Neutrino Mixing Results from T2K

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Outline

- Neutrino mixing
- Open questions
- Leptonic CP violation
- Testing leptonic CP violation at T2K
- Recent results
- Future prospects

Neutrino oscillations

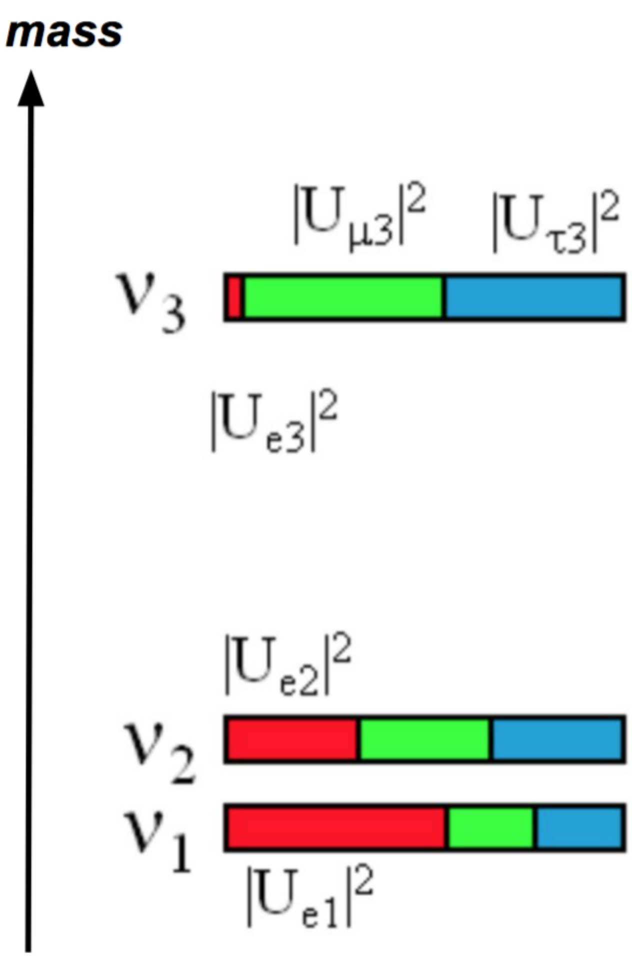
Each flavour eigenstate is a **superposition of mass eigenstates**.

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

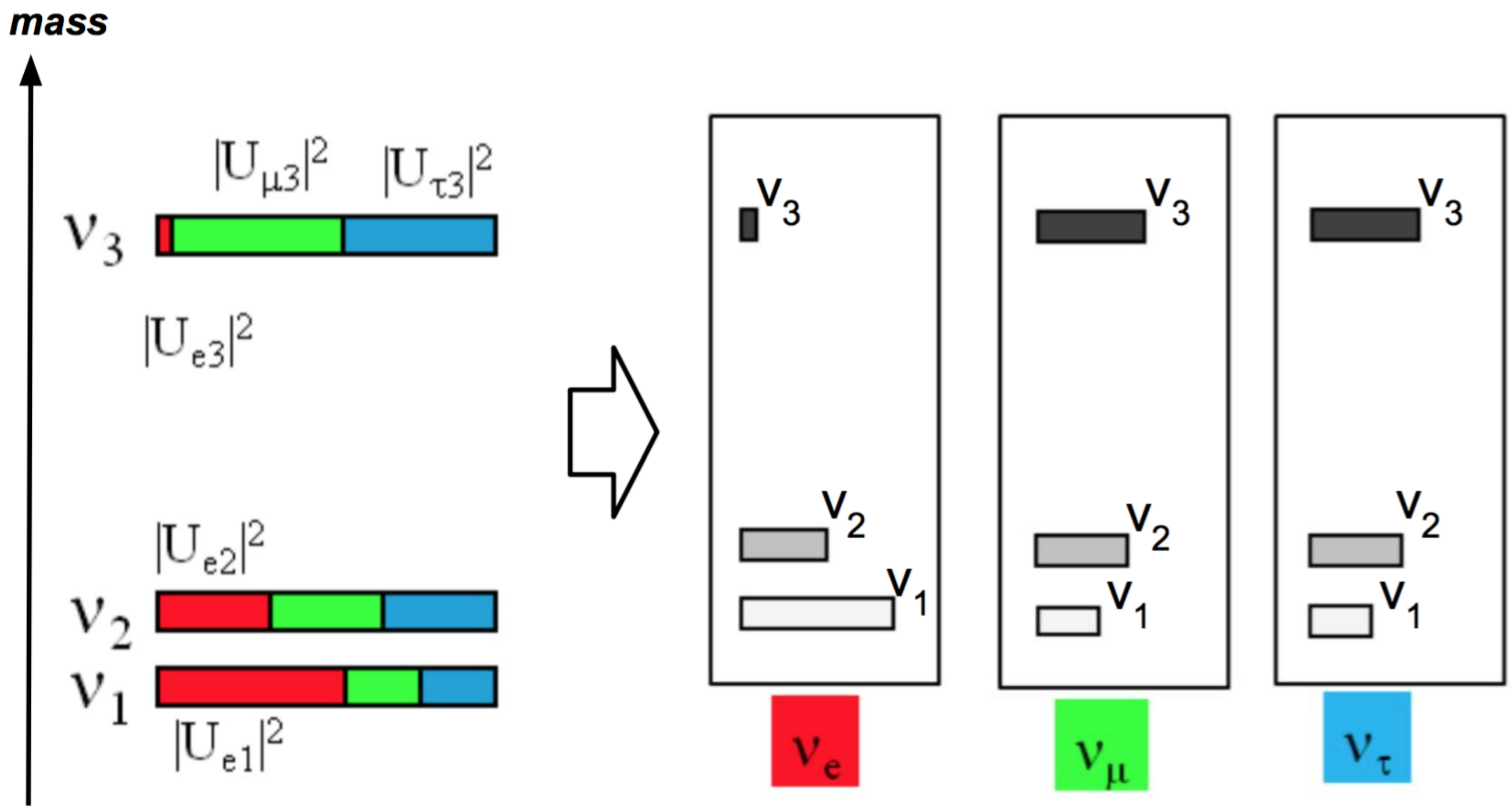
For antineutrinos:

$$U_{PMNS} \rightarrow U^{\star}_{PMNS}$$

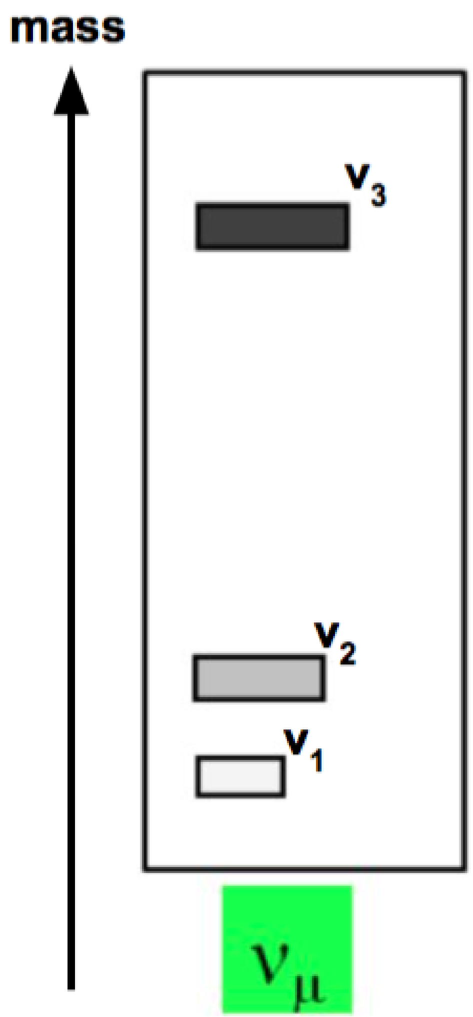
PMNS: **P**ontecorvo-**M**aki-**N**akagawa-**S**akata



Neutrino oscillations

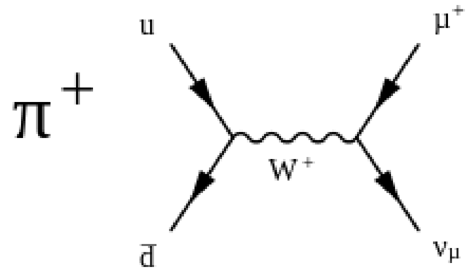


Neutrino oscillations



A muon-neutrino, **at the very moment it gets created**, is described by the following state:

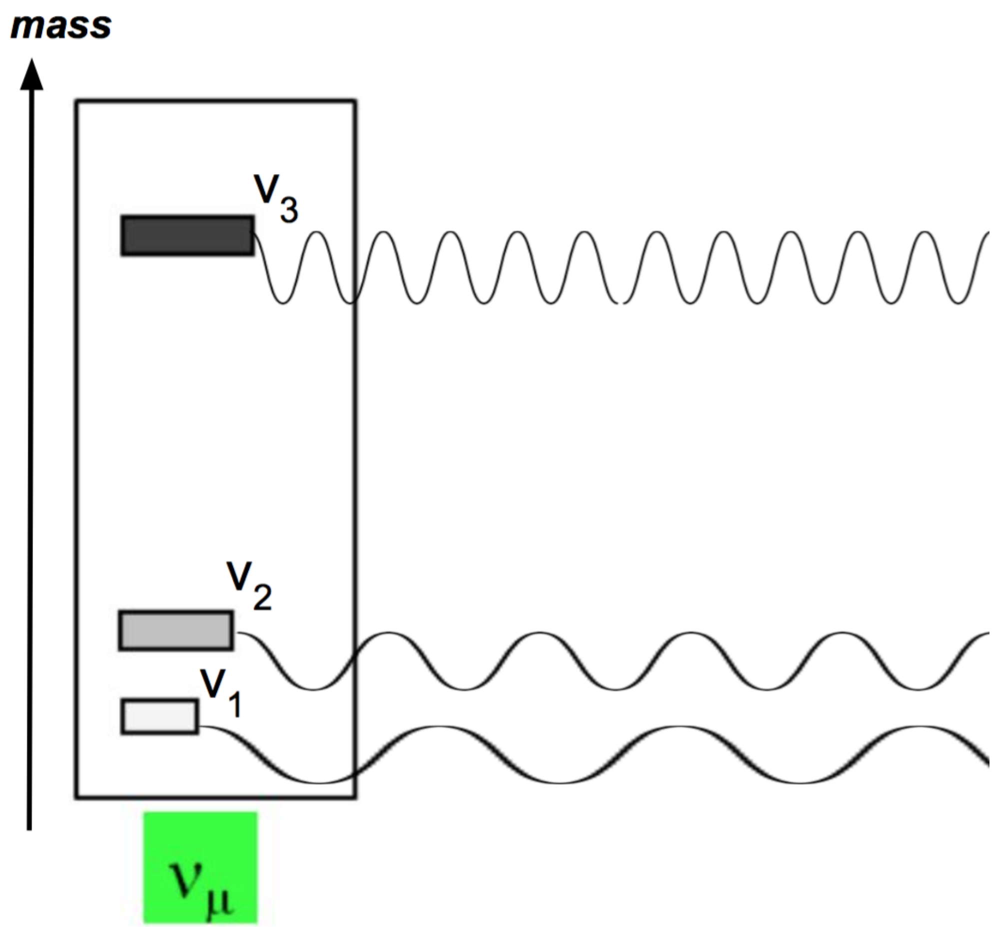
$$|\nu_\mu > \approx 0.4 \cdot |\nu_1 > + 0.6 \cdot |\nu_2 > +0.7 \cdot |\nu_3 >$$



So, at that time, a muon-neutrino is:

- $100 * (0.4)^2 \approx 15\% \; \nu_1$
- $100 * (0.6)^2 \approx 35\% \; \nu_2$
- $100 * (0.7)^2 \approx 50\% \; \nu_3$

Neutrino oscillations



The propagation of each mass eigenstate i (i=1,2,3) is described by a plane wave:

$$|\nu_i(L)> = e^{-i m_i^2 L/2E} \cdot |\nu_i(0)>$$

Immediately after its creation, **the superposition** that makes up a flavour eigenstate **gets altered**.

The neutrino now has a **finite probability to be observed as a different flavour state**.

What do we measure in neutrino oscillation experiments?

Probability for $\nu_\alpha \to \nu_\beta$ $(\alpha, \beta : e, \mu, \tau)$ flavour oscillation:

$$P_{\alpha\beta} = \delta_{\alpha\beta} \quad - \quad 4\sum_{i>j} Re[U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}] sin^2(\frac{1}{4}\frac{L}{E}\Delta m^2_{ij})$$
$$+ \quad 2\sum_{i>j} Im[U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}] sin(\frac{1}{2}\frac{L}{E}\Delta m^2_{ij})$$

Sensitivity to oscillations by tuning L/E (baseline to energy ratio)

For a purely phenomenological description of neutrino oscillations, assuming 3 active neutrinos, we need:

- Any 2 squared mass splittings (e.g. Δm^2_{21},Δm^2_{32})
- 3 mixing angles (θ_{12}, θ_{13}, θ_{23})
- 1 CP invariance violating phase (δ_{CP})

What do we measure in neutrino oscillation experiments?

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$

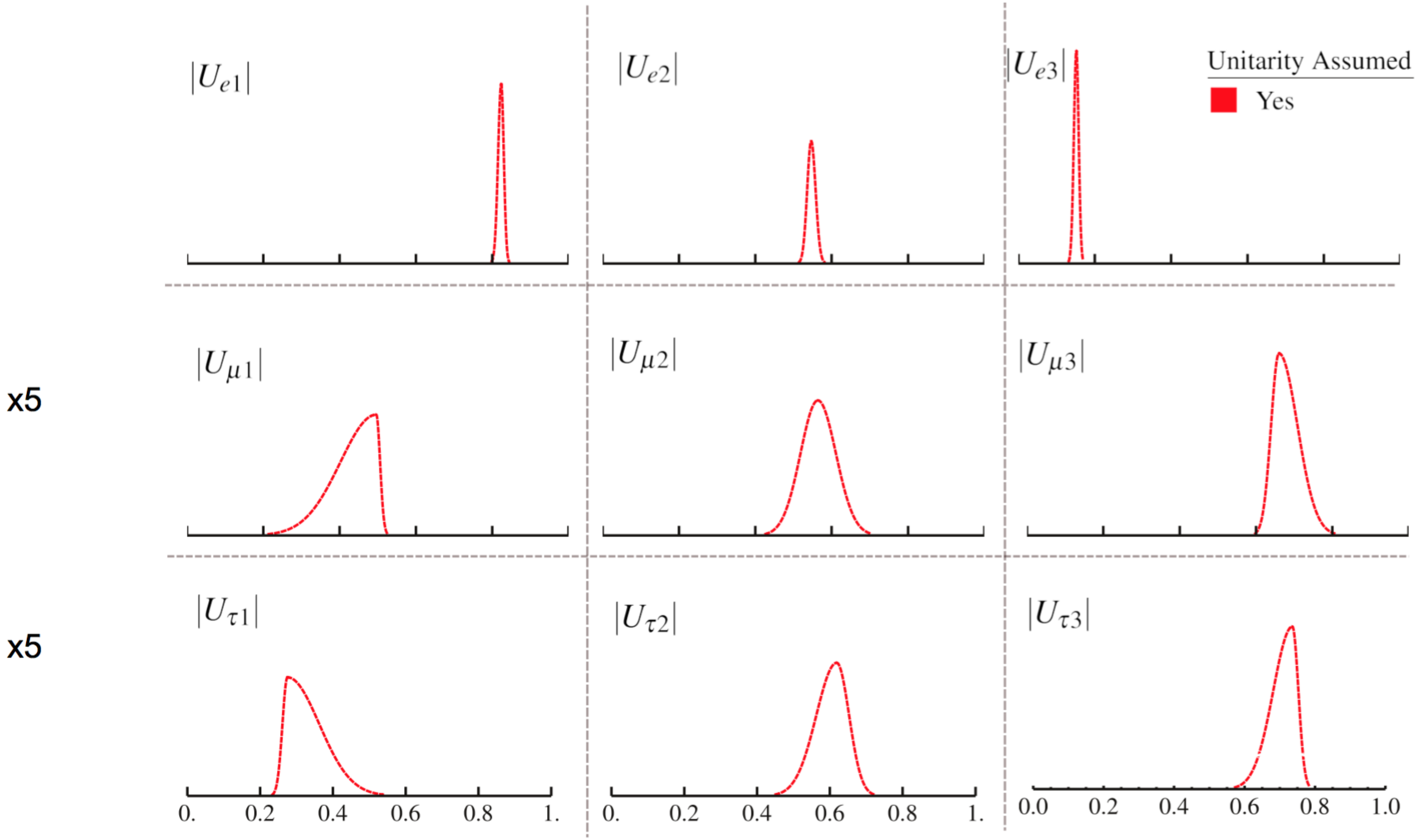
$s_{ij} = \sin\theta_{ij}$

Parameter	best-fit ($\pm 1\sigma$)	3σ
Δm^2_{21} [10^{-5} eV ^{2}]	$7.54^{+0.26}_{-0.22}$	$6.99 - 8.18$
$\lvert\Delta m^2\rvert$ [10^{-3} eV ^{2}]	2.43 ± 0.06 (2.38 ± 0.06)	$2.23 - 2.61$ $(2.19 - 2.56)$
$\sin^2\theta_{12}$	0.308 ± 0.017	$0.259 - 0.359$
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$	$0.374 - 0.628$
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	$0.455^{+0.039}_{-0.031}$,	$0.380 - 0.641$
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	$0.0234^{+0.0020}_{-0.0019}$	$0.0176 - 0.0295$
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	$0.0240^{+0.0019}_{-0.0022}$	$0.0178 - 0.0298$

$$U_{PMNS} \approx \begin{pmatrix} 0.80 & 0.55 & 0.15 \\ 0.40 & 0.60 & 0.70 \\ 0.40 & 0.60 & 0.70 \end{pmatrix}$$

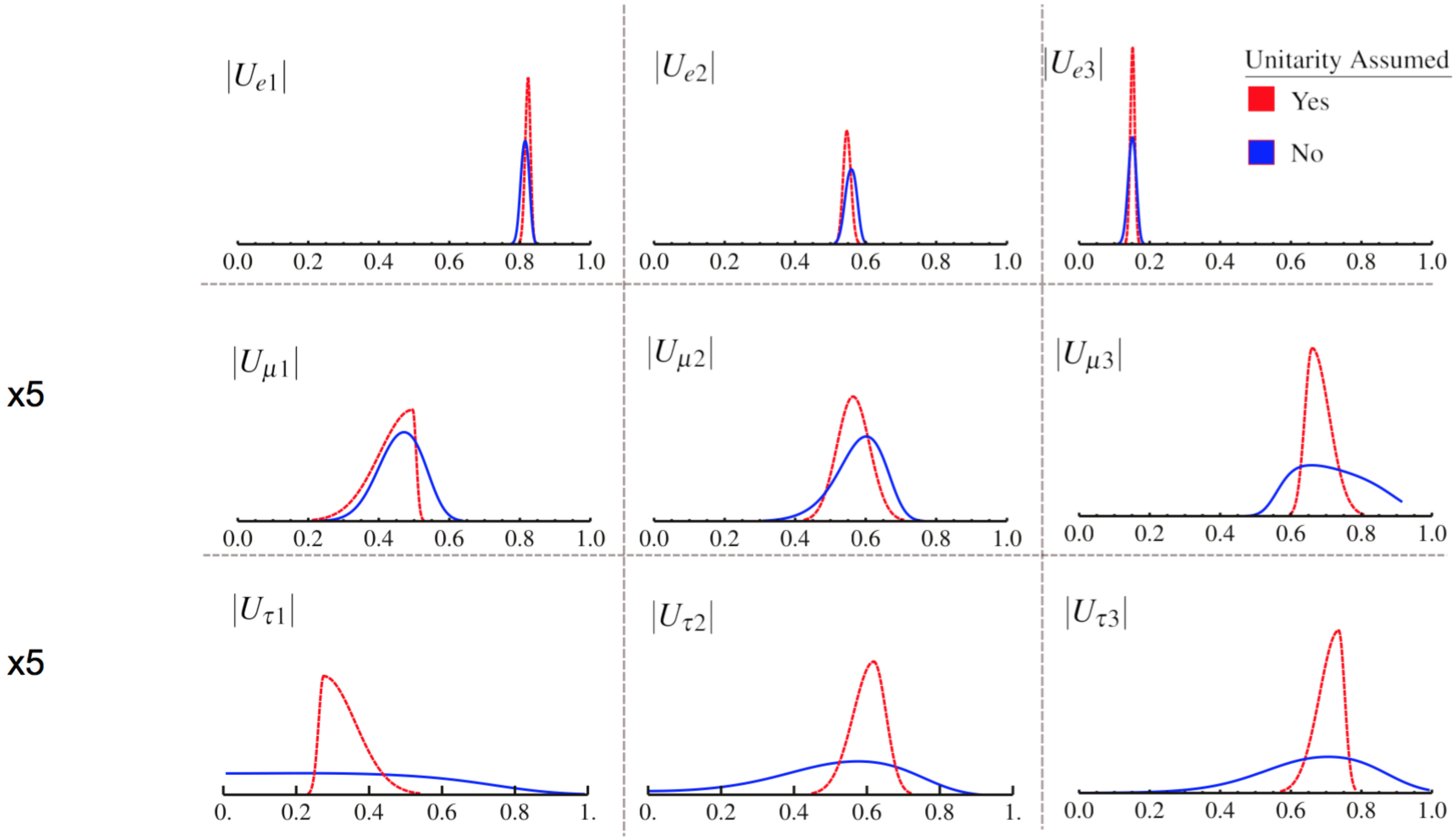
Several unknowns: Is U_{PMNS} unitary?

U_{PMNS} matrix elements:



Several unknowns: Is U_{PMNS} unitary?

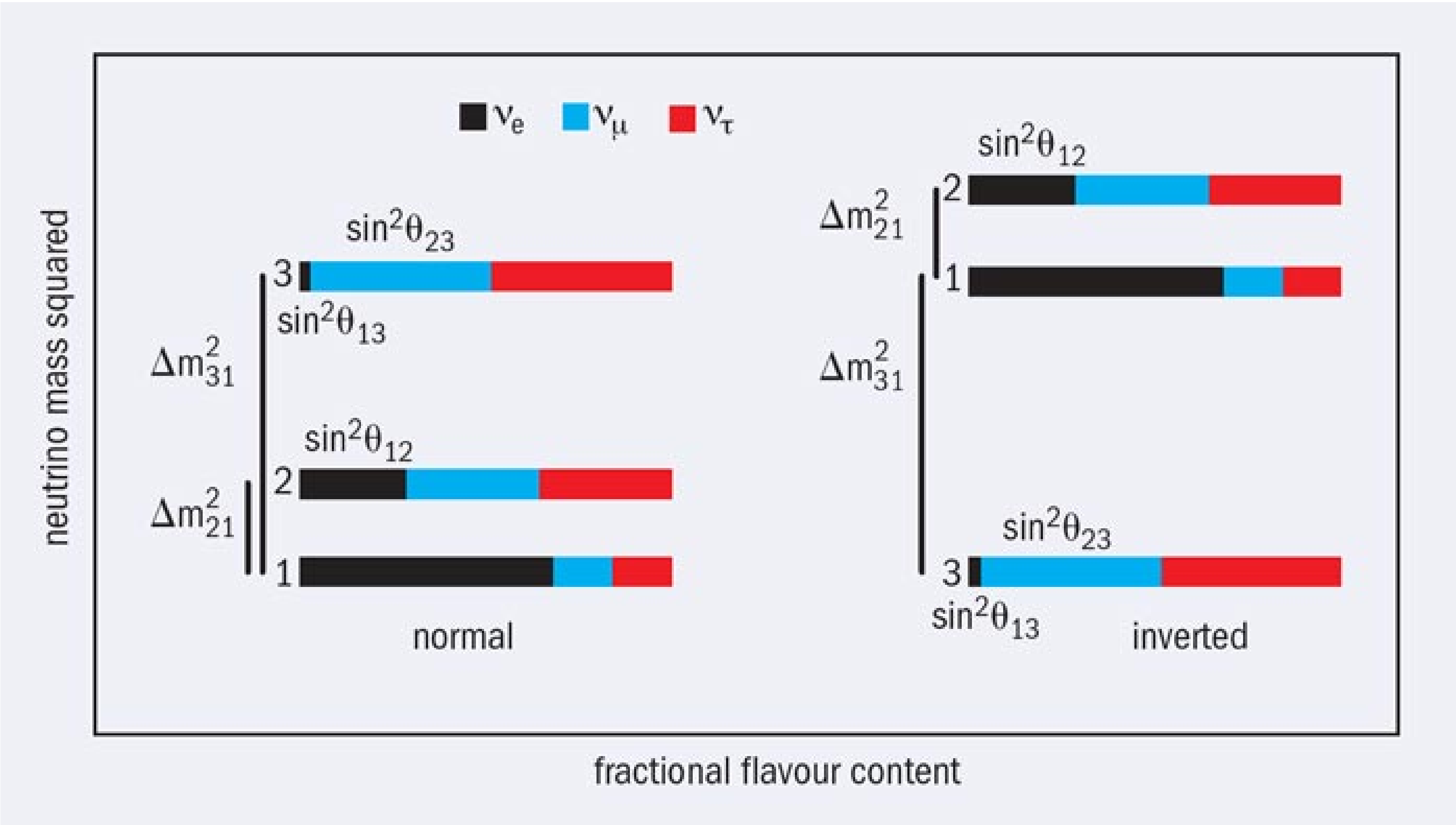
U_{PMNS} matrix elements:



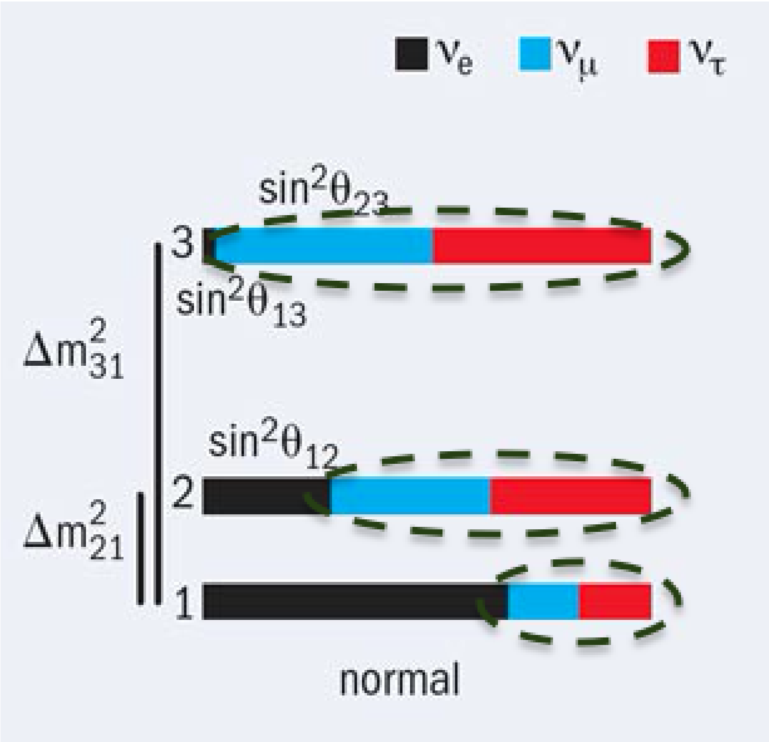
Several unknowns: What is the neutrino mass hierarchy?

The sign of Δm^2_{21} known ($m_2 > m_1$) but the **sign of Δm^2_{31} is unknown**.

- 1 heavy + 2 light neutrinos (normal hierarchy)?
- Or, 2 heavy + 1 light neutrinos (inverted hierarchy)?



Several unknowns: is θ_{23} maximal?



Are μ and τ flavours interchangeable?

Or, equivalently, **is θ_{23} maximal** (45^o)?

This is currently unknown!

A maximal mixing could imply some previously unknown discrete symmetry, and hint at connections between the PMNS and CKM mixing matrices.

Several unknowns: Is there leptonic CP violation?

The CP-violating phase in PMNS is largely unconstrained.

The magnitude of the CP effect is given by the **Jarlskog Invariant**:

$$J_{CP}^{PMNS} = \frac{1}{8}\, sin2\theta_{12}\; sin2\theta_{13}\; sin2\theta_{23}\; cos\theta_{13}\; sin\delta_{CP}$$

Given the current best fit values, and assuming the normal hierarchy:

$$J_{CP}^{PMNS} = 0.035\; sin\delta_{CP}$$

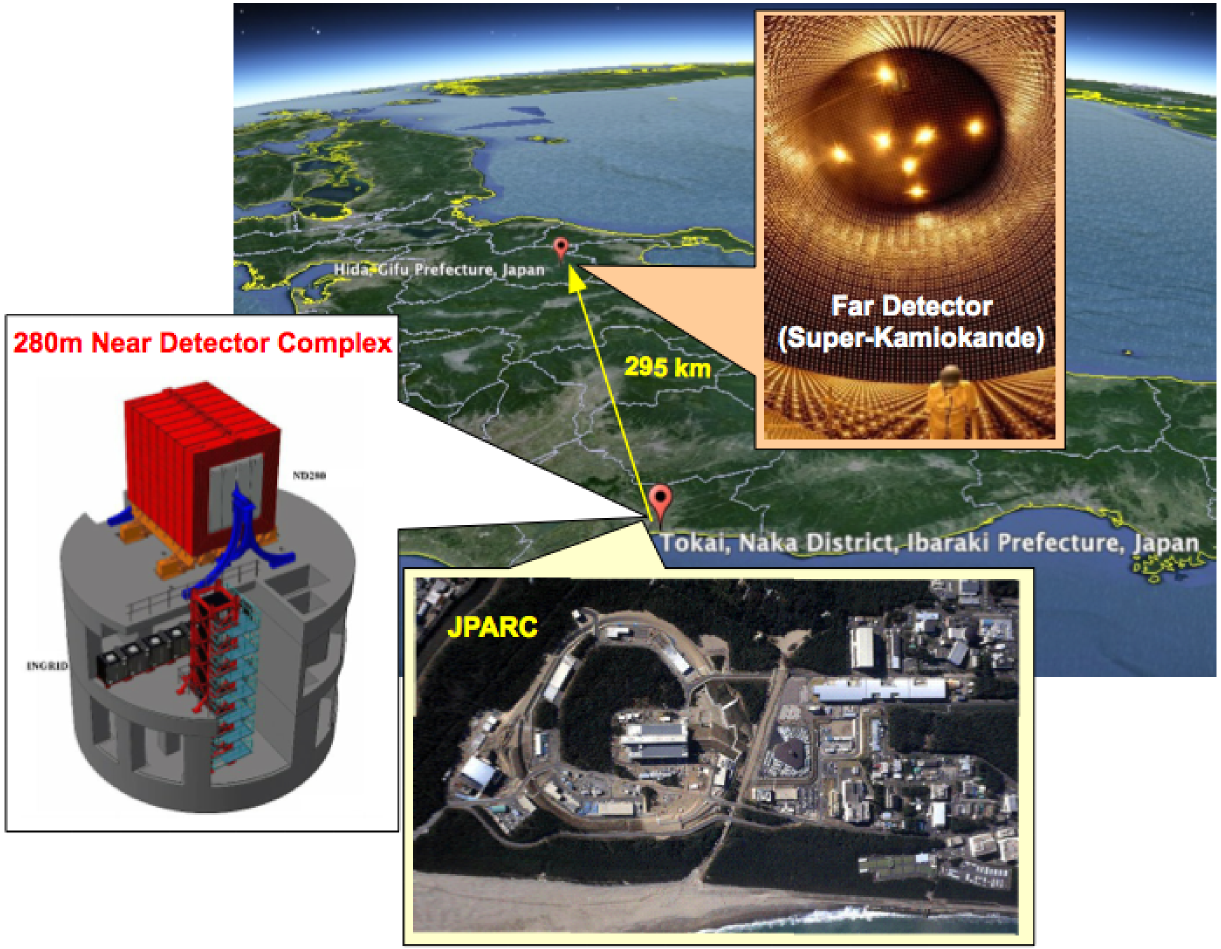
In contrast, in the quark sector, despite the large value of the CP phase:

$$J_{CP}^{CKM} \approx (3 \pm 1) \times 10^{-5}$$

J_{CP}^{PMNS} is **potentially large!**

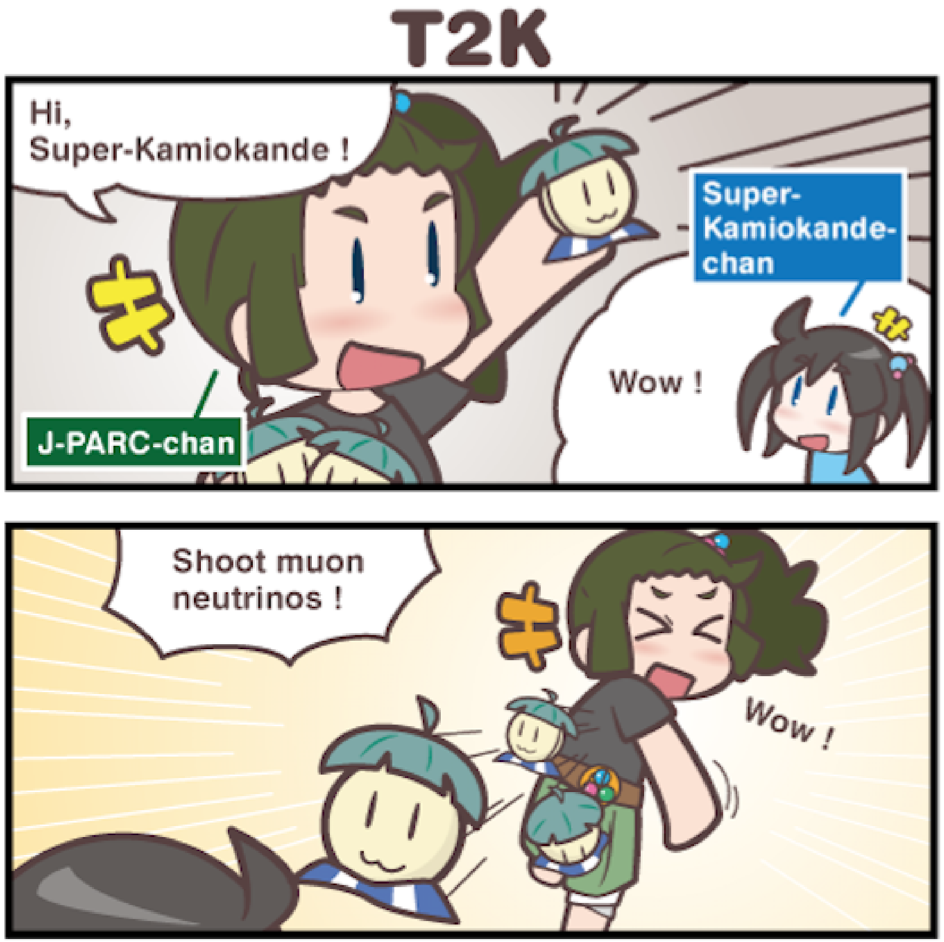
Measurement of leptonic CPV could have a tremendous impact on our understanding of the origin of the **Baryon Asymmetry of the Universe**.

T2K Experiment



- Pure ν_μ beam.
- Produced using the 30-GeV proton beam at J-PARC
- Design Power of 750 kW (420 kW achieved to date)
- Far detector: SuperK 50-kton (22.5 kton fiducial) water Cherenkov detector, 2.5 degrees off-axis, 295 km away.
- Neutrino flux at SuperK peaked at $\sim$0.6 GeV.
- L/E tuned to the 'atmospheric' Δm^2 scale ($\sim 2.4 \times 10^{-3}$ eV^2/c^4).

Measuring neutrino oscillations at T2K



J-PARC-chan
lives in Tokai-mura, Naka-gun, Ibaraki, Japan.

Super-Kamiokande-chan
lives in Kamioka-cho, Hida-city, Gifu, Japan.

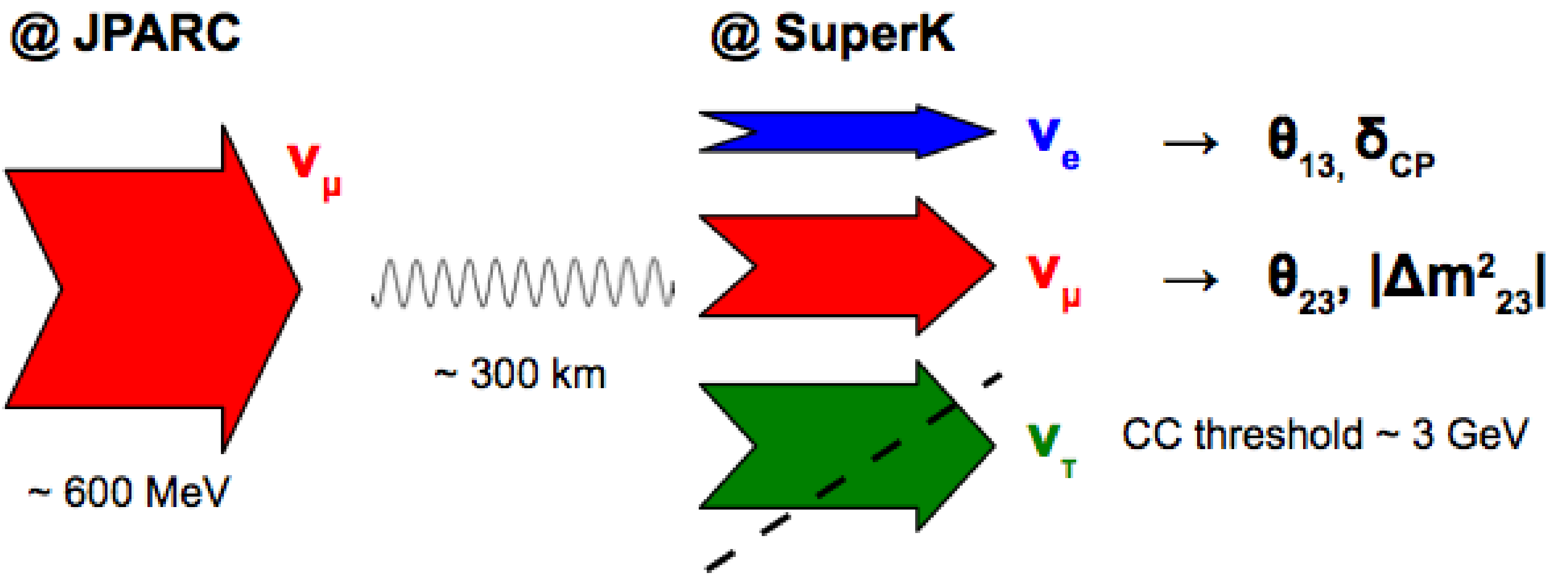
Measuring neutrino oscillations at T2K

Muon-neutrino disappearance ($\nu_\mu \to \nu_\mu$)

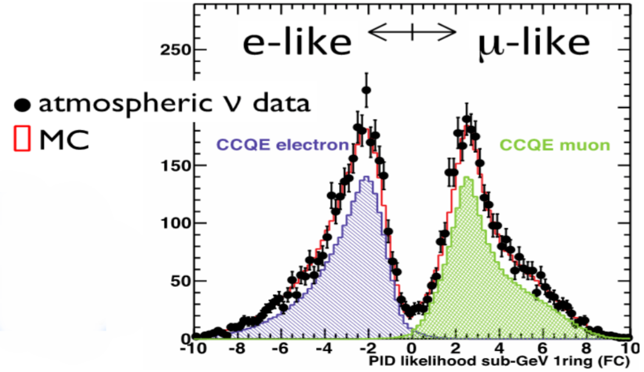
$$P(\nu_\mu \to \nu_\mu) = 1 - cos^4\theta_{13} \cdot sin^2 2\theta_{23} \cdot sin^2(\frac{\Delta m^2_{31} L}{4E}) + \text{sub-leading terms}$$

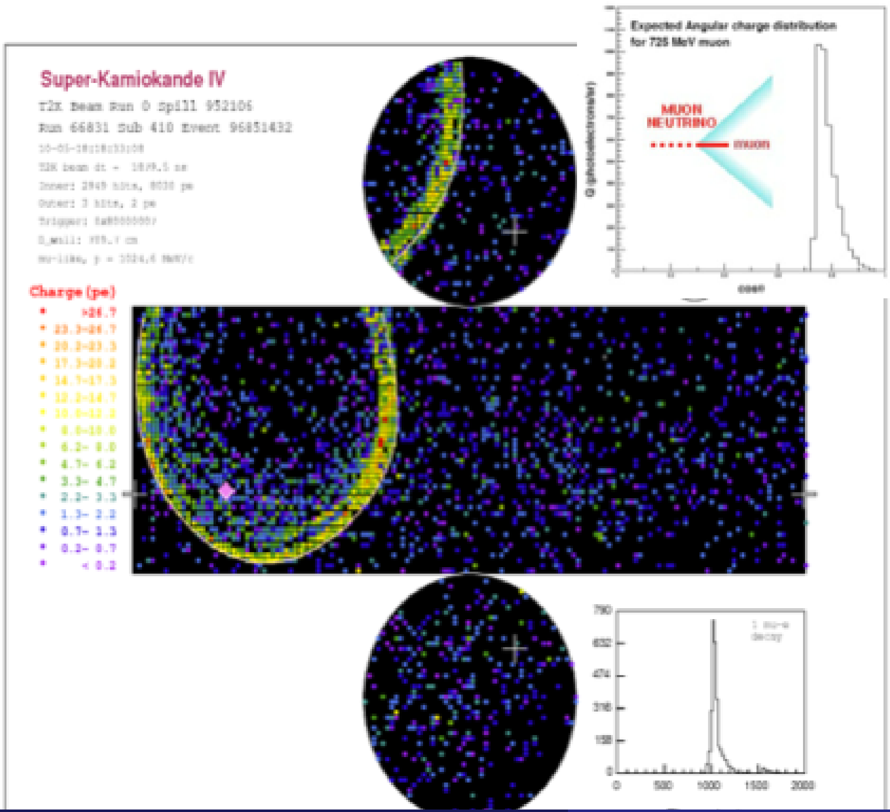
Electron-neutrino appearance ($\nu_\mu \to \nu_e$)

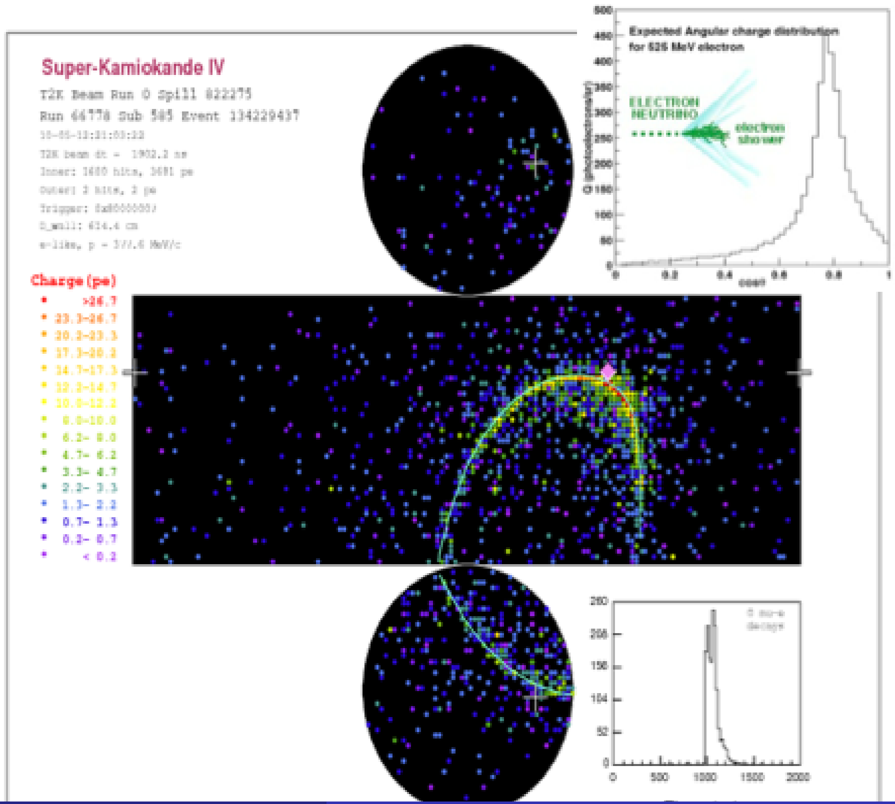
$$P(\nu_\mu \to \nu_e) = 4 \cdot cos^2\theta_{13} \cdot sin^2\theta_{13} \cdot sin^2\theta_{23} \cdot sin^2(\frac{\Delta m^2_{31} L}{4E}) + \text{sub-leading terms}$$



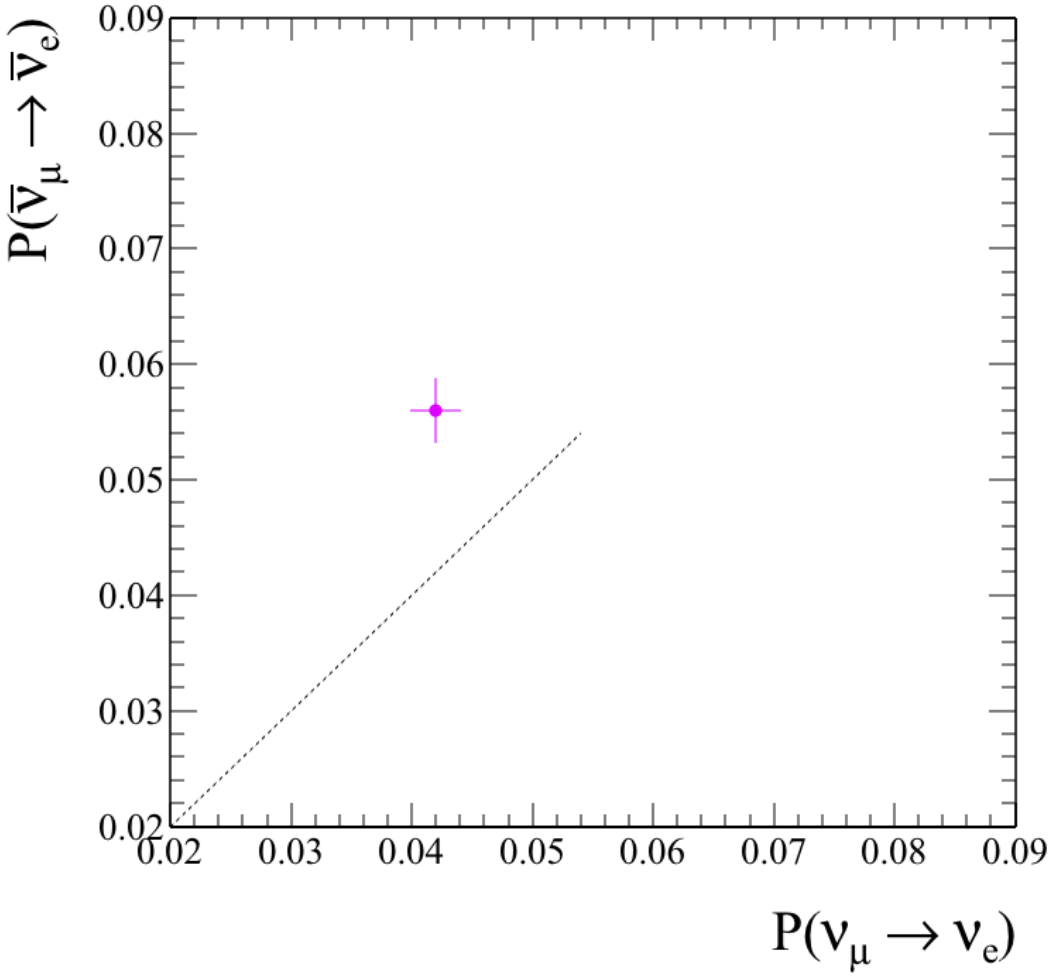
- Excellent e/μ separation.
- Probability to misidentify a muon as an electron is smaller than 1%.







Measuring δ_{CP}



If CP is violated:

$$P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$$

So a measurement in the

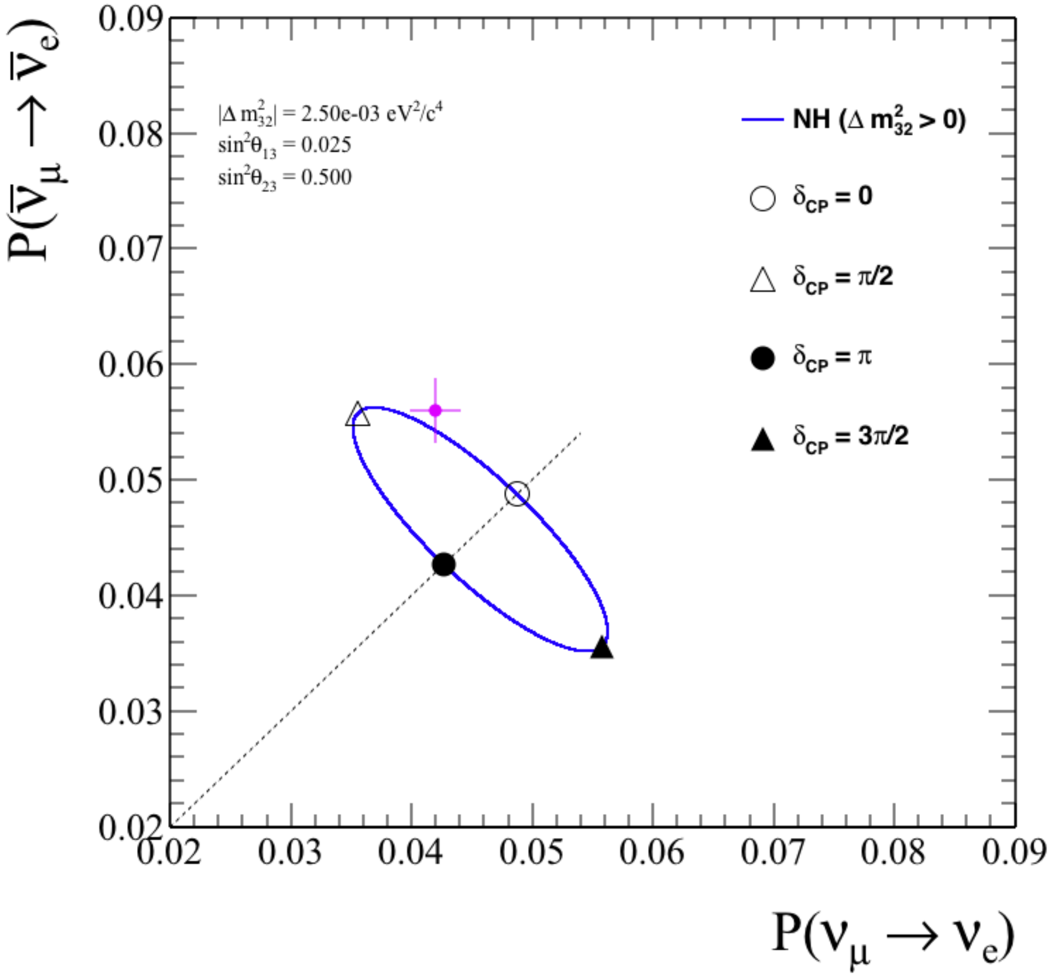
$$\Big(P(\nu_\mu \to \nu_e), P(\bar{\nu}_\mu \to \bar{\nu}_e)\Big)$$

space will be off the diagonal.

Within the standard 3-flavour model, the only source of CP violation is the δ_{CP} phase:
This measurement can be used to determine the value of δ_{CP}.

Measuring δ_{CP}

Within the standard 3-flavour model, the only source of CP violation is the δ_{CP} phase: It enters as an $e^{\pm i\delta_{CP}}$ term, so it has a **cyclical effect**.



Note that:

- Points for $\delta_{CP} = 0$ or π are on the diagonal (no CP).
- $\pi/2$ corresponds to more $\bar{\nu}_e$ appearance
- $3\pi/2$ (-$\pi/2$) corresponds to more ν_e appearance

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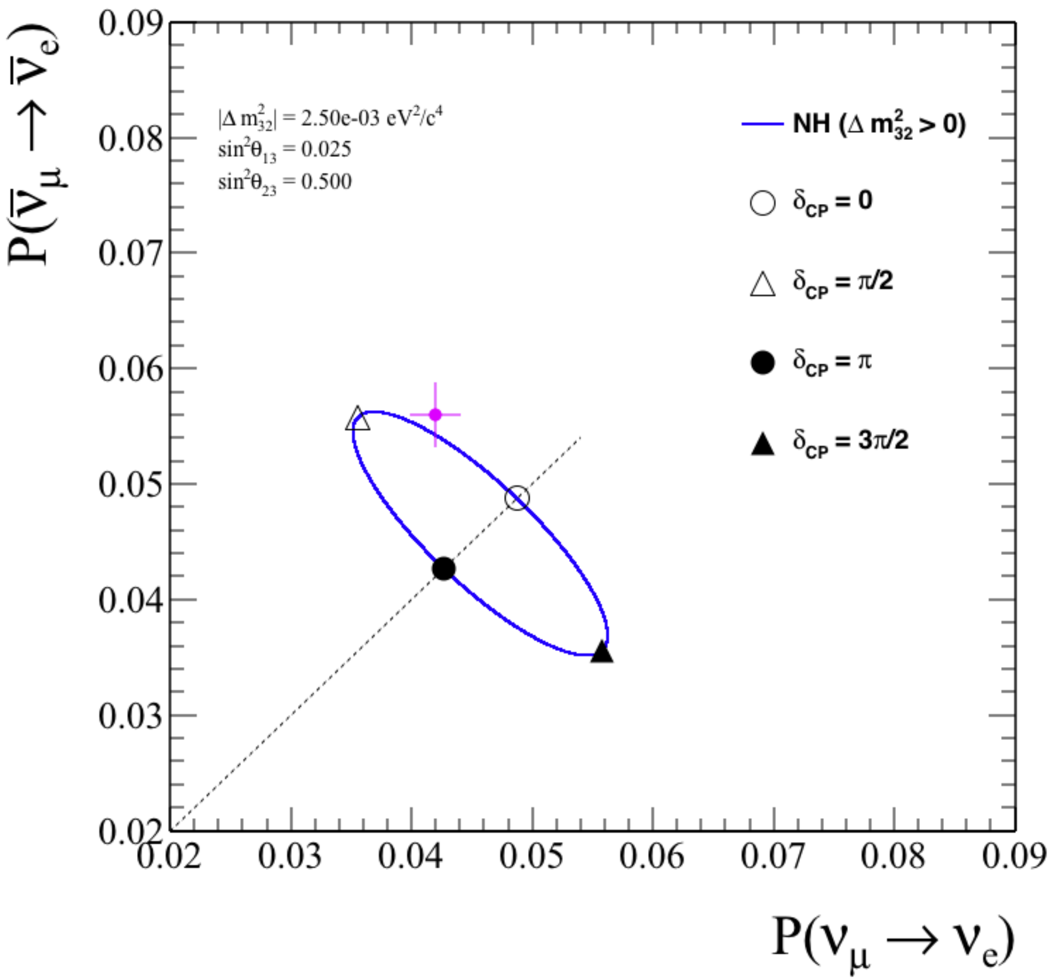

Possible to do a beautiful measurement of δ_{CP}.

Measuring δ_{CP}

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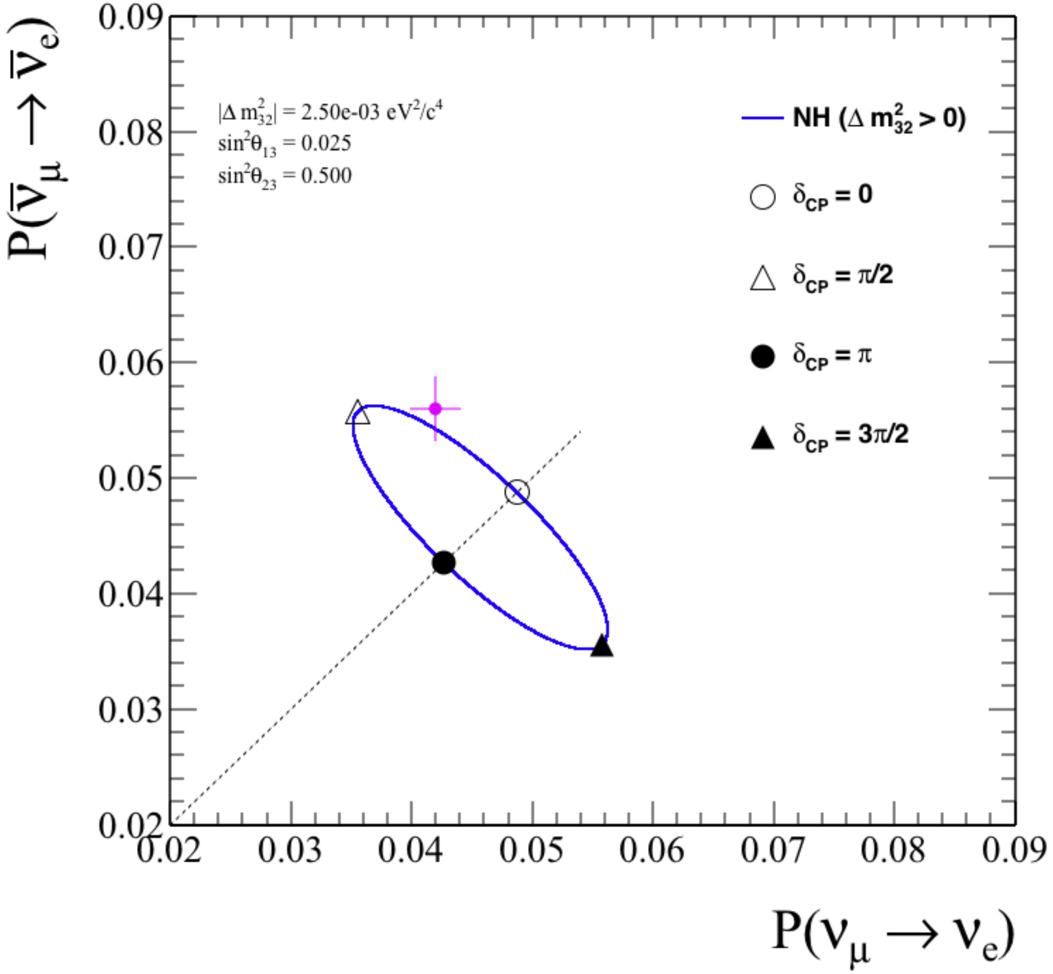
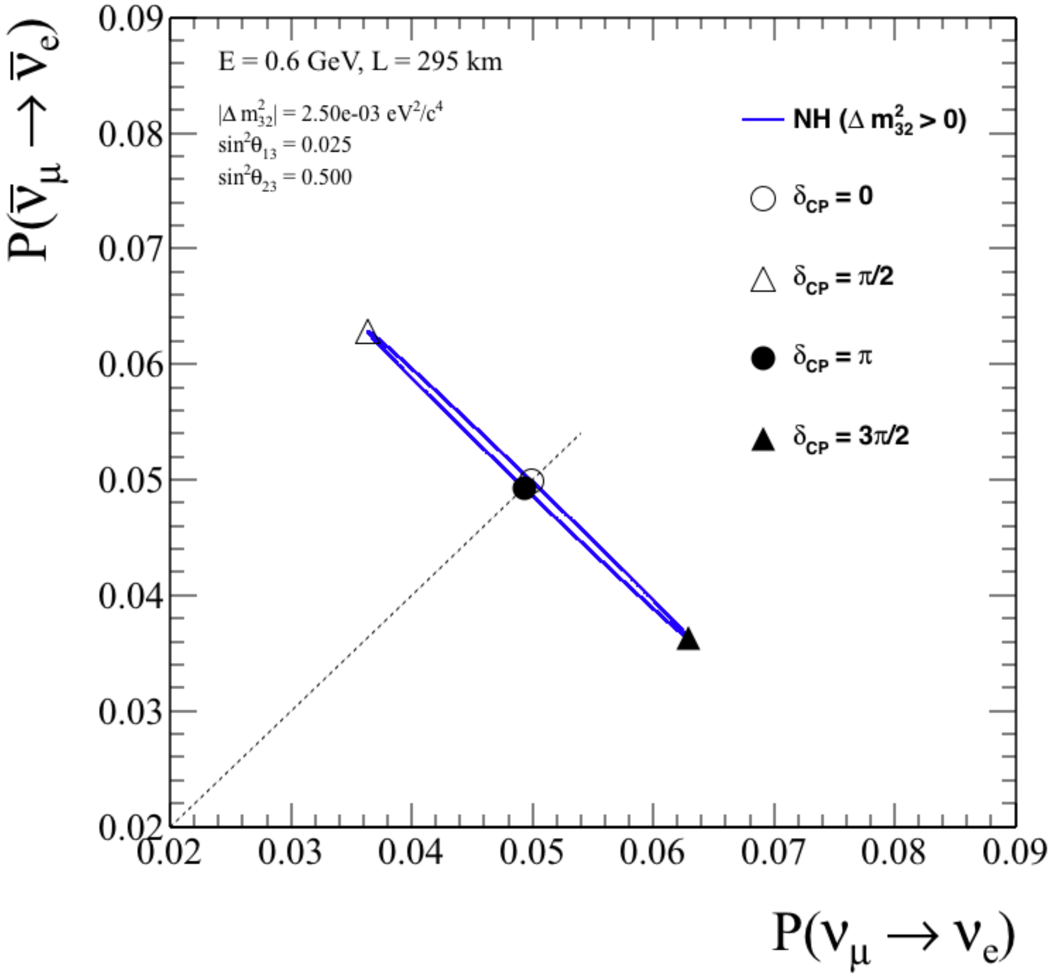


~~Possible to do a beautiful measurement of δ_{CP}~~.

Unfortunately, this is not T2K.

Measuring δ_{CP}

T2K is less able to discriminate between the CP conserving values of δ_{CP} $(0, \pi)$, so the ellipse is flattened.



Large ranges of δ_{CP} values give nearly-identical asymmetry: Difficult to do much more than just discriminating between $(0, \pi)$ and $(\pi, 2\pi)$...

So the T2K δ_{CP} measurement resolution is quite poor.

This is made even worst by matter effects, ignored in this plot (vacuum oscillation probabilities are shown).

Measuring δ_{CP}

Matter effect can play an important role in neutrino oscillations.

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

In the 3-flavour model, A_{CP} can be approximated as:

$$A_{CP} \approx \frac{cos\theta_{23} sin2\theta_{12} sin\delta_{CP}}{sin\theta_{23} sin\theta_{13}} \left(\frac{\Delta m^2_{21} L}{4E}\right) + \ matter\ effects$$

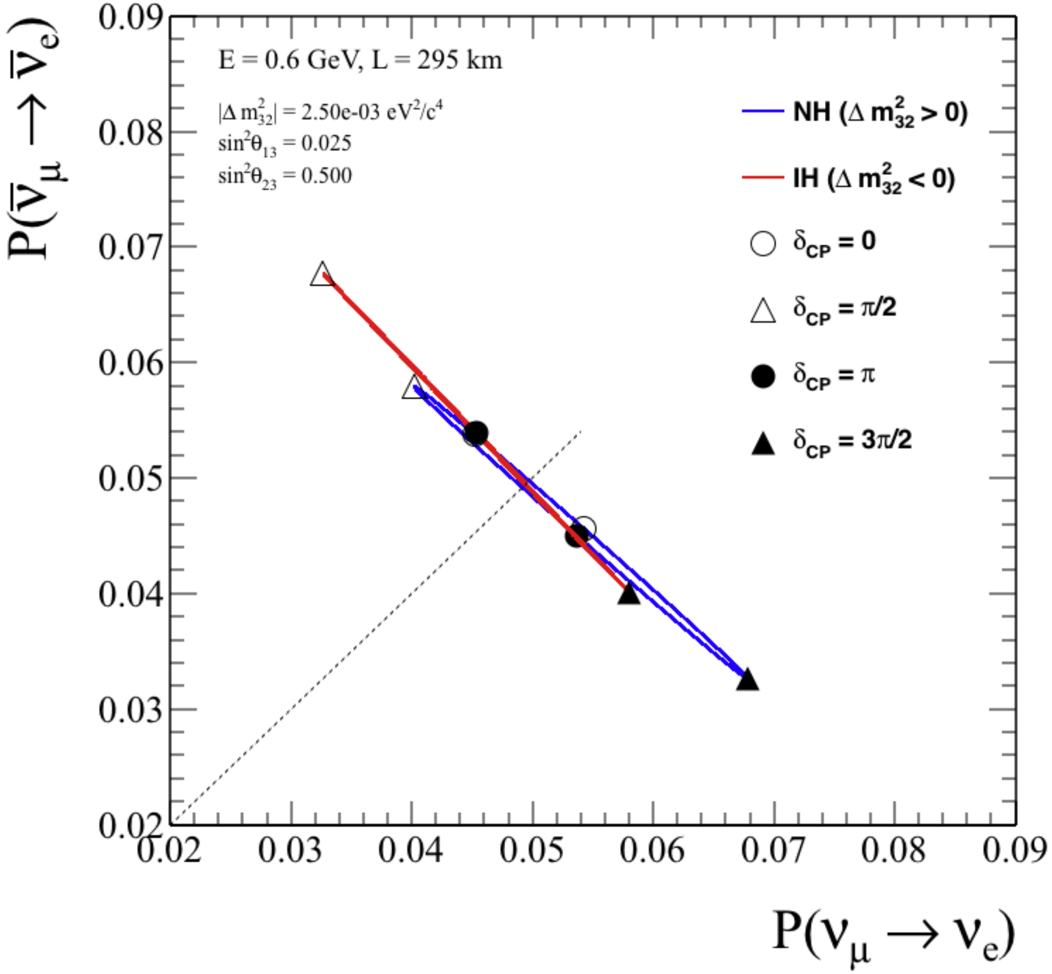
Matter induced asymmetry in $P(\nu_\mu \to \nu_e)$, $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ in addition to CP.
In general:

$$A_{CP} \propto L/E \quad and \quad A_{matter} \propto L \cdot E$$

Experimental sensitivity to CP violation and the MH from measurements of the total asymmetry between $P(\nu_\mu \to \nu_e)$, $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ requires the **disambiguation of the asymmetries** induced by matter and CP violation.

Measuring δ_{CP}

Matter effect can play an important role in neutrino oscillations.



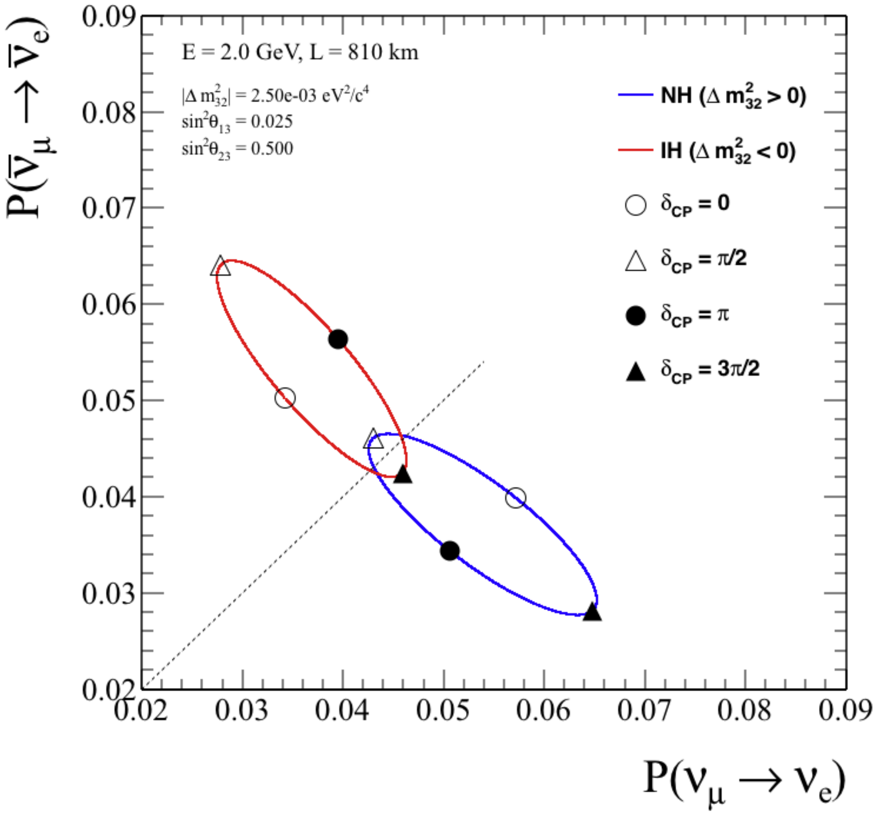
Important to know the MH.

- For NH, ν_e appearance is enhanced and $\bar{\nu}_e$ appearance is suppressed.
- For IH, ν_e appearance is suppressed and $\bar{\nu}_e$ appearance is enhanced.

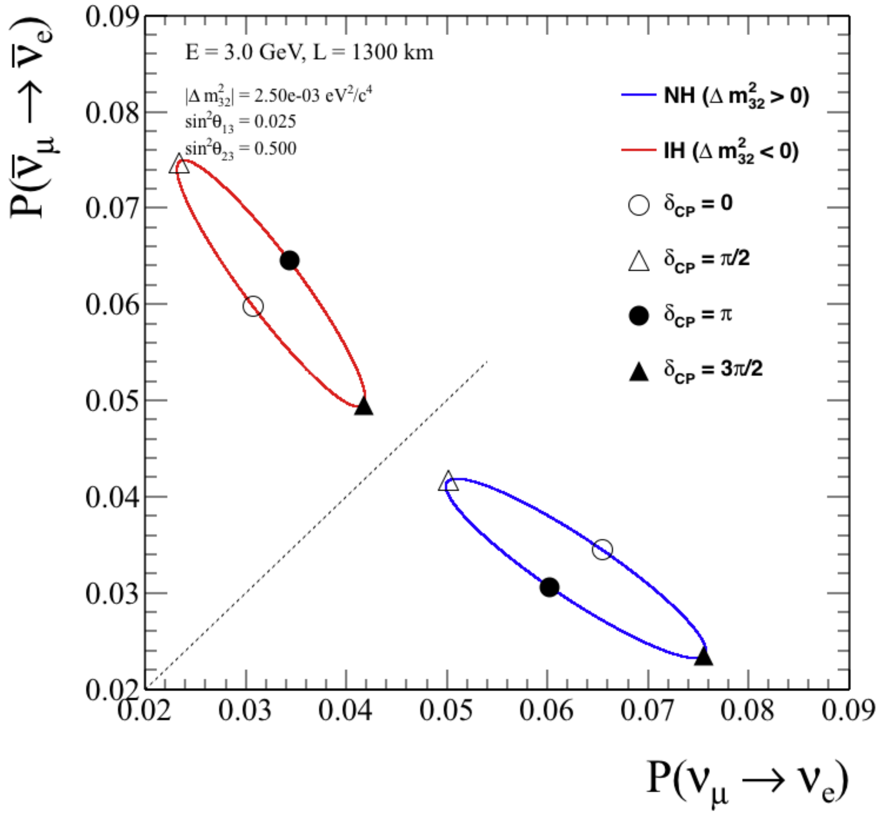
Matter effects useful for lifting degeneracies, identifying the hierarchy and measuring δ_{CP}.

T2K: Not enough matter effect!

Example: NOvA

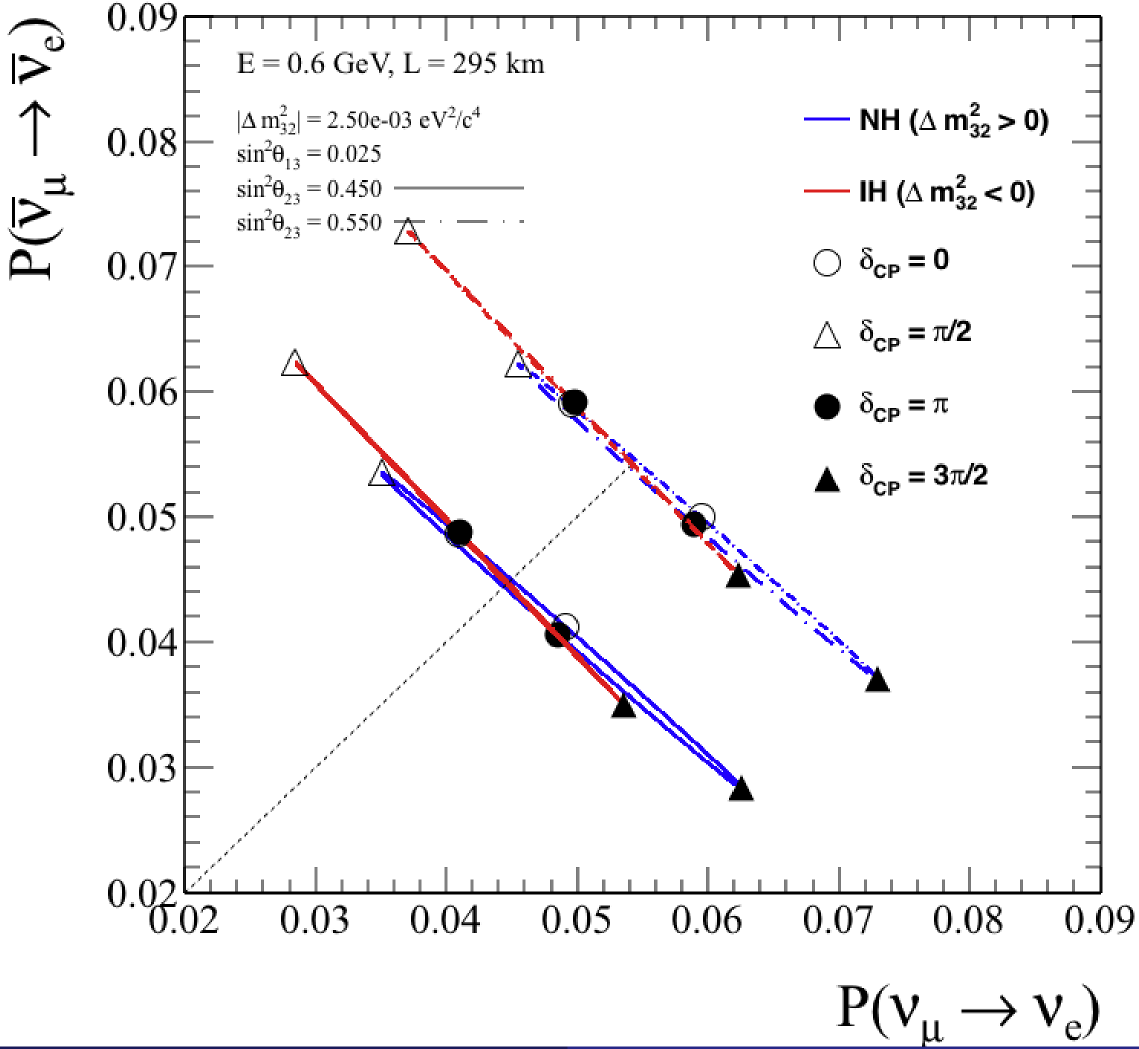


Example: DUNE



Measuring δ_{CP}

The θ_{23} **octant degeneracy** further limits our CP sensitivity and measurement resolution.



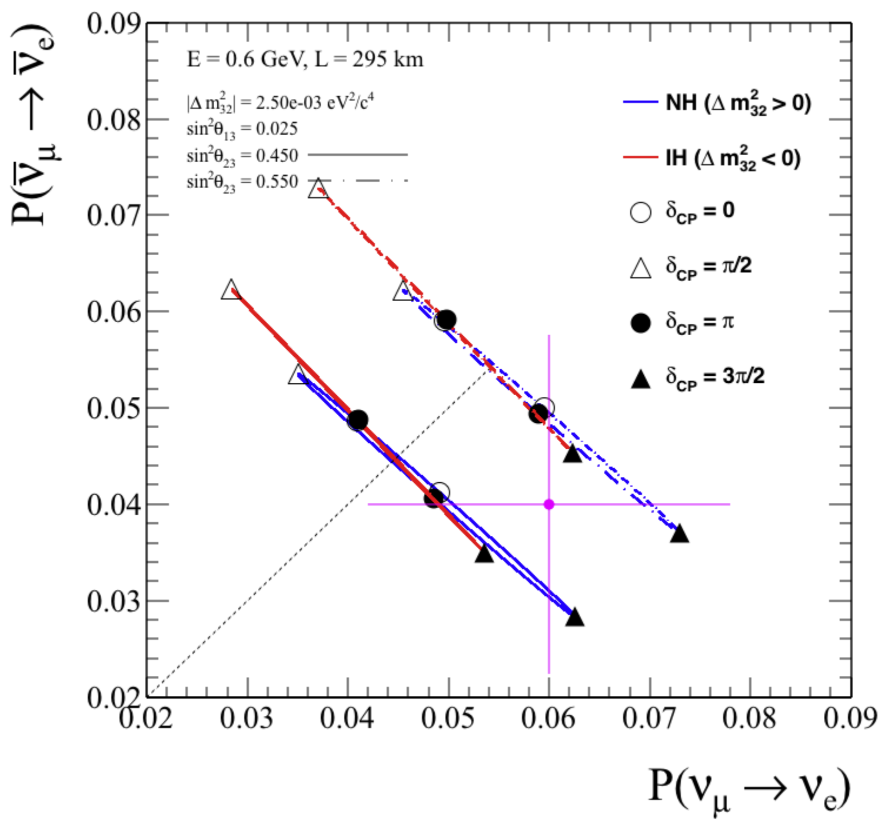
$$1 - P(\nu_\mu \to \nu_\mu) \propto sin^2 2\theta_{23}$$

$$P(\nu_\mu \to \nu_e) \propto sin^2\theta_{23}$$

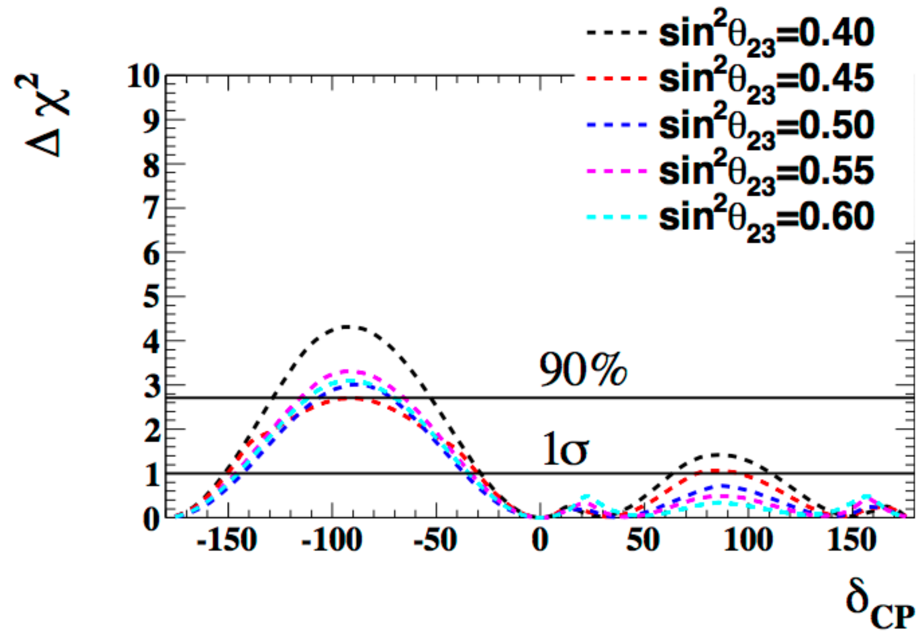
Measuring δ_{CP}

Quite difficult for T2K to "measure" δ_{CP}.

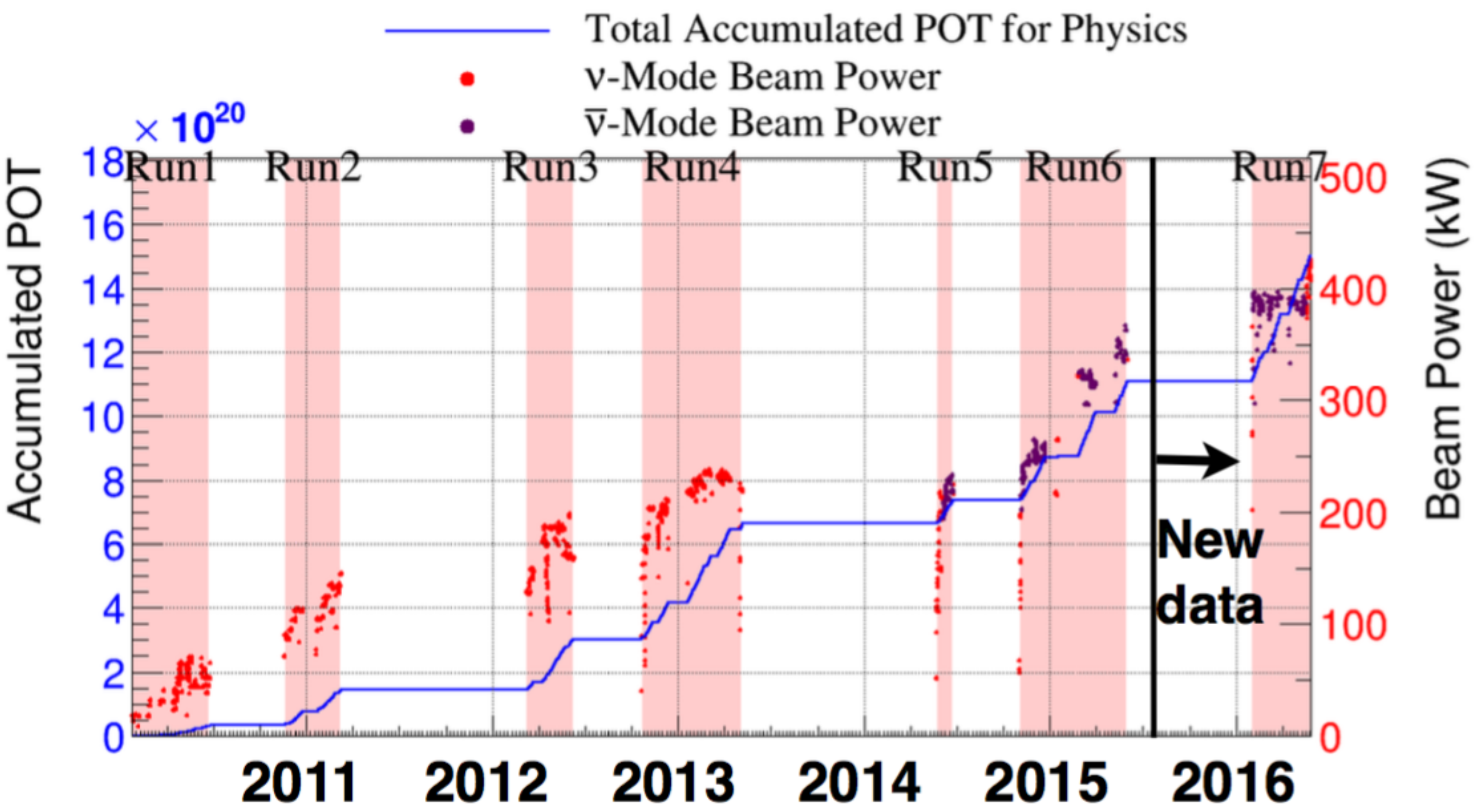
T2K could exclude the *$\sin\delta_{CP}$=0, π* (conserved CP) hypothesis, at some modest significance level, if the true δ_{CP} value lies in a favourable region...



True MH: NH, Full T2K exposure,
50% ν - 50% $\bar{\nu}$



T2K Datasets

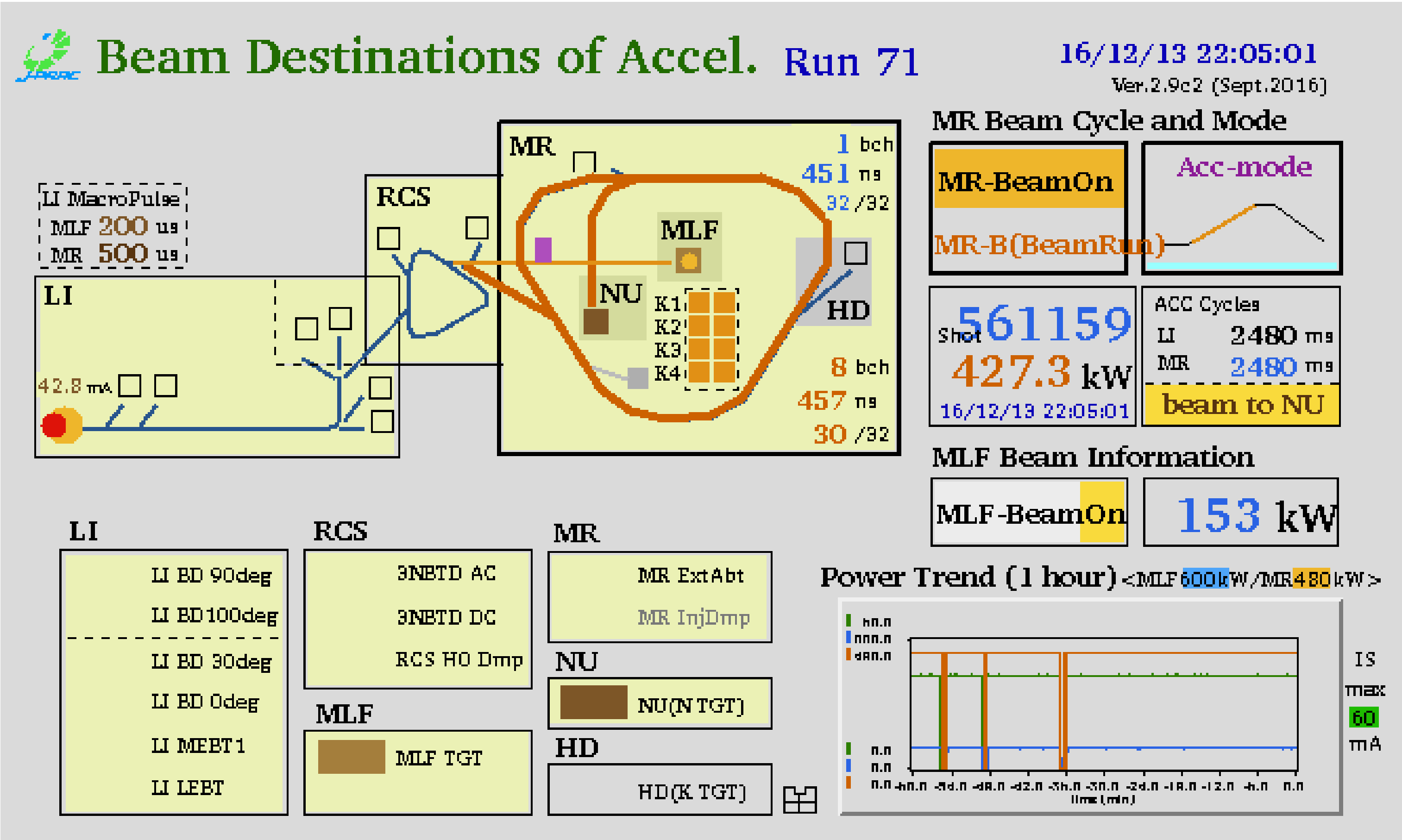


Mode	Exposure in protons on target (POT)
Neutrino	7.57×10^{20}
Antineutrino	7.53×10^{20}
Combined	1.510×10^{21}

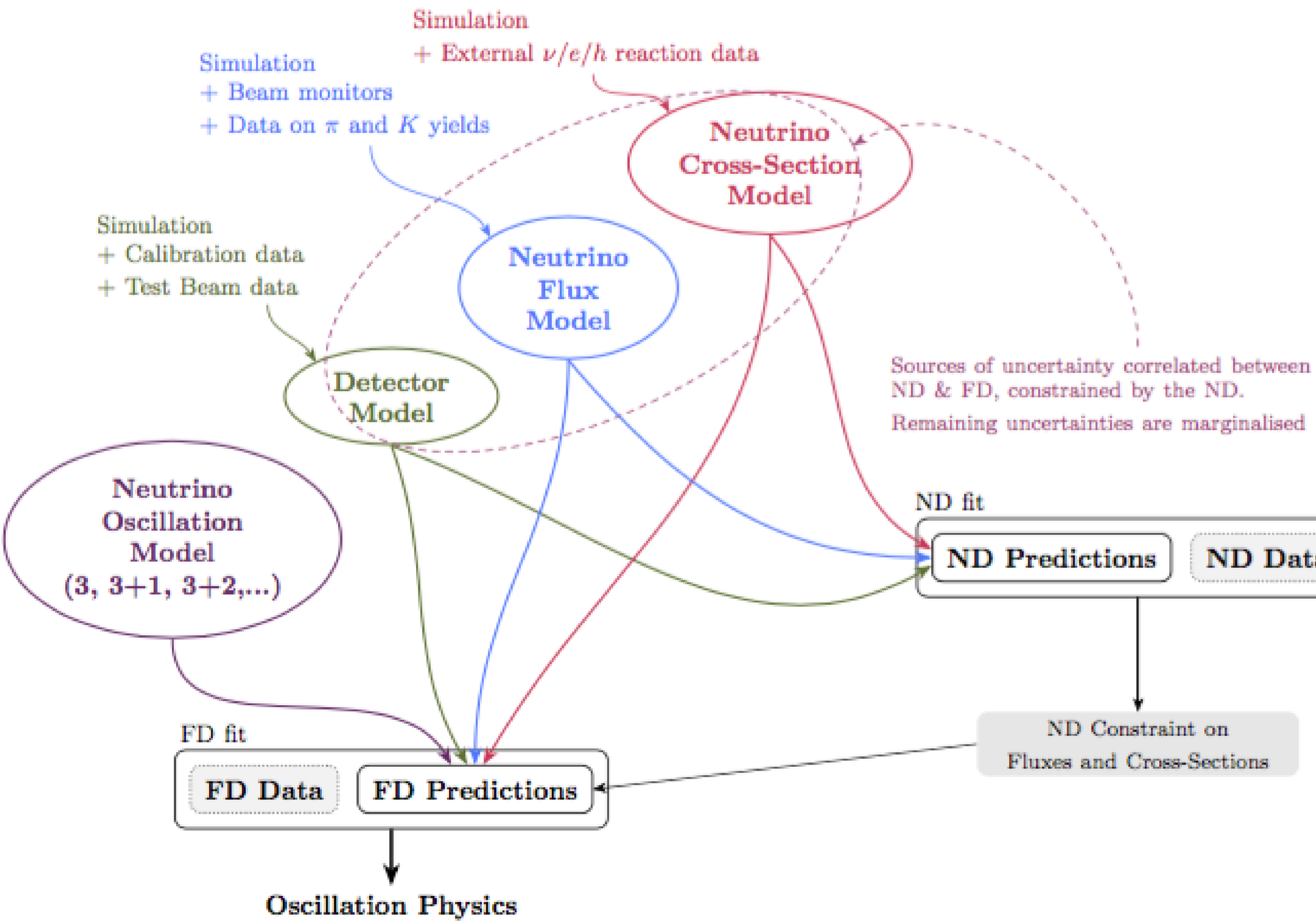
- Steady improvement of beam power (increased up to 420 kW).
- Double antineutrino exposure in 2016.

We take more data as we speak

Live updates:
http://j-parc.jp/ctrl/jkwww/accsts/li/rss/BeamDestShot.png

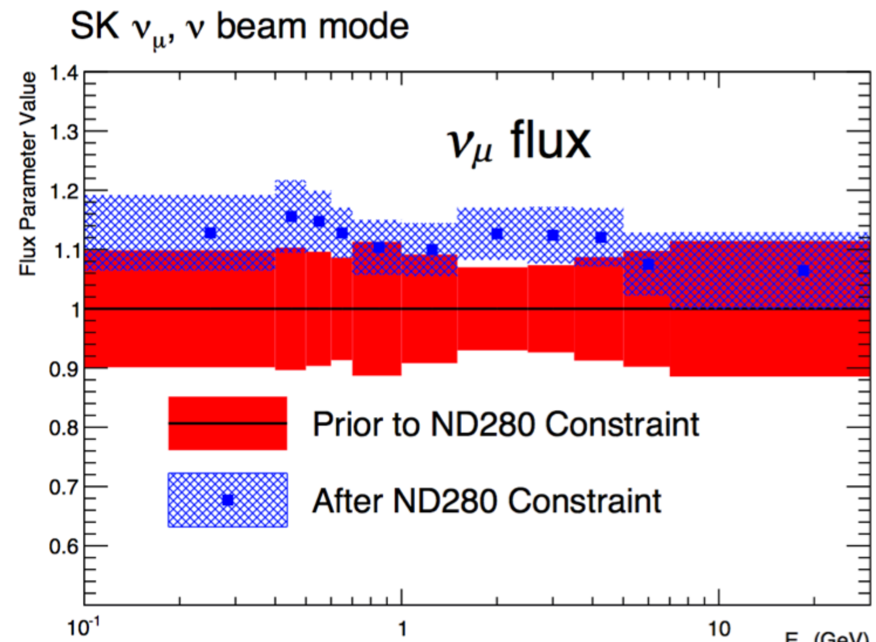


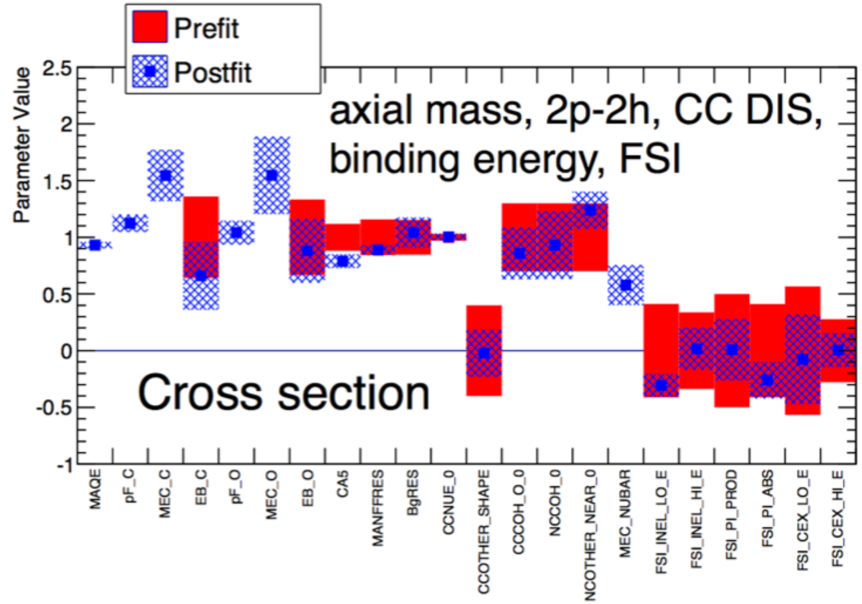
Oscillation analysis method



Systematics constraint from the Near Detector

Simultaneous fit to Near Detector neutrino and anti-neutrino event samples **constraints flux and cross-section systematics**.

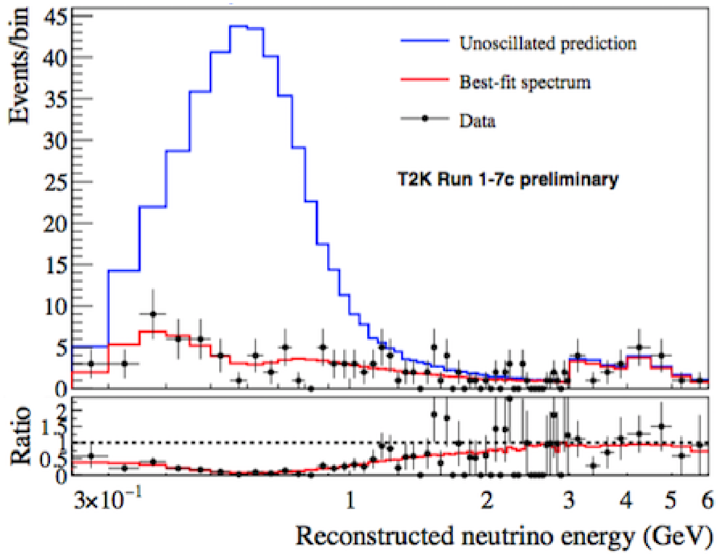




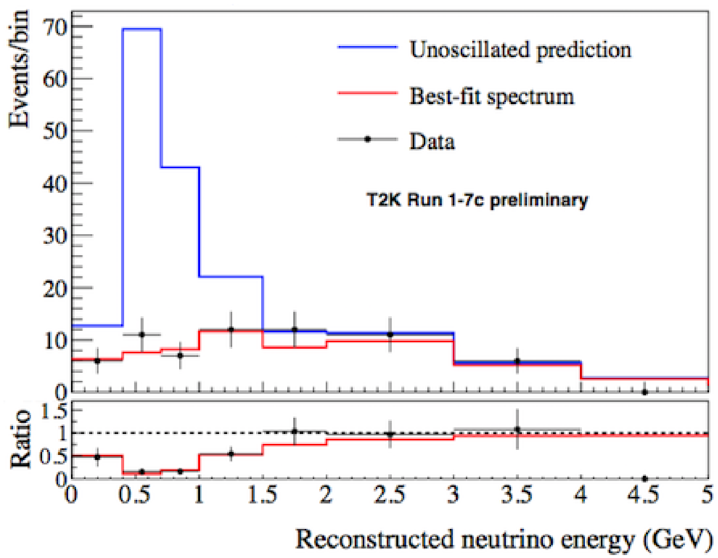
- Flux parameters increase by $\sim$15%.
- Cross-section parameters consistent with nominal values.
- Flux and cross-section parameter highly anti-correlated after the Near Detector data fit.
- Systematic uncertainties in neutrino oscillation analyses from 12-14% to 5-6%.

T2K ν_μ and $\bar{\nu}_\mu$ disappearance

ν-mode, 1-ring μ-like candidates:



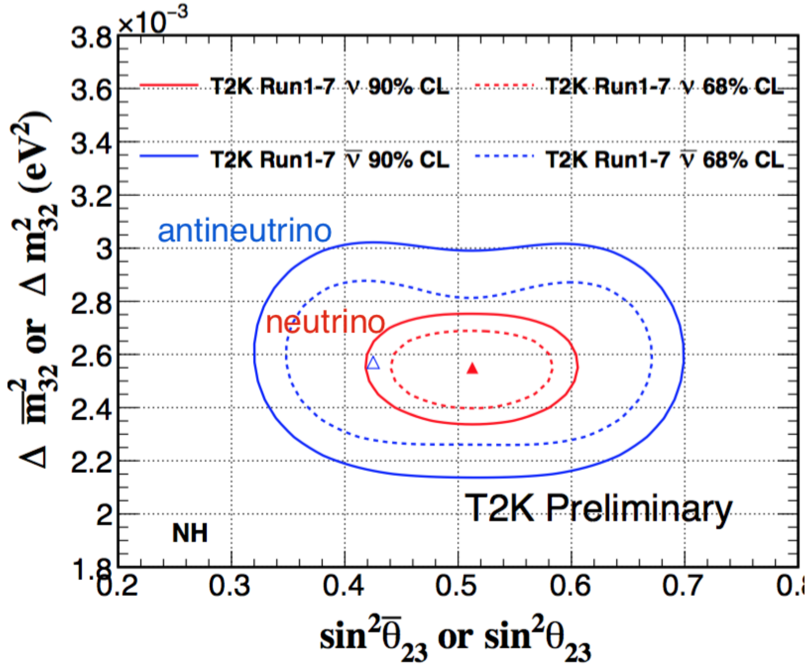
$\bar{\nu}$-mode, 1-ring μ-like candidates:



Mode	Expected (no osc.)	Observed
Neutrino	521.8	135
Antineutrino	184.8	66

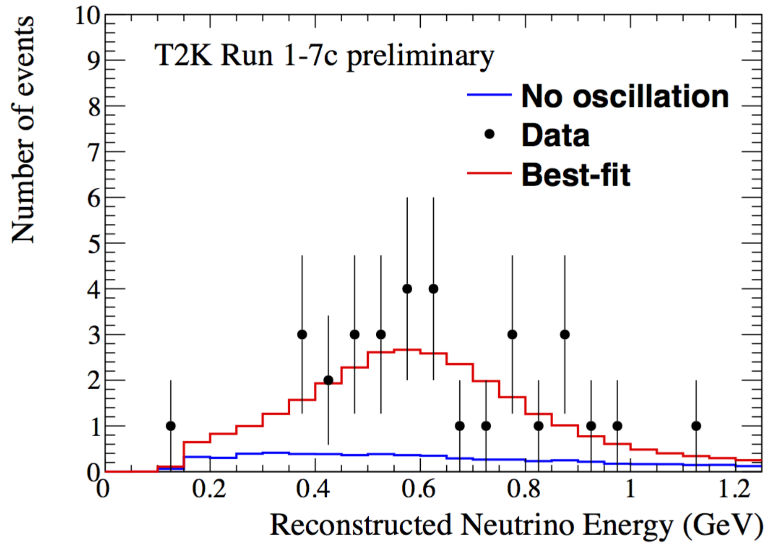
Dramatic energy-dependent deficit allows stringent constraints on ν_μ and $\bar{\nu}_\mu$ disappearance parameters.

$$P(\nu_\mu \to \nu_\mu) \approx 1 - cos^4\theta_{13}\cdot sin^2 2\theta_{23}\cdot sin^2(\frac{\Delta m^2_{31} L}{4E})$$

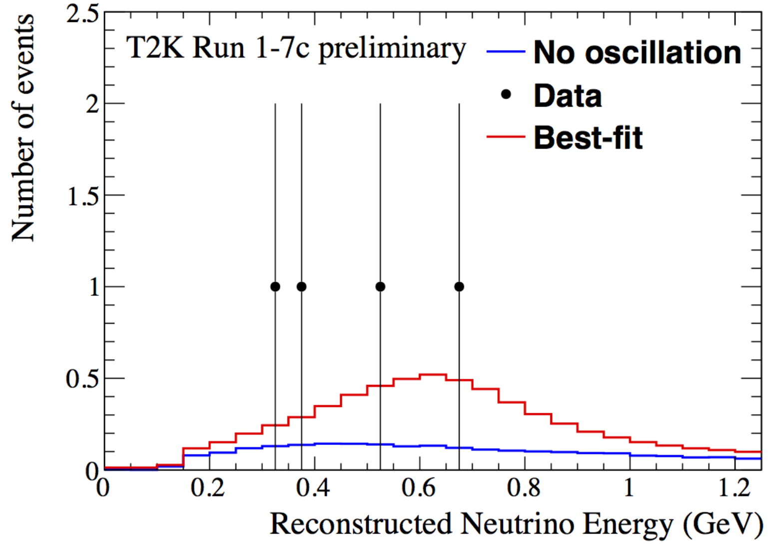


T2K ν_e and $\bar{\nu}_e$ appearance

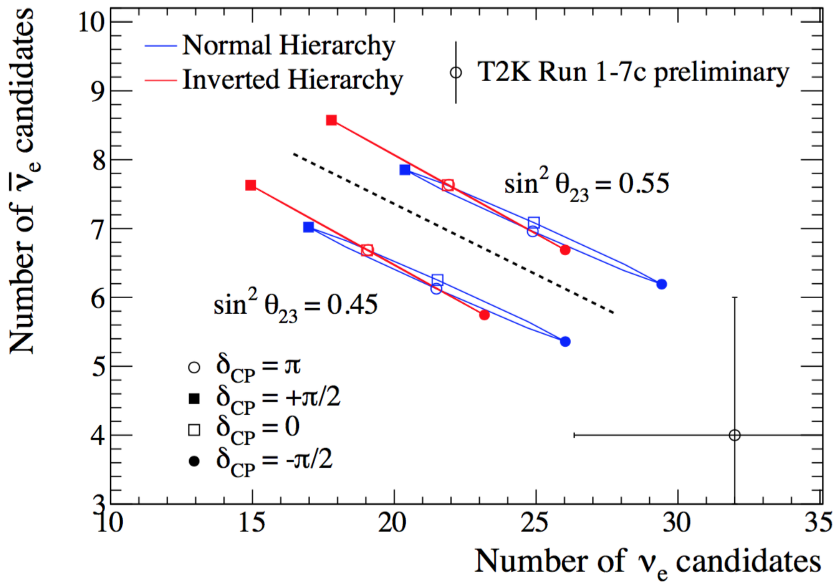
ν-mode, 1-ring e-like candidates:



$\bar{\nu}$-mode, 1-ring e-like candidates:



- more nue-like event appearance than expected in neutrino mode, and
- less nue-like event appearance than expected in anti-neutrino mode

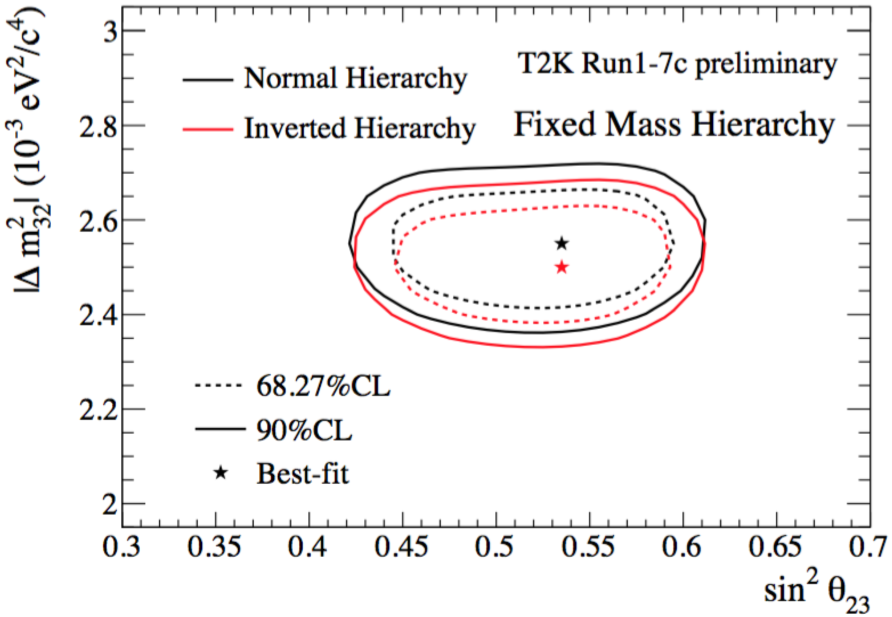


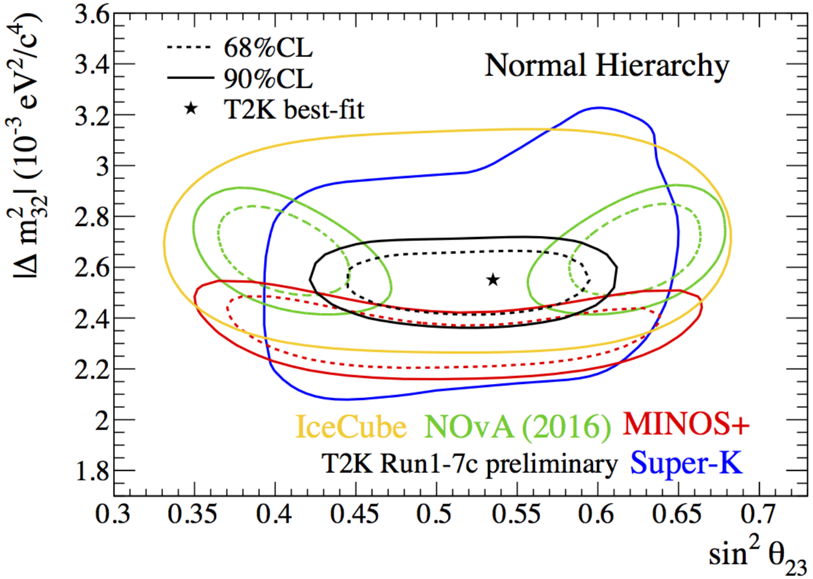
Mode	δ_{CP}, Normal hierarchy				Obs.
	$-\pi/2$	0	π	$\pi/2$	
ν	28.7	24.1	24.2	19.6	32
$\bar{\nu}$	6.0	6.9	6.8	7.7	4

T2K joint 3-flavour analysis: $sin^2\theta_{23}$ and $|\Delta m^2_{32}|$

Joint measurement of $sin^2\theta_{23}$ and $|\Delta m^2_{32}|$

- The ν_μ, $\bar{\nu}_\mu$ disappearance constrain $sin^2 2\theta_{23}$ and $|\Delta m^2_{32}|$.
- The ν_e, $\bar{\nu}_e$ appearance samples help lift the θ_{23} octant degeneracy.





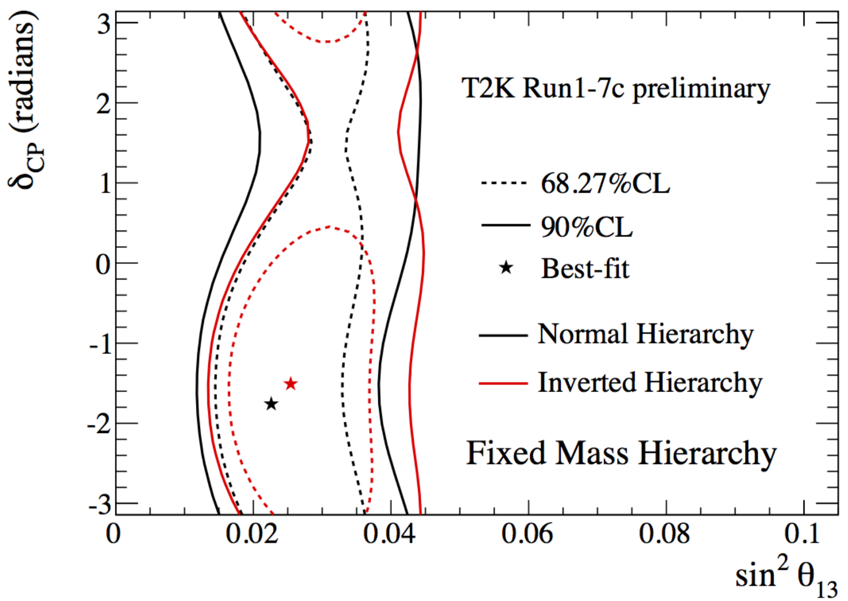
- Consistent with **maximal mixing**.
- Some tension with NOvA results.

Best-fit parameter	NH	IH
$sin^2\theta_{23}$	0.532	0.534
$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-3}$ eV^2)	2.545	2.510

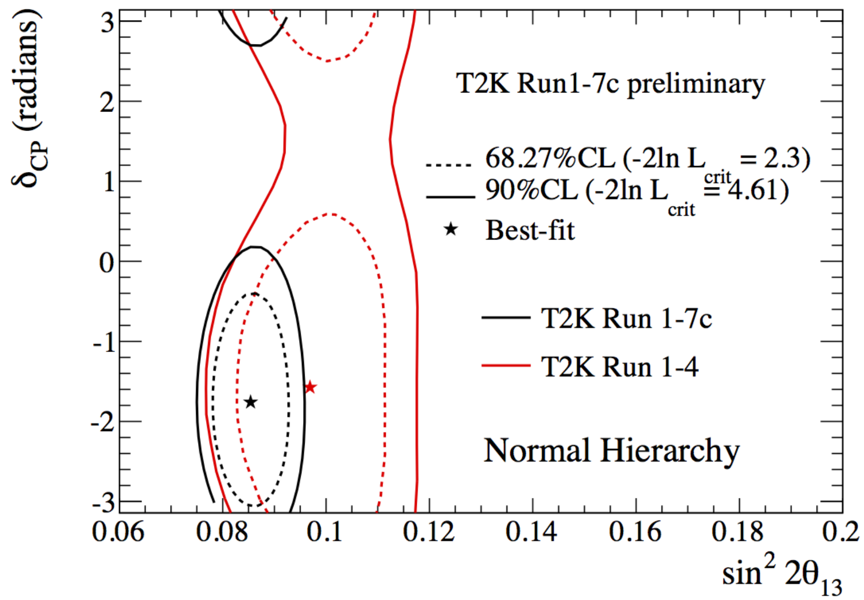
T2K joint 3-flavour analysis: θ_{13} and δ_{CP}

- Confidence intervals are slightly tighter than expected ones.

T2K sensitivity, $\delta_{CP} = \pi/2$



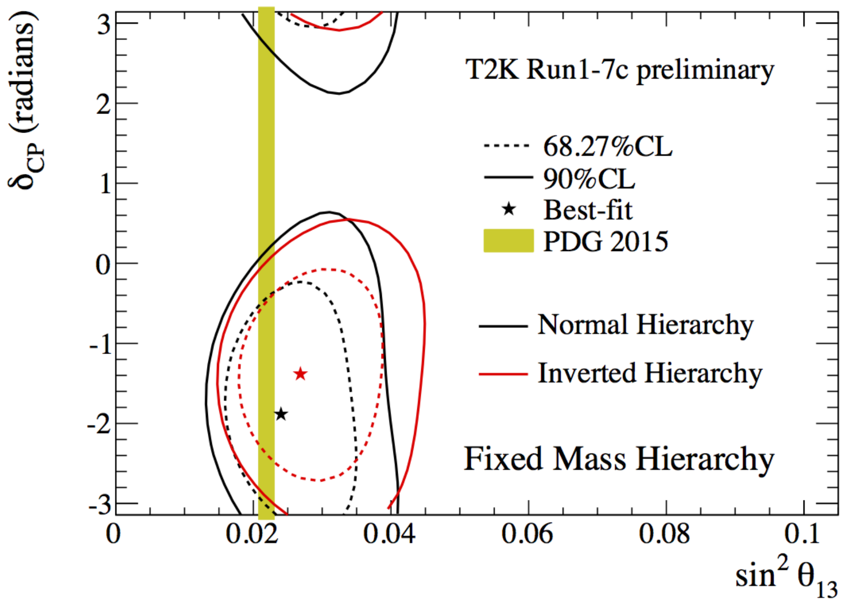
T2K-only data fit



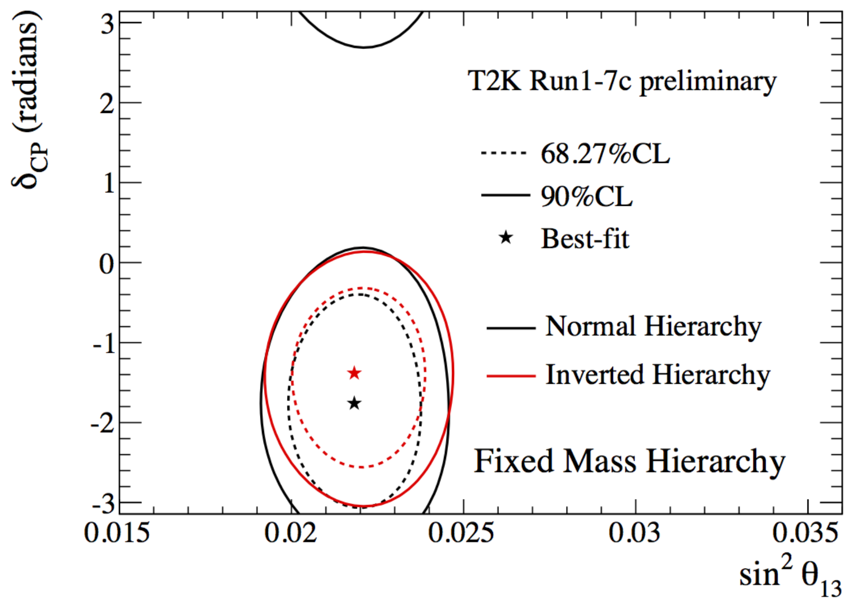
Mass hierarchy is fixed to either normal or inverted. Contours with constant $\Delta\chi^2$ method (gaussian approximation)

- Good agreement with the reactor measurement of θ_{13}
  - $sin^2 2\theta_{13} = 0.085 \pm 0.005$ [PDG2015]
- T2K-only data **disfavor the region of δ_{CP} around $\pi/2$**.
- T2K **prefers -π/2** for both NH and IH.

T2K-only data fit



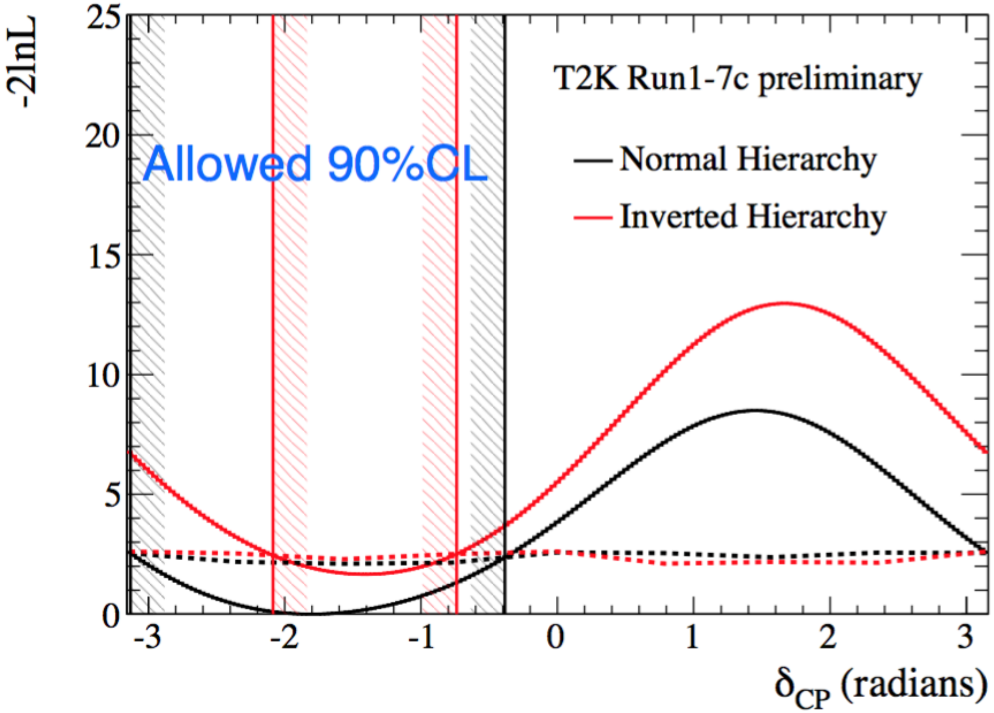
T2K data fit with reactor constraint



Mass hierarchy is fixed to either normal or inverted. Contours with constant $\Delta\chi^2$ method (gaussian approximation)

T2K joint 3-flavour analysis: δ_{CP}

- Best-fit: δ_{CP} = -1.885, NH
- $\delta_{CP} = 0$ is excluded at 2σ C.L., while $\delta_{CP} = \pi$ is excluded at 90% C.L.
- Allowed 90% C.L. regions: [-3.13,0.39] (NH), [-2.09,-0.74] (IH)



"Conserved CP' hypothesis excluded at 90% C.L.

$sin^2 2\theta_{13} = 0.085 \pm 0.005$ [PDG2015]

Note: With the current exposure, there is about 5% chance to exclude the conserved CP hypothesis at 90% C.L., even if CP is actually conserved.

Confidence intervals computed with Feldman-Cousins method to guarantee frequentist coverage.

Liverpool group centrally involved in T2K physics

People (AC/Staff, RA, PhD):

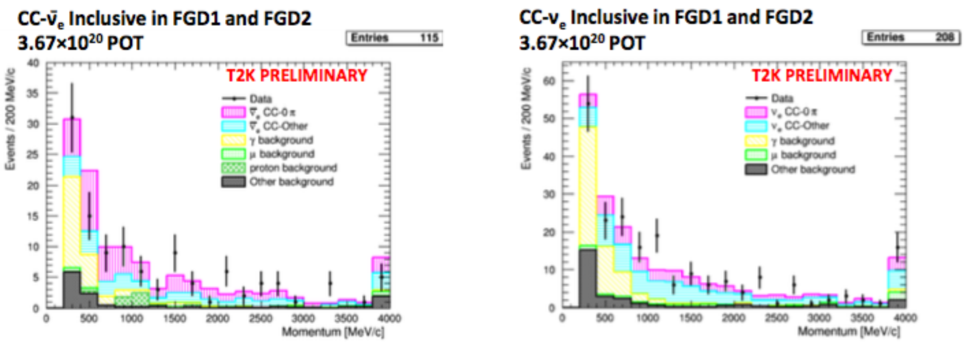
- Costas Andreopoulos
- Lauren Anthony
- Chris Barry
- Francis Bench
- Georgios Christodoulou
- Jon Coleman
- Steve Dennis
- Kostas Mavrokoridis
- Neil McCauley **[PI]**
- Carl Metelko
- Matt Murdoch
- Pratiksha Paudyal
- Christos Touramanis
- David Payne
- Adrian Pritchard
- Michail Lazos

Andreopoulos, Barry, Bench, Dennis and collaborators
VALOR oscillation analysis (https://valor.pp.rl.ac.uk)

- 13 completed, documented and fully internally-reviewed oscillation analyses since 2010.
- Contributions to 4 PRL papers (+ 1 in preparation) and 2 PRD papers (+ 1 in preparation).

McCauley, Christodoulou, Paudyal and collaborators
Crucial neutrino cross-section measurements at ND280

- Understanding of ν_e, $\bar{nu}_e$ beam contamination.
- ν_e cross-section measurement (PRL).
- Ongoing work to measure $\bar{nu}_e$ cross-sections.



Future prospects

Expect to reach the approved T2K exposure (7.8×10^{21} POT) around 2021.

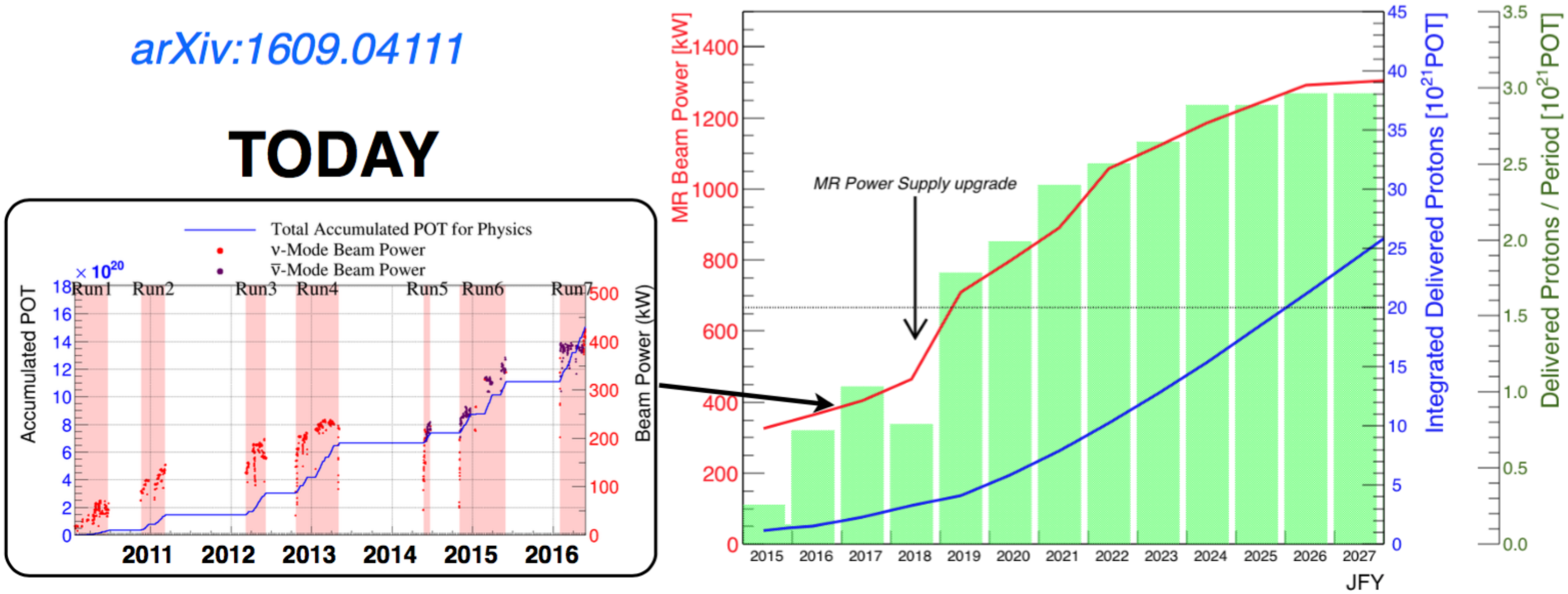
There is a proposal to extend the T2K run (T2K-II) to 20×10^{21} POT by 2025.

- Stage-I approval by JPARC PAC.

Aiming for >1 MW intensity for 2021 and 1.3 MW in 2026.

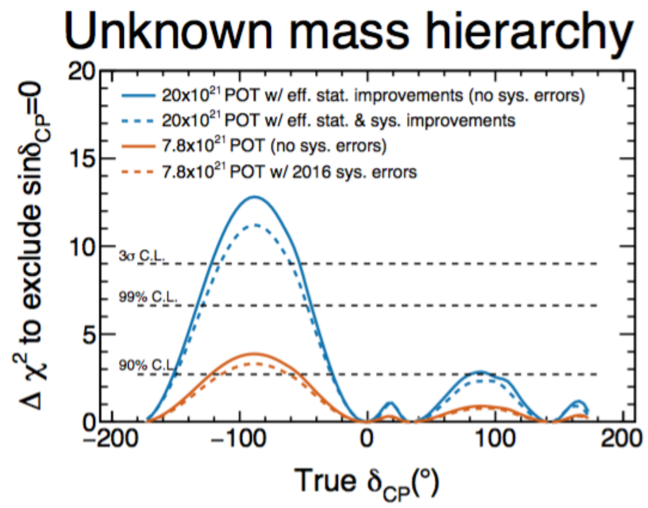
- Accelerator and beam-line upgrade is needed

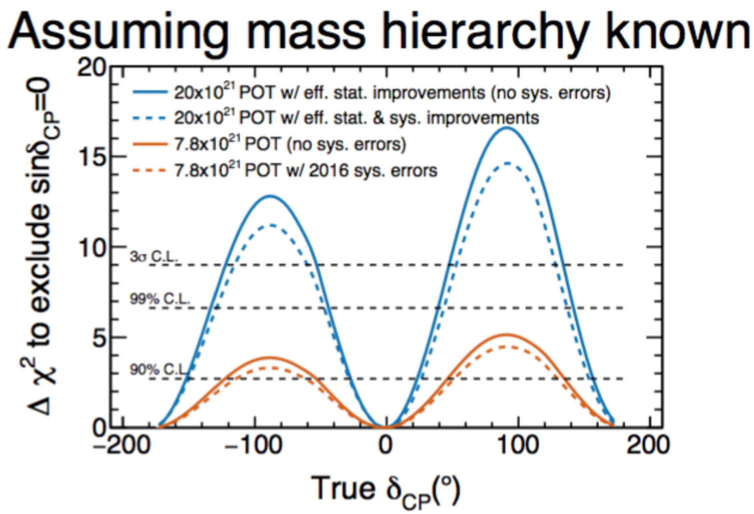
Demonstrated 3.41×10^{13} protons per pulse operation → 1 MW equivalent.

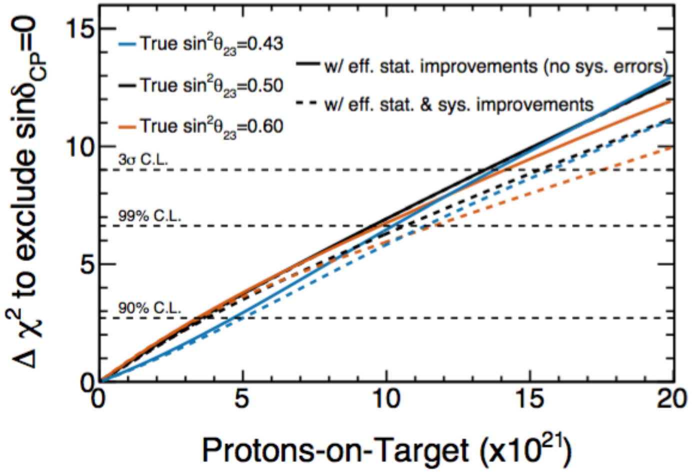


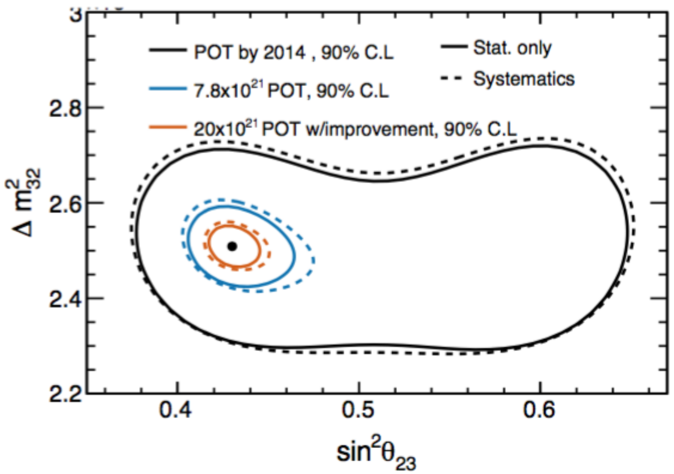
Future prospects

- Exclude CP conservation hypothesis at more than 3σ if $\delta_{CP} \approx \pi/2$ and NH.
- Measure θ_{23} with resolution of $\leq 1.7^o$.





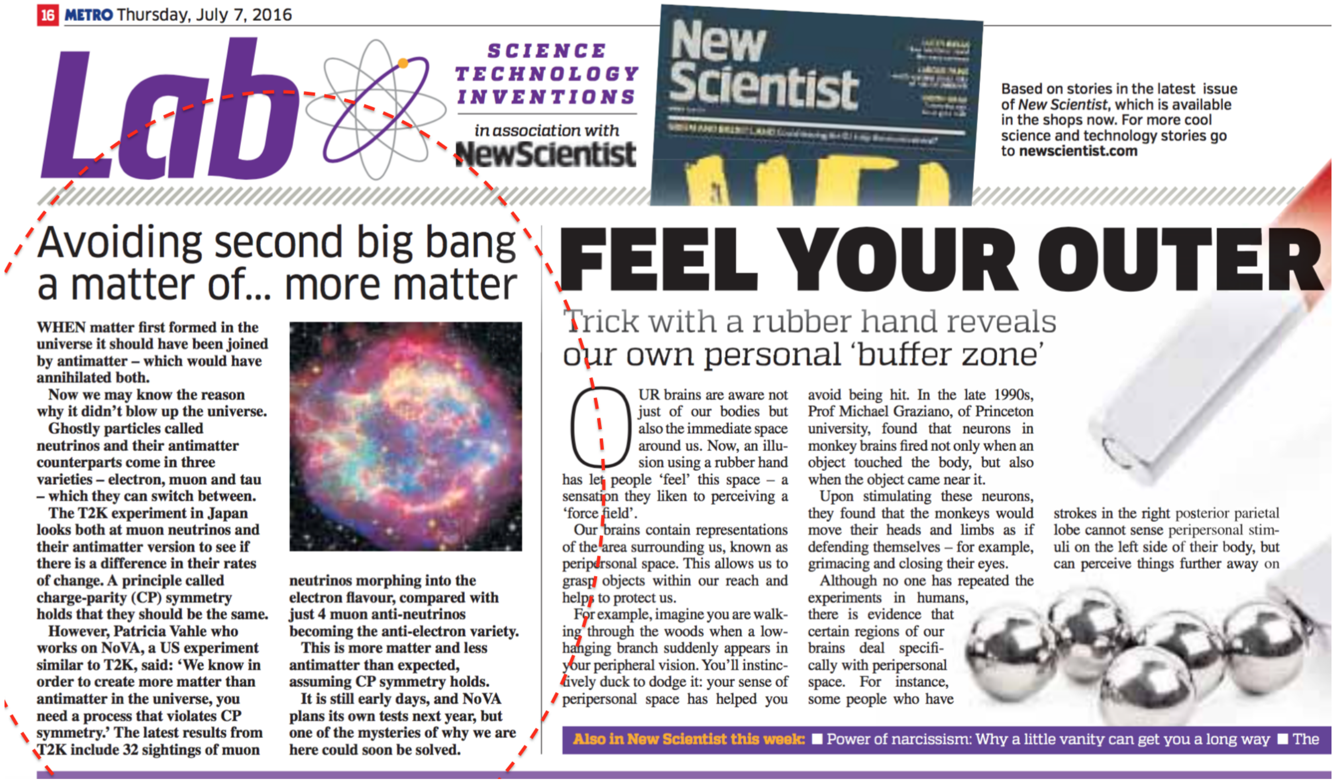




Substantial interest in T2K (and NOvA) δ_{CP} measurement

Both T2K and NOvA point towards **large neutrino CP violation**.

"Why do we even need DUNE?" (actual question asked!)



16 METRO Thursday, July 7, 2016

Lab

SCIENCE TECHNOLOGY INVENTIONS

in association with NewScientist

Based on stories in the latest issue of *New Scientist*, which is available in the shops now. For more cool science and technology stories go to **newscientist.com**

Avoiding second big bang a matter of... more matter

WHEN matter first formed in the universe it should have been joined by antimatter – which would have annihilated both.

Now we may know the reason why it didn't blow up the universe.

Ghostly particles called neutrinos and their antimatter counterparts come in three varieties – electron, muon and tau – which they can switch between.

The T2K experiment in Japan looks both at muon neutrinos and their antimatter version to see if there is a difference in their rates of change. A principle called charge-parity (CP) symmetry holds that they should be the same.

However, Patricia Vahle who works on NoVA, a US experiment similar to T2K, said: 'We know in order to create more matter than antimatter in the universe, you need a process that violates CP symmetry.' The latest results from T2K include 32 sightings of muon neutrinos morphing into the electron flavour, compared with just 4 muon anti-neutrinos becoming the anti-electron variety.

This is more matter and less antimatter than expected, assuming CP symmetry holds.

It is still early days, and NoVA plans its own tests next year, but one of the mysteries of why we are here could soon be solved.

FEEL YOUR OUTER

Trick with a rubber hand reveals our own personal 'buffer zone'

OUR brains are aware not just of our bodies but also the immediate space around us. Now, an illusion using a rubber hand has let people 'feel' this space – a sensation they liken to perceiving a 'force field'.

Our brains contain representations of the area surrounding us, known as peripersonal space. This allows us to grasp objects within our reach and helps to protect us.

For example, imagine you are walking through the woods when a low-hanging branch suddenly appears in your peripheral vision. You'll instinctively duck to dodge it: your sense of peripersonal space has helped you avoid being hit. In the late 1990s, Prof Michael Graziano, of Princeton university, found that neurons in monkey brains fired not only when an object touched the body, but also when the object came near it.

Upon stimulating these neurons, they found that the monkeys would move their heads and limbs as if defending themselves – for example, grimacing and closing their eyes.

Although no one has repeated the experiments in humans, there is evidence that certain regions of our brains deal specifically with peripersonal space. For instance, some people who have strokes in the right posterior parietal lobe cannot sense peripersonal stimuli on the left side of their body, but can perceive things further away on

Also in New Scientist this week: ■ Power of narcissism: Why a little vanity can get you a long way ■ The

Substantial interest in T2K (and NOvA) δ_{CP} measurement

However, as explained, results are very likely statistical flukes.
Probably we won't reach the end of the CP tunnel < 2030 (See Christos' talk).

But with neutrinos, you never know what will jump in front of you from the dark!
We may be seeing a CP asymmetry that doesn't come from the 3-flavour δ_{CP} ??

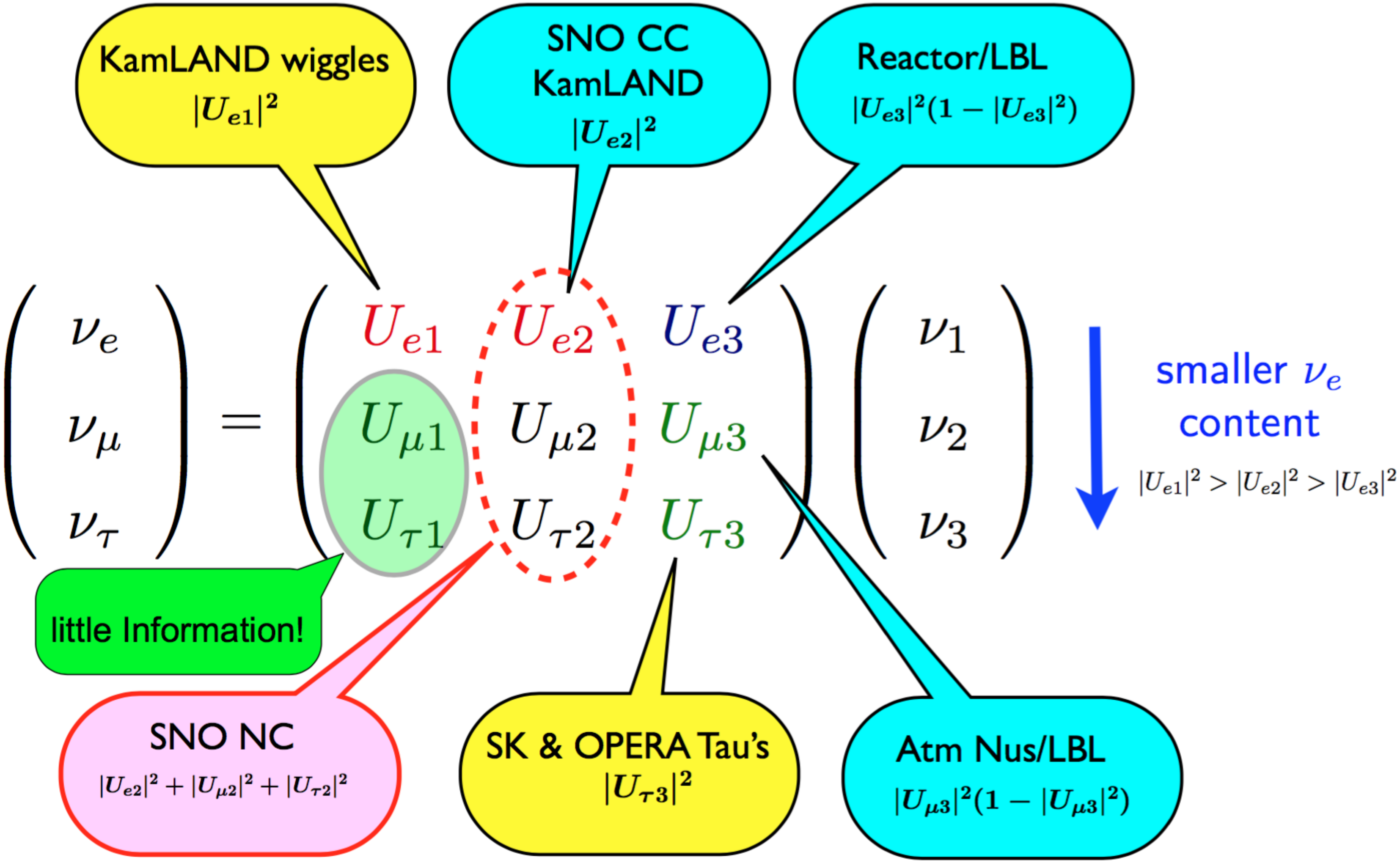
But if you were expecting T2K to "measure" the PMNS δ_{CP},
don't put the champagne on the fridge just yet...

Or maybe you should anyway
(and forget about CP for a while)!

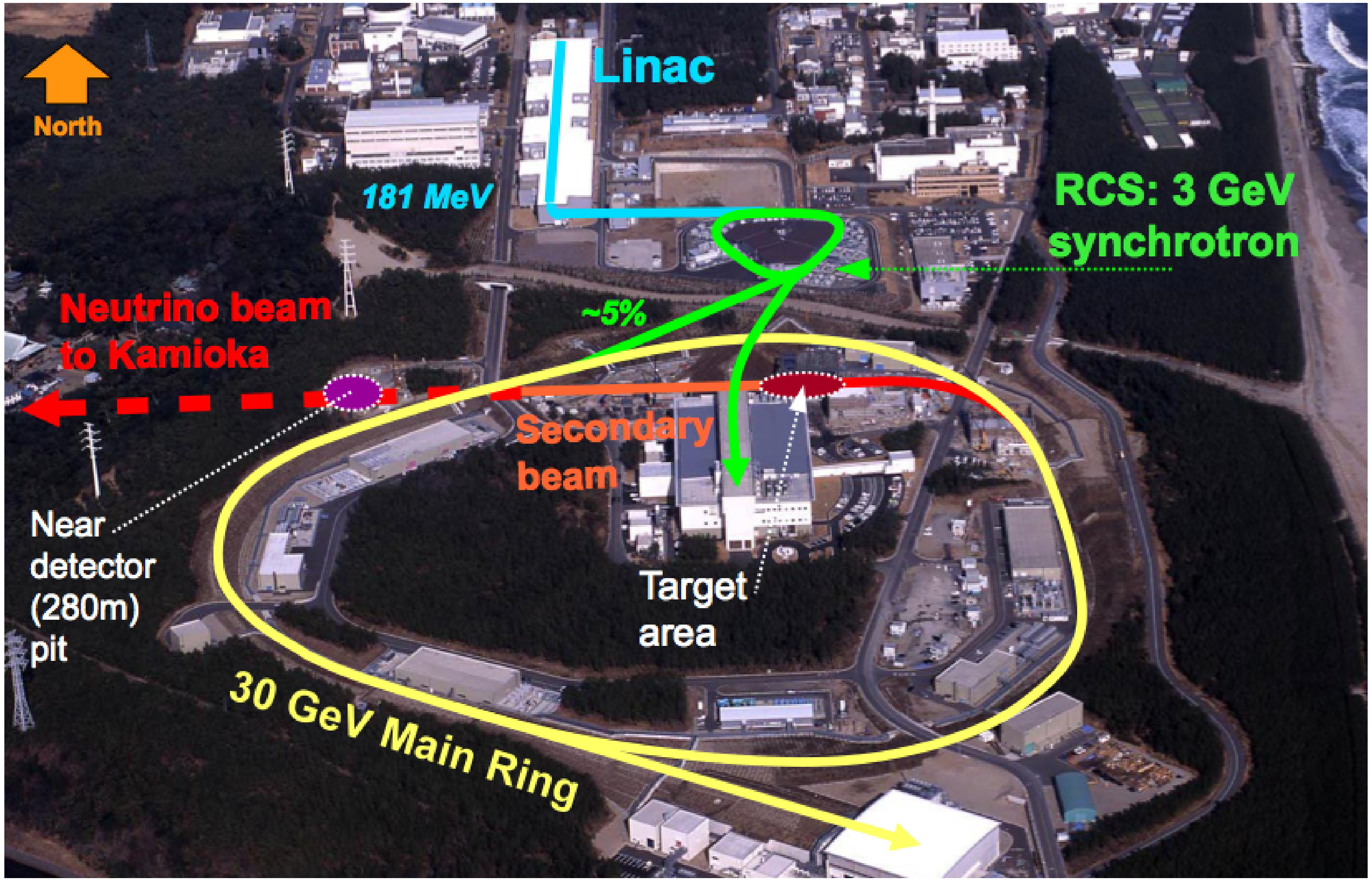
Merry Christmas!

Supplementary slides

What do we measure in neutrino oscillation experiments?

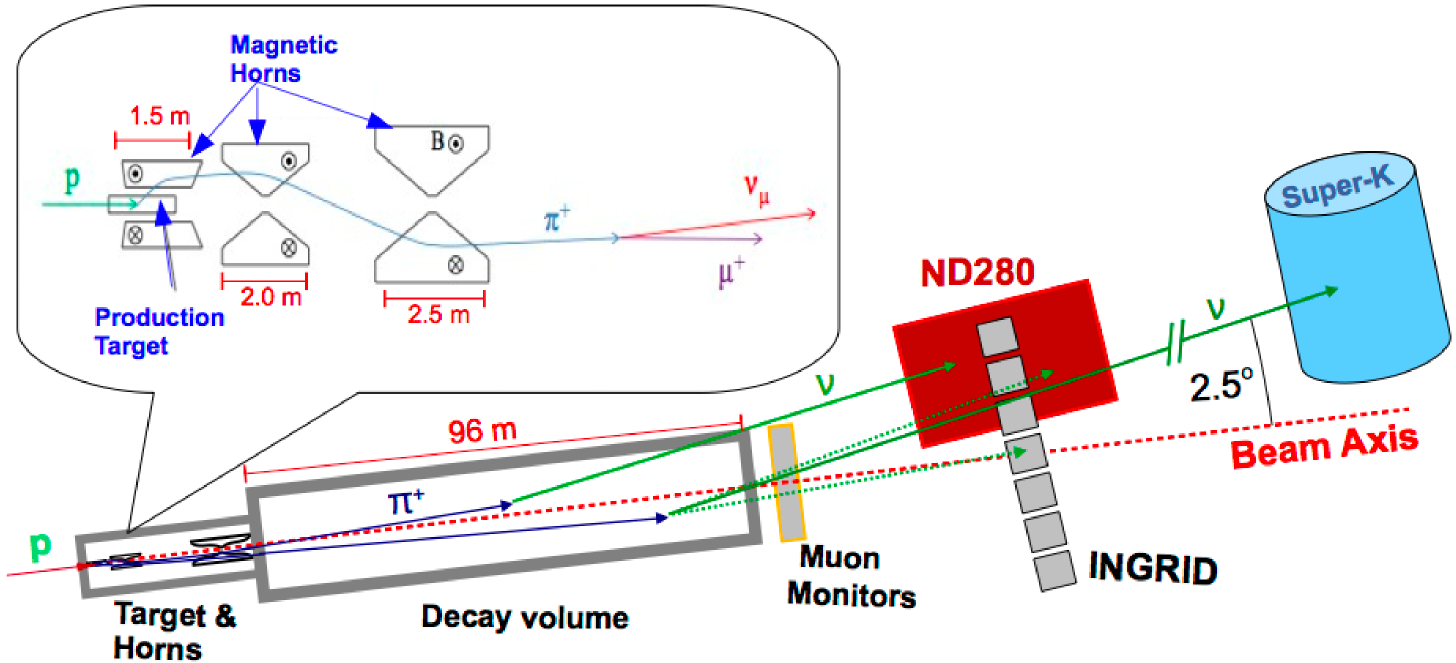


Using the 30-GeV J-PARC proton accelerator.
Design power 750 kW (∼230 kW achieved to date)



- Fast extraction
- 3.3×10^{14} p/spill
- 0.3 Hz cycle
- 8 bunches/spill
- 581 nsec bunch interval
- 58 nsec bunch width

Making a neutrino beam / The neutrino beam-line

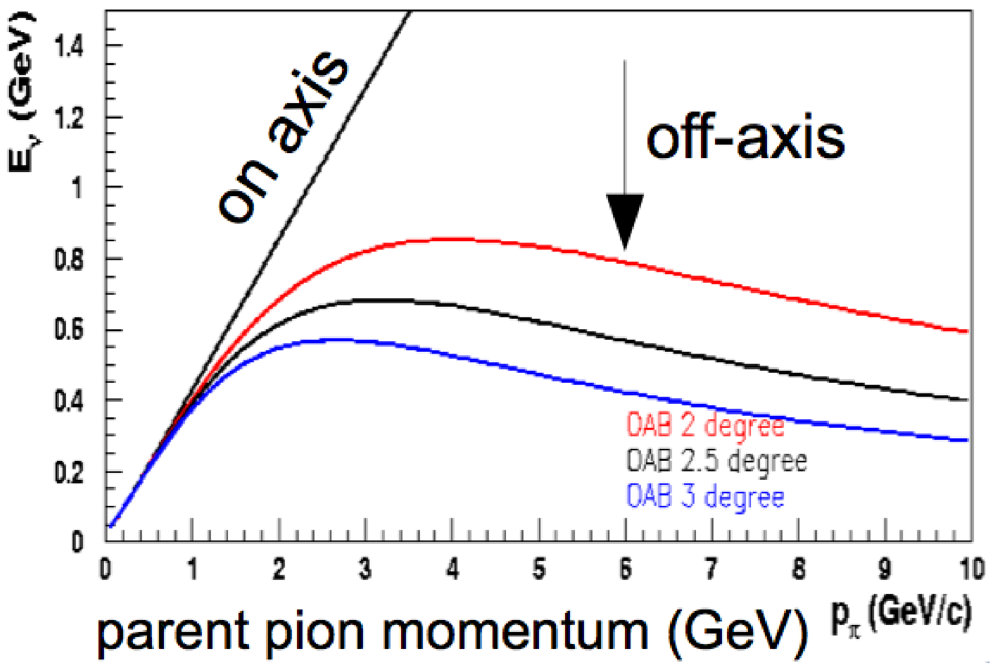


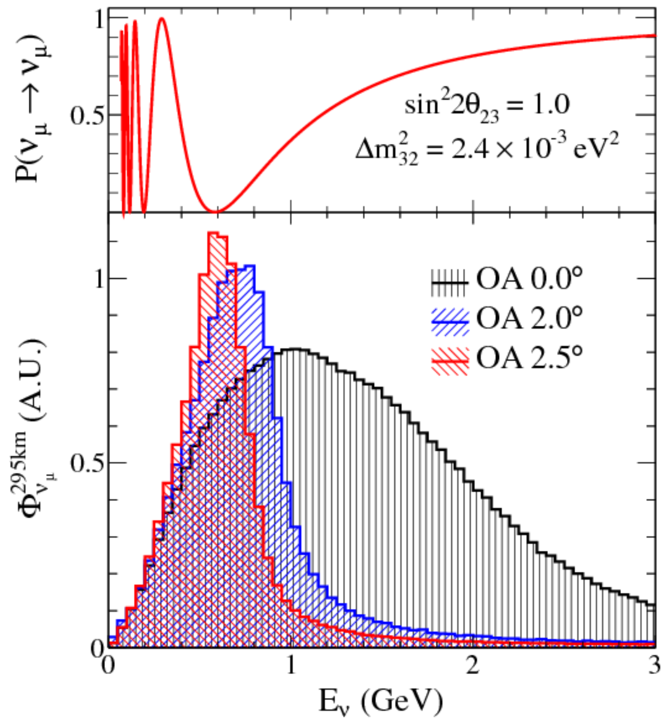
Where do our ν's come from?

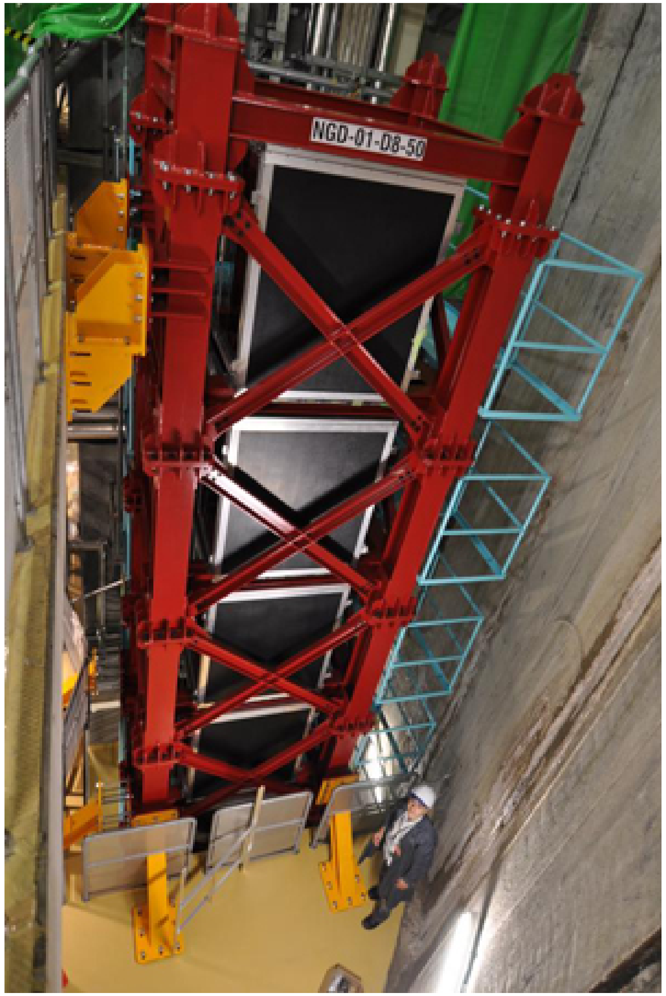
$\pi^+ \rightarrow \nu_\mu + \mu^+$
$\pi^- \rightarrow \bar{\nu}_\mu + \mu^-$
$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$
$\mu^- \rightarrow \bar{\nu}_e + \nu_\mu + e^-$
$K^+ \rightarrow \nu_\mu + \mu^+$
$K^+ \rightarrow \nu_e + \pi^0 + e^+$
$K^+ \rightarrow \nu_\mu + \pi^0 + \mu^+$
$K^- \rightarrow \bar{\nu}_\mu + \mu^-$
$K^- \rightarrow \bar{\nu}_e + \pi^0 + e^-$
$K^- \rightarrow \bar{\nu}_\mu + \pi^0 + \mu^-$
$K_L^0 \rightarrow \bar{\nu}_\mu + \pi^+ + \mu^-$
$K_L^0 \rightarrow \nu_\mu + \pi^- + \mu^+$
$K_L^0 \rightarrow \bar{\nu}_e + \pi^+ + e^-$
$K_L^0 \rightarrow \nu_e + \pi^- + e^+$

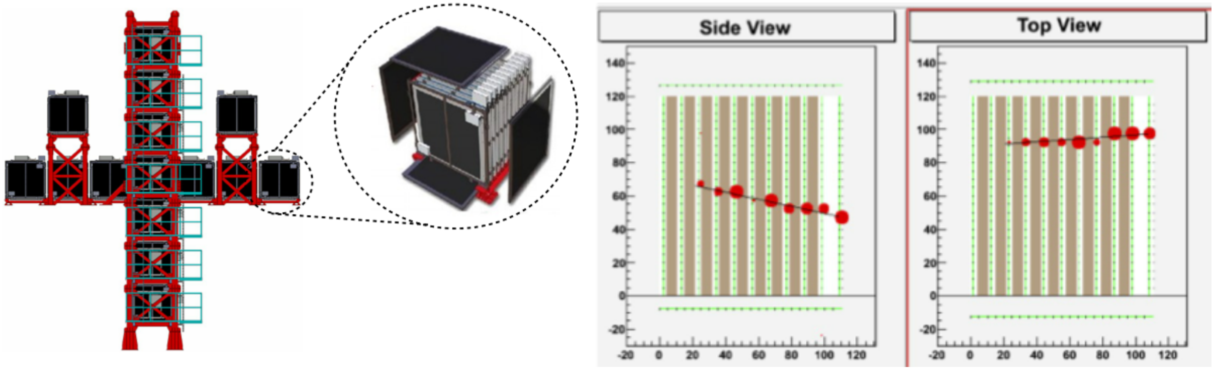
Production target: A long graphite rod (diameter: 2.6 cm, length: 91.4 cm / 1.9 interaction lengths).
Pion focussing:
3 magnetic horns pulsed with 320 kA currents: 2.1 (max) Tesla B field. 16$\times$ increase in ν flux w.r.t unfocussed beam.
Decay volume: A 96 m long steel decay tunnel (1.4 m (upstream) - 3.0 m (downstream) wide, 1.7 m - 5.0 m high).

T2K is the first accelerator experiment employing the off-axis trick.
Exploits kinematical properties of pion decay to create a narrow-band neutrino beam peaked at an energy chosen so as to maximize the oscillation probability at the SuperK location.



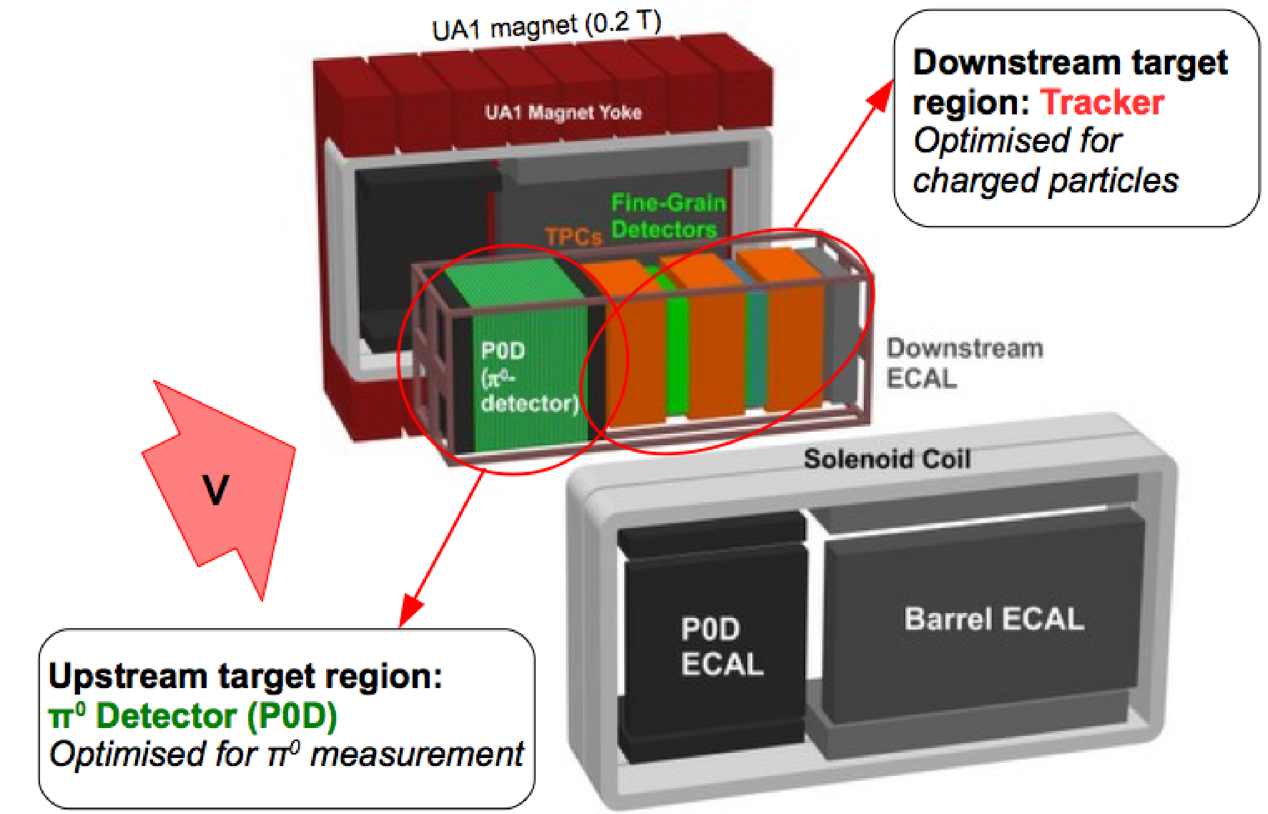






- 16 modules (14 in cross configuration).
- Each module: 7 tons, alternating scintillator / iron planes.
- 10 m $\times$ 10 m beam area coverage
- 1 event per $\sim 6 \times 10^{13}$ protons on target.
- Monitors neutrino beam rate and profile.

The Off-Axis Near Detector at 280 m



Tracking Calorimeters and Time Projection Chambers in 0.2T magnetic field.

Polystyrene and water targets.

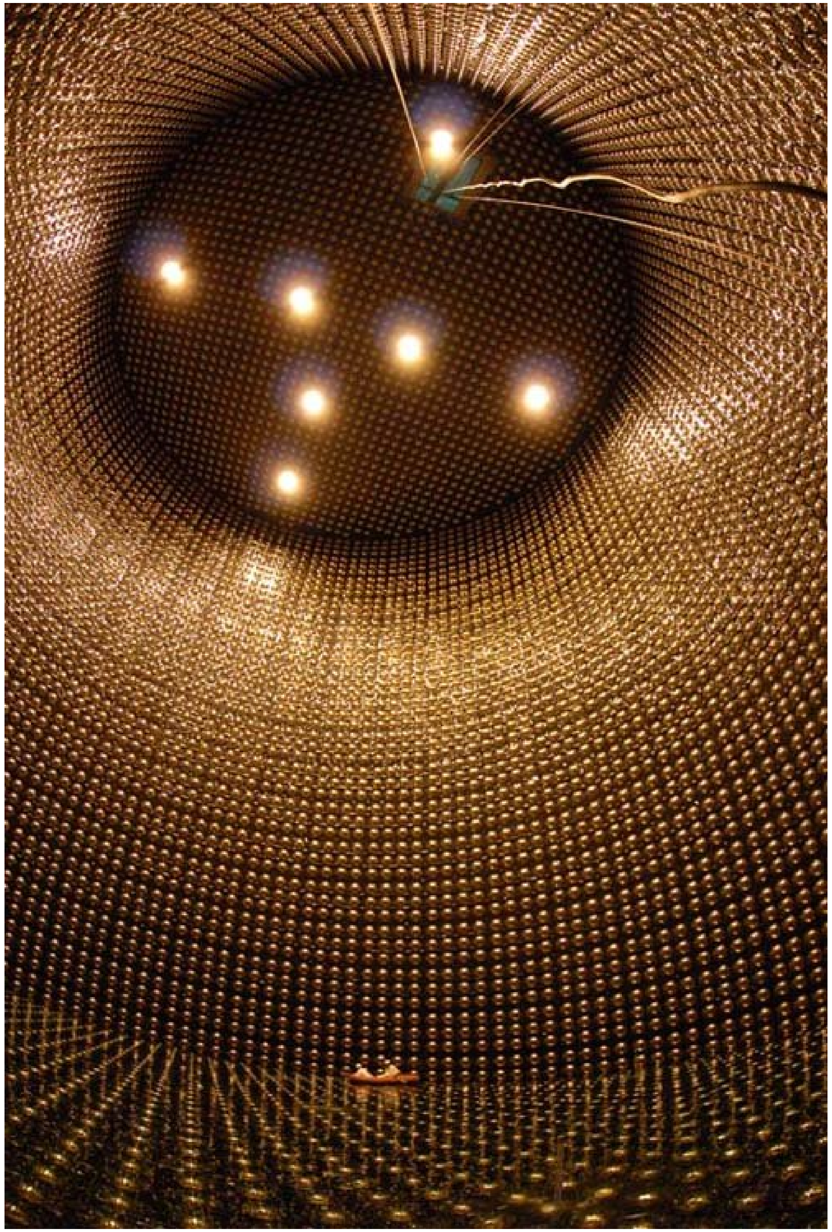
Tracker

- 2 fine-grained scintillator detectors (FGDs) + 3 time projection chambers (TPCs)
- FGDs provide the target mass (FGD1: 1 ton scintillator, FGD2: 0.5 ton scintillator + 0.5 ton water)
- Momentum measurement of charged particles, PID via dE/dx.

P0D

- Scintillator planes interleaved with lead and water layers.
- 13 tons of lead + 3 tons of water.
- Optimized for γ detection.

The Far Detector (Super-Kamiokande IV)



- 50 kt Water Cherenkov detector (22.5 kton fiducial)
- Overburden (shielding): 2700 mwe
- Inner Detector (ID): 11,129 20" PMTs (40% photo-cathode coverage)
- Outer Detector (OD): 1,885 8" PMTs
- DAQ: No dead-time
- Energy threshold: $\sim$ 4.5 MeV