Muon Decay at Rest for CP Measurements

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Neutrino Mass Eigenstates

Neutrino flavors are measured via charged current interactions.

The observed final state contains a charged lepton in a mass eigenstate: e, μ or τ

The neutrino which creates this charged lepton, via the absorption or emission of single W boson, is called ν_e, ν_μ or ν_τ respectively.

These are not mass eigenstates.

If there are only 3 neutrino flavors, these may be expanded in terms of three mass eigenstates ν_1, ν_2 and ν_3 via the Maki-Nakagawa-Sakata matrix U

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The Parameters

The Maki-Nakagawa-Sakata matrix can be parametrized by four angles: θ_{12}, θ_{13}, θ_{23} and δ as

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta_{23}) & \sin(\theta_{23}) \\ 0 & -\sin(\theta_{23}) & \cos(\theta_{23}) \end{pmatrix} \begin{pmatrix} \cos(\theta_{13}) & 0 & \sin(\theta_{13})e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin(\theta_{13})e^{i\delta} & 0 & \cos(\theta_{13}) \end{pmatrix}$$

$$\times \begin{pmatrix} \cos(\theta_{12}) & \sin(\theta_{12}) & 0 \\ \text{-}\sin(\theta_{12}) & \cos(\theta_{12}) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{12},\ \theta_{13},\ \theta_{23} \in [0^\circ, 90^\circ]$ and $\delta \in [0^\circ, 360^\circ]$

Let the mass of ν_i be M_i and $\Delta M^2_{ij} = M^2_i - M^2_j$

In 2011-2012 T2K and then Daya Bay and RENO measured θ_{13}. The only unknown parameter is now δ.

Solar neutrino oscillations

Solar neutrino experiments together with the long baseline reactor neutrino experiment KamLAND determine the solar mass splitting and mixing angle:

$\Delta M^2_{21} = 7.5 \times 10^{-5}\ \mathrm{eV}^2, \quad \sin^2(2\theta_{12}) = 0.857$

The sign of ΔM^2_{21} is determined from matter effects in ν oscillations inside of the sun.

Due to the very small solar mass splitting, the corresponding oscillations only occur over long baselines

$\Rightarrow$ they will not play a central role in this talk.

First Oscillation Maximum

As ΔM^2_{31} and ΔM^2_{32} are much larger than ΔM^2_{21}, 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

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

The off-axis beams used at T2K and NOνA (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 $\alpha = \frac{\Delta M^2_{21}}{|\Delta M^2_{31}|} \sim 0.032$ the probability of conversion in a vacuum, at the first oscillation maximum, is

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

Therefore, to extract δ from $\nu_\mu \to \nu_e$ 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 $\sin^2(2\theta_{13}) = 0.0856 \pm 0.0029$.

ν_μ disappearance experiments measure (approximating $\theta_{13} = 0$) $\sin(2\theta_{23}) \sim 1$ but to separate δ from the constant term in $P_{\nu_\mu \to \nu_e}$ 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, T2K finds (2018)

$\sin^2(\theta_{23}) = 0.53 \pm 0.03$

Putting everything together, at the first oscillation maximum

$P_{\nu_\mu \to \nu_e} \sim (0.045 \pm 0.003) - (0.014) \sin(\delta)$

The 1σ uncertainty on the constant term is more than 1/5 as large as the δ-dependent signal, so δ cannot be determined precisely

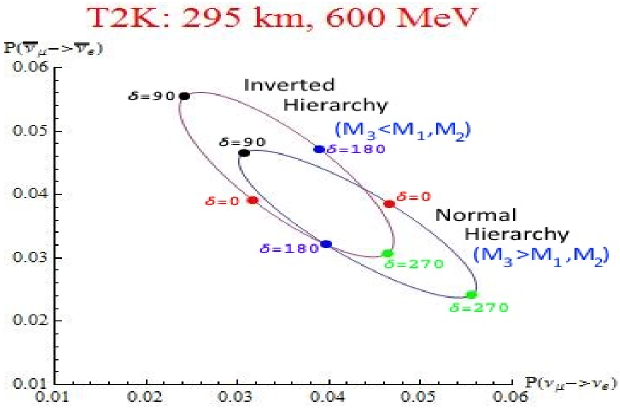
(At 2σ the lower octant is allowed so the allowed range more than doubles).

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

$P_{\overline{\nu}_\mu \to \overline{\nu}_e} \sim (0.045 \pm 0.003) + (0.014) \sin(\delta)$

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

Minakata-Nunokawa Diagram: T2K



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

Limitations of a Long-Baseline Accelerator Approach

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

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

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

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

2) Even with a perfect measurement, only $\sin(\delta)$ is determined and so δ cannot be distinguished from $\pi - \delta$.

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

   This is the strategy of IHEP's MOMENT experiment

μ^+ Decay at Rest

Solution: Measure $\overline{\nu}$ 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
$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$.

4) The $\overline{\nu}_\mu$ travel isotropically in all directions, oscillating as they go

5) A detector measures the $\overline{\nu}_e$ arising from the oscillations $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$.

Muon Decay at Rest Neutrinos

The spectrum of μDAR neutrinos leads to many advantages

1) The spectrum is known extremely well, it is the Michel spectrum

2) 30-50 MeV $\overline{\nu}_e$ interact via inverse β decay, whose cross section is known very precisely

3) The resulting $\overline{\nu}$ 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 $\overline{\nu}_e$ and not ν_e, their capture by IBD yields a neutron. The subsequent neutron capture provides a double coincidence which strongly reduces the backgrounds if detected

5) The spectrum is broad enough so that its shape breaks the $\delta \rightarrow \pi - \delta$ degeneracy

What proton energies are acceptable?

A proton beam energy $\gtrsim$ 400 MeV is necessary to have sufficient $\overline{\nu}$.
At least 600 MeV would be optimal.

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

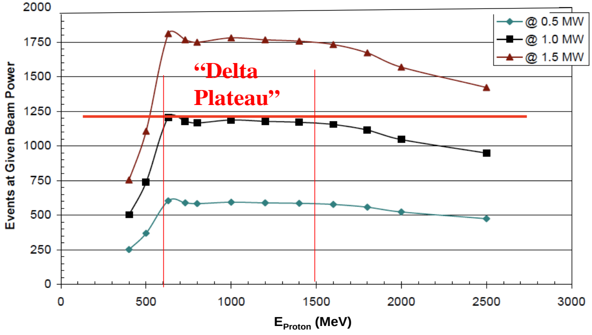


Figure: Simulated by DAEδALUS

Problem Solved?

Combining $\nu_\mu \to \nu_e$ oscillations from a long-baseline experiment with $\overline{\nu}_\mu \to \overline{\nu}_e$ 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 $\nu_\mu \to \nu_e$ oscillations drops by $\sqrt{3}$.

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

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

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

The DAEδALUS Project

The first proposal along these lines was the DAEδALUS 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 DAEδALUS is expensive and technologically challenging for one reason:

Why DAEδALUS is Hard

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

So DAEδALUS can't tell which $\overline{\nu}_e$ came from which accelerator

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

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

Therefore the instantaneous intensity 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^+, but then they will need invent a way to extract the excited molecules

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 DAEδALUS.

So we suggest that Daya Bay or RENO detectors at 50-100 meters be used to determine the flux normalization

Summary:
DAEδALUS 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 (KNO?) 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 DAEδALUS.

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) This will be MUCH cheaper: Only one accelerator complex is needed instead of three and it will have a five times lower intensity

Proposal

Our proposal:

1) A high intensity proton beam (400 MeV$< E <$2 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 $\overline{\nu}_\mu + e^+ + \nu_e$

4) The $\overline{\nu}_\mu$ oscillate to $\overline{\nu}_e$

5) $\overline{\nu}_e$ inverse β decay in 2 large detectors at 5-30 km

6) ν flux normalization determined by elastic $\nu - e$ scattering in Daya Bay/RENO detectors at 20-100 m

(may refill with water or oil based scintillator to get more Cherenkov light)

Proposals

Disadvantage: You need to build a second detector!

But in some cases a second detector may anyway be built, at just the right distance from the first detector

Our proposals:

1) μ^+ Decay At Rest with Two Scintillators (μDARTS)

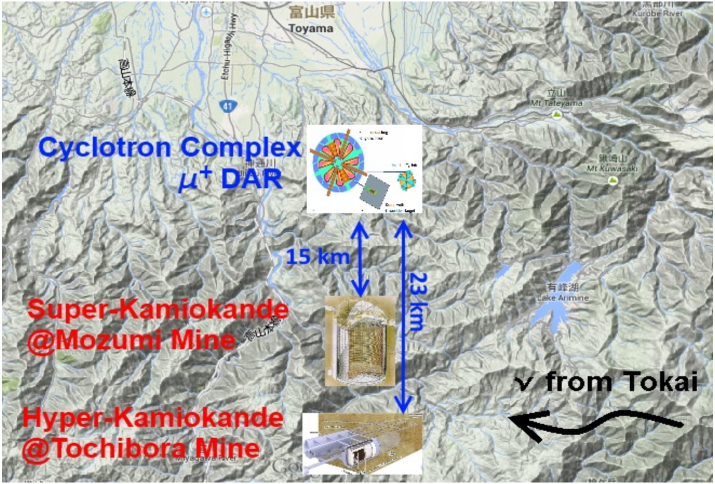
Two 20 kton liquid scintillator detectors separated by 20-35 km

2) Tokai 'N Toyama To Kamioka (TNT2K)

Near: Super-K, Far: Hyper-K at the Tochibora mine

The future of Hyper-K is bright but perhaps elastic
$\Rightarrow$ we consider TNT2K with Hyper-K fiducial masses of 0, 112 kton and 560 kton (2018 Design Report: 187 kton/tank)

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 $\overline{\nu}_\mu$ from μ^+ DAR oscillate to $\overline{\nu}_e$ 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*

What Proton Beam?

Once J-PARC protons are diverted from the Main Ring to the primary beam line, they are no longer available for other J-PARC experiments

μDAR $\overline{\nu}_\mu$, like reactor $\overline{\nu}_e$, do not require a special target station

So long as the beam hits a thick enough target, μ^+ will decay at rest and the resulting $\overline{\nu}_\mu$ will isotropically disperse

The accelerator facility can simultaneously do what it likes with the target, for example use it for a neutron source (like CI-ADS and LAMPF), for materials testing (like LAMPF) or to create isotopes (like LAMPF)

Conservative Assumptions

Our study is very conservative:

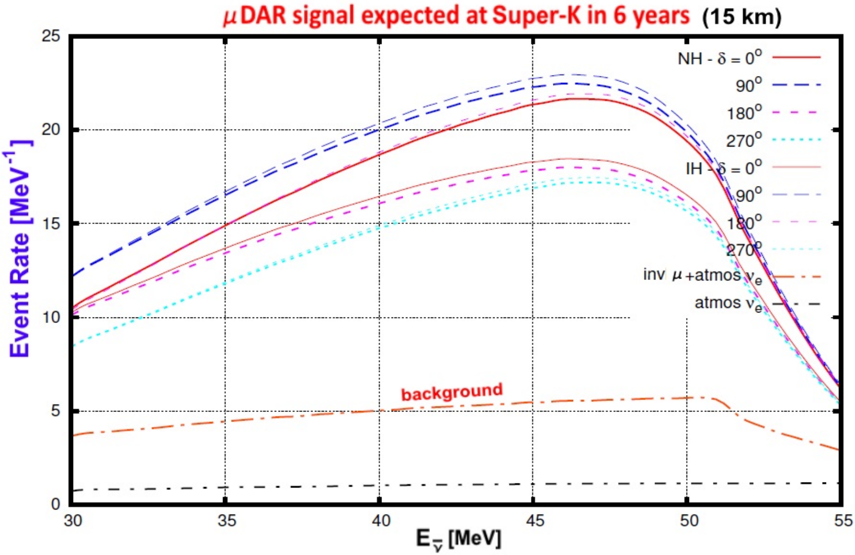
1) We assume a 750 kW J-PARC beam (but 1.3 MW is planned)

2) We do not consider Gd in Super-K (but 0.2% Gd is planned)

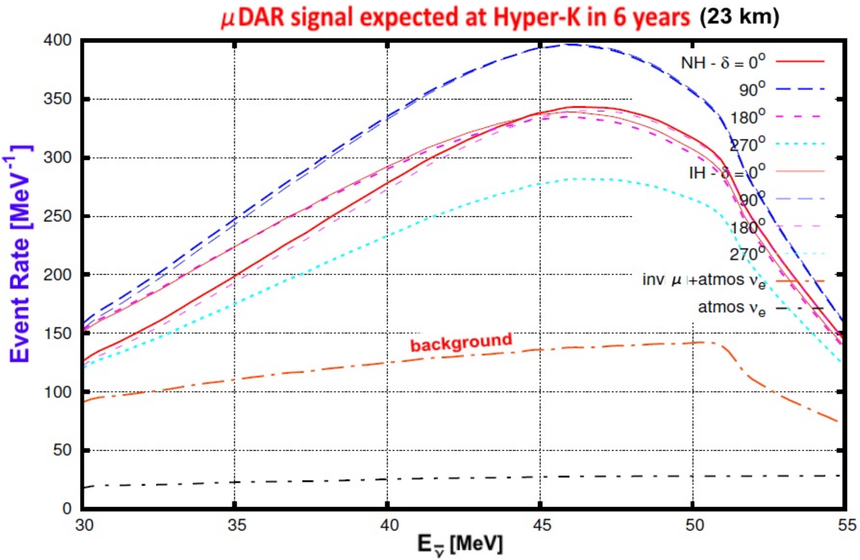
3) We consider a fractional energy resolution of $60\%/\sqrt{E(\mathrm{MeV})}$ for μDAR at HK
(but HK should be better than SK because of same PMT coverage and higher photon detection efficiency)

Figs 112 and 113 of the 2018 Hyper-K Design Report suggest an energy resolution better than $50\%/\sqrt{E(\mathrm{MeV})}$ at μDAR energies

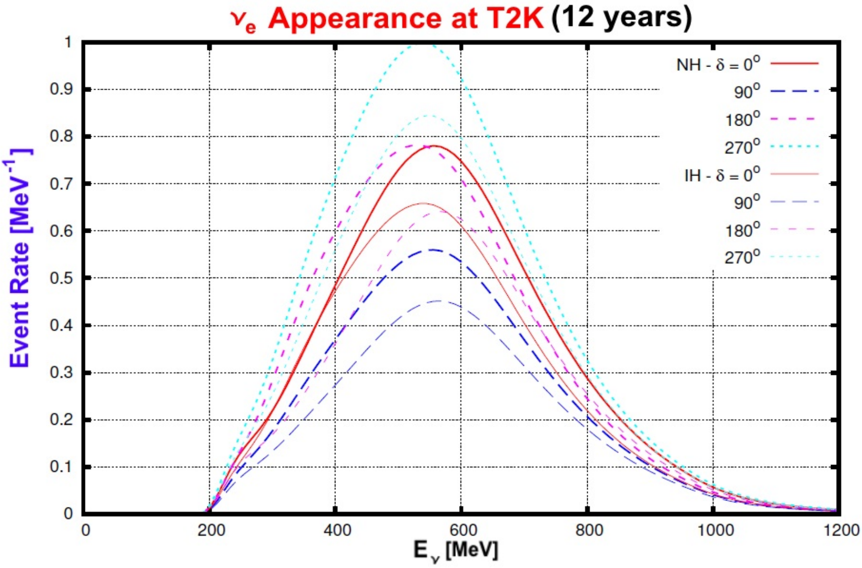
Expected μ^+ DAR Signal at TNT2K: Super-K



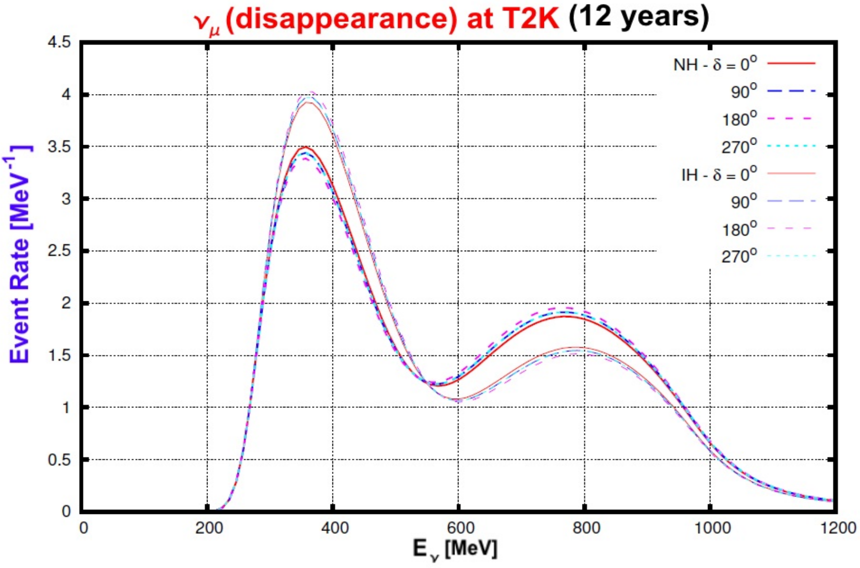
Expected μ^+ DAR Signal at TNT2K: Hyper-K



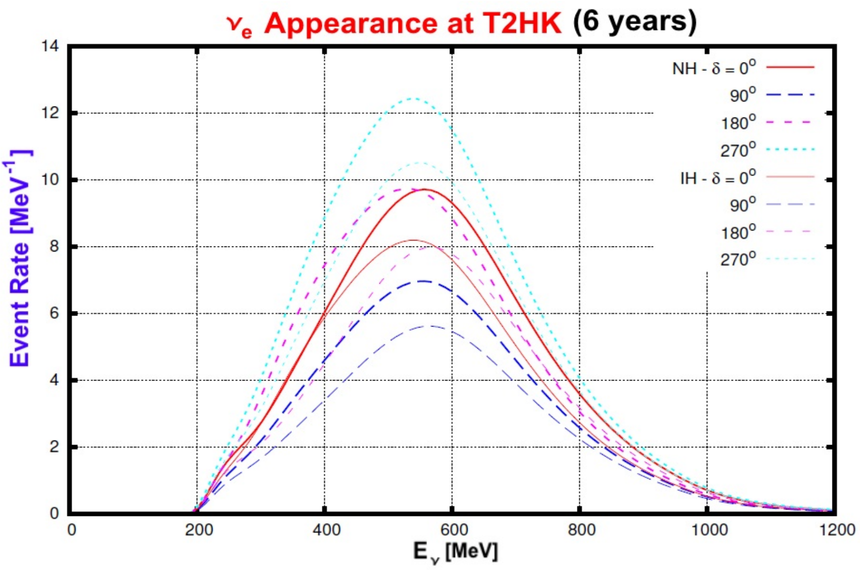
Expected ν_e Appearance Signal at TNT2K: T2K



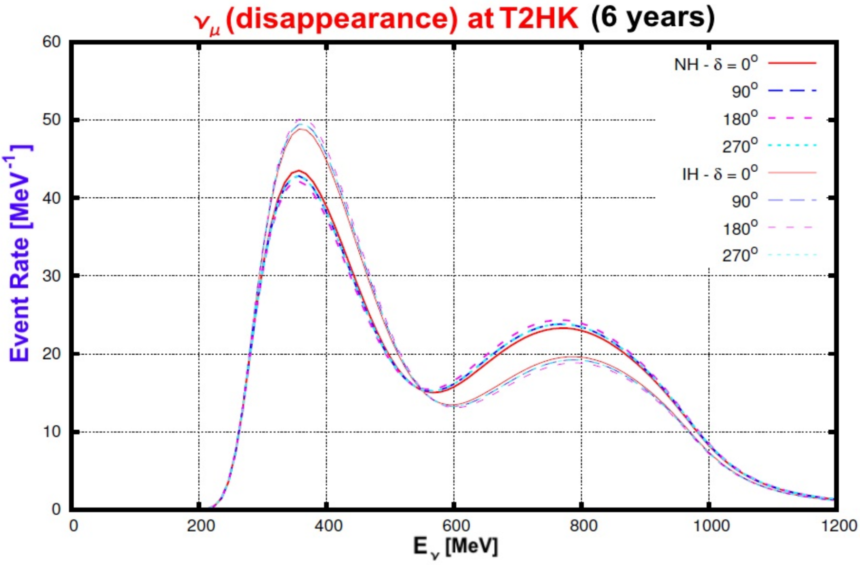
Expected ν_μ Disappearance Signal at TNT2K: T2K



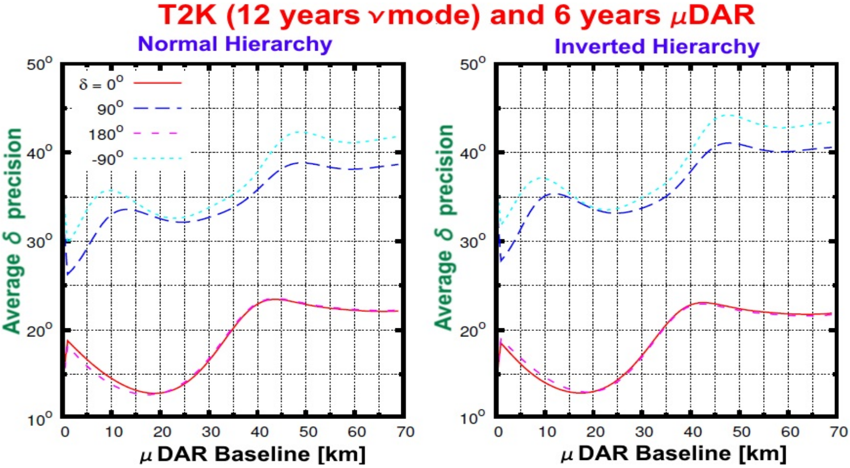
Expected ν_e Appearance Signal at TNT2K: T2HK



Expected ν_μ Disappearance Signal at TNT2K: T2HK



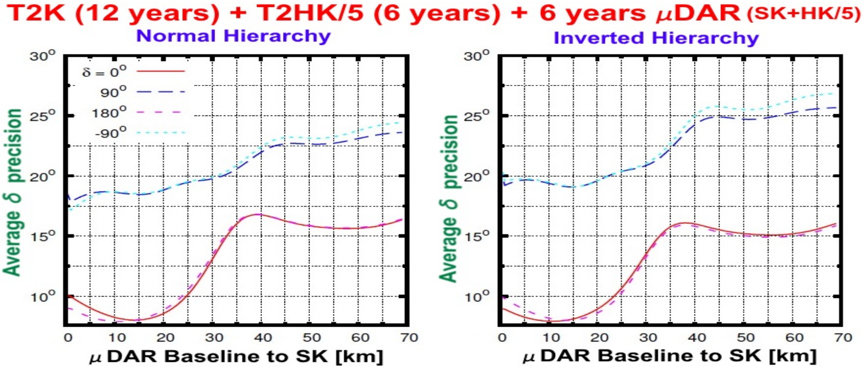
Precision of δ Measurement at TNT2K: SK Only



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

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

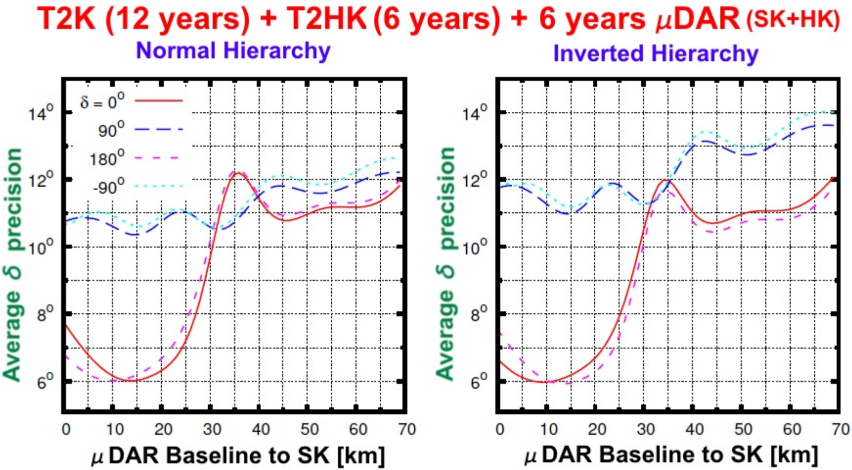
Precision of δ Measurement at TNT2K: SK and HK/5



W/ 112 kton of HK: Best baseline to SK (HK) is 13-15 (21-23) km and δ can be measured with a precision of $8^\circ - 18^\circ$

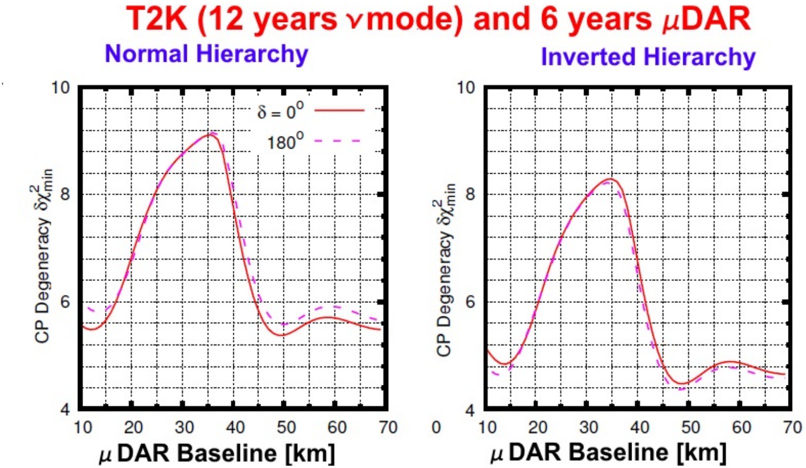
Compare: 560 kton HK, 6 years of T2HK (4.5 ν, 1.5 $\overline{\nu}$) $\rightarrow 9^\circ - 24^\circ$

Precision of δ Measurement at TNT2K: SK and HK



W/ 560 kton HK: Best baseline to SK (HK) is 13-15 (21-23) km and δ can be measured with a precision of $6^\circ - 11^\circ$

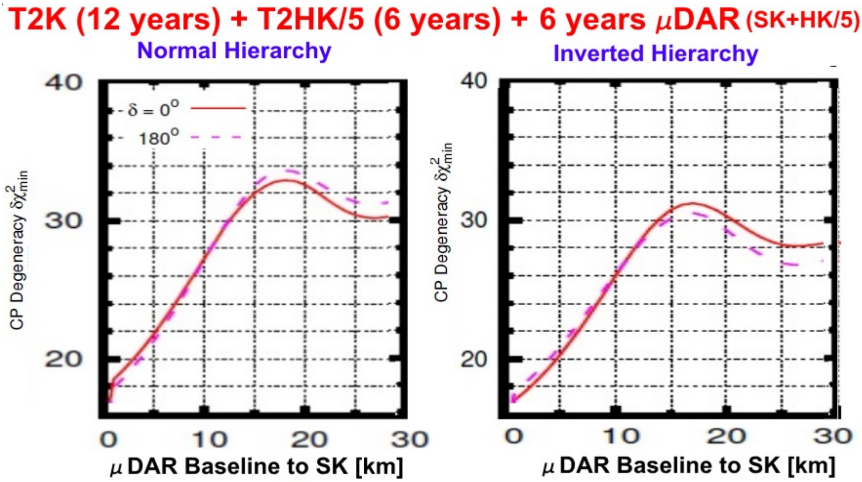
Distinguish δ and $\pi - \delta$ at TNT2K: SK Only



Without HK, 15 km from SK:

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

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



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

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

Nonunitary Mixing: Theory

Flavor basis and mass eigenstate ν are related by

$$\nu_\alpha = U_{\alpha i}\nu_i$$

What is ν_α?

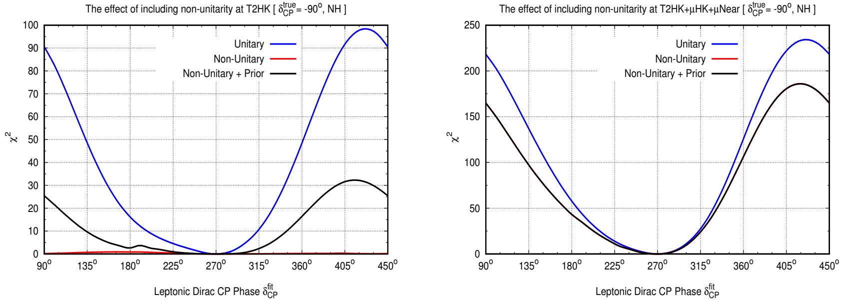
1) The ν which appears in the 3-particle vertex with $W^\pm$ and l_α
$\Rightarrow$ U is unitary

2) The ν which appears a macroscopic distance from an energy E charged current interaction involving l_α
$\Rightarrow$ U is not unitary if there is mixing with a ν mass eigenstate of mass $M > E$, as those components cannot be on shell

If U is not unitary, it contains additional parameters which are degenerate with δ

Nonunitary Mixing: Results

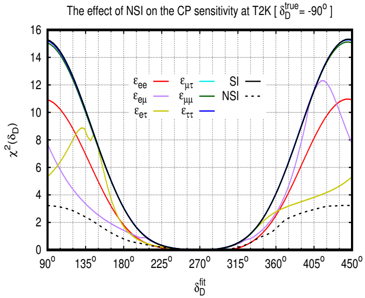
The loss in sensitivity to δ when also fitting nonunitarity mixing is greatly reduced in TNT2K with respect to T2HK (Ge, Pasquini, Tortola and Valle, 2017)

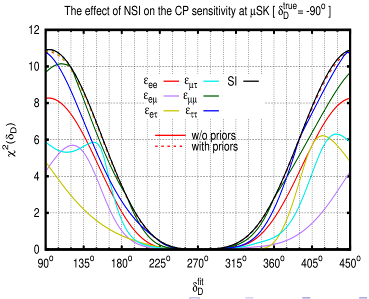


NonStandard Interactions

$$\mathbb{V} \sim V \begin{pmatrix} V & & \\ & 0 & \\ & & 0 \end{pmatrix} + V \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix} .$$

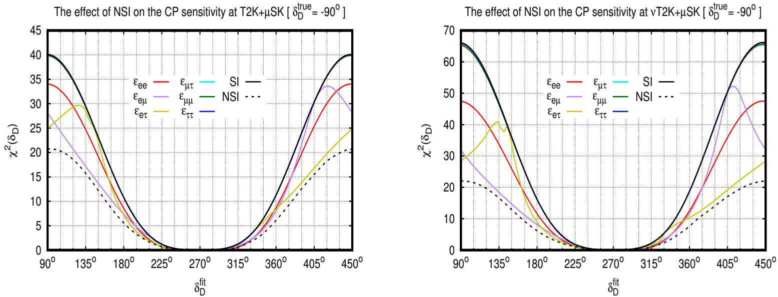
NSI of the form above can have a big effect on T2K, but with priors for current constraints there is little effect on μDAR as a result of the much lower neutrino energy (Ge and Smirnov, 2016)





NSI at TNT2K

Combining T2K and μDAR, NSI still causes a moderate reduction on sensitivity with current constraints (Ge and Smirnov, 2016)



Without NSI, TNT2K is best if the J-PARC beam is always in neutrino mode

This advantage evaporates in the presence of NSI

Atmospheric Neutrino IBD Background

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

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

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

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*:

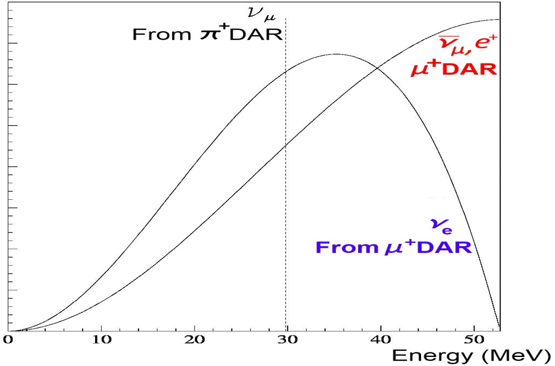
These are muons with kinetic energies below the Cherenkov threshold in water (52 MeV), and so invisible to the detector, mostly created from atmospheric ν_μ and $\overline{\nu}_\mu$ via CC interactions with oxygen in the water.

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 $\overline{\nu}_\mu$ 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 (ν_μ + nucleon$\rightarrow \mu + X$) events into the atmospheric ν_μ and $\overline{\nu}_\mu$ 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 $\overline{\nu}$ 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)

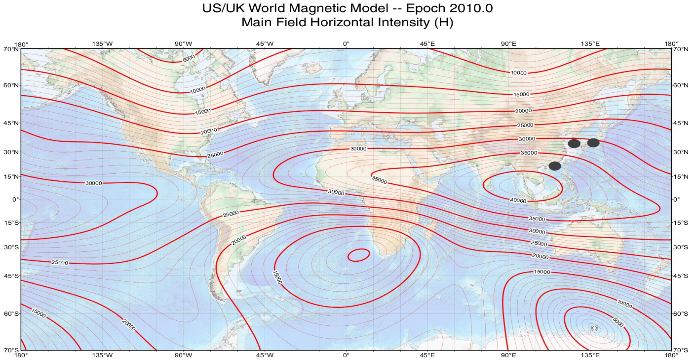
Hyper-K Inv μ Background: 2875 events (signal$\sim$5000 events)

We do not include further vetoes in the analysis above, however: With Gd doping we can remove all events without precisely one final state neutron, our simulation indicates that this eliminates 40% of events

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

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.

CIADS/JUNO (0.38 G), KNO/Kamioka mines (0.31 G) *vs* LBNE (0.17 G), LENA in the Pyhäsalmi mine (0.13 G)

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

Conclusions

1) Combine J-PARC 750 kW $\nu_\mu \to \nu_e$ with μDAR $\overline{\nu}_\mu \to \overline{\nu}_e$ at SK : measure δ with a precision of $12^\circ - 35^\circ$, and distinguish $\delta = 0$ and 180 at $2 - 2.5\sigma$

2) Combine J-PARC 750 kW $\nu_\mu \to \nu_e$ with μDAR $\overline{\nu}_\mu \to \overline{\nu}_e$ at SK and 112 kton fiducial mass HK : measure δ with a precision of $8^\circ - 18^\circ$ (almost good enough for Serguey) and distinguish $\delta = 0$ and 180 at $5.5 - 6\sigma$

3) The optimal location for the accelerator is 15 km north of Mozumi mine (Super-K), 23 km north of Tochibora mine (Hyper-K)

4) This is more robust against nonunitary mixing than a long baseline approach alone

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LSND Anomaly

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

Their mass splittings are:

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

The corresponding oscillations occur at baselines of

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

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, $\overline{\nu}_\mu \to \overline{\nu}_e$ conversion at just 30 meters

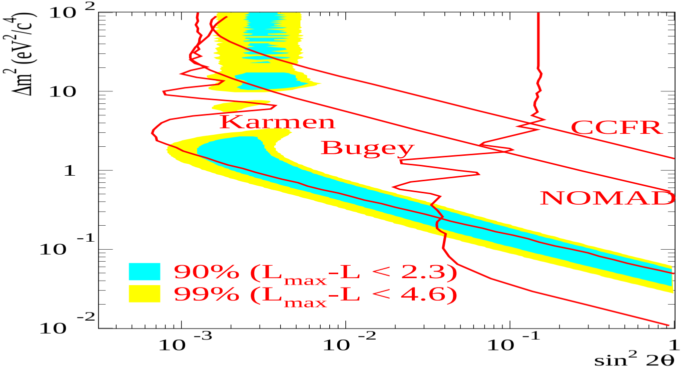
The MiniBooNE experiment also observed anomalous appearance with 1 GeV ν and $\overline{\nu}$ at a similar E/L

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 $(1\ eV^2, 3\times 10^{-3})$ to $(0.2\ eV^2, 3\times 10^{-2})$



Sterile neutrinos with μDARTS

	μDARTS	LSND
proton energy	800 MeV	798 MeV
proton current	10 mA (C-ADS)	1 mA (LANSCE)
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, μDARTS can use N old Daya Bay detectors at 50-100 meters, detecting $\overline{\nu}$ 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 DAEδALUS project invisages 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 ^{9}Be target, releasing neutrons

2) The neutrons enter a ^{7}Li sleeve and are captured, creating ^{8}Li

3) The ^{8}Li β decays, producing $\overline{\nu}_e$ with an average energy of 6 MeV and max energy of 13 MeV (cosmogenic backgrounds are large)

4) $\overline{\nu}_e$ 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 $\rightarrow$ $\overline{\nu}_e$ *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 ν $\rightarrow$ 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