

The Leptonic CP Phase from μ^+ Decay at Rest

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Based on work done in collaboration with:

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Summary

DAR of μ^+ created using an intense p^+ beam yields $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

The synergy with $\nu_\mu \rightarrow \nu_e$ oscillations from present long baseline experiments yields a precise measurement of the CP phase δ

In (south-)east Asia atmospheric neutrino backgrounds are low and 4 sites may have some of the experimental components

- 1) An Accelerator Driven Subcritical Reactor (ADS) is a powerful source of μ^+ DAR $\bar{\nu}_\mu$, which can be detected with two 20 kton low resolution liquid scintillator detectors
- 2) μ^+ source in Toyama with SuperK/HyperK as near/far detectors
- 3) If JUNO or RENO 50 opt for two detectors, a μ^+ source (phase II of the ADS program C-ADS?) can use them for μ DAR, simultaneously with the hierarchy experiment

Note: These proposals are inspired by DAE δ ALUS but in our opinion offer some advantages to be described below

First Oscillation Maximum

As ΔM_{31}^2 and ΔM_{32}^2 are much larger than ΔM_{21}^2 , at short baselines oscillations are dominated by the corresponding oscillations

In this talk we will be interested in the conversion of ν_μ to ν_e .

The shortest baseline at which the maximal conversion occurs, for energy E neutrinos is

$$L = \frac{2\pi E}{|\Delta M_{31}^2|} \sim \frac{2\pi E}{|\Delta M_{32}^2|}$$

The off-axis beams used at T2K and NO ν A (and in the past MINOS and future MOMENT (Daya Bay III) and T2HK) have energies peaked at this first maximum.

Mixing Angles Relevant for T2(H)K

To leading order in $\alpha = \frac{\Delta M_{21}^2}{|\Delta M_{31}^2|} \sim 0.032$ the probability of conversion in a vacuum, at the first oscillation maximum, is

$$P_{\nu_\mu \rightarrow \nu_e} = \sin^2(2\theta_{13})\sin^2(\theta_{23}) - \frac{\pi}{2}\alpha \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23})\cos(\theta_{13}) \sin(\delta)$$

Therefore, to extract δ from $\nu_\mu \rightarrow \nu_e$ oscillations, it is essential to measure the constant term :

$$\sin^2(2\theta_{13})\sin^2(\theta_{23})$$

Even then, at the oscillation maximum one only learns $\sin(\delta)$ and so cannot distinguish δ from $\pi - \delta$.

Mixing parameter values

So what is $\sin^2(2\theta_{13})\sin^2(\theta_{23})$?

The angle $\sin^2(2\theta_{13})$ has been measured using km baseline reactor neutrino experiments and also long-baseline accelerator experiments, both around the first oscillation maximum.

Daya Bay has found $\sin^2(2\theta_{13}) = 0.084 \pm 0.005$.

ν_μ disappearance experiments measure (approximating $\theta_{13} = 0$) $\sin(2\theta_{23}) \sim 1$ but to separate δ from the constant term in $P_{\nu_\mu \rightarrow \nu_e}$ we need $\sin(\theta_{23})$. Unfortunately:

$$\frac{\partial \sin(2\theta_{23})}{\partial \sin(\theta_{23})} = 2 \frac{\partial \left(\sin(\theta_{23}) \sqrt{1 - \sin^2(\theta_{23})} \right)}{\partial \sin(\theta_{23})} = \frac{2 - 4\sin^2(\theta_{23})}{\cos(\theta_{23})} \sim 0$$

So the measured $\sin(2\theta_{23})$ (ν_μ disappearance) is not very sensitive to $\sin(\theta_{23})$ (ν_e appearance).

Neutrino Oscillation Probability

As a result, ν_μ disappearance at T2K yields (Abe et al., 2014)

$$\sin^2(\theta_{23}) = 0.51 \pm 0.06$$

Putting everything together, at the first oscillation maximum

$$P_{\nu_\mu \rightarrow \nu_e} \sim (0.043 \pm 0.006) - (0.013) \sin(\delta)$$

The uncertainty on the constant term is nearly half as large as the δ -dependent signal, so δ cannot be determined.

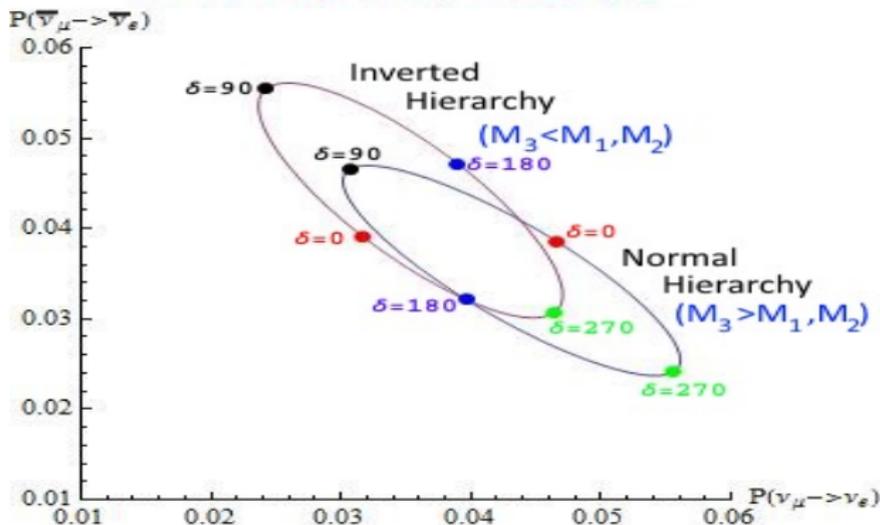
The solution of course is to also run the accelerator in $\bar{\nu}$ mode, as

$$P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e} \sim (0.043 \pm 0.006) + (0.013) \sin(\delta)$$

Therefore the **difference** between ν and $\bar{\nu}$ appearance yields $\sin(\delta)$ and the sum yields $\sin^2(2\theta_{13})\sin^2(\theta_{23})$.

Minakata-Nunokawa Diagram: T2K

T2K: 295 km, 600 MeV



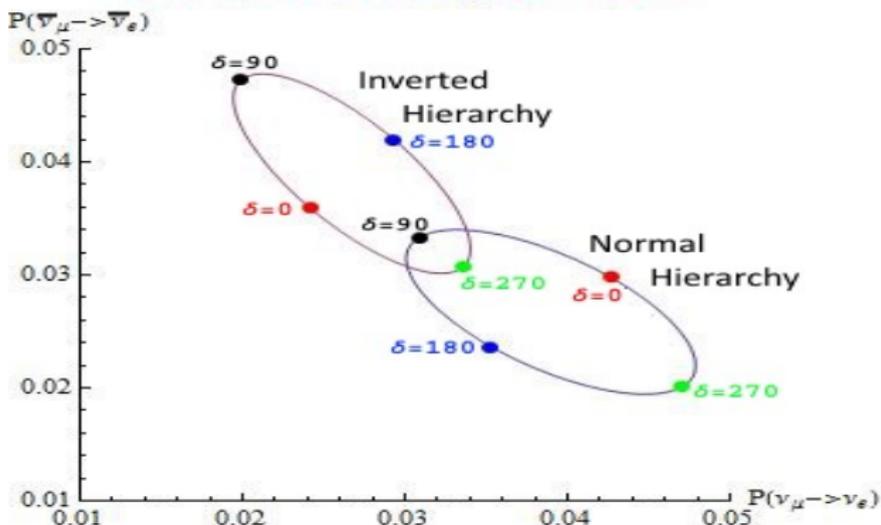
Above are the corresponding appearance probabilities for T2K

$\delta = 0^\circ, 90^\circ, 180^\circ, 270^\circ$

Coherent scattering in the Earth separate the upper and lower ellipses, corresponding to the inverted and normal hierarchies.

Minakata-Nunokawa Diagram: $\text{NO}\nu\text{A}$

$\text{NO}\nu\text{A}$: 820 km, 2.3 GeV



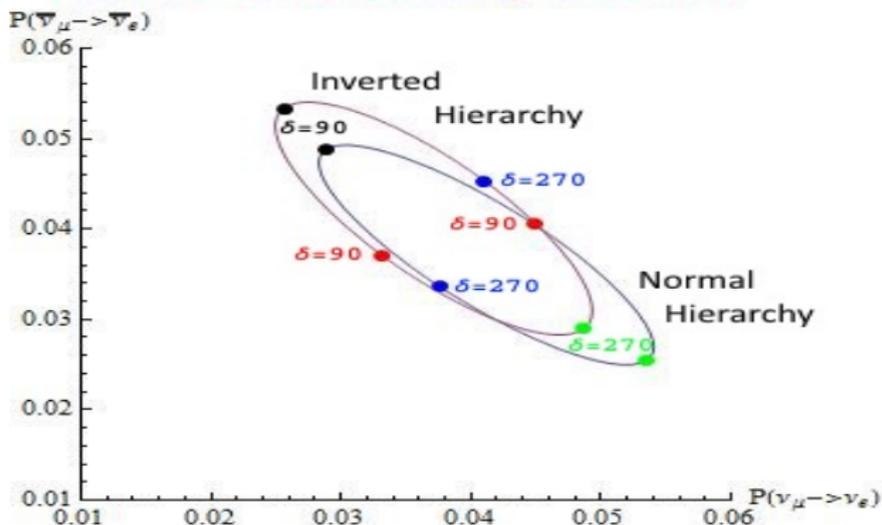
$\delta = 0^\circ, 90^\circ, 180^\circ, 270^\circ$

At $\text{NO}\nu\text{A}$ a larger matter effect separates the ellipses

So for some values of δ , there is no degeneracy

Minakata-Nunokawa Diagram: MOMENT

MOMENT: 150 km, 300 MeV



$$\delta = 0^\circ, 90^\circ, 180^\circ, 270^\circ$$

At MOMENT the matter effect will be small

Limitations of a Long-Baseline Accelerator Approach

This off-axis, accelerator approach, comparing ν_e and $\bar{\nu}_e$ appearance at the oscillation maximum, has two disadvantages:

- 1) High energy proton accelerators produce ν more efficiently than $\bar{\nu}$.

This is because they use ν_μ from $\pi^+ \rightarrow \mu^+ + \nu_\mu$

As a result the $\bar{\nu}$ mode occupies most of the beam time and still dominates the uncertainty

- 2) Even with a perfect measurement, only $\sin(\delta)$ is determined: Can't distinguish δ from $\pi - \delta$. (importance stressed in Titov's talk)

Note: You could get antineutrinos from $\pi^+ \rightarrow \mu^+ + \nu_\mu$ followed by $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ in a decay tunnel

This is the strategy of IHEP's MOMENT experiment

μ^+ Decay at Rest

Solution: Measure $\bar{\nu}$ oscillations using μ^+ decay at rest (DAR)

How does it work?

- 1) A high intensity 400 MeV-2 GeV proton beam hits a fixed target
- 2) The target produces pions which stop.
The π^- are absorbed in the target while the π^+ decay at rest
$$\pi^+ \rightarrow \mu^+ + \nu_\mu.$$
- 3) The μ^+ then stop and also decay at rest
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu.$$
- 4) The $\bar{\nu}_\mu$ travel isotropically in all directions, oscillating as they go
- 5) A detector measures the $\bar{\nu}_e$ arising from the oscillations $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

Muon Decay at Rest Neutrinos

The spectrum of μ DAR neutrinos leads to many advantages

- 1) The spectrum is known extremely well, it is the Michel spectrum
- 2) 30-50 MeV $\bar{\nu}_e$ interact via inverse β decay, whose cross section is known very precisely
- 3) The resulting $\bar{\nu}$ energies are 30-50 MeV, higher energies than reactor, spallation or geoneutrino backgrounds but low enough so that atmospheric neutrino backgrounds are small
- 4) As these are $\bar{\nu}_e$ and not ν_e , their capture by IBD yields a neutron. The subsequent neutron capture provides a double coincidence which strongly reduces the backgrounds
- 5) The spectrum is broad enough so that its shape breaks the $\delta \rightarrow \pi - \delta$ degeneracy

Problem Solved?

Combining $\nu_\mu \rightarrow \nu_e$ oscillations from a long-baseline experiment with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations from μ^+ DAR solves the two problems described above:

- 1) The high energy accelerator, for example, triples its time in ν mode, so the statistical uncertainty on $\nu_\mu \rightarrow \nu_e$ oscillations drops by $\sqrt{3}$.

If the μ^+ source is sufficiently high intensity, the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, whose statistical fluctuations dominated the error budget, now are far more plentiful

- 2) The DAR $\bar{\nu}_e$ are not only at the oscillation maximum, so the shape of the observed spectrum breaks the $\delta \rightarrow \pi - \delta$ degeneracy.

These $\bar{\nu}_e$ are detected via inverse β decay (IBD) and so the observed e^+ energy is easily related to the $\bar{\nu}_e$ energy, allowing a reliable determination of the shape

The DAE δ ALUS Project

The first proposal along these lines was the DAE δ ALUS project.

They plan to create μ^+ at 3 high intensity cyclotron complexes, located 1.5, 8 and 20 km from a detector.

The multiple baselines are useful to break various degeneracies between the height and shape of the observed spectrum and the mixing angles, although the relative intensities of the accelerators is a source of uncertainty

But DAE δ ALUS is expensive and technologically challenging for one reason:

Why DAE δ ALUS is Hard

At the low energies of IBD, the direction of the measured e^+ is virtually independent of that of the incoming $\bar{\nu}_e$

So DAE δ ALUS can't tell which $\bar{\nu}_e$ came from which accelerator

As a result, no two accelerator complexes can run at the same time

To also measure the background, DAE δ ALUS has chosen to run each accelerator with a 20% duty factor

Therefore the instantaneous current of each beam needs to be 5 times higher: 30-50 mA!

This can be compared with the current state of the art 2.2 mA accelerator at the Paul Scherrer Institute

To increase the current they have suggested accelerating H_2^+

Two detectors

Our idea: A single μ^+ source for the DAR and *two* large detectors, at sufficiently different baselines to maximize their synergy.

By having two baselines instead of three, potentially we will have larger systematic errors than DAE δ ALUS.

So we suggest that Daya Bay detectors at 50-100 meters be used to determine the flux normalization (and test the LSND anomaly)

Summary:

DAE δ ALUS has 3 μ^+ sources and 1 large detector.

We have 1 μ^+ source and 2 large detectors.

Note: We will see below that even with *one* detector we obtain a reasonably precise determination of δ

Advantages of Having 2 Detectors and 1 μ^+ Source

Advantages:

- 1) **The accelerator can run with essentially a 100% duty factor.**

Some dead time can be useful to measure backgrounds, but we find that the backgrounds are quite subdominant and so this can be much less than the 40% at DAE δ ALUS.

- 2) **As the duty factor is five times higher, the necessary instantaneous intensity to achieve the same signal is five times lower.**

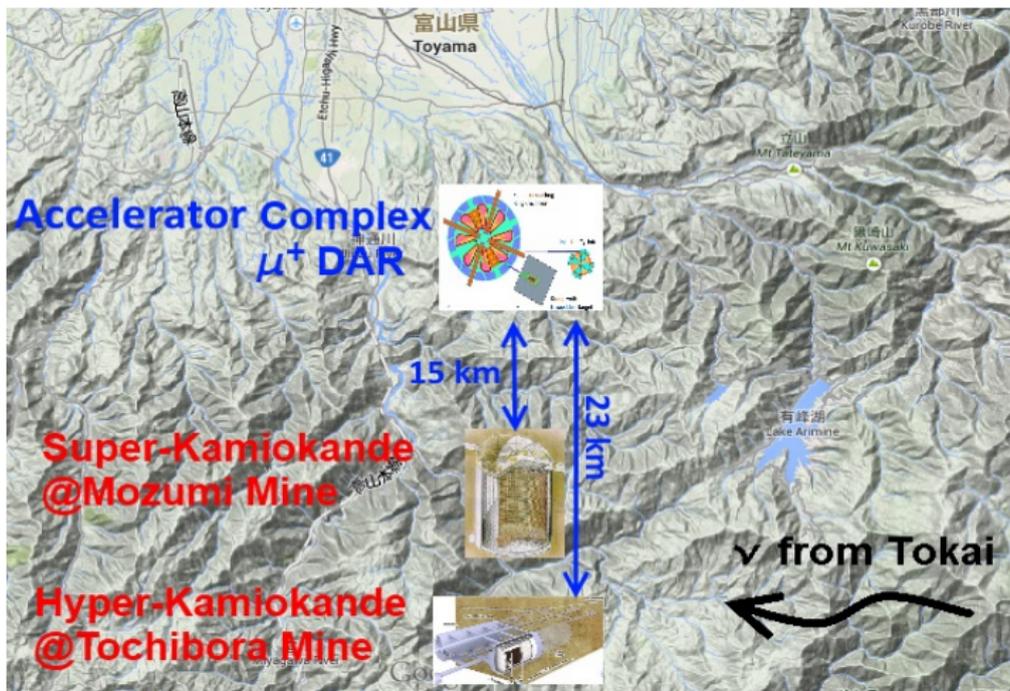
In JHEP 1412 (2014) 051, we find that a 7 MW beam yields a good determination of δ (see more below)

- 3) **Can be cheaper: Only one accelerator complex is needed instead of three and it will have a five times lower instantaneous intensity**
ADS will be constructed anyway, so it is free: **These are reactor $\bar{\nu}_\mu$!**

Our proposals:

- 1) A high intensity proton beam ($400 \text{ MeV} < E < 2 \text{ GeV}$) strikes a target, creating pions
- 2) The pions stop. π^- are absorbed. π^+ decay to $\mu^+ + \nu_\mu$.
- 3) The μ^+ stop and decay at rest to $\bar{\nu}_\mu + e^+ + \nu_e$
- 4) The $\bar{\nu}_\mu$ oscillate to $\bar{\nu}_e$
- 5) At μ DARTS (TNT2K): $\bar{\nu}_e$ interact via inverse β decay in 2 large liquid scintillator (water Cherenkov) detectors at 2-30 km
- 6) ν flux normalization determined by elastic $\nu - e$ scattering in Daya Bay detectors at 50-100 m

TNT2K map



If Hyper-K is built at the **Tochibora mine**: A more precise determination of δ can be made in Japan with **Tokai 'N Toyama to Kamioka (TNT2K)**

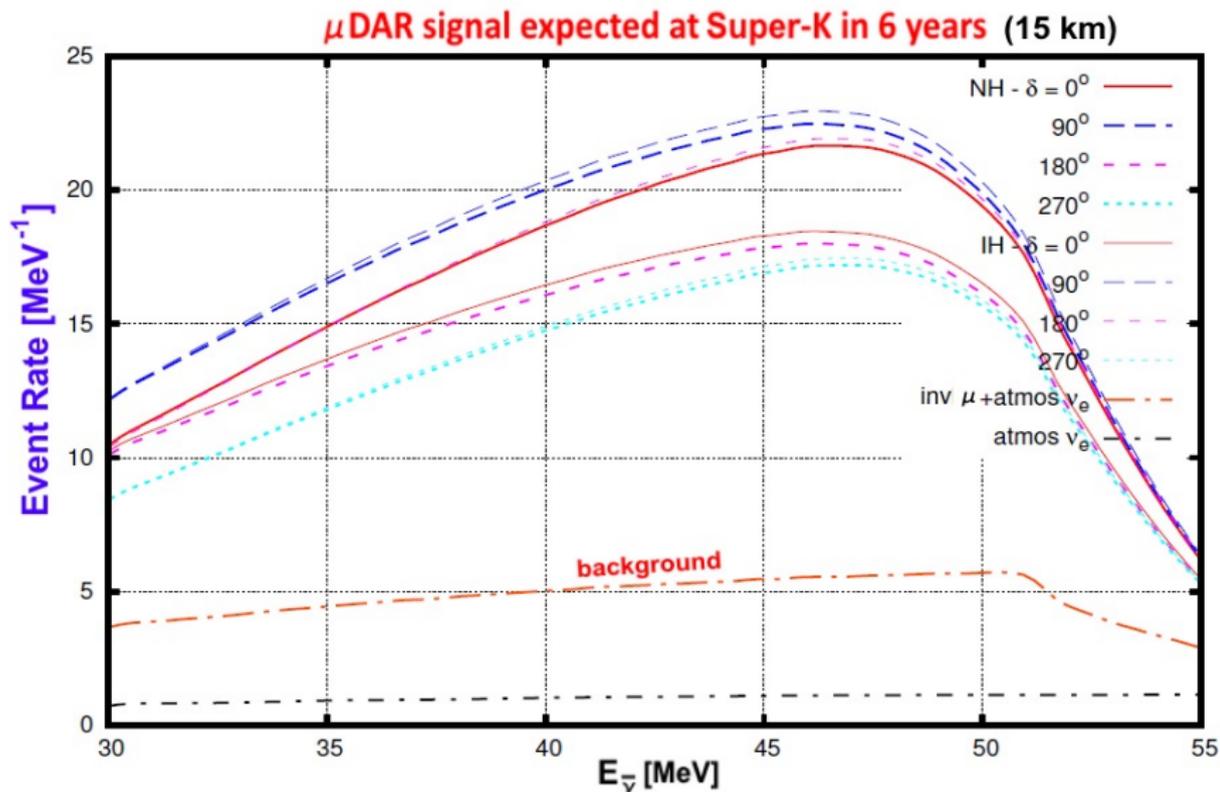
What is TNT2K?

TNT2K consists of the following components:

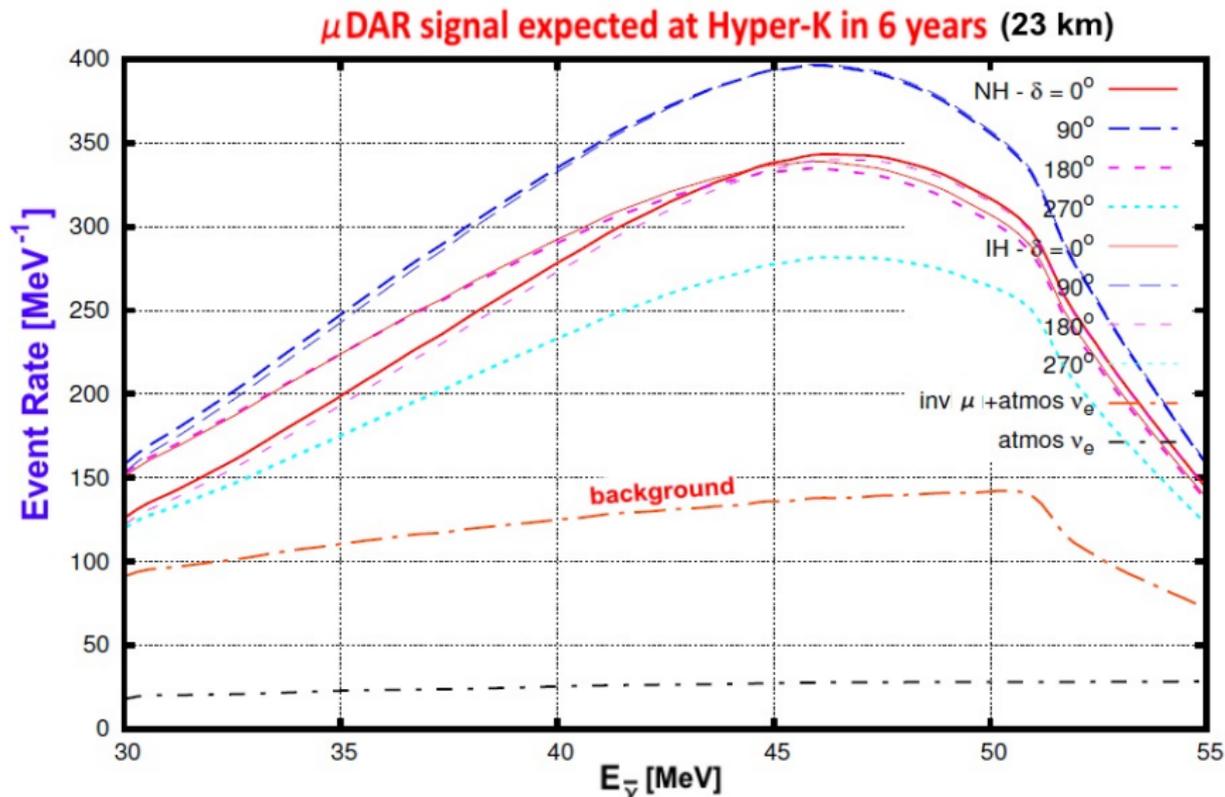
- 1) Just south of Toyama, a 9 mA, 800 MeV proton beam striking a stationary target provides a μ^+ DAR source
- 2) The $\bar{\nu}_\mu$ from μ^+ DAR oscillate to $\bar{\nu}_e$ as they travel 15 km to Super-K and, if built, 23 km to Hyper-K, where they are detected via IBD
- 3) T2K runs for 12 years and T2HK for 6 years using a 750 kW, 30 GeV proton beam at J-PARC *in ν mode*

If Hyper-K is built at the Mozumi mine instead of the Tochibora mine, both Hyper-K and Super-K will be at the same baseline from the μ^+ source and so will not enjoy the same degeneracy-breaking synergy as at the Tochibora site \Rightarrow **less sensitivity to δ**

Expected μ^+ DAR Signal at TNT2K: Super-K

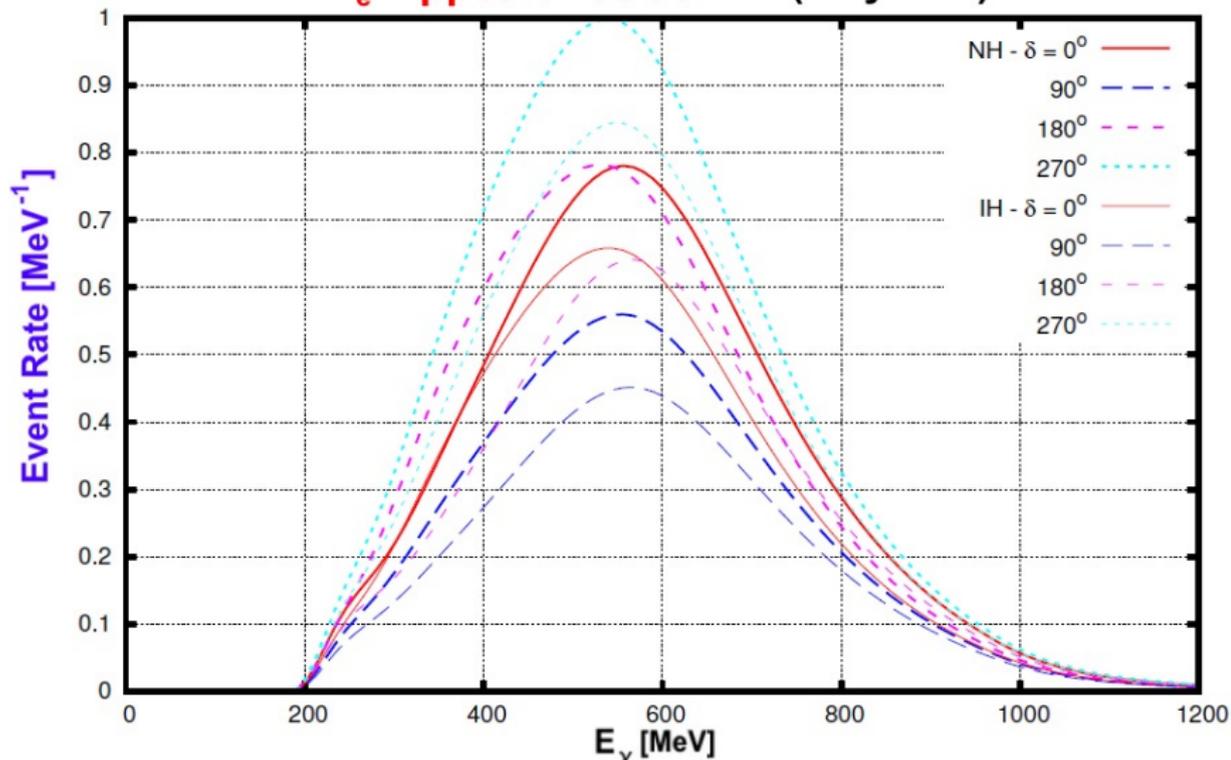


Expected μ^+ DAR Signal at TNT2K: Hyper-K

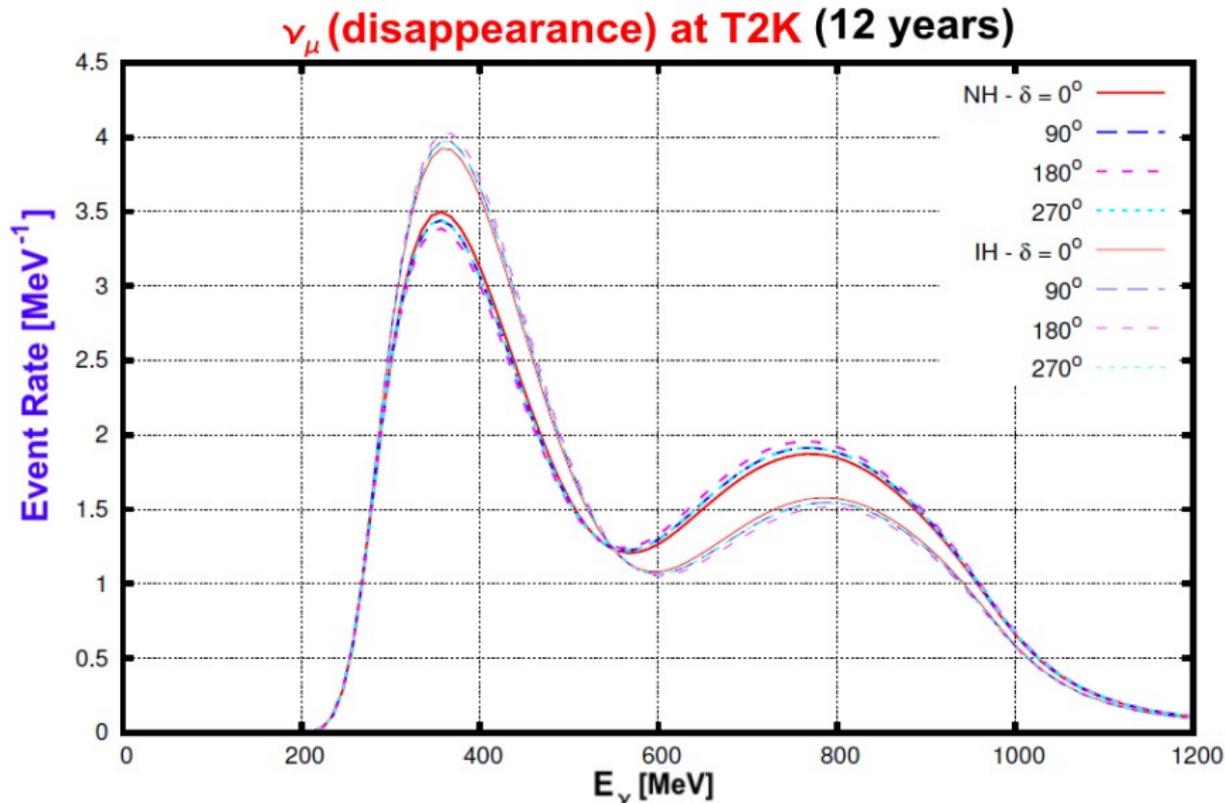


Expected ν_e Appearance Signal at TNT2K: T2K

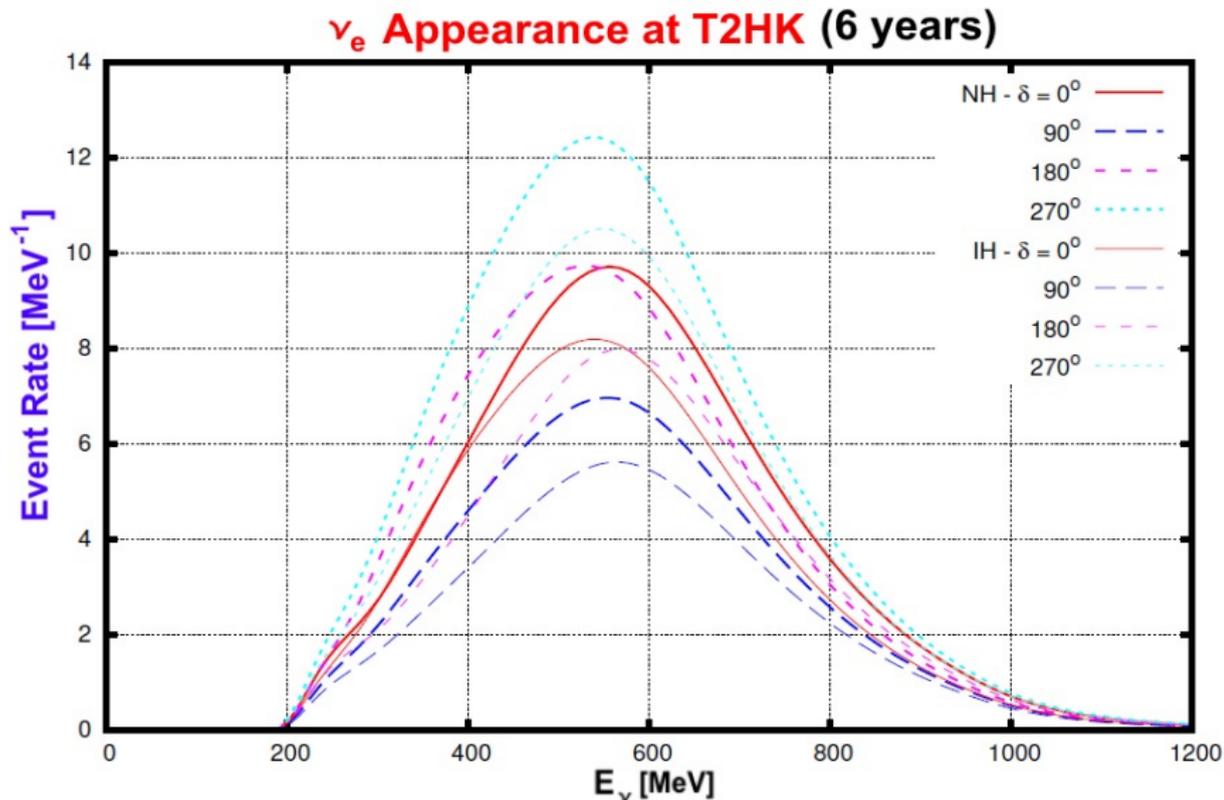
ν_e Appearance at T2K (12 years)



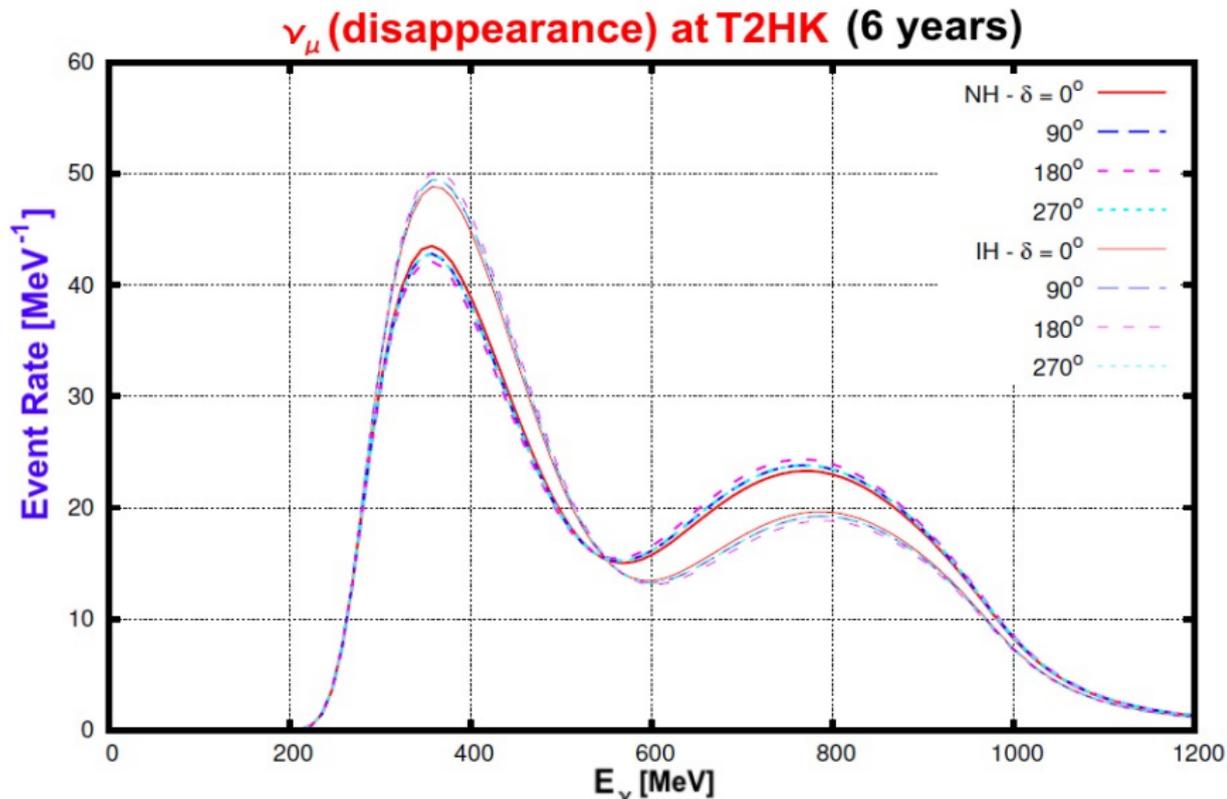
Expected ν_μ Disappearance Signal at TNT2K: T2K



Expected ν_e Appearance Signal at TNT2K: T2HK



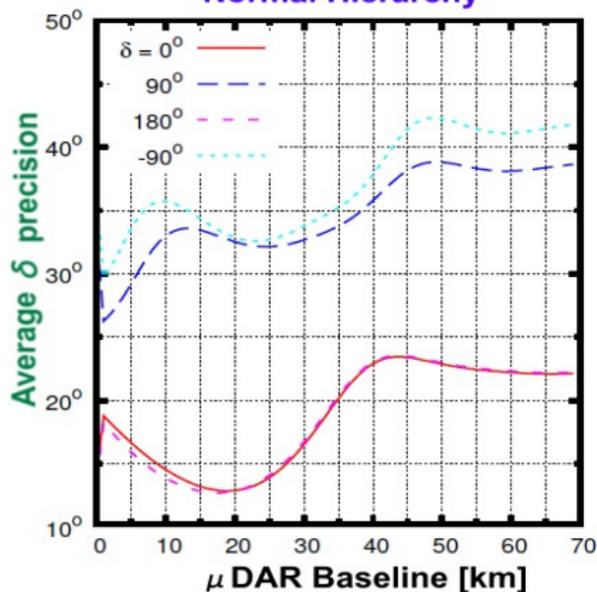
Expected ν_μ Disappearance Signal at TNT2K: T2HK



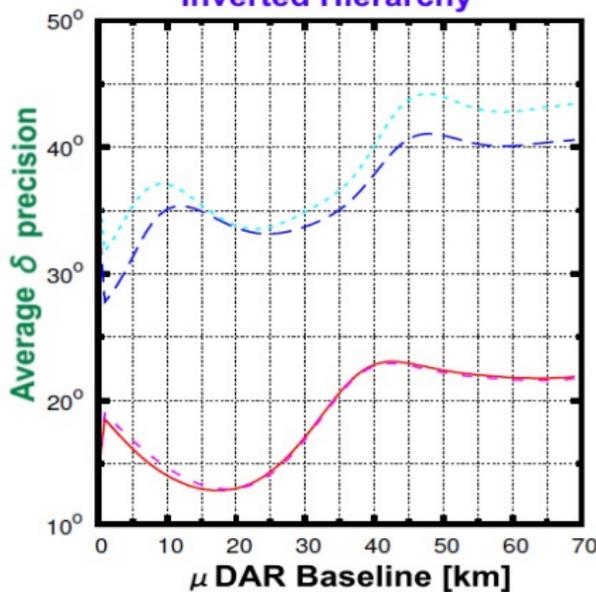
Precision of δ Measurement at TNT2K: SK Only

T2K (12 years ν mode) and 6 years μ DAR

Normal Hierarchy



Inverted Hierarchy



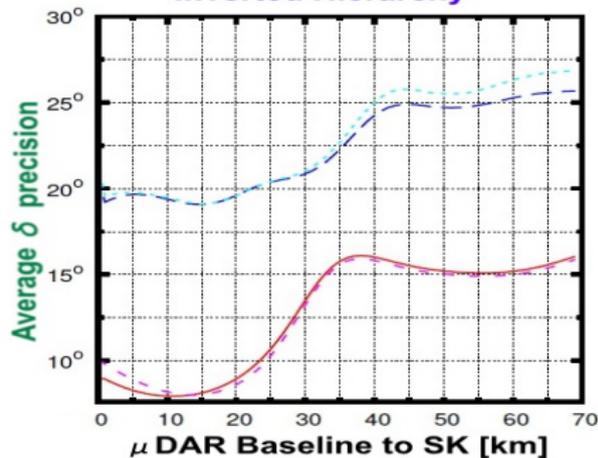
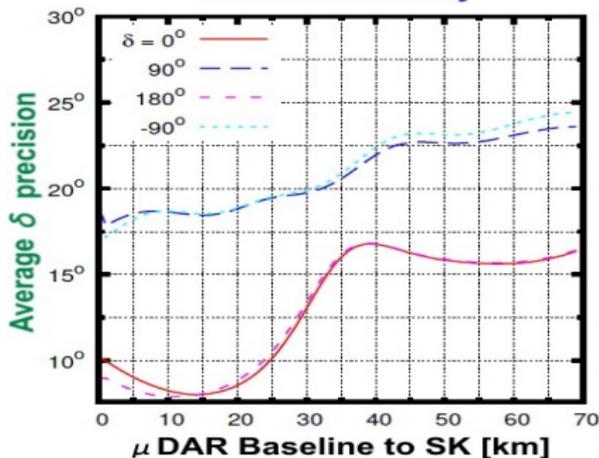
Without Hyper-K: Optimal baseline is 15-20 km

and δ can be measured with a precision of $12^\circ - 35^\circ$



Precision of δ Measurement at TNT2K: SK and HK/5

T2K (12 years) + T2HK/5 (6 years) + 6 years μ DAR (SK+HK/5)
Normal Hierarchy Inverted Hierarchy

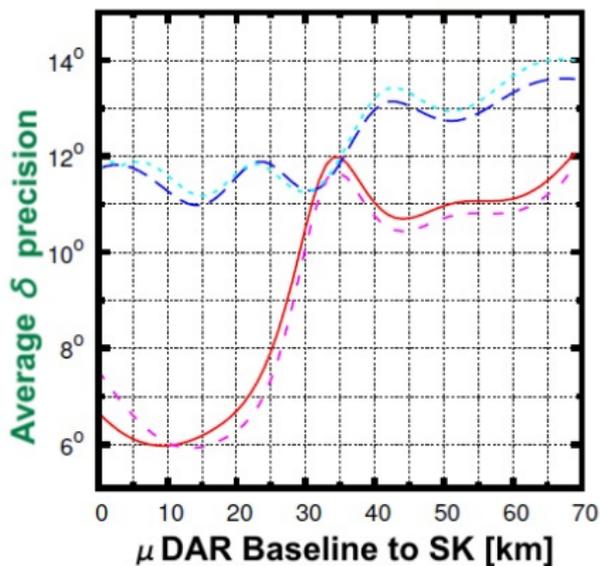
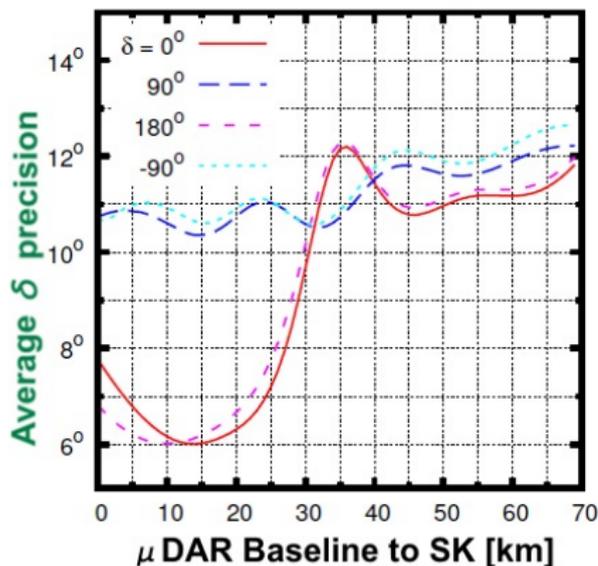


With 1/5 of HK: Best baseline to SK (HK/5) is 13-15 (21-23) km
and δ can be measured with a precision of 8° – 18°

Compare: Full HK, 6 years of T2HK (4.5 ν , 1.5 $\bar{\nu}$) yields 9° – 24°

Precision of δ Measurement at TNT2K: SK and HK

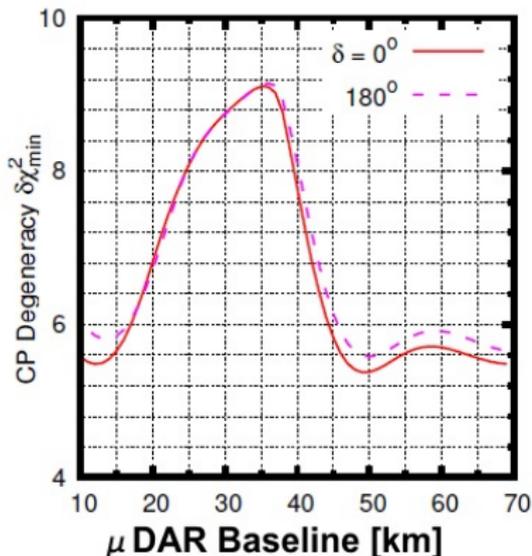
T2K (12 years) + T2HK (6 years) + 6 years μ DAR (SK+HK)
Normal Hierarchy Inverted Hierarchy



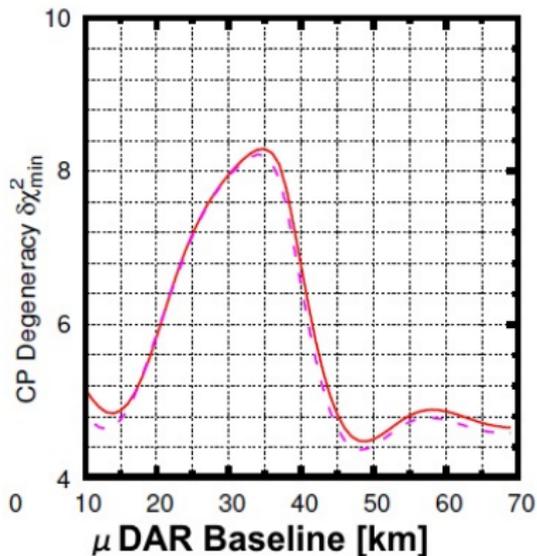
With full HK: Best baseline to SK (HK) is 13-15 (21-23) km
and δ can be measured with a precision of $6^\circ - 11^\circ$

T2K (12 years ν mode) and 6 years μ DAR

Normal Hierarchy



Inverted Hierarchy



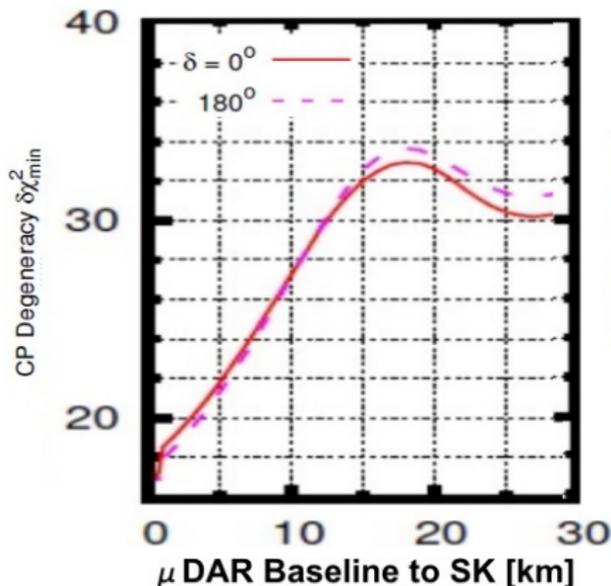
Without HK, 15 km from SK:

Break $\delta \rightarrow \pi - \delta$ degeneracy at $2 - 2.5\sigma$

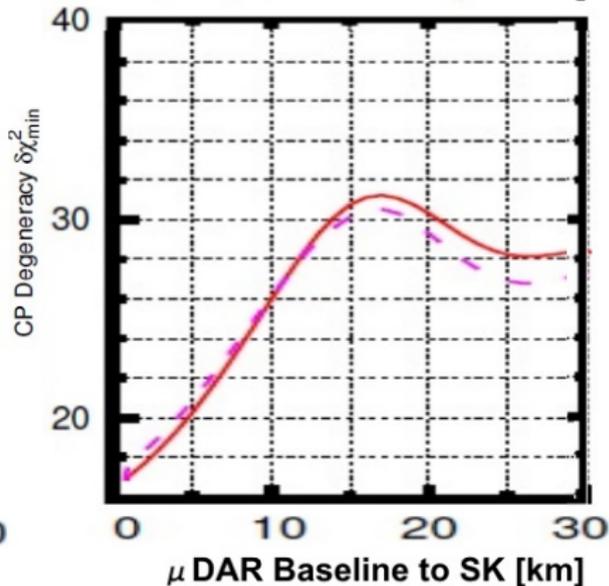
Distinguish δ and $\pi - \delta$ at TNT2K: SK and HK/5

T2K (12 years) + T2HK/5 (6 years) + 6 years μ DAR (SK+HK/5)

Normal Hierarchy



Inverted Hierarchy



With 1/5 size HK, 15 km from SK and 23 km from HK/5:

Break $\delta \rightarrow \pi - \delta$ degeneracy at $5.5 - 6\sigma$

Atmospheric Neutrino IBD Background

In our signal range, 30 to 53 MeV, the unoscillated atmospheric $\bar{\nu}$ rate will be about 105 $\bar{\nu}_e$ and 230 $\bar{\nu}_\mu$ per $\text{m}^2\text{sr sec}$ with an uncertainty of about 30%

Weighting by the average oscillation probability and integrating over solid angles yields $1.4 \times 10^3 \bar{\nu}_e/\text{m}^2\text{sec}$.

Each kton of detector contains 7×10^{31} free protons (110 tons) with an average IBD cross section of $2 \times 10^{-44}\text{m}^2$.

6 years at Super-K: 8 IBD events (signal of about 350 events)

6 years at Hyper-K: 200 IBD events (signal of about 5000 events)

So the IBD background should be subtracted, but it has little effect on the measurement of δ .

Even if CC QE atmospheric ν_e contribute a comparable number of background events, the total will still be very small.

Invisible Muon Background

The largest background for μ^+ DAR in a water Cherenkov detector comes from *invisible muons*:

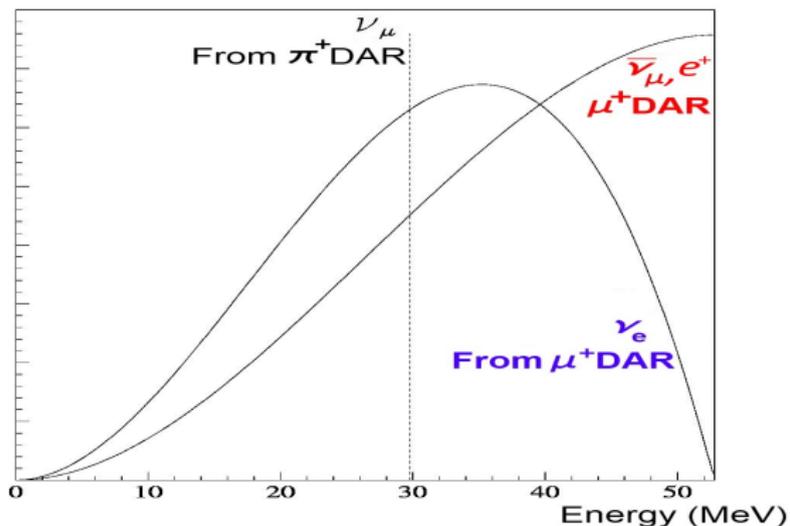
These are muons with kinetic energies below the Cherenkov threshold in water (52 MeV), and so invisible to the detector, mostly created from atmospheric ν_μ and $\bar{\nu}_\mu$ via CC interactions with oxygen in the water.

The muon decays at rest producing electrons or positrons with a Michel spectrum, whose Cherenkov cones provide the background.

The invisible muon background can be measured during the accelerator's down time and subtracted.

To some extent a shape analysis can separate the backgrounds, but the shapes are similar (see the next slide)

π and μ DAR spectra



Energy spectra of π^+ and μ^+ DAR products.

The DAR signal is the $\bar{\nu}_\mu$ spectrum and the invisible muon background will have a reconstructed energy equal to the e^+ spectrum plus 1.3 MeV.

Δ Resonance Component of the Invisible μ Background

We have studied the invisible muon background by folding the results of GENIE simulations of CC ($\nu_\mu + \text{nucleon} \rightarrow \mu + X$) events into the atmospheric ν_μ and $\bar{\nu}_\mu$ spectra.

One half of the events with invisible μ are Δ -resonance events:

Essentially all of these events produce π .

As the ν cross section with nucleons is much larger than the $\bar{\nu}$ cross section, nearly all of these events produce π^+ or π^0 .

The π^+ nearly all stop and decay at rest, producing *another* invisible μ^+ which decay at rest producing an e^+ which yields a *second* Cherenkov cone, which can be used to veto these events

The π^0 decay immediately to 2 γ , these can be vetoed

For those few events with a π^- , it will generally be absorbed by oxygen, liberating ≥ 2 nucleons. If precisely one of these nucleons is a neutron and no γ is emitted at any point, this event cannot be vetoed. **This is quite rare.**

Invisible μ Background Estimates

Super-K's best fit of its diffuse supernova ν search (Bays, 2011) finds 150 invisible μ events in 2853 days (36-56 MeV)

Scaling to six years:

Super-K Inv μ Background: 115 events (signal \sim 350 events)

Hyper-K Inv μ Background: 2875 events (signal \sim 5000 events)

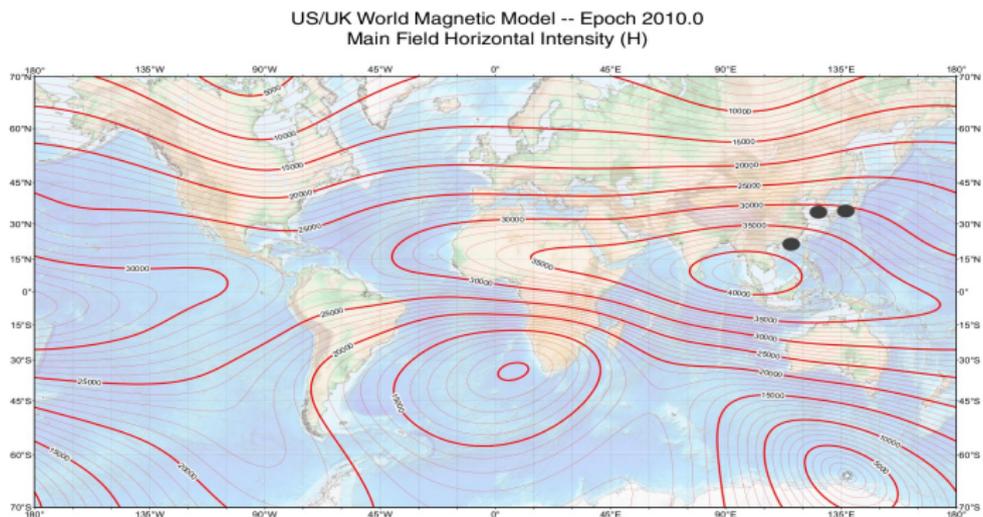
Vetoing all events with an extra final state γ , as suggested by GADZOOKS! eliminates another 30%

We do not include further vetoes in the analysis above, however:

Requiring one neutron capture on H (or Gd if present) we can remove all events without precisely one final state neutron, our simulation indicates that this eliminates 40% of events

About half of those remaining are Δ resonance events, which can be vetoed.

Horizontal Geomagnetic Field Map



A strong horizontal geomagnetic field deflects low energy cosmic rays, reducing the low energy atmospheric ν flux.

C-ADS/JUNO (0.38 G), RENO 50/Kamioka mines (0.31 G) *vs* DUNE (0.17 G), LENA in the Pyhäsalmi mine (0.13 G)

⇒ Backgrounds will be reduced by about a factor of 2 at our proposed DAR sites as compared with other proposals

What is ADS?

An Accelerator Driven Subcritical system (ADS) nuclear reactor, of the kind being developed in China (C-ADS), consists of a 10 mA, 1.5 GeV proton beam which strikes a fixed target

The high Z fixed target serves as a neutron source to drive a nuclear reactor

It is hoped that the reactor will generate 100 MW of power and it can also be used to enrich spent nuclear fuel

The reactor cannot melt down, because the reaction stops when the accelerator is turned off

μ^+ DAR in the target creates just the $\bar{\nu}_\mu$ that we need

C-ADS will take a long time to develop, so in what follows we only use phase II, which uses a 8 MW beam

ADS Here in Europe?

Europe is also serious about the development of ADS:

MYRRHA included in European Commission investment plan for 1.5 billion euros

Date: 2015-01-09

The federal government has decided to allow the future MYRRHA research installation to be included in the list of Belgian projects for the new investment plan of the European Commission to the amount of 1.5 billion euros. In 2009, the investment was estimated as being 960 million euros as of 2009. This amount, updated in terms of euros as of 2014, approximates to 1.1 billion.

MYRRHA is an ADS research reactor

2017-2021: Construction

2025: 600 MeV, 4 mA beam at full power

Definition of μ DARTS

In our simulations we have considered a detector with the energy resolution of Daya Bay and a proton beam such that:

For a 10 year run and $\delta = 0$, there will be 650 $\bar{\nu}_e$ IBD events arising from μ^+ DAR at a 20 kton liquid scintillator detector 10 km from the accelerator source.

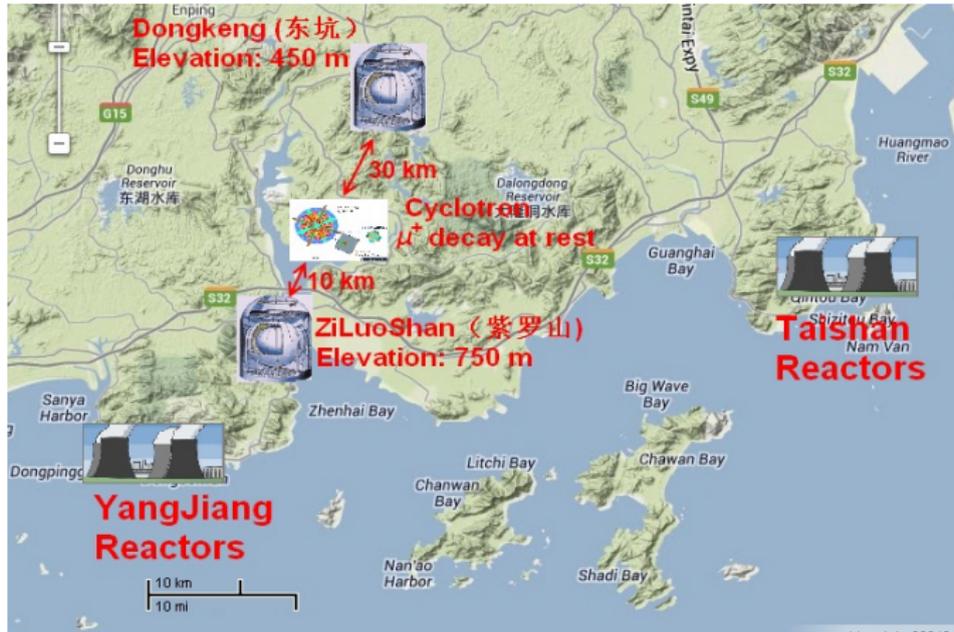
Scaling the results of LSND, this corresponds to:

- 1) A target which is 12% free protons per weight
- 2) A 10 mA, 800 MeV proton beam running with a 100% duty factor

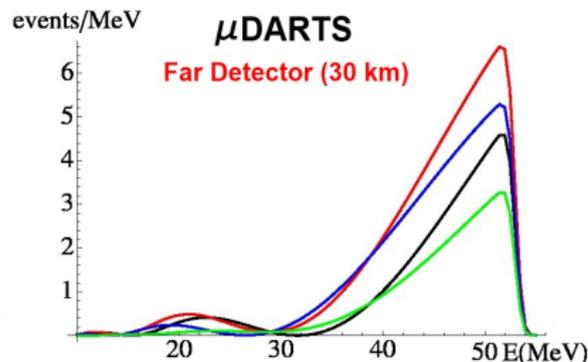
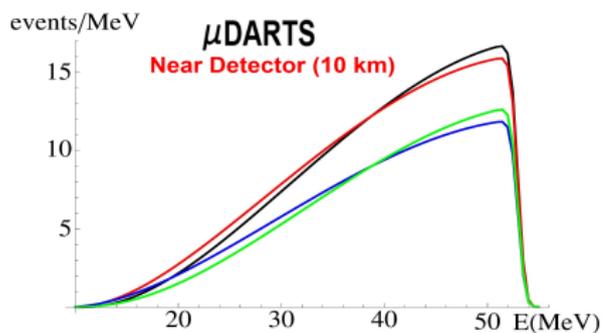
This roughly corresponds to phase II of C-ADS.

Summary: 2×10^{25} POT in 10 years, 100 times more than LSND.

One location for μ DARTS near JUNO



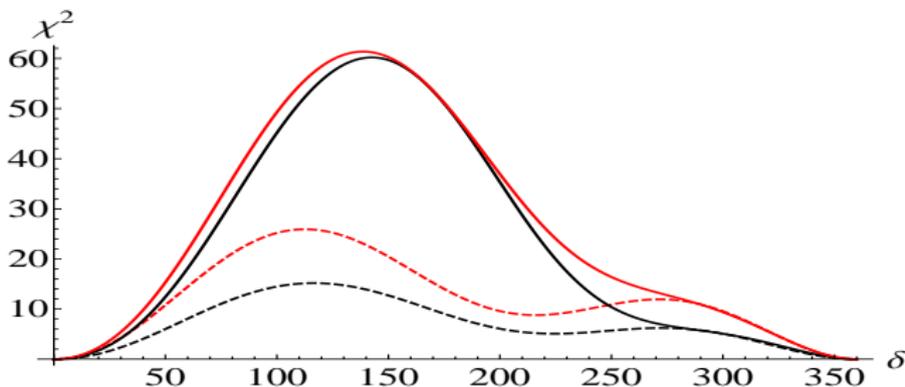
The best location for a second detector for JUNO is ZiLuoShan.
The distance between two detectors is compatible with optimal baselines for μ DARTS



The DAR expected signal in 10 years at μ DARTS for $\delta = 0^\circ$, 90° , 180° and 270° , normal hierarchy

μ DARTS uses a liquid scintillator, not a Cherenkov, detector and so the dominant invisible μ background is absent

No Degeneracies at μ DARTS

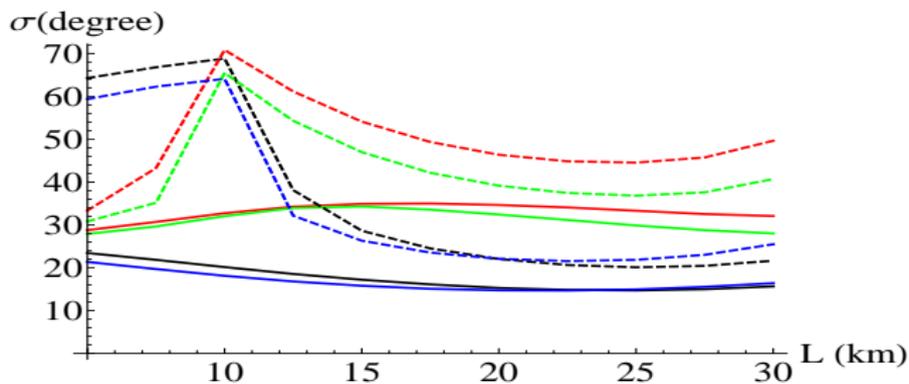


χ^2 fit of various values of δ to the expected signal if $\delta = 0$
with(out) $\text{NO}\nu\text{A}$ in red (black)

Solid curves include a near detector at 2.5 km, all curves include a
far detector at 25 km

With two detectors $\delta = 0^\circ$ and 180° can be cleanly distinguished

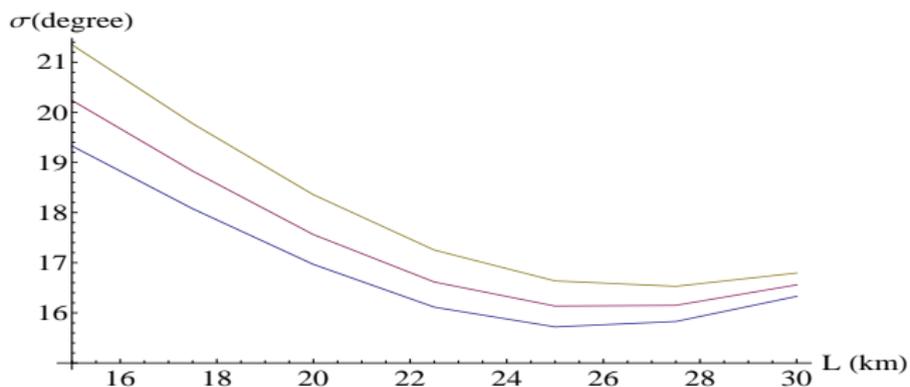
Measuring δ with μ DARTS and only 1 detector



1σ precision with which δ can be determined by μ DARTS in 10 years with a single detector for $\delta = 0^\circ$, 90° , 180° , 270°

Solid curves include the appearance channel at $\text{NO}\nu\text{A}$

μ DARTS with 2 detectors



δ -averaged 1σ precision with which δ can be determined by μ DARTS in 10 years with a single detector at baseline L and a near detector at 2.5 km, 5 km and 7.5 km (from bottom to top).

All curves include appearance at $\text{NO}\nu\text{A}$

Conclusions

- 1) Combine J-PARC $\nu_\mu \rightarrow \nu_e$ with μ DAR $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ at SK (+HK/5):
measure δ with a precision of $12^\circ - 35^\circ$ ($8^\circ - 18^\circ$) in 6 years,
and distinguish $\delta = 0$ and 180 at $2 - 2.5\sigma$ ($5.5 - 6\sigma$)
- 2) The optimal location for the accelerator is 15 km north of Mozumi mine (Super-K), 23 km north of Tochibora mine (Hyper-K)
- 3) Alternately, a δ -averaged precision of 16° is attainable in 10 years with 2 liquid scintillator detectors in China or Korea
- 4) Phase II of the Accelerator Driven Subcritical (C-ADS) reactor would provide the required $\bar{\nu}_\mu$ while a working ADS reactor would provide twice this flux

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What proton energies are acceptable?

A proton beam energy $\gtrsim 400$ MeV is necessary to have sufficient $\bar{\nu}$.

At least 600 MeV would be optimal.

$\bar{\nu}$ yield at fixed beam power for various proton beam energies:

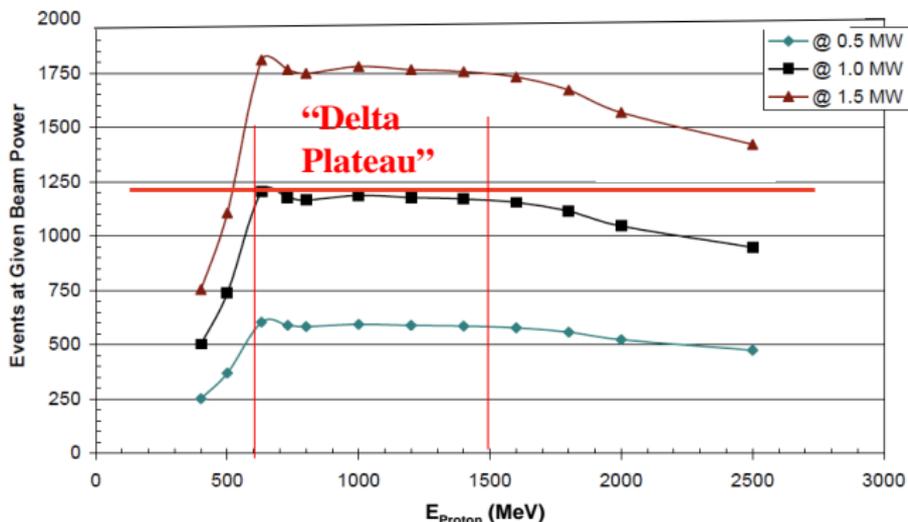


Figure: From DAE δ ALUS Expression of Interest [arXiv:1006.0260](https://arxiv.org/abs/1006.0260)

LSND Anomaly

Z-decay at LEP has shown that 3 generations of neutrinos are charged under electroweak symmetry.

Their mass splittings are:

$$\Delta M_{21}^2 = 7.5 \times 10^{-5} \text{ eV}^2, \quad |\Delta M_{31}^2| \sim |\Delta M_{32}^2| = 2.4 \times 10^{-3} \text{ eV}^2.$$

The corresponding oscillations occur at baselines of

$$L_{12} \sim \frac{2\pi E}{|\Delta M_{21}^2|} \sim 17 \frac{E}{\text{MeV}} \text{ km}, \quad L_{13} \sim L_{23} \sim \frac{2\pi E}{|\Delta M_{31}^2|} \sim 0.5 \frac{E}{\text{MeV}} \text{ km}$$

Therefore for μ DAR neutrinos, which have energies of 30-50 MeV, one expects oscillations to first peak around 20 km.

LSND Anomaly:

LSND detected, at 4σ , $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ conversion at just 30 meters

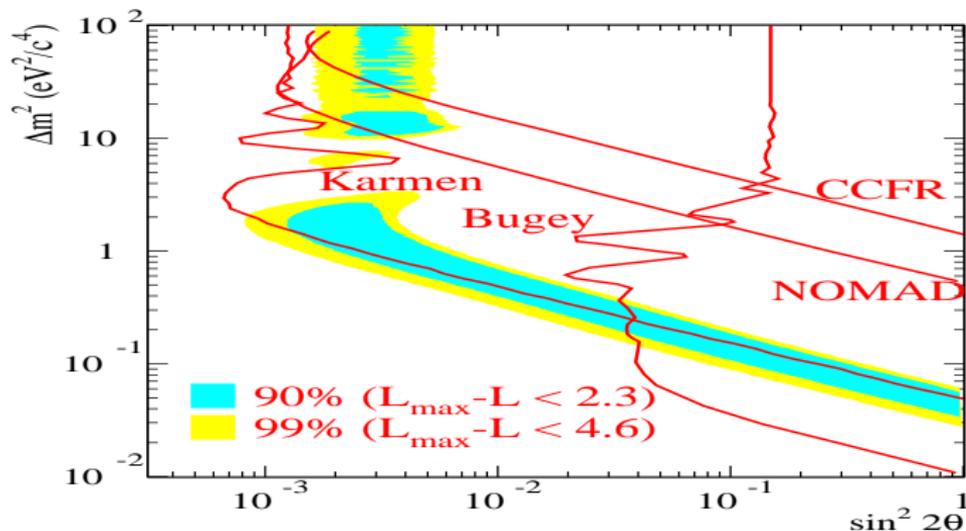
The MiniBooNE experiment also observed anomalous appearance with 1 GeV ν and $\bar{\nu}$ at a similar E/L

LSND Anomaly and Sterile Neutrinos

A fourth, sterile neutrino has been proposed to explain the data

The blue and yellow regions below fit the data, while areas right of the red curves are ruled out by other experiments

$(\Delta m^2, \sin^2(2\theta))$ extends from $(1 \text{ eV}^2, 3 \times 10^{-3})$ to $(0.2 \text{ eV}^2, 3 \times 10^{-2})$



Sterile neutrinos with μ DARTS

	μ DARTS	LSND
proton energy	800 MeV	798 MeV
proton current	10 mA (C-ADS)	1 mA (LANSCÉ)
runtime	6 years	17 months
protons on target	2×10^6 C	3×10^4 C
detector	liq. scintillator	liq. scintillator
target mass	$N \times 20$ ton	167 ton
baseline	50-100 meters	30 meters

To determine the unoscillated flux, μ DARTS can use N old Daya Bay detectors at 50-100 meters, detecting $\bar{\nu}$ via elastic scattering.

If the LSND anomaly is a real effect, *each* Daya Bay detector will observe more ν via IBD than LSND.

Distance dependence \rightarrow whether the anomaly is due to sterile ν

Longer baseline \rightarrow sensitivity to $3 \times$ lighter sterile ν

Sterile neutrinos with IsoDAR

Like C-ADS, the DAE δ ALUS project envisages staged progress to a GeV energy, high intensity accelerator.

The first phase is called IsoDAR.

- 1) A 60 MeV/amu, 600 KW H_2^+ beam strikes a ^9Be target, releasing neutrons
- 2) The neutrons enter a ^7Li sleeve and are captured, creating ^8Li
- 3) The ^8Li β decays, producing $\bar{\nu}_e$ with an average energy of 6 MeV and max energy of 13 MeV (cosmogenic backgrounds are large)
- 4) $\bar{\nu}_e$ detected by KamLAND or JUNO, 5 meters away

First measurement of θ_W using ν , so sensitive to some new physics

2.7×10^7 IBD events at JUNO $\rightarrow \bar{\nu}_e$ disappearance is sensitive to the LSND anomaly

Sterile neutrinos with CIADS

The θ_W measurement is very sensitive to cosmogenic backgrounds, so requires a depth of at least 700 meters

A depth of 700 meters would also be required to build the accelerator next to JUNO

However I suspect that a test of the LSND anomaly may be done using CIADS at a depth of less than 300 meters (maybe near the surface with a good muon veto), using old Daya Bay detectors

CIADS has the same nucleon current as IsoDAR but the beam energy is 4 times higher

If 4 times more $\nu \rightarrow$ for Daya Bay detectors at 5 meters about $2.8 \times 10^7 \times 4 \times (20/20000) \times (15/5)^2 \sim 10^6$ IBD events/detector

This means sensitivity to $\sin^2(2\theta) \sim 10^{-3}$, sufficient to test the LSND anomaly

Summary

In 7 years the Daya Bay experiment will be finished and will no longer need its 8, 20 ton liquid scintillator detectors.

An ADS with an energy $\gtrsim 400$ MeV will allow a first-ever measurement of the CP-violating phase δ , using 1 or 2 large scintillator detectors 5-30 km away

Near detectors borrowed from Daya Bay at 50-100 meters, besides providing real-time monitoring of the reactor, can test the LSND anomaly and be sensitive to sterile neutrinos with masses 3 times smaller than LSND

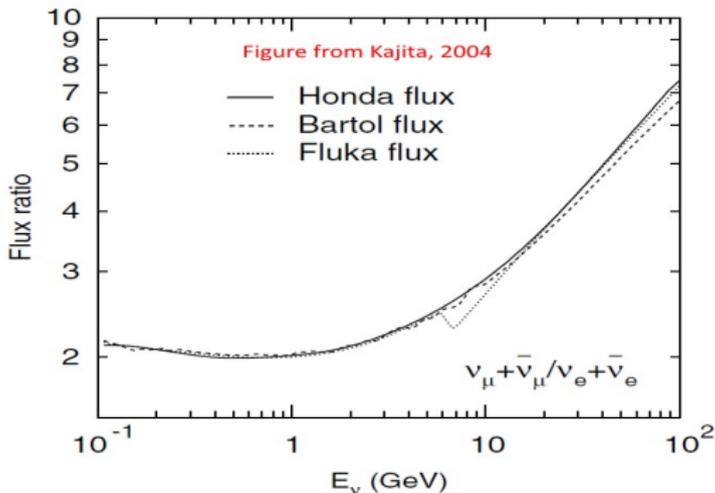
At a proton energy of 250 MeV, Daya Bay detectors at 5 meters may be sensitive to the LSND anomaly, but (due to backgrounds) the experiment may need to be 100-300 meters underground

Atmospheric Neutrinos

Low energy atmospheric ν largely come from the decay chain



π^+ created by a collision of a cosmic ray p with the atmosphere.



So, at low energies, there are twice as many μ as e neutrinos.

δ from Atmospheric Neutrinos

At low energies there are as many ν_μ and $\bar{\nu}_\mu$

The CP-dependent terms in $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ and $P(\nu_\mu \rightarrow \nu_e)$ are opposite and so cancel in $\nu_\mu + \bar{\nu}_\mu \rightarrow \nu_e + \bar{\nu}_e$

CPT invariance:

$$P(\nu_e \rightarrow \nu_\mu) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = (0.043 \pm 0.006) + 0.013 \sin(\delta)$$

Observed low energy atmospheric $\nu_e + \bar{\nu}_e$ excess

$$\Rightarrow P(\nu_e \rightarrow \nu_\mu) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) < P(\nu_\mu \rightarrow \nu_e)$$

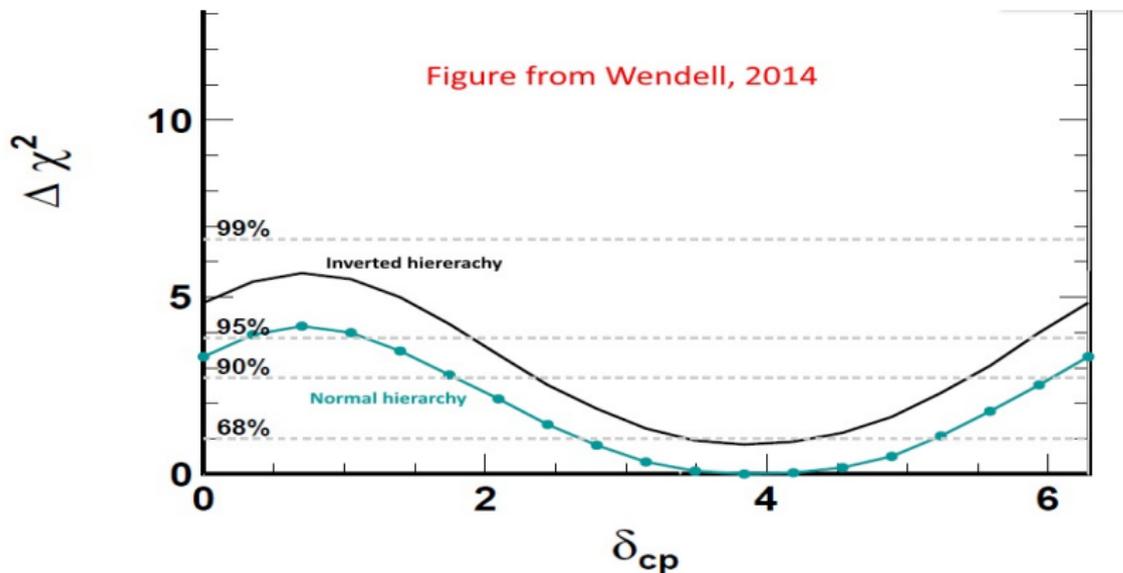
$$\Rightarrow \sin(\delta) < 0$$

and as a result of the matter effect

$$\Rightarrow \text{the } \textit{normal} \text{ hierarchy}$$

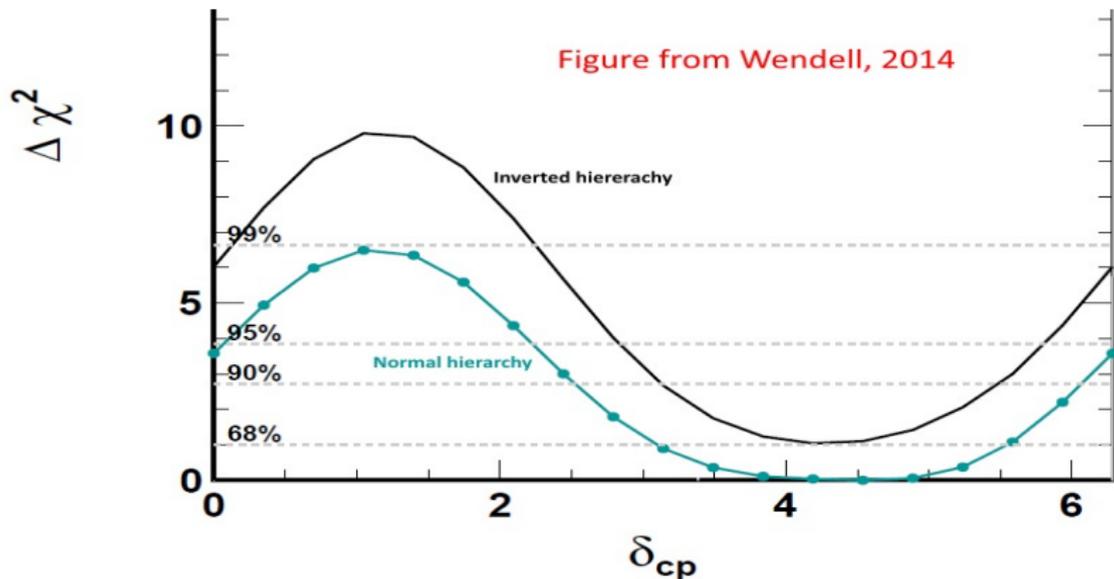
δ from Super-Kamiokande Atmospheric

Such an excess was observed by Super-Kamiokande



\Rightarrow 1σ preference for the normal hierarchy and “ 2σ ” for $\sin(\delta) < 0$

T2K has seen an excess in ν_e appearance in a ν_μ beam
 \Rightarrow large $P(\nu_\mu \rightarrow \nu_e)$ and normal hierarchy



Combined with the Super-K atmospheric excess

\Rightarrow 1-2 σ normal hierarchy and "2.5 – 3 σ " for $\sin(\delta) < 0$

Data from MINOS Appearance

MINOS was a similar experiment to T2K, with higher energies.

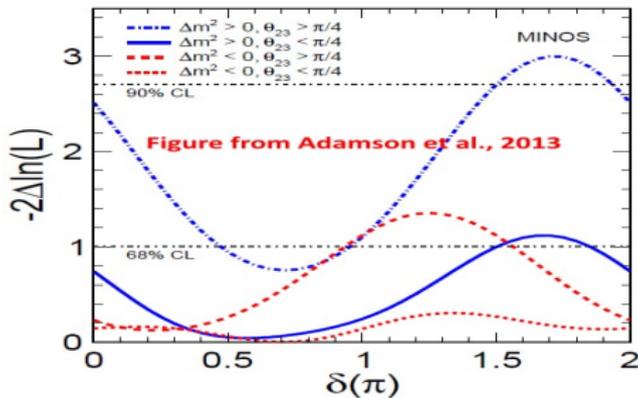
If $\sin^2(2\theta_{13}) = 0.1$, $\theta_{23} = 45^\circ$, $\delta = 0$, normal hierarchy (NH)

	ν mode	$\bar{\nu}$ mode	T2K ν mode
Expected signal	33 events	3.2 events	17.3 events
Expected sig+bkgd	161.4 events	21.4 events	21.6 events
Observed	152 events	20 events	28 events

MINOS $\nu_\mu \rightarrow \nu_e$ 1σ deficit \Rightarrow slight preference for IH, $\sin(\delta) > 0$

These preferences would disappear with the new Daya Bay
 $\sin^2(2\theta_{13}) = 0.084 \pm 0.005$.

Preference for the inverted hierarchy and $\sin(\delta) > 0$ is $< 1\sigma$



A large value of θ_{23} is disfavored as it would lead to an excess, which would be large in combination with the normal hierarchy

T2K prefers a large θ_{23} , a normal hierarchy and $\sin(\delta) < 0$ precisely because it *does* see an excess in $\nu_\mu \rightarrow \nu_e$