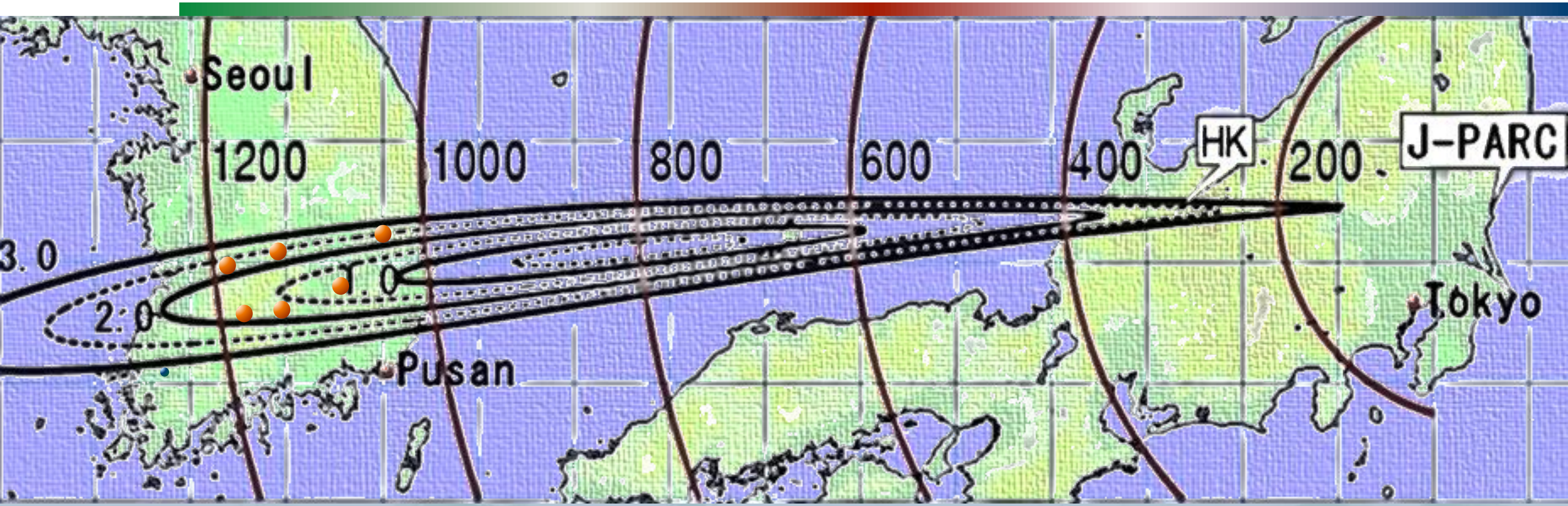
Imperial College London

A new Kamiokande in Korea

-Phill Litchfield



Outline

A short history of the Kamioka program

Neutrino oscillation physics & T2K

Hyper-K and the Korean detector

Proton decay

Late 70's: Grand Unified Theories are very popular

- Started with $SU(5)$ & $SO(10)$ [1974]
- Predict `Leptoquark` operators that conserve $B - L$, but not B

$$u + u \rightarrow \bar{\mathrm{d}} + \mathrm{e}^{+}$$
gives rise to $\boldsymbol{p} \rightarrow \boldsymbol{\pi}^{\mathbf{0}} + \boldsymbol{e}^{+}$

"Proton decay"

Predicted lifetime of the proton $10^{30} \sim 10^{35}$ years.

$$18\mathrm{g}\ \mathrm{H_2O} = 10N_A = 6 \times 10^{24} \text{ protons}$$

Therefore a few kilotonnes (gigagram) of material would be enough to start testing the theories…

Early 80's: Experiments designed and built to test these predictions

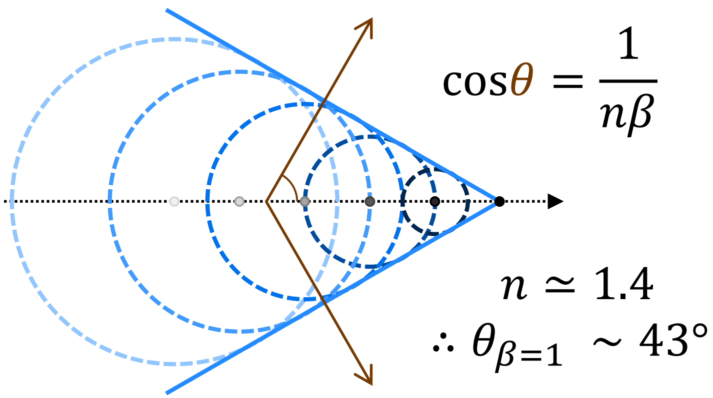
A kilotonne-scale detector

A few tonnes is still a **lot of material** to instrument. Practically you need:

- Something cheap and easy to maintain.
- That your source is also the detector
- Surface instrumentation (L^2 instead of L^3)

Suitable technology: **Water-Cherenkov**

Water is cheap, and (if purified) can be very transparent.

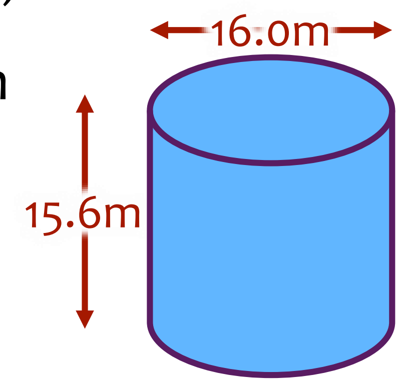


Conical radiation pattern intersects surface to make a **ring**

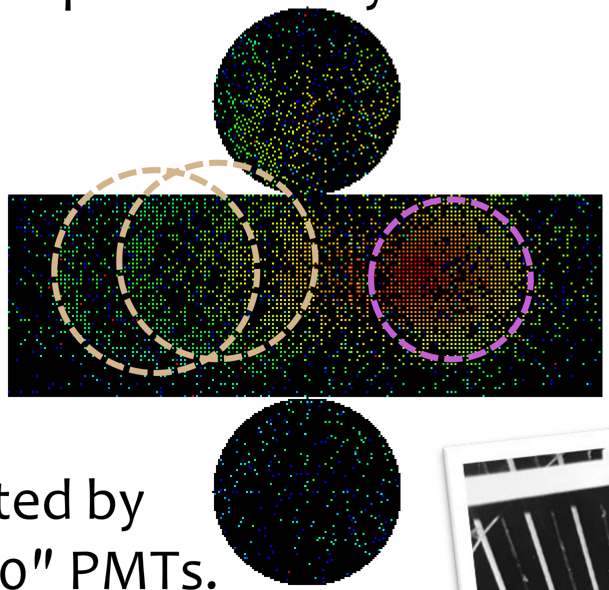
- Direction from centre of ring
- Energy from range (thickness of ring)
- Works nicely for low mass particles.

KamiokaNDE

1982 ~ 1983: The "Kamioka Nucleon Decay Experiment" was constructed in Mozumi mine near Kamioka town in central Japan to look for proton decay.

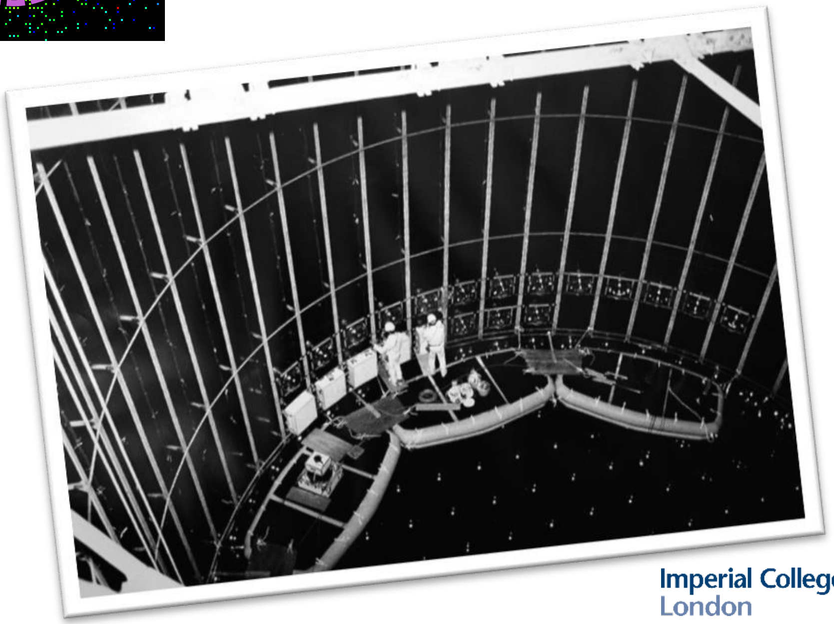


$$p \to \pi^0 + e^+$$
$$\hookrightarrow \gamma + \gamma$$



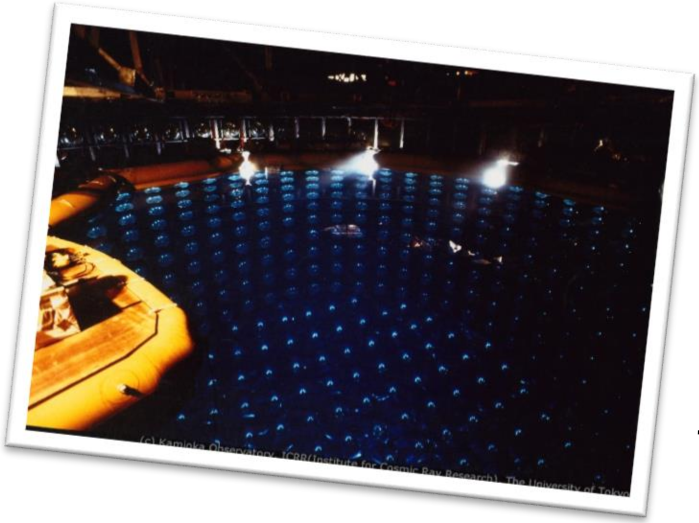
Cherenkov light collected by 1k specially-designed 20″ PMTs.

- Large PMTs meant more of the tank surface was sensitive to photons.
- **More photocoverage means better energy resolution.**



Kamiokande-II

1985: The Kamiokande detector was upgraded to enable it to see solar neutrinos. Now also "Kamioka Neutrino Detection Experiment"



- Needed low threshold (few MeV).
- Outer detector (OD) added to veto entering particles.
- The water is highly purified and recycled to remove Radon (low-energy B/G.)

This work paid off spectacularly (& luckily):

1987: Neutrinos are detected from SN1987A in the LMC.

- (First) Nobel Prize for Kamioka neutrino program in 2012.
- Supernova close enough so see with neutrinos are expected ~30 years…
  <hint> <hint>

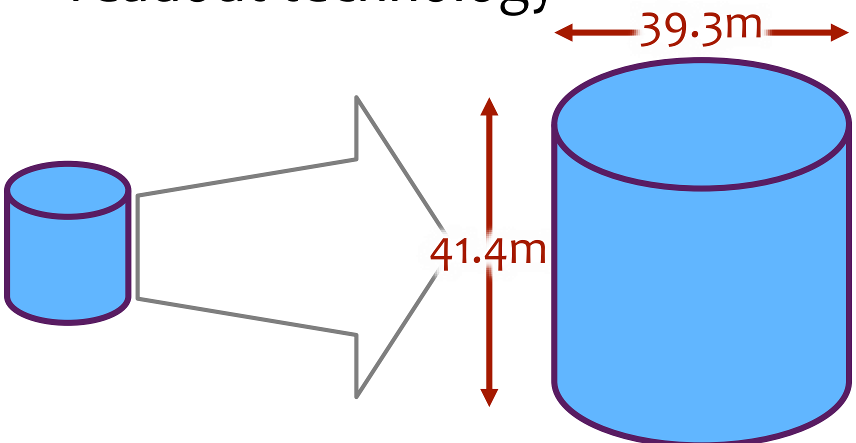
Super-Kamiokande

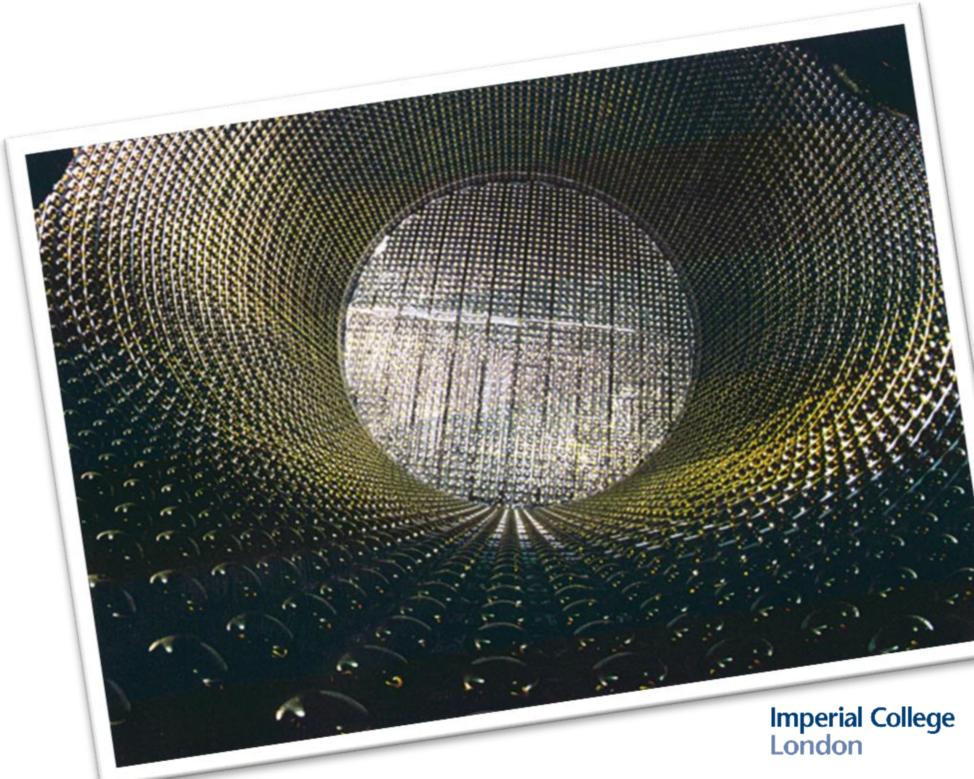
1990's: 'Oscillation' phenomenon suspected to be explanation of deficit seen in both solar neutrinos and atmospheric neutrinos.

- A larger experiment could investigate 'shape' predictions of oscillation mechanism with much better statistics.
- Improvements to purification meant water is usefully transparent for longer distances.

Build Super-Kamiokande!

- Also incorporate things learnt (e.g. better OD) and upgrade readout technology

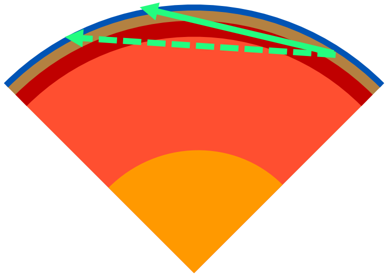




K2K and T2K

By 2000, experiments with atmospheric neutrinos were showing some limitations:

- Neutrino flux estimates rely on detailed simulation of the **hadronic cascades,** over several **orders of magnitude** in energy.
- Small errors in reconstructing the neutrino direction result in **big changes** in guessing the origin point.



Neutrinos from accelerators are much better! Even if you don’t understand the source fully:

- **You know where it is.**
- **You can measure it.**

K2K was the first experiment to try this approach to measuring oscillations, T2K is its (currently running) successor.

The question is, where do we go next?

Outline

A short history of the Kamioka program

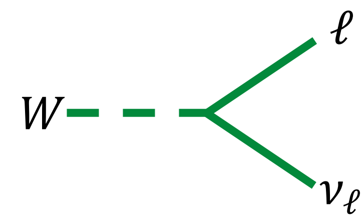
Neutrino oscillation physics & T2K

Hyper-K and the Korean detector

Oscillation mechanism

Neutrinos are 'born' in weak processes.

- They are defined by the associated charge lepton.



Also detected by weak interactions → well defined flavour state.

So the oscillation probability is: $P(\nu_\alpha \to \nu_\beta) = \left|\langle \nu_\beta | Time\ passes | \nu_\alpha \rangle\right|^2$

The passage of (space-)time is through the usual operator: $e^{-\mathrm{i}(\hat{E}t - \hat{\boldsymbol{p}}\cdot\boldsymbol{x})}$

In vacuum the eigenstates of this operator are *mass* eigenstates m_i

Therefore transform flavour into mass states and back:

$$P(\nu_\alpha \to \nu_\beta) = \left|\left\langle \nu_\beta \middle| U^\dagger_{\beta i} e^{-\mathrm{i}(E_i t - \boldsymbol{p}_i\cdot\boldsymbol{x})} U^\dagger_{\alpha i} \middle| \nu_\alpha \right\rangle\right|^2$$

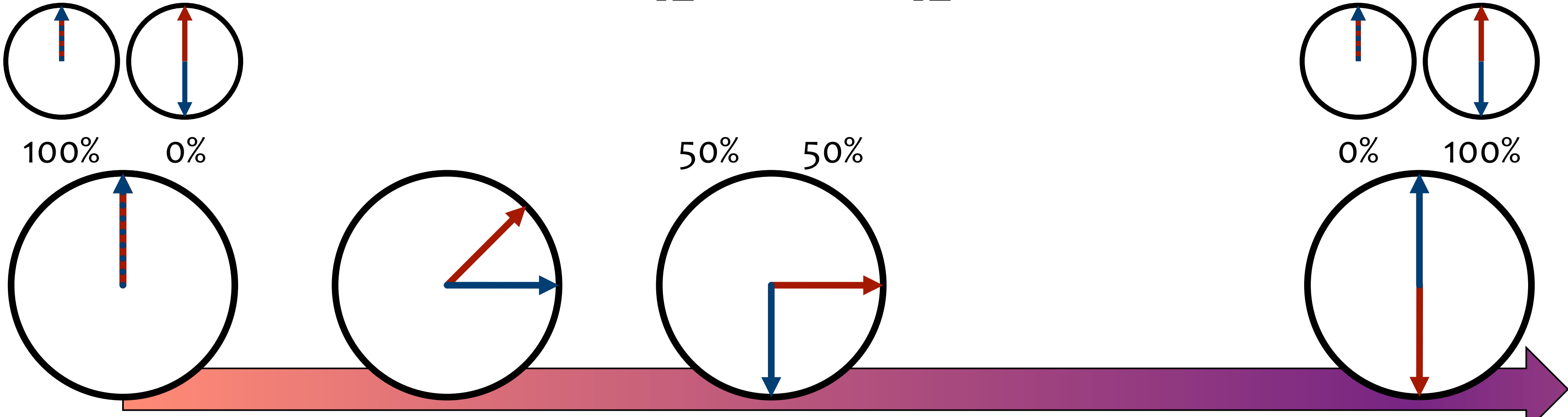
Oscillation mechanism

$$P(\nu_\alpha \to \nu_\beta) = \left|\left\langle \nu_\beta \middle| U^\dagger_{\beta i} e^{-i(E_i t - \boldsymbol{p}_i \cdot \boldsymbol{x})} U^\dagger_{\alpha i} \middle| \nu_\alpha \right\rangle\right|^2$$

The phase evolution can be expanded in two parts:

1. Global phase advance that disappears in the modulus
2. Relative phase between the different ν_i. For ultra-relativistic neutrinos this is:

$$\frac{(m_i^2 - m_j^2)L}{4E} = \frac{\Delta m_{ij}^2 L}{4E}$$



Oscillation mechanism

The pl

1. Gl

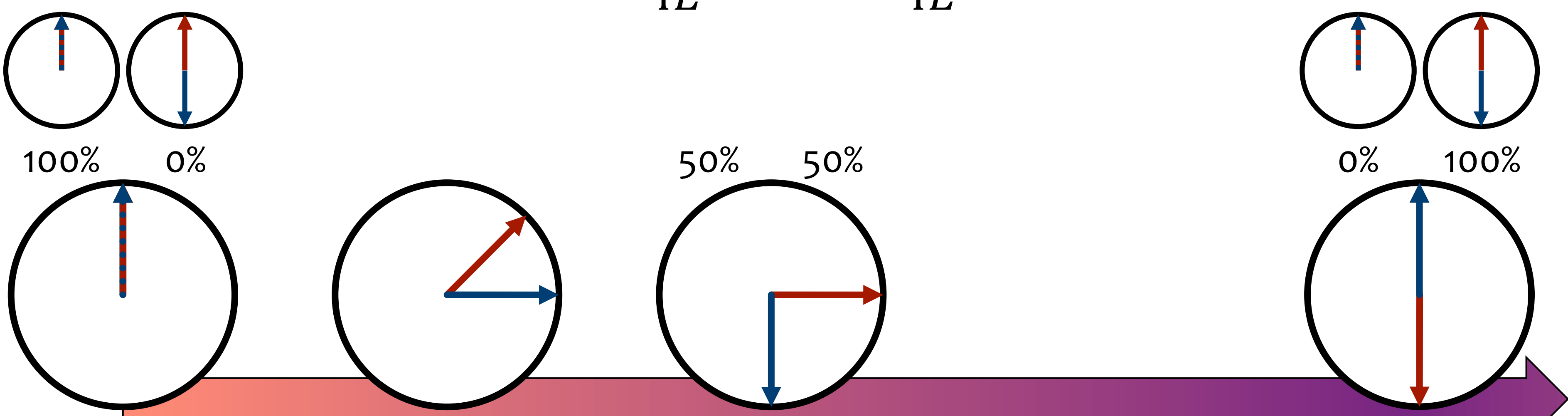
2. Re
 ne

Upshot:

Oscillations occur based on 2 independent mass² splittings, provided the propagation distance satisfies $\Delta m_{ji}^2 L > 4E$.

For 3 generations, the most general mixing matrix is complex and has 4 real parameters.

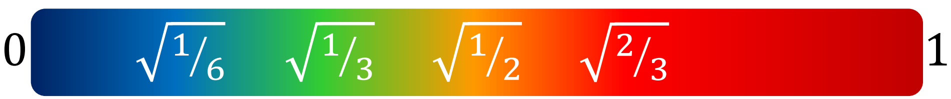
$4E$ $4E$



Neutrino mixing

With 3 generations and non-zero mass, CKM- style mixing is natural:

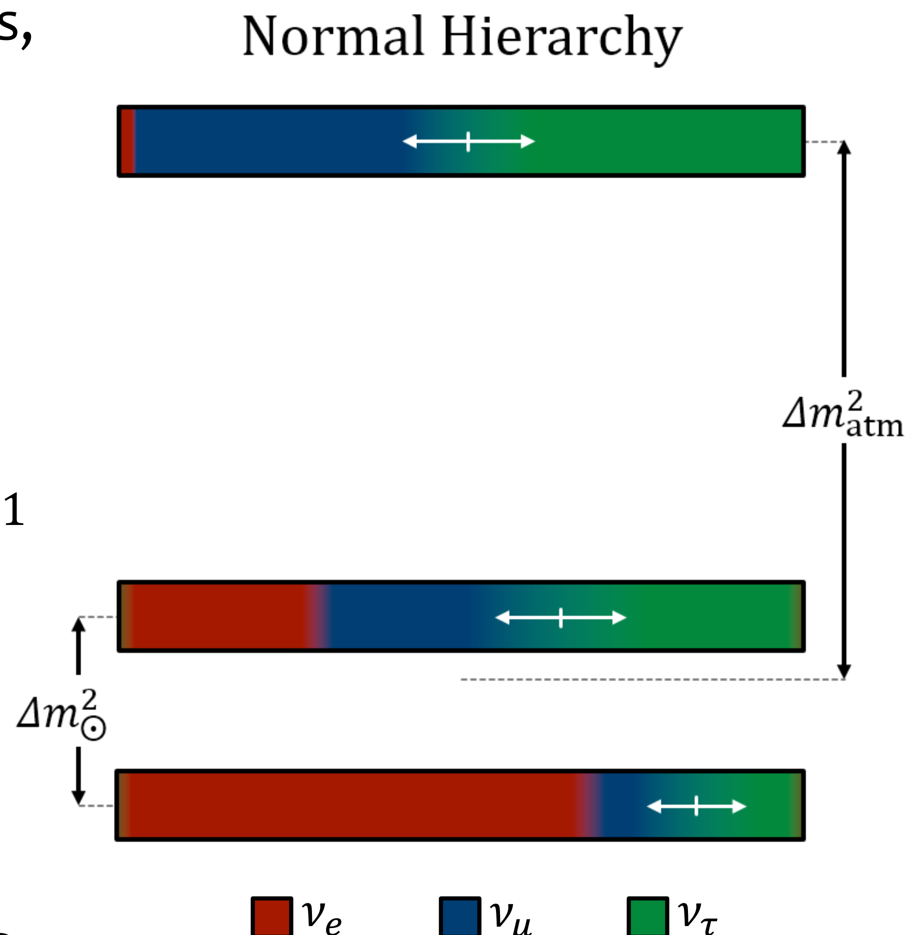
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & \boldsymbol{U_{e3}} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



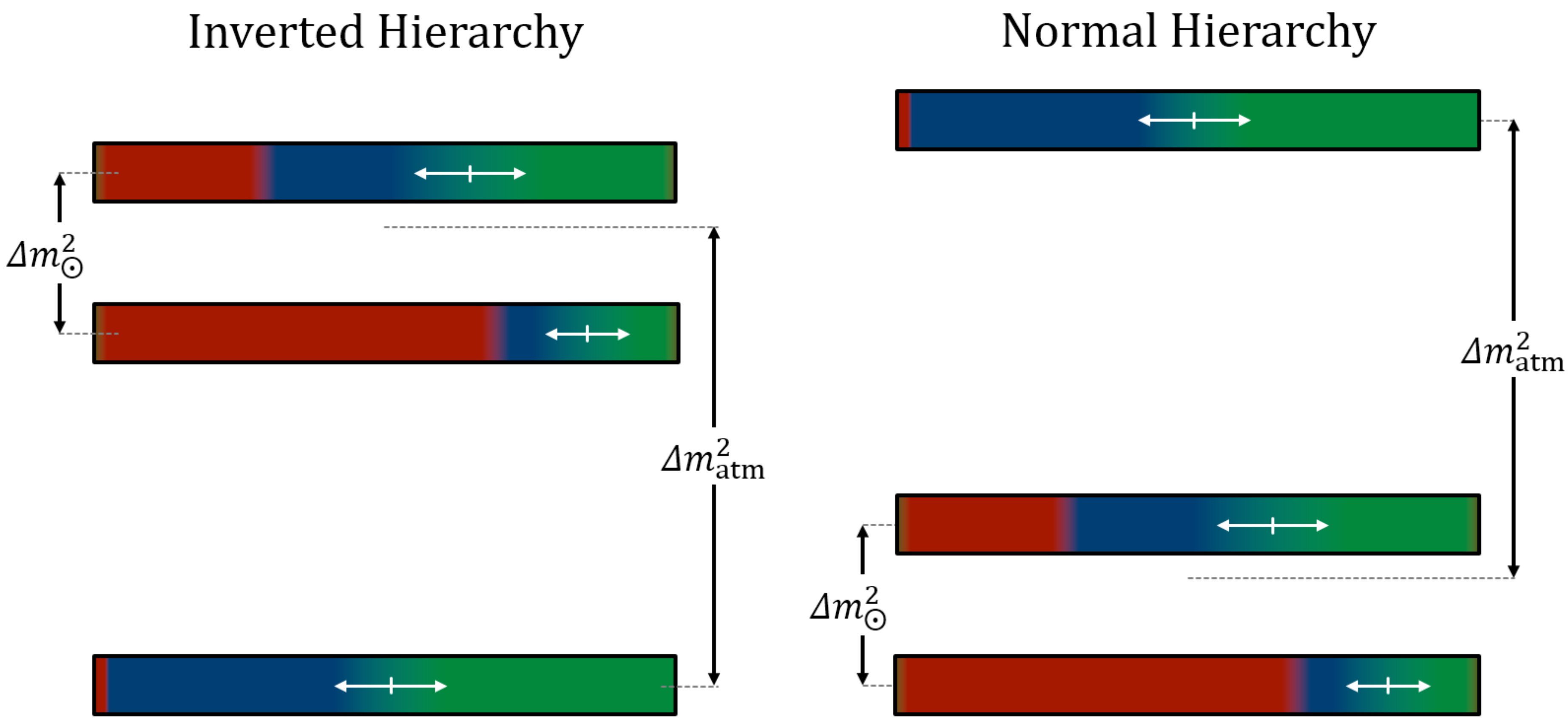
More surprising: 8 elements are large

- $\boldsymbol{U_{e3}}$ is significant as the smallest element, and the last to be measured (or inferred).

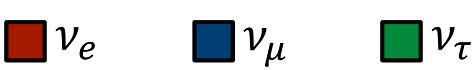
Important to note: **KM-mechanism CPv requires that *all* elements are non-zero**



Note on hierarchies



Sign of $\Delta m^2_\odot$ is known is known from solar experiments



Angle parameterisation

The mixing matrix is commonly parameterised as the product of two rotations and a unitary transformation.
Writing $s_{ij} = \sin\theta_{ij}$, and $c_{ij} = \cos\theta_{ij}$:

$$\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

This choice is convenient as the original **solar** and **atmospheric** disappearance signals could be approximated as functions of $\boldsymbol{\theta_{12}}$ and $\boldsymbol{\theta_{23}}$, respectively.

Essentially this was a careful (lucky?) choice of variables S.T. the third angle $\boldsymbol{\theta_{13}}$ describes the magnitude of the smallest element:

$$U_{e3} = \sin\theta_{13}\, e^{-i\delta}$$

$\nu_\mu \rightarrow \nu_e$ appearance

The ν_e appearance probability can be written approximately as a sum of terms quadratic in the small parameters $\alpha = \Delta m^2_{21}/\Delta m^2_{31} \approx \pm 1/32$, and $\sin 2\theta_{13}$:

$$P(\nu_\mu \rightarrow \nu_e) \approx T_{\theta\theta} \sin^2 2\theta_{13} \frac{\sin^2([1-A]\Delta)}{[1-A]^2} + T_{\alpha\alpha}\alpha^2 \frac{\sin^2(A\Delta)}{A^2}$$
$$+ T_{\alpha\theta}\alpha \sin 2\theta_{13} \frac{\sin([1-A]\Delta)}{(1-A)} \frac{\sin(A\Delta)}{A} \cos(\delta + \Delta)$$

where

$$T_{\theta\theta} = \sin^2\theta_{23},\ T_{\alpha\alpha} = \cos^2\theta_{23} \sin^2 2\theta_{12},$$
$$T_{\alpha\theta} = \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$$

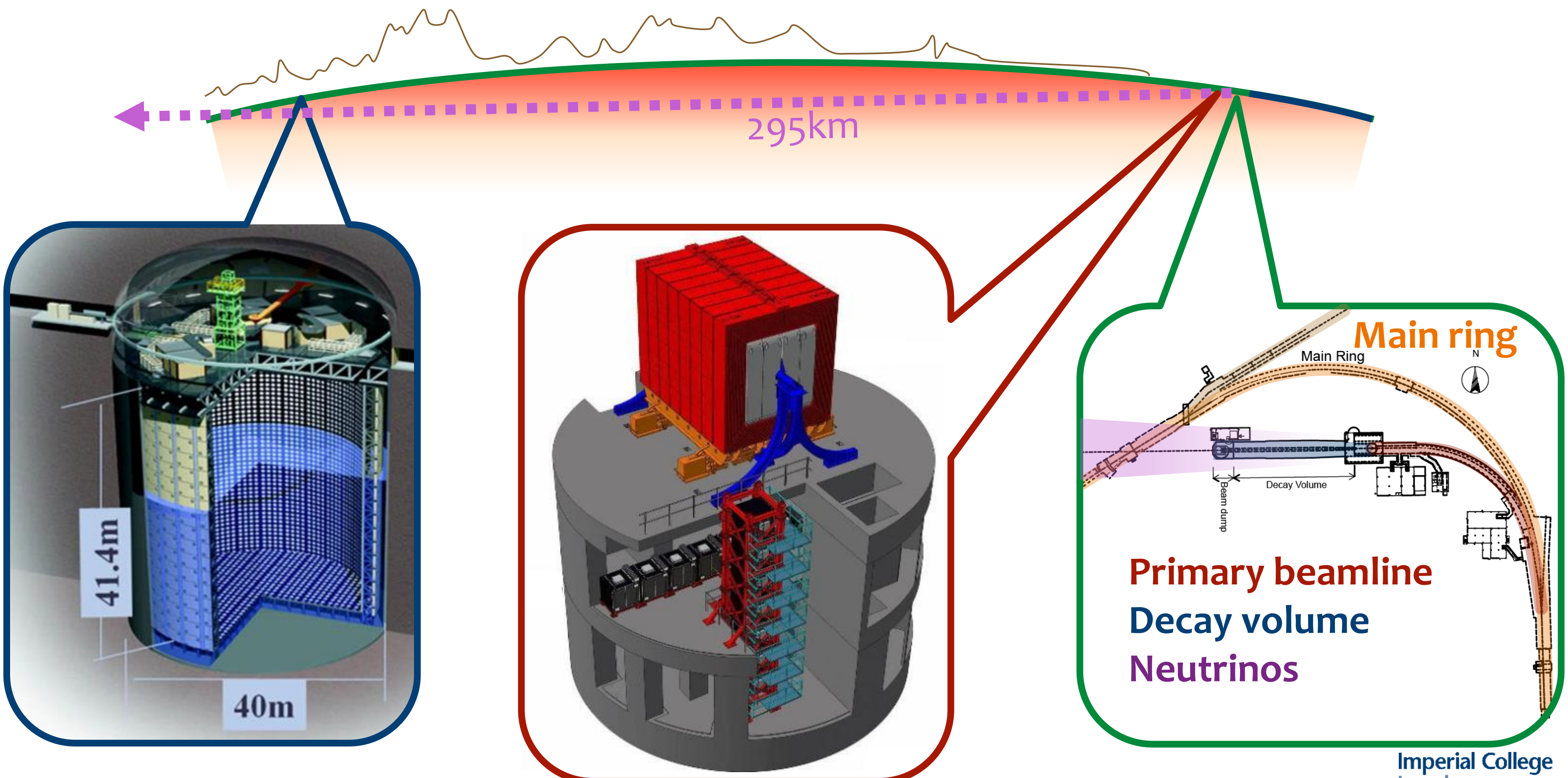
and $\Delta = \frac{\Delta m^2_{31} L}{4E} \sim \frac{(2n-1)\pi}{2}$ at 1st osc. max.

$A\ (= 2\sqrt{2} G_F n_e E\ /\Delta m^2_{31})$ is the matter density parameter. Here, $|A| \simeq E/10\text{GeV}$

Tokai-to-Kamioka (T2K)

Uses the existing Super-K detector and J-PARC high-power proton facility on the east cost of Japan.

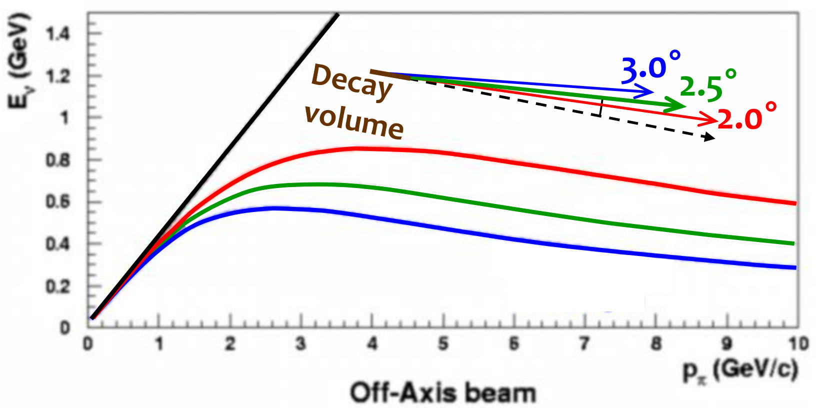
- Near detector suite “ND280” characterises neutrino beam

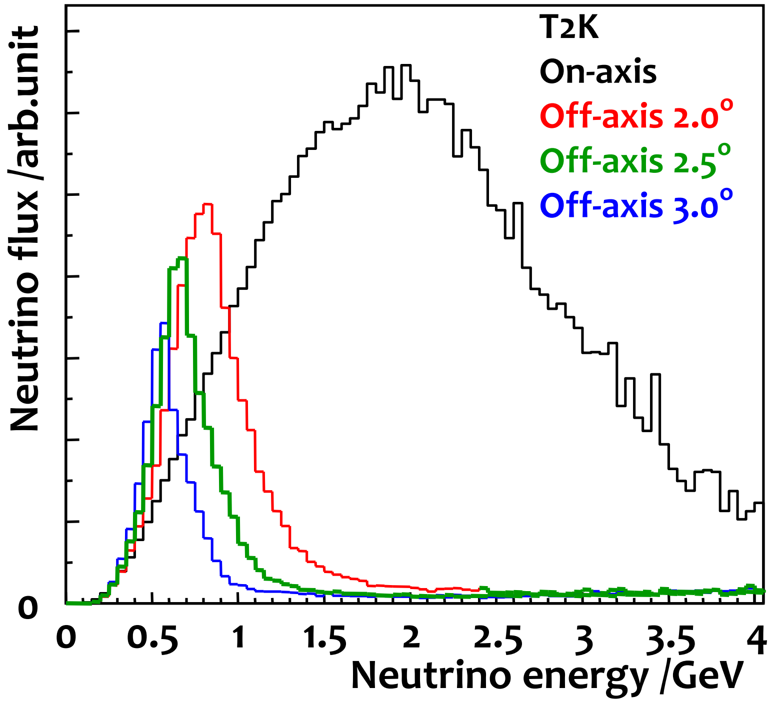


The Off-axis 'trick'

T2K is the first experiment to have its detectors off-axis

Relativistic kinematics → at a small angle to the beam axis, neutrino energy is insensitive to parent pion energy.





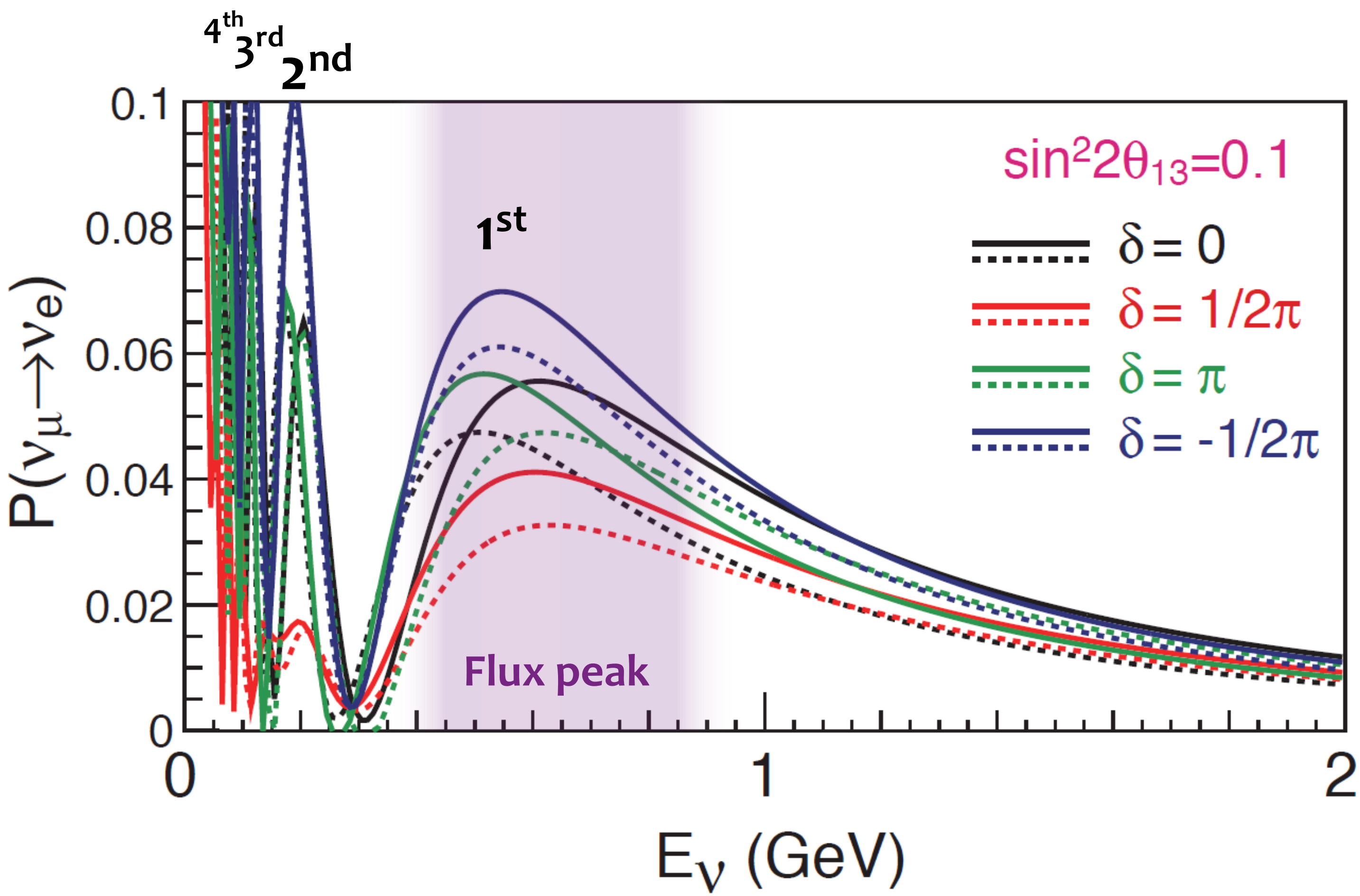
Gives slightly narrower flux peak, and **drastically reduces high energy tail**.

- Ideal for ν_e appearance (much reduced NC BG)

Imperial College London

Oscillation spectra

The oscillation probability is measured as a function of energy, and typically has peaks spaced at $\frac{1}{E}$, with a tail down to no oscillation at high energies.



T2K original goal

For $\Delta \sim \frac{\pi}{2}$, we know the magnitude of the second term is small (~10⁻³) so any signal above that is evidence that $\sin^2 2\theta_{13} > 0$, **regardless of the value of the other unknowns.**

$$P(\nu_\mu \to \nu_e) \approx T_{\theta\theta} \sin^2 2\theta_{13} \frac{\sin^2([1-A]\Delta)}{[1-A]^2} + T_{\alpha\alpha}\alpha^2 \frac{\sin^2(A\Delta)}{A^2}$$
$$+ T_{\alpha\theta}\alpha \sin 2\theta_{13} \frac{\sin([1-A]\Delta)}{(1-A)} \frac{\sin(A\Delta)}{A} \cos(\delta + \Delta)$$

It turned out that $P(\nu_\mu \to \nu_e) \sim 0.1$, slightly above previous limit.

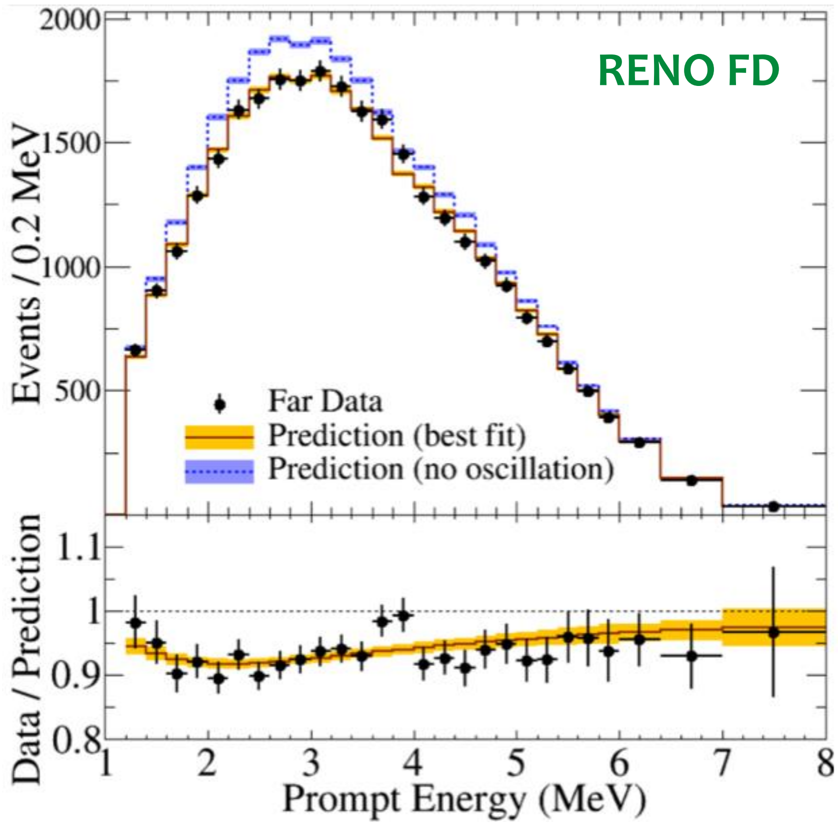
- Easy to see, requiring <10% of T2K design sensitivity.
- Also means we can essentially ignore the second term.

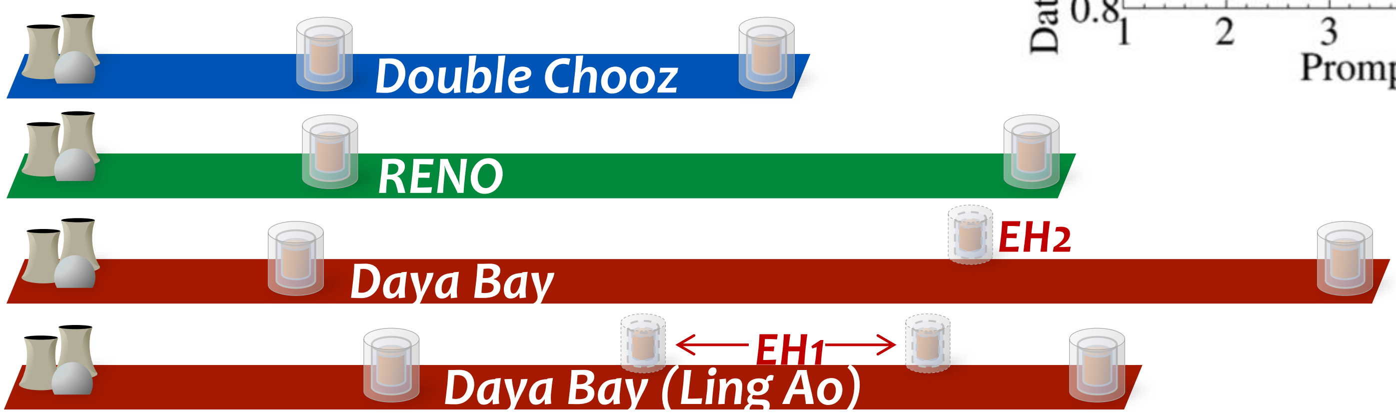
Reactor experiments

At about the same time, new reactor experiments (RENO, Double Chooz & Daya bay) independently measured $\sin^2 2\theta_{13}$ via disappearance:

$$P(\nu_e \rightarrow \nu_e) \approx 1 - \sin^2 2\theta_{13} \sin^2(\Delta)$$

2017: This is now the most precise input to the appearance prob. $P(\nu_\mu \rightarrow \nu_e)$





Current analysis: T2K + reactors.

$\alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$ $\Delta = \frac{\Delta m_{31}^2 L}{4E}$

$A = 2\sqrt{2} G_F n_e E / \Delta m_{31}^2$

At about the same time, new reactor experiments (RENO, Double Chooz & Daya bay) independently measured $\sin^2 2\theta_{13}$ via disappearance:

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2([1-A]\Delta)}{[1-A]^2}$$

$$+\alpha \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \cos\theta_{13} \frac{\sin([1-A]\Delta)}{(1-A)} \frac{\sin(A\Delta)}{A} \cos(\delta + \Delta)$$

T2K + reactors

At about the same time, new reactor experiments (RENO, Double Chooz & Daya bay) independently measured $\sin^2 2\theta_{13}$ via disappearance:

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \Delta = \frac{\Delta m^2_{31} L}{4E}$$

$$A = 2\sqrt{2} G_F n_e E \,/ \Delta m^2_{31}$$

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2([1-A]\Delta)}{[1-A]^2}$$

$$+\alpha \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \cos\theta_{13} \frac{\sin([1-A]\Delta)}{(1-A)} \frac{\sin(A\Delta)}{A} \cos(\delta + \Delta)$$

Goal: To find out the remaining unknowns;
δ, and sign(Δ) [i.e. whether or not $m_3^2 > m_1^2$]

T2K + reactors

At about the same time, new reactor experiments (RENO, Double Chooz & Daya bay) independently measured $\sin^2 2\theta_{13}$ via disappearance:

$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$ $\Delta = \frac{\Delta m^2_{31} L}{4E}$

$A = 2\sqrt{2} G_F n_e E / \Delta m^2_{31}$

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2([1-A]\Delta)}{[1-A]^2}$$

$$+\alpha \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \cos\theta_{13} \frac{\sin([1-A]\Delta)}{(1-A)} \frac{\sin(A\Delta)}{A} \cos(\delta + \Delta)$$

We already knew $\sin 2\theta_{12}$ and α from solar neutrino experiments

T2K + reactors

$\alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$ $\Delta = \frac{\Delta m_{31}^2 L}{4E}$

$A = 2\sqrt{2} G_F n_e E \,/ \Delta m_{31}^2$

At about the same time, new reactor experiments (RENO, Double Chooz & Daya bay) independently measured $\sin^2 2\theta_{13}$ via disappearance:

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2([1-A]\Delta)}{[1-A]^2}$$

$$+ \quad \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \cos\theta_{13} \frac{\sin([1-A]\Delta)}{(1-A)} \alpha\Delta \cos(\delta + \Delta)$$

We already knew $\sin 2\theta_{12}$ and α from solar neutrino experiments

Can also reduce the second 'sinc' function to just Δ

T2K + reactors

$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$ $\Delta = \frac{\Delta m^2_{31} L}{4E}$

$A = 2\sqrt{2} G_F n_e E \,/\Delta m^2_{31}$

At about the same time, new reactor experiments (RENO, Double Chooz & Daya bay) independently measured $\sin^2 2\theta_{13}$ via disappearance:

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2([1-A]\Delta)}{[1-A]^2}$$

$$+ \quad \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \cos\theta_{13} \frac{\sin([1-A]\Delta)}{(1-A)} \alpha\Delta \cos(\delta + \Delta)$$

We already knew $\sin 2\theta_{12}$ and α from solar neutrino experiments

Can also reduce the second 'sinc' function to just Δ

And $\sin^2 2\theta_{23}$ is measured by ν_μ disappearance results

Unpacking the probability

Split the cos$(\delta + \Delta)$ term and we find that the second term is the equation of an ellipse.

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \Delta = \frac{\Delta m^2_{31} L}{4E}$$

$$A = 2\sqrt{2} G_F n_e E \,/\Delta m^2_{31}$$

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2([1-A]\Delta)}{[1-A]^2}$$
$$+ \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \cos\theta_{13} \frac{\sin([1-A]\Delta)}{(1-A)} \alpha\Delta \cos\Delta \cos\delta$$
$$- \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \cos\theta_{13} \frac{\sin([1-A]\Delta)}{(1-A)} \alpha\Delta \sin\Delta \sin\delta$$

Unpacking the probability

Split the $\cos(\delta + \Delta)$ term and we find that the second term is the equation of an ellipse.

The relative amplitudes are calculated to show they are quite similar.

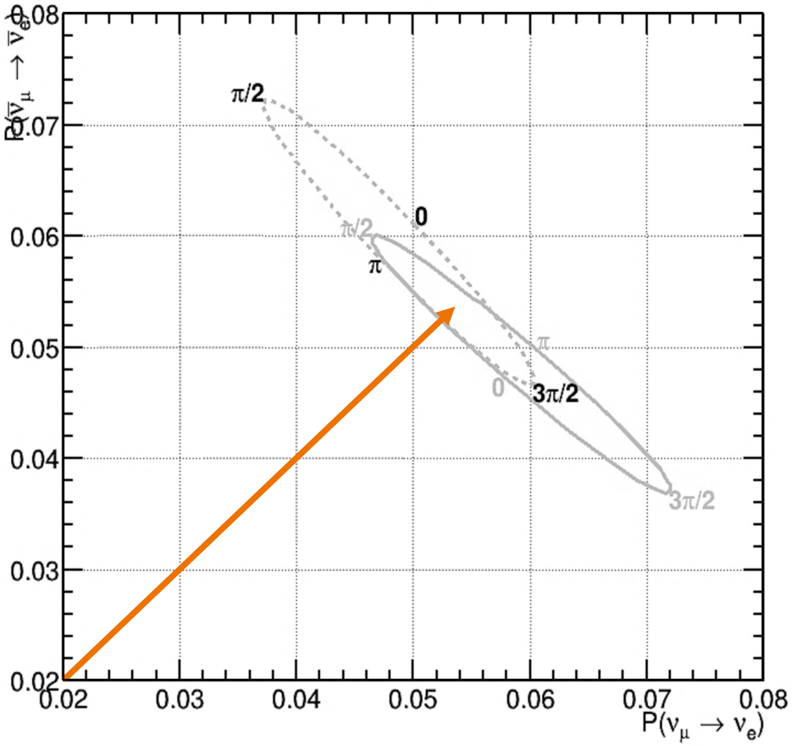
$$P(\nu_\mu \to \nu_e) \approx k_0[\simeq 0.049] \frac{\sin^2([1-A]\Delta)}{[1-A]^2}$$

$$+ \, k_{CP}[\simeq 0.014] \times \Phi \frac{\sin([1-A]\Delta)}{(1-A)} \cos\Delta \cos\delta$$

$$- \, k_{CP}[\simeq 0.014] \times \Phi \frac{\sin([1-A]\Delta)}{(1-A)} \sin\Delta \sin\delta$$

Here $\Phi = \frac{2\Delta}{\pi} = \frac{\Delta m_{31}^2 L}{2\pi E}$ $(= 2\text{n} - 1$ at the n^{th} maximum$)$

Biprobability plots



Drawn for a particular energy, as a function of δ and the mass hierarchy.

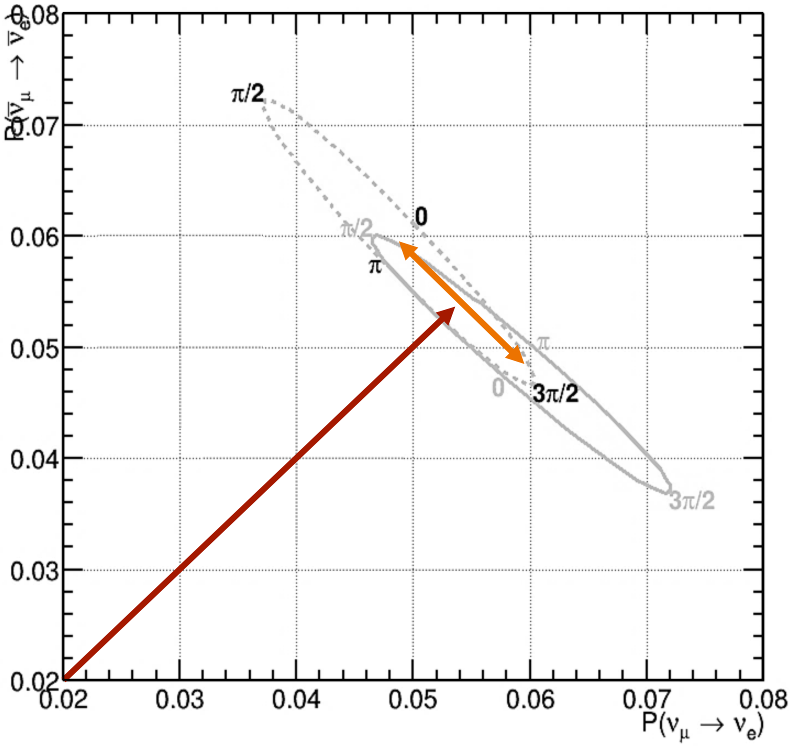
- The size of k_0 specified the centre of the ellipse (in vacuum).

$$P\left(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e\right) \approx k_0 \frac{\sin^2([1-A]\Delta)}{[1-A]^2}$$

$$+ \, k_{\mathrm{CP}} \Phi \frac{\sin([1-A]\Delta)}{(1-A)} \cos\Delta \cos\delta$$

$$\mp \, k_{\mathrm{CP}} \Phi \frac{\sin([1-A]\Delta)}{(1-A)} \sin\Delta \sin\delta$$

Biprobability plots

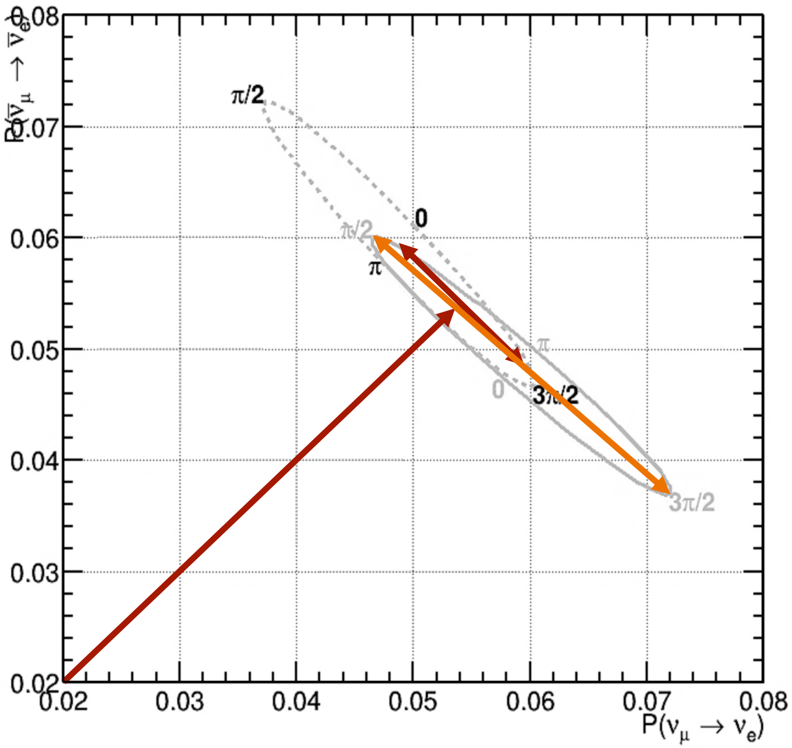


Drawn for a particular energy, as a function of δ and the mass hierarchy.

- The size of k_0 specified the centre of the ellipse (in vacuum).
- A nonzero value of A splits the ellipses.

$$P\left(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e\right) \approx k_0 \frac{\sin^2([1-A]\Delta)}{[1-A]^2}$$
$$+ k_{\mathrm{CP}}\Phi \frac{\sin([1-A]\Delta)}{(1-A)} \cos\Delta \cos\delta$$
$$\mp k_{\mathrm{CP}}\Phi \frac{\sin([1-A]\Delta)}{(1-A)} \sin\Delta \sin\delta$$

Biprobability plots

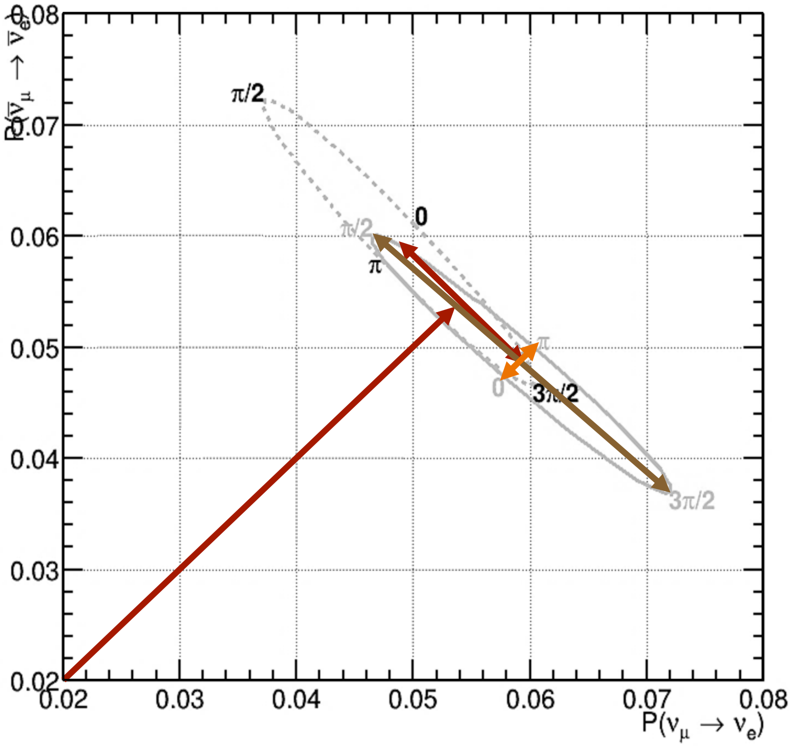


Drawn for a particular energy, as a function of δ and the mass hierarchy.

- The size of k_0 specifies the centre of the ellipse (in vacuum).
- A nonzero value of A splits the ellipses.
- The $\sin\delta$ term causes CP violation.

$$P\left(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e\right) \approx k_0 \frac{\sin^2([1-A]\Delta)}{[1-A]^2}$$
$$+\, k_{CP}\Phi \frac{\sin([1-A]\Delta)}{(1-A)} \cos\Delta \cos\delta$$
$$\mp\, k_{CP}\Phi \frac{\sin([1-A]\Delta)}{(1-A)} \sin\Delta \sin\delta$$

Biprobability plots

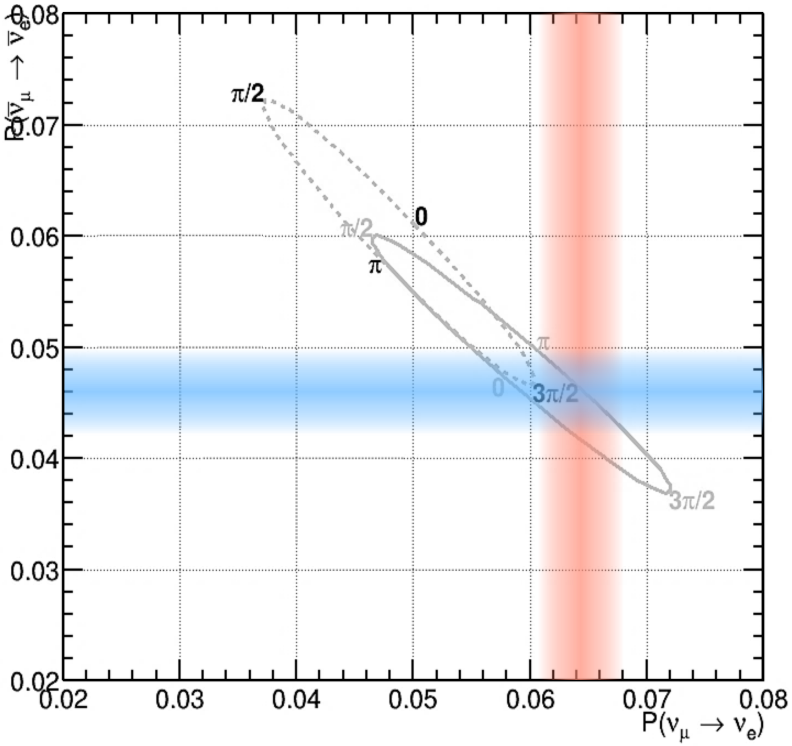


$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx k_0 \frac{\sin^2([1-A]\Delta)}{[1-A]^2}$$
$$+ k_{CP}\Phi \frac{\sin([1-A]\Delta)}{(1-A)} \cos\Delta \cos\delta$$
$$\mp k_{CP}\Phi \frac{\sin([1-A]\Delta)}{(1-A)} \sin\Delta \sin\delta$$

Drawn for a particular energy, as a function of δ and the mass hierarchy.

- The size of k_0 specifies the centre of the ellipse (in vacuum).
- A nonzero value of A splits the ellipses.
- The $\sin\delta$ term causes CP violation.
- The $\cos\delta$ term causes a CP conserving effect (with opposite sign between NH and IH)

Biprobability plots



$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx k_0 \frac{\sin^2([1-A]\Delta)}{[1-A]^2}$$
$$+ k_{\mathrm{CP}} \Phi \frac{\sin([1-A]\Delta)}{(1-A)} \cos\Delta \cos\delta$$
$$\mp k_{\mathrm{CP}} \Phi \frac{\sin([1-A]\Delta)}{(1-A)} \sin\Delta \sin\delta$$

Measure **neutrino** and **anti-neutrino** appearance probabilities.

Other parameters need to be constrained to sufficient precision.

Then can establish value of δ and $\mathrm{sign}(\Delta m_{31}^2)$.

But may be ambiguous

- Degenerate solutions
- Or just because of finite resolution.

What does current T2K data say?

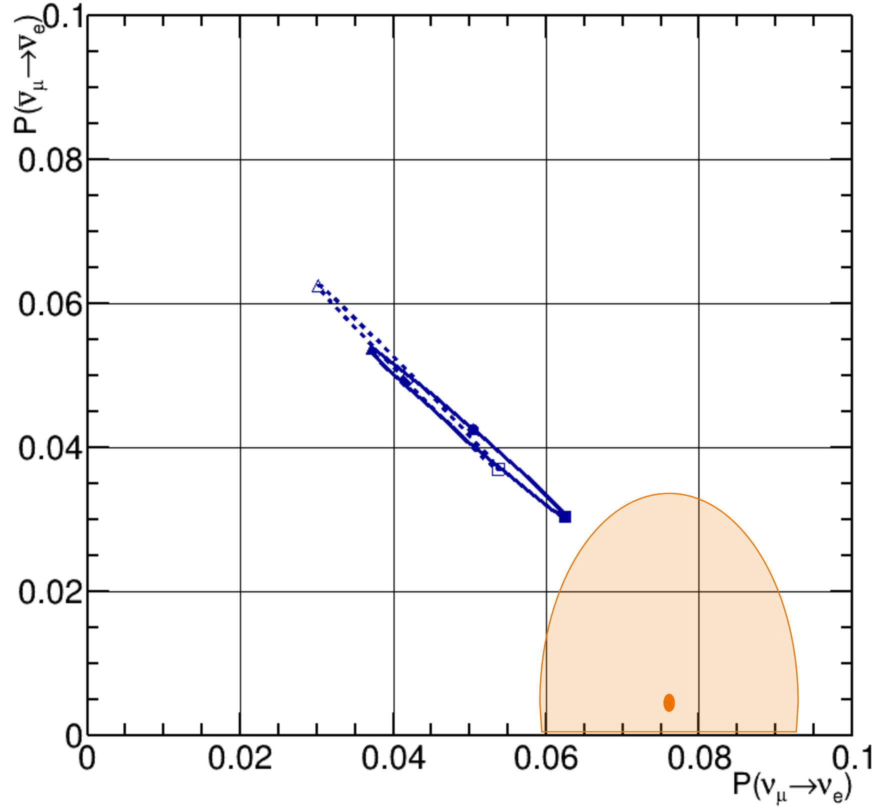
There's a catch here.

$$P(\nu_\mu \to \nu_e) \approx k_0 \frac{\sin^2([1-A]\Delta)}{[1-A]^2} + k_{CP}\Phi \frac{\sin([1-A]\Delta)}{(1-A)} \cos\Delta \cos\delta - k_{CP}\Phi \frac{\sin([1-A]\Delta)}{(1-A)} \sin\Delta \sin\delta$$

The bi-probablitiy plots are drawn for a ***single*** neutrino energy, but a real beam has a ***range of energies***.

However, if one naively converts from event rates to probabilities you get a **rough idea** of what T2K's (2016) measurement implies.

Hand-waving summary of T2K results



Taking the spectrum into account

The energy spectrum does matter though; can we find a way to show this?

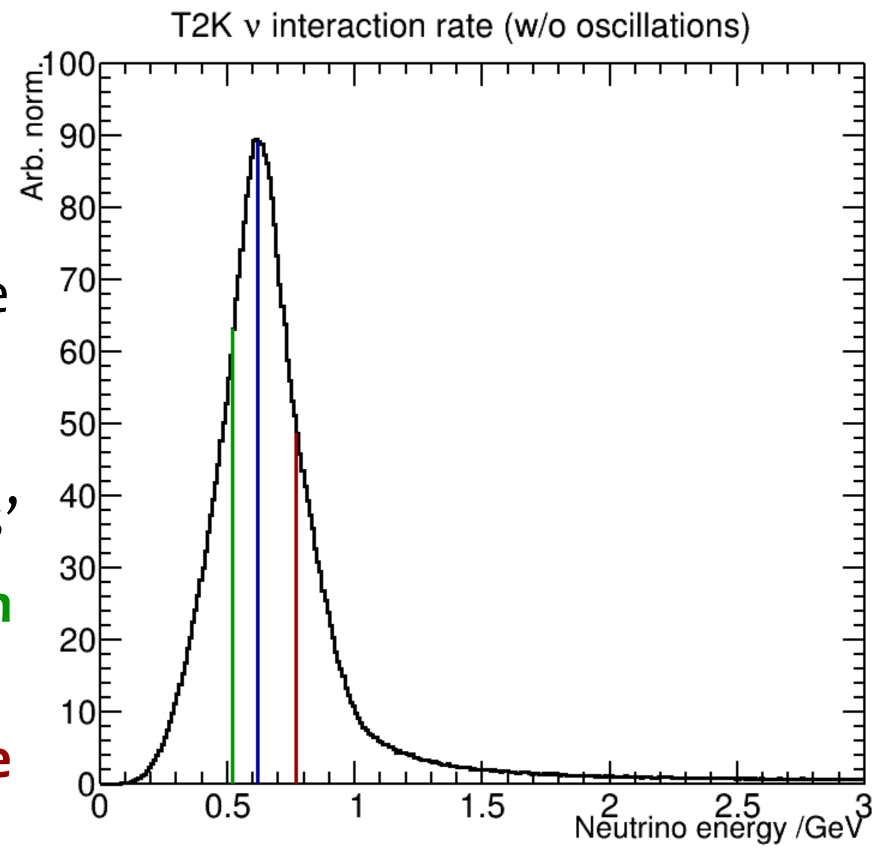
Choose 3 representative points

- **Take the peak of the neutrino (interaction) spectrum.** This value is commonly used as a summary.

This divides the spectrum into 2 'tails'

- **Scan to the left & find the median of the lower tail.**
- **Scan to the right and do the same**

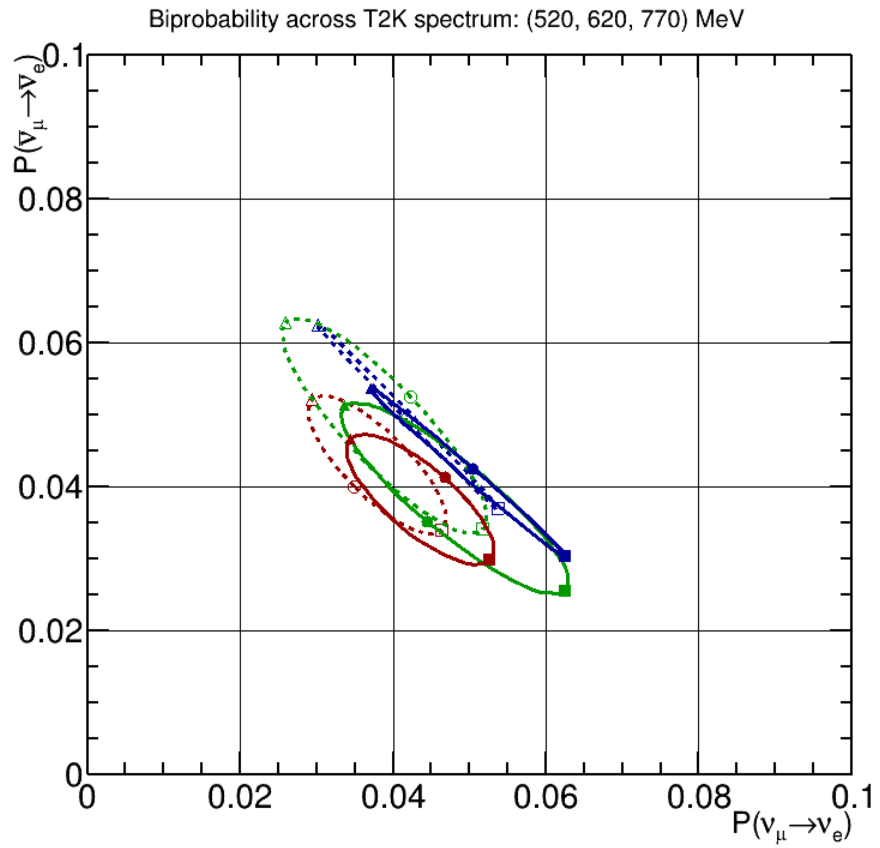
Now 50% of the spectrum will be between green and red



Taking the spectrum into account

The energy spectrum does matter though; can we find a way to show this?

Now calculate ellipses for each energy: 520, 620 and 770 MeV



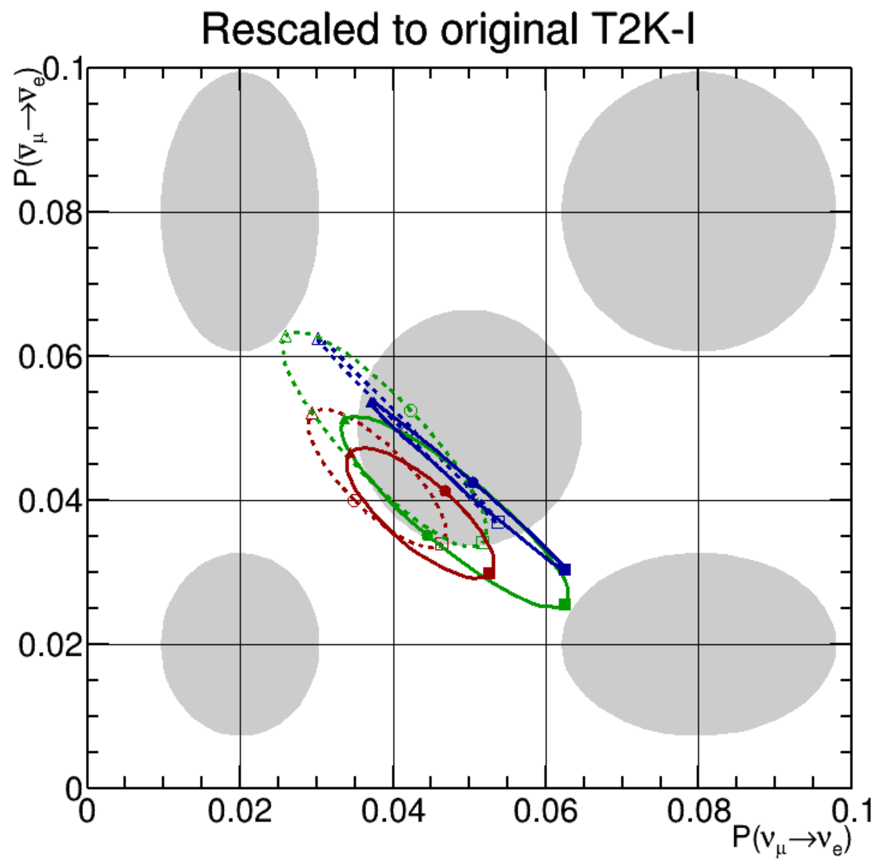
Can see there is *some* justification for just integrating across the spectrum, even if it isn't perfect.

Estimating statistical sensitivity

Finally, estimate the sensitivity a single probability ellipse.

- Number of events estimated for nominal exposure* (T2K: 0.75 MW × 5 years)
- 3 ellipses and we ignored extreme tails, so assume **25%** of expected events contribute to each.
- Then estimate fractional error as a function of estimated signal and background at particular probabilities:

$$\frac{\sqrt{S+B}}{S}$$



***3:1 RHC:FHC→ similar numbers of ν and $\bar{\nu}$**

Imperial College London

Outline

A short history of the Kamioka program

Neutrino oscillation physics & T2K

Hyper-K and the Korean detector

The future

In the next ~5y we expect (4×) more data from T2K, plus full results from NOvA. In addition we may have useful measurements from non-LBL experiments (e.g. IceCube).

In 10~20y: **Next generation experiments - Hyper-K and Dune**

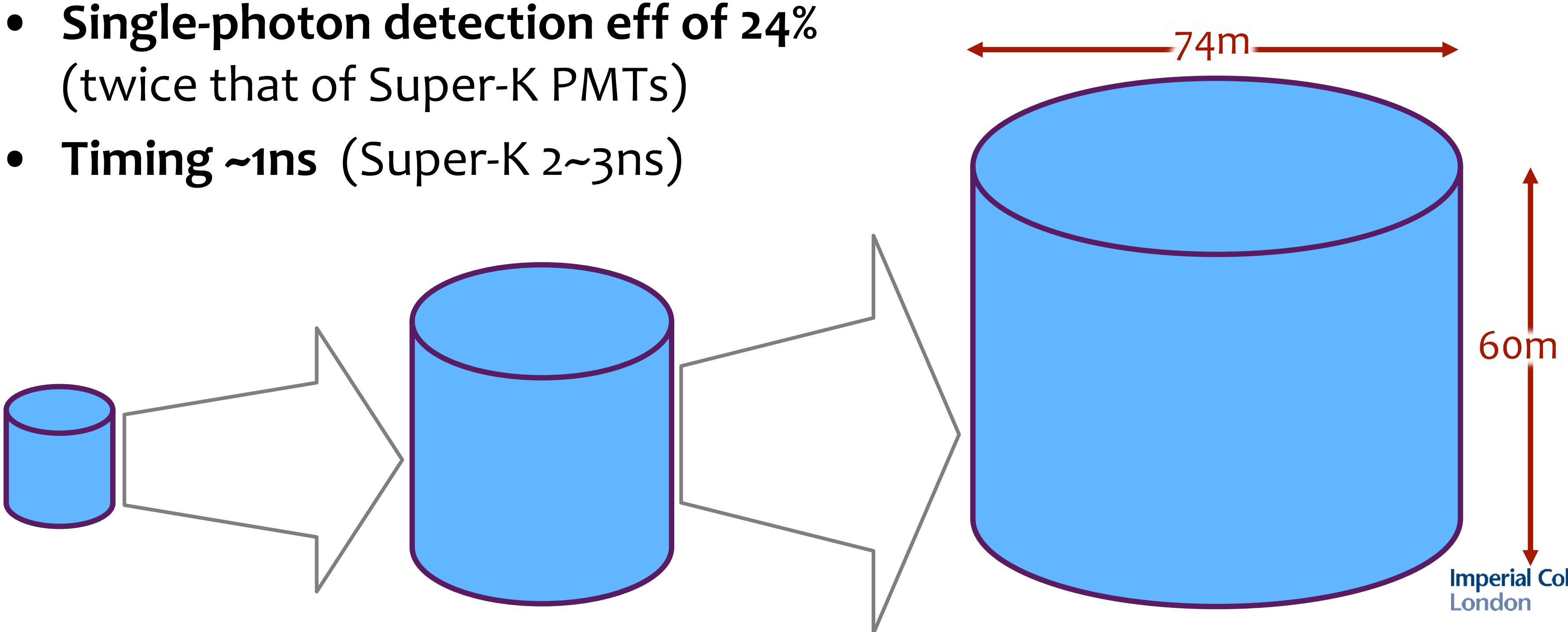
T2K best fit is one of the 'easy points'. Consider 2 options:

1. **T2K is correct, and other experiments agree**
   - Fair chance that T2K + NOνA + IceCube together favour NH at "$> 3\sigma$"
     - IceCube and NOvA both have higher sensitivity to mass hierarchy
   - Most important goal is to establish CPv, and then *measure* δ.
2. **T2K best fit is not correct, &/or other experiments disagree**
   - Testing measurements in other regimes is useful. Unlikely to be able to resolve disagreement without *different* data.

Hyper-Kamiokande

Hyper-K is the proposed next generation WC detector. The baseline design calls for 2 new tanks, both situated in a mine near the existing Kamioka Lab.

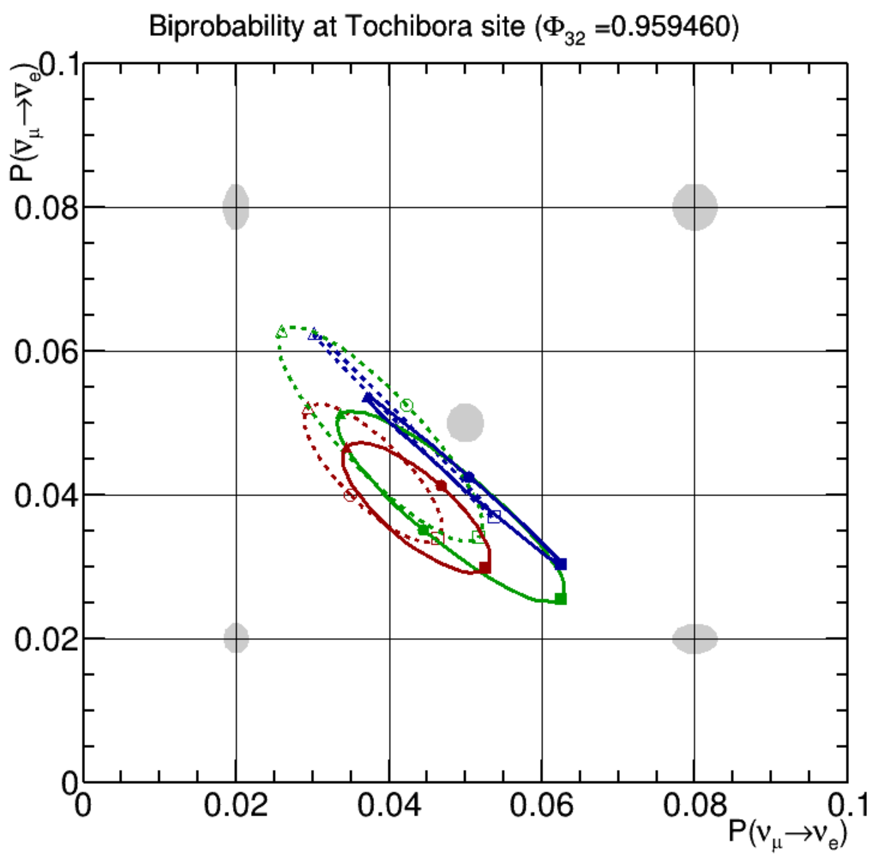
- **Each tank is 5× larger than Super-K (8× after fiducial cuts)**
- **40% photocoverage**
  (same as Super-K)
- **Single-photon detection eff of 24%**
  (twice that of Super-K PMTs)
- **Timing ~1ns** (Super-K 2~3ns)

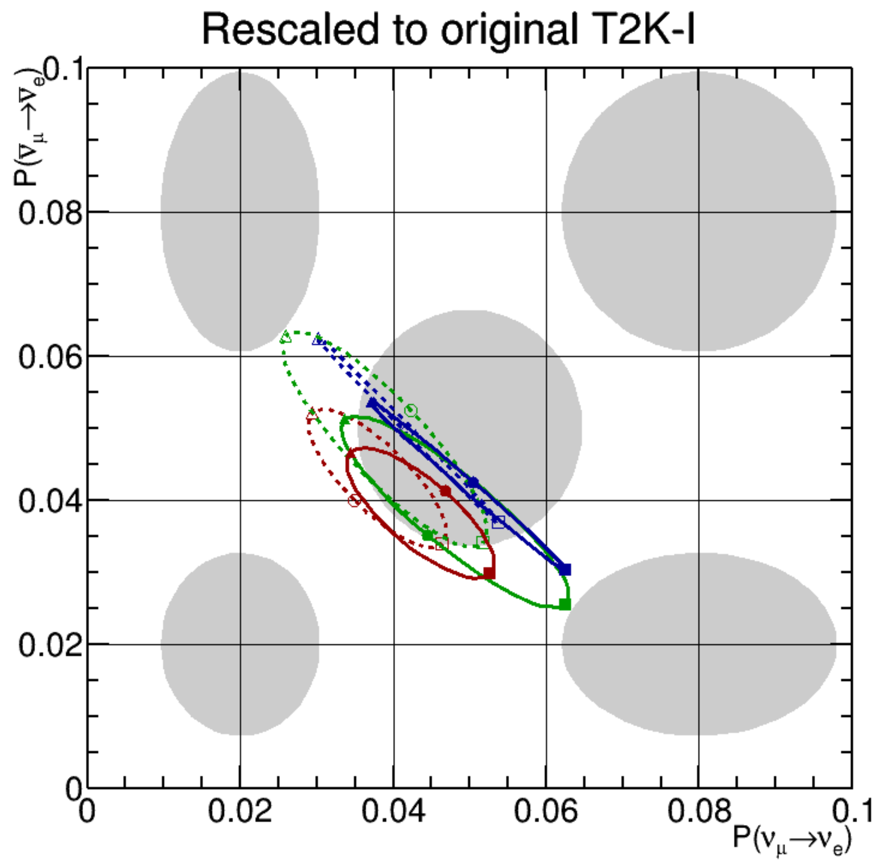


Imperial College London

How does Hyper-K improve things?

Hyper-K (1 tank × 10y) compared to T2K nominal





Stats ellipses get smaller, giving better sensitivity

The Korea proposal

The 2 tanks in the baseline design are staged, with the second tank coming into use 6 years after the first.

An alternative possibility is to put a second tank in Korea ("T2HKK")

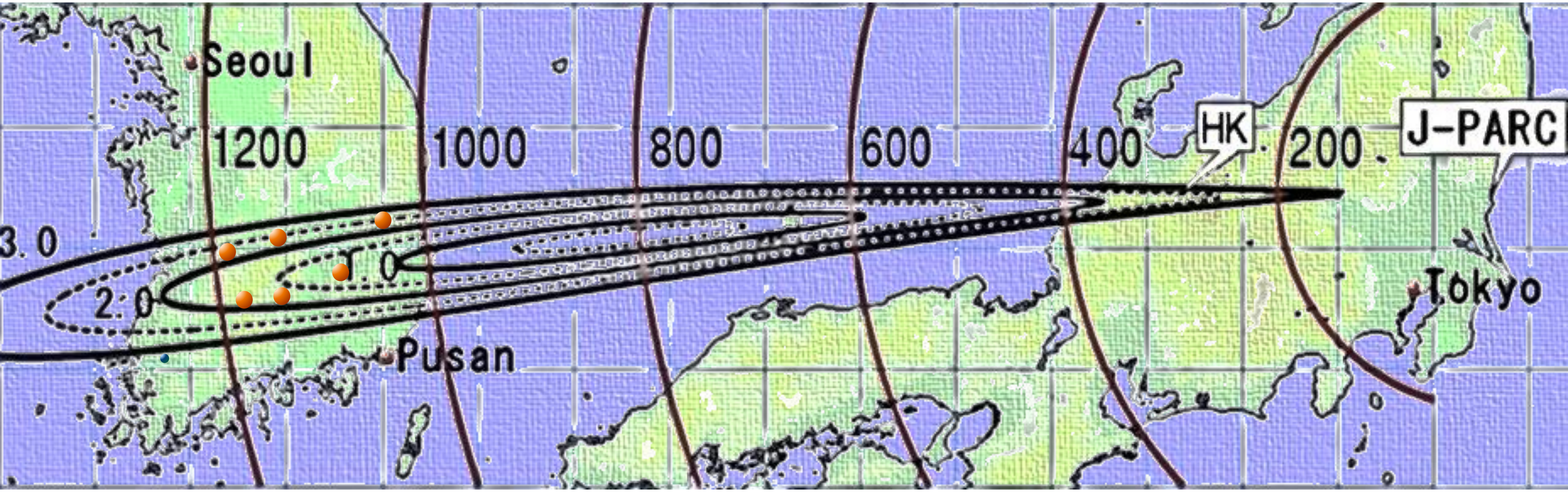
- Work on the second tank could conceivably start much sooner
- This is possible because of the off-axis choice
  - The beam is below (and slightly to the south of) the Super-K at 295km
  - The centre surfaces at a distance of about 800km, in the Sea of Japan
  - The 2.5° cone around this point extends to about 1250km, past the west coast of South Korea.

The Korea proposal

The 2 tanks in the baseline design are staged, with the second tank coming into use 6 years after the first.

An alternative possibility is to put a second tank in Korea

- Work on the second tank could conceivably start much sooner
- This is possible because of the off-axis choice (c.f. NuMI, Dune)



What changes for a Korean site?

Obviously, the baseline is longer.

Candidate sites In Korea are between 1000km and 1200km,
i.e. 3~4× times as distant as Kamioka

- Can observe the second oscillation maxima
- Flux drops as L^{-2}, therefore stat. uncertainties grow as L
- The interesting oscillation terms grow as $\sim L$

} Effects cancel out

There is more freedom to choose a different off-axis angle

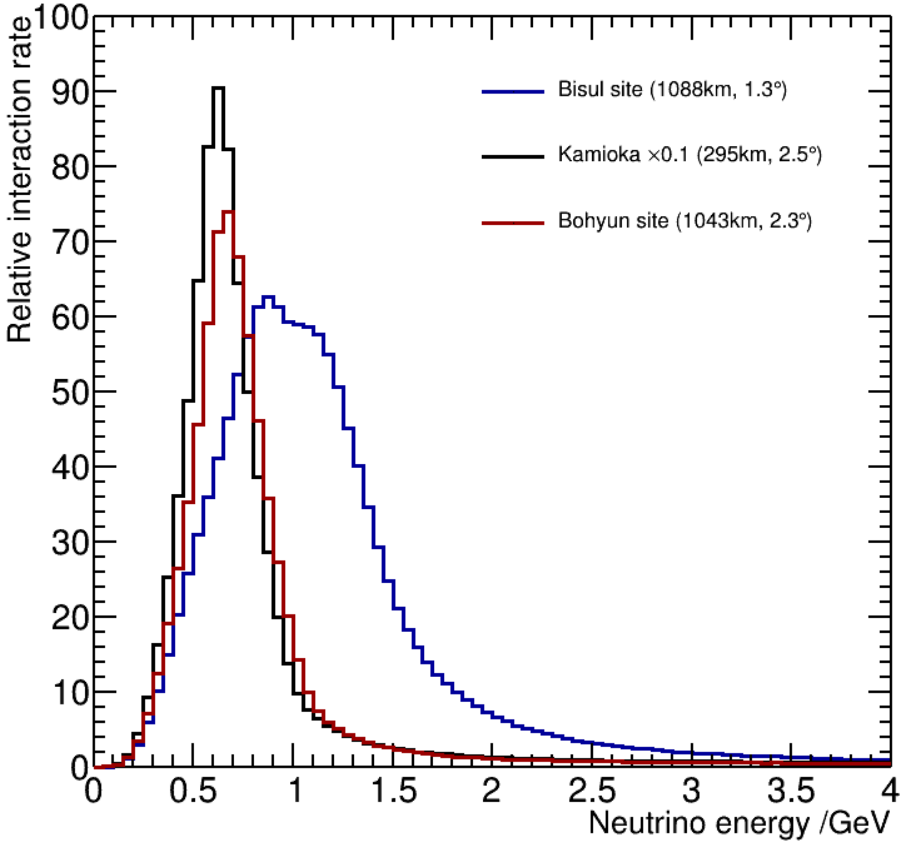
- Means we can choose a beam energy to optimise measurement.

Site choice can follow 2 principles:

1. Minimise off-axis angle for higher energy, increasing matter effect
2. Stay at similar off-axis angle to Super-K (and ND280 detectors) to cancel systematic uncertainties "ratio measurement"

Potential sites

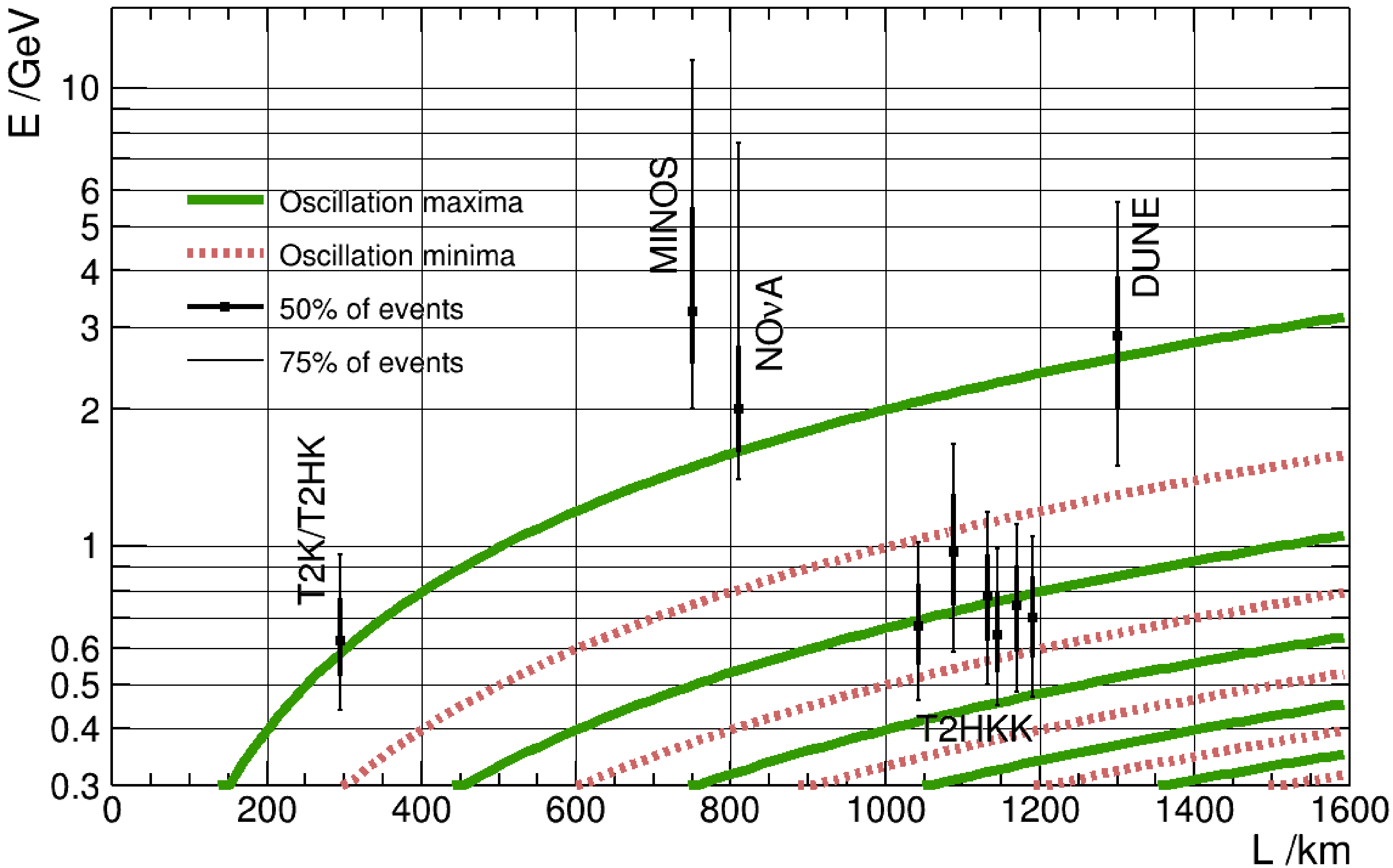
Site	Distance /km	Angle
Kamioka	295	2.52°
Mt. Bisul	**1089**	**1.31°**
Mt. Hwangmae	1142	1.93°
Mt. Sambong	1170	2.06°
Mt. Bohyun	**1043**	**2.29°**
Mt. Minjuji	1145	2.38°
Mt. Unjang	1190	2.21°



1. Minimise off-axis angle for higher energy, increasing matter effect
2. Stay at similar off-axis angle to Super-K (and ND280 detectors) to cancel systematic uncertainties “ratio measurement”

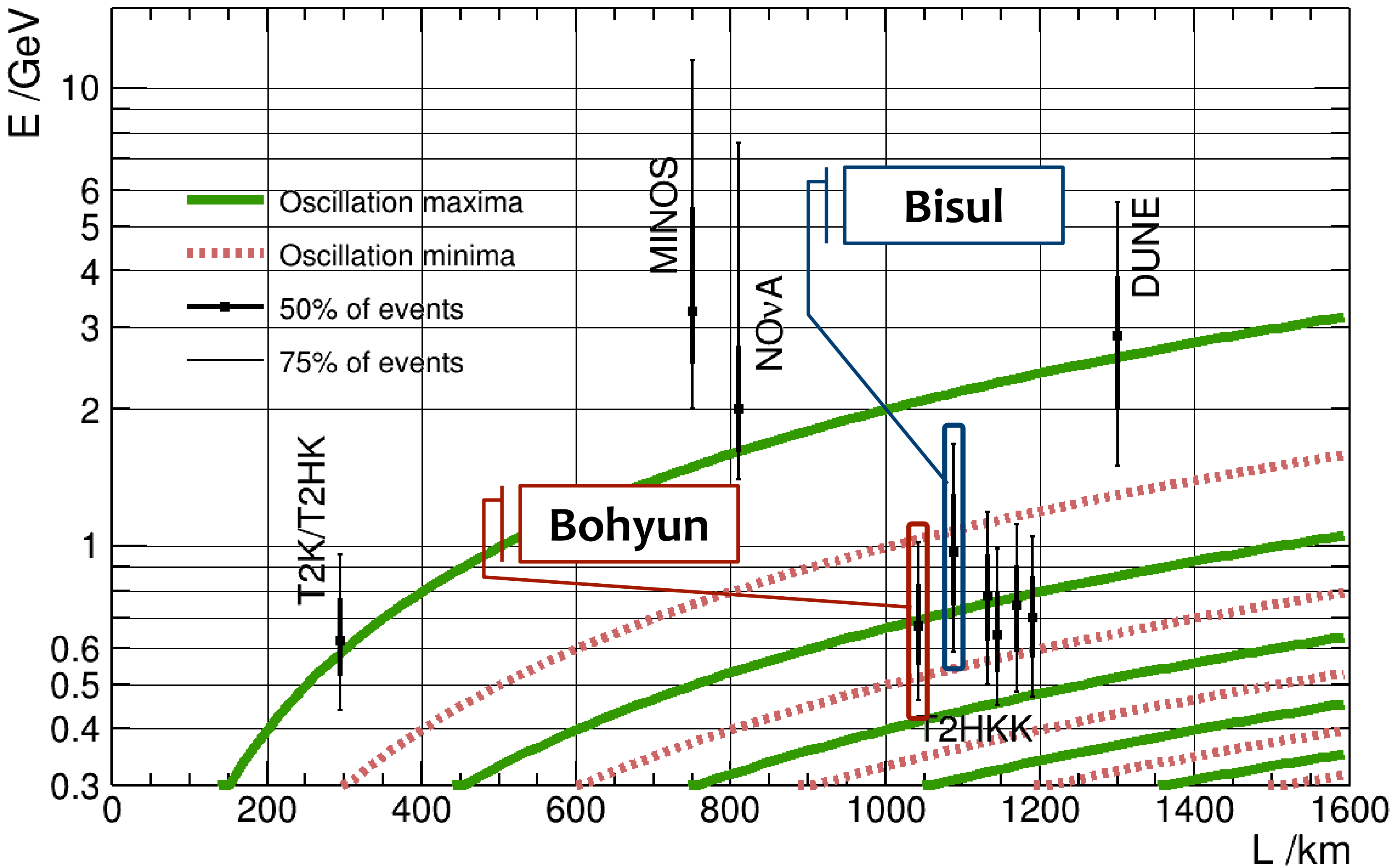
Imperial College London

Observing the second maximum



College London

Observing the second maximum



CP term enhancement

Remember the appearance probability:

$$P(\nu_\mu \to \nu_e) \approx k_0 \frac{\sin^2([1-A]\Delta)}{[1-A]^2}$$
$$+\, k_{\mathrm{CP}} \Phi \frac{\sin([1-A]\Delta)}{(1-A)} \cos\Delta \cos\delta$$
$$-\, k_{\mathrm{CP}} \Phi \frac{\sin([1-A]\Delta)}{(1-A)} \sin\Delta \sin\delta$$

Where $k_0 \simeq 0.049$
and $k_{\mathrm{CP}} \simeq 0.014$

The factor $\Phi = \frac{2\Delta}{\pi}$ is:

1 at the first maximum

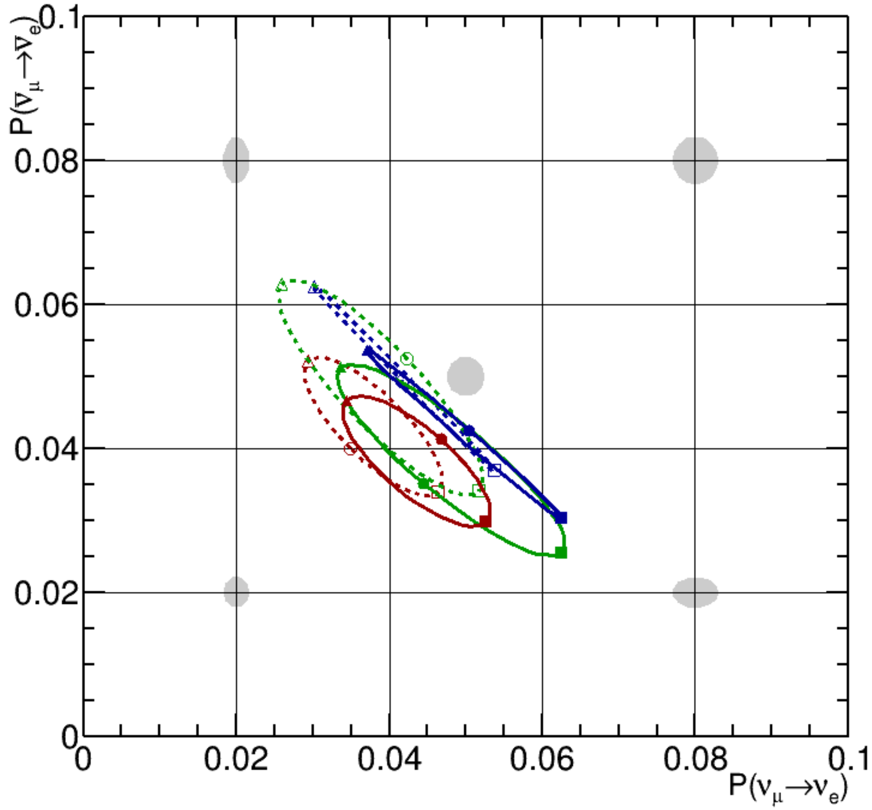
3 at the second maximum

The CP violating (& CP conserving) term is enhanced!

For $\Phi \ll 32$ (i.e. as long as solar terms are small) this enhancement cancels out the statistical loss…

Pictorially

Kamioka, for comparison



The CP violating (& CP conserving) term is enhanced!

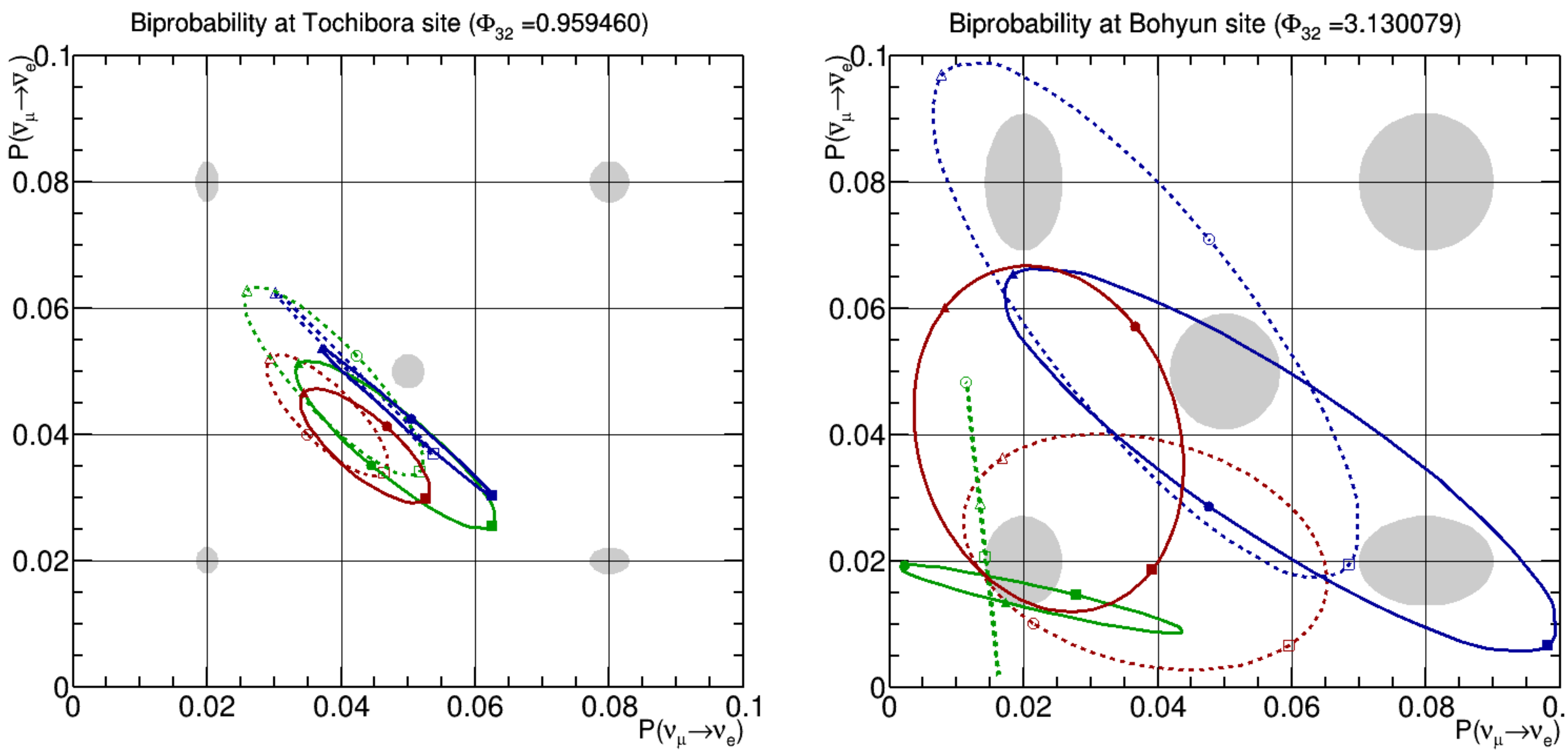
For $\Phi \ll 32$ (i.e. as long as solar terms are small) this enhancement cancels out the statistical loss…

Time to see what it looks like in practice. Remember, the CP parameters control the size of the ellipses.

[Also note: these are made with with full numerical calculation.]

Pictorially

Kamioka compared to Bohyun (2.29° off-axis site)



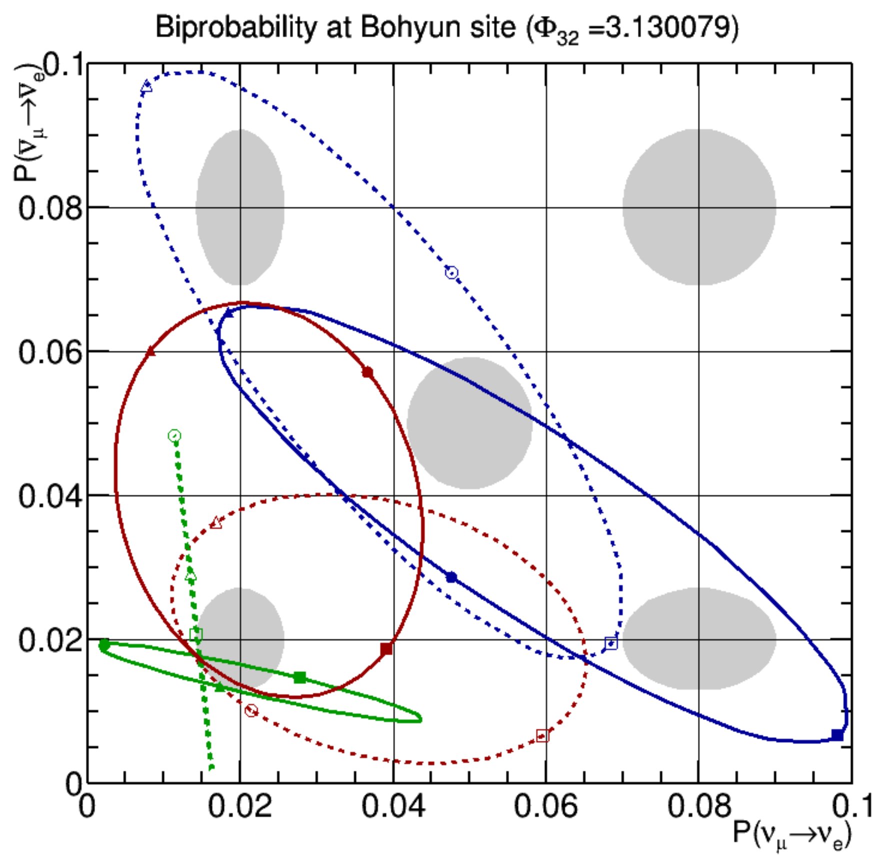
Nuisance parameters

'The CP term enhancement cancels out the statistical loss…'

…can see this wasn't the whole story!

The interesting part is in the nuisance parameters. There are two helpful features:

Because the stat error grows while preserving sensitivity, **any systematic that is a fixed size is a factor 3 less important.**



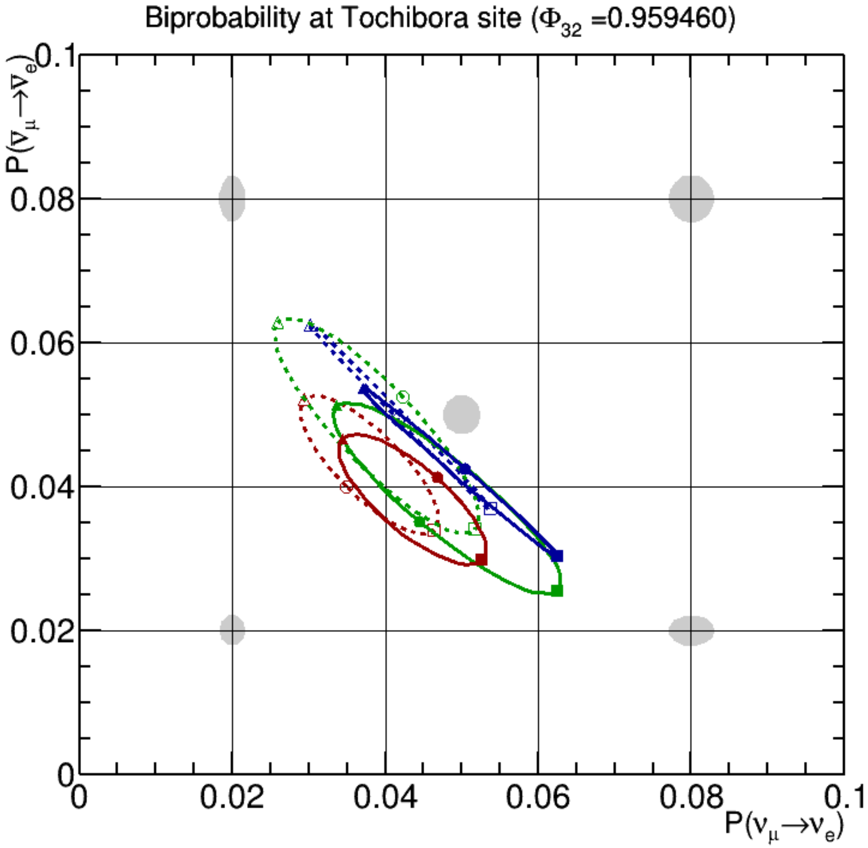
Nuisance parameters

The second helpful feature is a little less obvious.

To affect a measurement, a nuisance parameter must *mimic the oscillation signal*.

Example: Suppose the excess in current T2K results is an unknown systematic, rather than a fluctuation.

It is quite easy for it to mimic a signal, because at Kamioka more ν_e favours 'NH, $\delta = -\pi/2$' for all energies.



Nuisance parameters

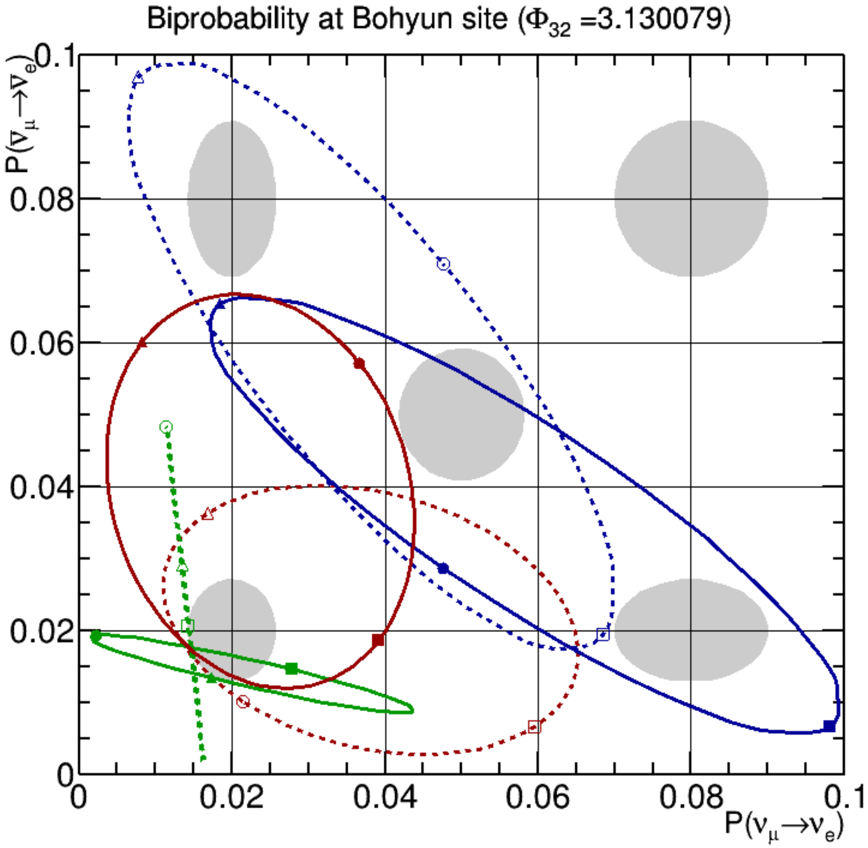
The second helpful feature is a little less obvious.

To affect a measurement, a nuisance parameter must *mimic the oscillation signal*.

Example: Suppose the excess in current T2K results is an unknown systematic, rather than a fluctuation.

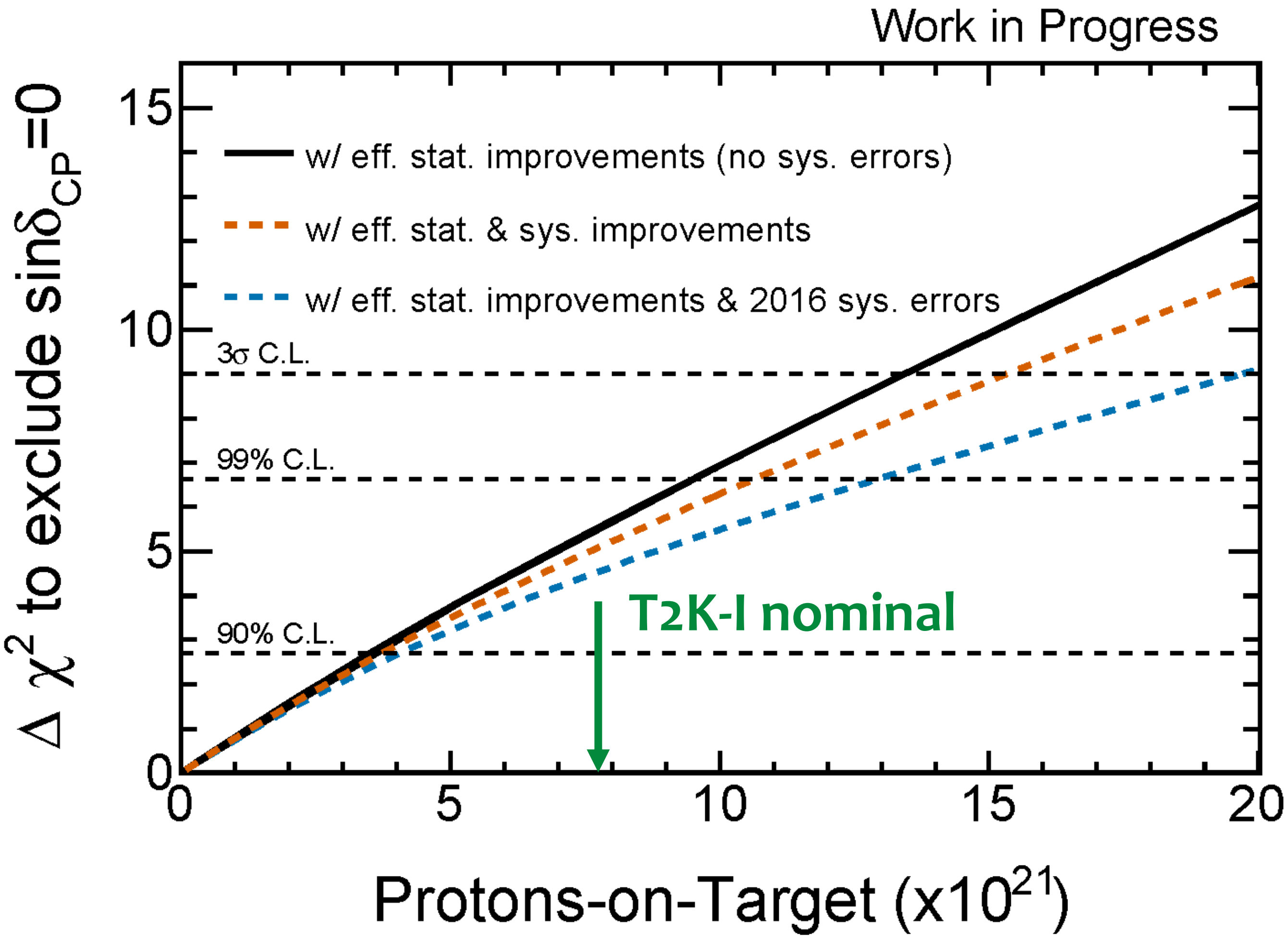
But for (e.g. Bohyun) interpretation is different at different energies.

The systematic does not mimic (the same) **oscillations**



Are systematic errors important?

In a word: **yes.**

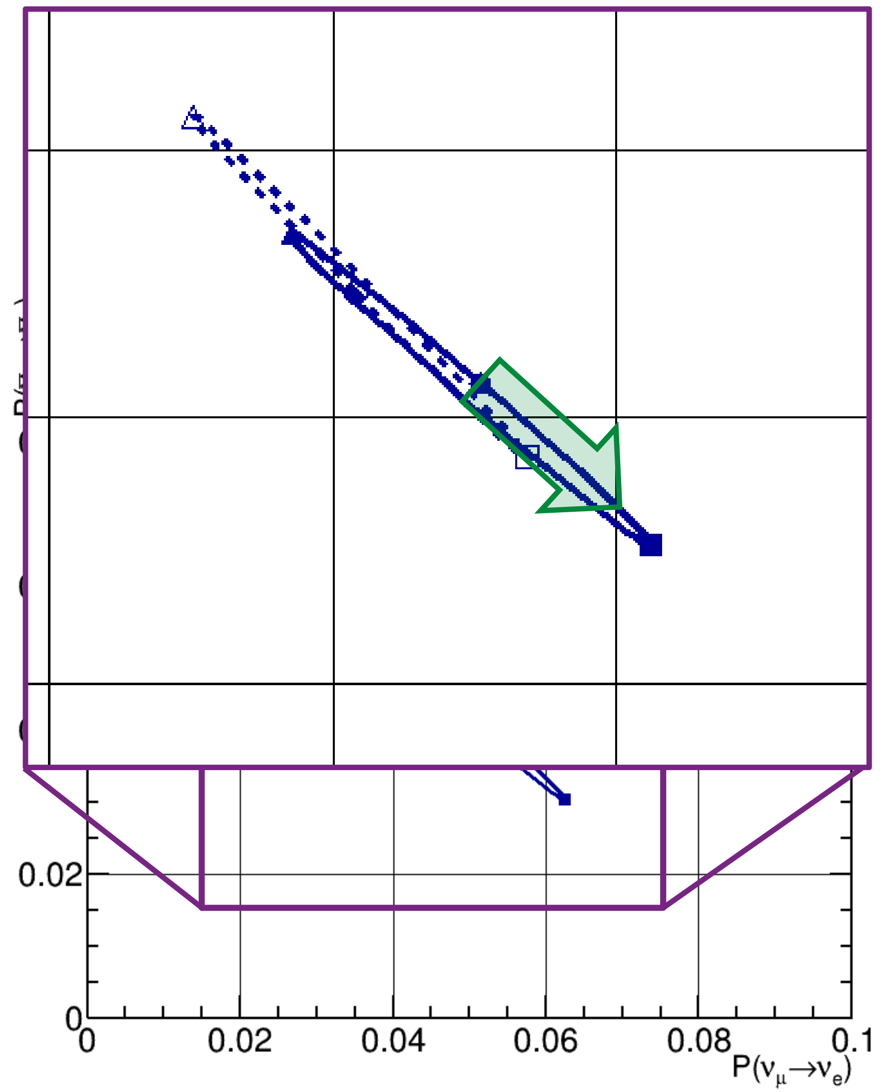


Plot from T2K-II (T2K run extension) LOI.

- Hyper-K proposal equivalent to much higher POT

One more thing: measuring δ

For *discovery* of CP non-conservation the important statistical issue is **"How likely is my measurement to be a fluctuation from a CP conserving point"**

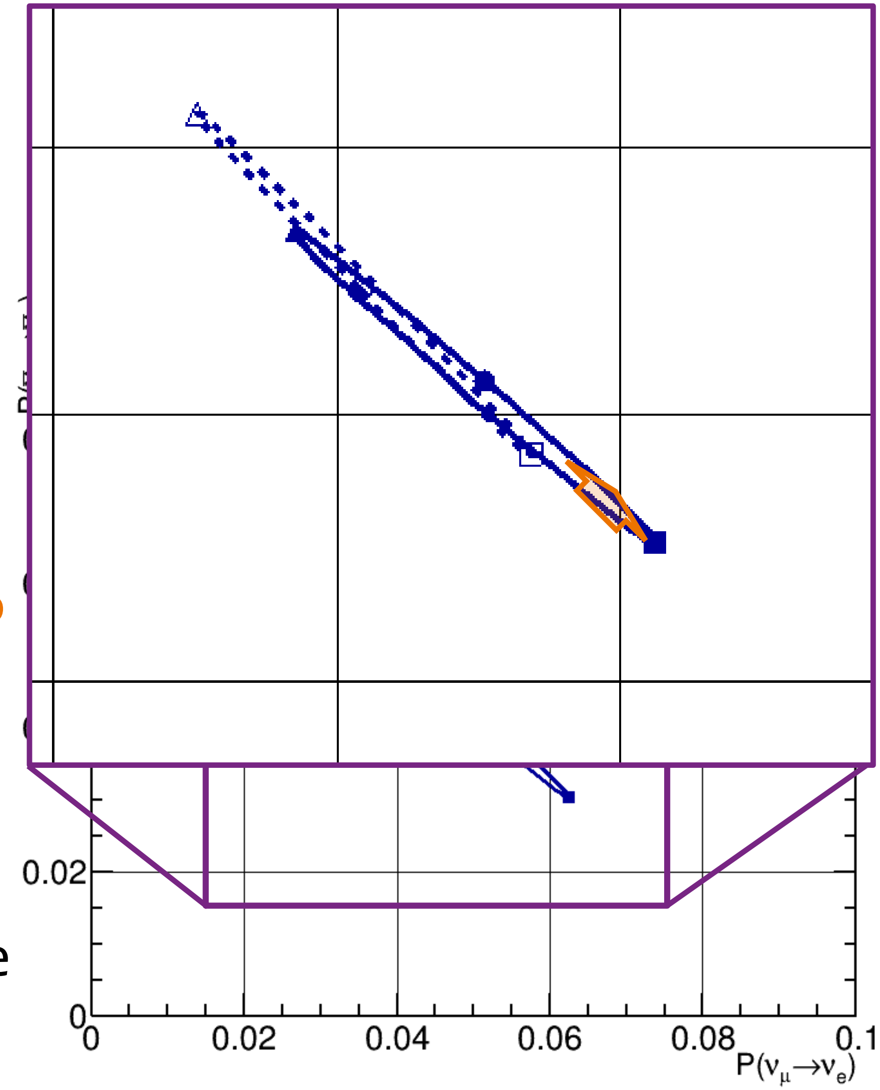


One more thing: measuring δ

For *discovery* of CP non-conservation the important statistical issue is
"How likely is my measurement to be a fluctuation from a CP conserving point"

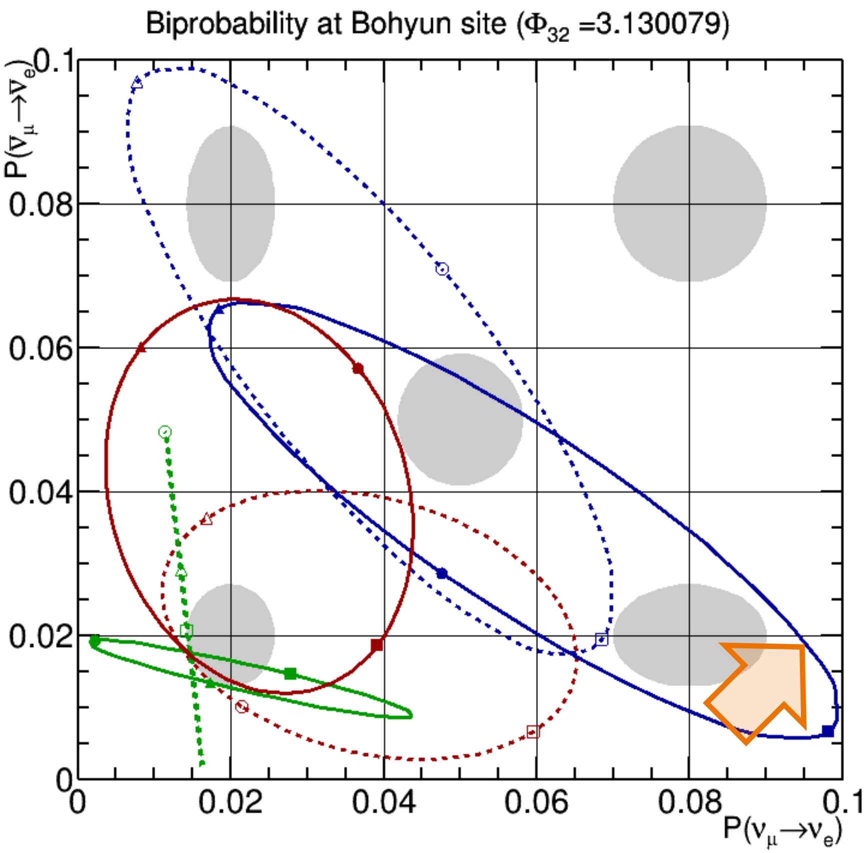
But to measure δ the statistical question is different:
"How likely is is my measurement to be a fluctuation from any other point"

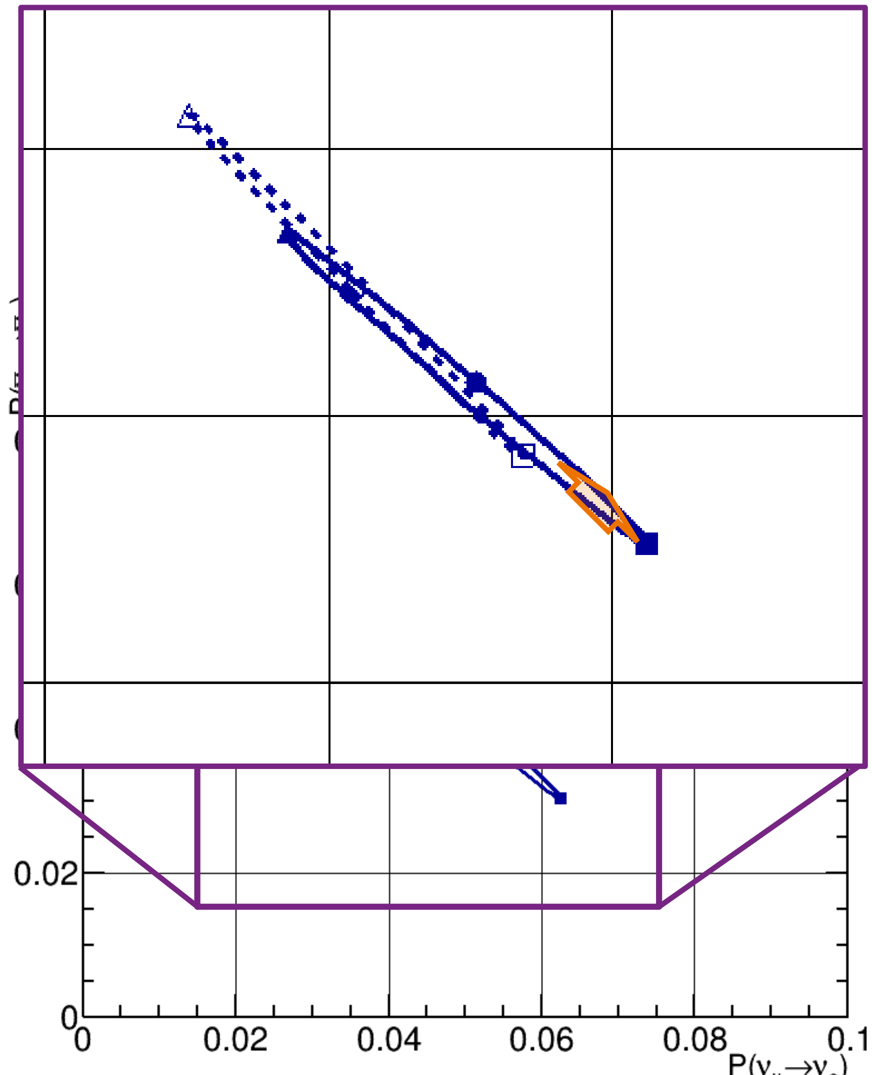
For textbook linear problems, the distinction is not important. But here it is.



One more thing: measuring δ

For actually making a measurement the more open ellipses associated with the Korean sites helps too.





Imperial College London

Bisul: Matter effect enhancement

Now consider just the leading (k_0) term:

$$P(\nu_\mu \to \nu_e) \approx k_0 \frac{\sin^2([1-A]\Delta)}{[1-A]^2}$$

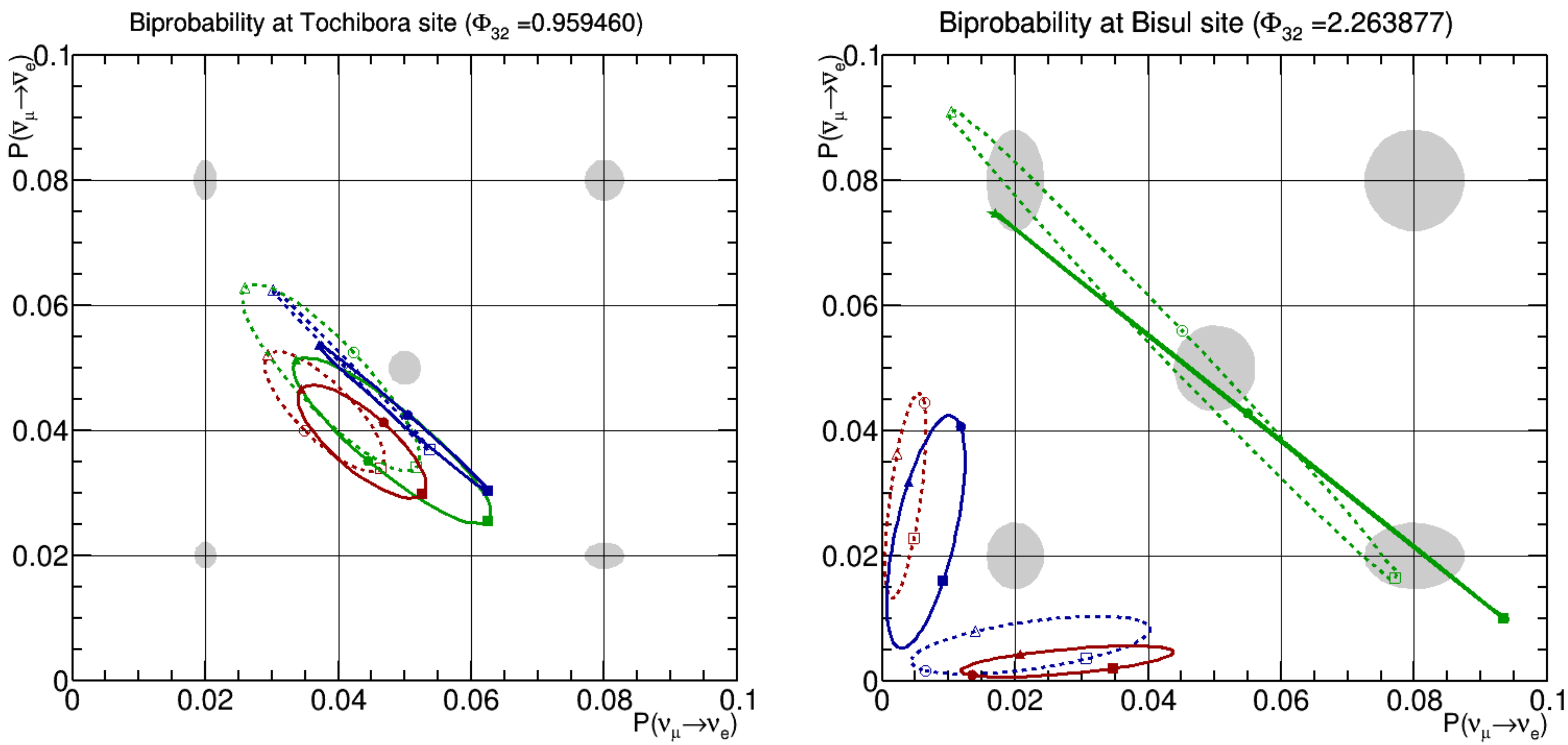
where $|A| \simeq E/10\mathrm{GeV}$

The **amplitude** of the oscillation will scale by $[1-A]^{-2}$ for *all maxima*.

But the **position** of the oscillation maximum is shifted by $A\Delta$, which is 3 times larger at 2nd maxima.

Energy	Baseline	Notes	Effect size: Amplitude	Effect size: Position
0.6 GeV	300 km	Like T2K	113%	6%
0.6 GeV	900km	2nd max	113%	18%
1.8 GeV	900km	Like Bisul, NOvA	149%	18%

Bisul compared to Kamioka



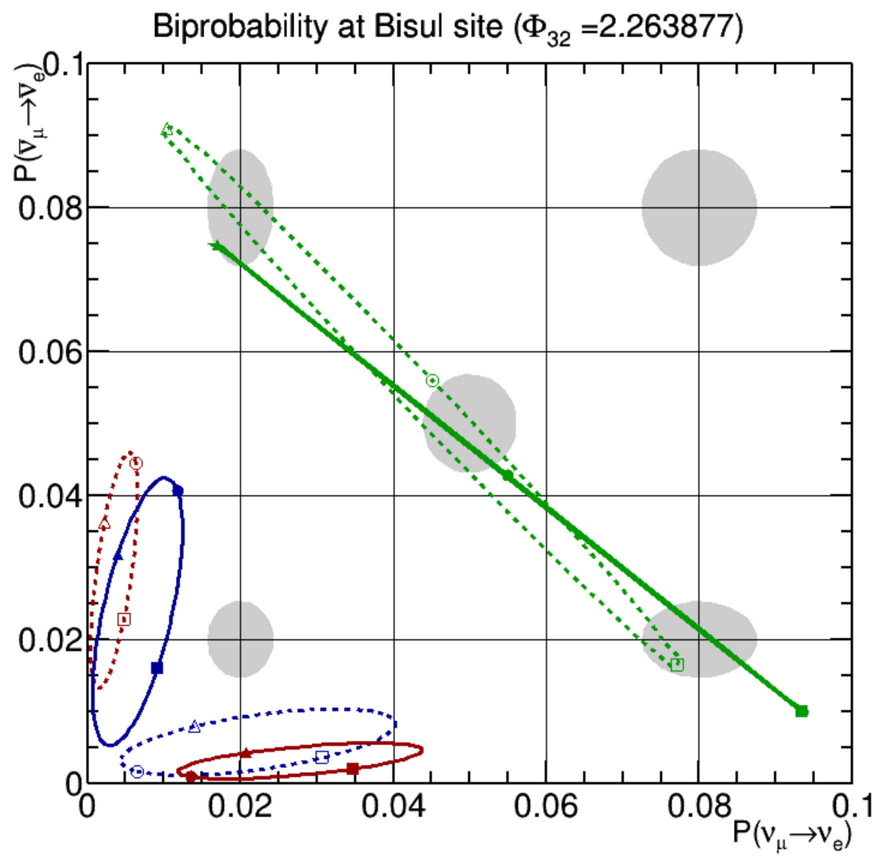
Bisul compared to Kamioka

At medium (**970MeV**) and high (**1300MeV**) energies, the two hierarchies can be completely distinguished.

There is actually better separation than at NOvA (event though it has higher energy)

- CP term does not mimic matter effect for Bisul configuration

Also around **970MeV**, NH enhances $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$, opposite effect to normal (1st maxima) configurations.



Sensitivities

Korean detector WG are now working on full sensitivities using code derived from T2K analyses.

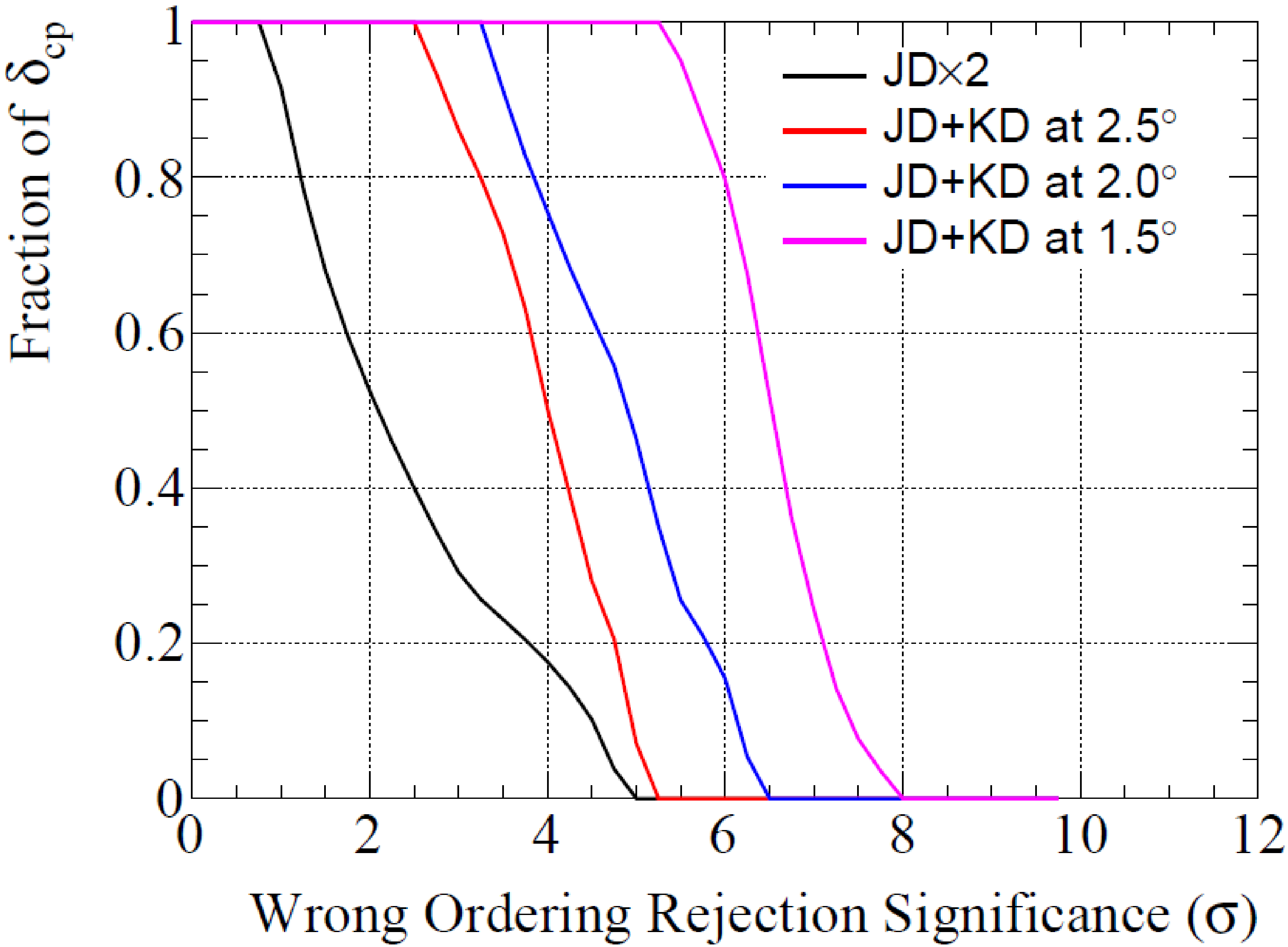
Current generation includes event selections, contamination and finite resolution, but does not include systematics or other oscillation parameters as nuisance parameters.

As a result, **can get a feel for sensitivity, but not yet able to investigate the degeneracy-breaking effects highlighted.**

Also uses old fluxes for generic sites: **1100km** at (**1.5°**, **2.0°**, **2.5°**) off-axis, together with a detector at Kamioka (295km, 2.5°).

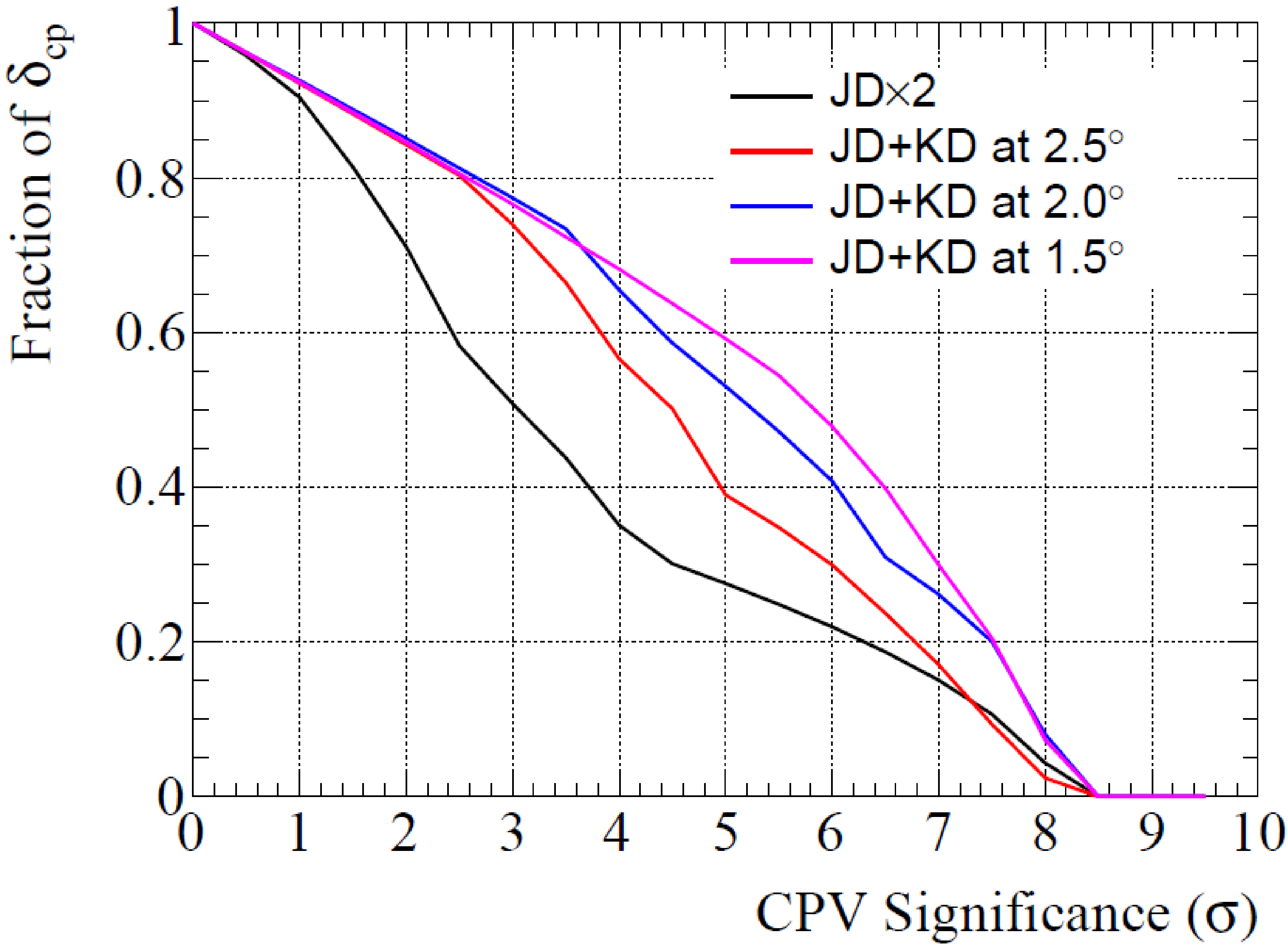
- **2 detectors** at Kamioka (both full 10y) shown for comparison.

Sensitivity to Mass Hierarchy

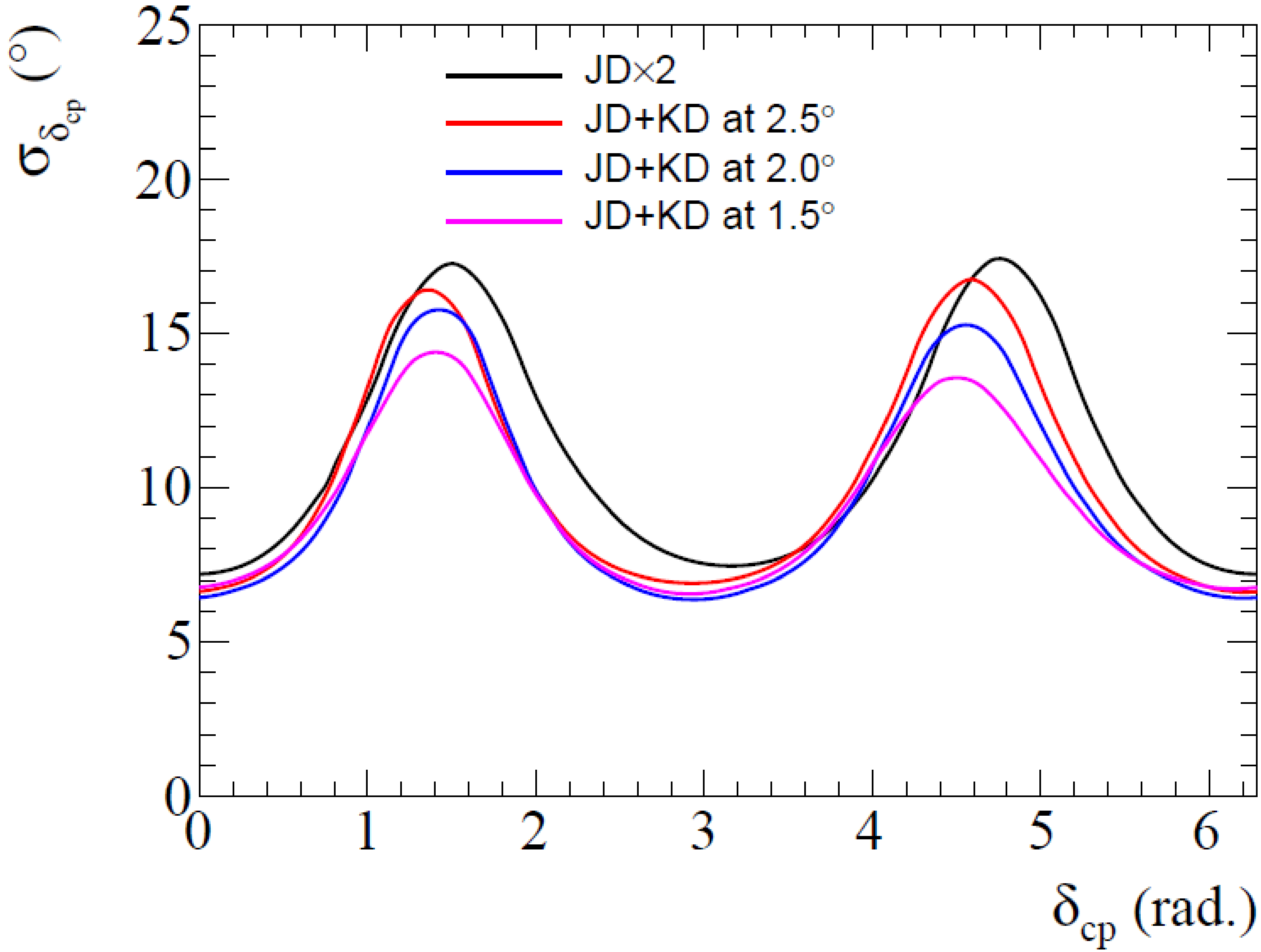


Imperial College London

Sensitivity to CPv



Measuring δ



$\sigma_{\delta_{cp}}$ (°)
25
20
15
10
5
0
0
1
2
3
4
5
6
δ_{cp} (rad.)
JD×2
JD+KD at 2.5°
JD+KD at 2.0°
JD+KD at 1.5°

Summary

White paper on arXiv: 1611.6118

For **proton decay** searches and **natural (solar, atmospheric, supernova, relic) neutrinos** there is no compelling reason for 2 Hyper-K tanks to be near each other.

- In fact, because the Hyper-K site is quite shallow (~650m), a deeper site in Korea (expected ~800m) is actually *preferable.*

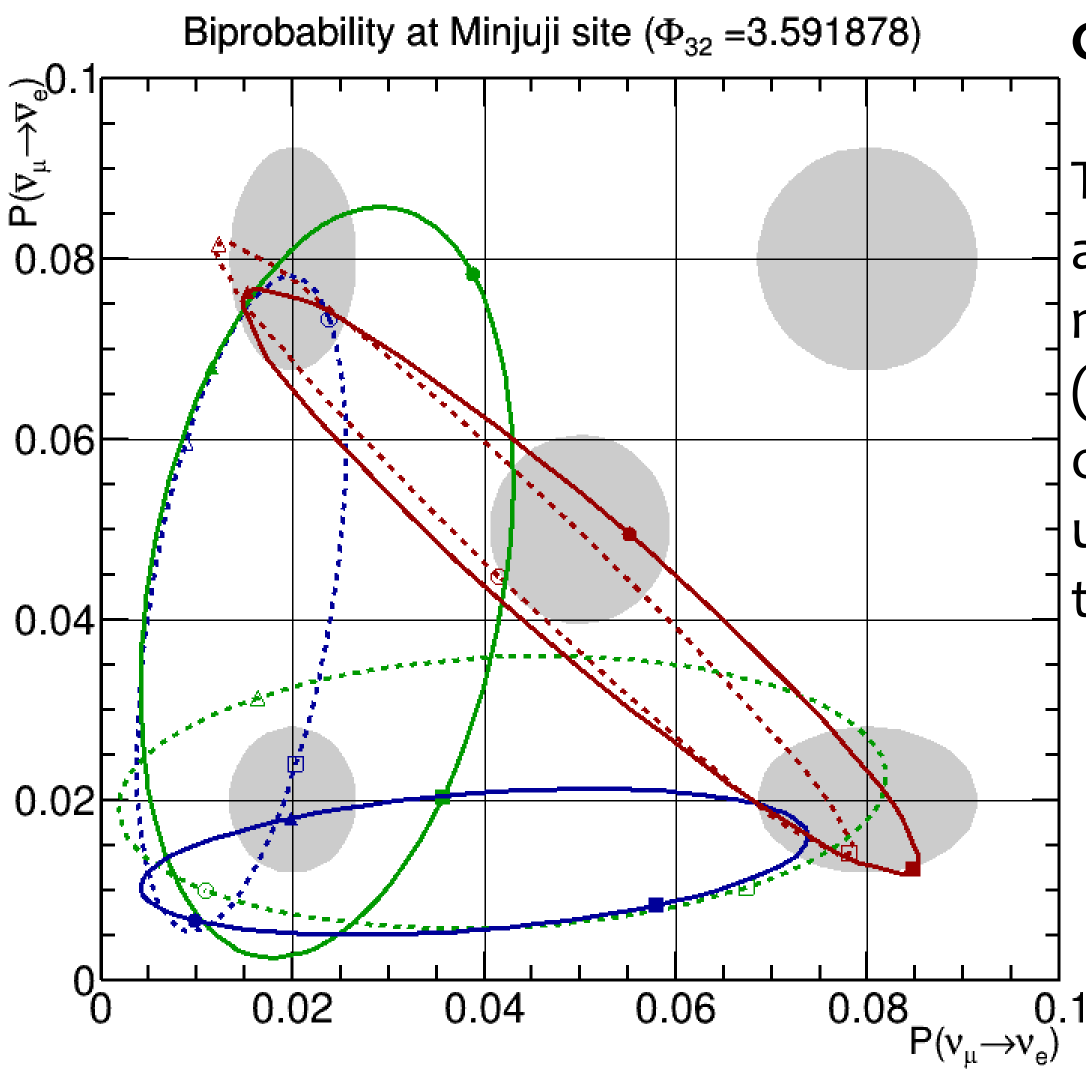
For long baseline physics there is a unique opportunity to reuse an existing beamline for a 2nd-maximum measurement.

- The increased effect size largely **compensates for lower statistics**
- Faster oscillations nearer the 2nd maximum mean the **same spectrum covers a larger interval** of the oscillation pattern
- Sensitivity to most parameters improves overall, and **importance of systematics is reduced**
- **Provides a very interesting test of the model in a new regime**

Imperial College London

Extra slides

Minjuji

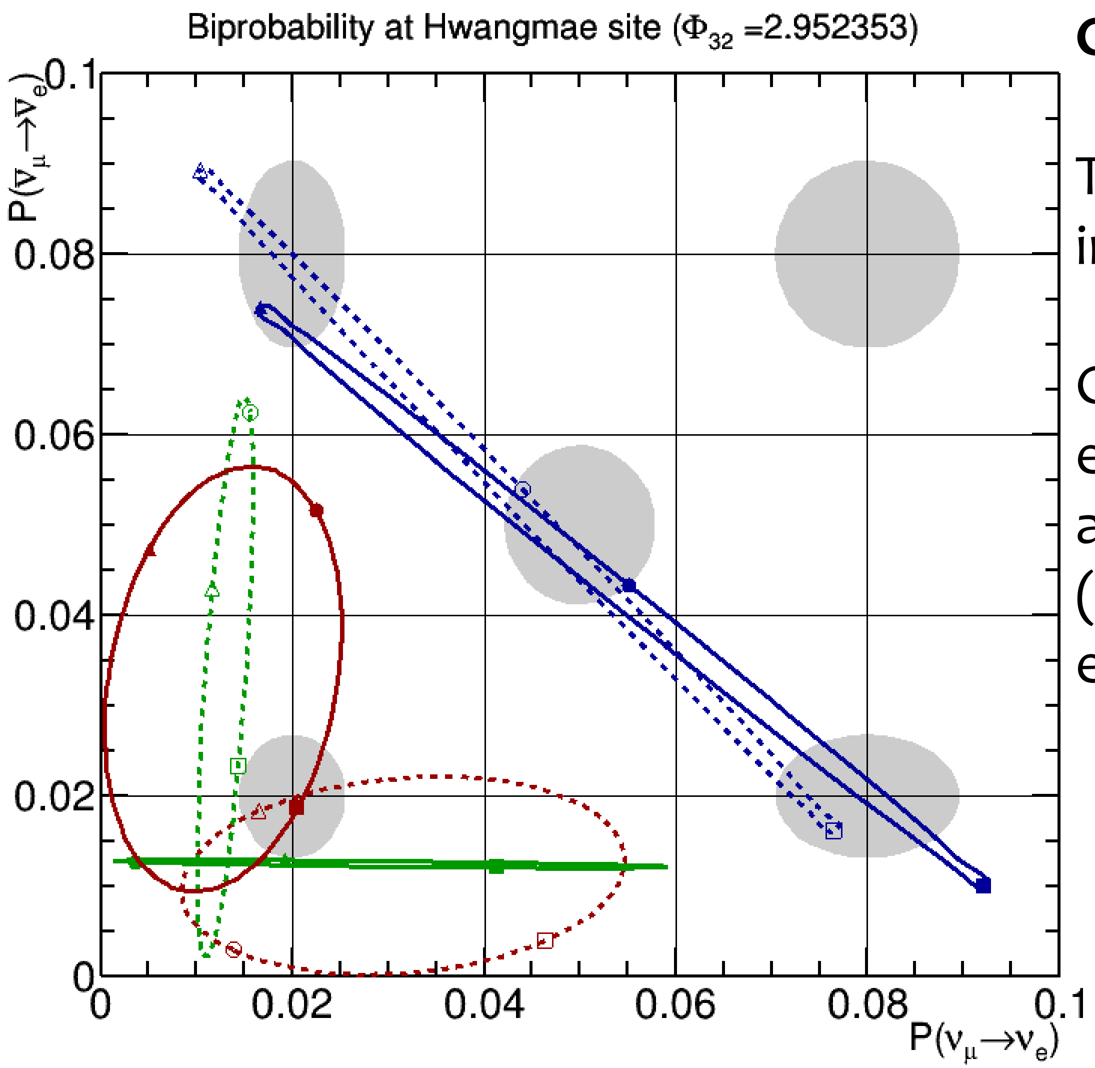


For energies /MeV:

G 530 **B** 640 **R** 800

The combination of larger off-axis angle and long baseline means that the low energy tail (green) is sampling the 3rd (!) oscillation peak, while the upper tail (red) is vary close to the 2nd oscillation peak.

Hwangmae



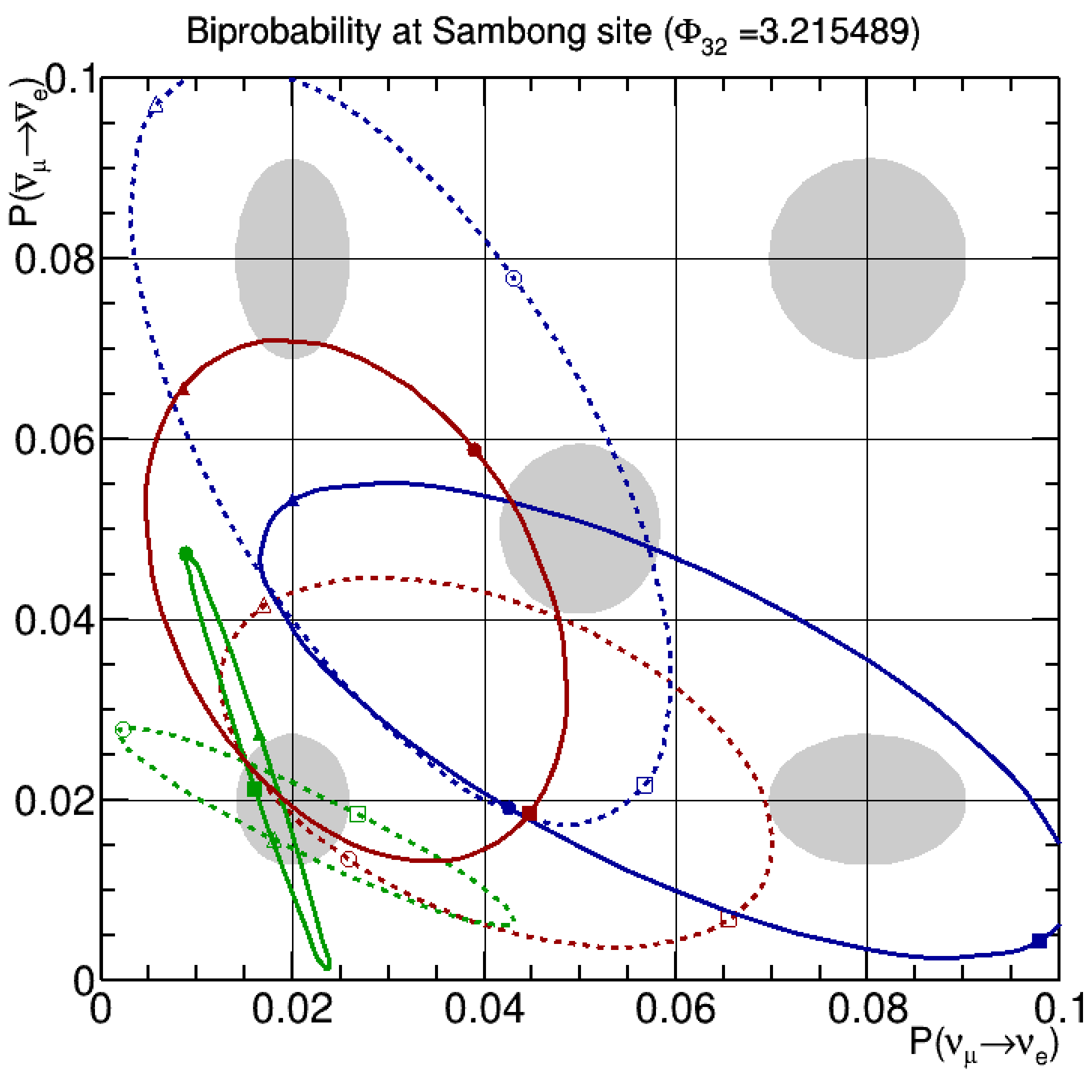
For energies /MeV:

G 620 **B** 780 **R** 960

This is quite similar to Bohyun in terms of L/E regime probed

Green NH is interesting: At this energy antineutrino rate is almost independent of delta (but other energies still see effect)

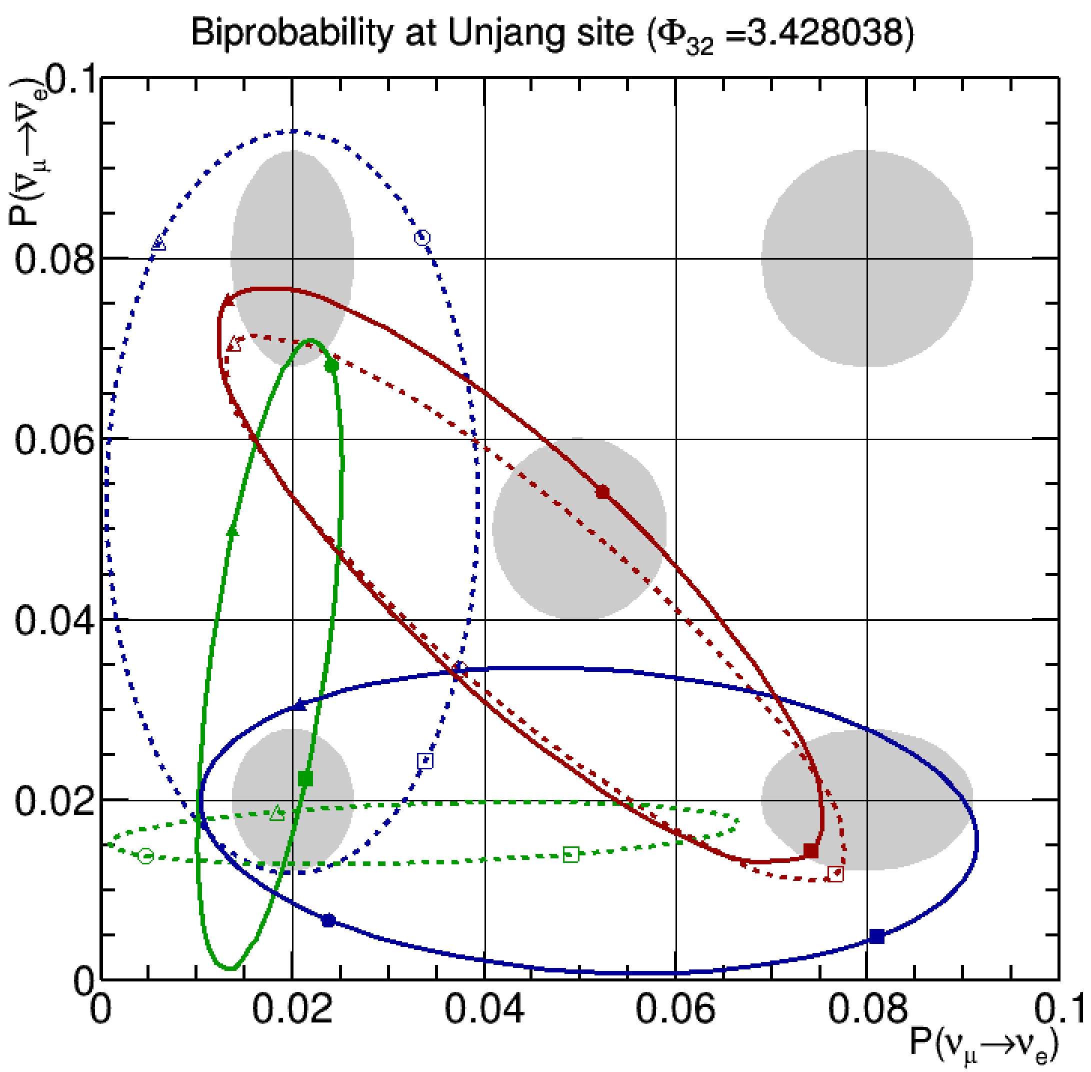
Sambong



For energies /MeV:

G 590 **B** 740 **R** 920

Unjang



For energies /MeV:

G 570 **B** 700 **R** 860

This is similar to Mt Minjuji, but with longer baseline and higher energy.