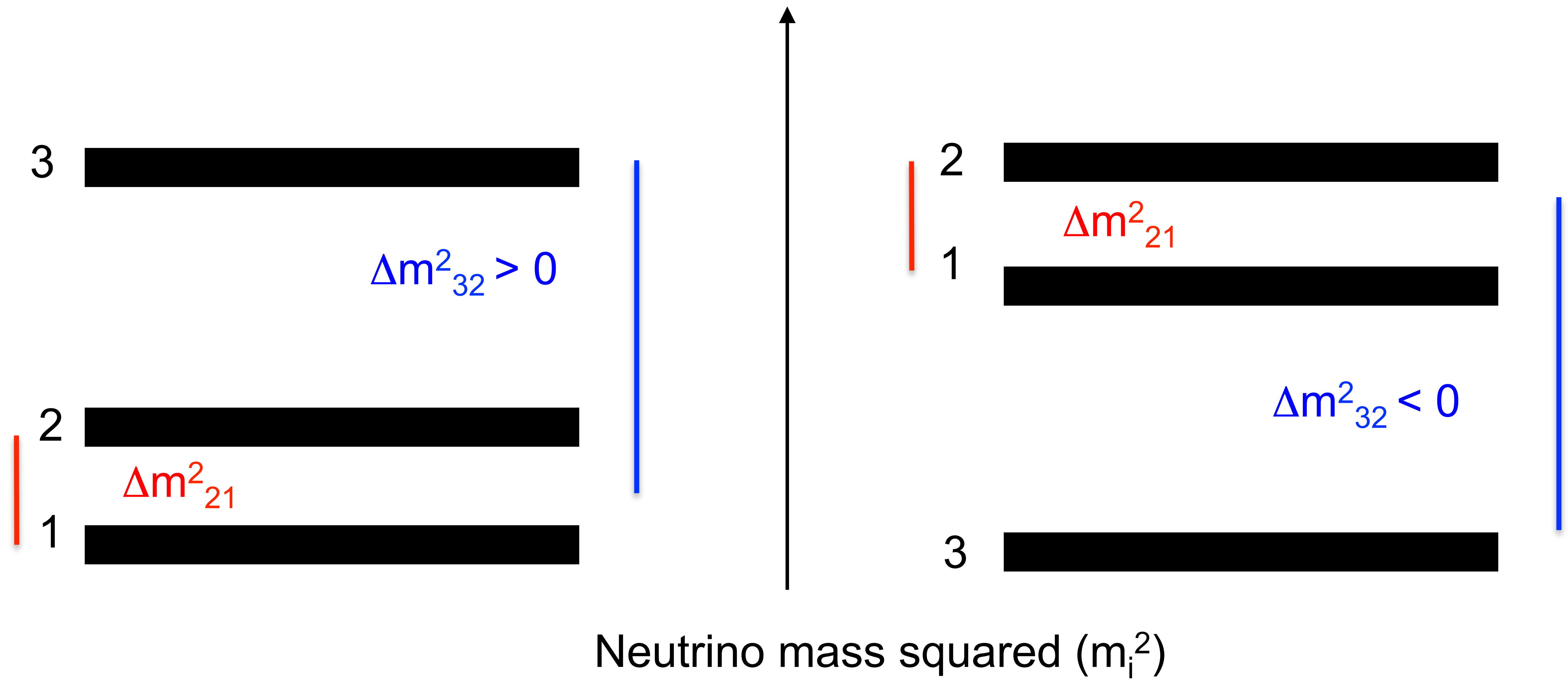
What do we know about neutrino oscillation?



- **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

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

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

Probability to transition from flavor **α** *to flavor* **β**

Accessing neutrino oscillation

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

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

Accessing neutrino oscillation

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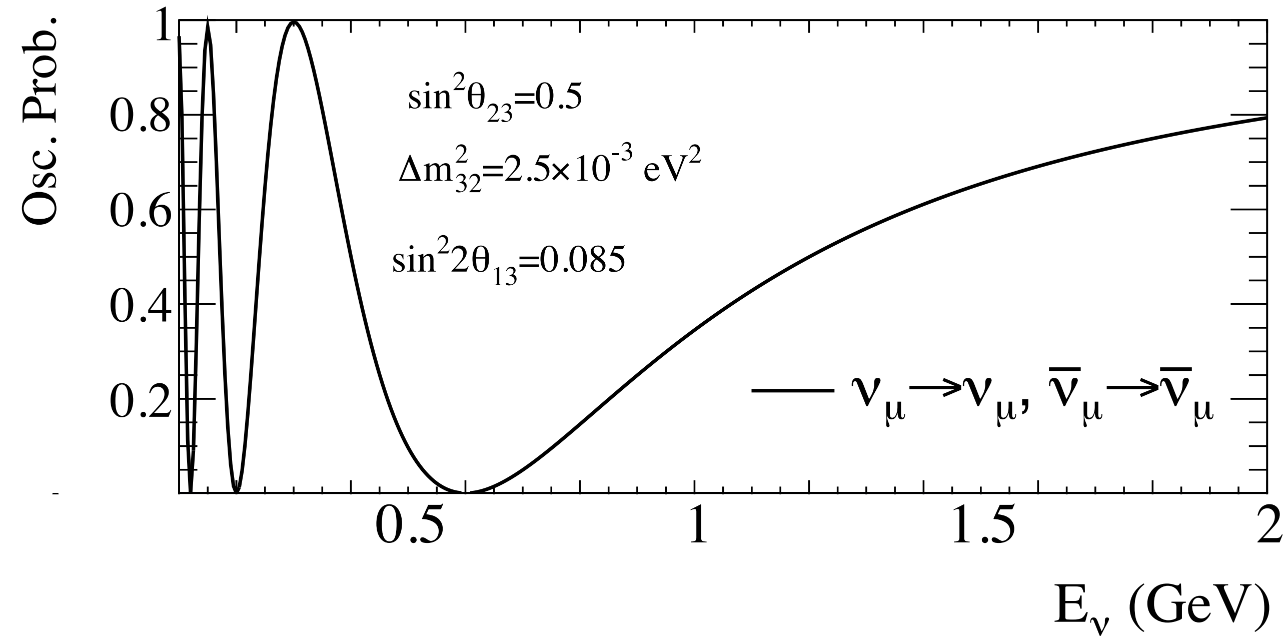
ν_μ and $\bar{\nu}_\mu$ disappearance channel

Accessing neutrino oscillation



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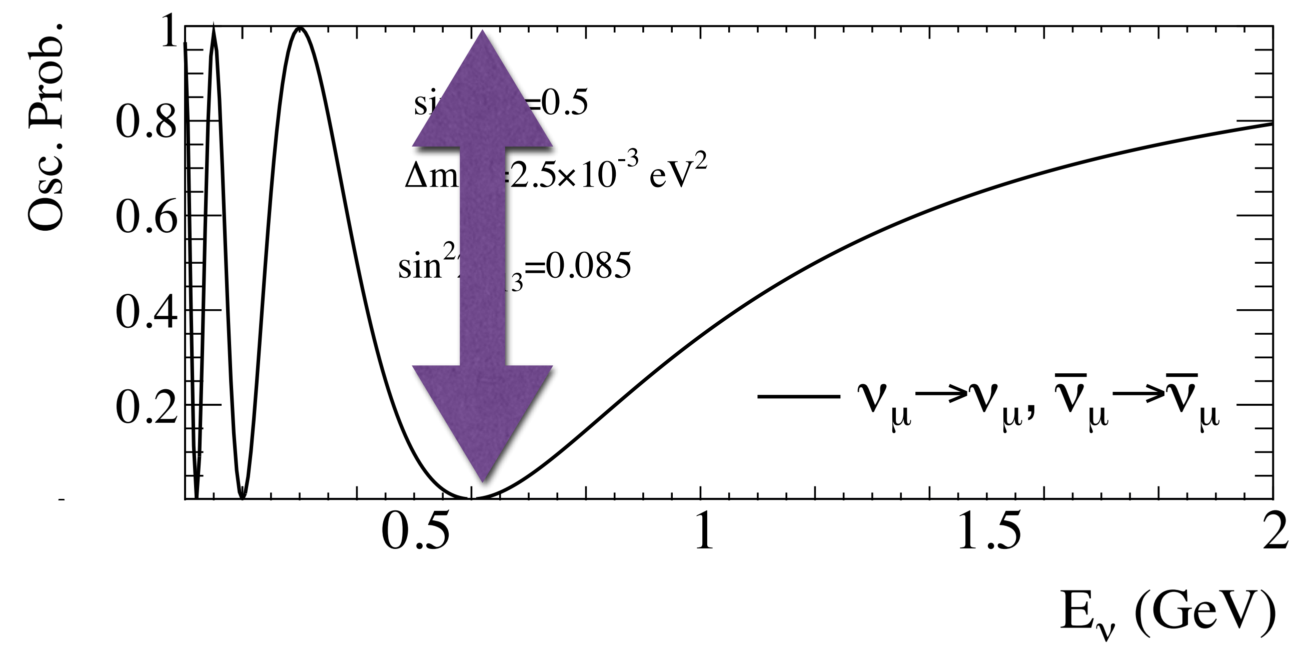
Accessing neutrino oscillation

Oscillation depends on:

- **Amplitude** determined by mixing angles: θ_{12}, $\boldsymbol{\theta_{23}}$, θ_{13}



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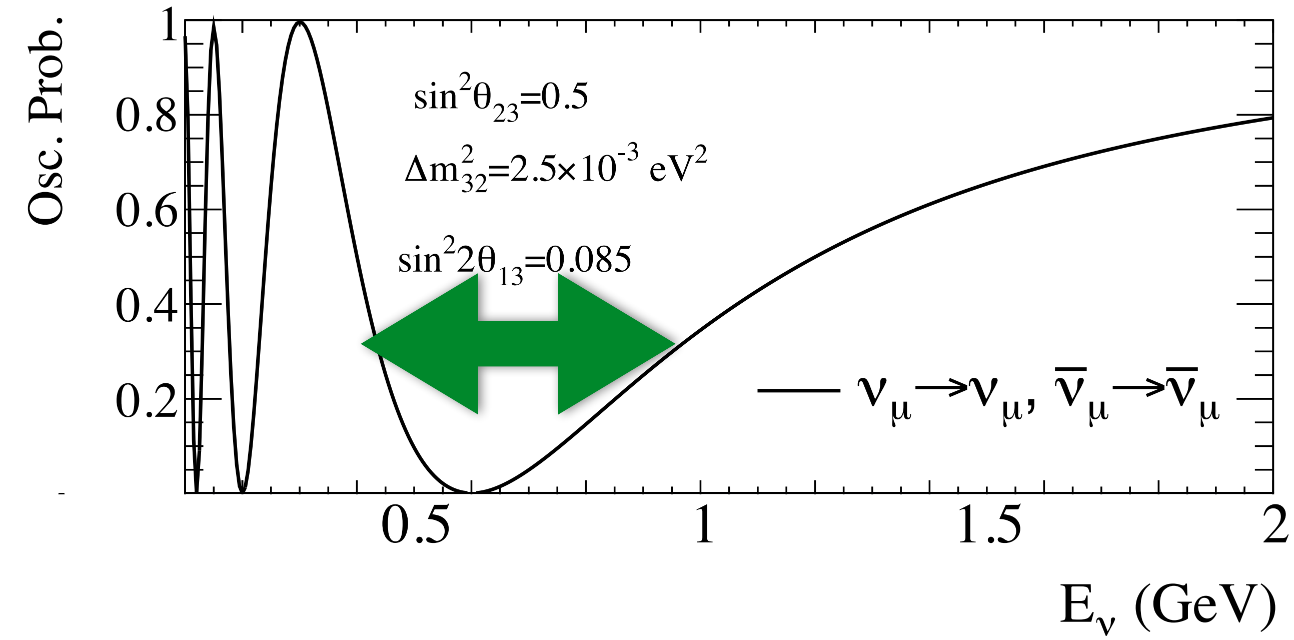
ν_μ and $\bar{\nu}_\mu$ disappearance channel

Accessing neutrino oscillation

Oscillation depends on:

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



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

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

Accessing neutrino oscillation

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

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

Sensitive to all oscillation parameters

$$\boxed{P(\nu_\mu \to \nu_e)}$$

Accessing neutrino oscillation

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

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

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

δ_{CP} changes the ν_e and $\bar{\nu}_e$ appearance in opposite directions

Accessing neutrino oscillation

- Amplitude determined by mixing angles: θ_{12}, θ_{23}, θ_{13}
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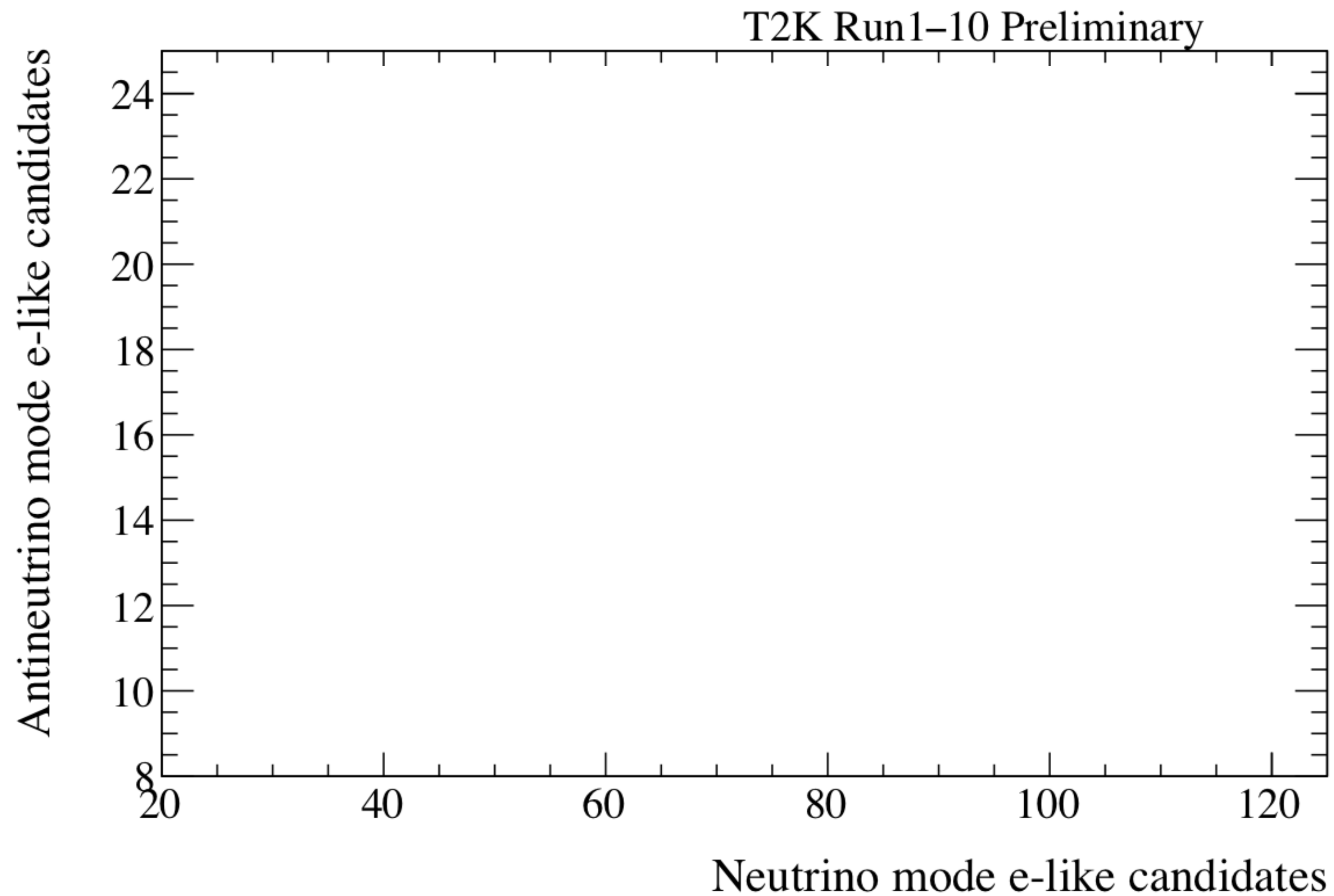
- **CP violating phase** (CPV): **δ_{CP}**



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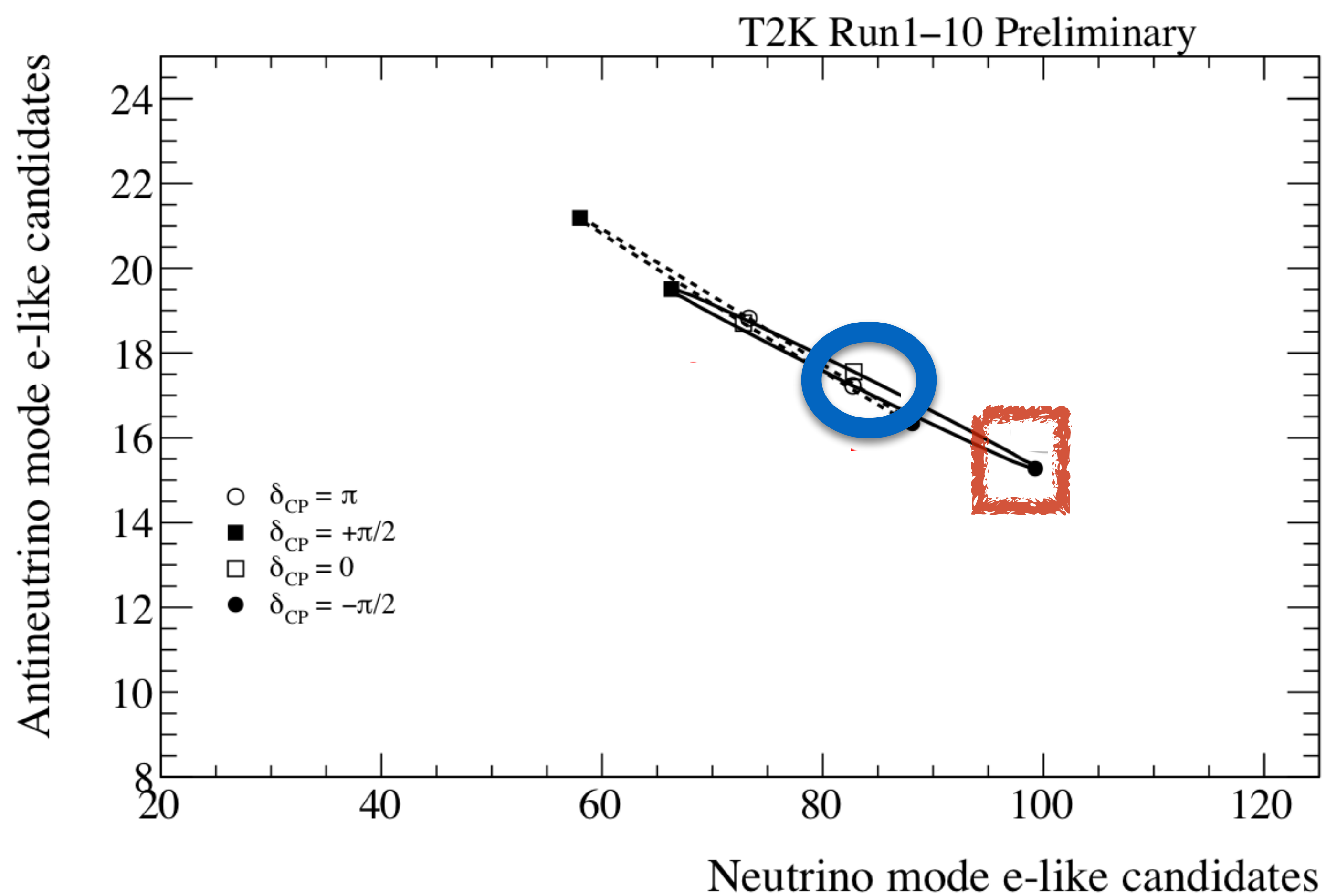
2D plot of neutrino appearance rate vs. antineutrino appearance rate

Accessing neutrino oscillation

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



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

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

Accessing neutrino oscillation

- **Amplitude** determined by mixing angles: θ_{12}, $\boldsymbol{\theta_{23}}$, θ_{13}
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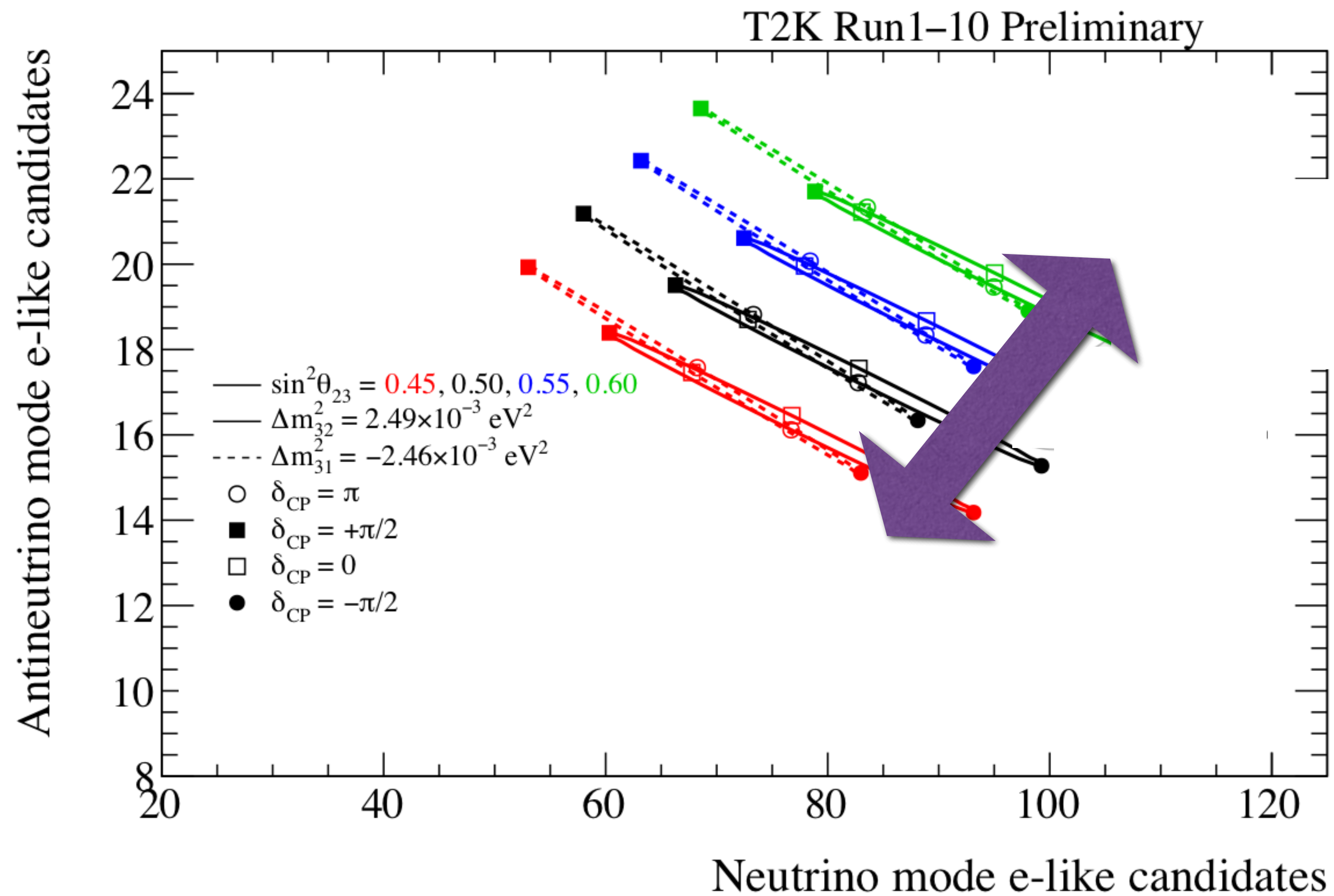

For increasing θ_{23} enhance both ν_e and $\bar{\nu}_e$ appearance

Accessing neutrino oscillation

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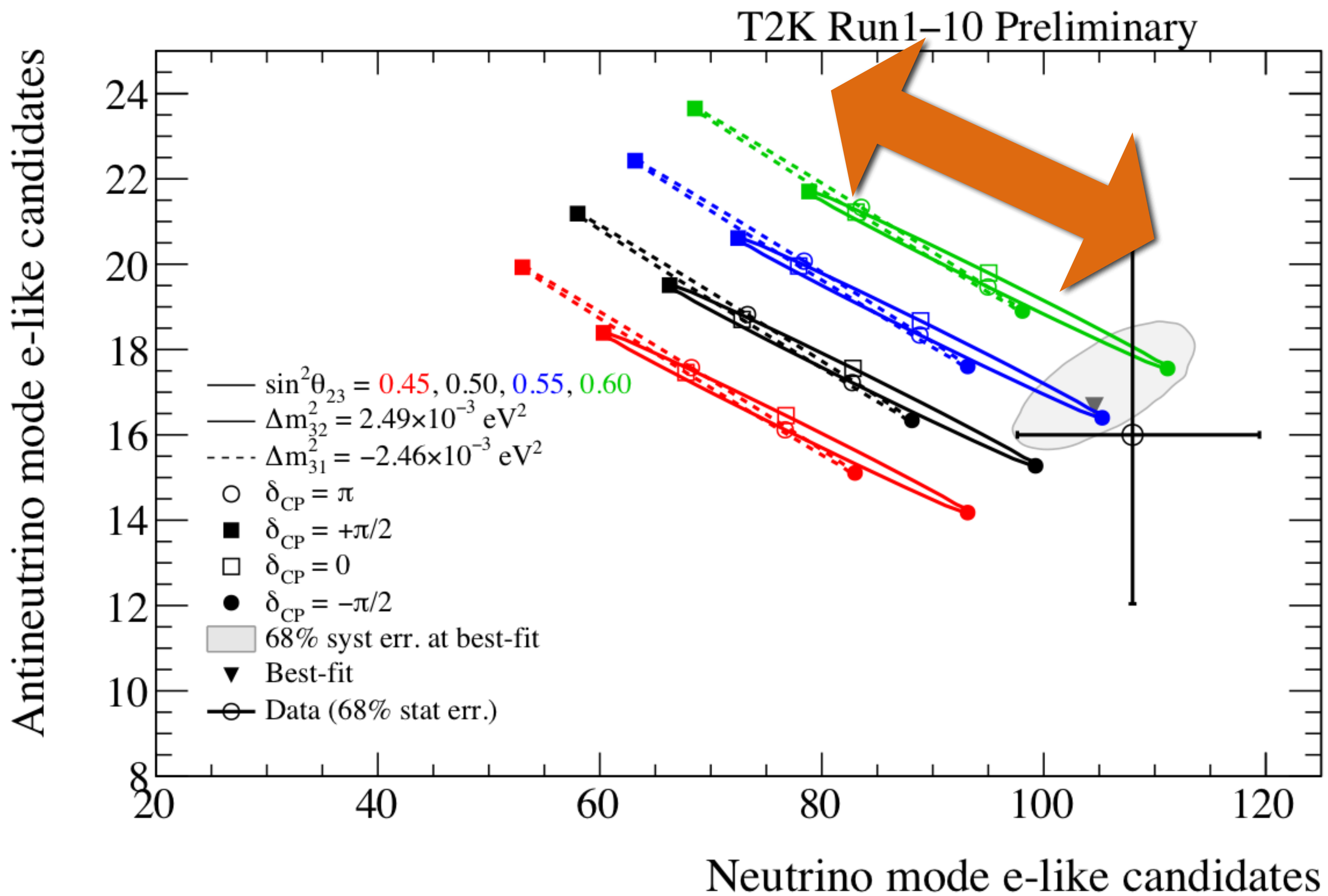
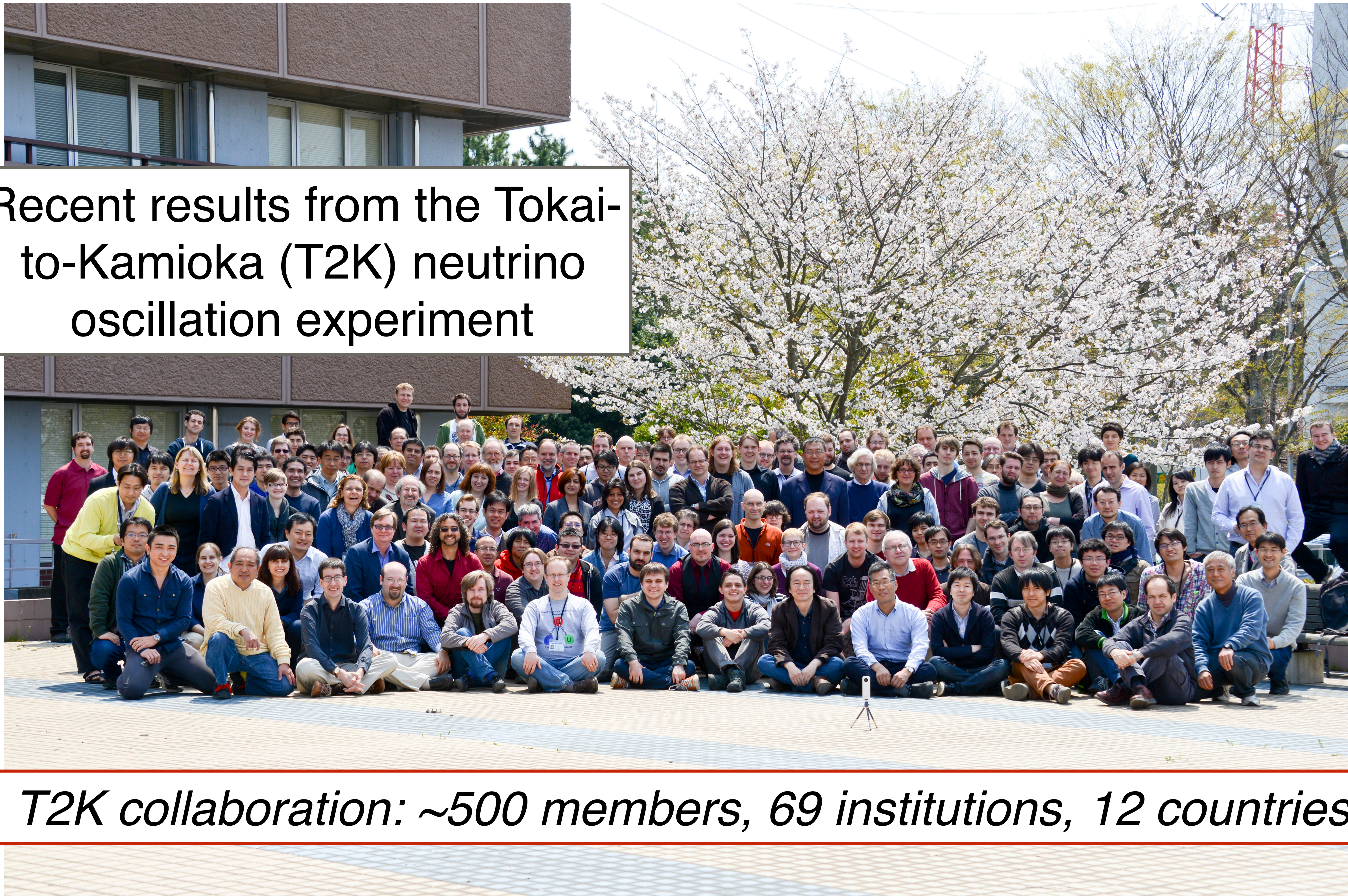


Normal to inverted hierarchy suppresses ν_e appearance, enhances $\bar{\nu}_e$ appearance

Outline



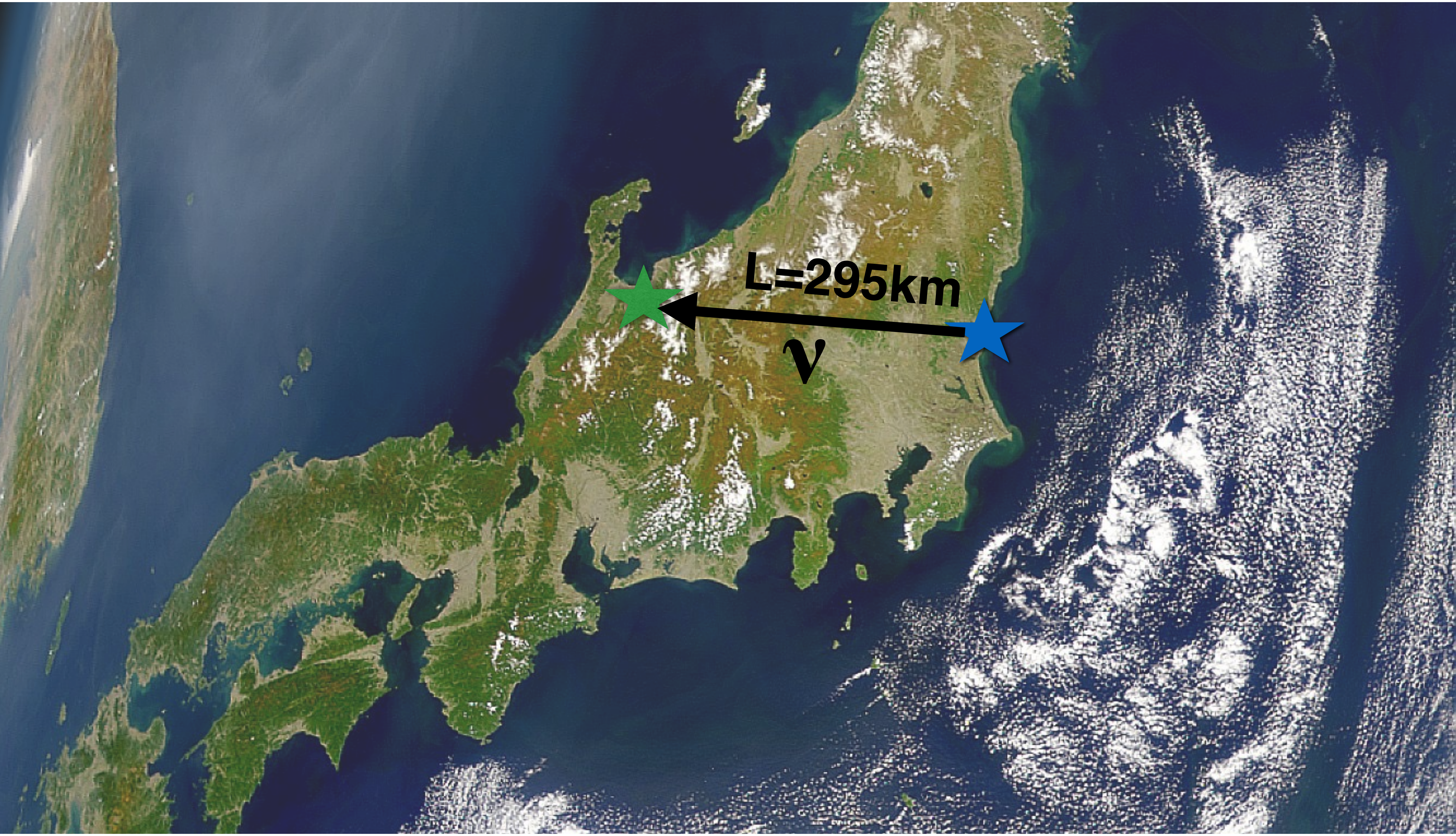
Recent results from the Tokai-to-Kamioka (T2K) neutrino oscillation experiment

T2K collaboration: ~500 members, 69 institutions, 12 countries

Long baseline experiments

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

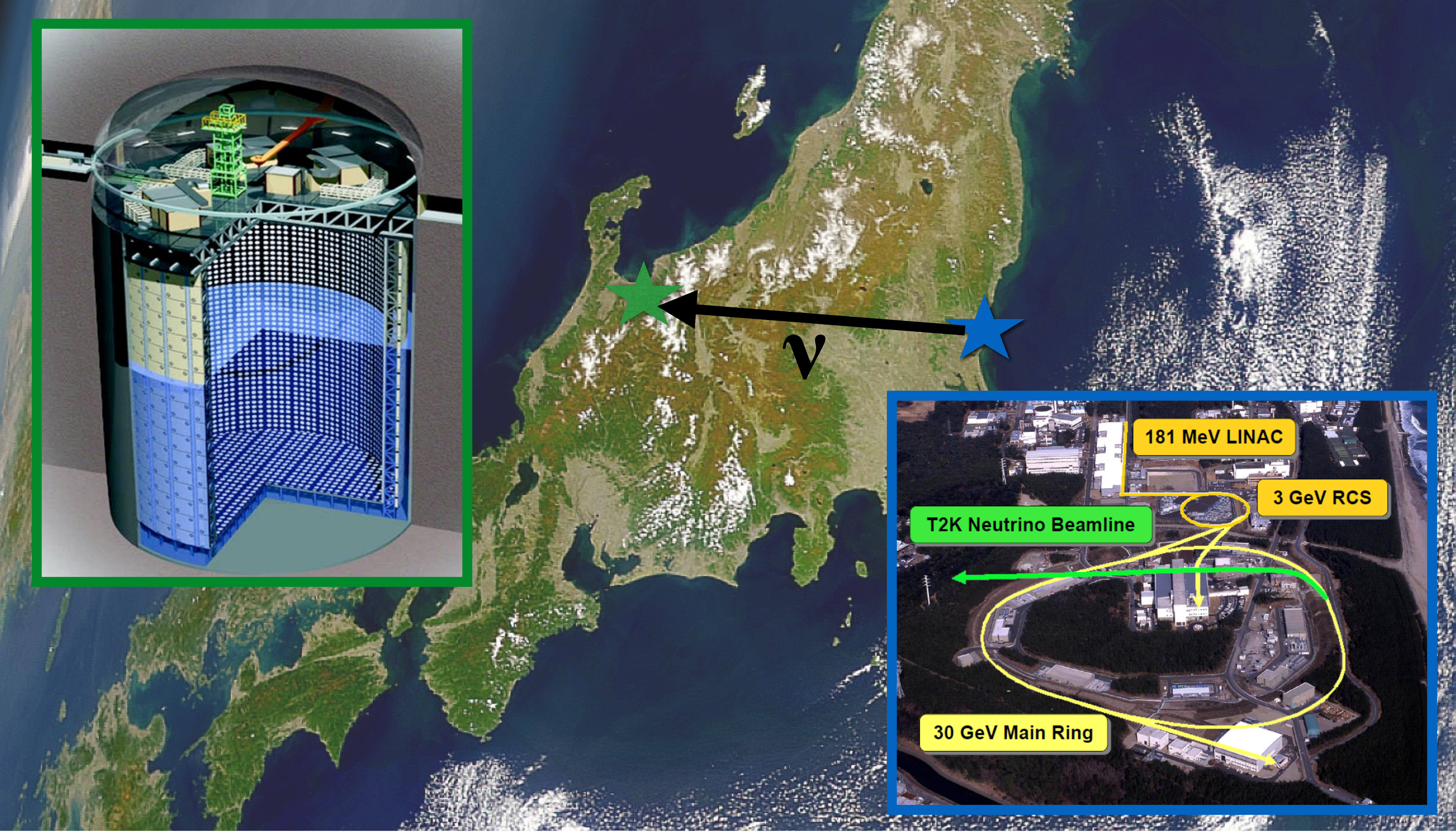
Long baseline experiments



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

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

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



Main ingredients:

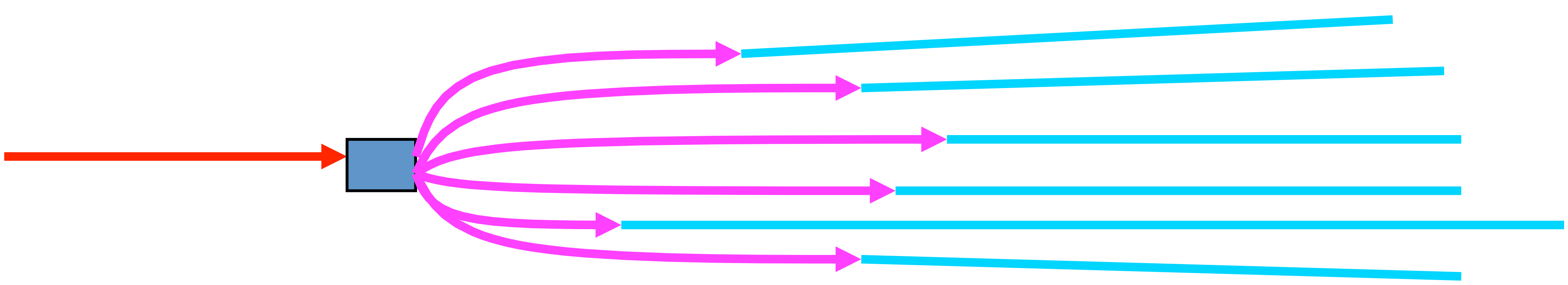
- **Accelerator** produces an intense source
- Massive **far detector** (Super-Kamiokande)

Shine a light on unknown physics
accelerator-produced neutrino beams

Credit: 123RF.com

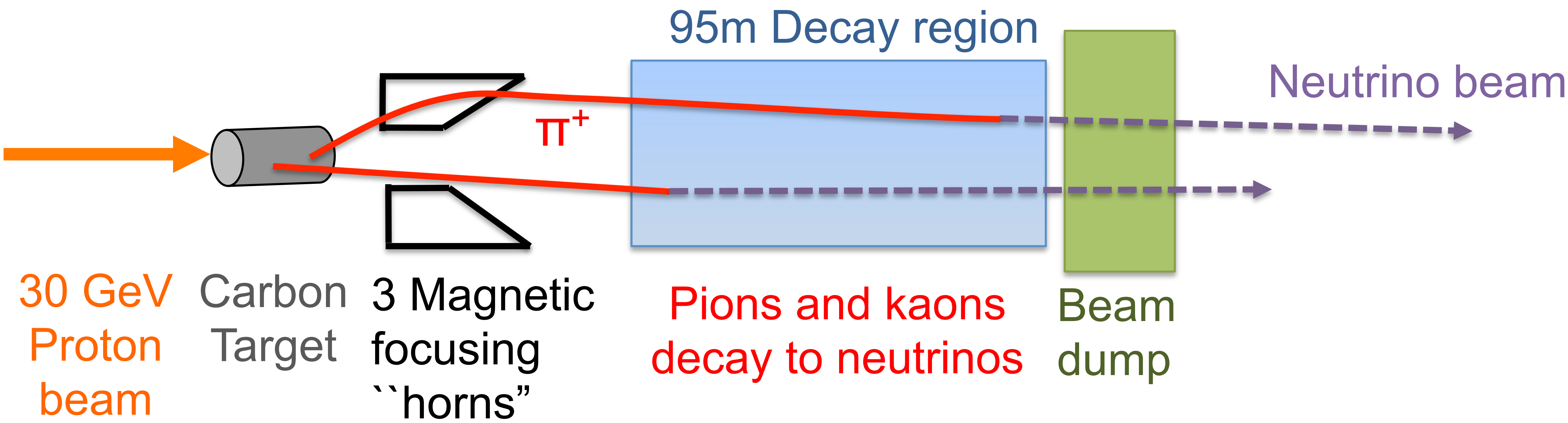
Shine a light on unknown physics
accelerator-produced neutrino beams

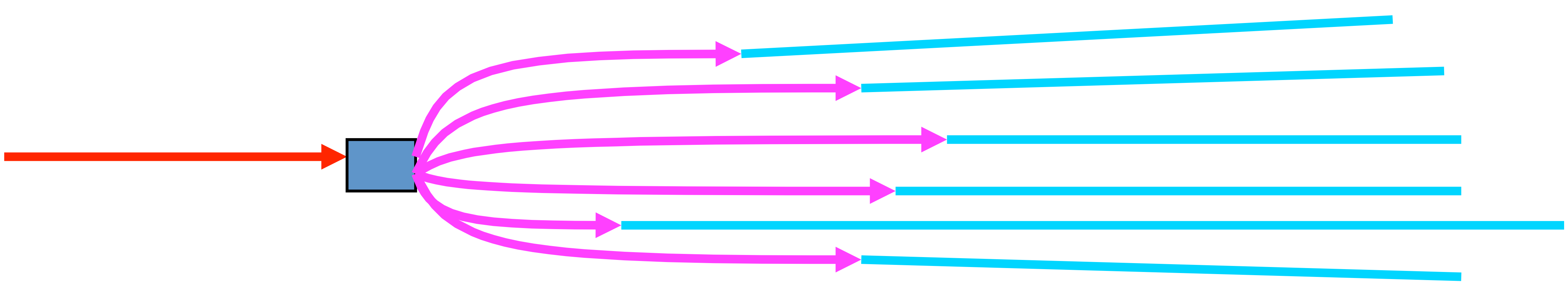
Electrical current hits a filament producing light focused into a beam



protons→carbon target→unstable particles→neutrinos

Accelerator-produced neutrino beams





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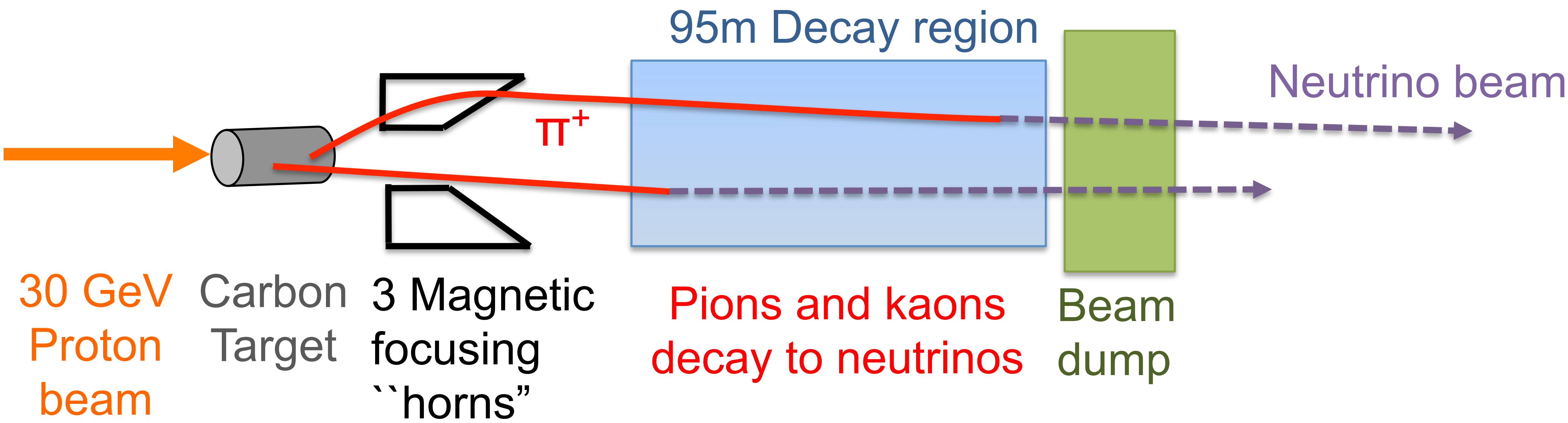
Accelerator-produced neutrino beams



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

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

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

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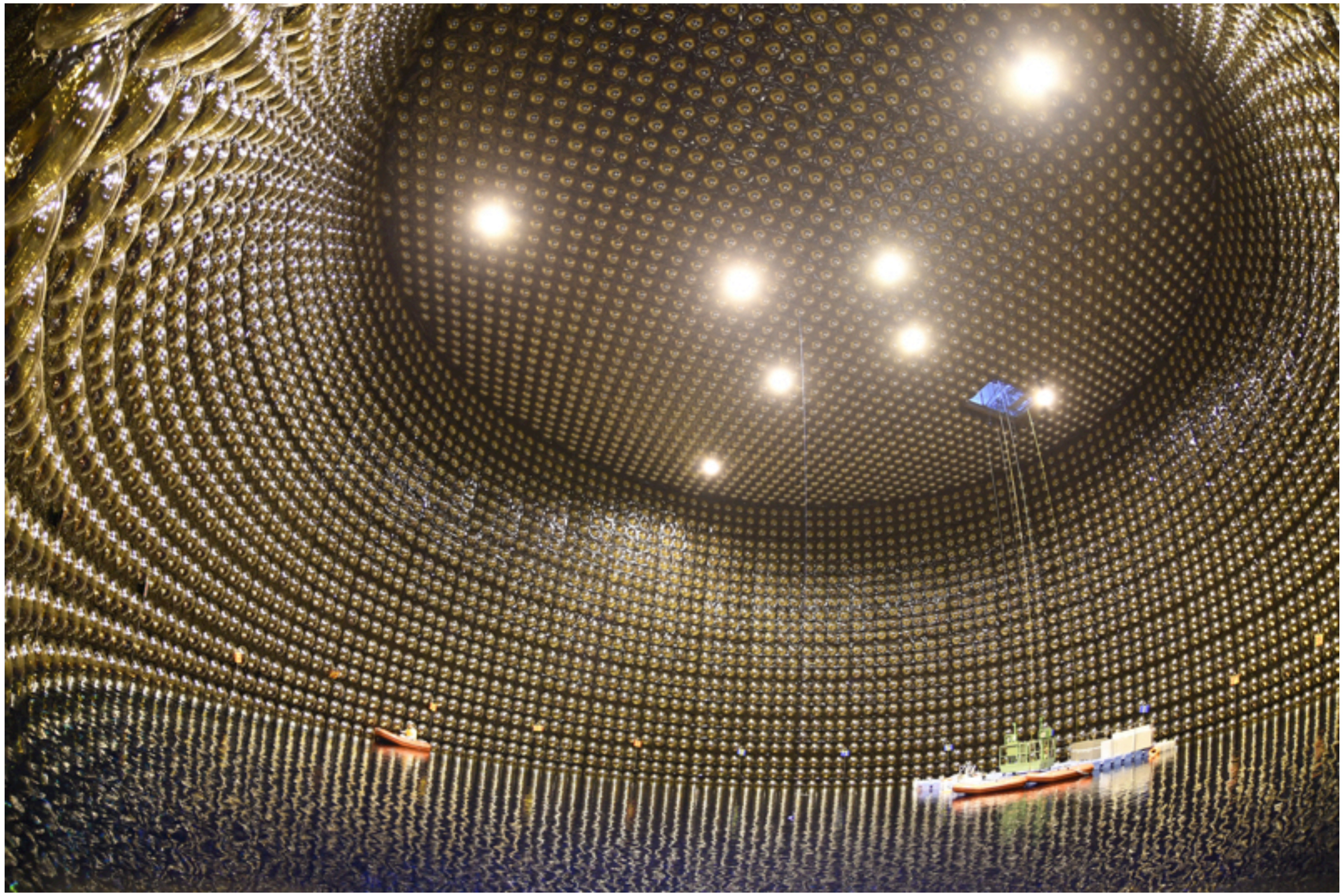
ν_e event rate

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



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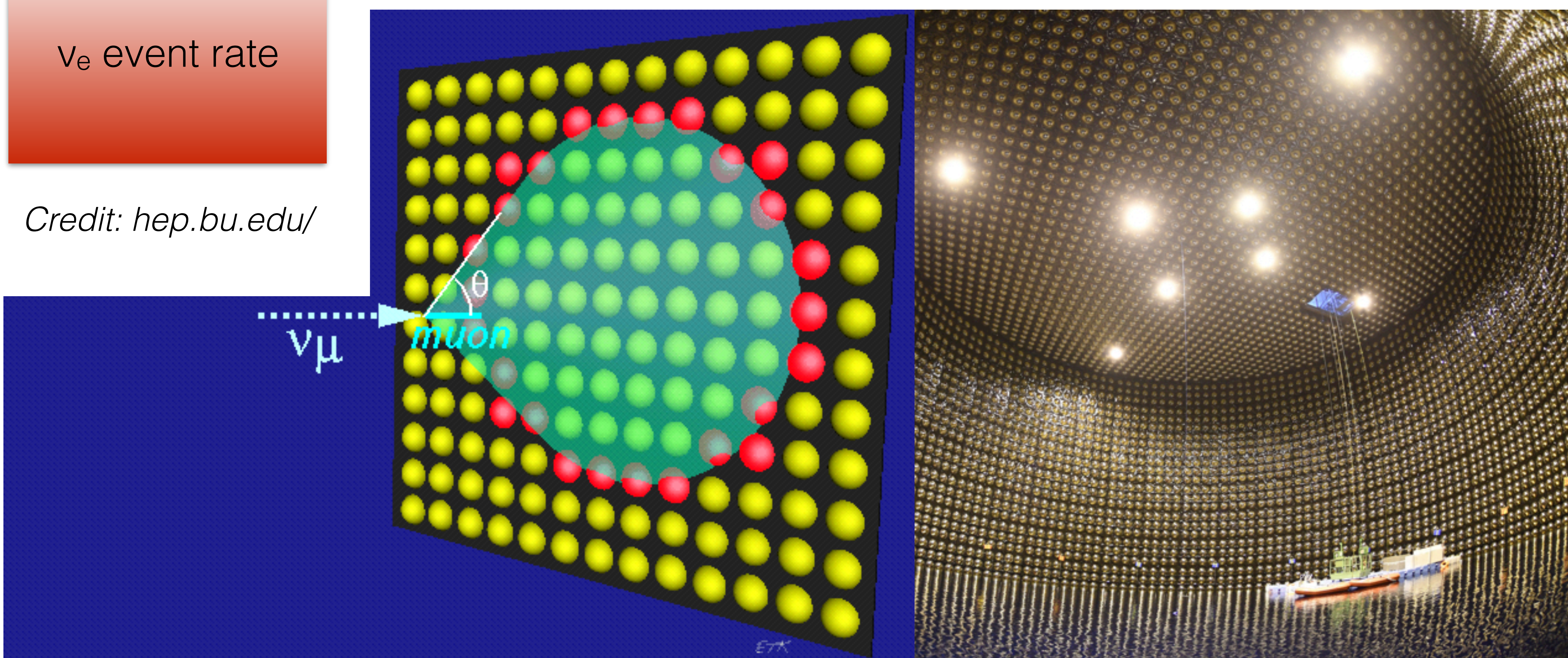
ν_e event rate

Credit: hep.bu.edu/



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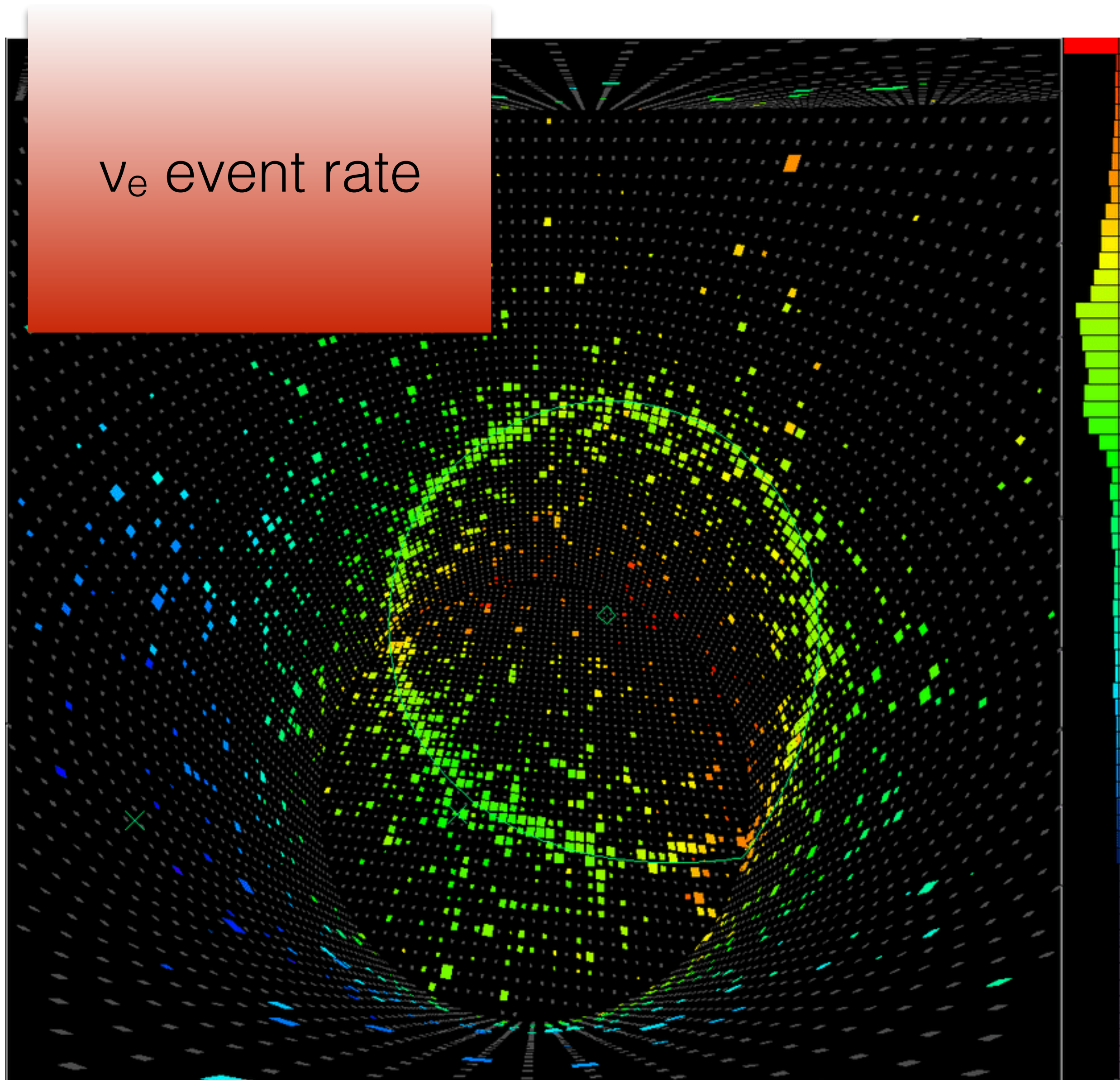
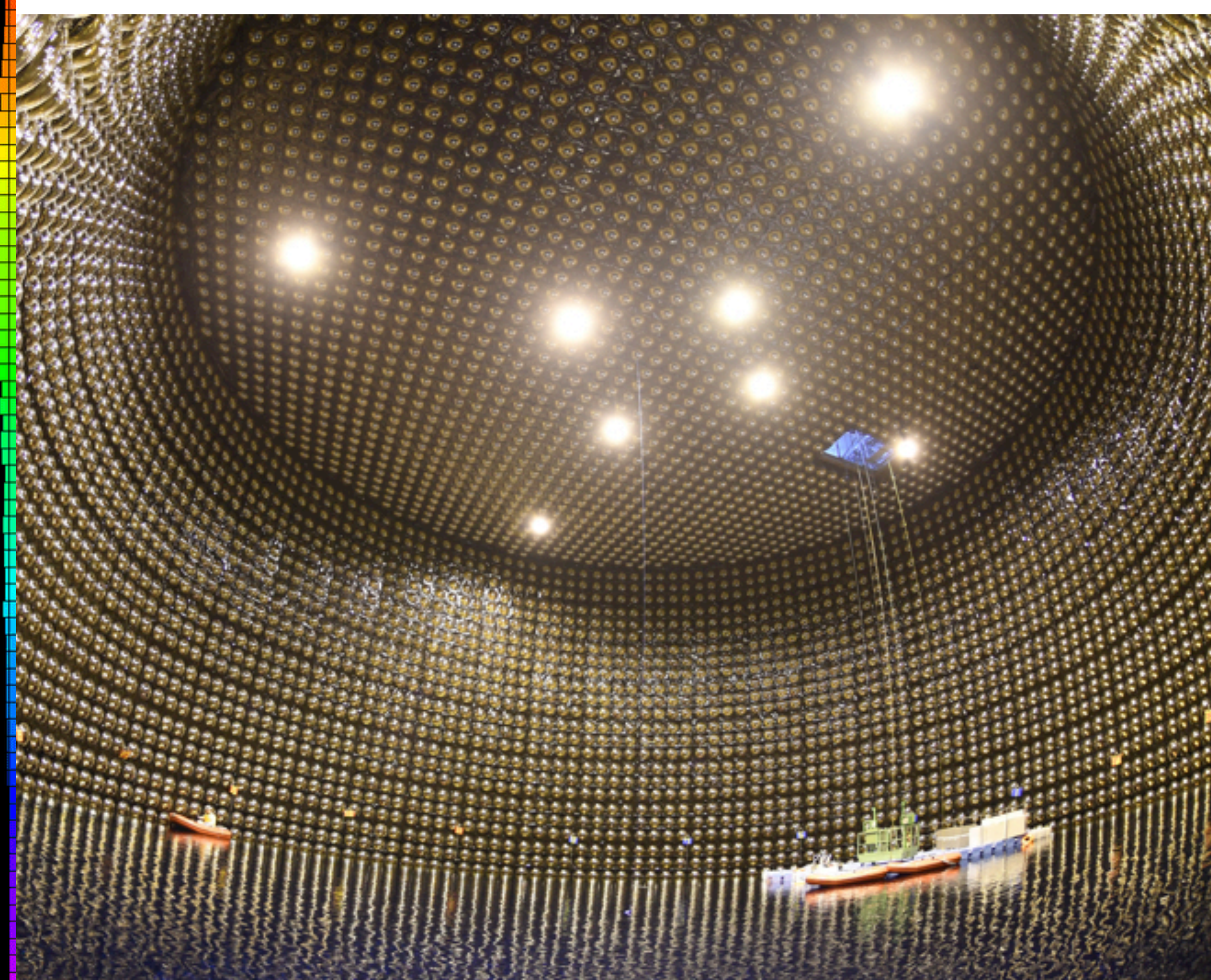


Credit: www-sk.icrr.u-tokyo.ac.jp/



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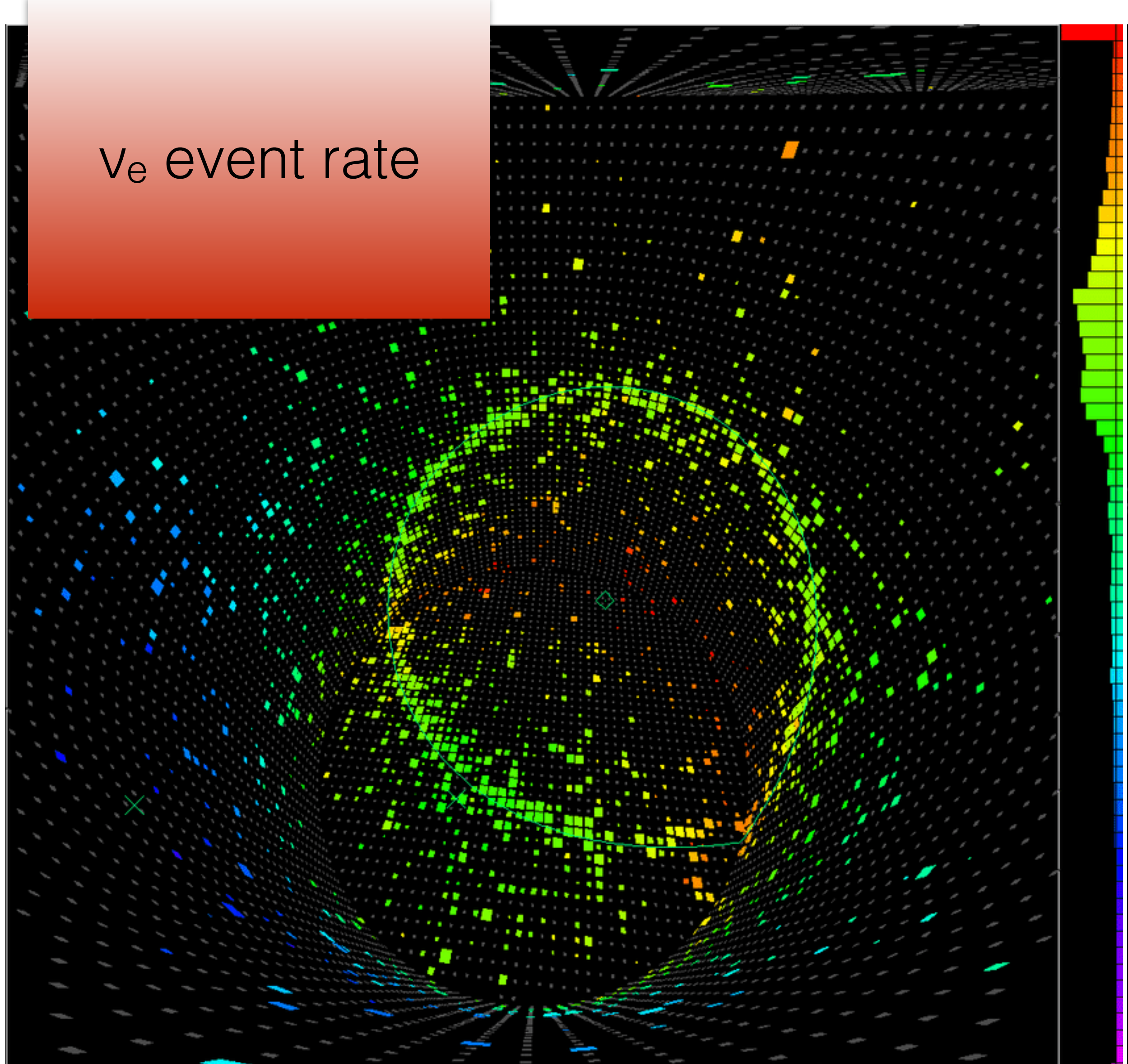

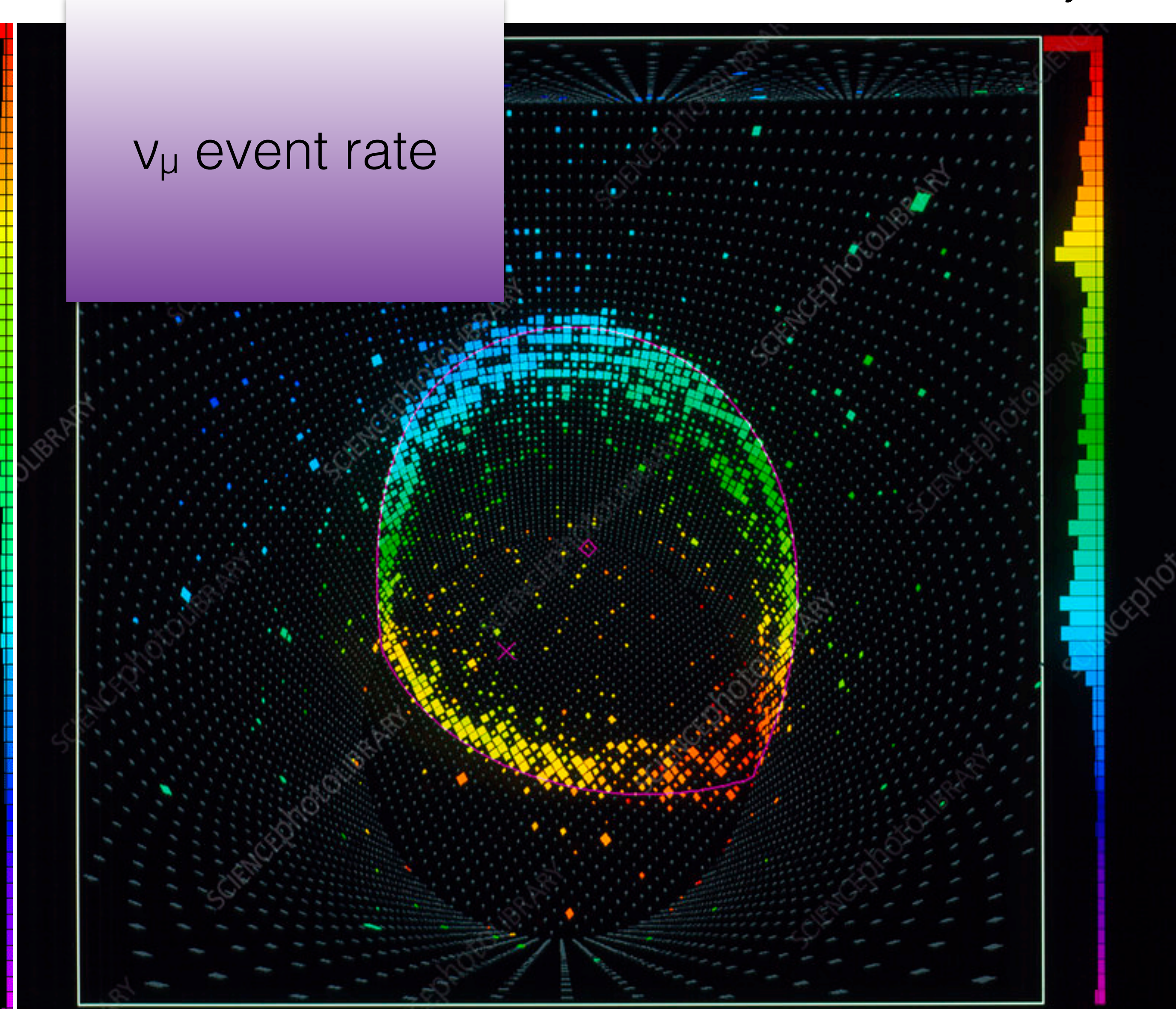

T2K oscillation analysis strategy

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

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

Flux (Φ)

Interaction model (cross section, σ)

Relationship between truth and observables (R)

Efficiency (ϵ)

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

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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

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

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

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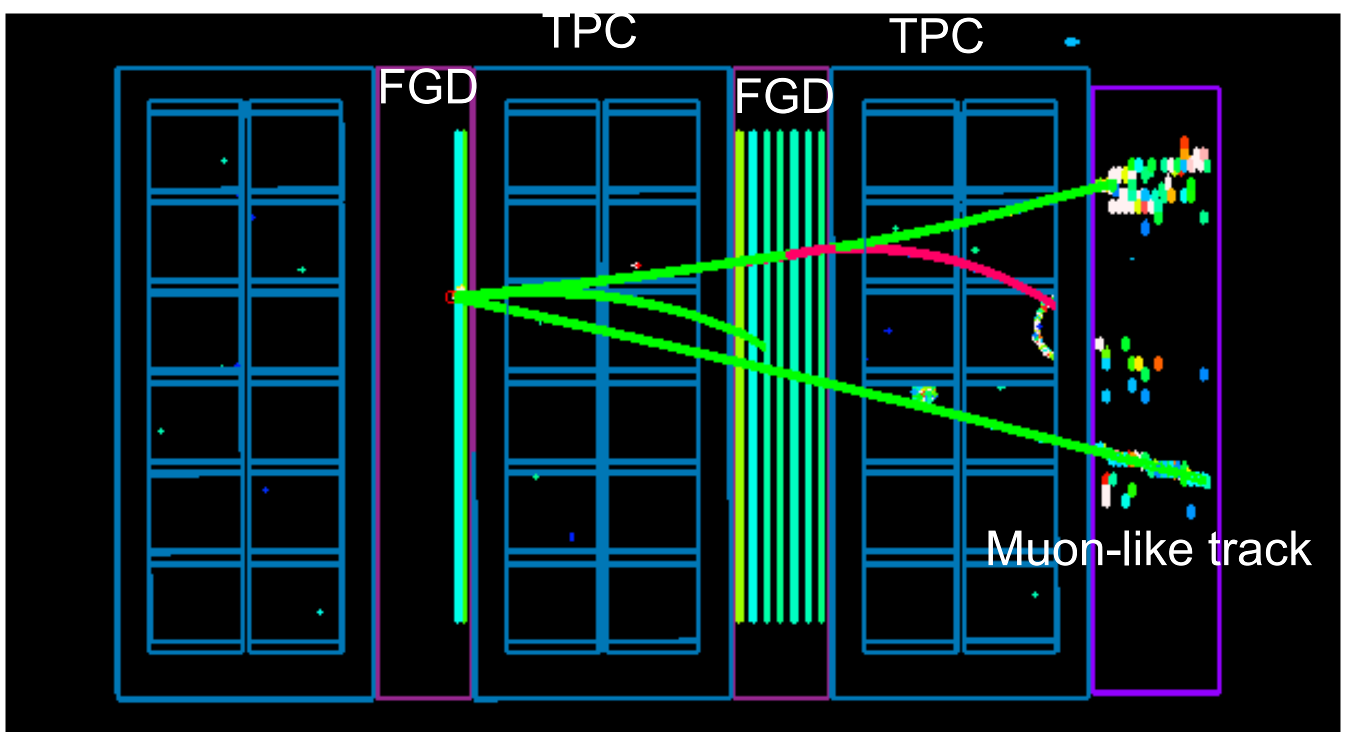

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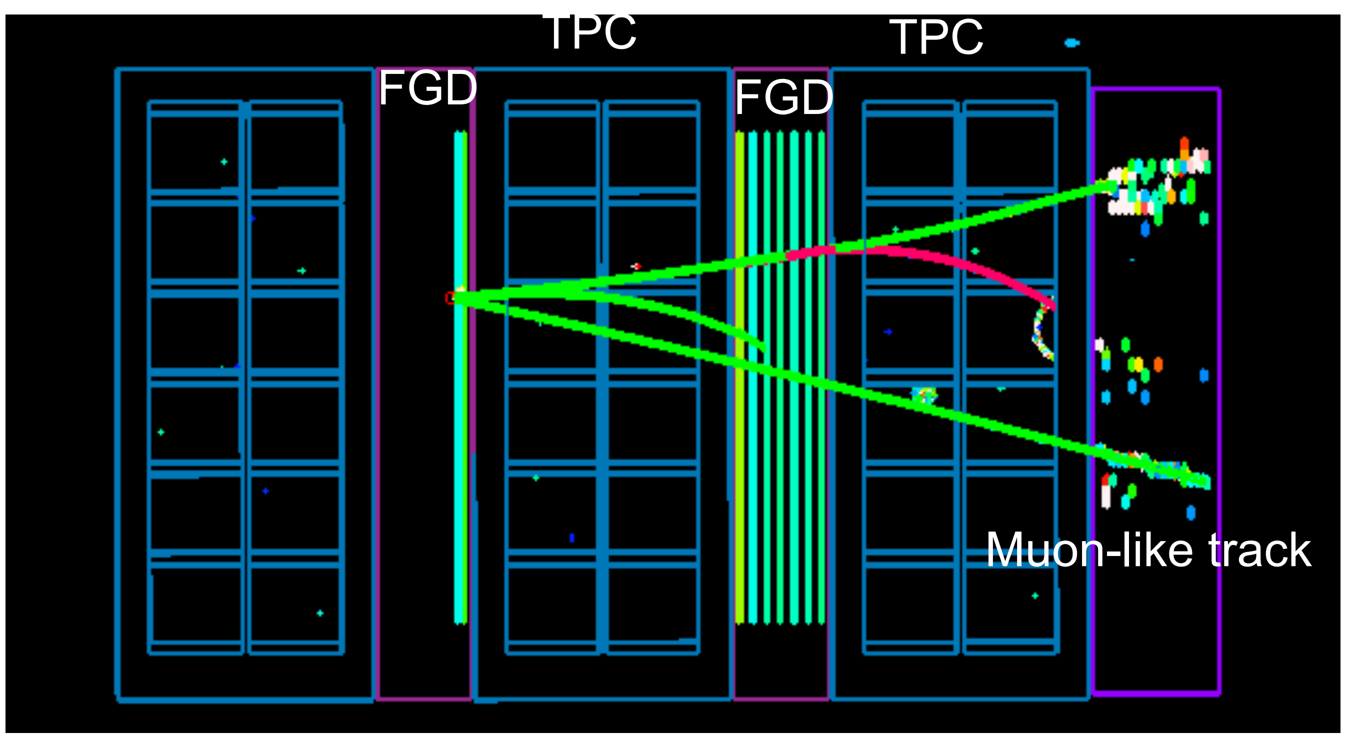
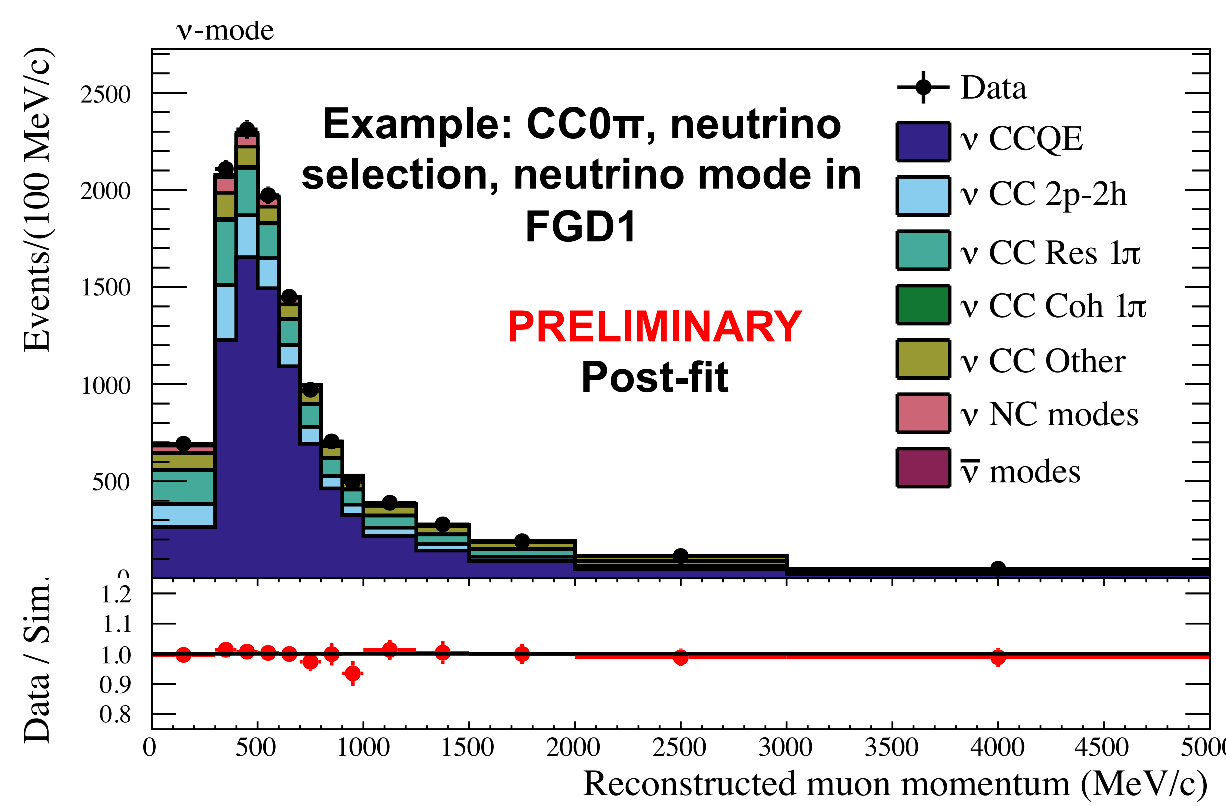
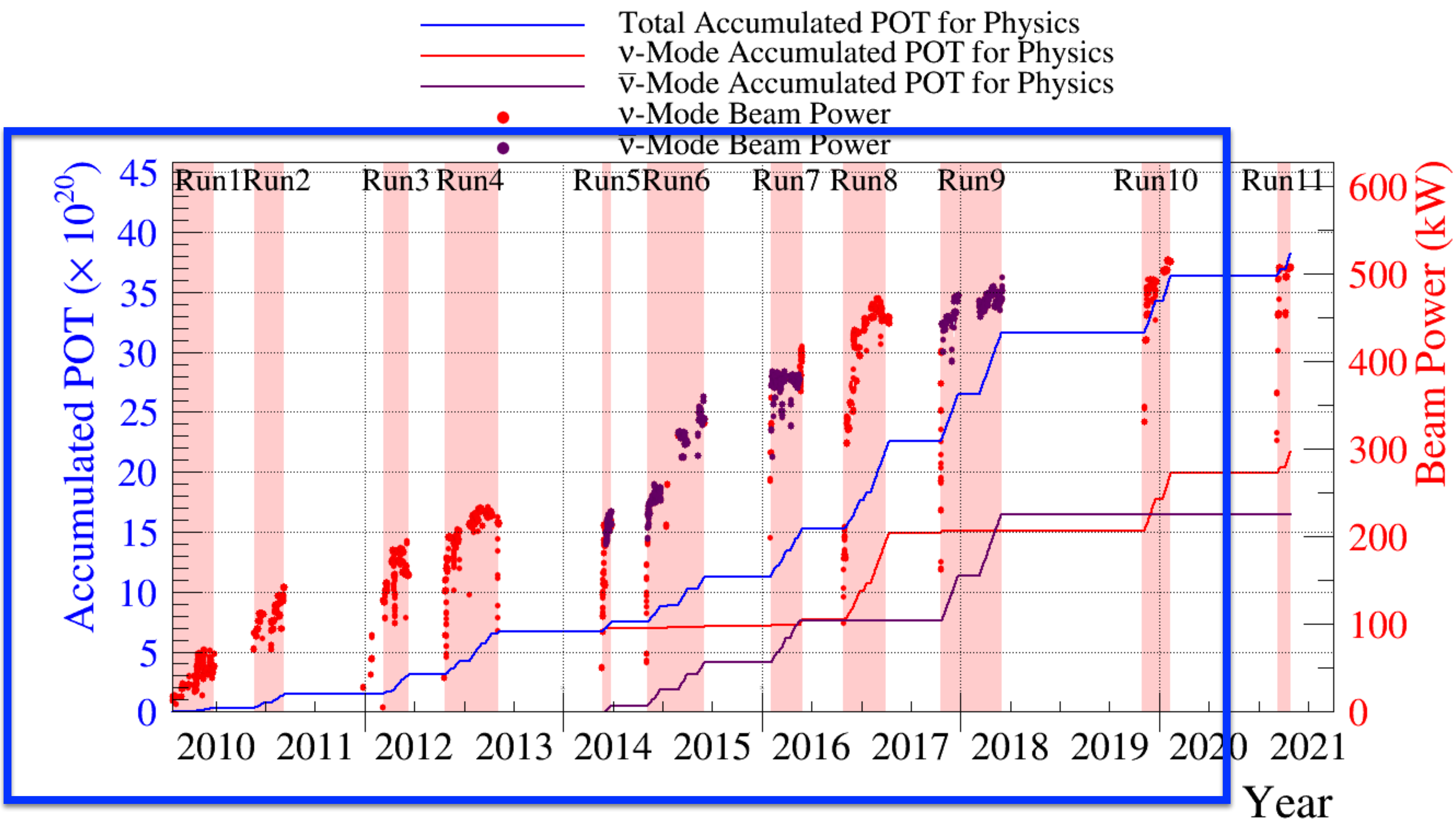




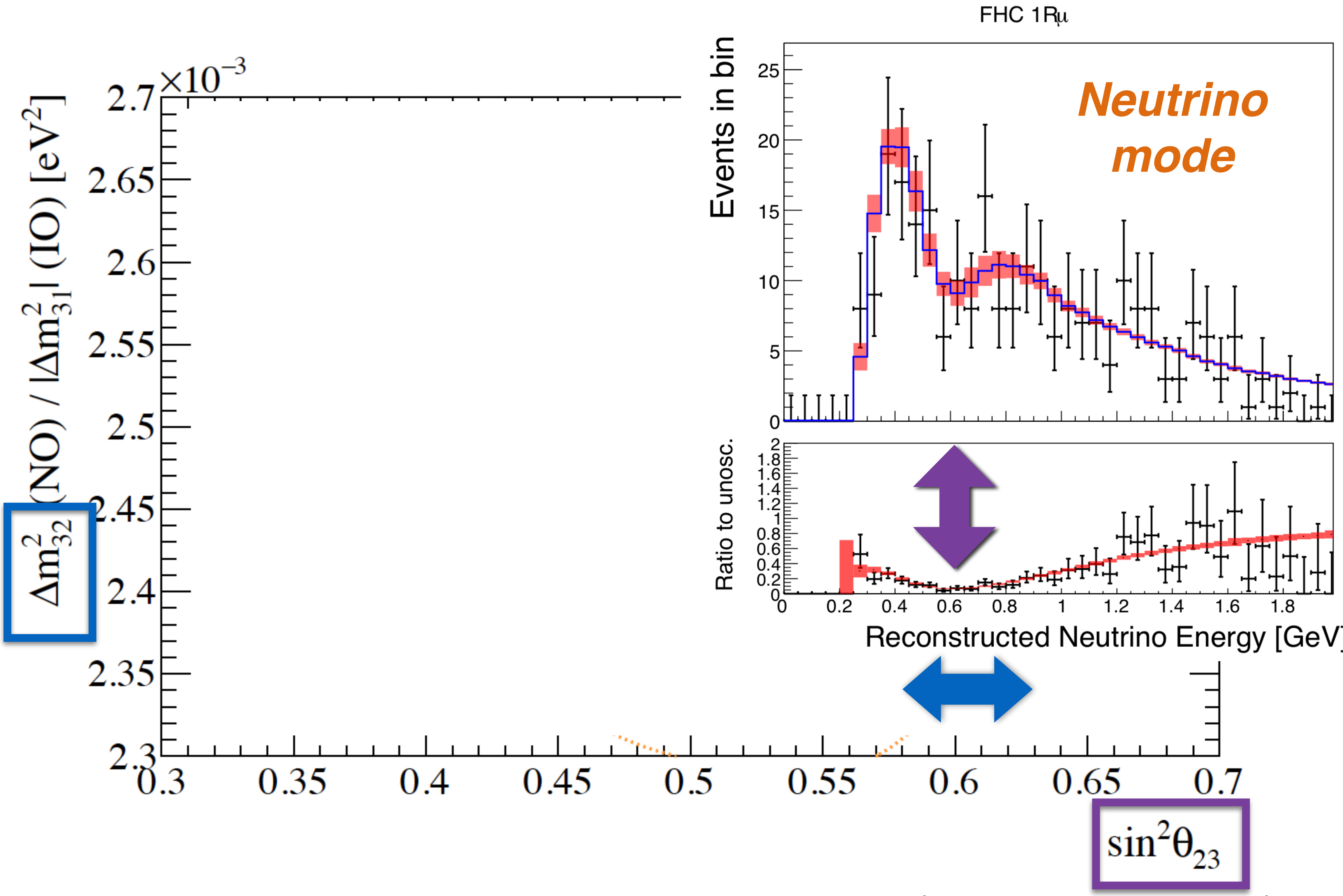
T2K: Data collection summary



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

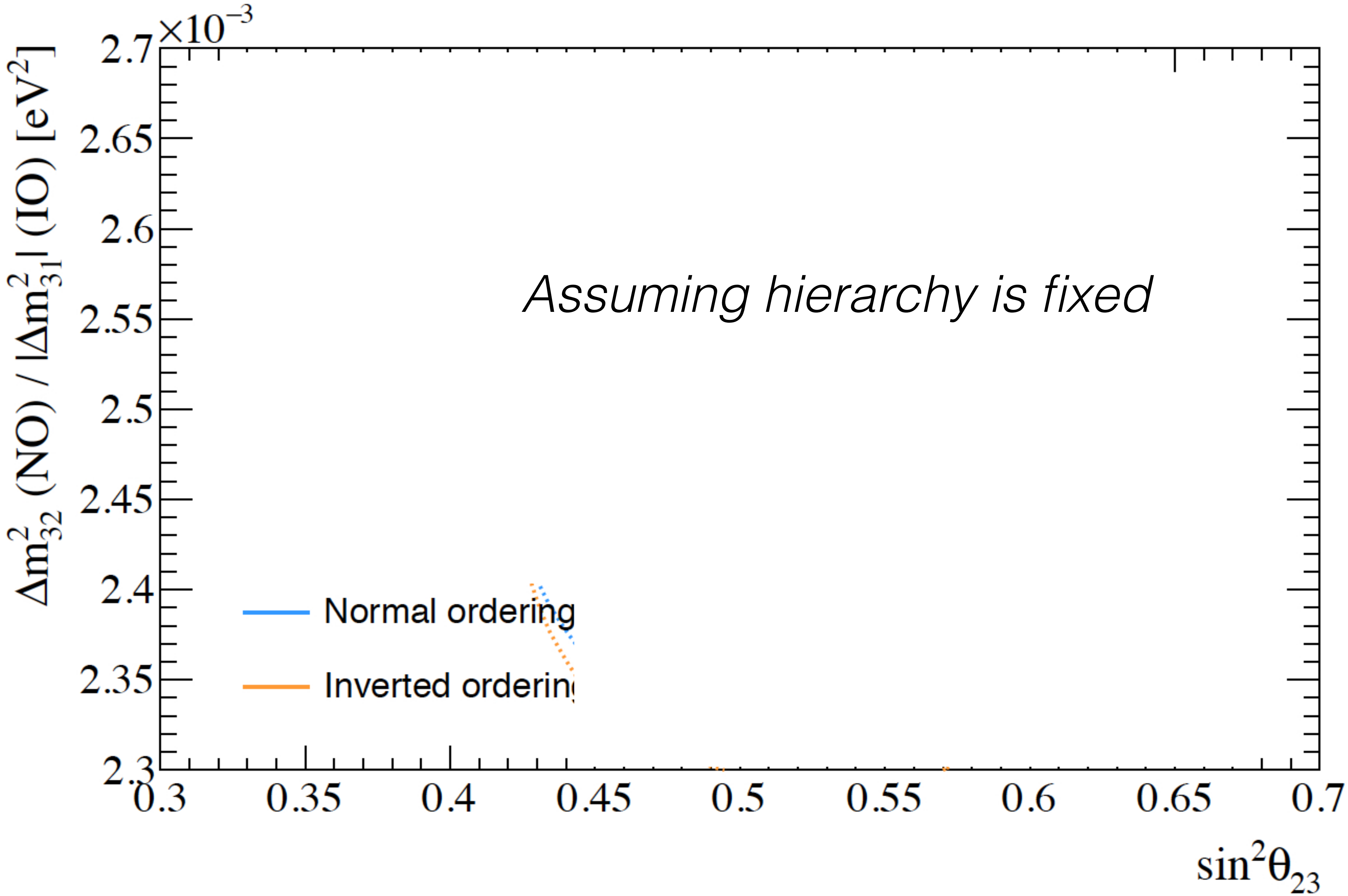
Data taken with SK Gd: Run 11:
ν-mode POT (FHC) : 2.116×10^{21}
$\bar{\nu}$-mode (RHC) POT : 1.651×10^{21}
Total delivered: 3.818×10^{21}

T2K: Precision disappearance results



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

T2K: Precision disappearance results



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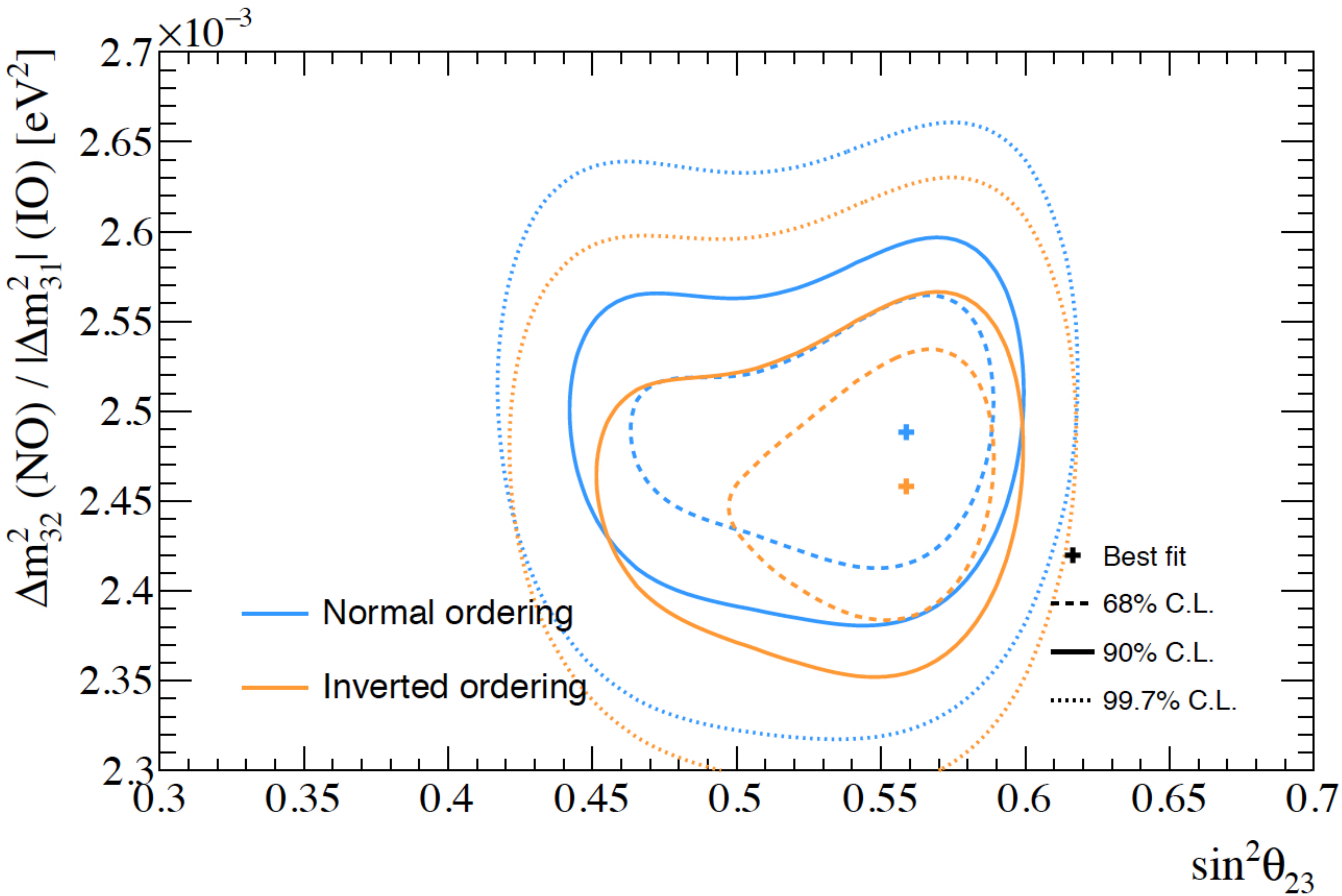
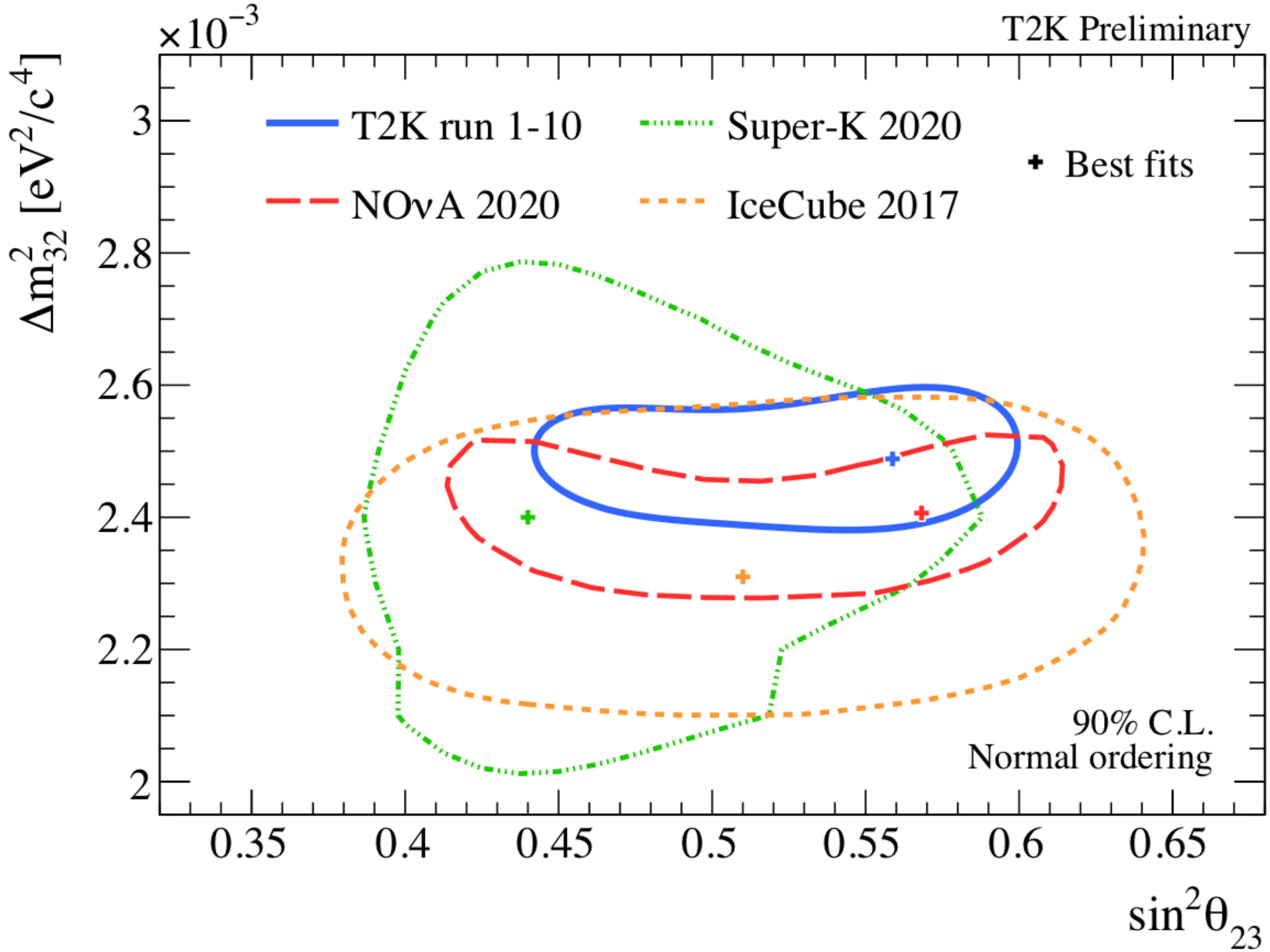


T2K data is consistent with maximal mixing (θ_{23}=45deg)

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

T2K: Window on CPV

	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Data
FHC 1Rμ	356.48	355.76	356.44	357.27	318
RHC 1Rμ	138.34	137.98	138.34	138.73	137
FHC 1Re	$\boxed{97.62}$	82.44	67.56	82.74	$\boxed{94}$
RHC 1Re	16.69	18.96	20.90	18.63	16
FHC 1R ν_e CC1π^+	$\boxed{9.20}$	8.01	6.51	7.71	$\boxed{14}$
FHC 1Rμ ($E_{\mathrm{rec}} < 1.2\,\mathrm{GeV}$)	213.40	213.06	213.36	213.81	191
RHC 1Rμ ($E_{\mathrm{rec}} < 1.2\,\mathrm{GeV}$)	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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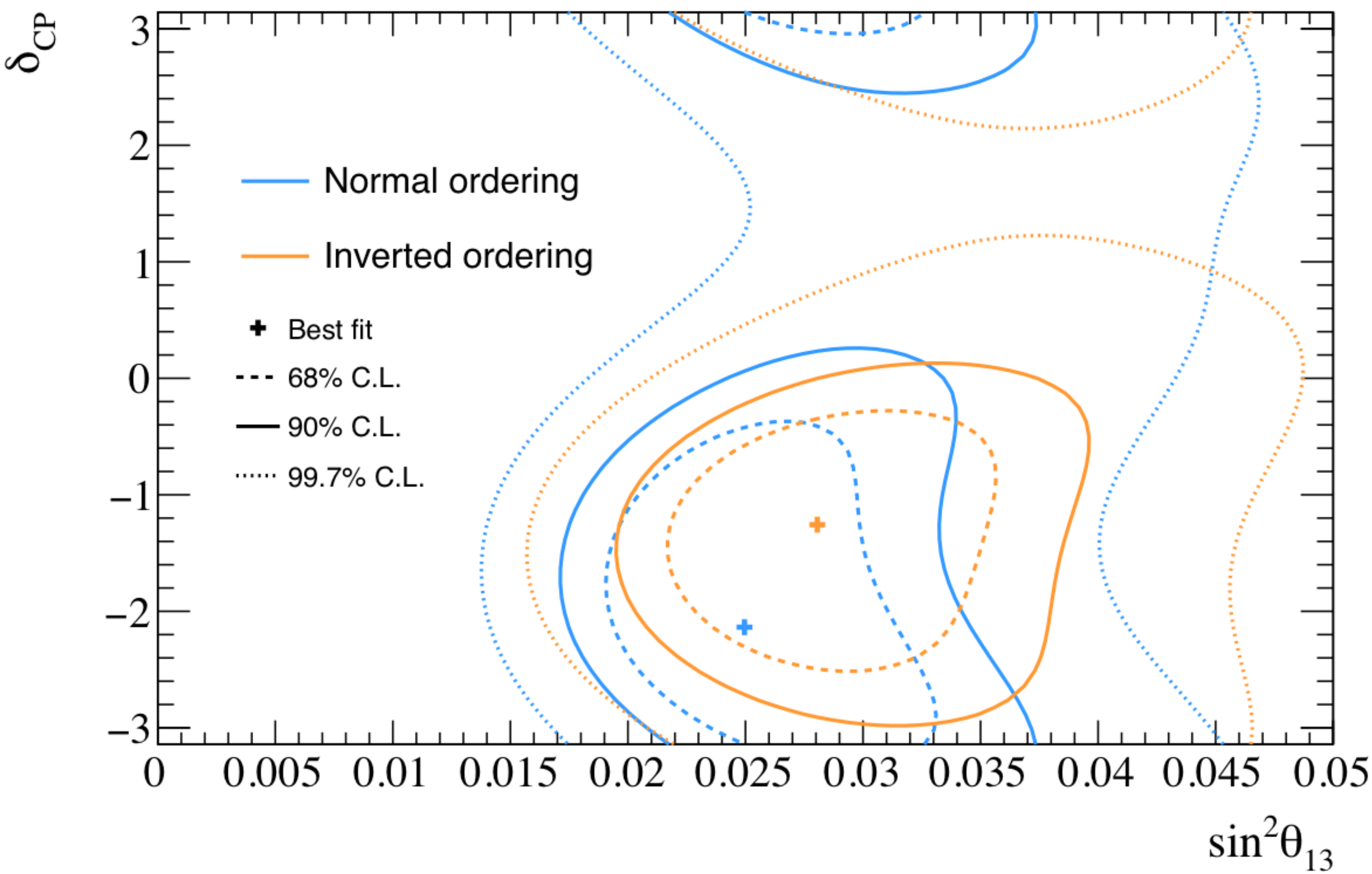
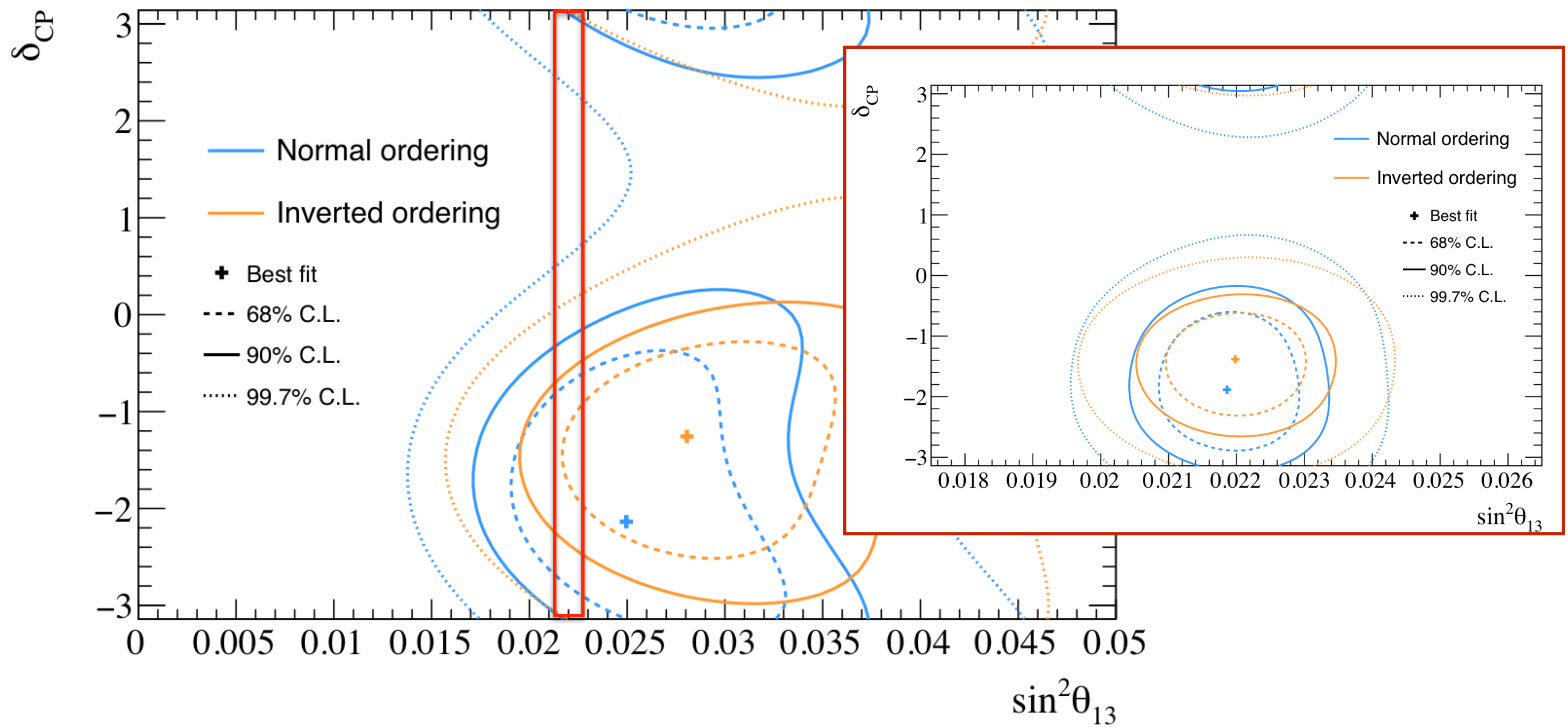
Data currently has an excess of electron neutrino events, and a deficit of electron antineutrino events...

T2K: Window on CPV



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

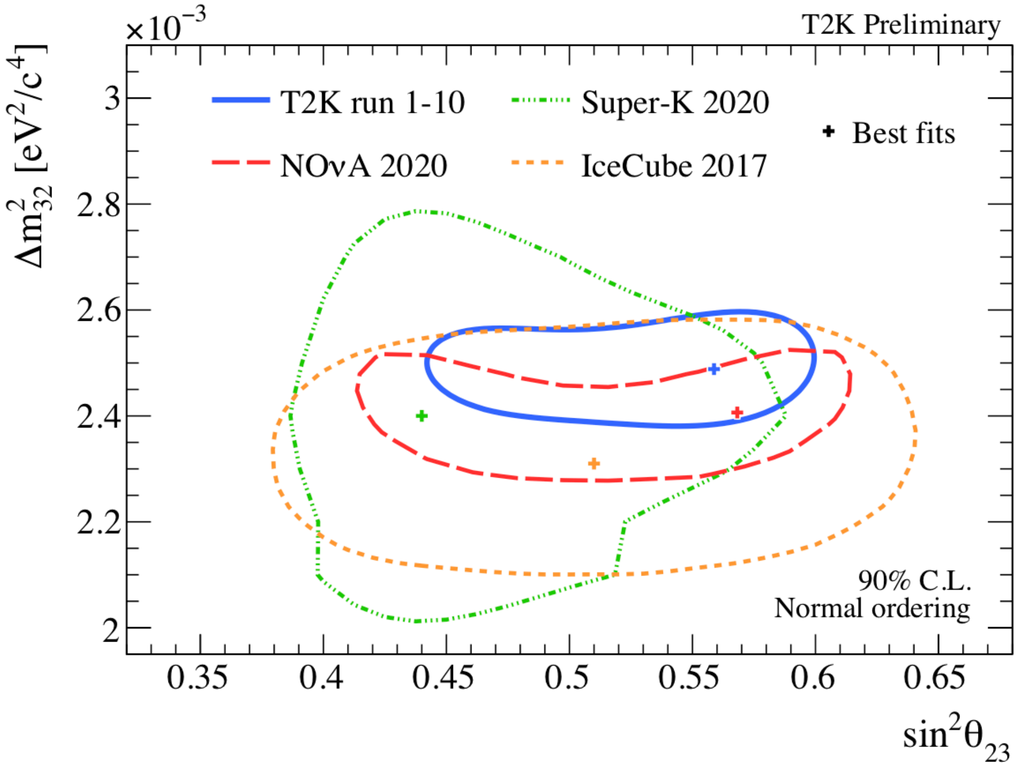
T2K: Window on CPV

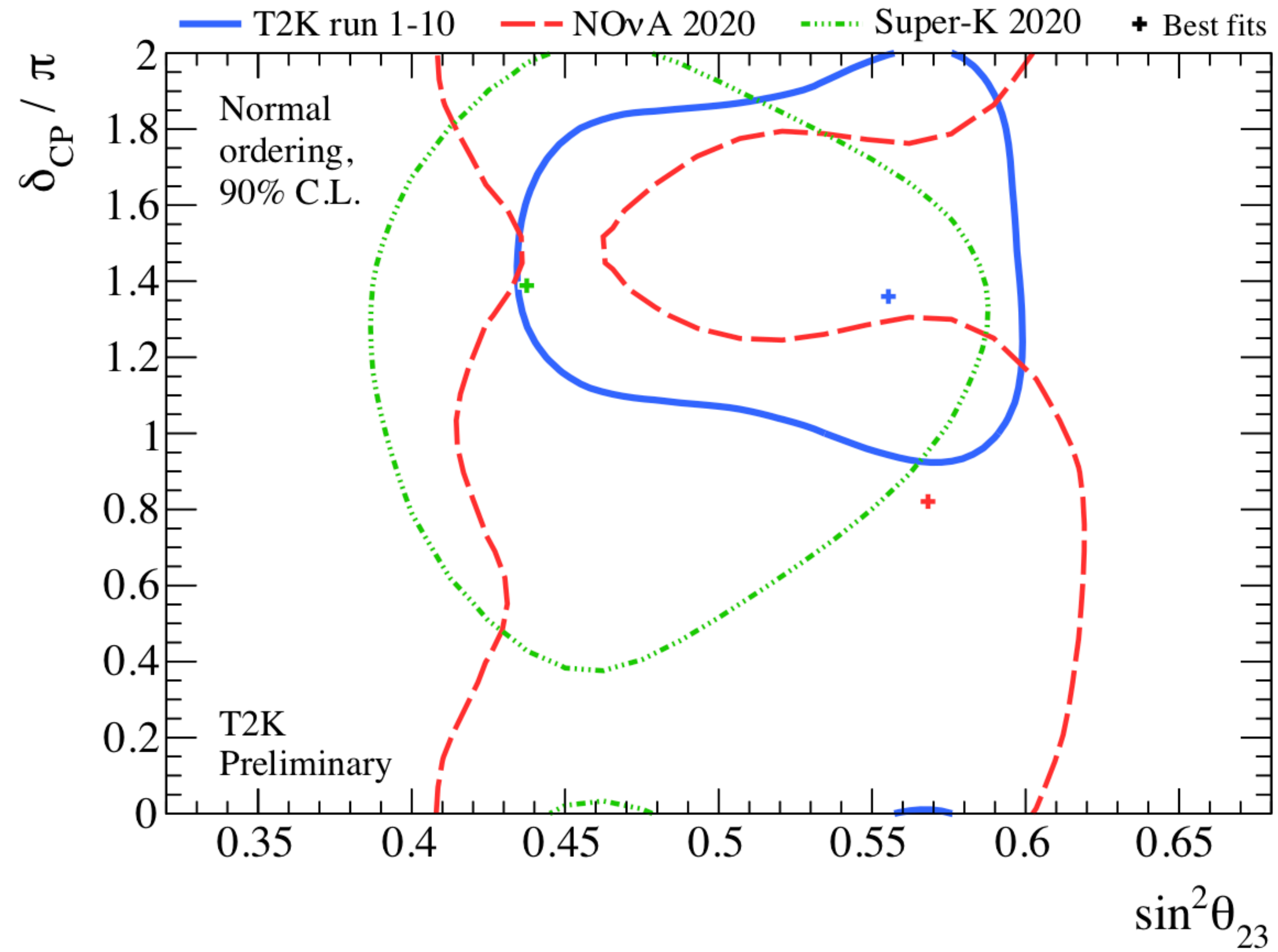


Our data is also consistent with independent results (reactor measurements of θ_{13} only)

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

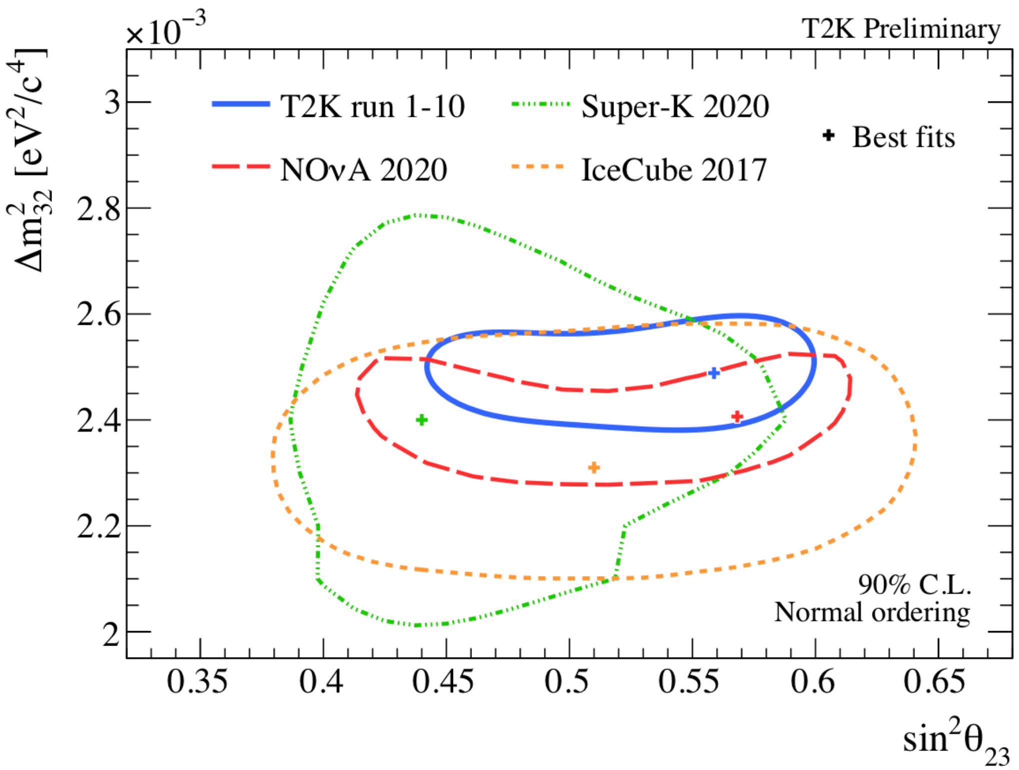
The current global picture, part 2

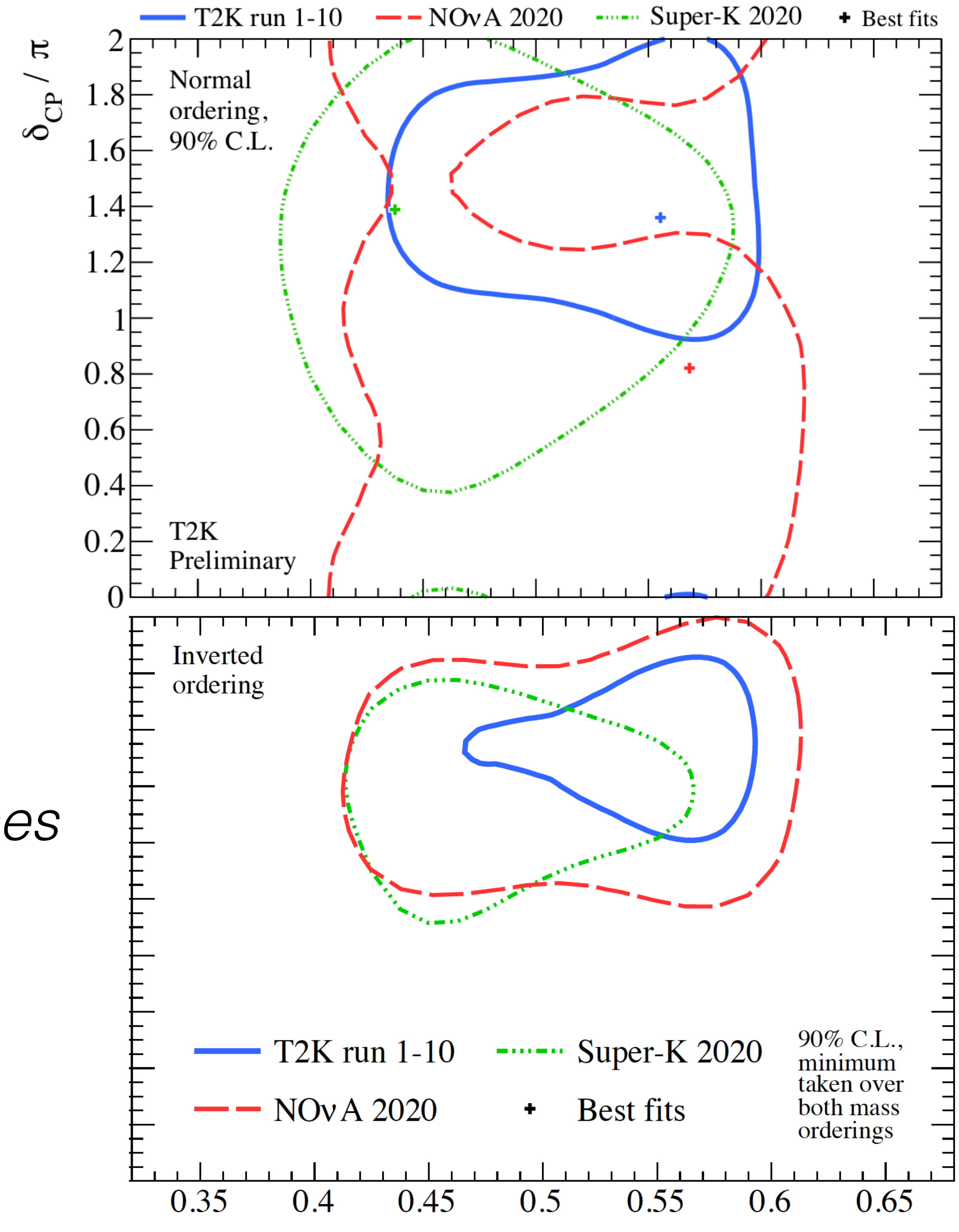




Projection now in δ_{CP} vs. θ_{23} space

The current global picture, part 2





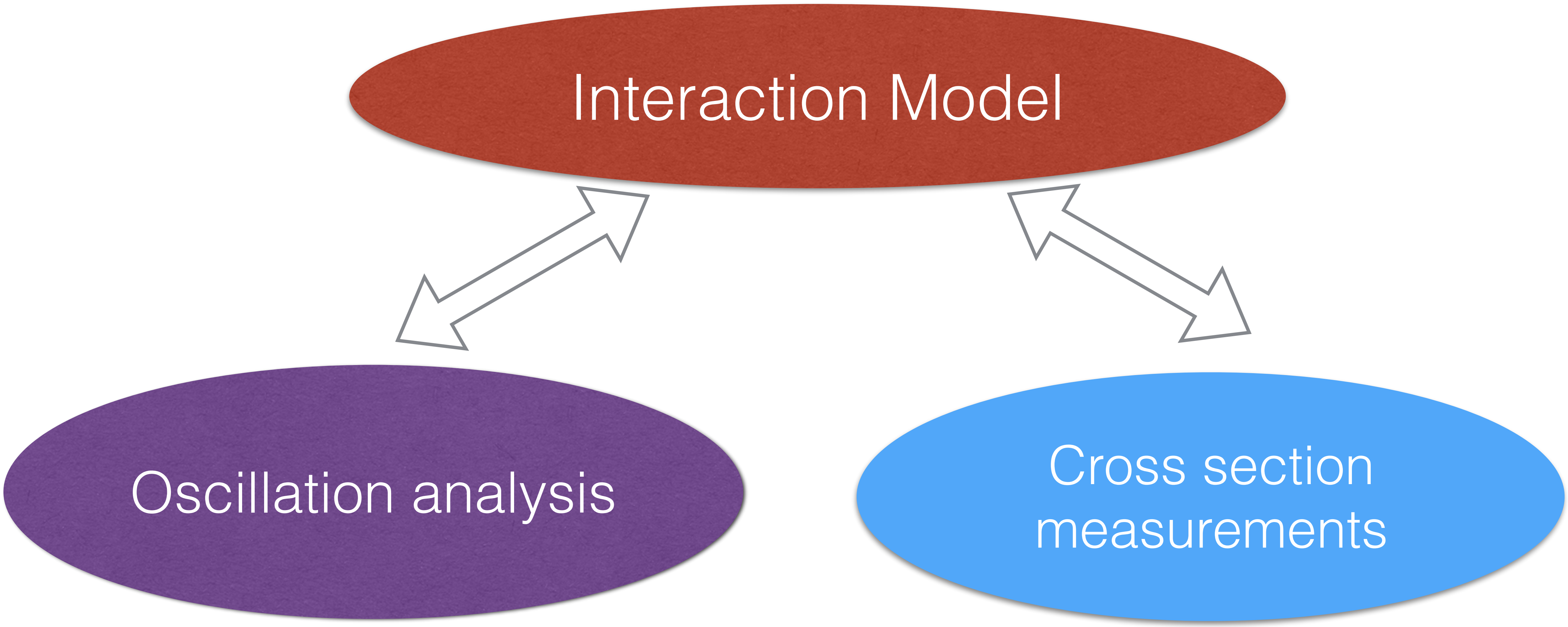
Plans underway for joint analyses with Super-Kamiokande and NOvA experiments

Outline

Recent results from the Tokai-to-Kamioka (T2K) neutrino oscillation experiment

Vibrant program in cross section and exotic physics

T2K: Tackling the challenge of interactions



Model Development: Reduced systematic uncertainty through external data, theory

Completeness: tests of impact of modeling with bias studies

Unique, new or improved, measurements for theory and current, future experimental program

Cross section results in 2020-2021

	Reference
First T2K measurement of transverse kinematic imbalance in the muon-neutrino charged-current single π+ production channel containing at least one proton	*PRD* 103 (2021) 11, 112009
Measurements of ν_μ and ν_μ charged-current cross-sections without detected pions or protons on water and hydrocarbon at a mean anti-neutrino energy of 0.86 GeV	*PTEP* 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	*PRD* 101 (2020) 11, 112004
Measurement of the charged-current electron (anti-)neutrino inclusive cross-sections at the T2K off-axis near detector ND280	*JHEP* 10 (2020) 114
First combined measurement of the muon neutrino and antineutrino charged-current cross section without pions in the final state at T2K	*PRD* 101 (2020) 11, 112001

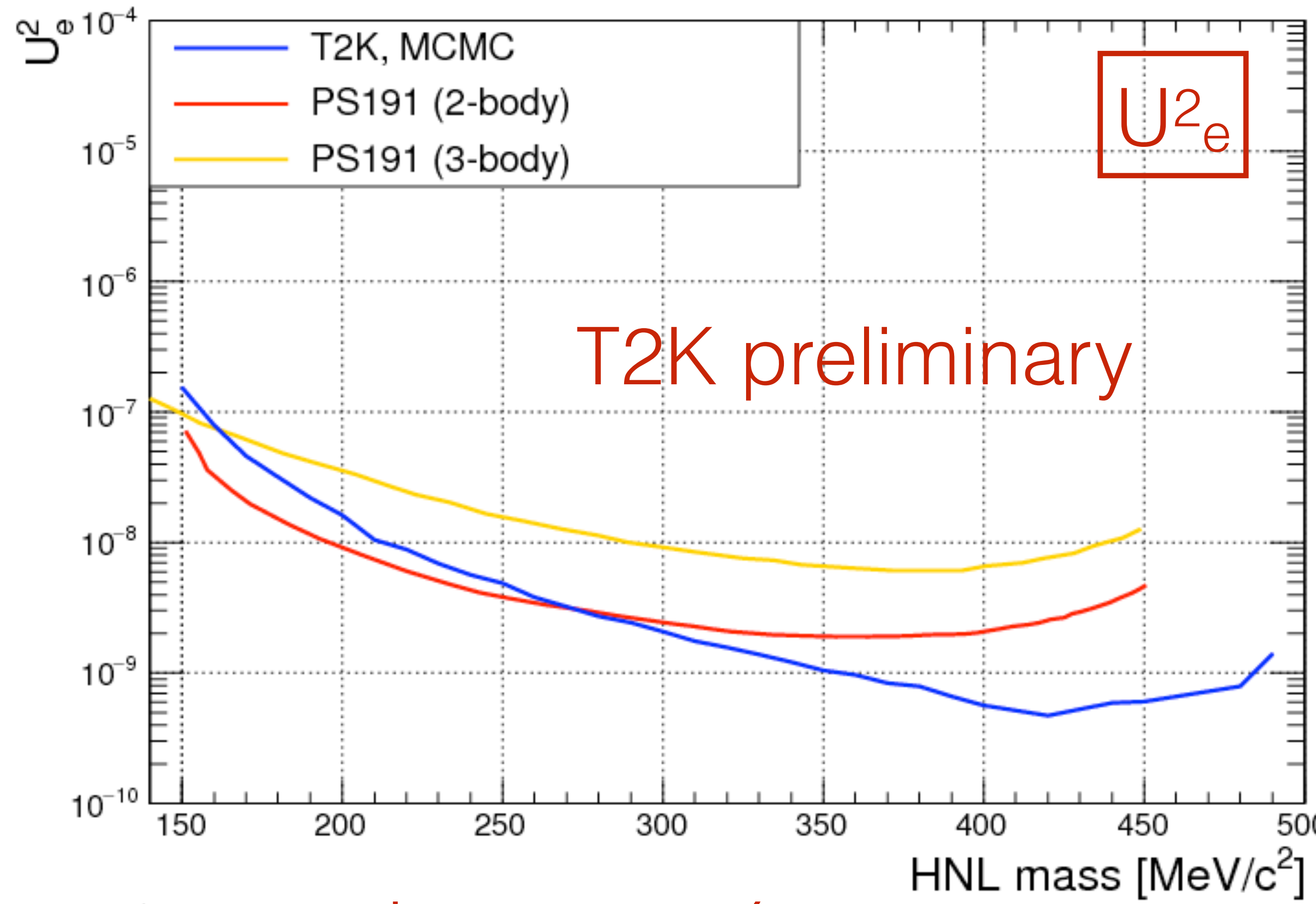
T2K exotics: Heavy Neutral Lepton search

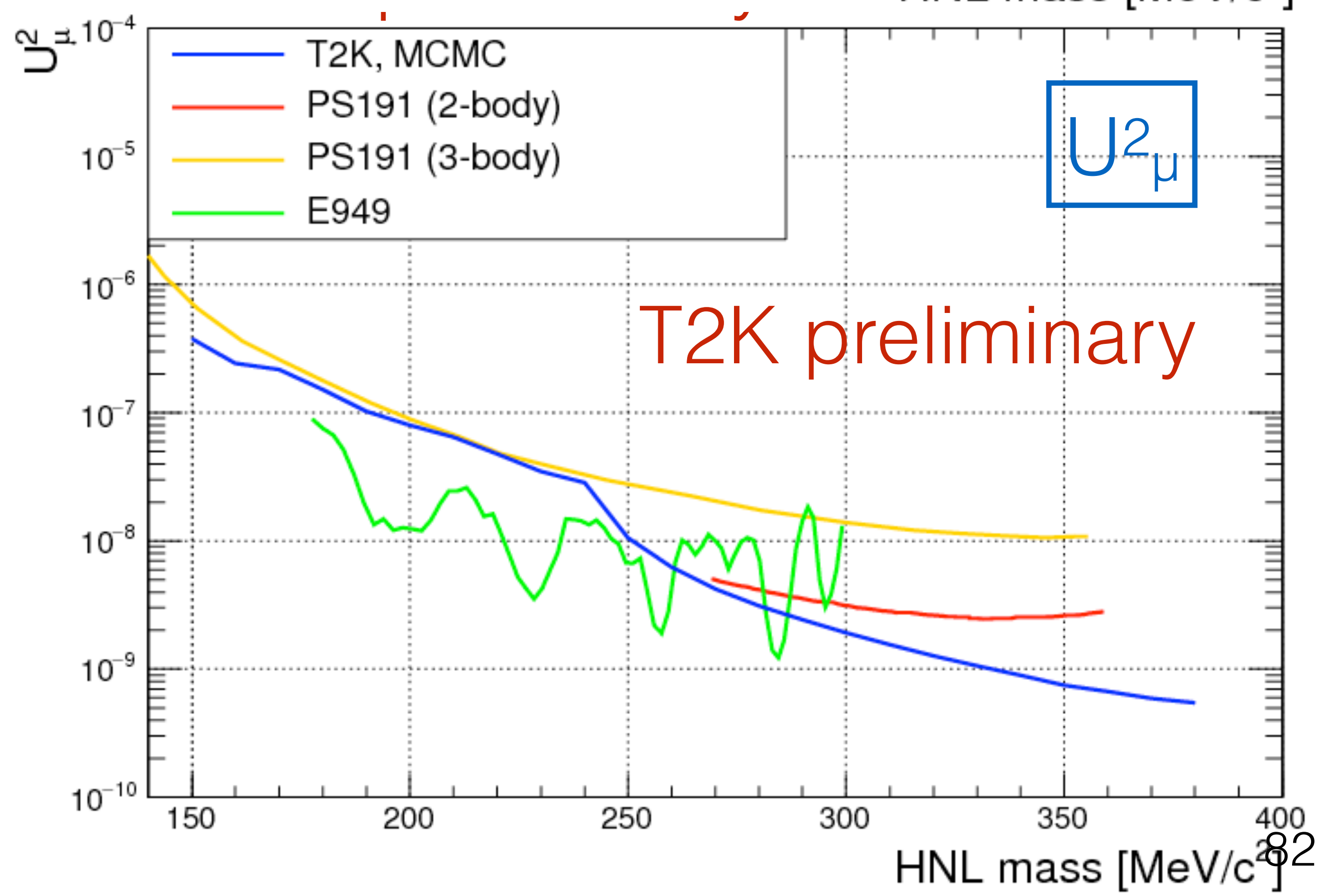
$$K^+ \to \ell^+ N$$

$$N \to \ell^\pm \pi^\mp, \ell^\pm \ell^\mp \nu$$

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

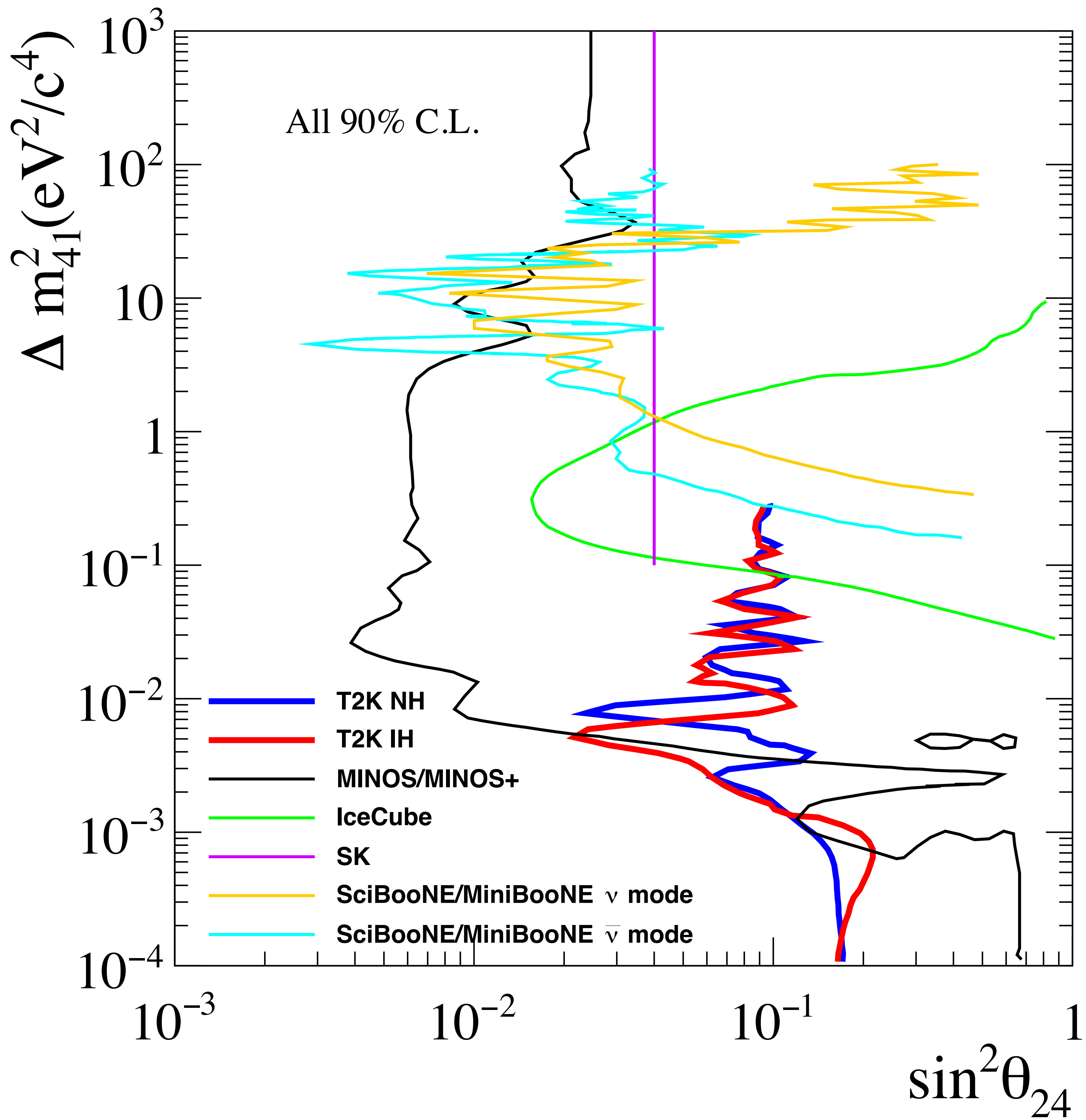




T2K: (light) sterile neutrino search

Search for sterile neutrinos…
with the far detector

- 3+1 model including muon, electron and neutral current samples



https://arxiv.org/abs/1902.06529

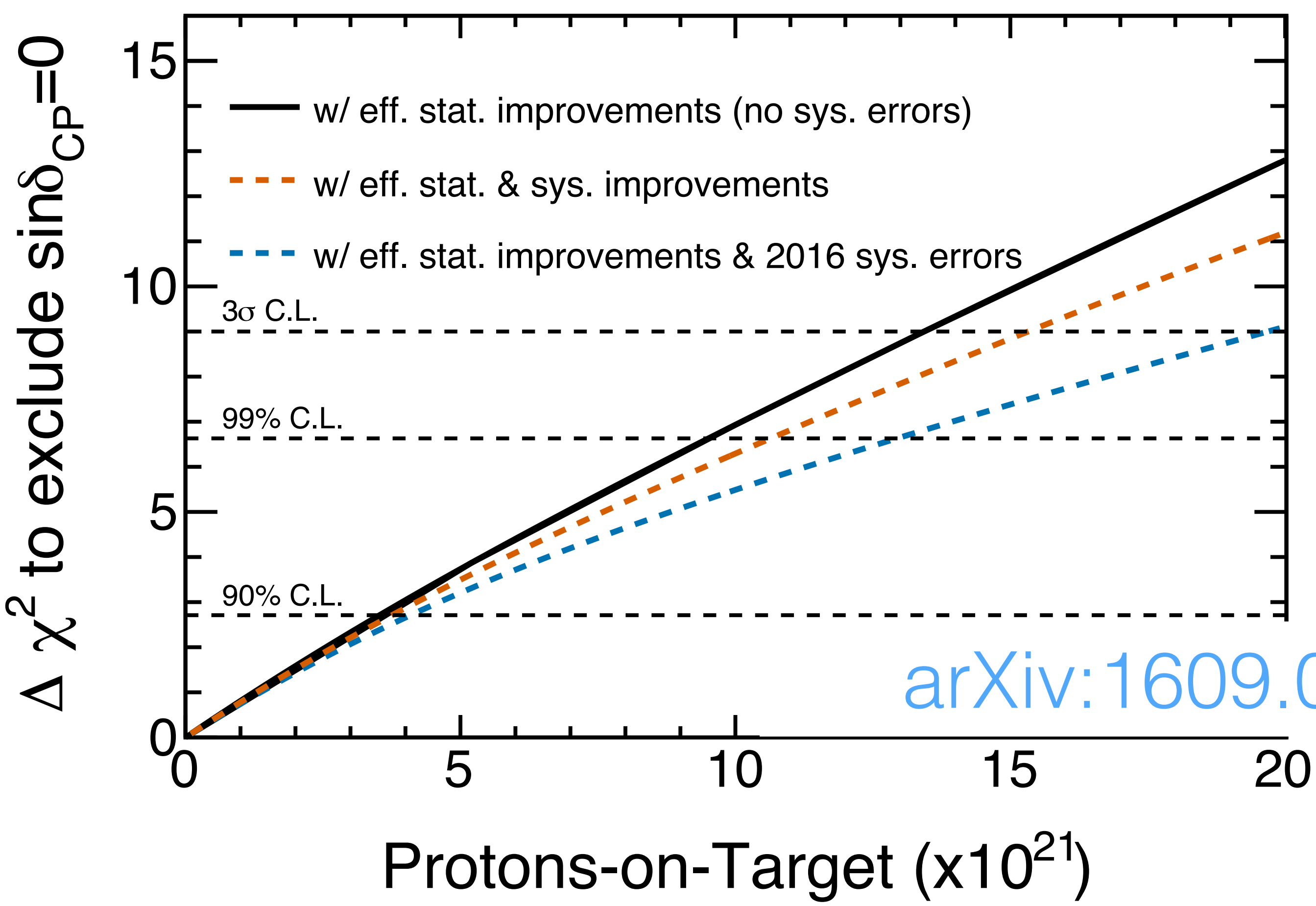
Outline

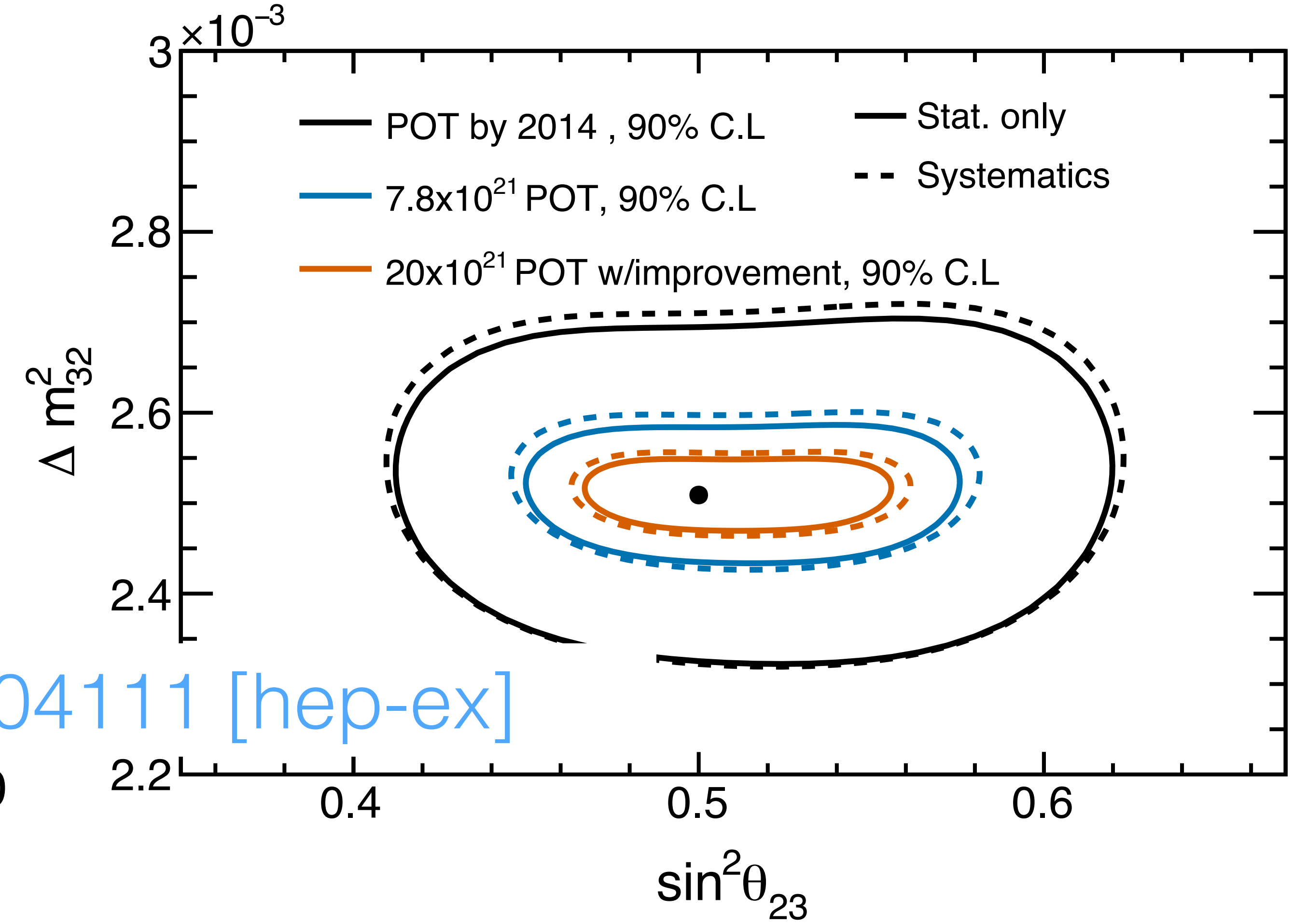
What is the future of accelerator-based oscillation experiments?

Continued run of T2K

- **Plan to collect at least 10 x10^{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





arXiv:1609.04111 [hep-ex]

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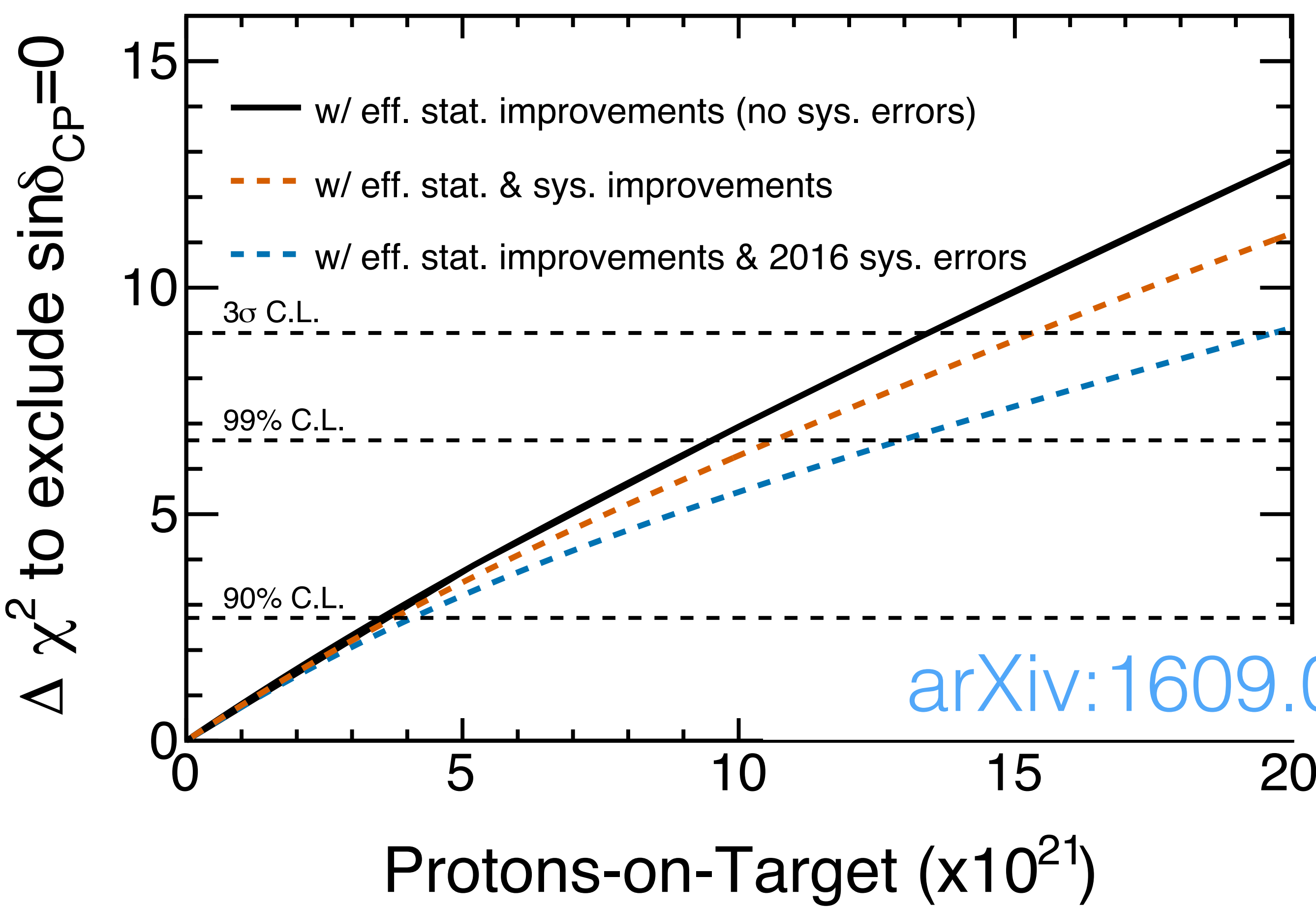
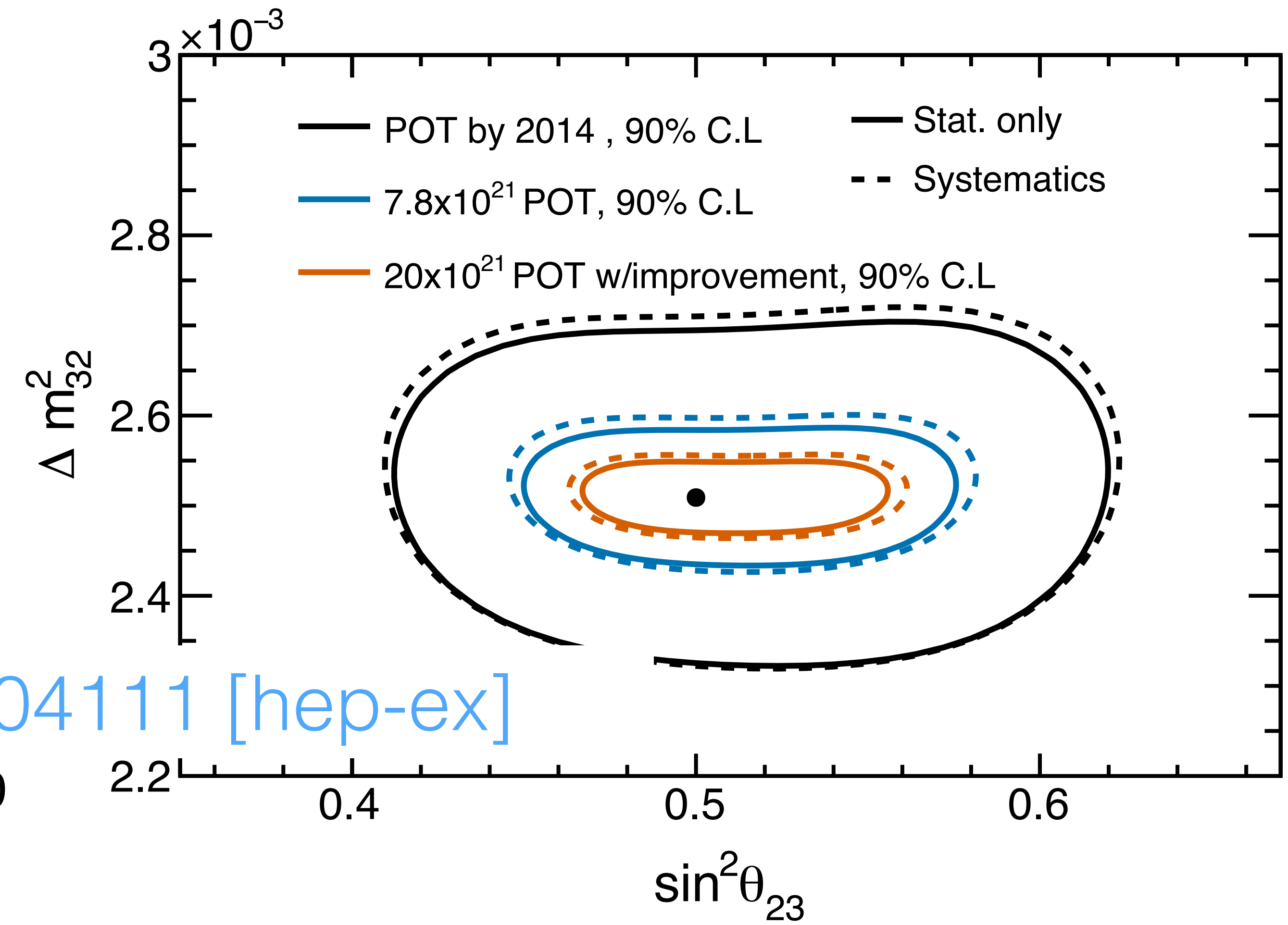
Continued run of T2K





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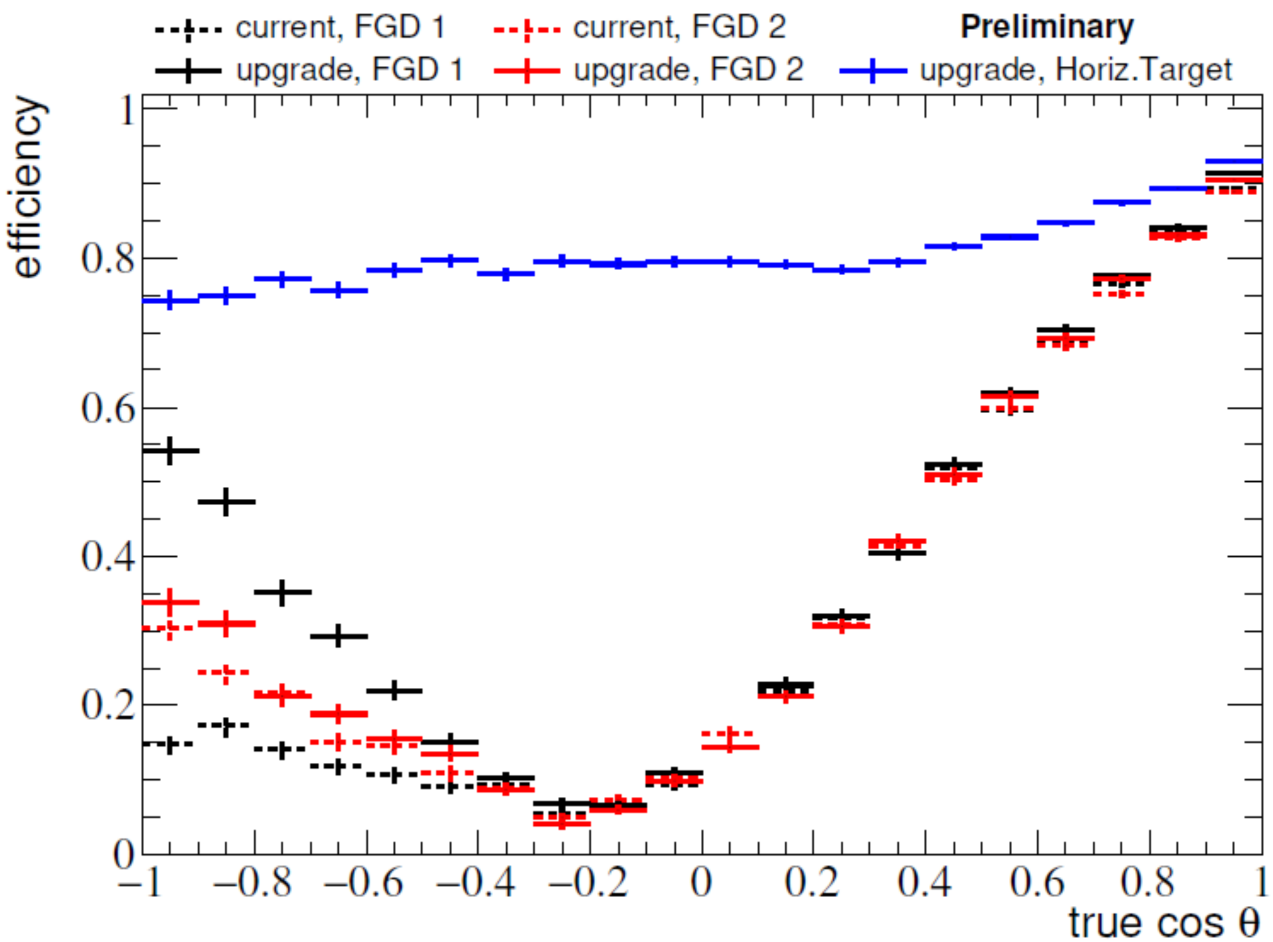
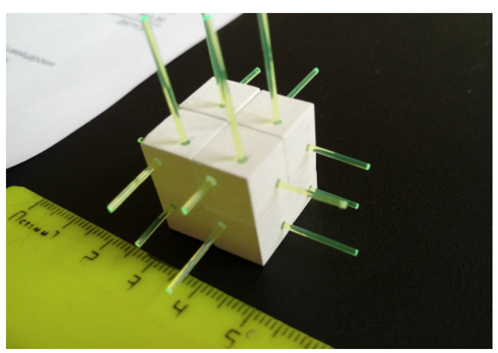
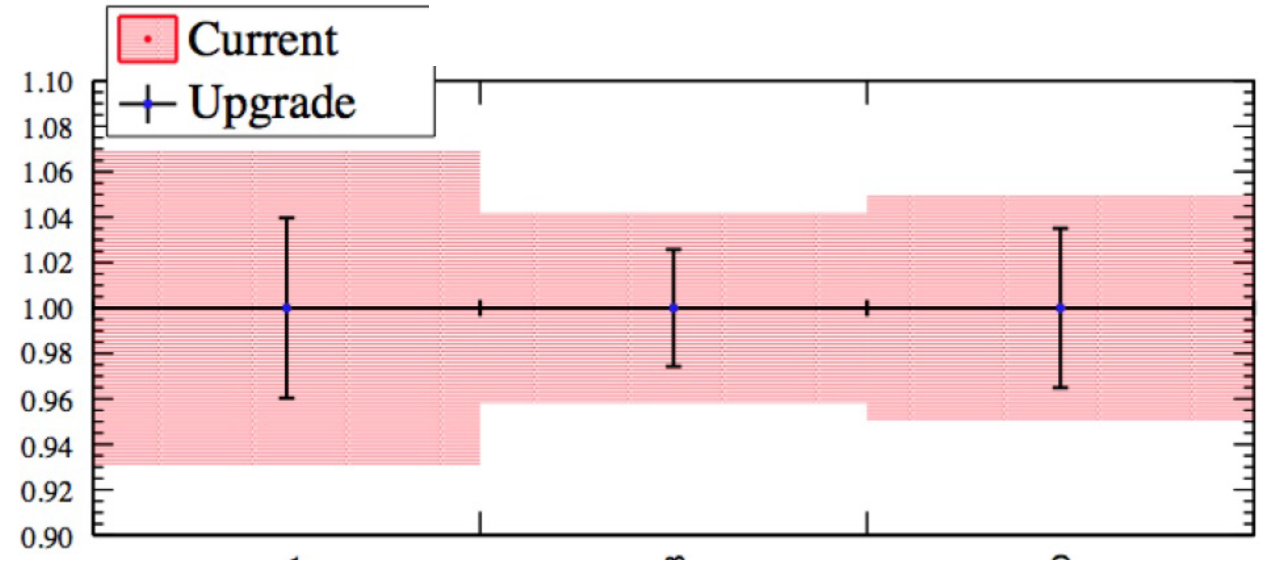
- Accelerator upgrade (to 1.3 MW)
  - 50% effective statistical gain from operational and systematic improvements (30% achieved)
- **Upgrade to T2K beam line and near detectors ("ND upgrade"); incorporation of WAGASCI+ BabyMind into T2K**

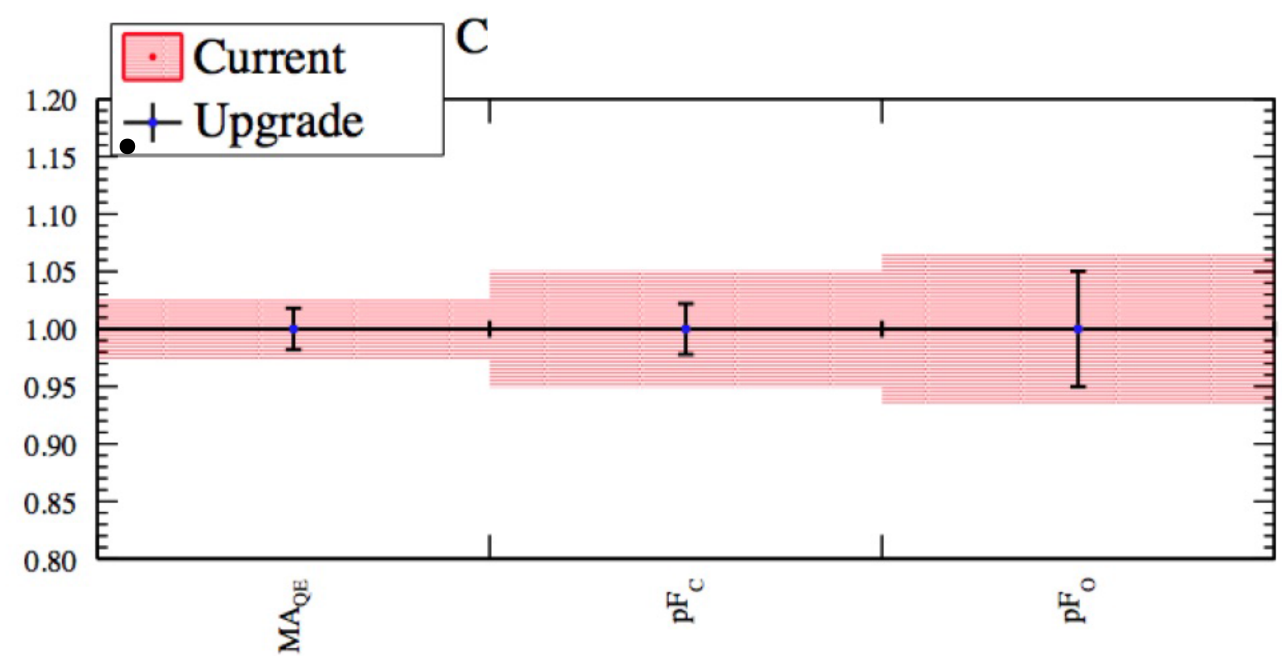
Prospects for T2K: ND upgrade





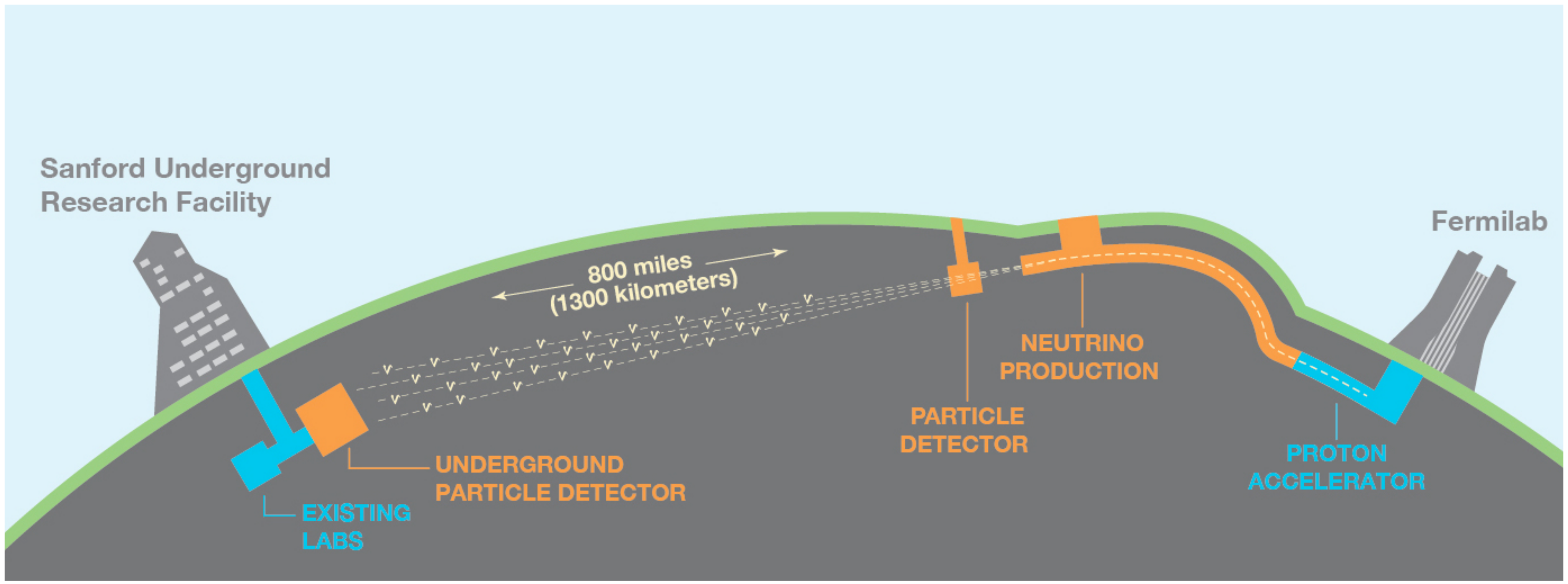


CCQE model parameters



- 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

The bright future of neutrino physics
Two big projects planned

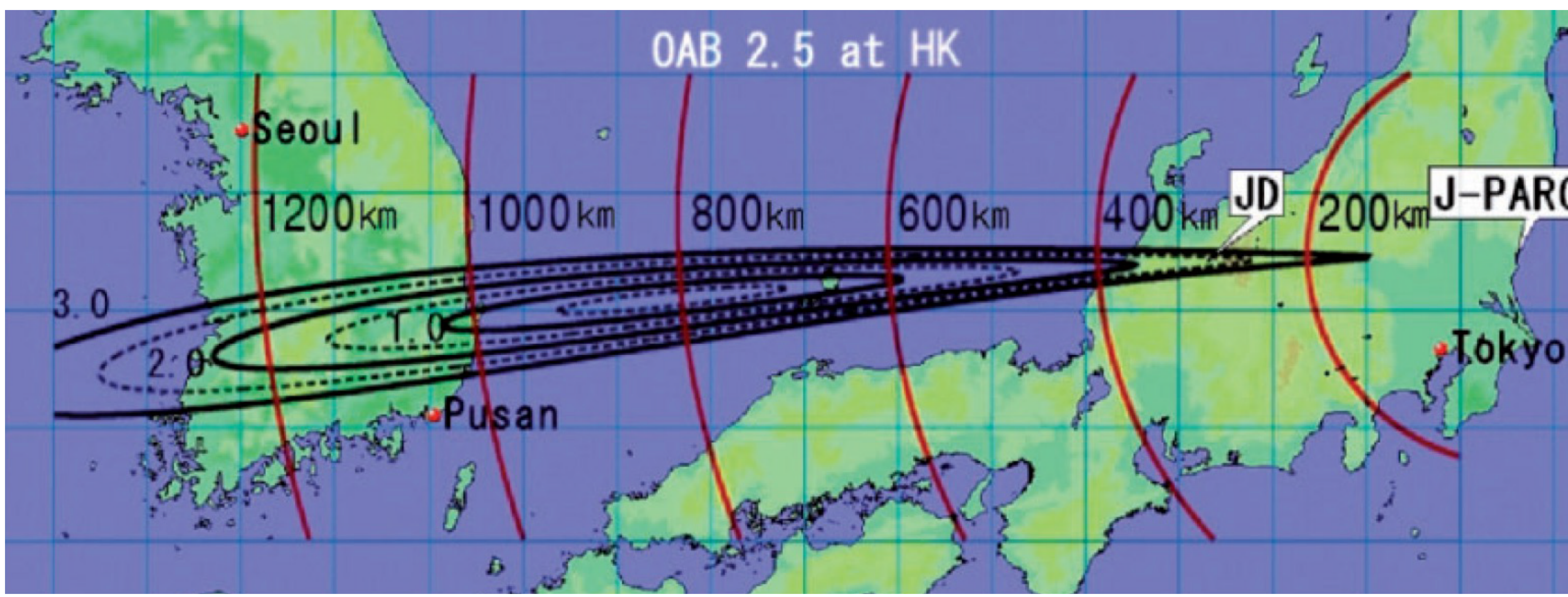


DUNE

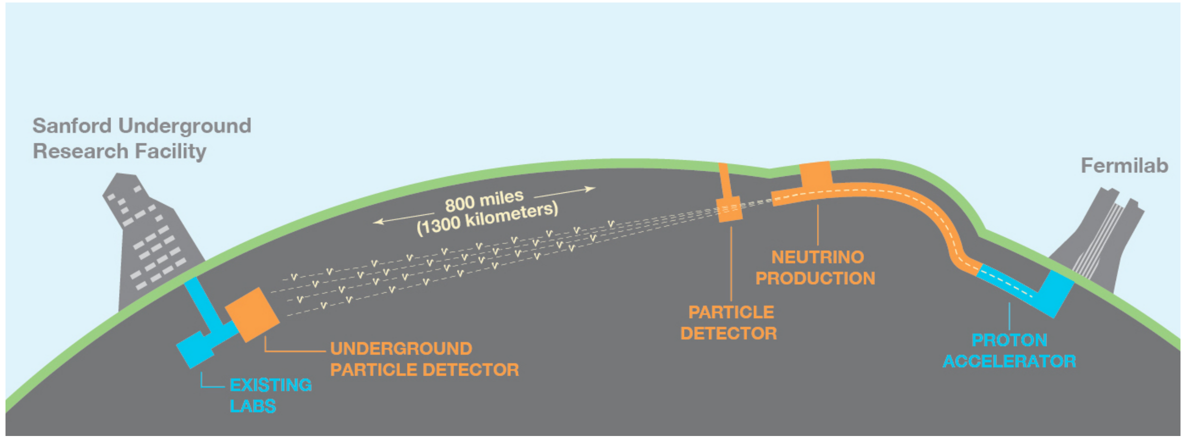
TDR, 4 volumes: arxiv2002.03005

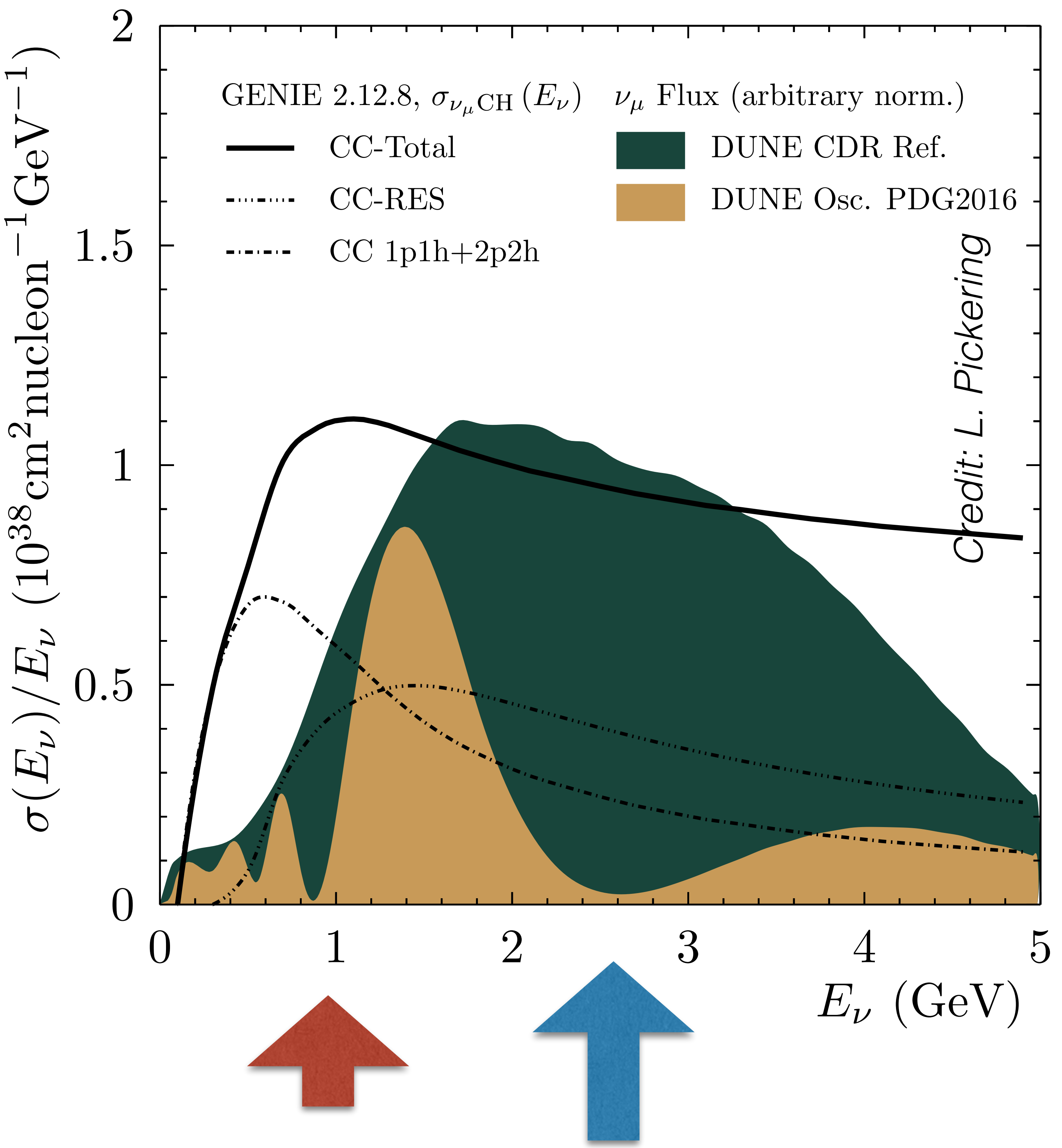
Hyper-K

Design report: arxiv1805.04163



Deep Underground Neutrino Experiment (DUNE)



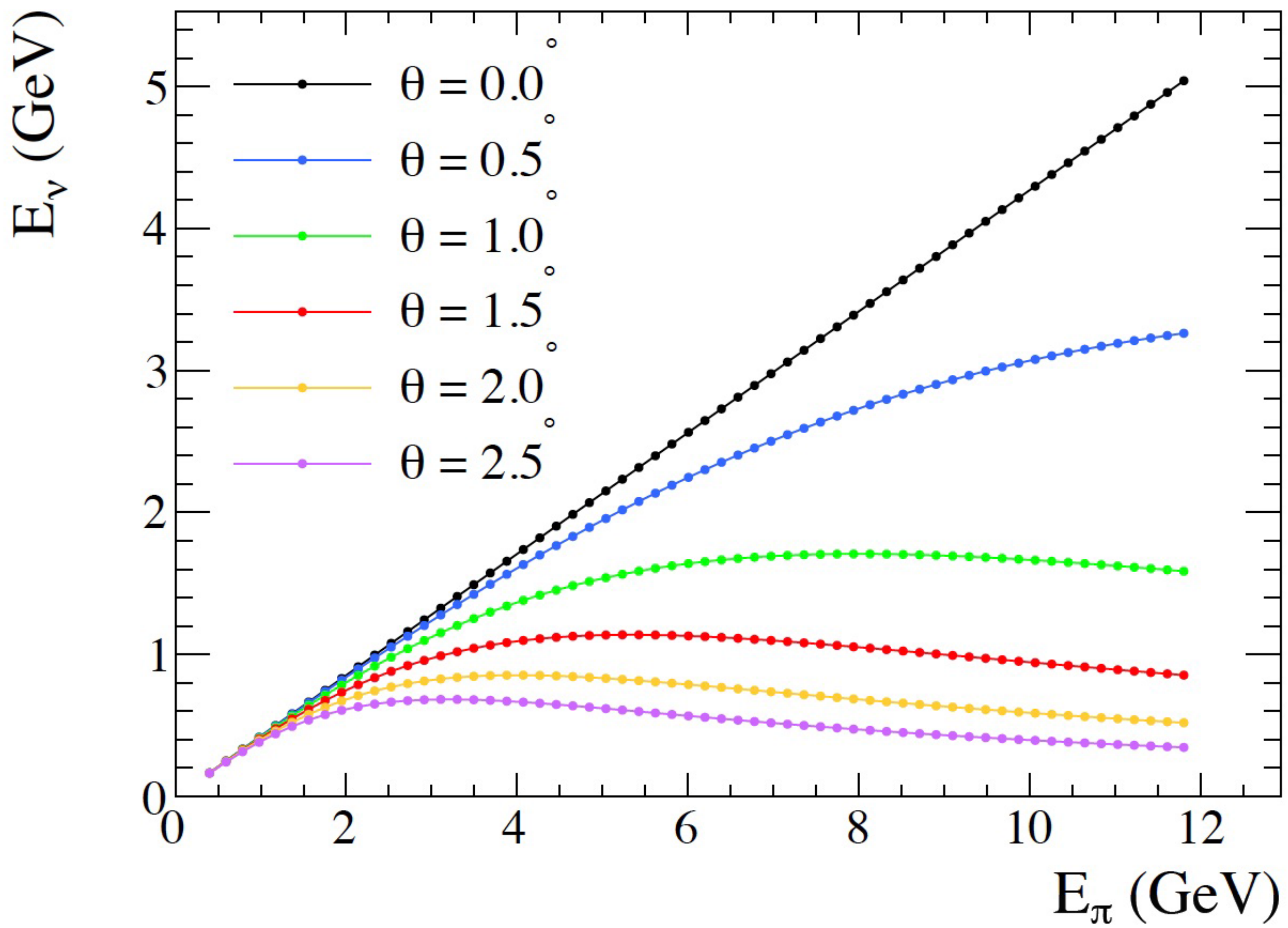


Second osc. max

First osc. max @ L=1300km

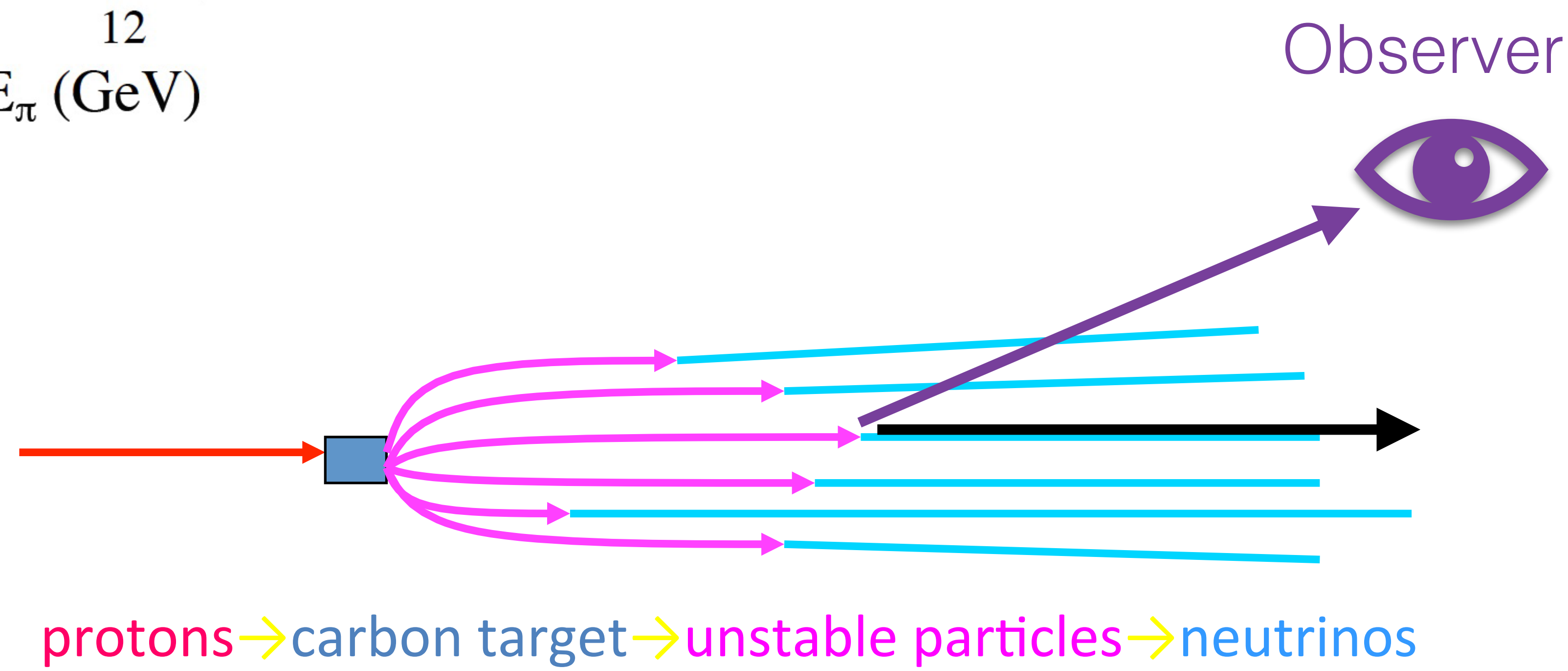
New capabilities!

Precision Reaction Independent Spectrum Measurement



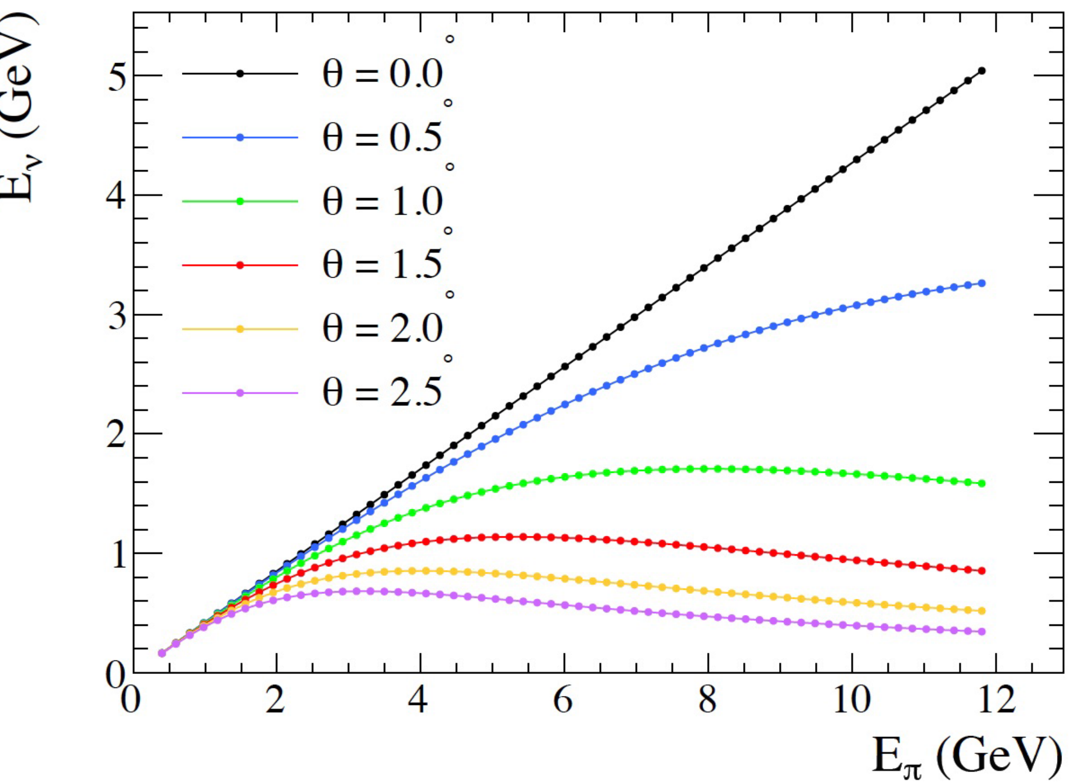
Credit: K. Duffy thesis

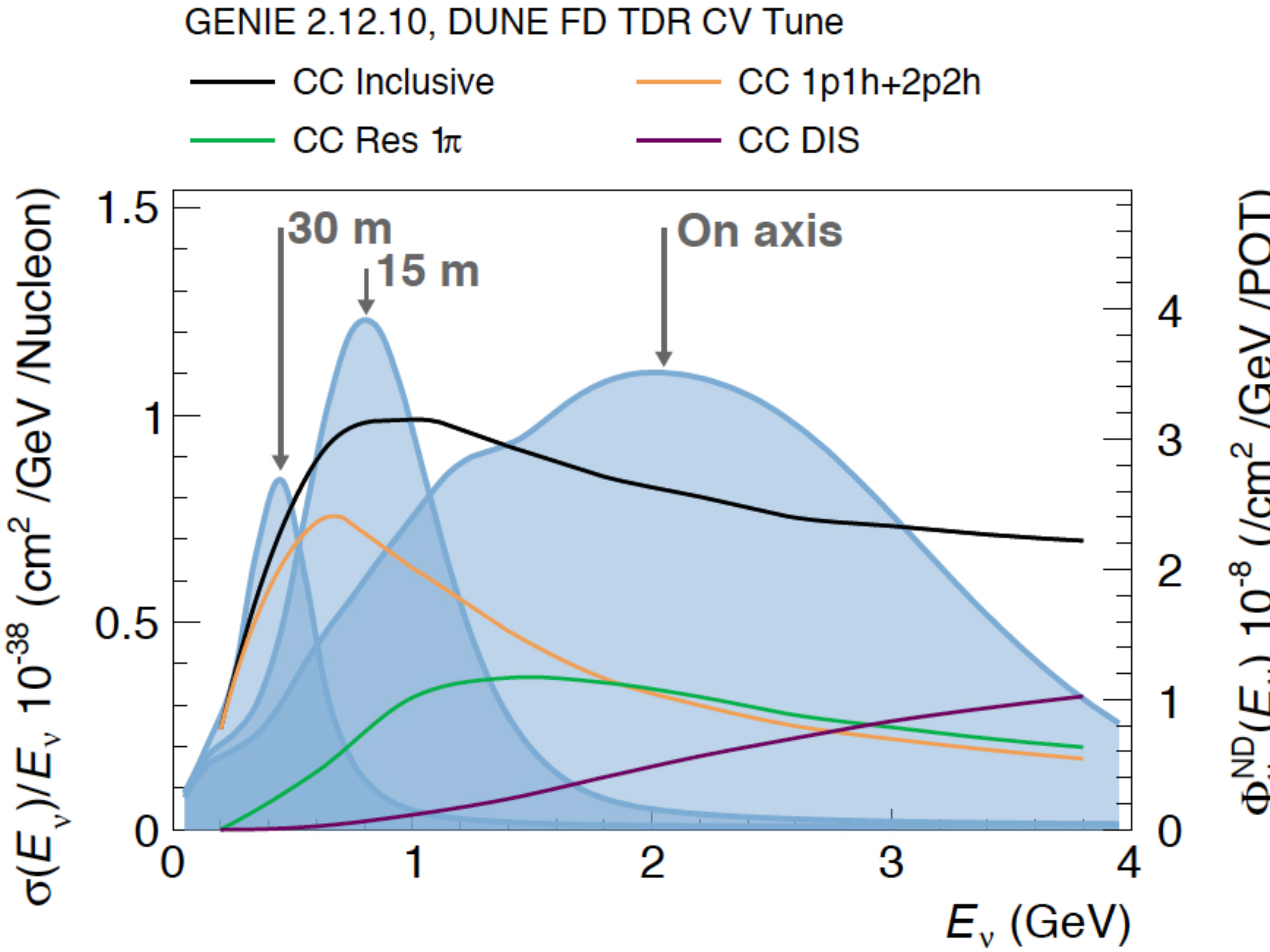
Neutrino energy spectrum changes in transverse direction to (proton) beam



New capabilities!

Precision Reaction Independent Spectrum Measurement

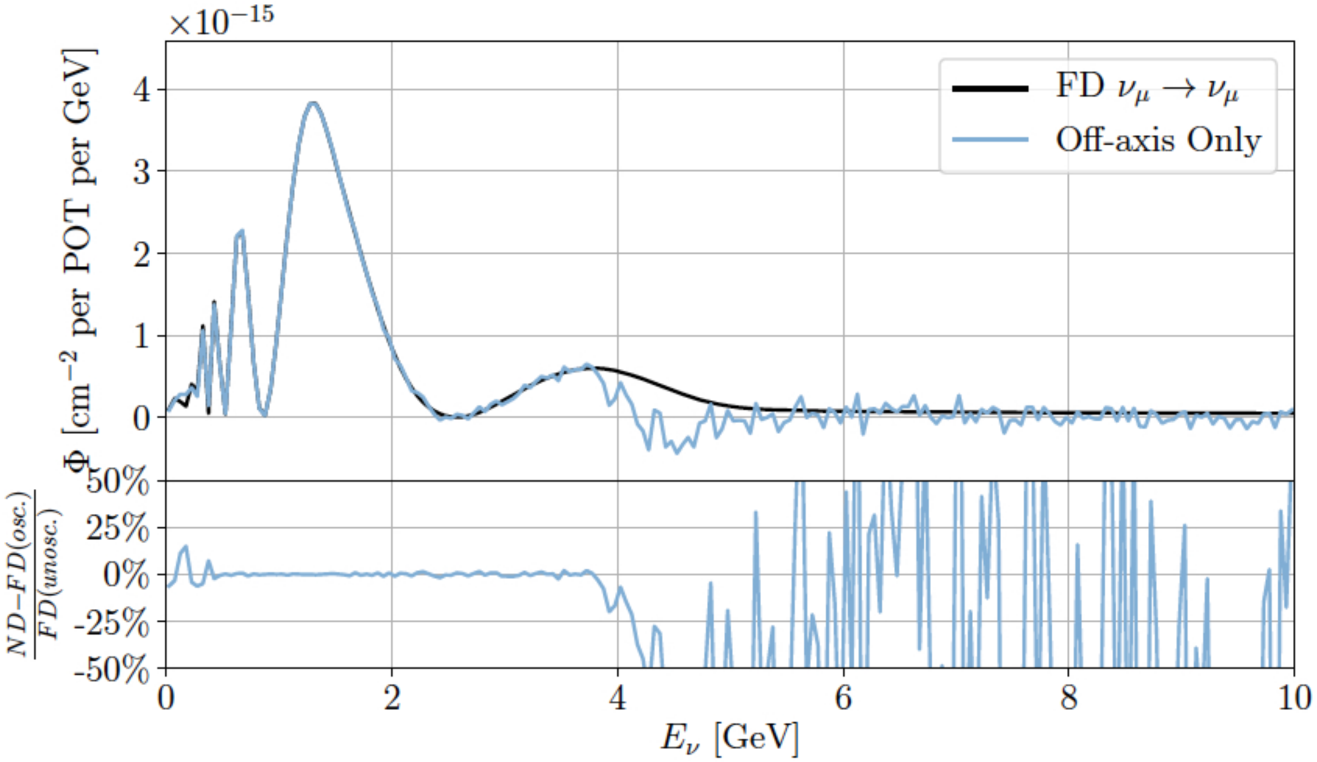


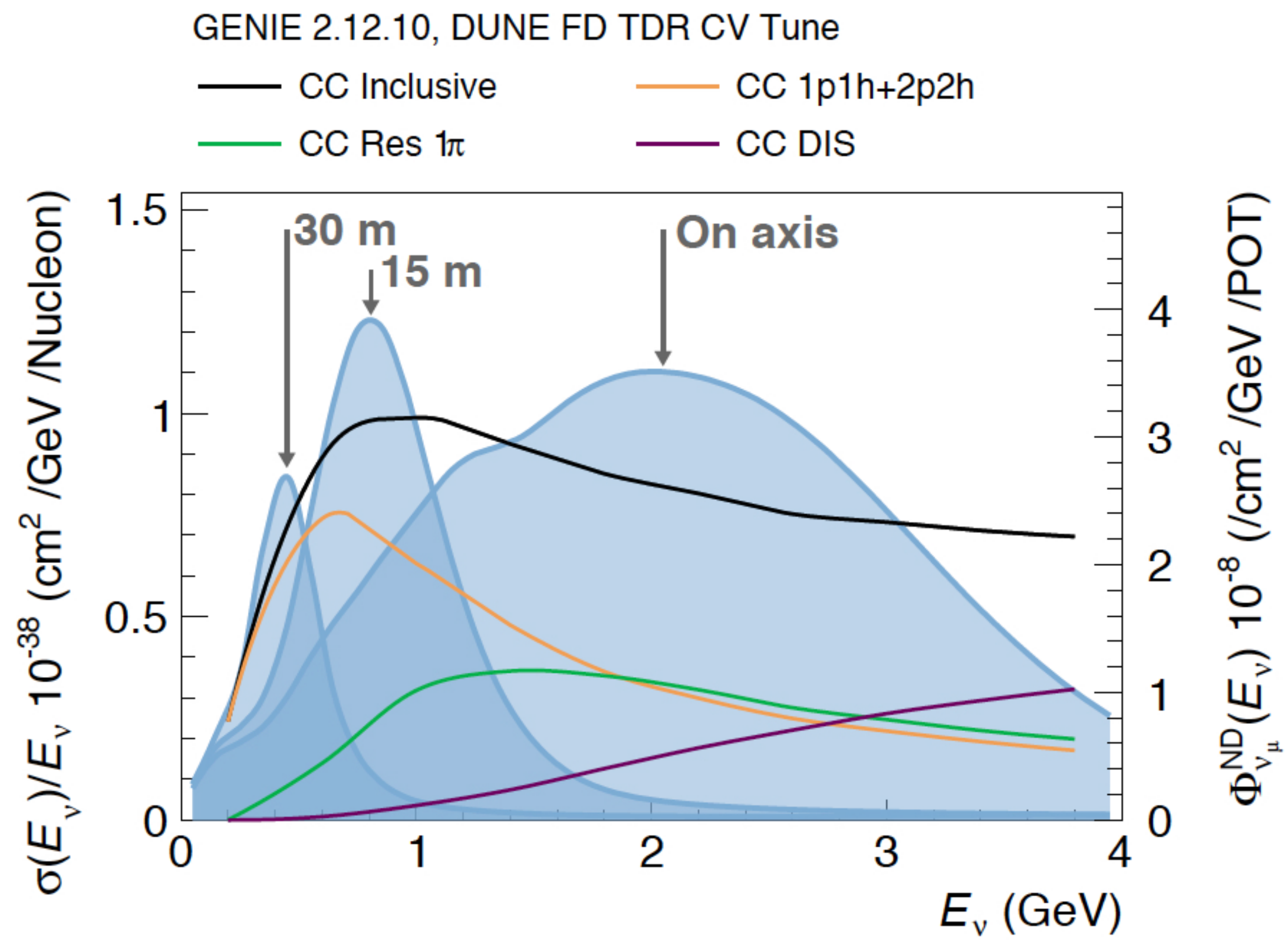


Energy peak shifts down, spectrum narrows

New capabilities!

Precision Reaction Independent Spectrum Measurement



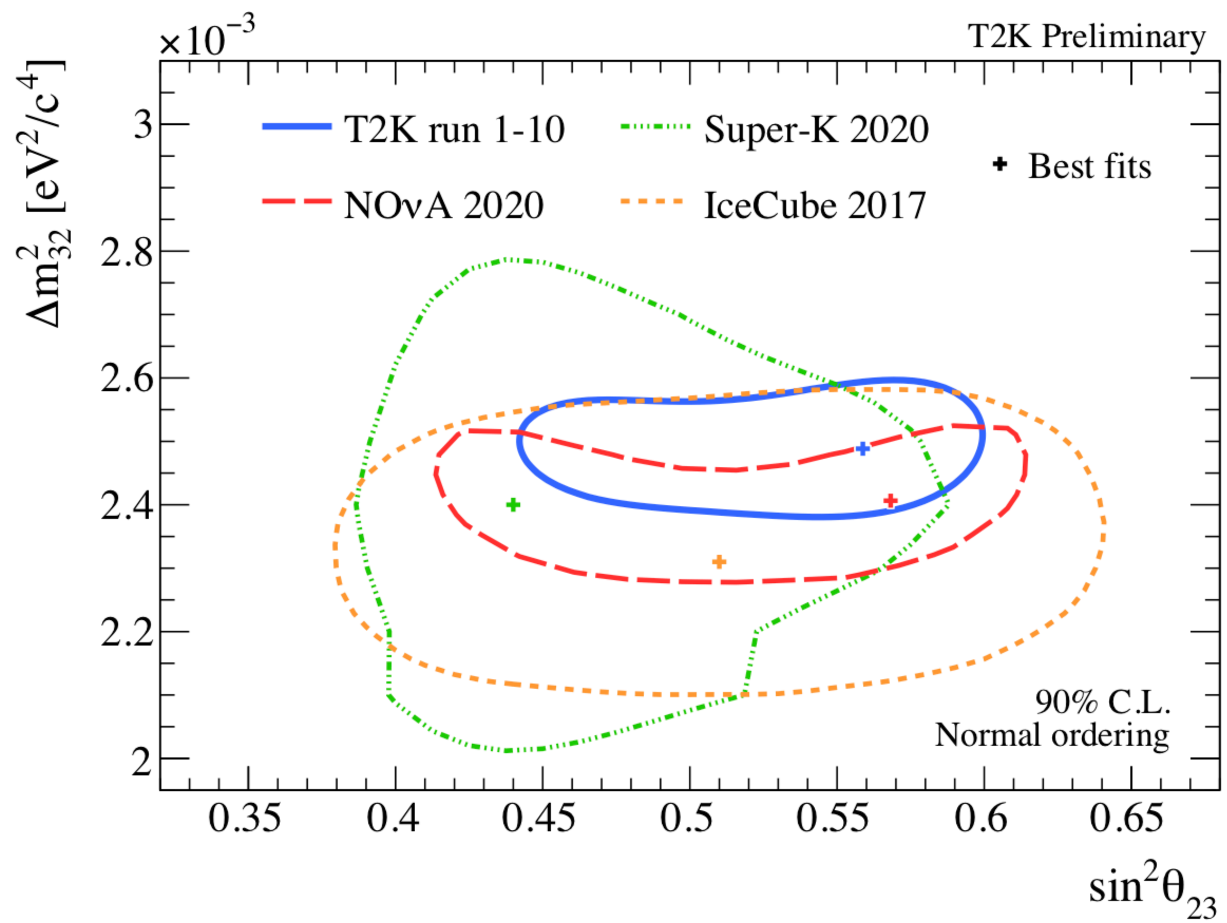


$$N_{FD}^{\alpha\to\beta}(\mathbf{p}_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(\mathbf{p}_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(\mathbf{p}_{true}) \times R_i(\mathbf{p}_{true};\mathbf{p}_{reco})$$

Many near detector positions can approximate far detector oscillated flux!

Details in arxiv 2103.13910

The frontier of neutrinos is exciting



Is the three flavor picture complete? Consistency between measurements?

Is there CPV in neutrinos?

Is θ_{23} maximal or not?

What is the mass hierarchy?

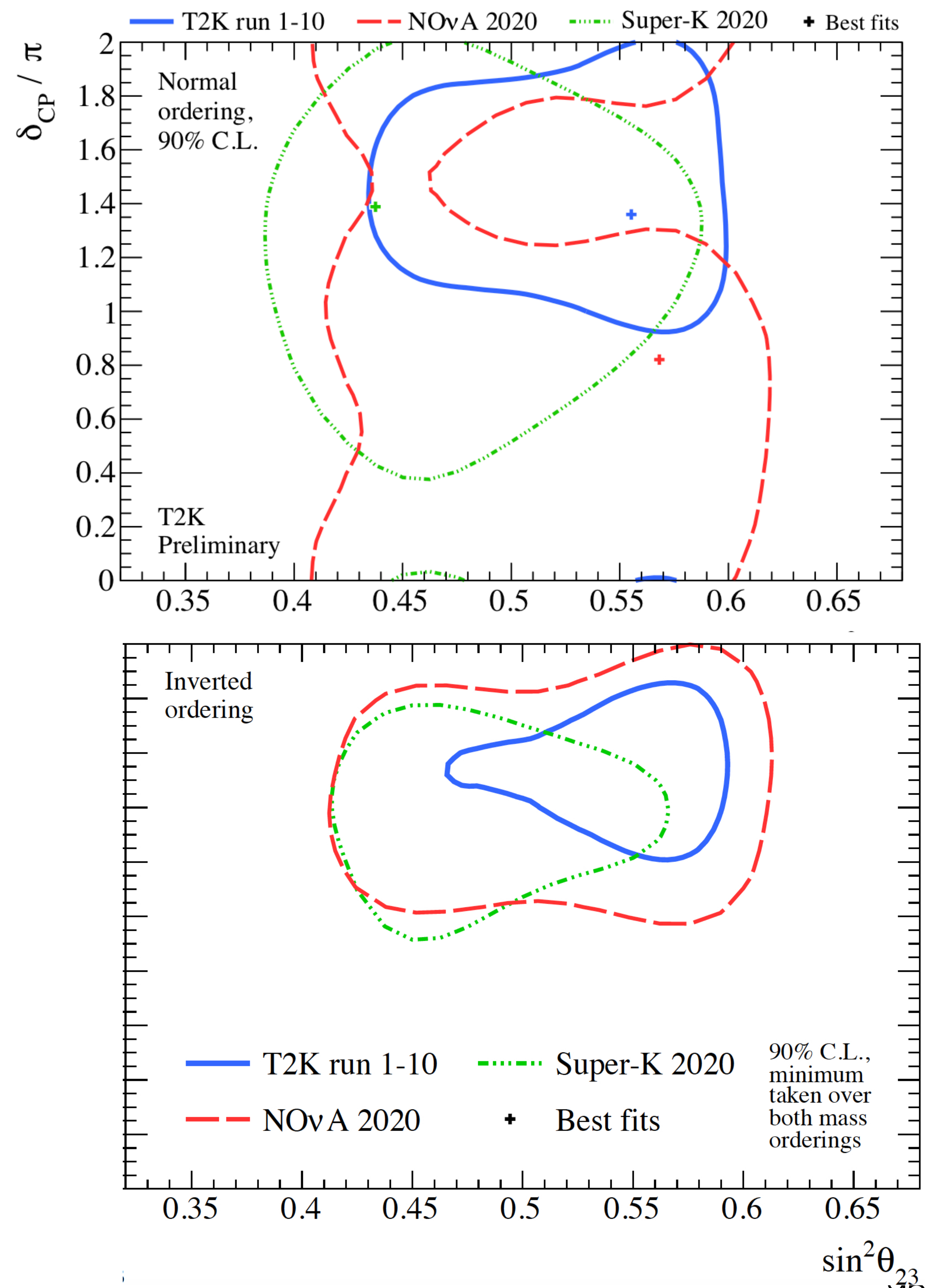
The frontier of neutrinos is still being explored

Complementarity measurements!

Is there CPV in neutrinos?

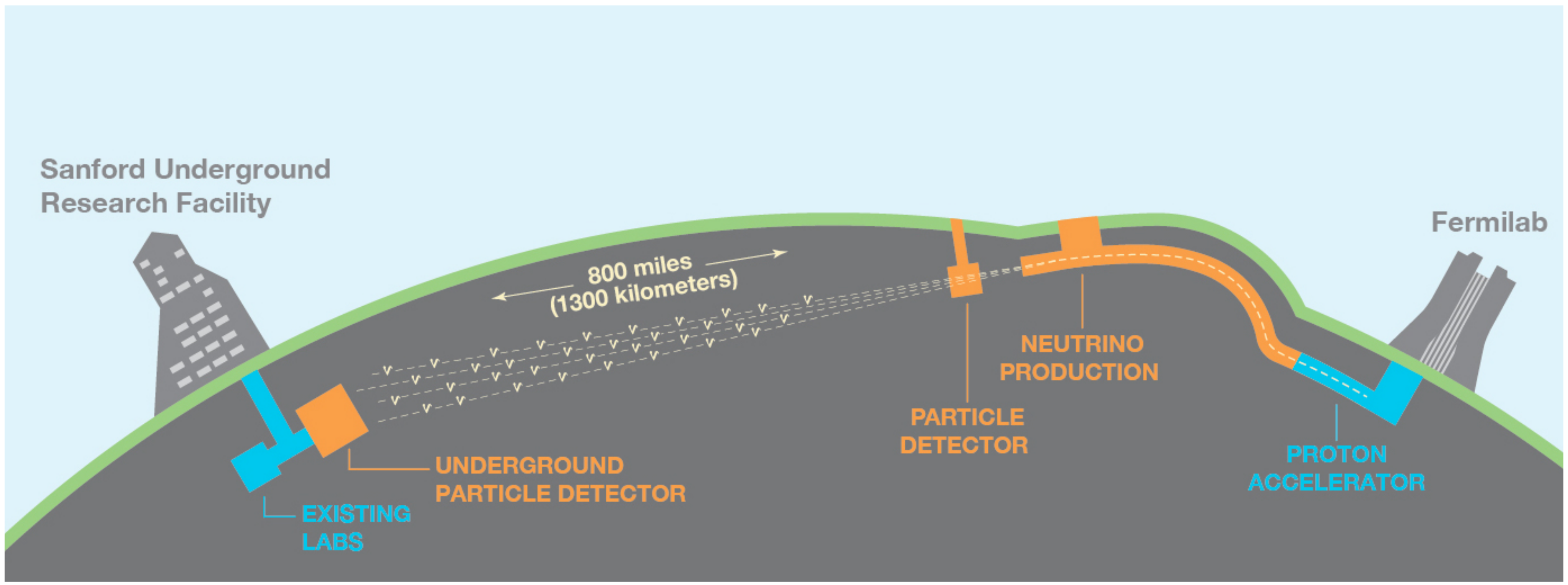
Is θ_{23} maximal or not?

What is the mass hierarchy?



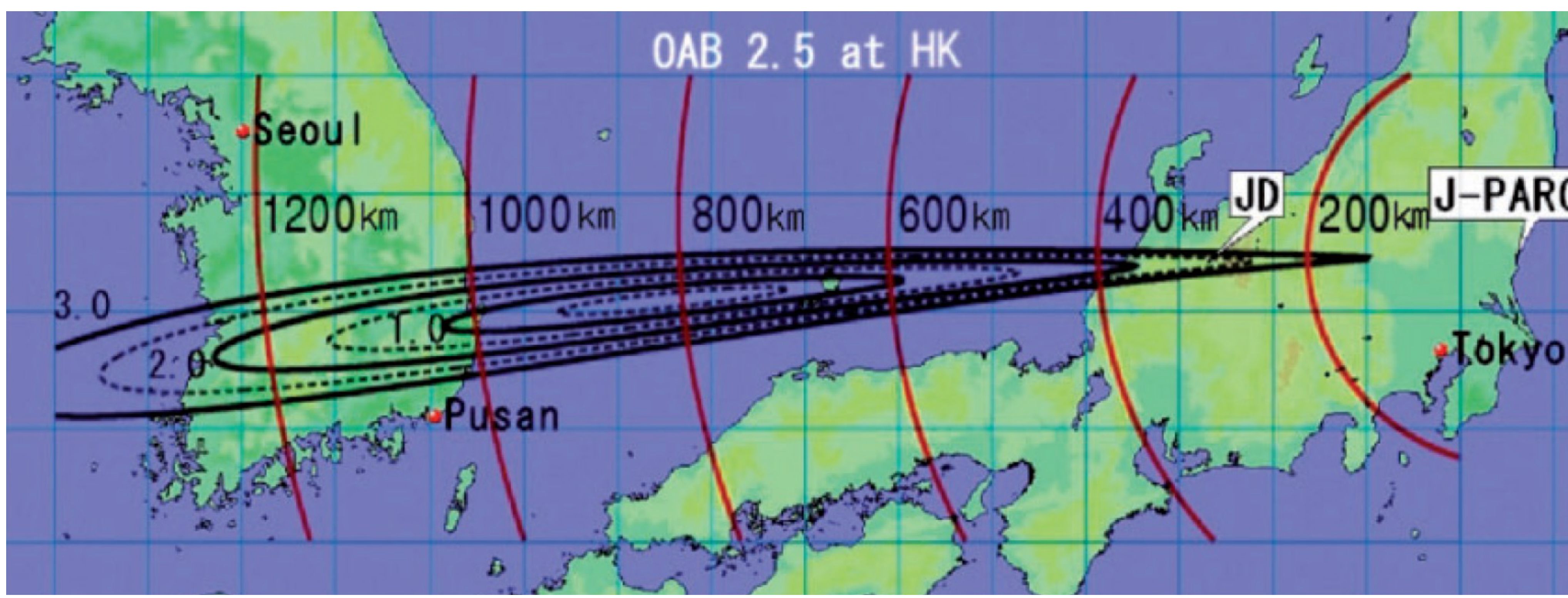
The future with neutrinos is bright

Let's keep exploring!



DUNE

Hyper-K



Come talk to me anytime about neutrinos!

mahn@msu.edu

Support from:

Department of Energy
award DE-SC0015903, DUNE project

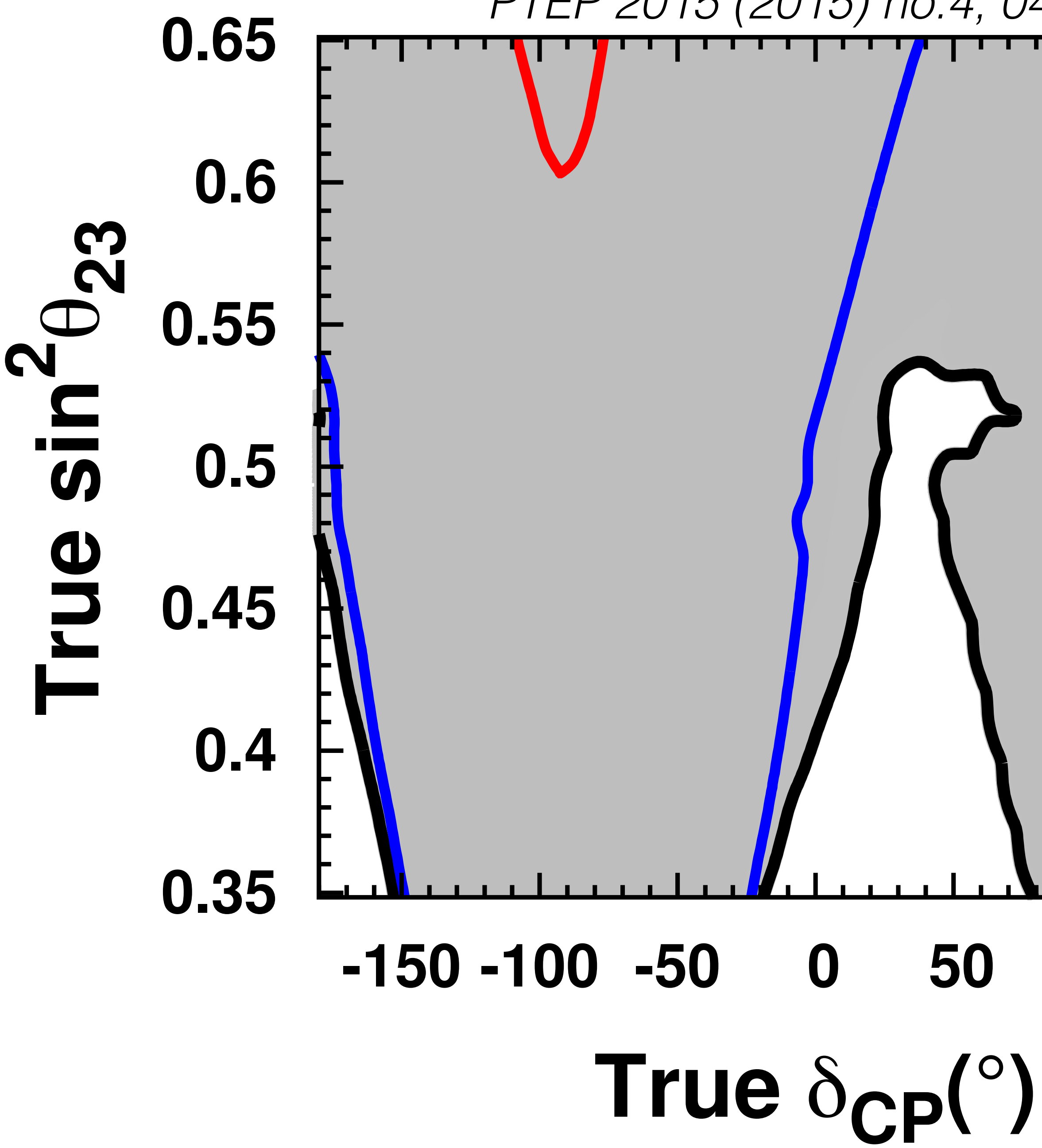
Backup

Complementary window: Matter effects

Strength of matter effect

T2K NOvA DUNE Super-Kamiokande IceCube

PTEP 2015 (2015) no.4, 043C01



T2K+NOvA 90%CL resolution of hierarchy

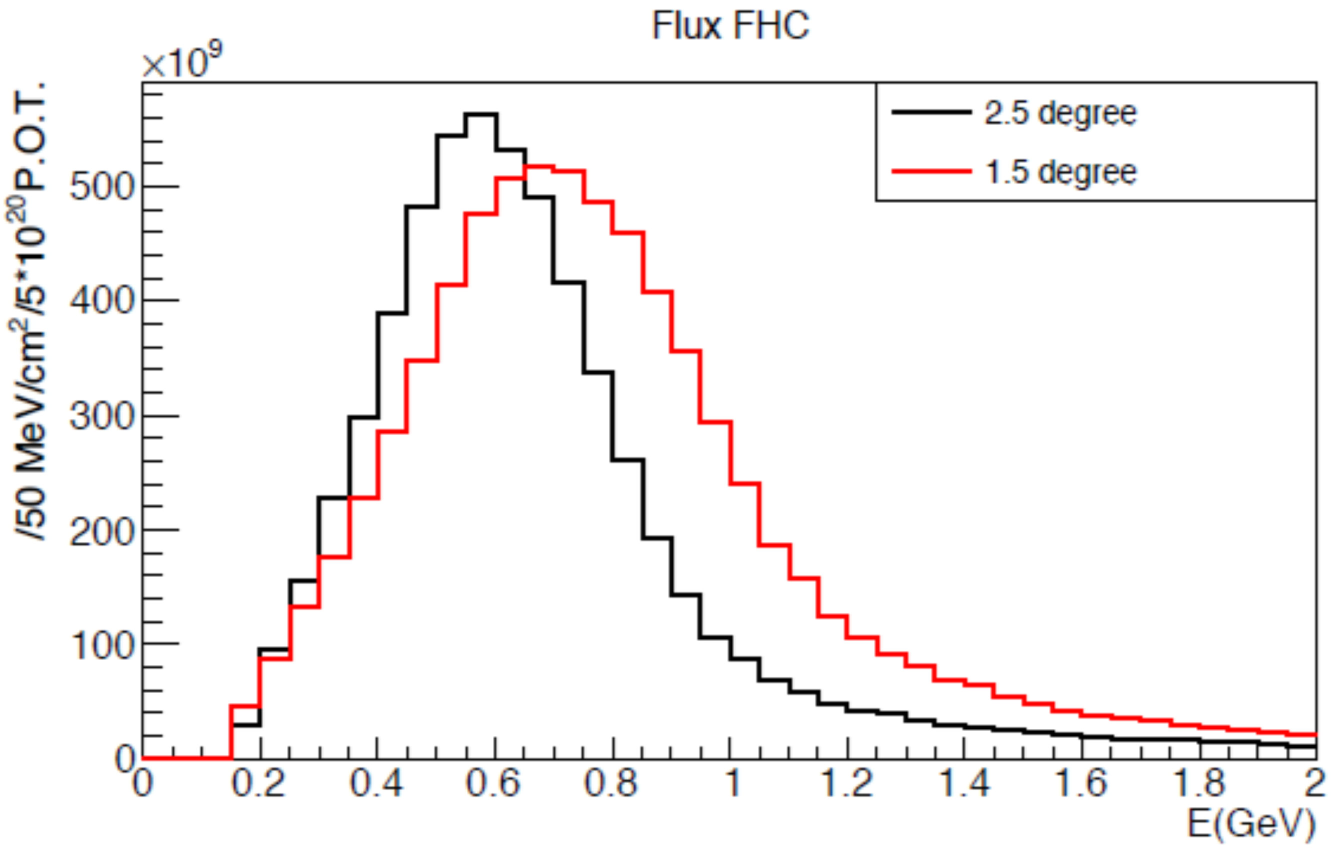
T2K alone NOvA alone

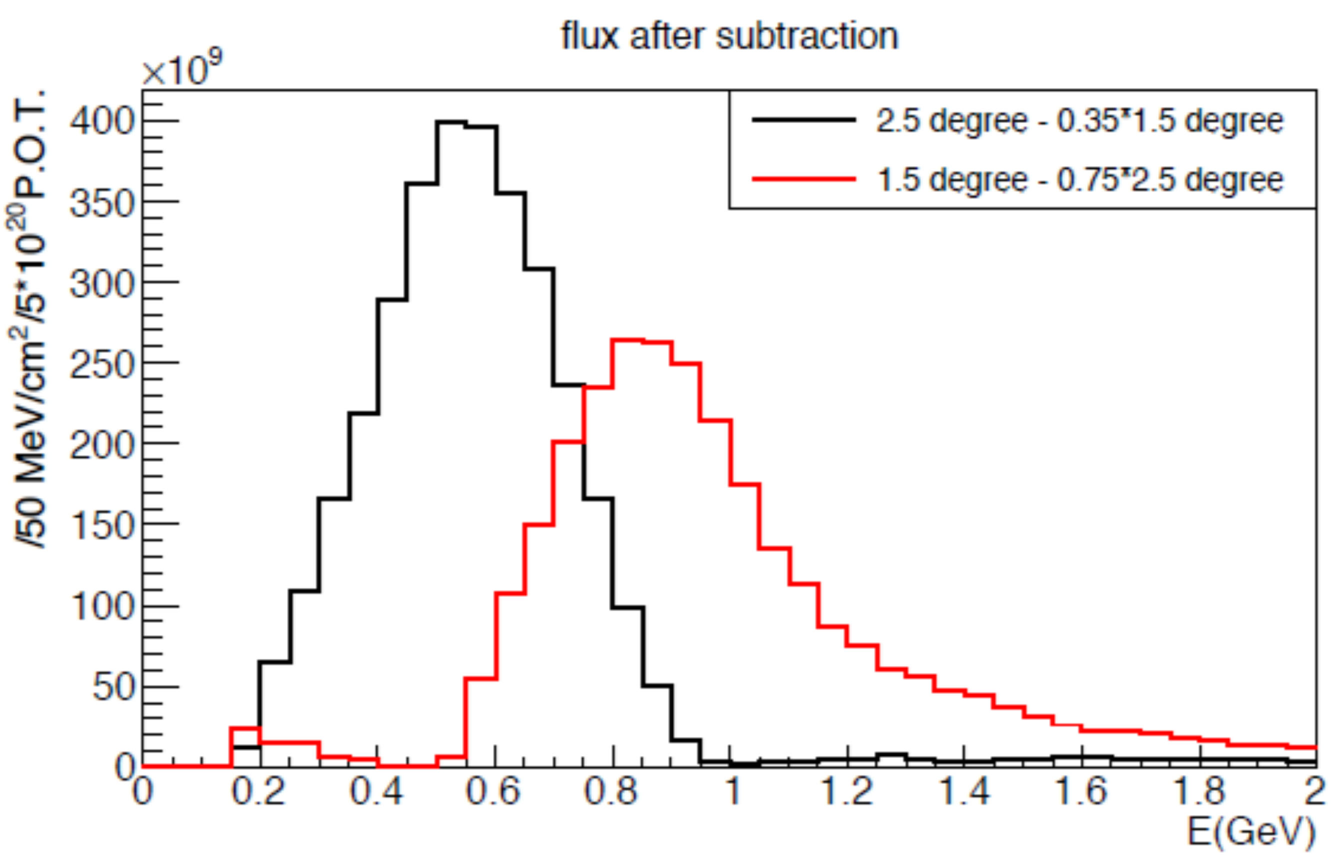
Model Progress on T2K

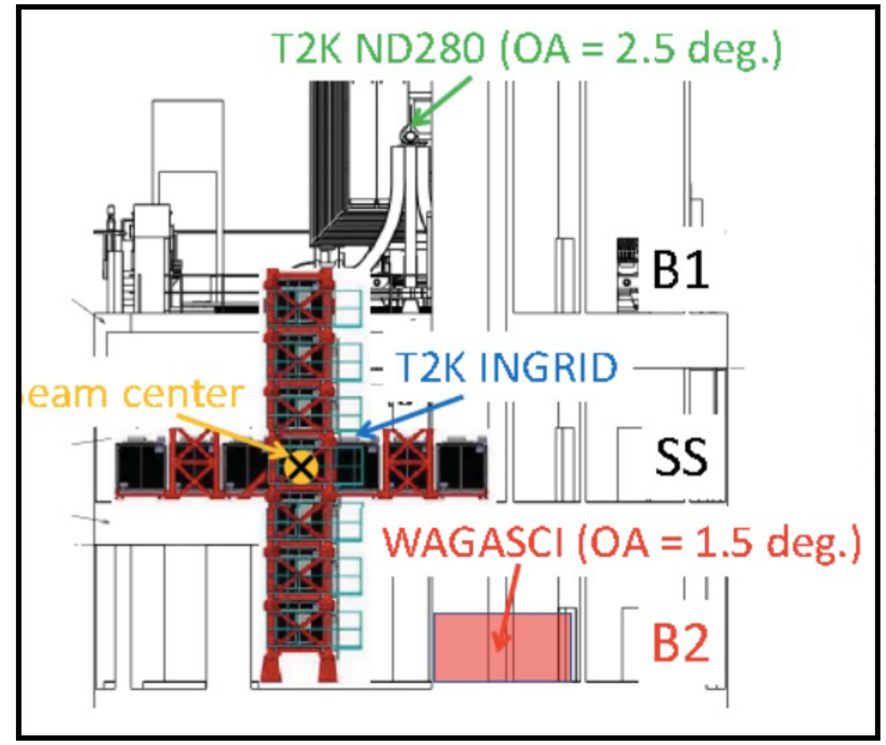
Dominant uncertainty in oscillation analysis from neutrino interaction (cross section) model

Error source	1-ring e-like		
	ν-mode	$\bar{\nu}$-mode	$\nu_e/\bar{\nu}_e$
SK Detector	**2.83**	**3.79**	**1.47**
SK FSI+SI+PN	**3.02**	**2.31**	**1.58**
Flux + Xsec constrained	**3.02**	**2.86**	**2.31**
E_b	**7.26**	**3.66**	**3.74**
$\sigma(\nu_e)/\sigma(\nu_\mu)$	**2.63**	**1.46**	**3.03**
NC1γ	**1.07**	**2.58**	**1.49**
NC Other	**0.14**	**0.33**	**0.18**
All Systematics	**8.81**	**7.03**	**5.87**

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

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

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

Flux (Φ)

Interaction model (cross section, σ)

Relationship between truth and observables (R)

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