Status of Long-Baseline Neutrino Experiments

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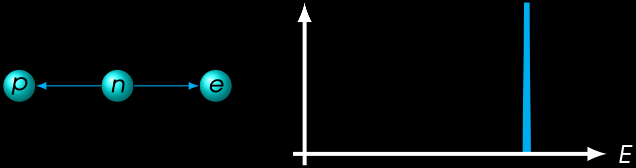
2015 CAP Congress

Outline

Outline

First hints of the Neutrino

- Spectrum from ``β-decay'' expected to be mono energetic
- Found to be a continuous spectrum
- Not consistent with two body decay



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- Spectrum shape indicated 3rd product had very low mass
- Later, it was identified as a neutrino

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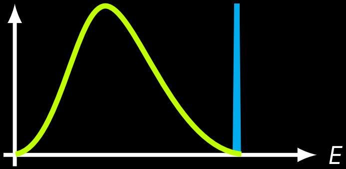

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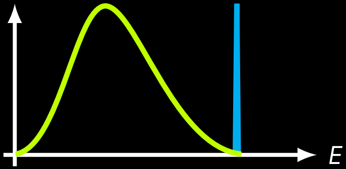

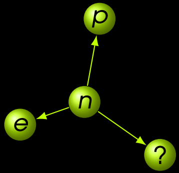

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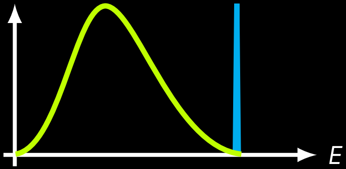

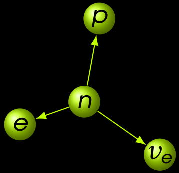

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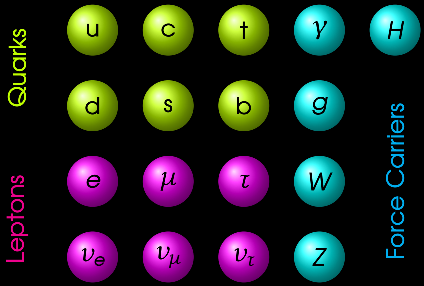
Neutrinos in The Standard Model



- Interact via the weak force: W and Z
- Three neutrino flavours
- Doublets with their charged counterparts

$$\begin{aligned} W^+ &\rightarrow e^+ \nu_e, \\ &\rightarrow \mu^+ \nu_\mu, \\ &\rightarrow \tau^+ \nu_\tau. \end{aligned}$$

- Distinct handedness:

- Massless

Neutrinos behaving badly

- But all was not well
- Neutrinos were disappearing

Solar neutrino problem

- Observed Deficit in ν_e from the sun

Atmospheric neutrino anomaly

- Deficit in ν_μ:ν_e ratio of ν produced in atmosphere

- Hypothesis: neutrino flavour can change while propagating
- Confirmed by experiment: SNO, Kamland, SK, K2K etc.

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Mixing with Three Neutrino Flavours

$$\underbrace{\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}}_{\text{Flavour}} = \overbrace{\underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmo \& Accel}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}}_{\text{Reactor \& Accel}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Reactor \& Solar}}}^{\text{PMNS Matrix}} \underbrace{\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}}_{\text{Mass}}$$

where $s_{ij} \equiv \sin\vartheta_{ij}$, $c_{ij} \equiv \cos\vartheta_{ij}$

- Solves:
  - Solar neutrino problem: Observed deficit of ν_e from the sun
  - Atmospheric anomaly: Observed deficit of ν_μ from atmosphere
- 3 mixing angles, 2 mass differences
- 1 *CP* violating complex phase: difference in ν and $\bar{\nu}$ oscillations
- Is there *CP* violation in the neutrino sector?

Why does matter dominate over anti-matter in the Universe?

Oscillations with a ν_μ beam

Leading order:

$$P_{\nu_\mu \to \nu_\mu} \simeq 1 - \sin^2 2\vartheta_{23} \sin^2 \Phi_{32}$$

$$P_{\nu_\mu \to \nu_e} \simeq \sin^2 2\vartheta_{13} \sin^2 \vartheta_{23} \sin^2 \Phi_{32}$$

Have measured

- $|\Delta m^2_{32}| = (2.44 \pm 0.06) \times 10^{-3}\ \mathrm{eV}^2$
- $\sin^2 2\vartheta_{23} = 1.000^{+0.000}_{-0.017}$
- $\sin^2 2\vartheta_{13} = 0.093 \pm 0.008$

Where:

$$\Phi_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}$$

Oscillations with a ν_μ beam

Looking at higher order terms:

$$P_{\nu_\mu \to \nu_\mu} \simeq 1 - (\cos^4 \vartheta_{13} \sin^2 2\vartheta_{23} + \sin^2 2\vartheta_{13} \sin^2 \vartheta_{23}) \sin^2 \Phi_{32} + \ldots$$

$$P_{\nu_\mu \to \nu_e} \simeq \sin^2 2\vartheta_{13} \sin^2 \vartheta_{23} \sin^2 \Phi_{32} - \frac{\sin 2\vartheta_{12} \sin 2\vartheta_{23}}{\sin 2\vartheta_{13}} \sin \Phi_{21} \sin^2 2\vartheta_{13} \sin^2 \Phi_{31} \sin \delta_{CP} + \ldots$$

New possibilities:

- $\sin^2 \vartheta_{23} \Rightarrow$ octant information?
- $\sin \delta_{CP} \Rightarrow$ CP violation?
- Sign of Δm^2_{32}? Is $m_3 > m_2$?
  ``Normal Hierarchy'' vs ``Inverted Hierarchy''

Where:

$$\Phi_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}$$

Outline

Tokai To Kamioka: "T2K"

Produce ν_μ beam at J-PARC and detect at Super-K

- Discovery of $\nu_\mu \to \nu_e$ oscillation ✓

  Phys. Rev. Lett. 112, 061802 (2014)
- Precision measurement of ν_μ disappearance ✓

  Phys. Rev. Lett. 112, 181801 (2014)
- Time to start looking at the more subtle questions

How to make an neutrino beam

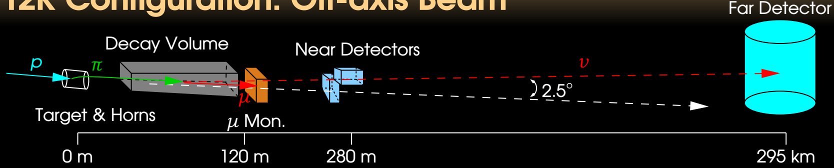
- Protons strike a target producing many pions
- Pions pass through ``Horn'' electromagnets
- Focusing π^+, deflecting π^-
- Charged pions decay to muons and muon type neutrinos:

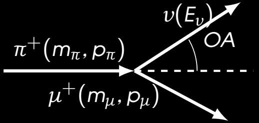
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

- Reverse Horn Current (RHC) to focus π^- to switch from ν to $\bar{\nu}$ beam

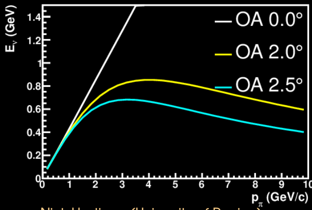
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

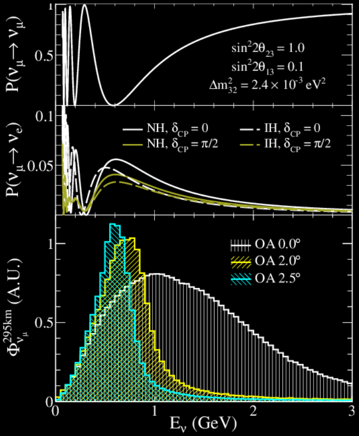
T2K Configuration: Off-axis Beam





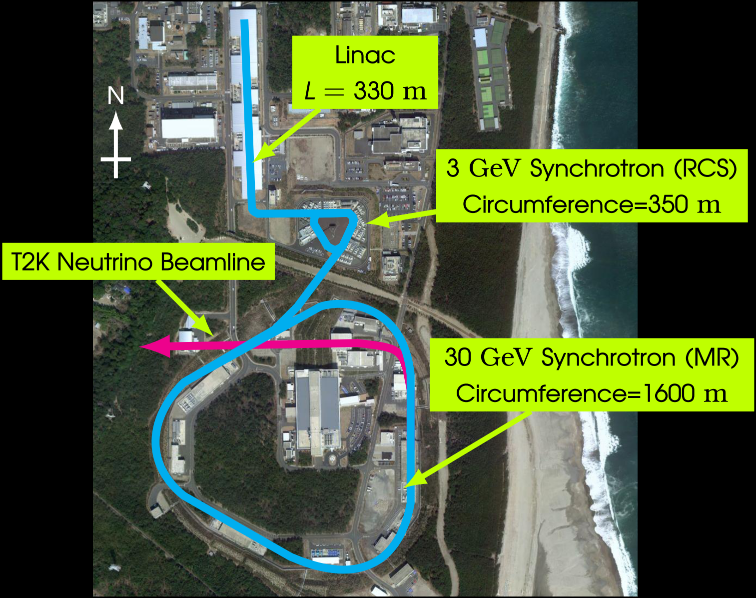
$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\vartheta_{OA})}$$



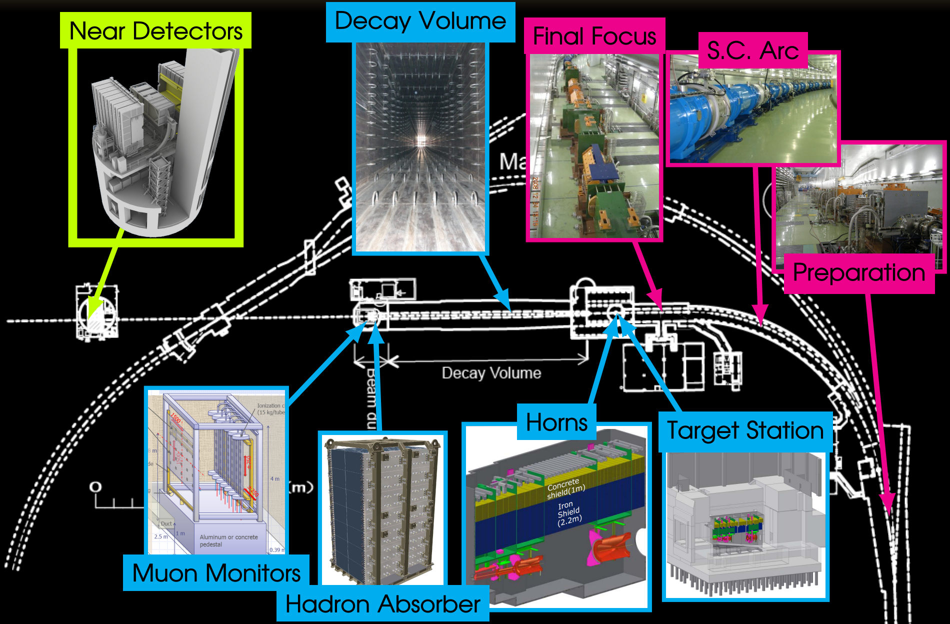


- Employ feature of π decay kinematics
- Narrow E band
- Tuned to osc. maximum
- Eliminates high E bkgs

Tokai Site


Linac
$L = 330$ m
N
3 GeV Synchrotron (RCS)
Circumference=350 m
T2K Neutrino Beamline
30 GeV Synchrotron (MR)
Circumference=1600 m

Tokai Site


Near Detectors
Decay Volume
Final Focus
S.C. Arc
Preparation
Decay Volume
Muon Monitors
Aluminum or concrete pedestal
Hadron Absorber
Horns
Concrete shield(1m)
Iron Shield (2.2m)
Target Station

Near Detectors

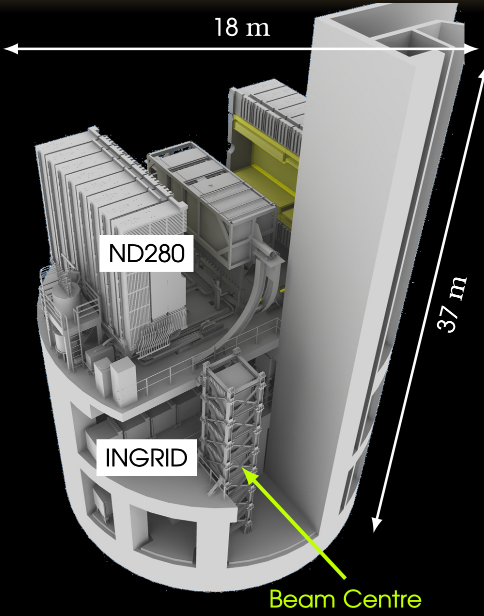
Pit 280 m from the target.

Off Axis

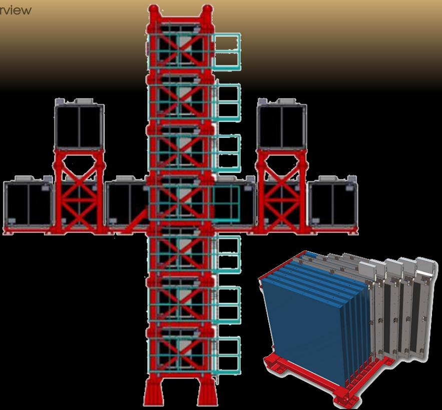
- ``ND280''
- Flux in SK direction
- ν cross sections

On Axis

- ``INGRID''
- ν_μ beam
    - profile
    - direction
    - intensity



On Axis Detector - INGRID



Design

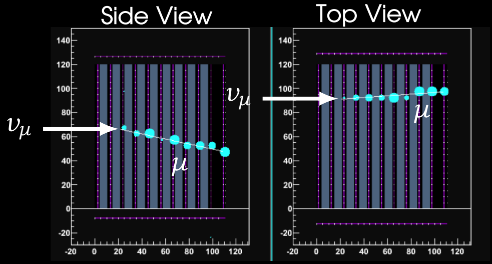
- 14 modules in cross arrangement
- $10\,\mathrm{m} \times 10\,\mathrm{m}$
- Iron scintillator sandwich

Provides

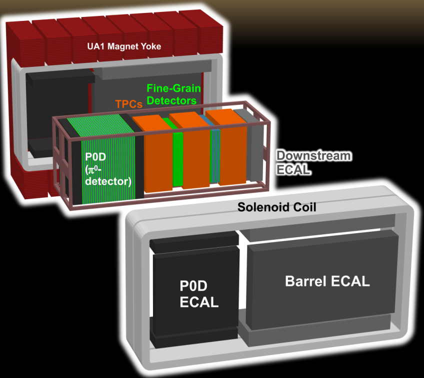
- Beam parameters
- Rate, direction and profile measurements

Note:

$\Delta\vartheta \simeq 1\,\mathrm{mrad} \Rightarrow \Delta E_{peak} \simeq 20\,\mathrm{MeV}$



Off Axis Detector - ND280

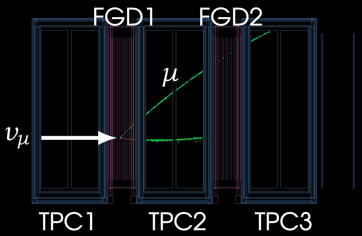


Design

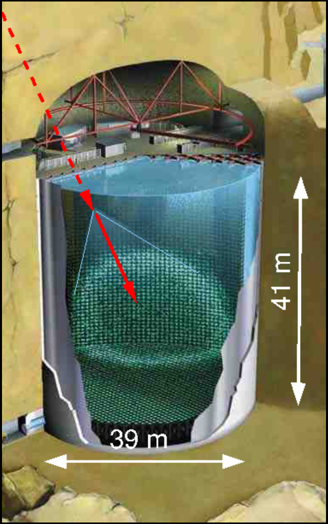
- UA1 magnet, B=0.2 T
- Tracker
  - Time projection chambers (TPCs)
  - Fine Grained Detectors (FGDs): Tracking and target material (scintillator and water)
- π^0 detector (P0D)
- Electromagnetic calorimeter (ECAL)
- Side muon range detector (SMRD)

For analyses

- Measure CC neutrino interactions

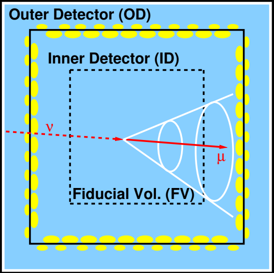


Far Detector: Super-Kamiokande



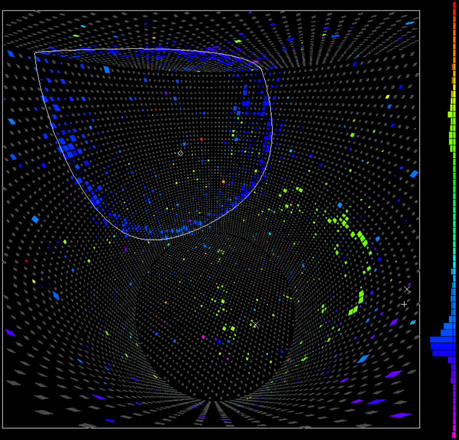
- Cerenkov light from charged leptons from ν interactions
- Use PMT pulse height & timing information
- Fit PMT hits to cone
  $\Rightarrow$ e/μ momentum & direction

- OD 1885 PMTs: Veto
- ID 11129 PMTs
- FV 22.5 kt
  2 m from ID wall

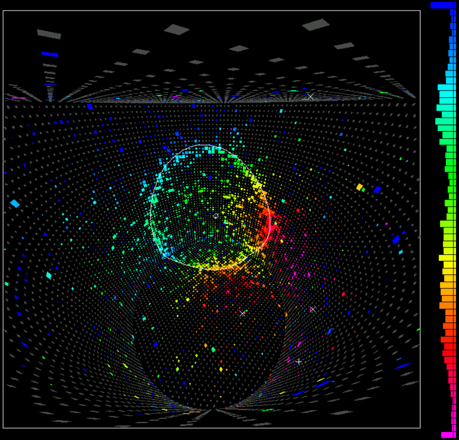


Far Detector: Particle Identification

Muon ``Sharp'' ring



Electron ``Fuzzy'' ring

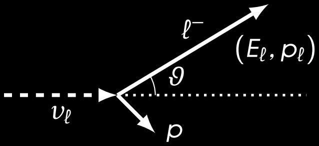


Excellent μ/e separation

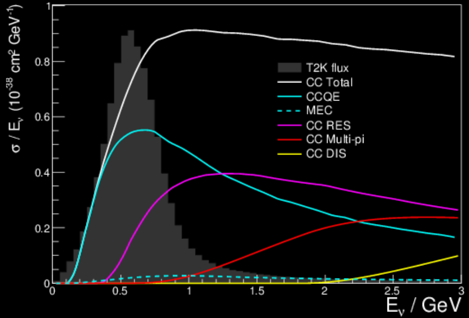
Far Detector: E_υ Reconstruction

Oscillation probability is a function of the neutrino energy

Charged Current Quasi-Elastic (CCQE),
$\upsilon_\ell + n \rightarrow \ell + p$



υ_μ CC cross sections



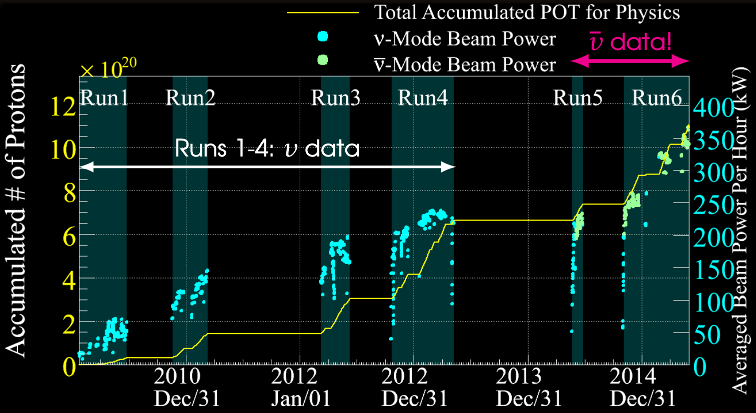
- Charged lepton, $\ell(\mu$ or $e)$
- Use energy and timing info. from PMTs
- Fit cone to PMT hits to reconstruct (E_ℓ, p_ℓ):

$\Rightarrow$ Calculate:

$$E_\upsilon^{\mathrm{rec}} = \frac{m_p^2 - m_{n'}^2 - m_\ell^2 + 2m_{n'}E_\ell}{2(m_{n'} - E_\ell + p_\ell \cos\vartheta_\ell)}$$

where: $m_{n'} = m_n - E_b$
$E_b = 27\ \mathrm{MeV}$ (binding energy of nucleon in ^{16}O nuclei)

T2K Data set



- T2K Run 1-4 data
  - Forward Horn Current (FHC): neutrino mode running
  - 6.57×10^{20} protons on target (POT), 8% of approved data set
- T2K Runs 5&6 data
  - Primarily Reverse Horn Current (RHC): anti-neutrino mode running
  - 4.47×10^{20} protons on target (90% RHC)

Combined ν_μ disappearance & ν_e appearance analysis

``Combined oscillation analysis´´ with T2K Run 1-4 data set

Neutrino Interactions
- Interaction models
- External cross-section data

ND280 measurments
- Constrain flux and cross-sections with ν_μ sample
- Measure ν_e beam component

Flux Prediction
- Proton beam stability
- Sim. Hadronic interactions in target, properties of secondary particles
- Hadron production experiment data

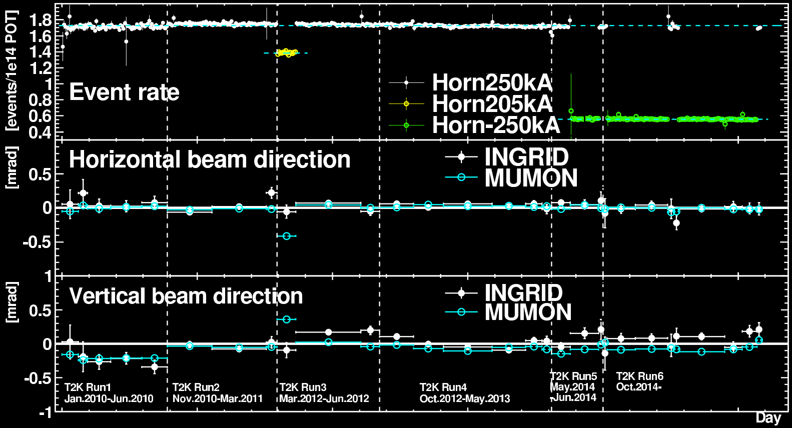
Prediction at the Far Detector

Combine flux, x-sec & ND280 to predict the expected events at SK

Fit to obtain oscillation parameters
- PDF constructed with PMNS model
- Simultaneous fit to ν_μ & ν_e distrubtions
- Extract: $\Delta m^2_{32}, \vartheta_{23}, \vartheta_{13}, \delta_{CP}, \ldots$

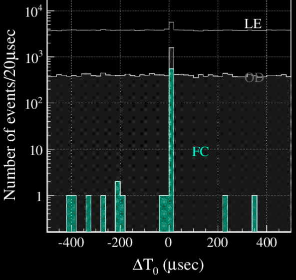
Super-K Measurements
- Select ν_μ And ν_e candidates

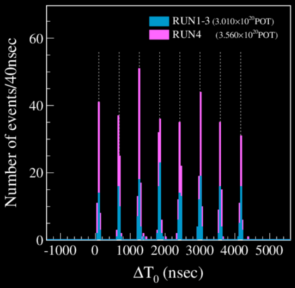
Beam measurements with INGRID and Muon Monitors

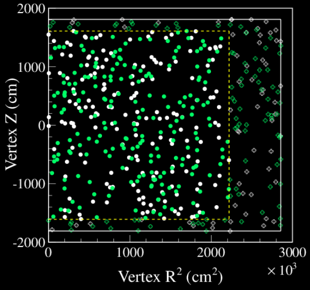


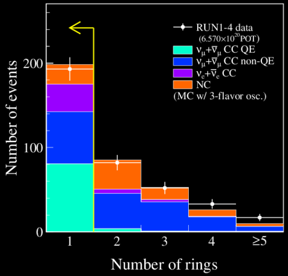
- Normalized daily event rate is stable
- Direction controlled to much better than 1 mrad

T2K Far Detector ν event selection





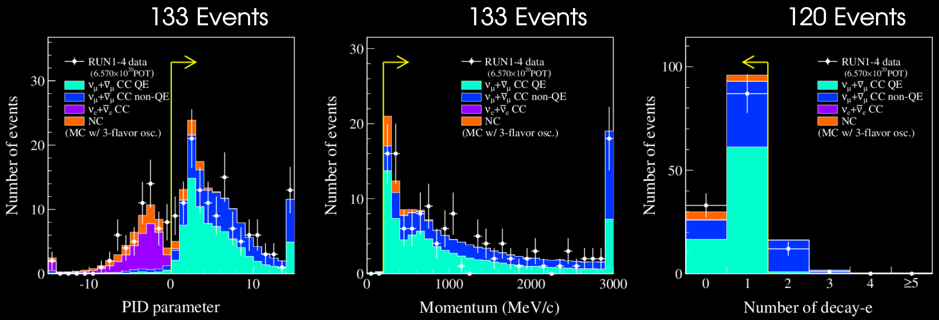




Criteria	Evts
Fully Contained with correct timing	549
Vertex in the Fiducial volume & $E > 30$ MeV	377
Single e/μ like ring	193

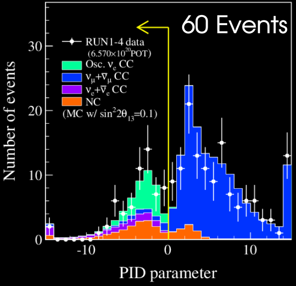
Jargon: *FCFV, 1 Ring*

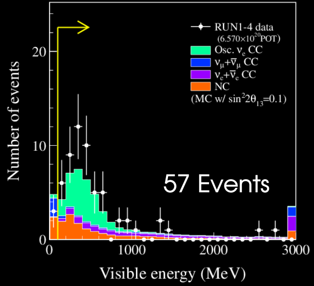
T2K Far Detector ν_μ event selection

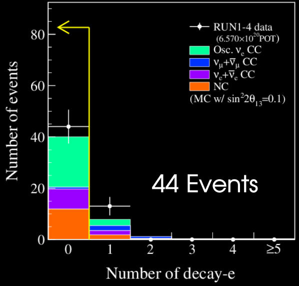


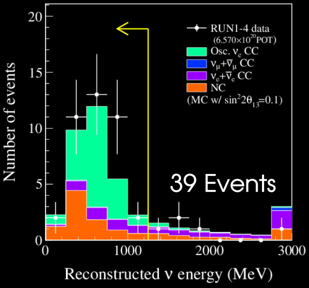
Criteria	Evts
FCFV, 1 Ring	193
PID (muon like)	133
$p_\mu > 200$ MeV/c	133
$N_{decay-e} \leq 1$	120

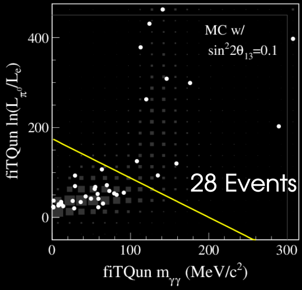
T2K Far Detector ν_e event selection







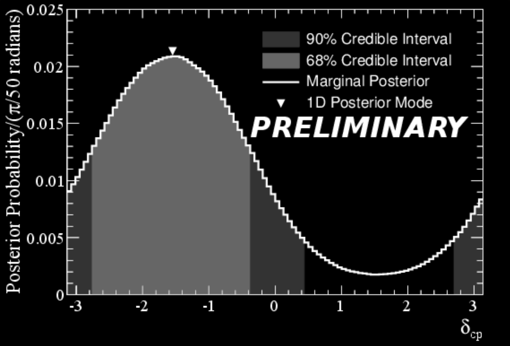




Criteria	Evts
FCFV, 1 Ring	193
PID (electron like)	60
$E_{vis} > 100$ MeV	57
$N_{decay-e} < 1$	44
$E_{\nu}^{rec} < 1250$ MeV	39
π^0 cut	28

Combined oscillation analysis results

- Simultaneous fit to ν_μ and ν_e energy spectra
- Constrain with reactor results
- Extract: Δm^2_{32}, ϑ_{23}, ϑ_{13}, δ_{CP}



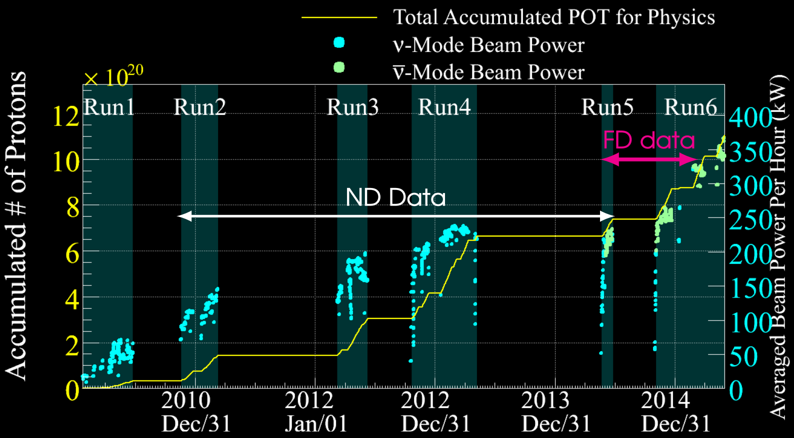
Results

- Best fit for $\delta_{CP} \sim -\pi/2$
- Weak preference for $m_3 > m_2$ and second octant

	Probability of Different Models		
	$m_3 > m_2$	$m_3 < m_2$	Sum
$\sin^2 \vartheta_{23} \leq 0.5$	17.9%	7.8%	25.7%
$\sin^2 \vartheta_{23} > 0.5$	50.5%	23.8%	74.3%
Sum	68.4%	31.6%	100.0%

- Constraints with only 8% of approved data set
- Phys. Rev. D 91, 072010 (2015)   http://arxiv.org/abs/1502.01550v2

$\bar{\nu}_\mu$ disappearance analysis

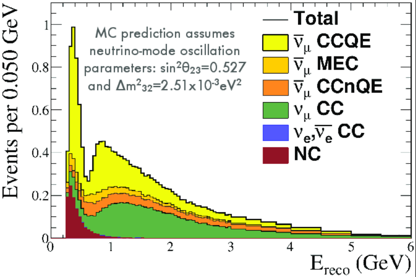


- Near Detector $\nu \& \bar{\nu}$: Use Runs 2-5
- Far Detector $\bar{\nu}$ data from runs 5&6 till March 12th: 2.32×10^{20} POT

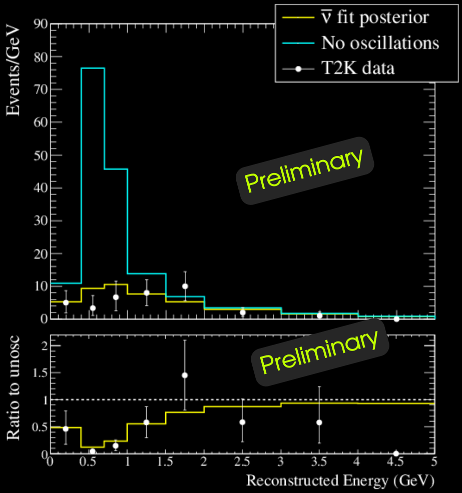
$\bar{\nu}_\mu$ disappearance analysis

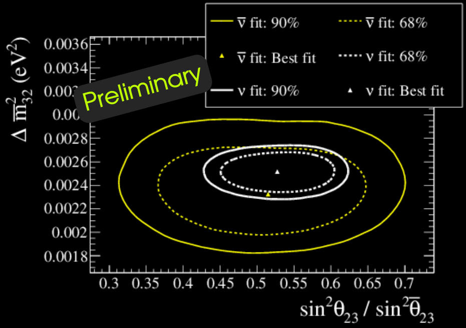
- Select single ring muon events at SK from RHC data
- Expect 19.9 events with oscillation, 59.8 without
- Higher backgrounds than ν_μ analysis
  - Cross section models and & ND constraints important
  - Use both FHC and RHC data from ND
- Simultaneous fit ND280 and SK distributions

Predicted spectra at SK



$\bar{\nu}_\mu$ disappearance results





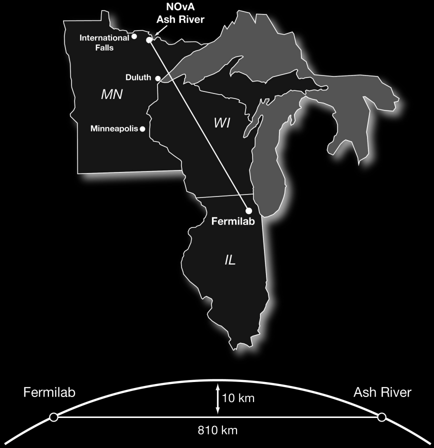
$$\Delta\bar{m}^2_{32} = \left(2.33^{+0.27}_{-0.23}\right) \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\bar{\vartheta}_{23} = 0.515^{+0.085}_{-0.095}$$

- Results consistent with ν_μ disappearance
- Errors are statistics dominated

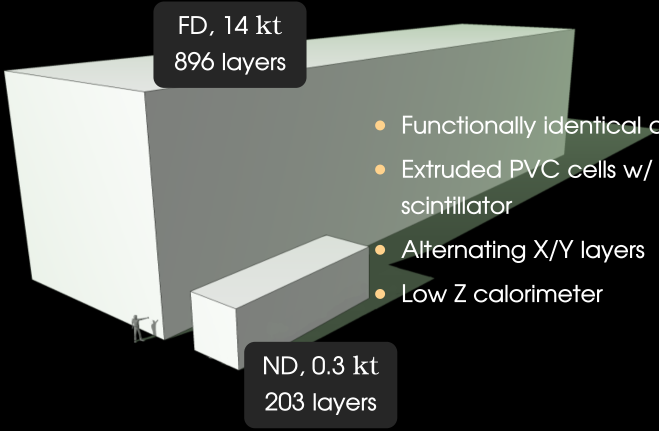
Outline

The NOνA Experiment



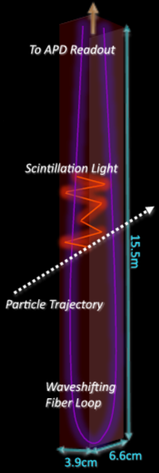
- Muon neutrino beam
- OA = 0.8 °, $E_{\text{peak}} = 2\ \text{GeV}$, $L = 810\ \text{km}$
- E/L tuned to be close to osc max
- Uses the NuMI beamline at Fermilab
- Far detector at Ash River
- Complimentary to T2K w/ slightly better sensitivity to mass hierarchy

Detectors Design



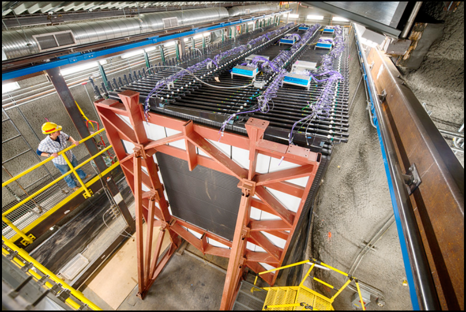
- Functionally identical detectors
- Extruded PVC cells w/ liquid scintillator
- Alternating X/Y layers
- Low Z calorimeter

A cell

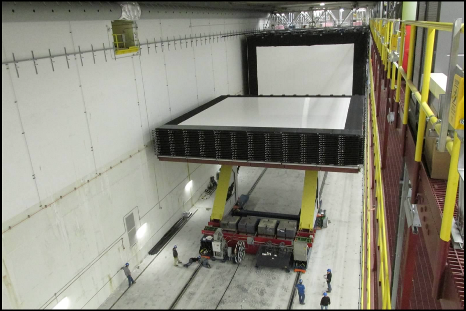


Detector Halls

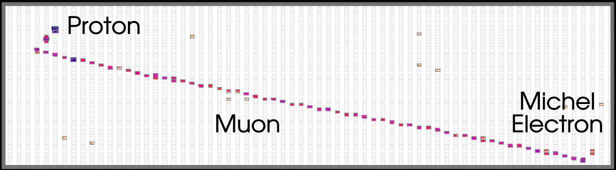
Near Detector



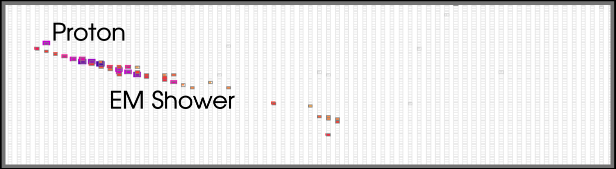
Far Detector (during installation)



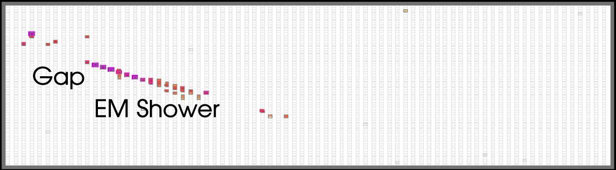
Simulated Events



$$N + \nu_\mu \rightarrow X + \mu^-$$



$$N + \nu_e \rightarrow X + e^-$$



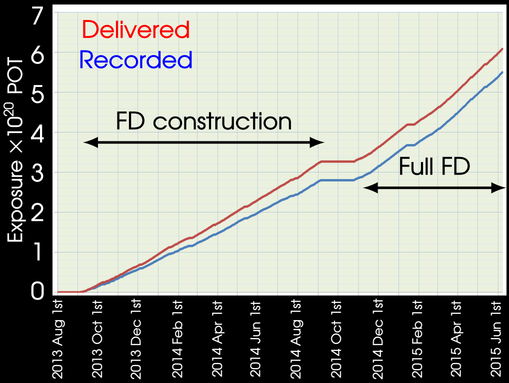
$$N + \nu_\mu \rightarrow X + \pi^0 + \nu_\mu$$

Excellent event identification

Data logging and plans

- Logging data since 2013
- Developing Analyses
- To release ν_μ disappearance and ν_e appearance results this Summer
- Expect about 2.5×10^{20} POT (full dectector equivalent)
- Corresponds to about 40% of a standard running year
- Current data set expect ν_e: $S \simeq 4.3$, $B \simeq 1.3$

Far Detector Exposure



Outline

Summary

- Long baseline neutrino oscillation experiments are an effective tool for investigating the neutrino sector.
- The T2K experiment:
  - Has achieved its initial goals:
    Discovered $\nu_\mu \to \nu_e$ and precision ν_μ disappearance measurements.
  - First results for the remaining questions:
    Is there *CP* violation? What is the mass hierarchy?
  - First preliminary $\bar{\nu}_\mu$ disappearance results.
  - Will continue to refine these measurements.
- The NOνA experiment:
  - Has been logging data for over a year.
  - Developing analyses.
  - Expecting first results this Summer.

Looking forward to many new results over the coming years.

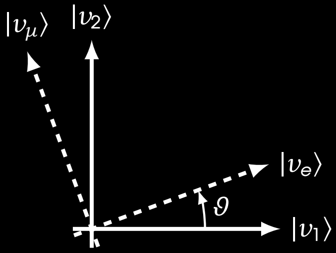
Supplementary Material

Neutrino Mixing

- Neutrino flavour states exist as superposition of mass states
- Consider a two neutrino system (instead of three) for simplicity

Flavour states:

$$|\nu_e\rangle = \cos\vartheta|\nu_1\rangle + \sin\vartheta|\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\vartheta|\nu_1\rangle + \cos\vartheta|\nu_2\rangle$$



As matrix equation:

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

- Flavour states rotated w.r.t. mass states by the *mixing angle* ϑ
- Allows mixing between ν_e and ν_μ

Time Evolution of ν_μ

$$|\nu_\mu(t=0)\rangle = |\nu_\mu\rangle = -\sin\vartheta|\nu_1\rangle + \cos\vartheta|\nu_2\rangle$$
$$|\nu_\mu(t)\rangle = -\sin\vartheta|\nu_1\rangle e^{-iE_1 t} + \cos\vartheta|\nu_2\rangle e^{-iE_2 t}$$

Where:

$$E_i = \sqrt{p^2 + m_i^2} = p\sqrt{1 + \frac{m_i^2}{p^2}} \simeq p + \frac{1}{2}\frac{m_i^2}{p}$$

Leading terms from binomial expansion since $\frac{m_i^2}{p^2} \ll 1$.

Next, let:

$$\Delta m^2 = m_1^2 - m_2^2 \quad \text{and} \quad e^{-iz} = e^{-i\left(p + \frac{1}{2}\frac{m_1^2}{p}\right)}$$

So now we have:

$$|\nu_\mu(t)\rangle = e^{-iz}\left(-\sin\vartheta|\nu_1\rangle + \cos\vartheta|\nu_2\rangle e^{+i\left(\frac{1}{2}\frac{\Delta_m^2}{p}\right)t}\right)$$

Oscillation $\nu_\mu \to \nu_e$

$$P(\nu_\mu \to \nu_e) = |\langle \nu_e | \nu_\mu \rangle|^2 = \left| e^{-iz} \left(-\sin\vartheta \cos\vartheta + \sin\vartheta \cos\vartheta e^{\frac{i}{2}\frac{\Delta m^2}{p} t} \right) \right|^2$$
$$= e^{+iz} e^{-iz} \sin^2\vartheta \cos^2\vartheta \left(-1 + e^{\frac{i}{2}\frac{\Delta m^2}{p} t} \right) \left(-1 + e^{-\frac{i}{2}\frac{\Delta m^2}{p} t} \right)$$

Highly relativistic can substitute $p = E$ and $t = L$, and remembering our trig, identities crunch it through:

$$P(\nu_\mu \to \nu_e) = \frac{1}{2} \sin^2 2\vartheta \left(1 - \cos\left(\frac{\Delta m^2 L}{2E} \right) \right)$$
$$= \sin^2 2\vartheta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$
$$= \sin^2 2\vartheta \sin^2 \left(\frac{1.27(\Delta m^2/\mathrm{eV}^2)(L/\mathrm{km})}{E/\mathrm{GeV}} \right)$$

Oscillation $\nu_\mu \to \nu_e$

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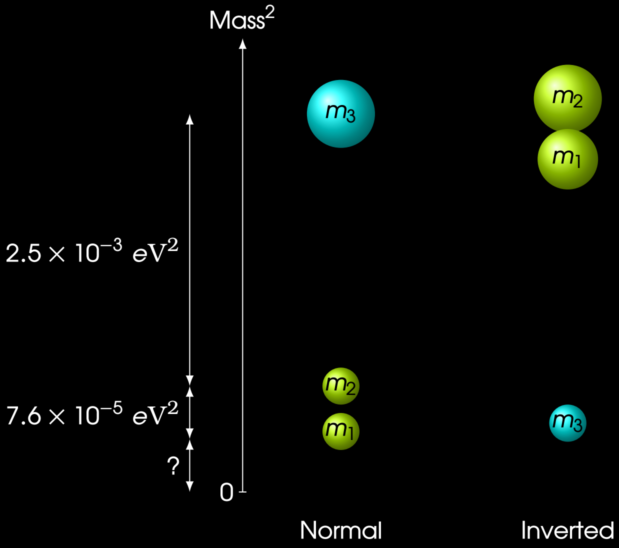
$$= \sin^2 2\vartheta \sin^2\left(\frac{1.27 (\Delta m^2/\mathrm{eV}^2)(L/\mathrm{km})}{E/\mathrm{GeV}} \right)$$

First maximum at:

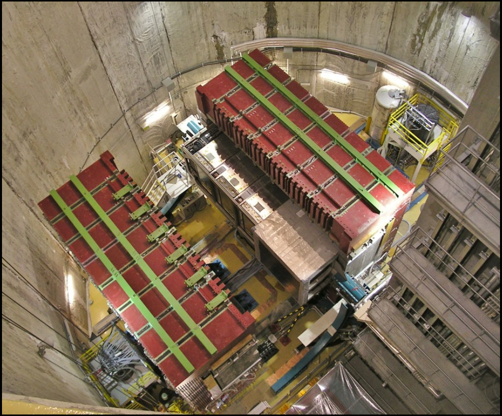
$$\frac{L}{E} = \frac{2\pi}{\Delta m^2}$$
$$\frac{L/\mathrm{km}}{E/\mathrm{GeV}} = \frac{1.24}{\Delta m^2/\mathrm{eV}^2}$$

Neutrino Mass Hierarchy



Near Detectors

ND280



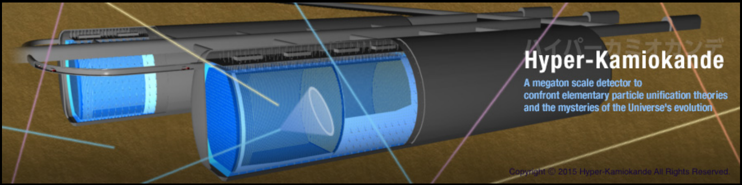
South side open

INGRID

Vertical modules

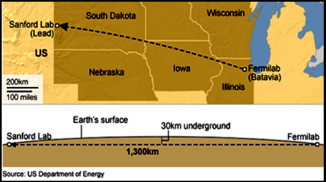
Hyper-K

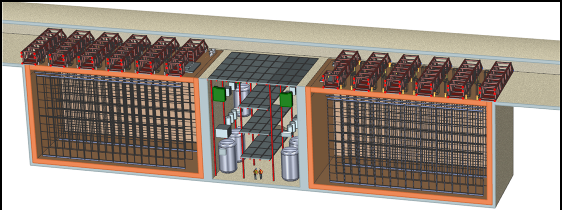
- New water Cerenkov detector at Kamioka
- 25 times fiducial volume of SK
- Extend proton decay search
- Existing J-PARC neutrino beamline with 750 kW beam
- New water Cerenkov ``Spectrometer'' near detector ``NuPrism''
- Determine δ_{CP} to better than 19 $^{\circ}$
- Expected to start taking data $\simeq$ 2025



DUNE

- New beamline at Fermilab (use main injector like NuMI beamline)
- Accelerator upgrades to achieve 1.2 MW beam (c.f. 700 kW for NOνA)
- 1300 km baseline
- Optimized for studying *CP* violation and determining the mass hierarchy
- Multi component magnetized near detector
  - Tracker in magnet field
  - Calorimeters
  - Embedded water, argon, and other targets
- New 10 kt (minimum) LArTPC far detector at Homestake (Stanford Lab)
- Expected to start taking data $\simeq$ 2023





$P(\nu_\mu \to \nu_e)$ with matter effect

$$P(\nu_\mu \to \nu_e) = P_0 + P_{\sin\delta} + P_{\cos\delta} + P_3$$

where

$$P_0 = \sin^2\vartheta_{23}\frac{\sin^2 2\vartheta_{13}}{(A-1)^2}\sin^2[(A-1)\Delta],$$

$$P_3 = a^2\cos^2\vartheta_{23}\frac{\sin^2 2\vartheta_{12}}{A^2}\sin^2(A\Delta),$$

$$P_{\sin\delta} = a\frac{8J_{CP}}{A(1-A)}\sin\Delta\sin(A\Delta)\sin[(1-A)\Delta],$$

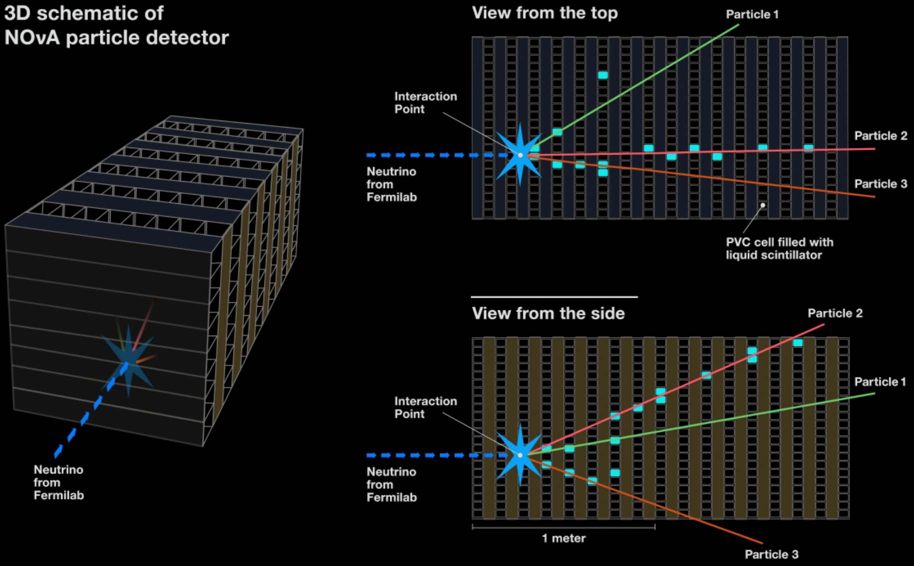
$$P_{\cos\delta} = a\frac{8J_{CP}\cot\delta_{CP}}{A(1-A)}\cos\Delta\sin(A\Delta)\sin[(1-A)\Delta]$$

and where

$$\Delta = \Delta m^2_{31}L/4E, \quad A = \sqrt{3}G_F N_e 2E/\Delta m^2_{31}, \quad a = |\Delta m^2_{21}|/|\Delta m^2_{31}|,$$

$$J_{CP} \equiv \frac{1}{8}\sin 2\vartheta_{12}\sin 2\vartheta_{13}\sin 2\vartheta_{23}\cos\vartheta_{13}\sin\delta_{CP}.$$

NOνA Detectors Design

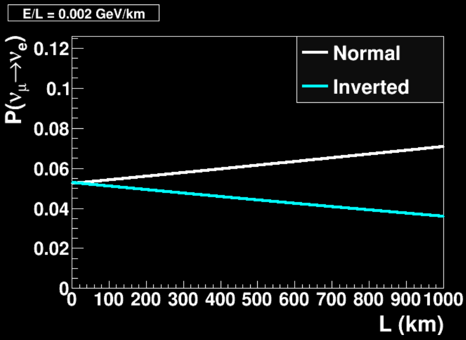


Determining Mass Hierarchy

- Matter effect enhances/decrease osc. amplitude for normal/inverted Hierarchy.
- Can employ different L's to alter size of matter effect

Example:

- Consider first oscillation max for: $\nu_\mu \to \nu_e$: $E/L = 0.002\ \mathrm{GeV/km}$
- Amplitude of first max changes with, L, and sign of Δm^2_{13}



$P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ w/ different baselines (NH)