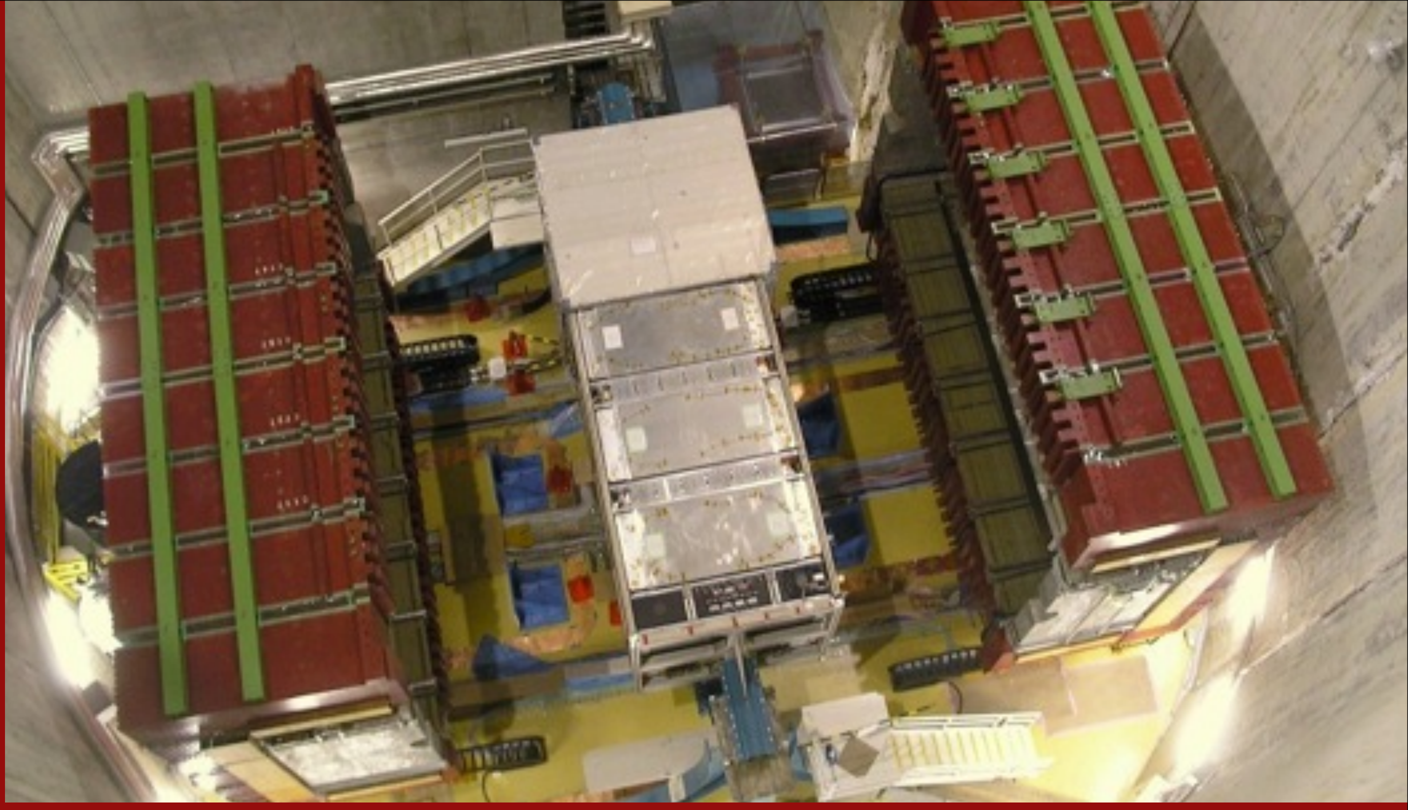


ν Oscillation Results From T2K

T. Wongjirad (Duke) on behalf of T2K

Outline

1. Brief review of neutrino oscillations and current state of measurements
2. Description of the T2K experiment
3. Present our latest oscillation results:
    1. Muon neutrino disappearance
    2. Electron neutrino appearance

State of Oscillation Measurements

3 Neutrino mixing matrix using the standard parameterization and
List of current parameter values

Flavor States

Note: $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$

Mass States

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1}/2 & 0 & 0 \\ 0 & e^{i\alpha_2}/2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

atmospheric/ accelerator	reactor/ accelerator	solar	Majorana phases
$\theta_{23} \sim$ **41°± 7.5°**	$\theta_{13} \sim$ **9.1°± 0.6°**	$\theta_{12} \sim$ **34°± 1°**	not yet observed
From Global Fits MINOS/SK	$\delta\theta_{13} \sim$ **7%**	$\delta\theta_{12} \sim$ **3%**	
	δ_{CP} **not measured**		

Mass Splittings

ν_3

$\Delta m^2_{32} \approx 2.5 \times 10^{-5}\ \mathrm{eV}^2/c^4$

ν_2

$\Delta m^2_{12} = 7.5 \times 10^{-5}\ \mathrm{eV}^2/c^4$

ν_1

Normal Hierarchy

OR

ν_2

$\Delta m^2_{12} = 7.5 \times 10^{-5}\ \mathrm{eV}^2/c^4$

ν_1

$\Delta m^2_{32} \approx 2.5 \times 10^{-5}\ \mathrm{eV}^2/c^4$

ν_3

Inverted Hierarchy

$\delta\Delta m^2_{32/13} \sim$ **4%**

$\delta\Delta m^2_{21} \sim$ **3%**

State of Oscillation Measurements

3 Neutrino mixing matrix using the standard parameterization and
List of current parameter values

Flavor States

Note: $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$

Mass States

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1}/2 & 0 & 0 \\ 0 & e^{i\alpha_2}/2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

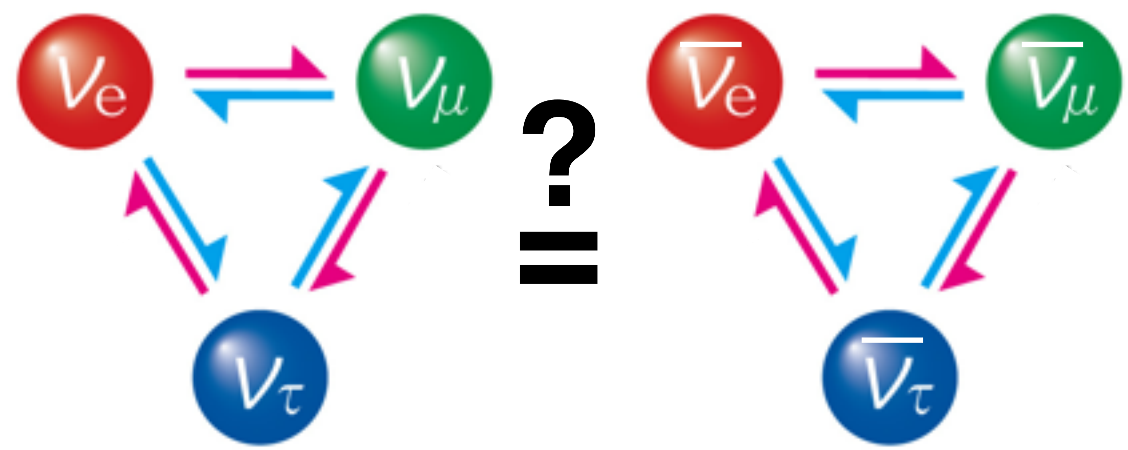
atmospheric/ accelerator	reactor/ accelerator	solar	Majorana phases
$\theta_{23} \sim$ **41°± 7.5°**	$\theta_{13} \sim$ **9.1°± 0.6°**	$\theta_{12} \sim$ **34°± 1°**	not yet observed
From Global Fits MINOS/SK	$\delta\theta_{13} \sim$ **7%**	$\delta\theta_{12} \sim$ **3%**	
	δ_{CP} **not measured**		

Almost all pars. measured with good precision
Exception: $\boldsymbol{\delta_{CP}}$ which has yet to be measured

$\delta\Delta m^2_{32/13} \sim$ **4%**
$\delta\Delta m^2_{21} \sim$ **3%**

Search for CP Violation

Can look for leptonic CP violation with oscillations



Testing for CP-violation is a top priority for the field

Method: Compare oscillation probabilities for v and anti-v

$$P_{\nu_\mu \to \nu_e} - P_{\bar{\nu}_\mu \to \bar{\nu}_e}$$
$$= -4\sin(2\theta_{12})\sin^2(2\theta_{23})\cos^2(\theta_{13}) \cdot [\boxed{\sin\delta_{CP}}\sin\theta_{13}] \cdot \sin\frac{\Delta m^2_{32}L}{4E}\sin\frac{\Delta m^2_{31}L}{4E}\sin\frac{\Delta m^2_{21}L}{4E}$$

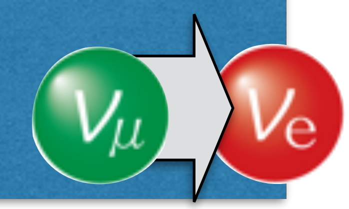
can look for CP-violation this way because all parameters other than δ_{CP} are now known to be non-zero

note: no matter effects in probability

Search for CP Violation

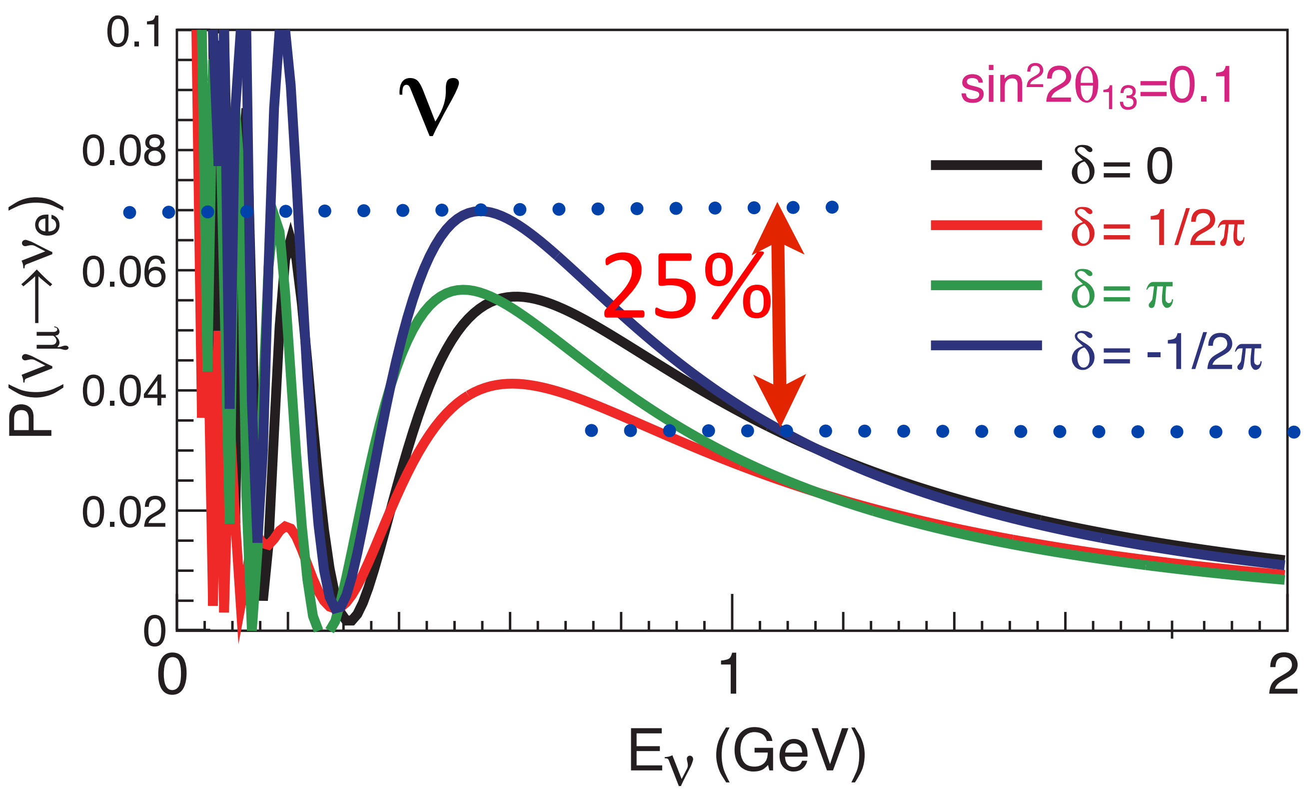
Another method:

Because reactors measured large θ_{13} with good precision, can start search for $\delta_{CP}\neq 0$ using precision measurements of



$$P(\nu_\mu \to \nu_e) = (\sin^2\theta_{23}\sin^2\theta_{13}$$
$$-\boxed{\sin\delta_{CP}}\sin\theta_{13}\cos\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\sin\frac{\Delta m^2_{21}L}{4E})\sin^2\frac{\Delta m^2_{31}L}{4E} + \ldots$$

Osc. Prob for different δ_{CP}



effect of δ_{CP} can be large for a given $\sin^2 2\theta_{13}$ value

current experiments (like T2K and NOvA) can begin search for hints of non-zero δ_{CP}

requires precision on all θ, Δm^2

value of $\boldsymbol{\theta_{23}}$ *important*

Oscillations at T2K

T2K designed to measure

ν_μ Disappearance: goal to measure **θ_{23} and Δm^2_{32}**

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right) + ...$$

ν_e Appearance: goal to measure **θ_{13}** and constrain **δ_{CP}**

$$P(\nu_\mu \rightarrow \nu_e) = (\sin^2\theta_{23}\sin^2\theta_{13}$$

$$- \sin\delta_{CP}\sin\theta_{13}\cos\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\sin\frac{\Delta m^2_{21}L}{4E})\sin^2\frac{\Delta m^2_{31}L}{4E} + ...$$

Where are the tau's?

At T2K energy (~0.6 GeV), ν_τ charged current interactions energetically forbidden as cannot produce τ lepton
— result: most ν_μ seem to "disappear"

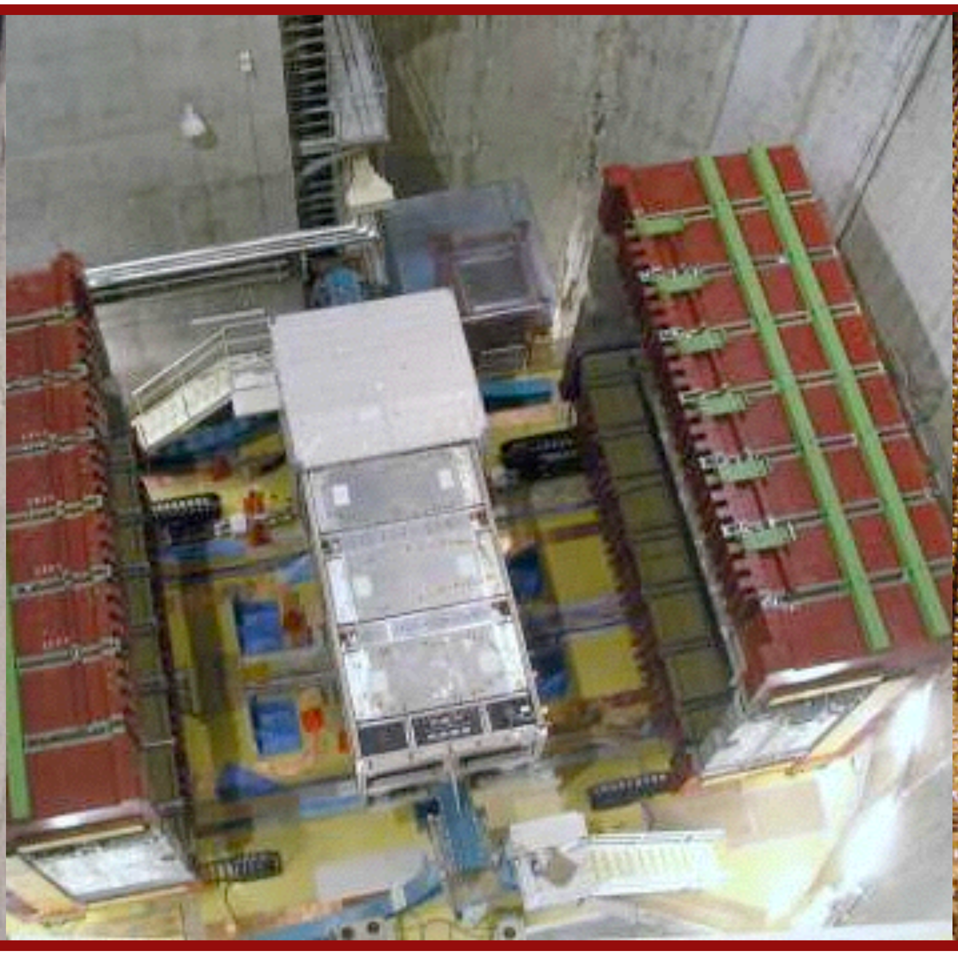
T2K Experiment

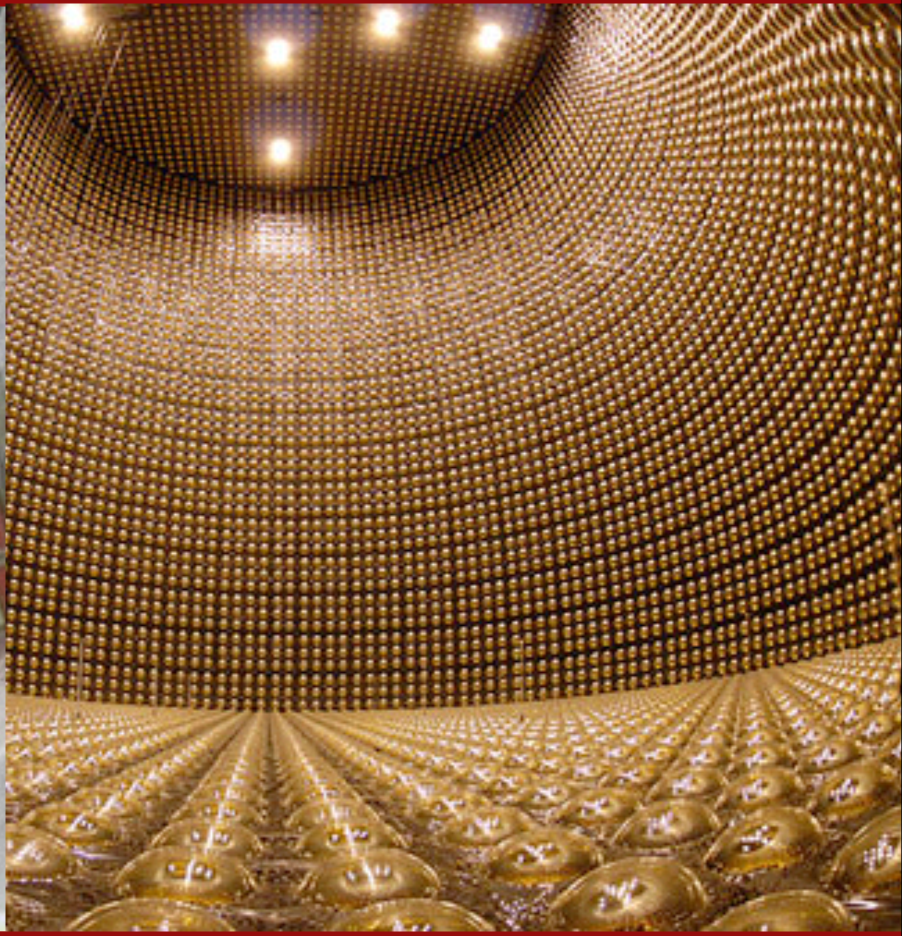
T2K Consists of Three Components

J-PARC

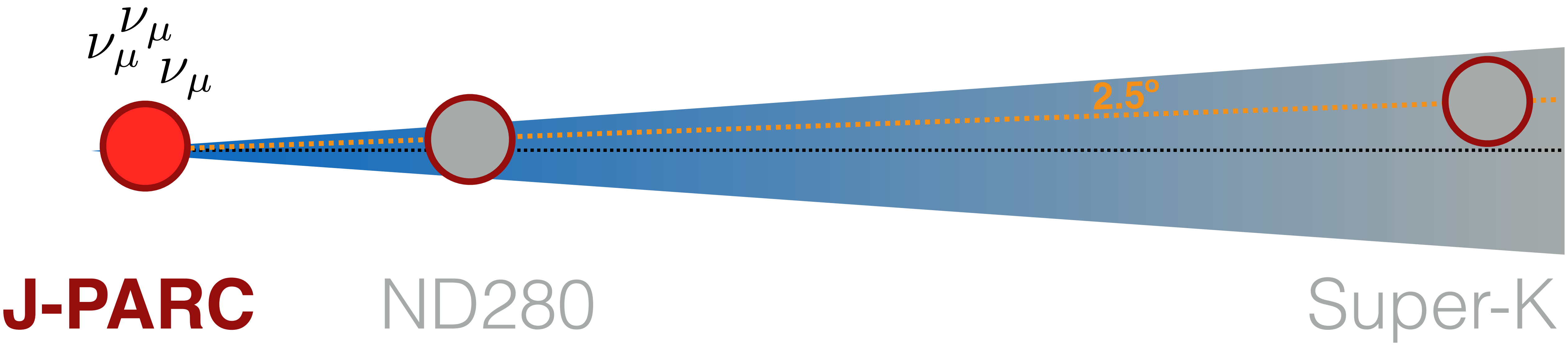
ND280

Super-K





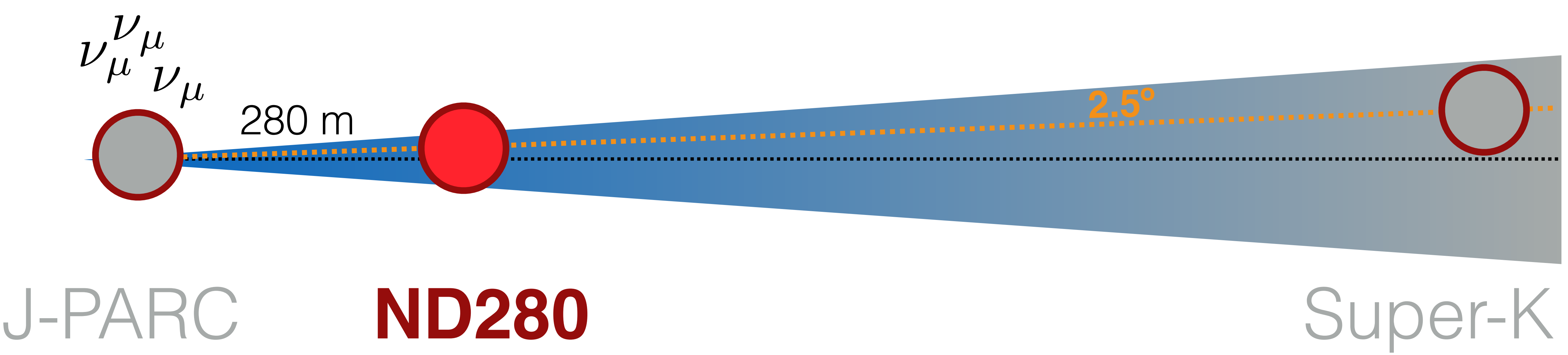
T2K Experiment



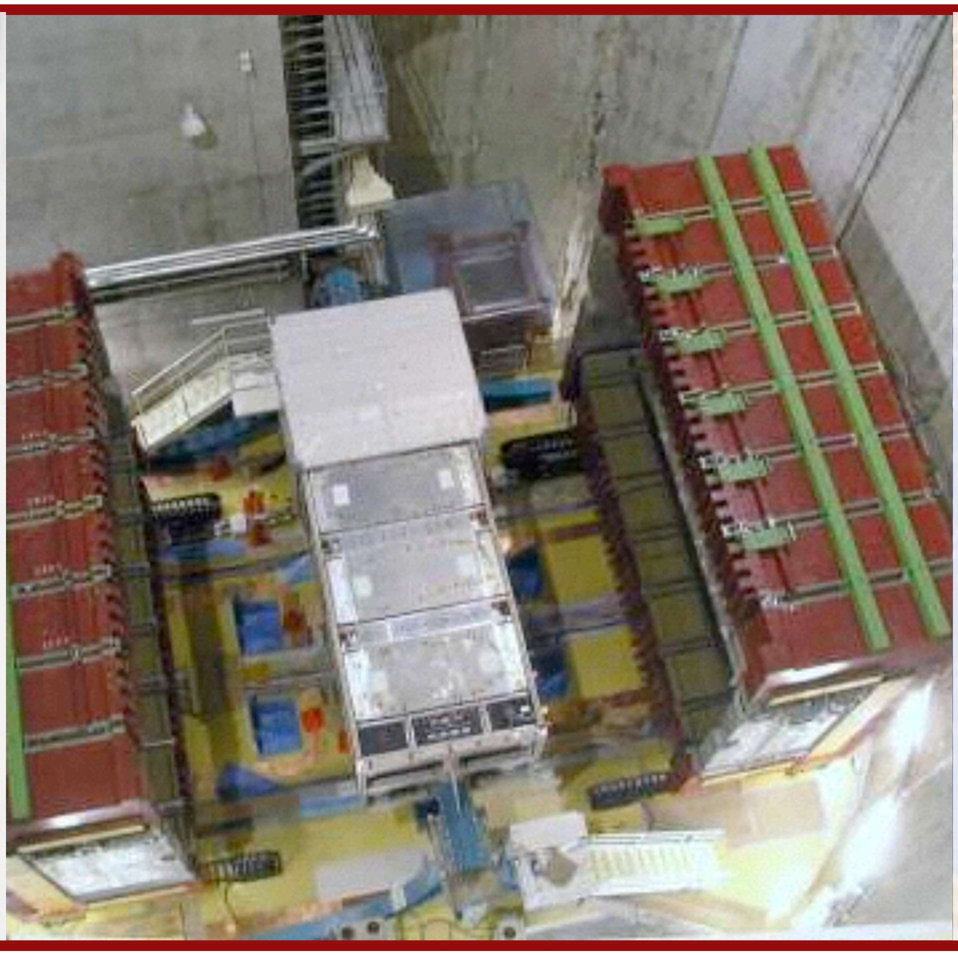
J-PARC creates a beam of mostly muon neutrinos

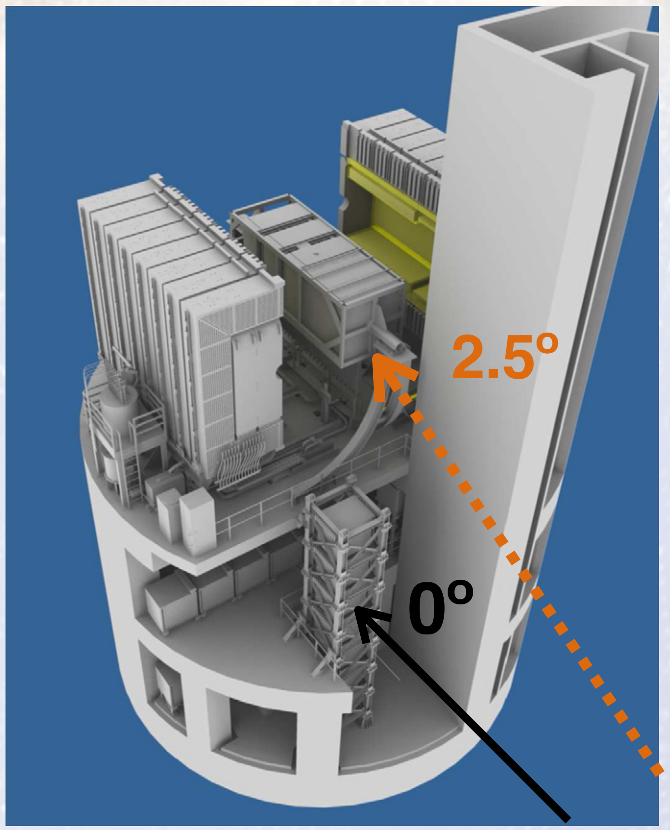
Beam is directed toward 2 detectors located 2.5° off-axis from the center of the beam

T2K Experiment

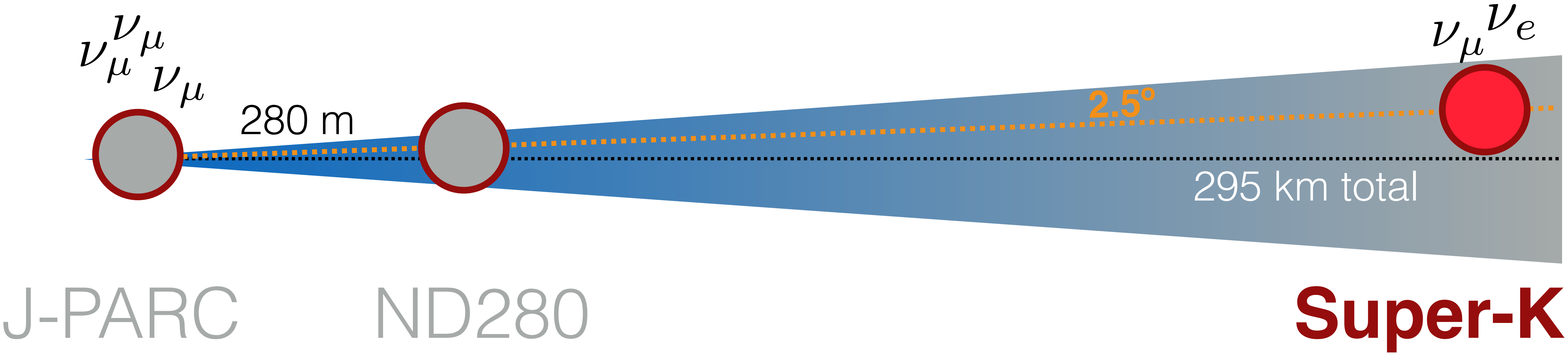


Near Detector
Complex measures neutrino beam prior to oscillations



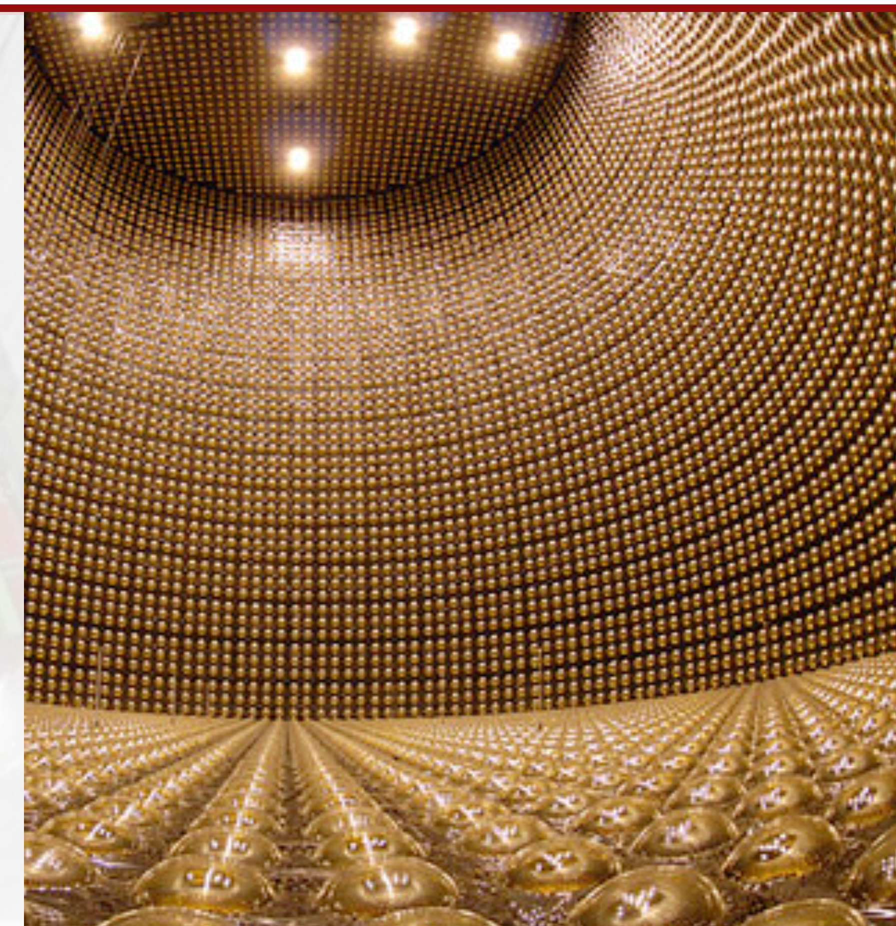


T2K Experiment

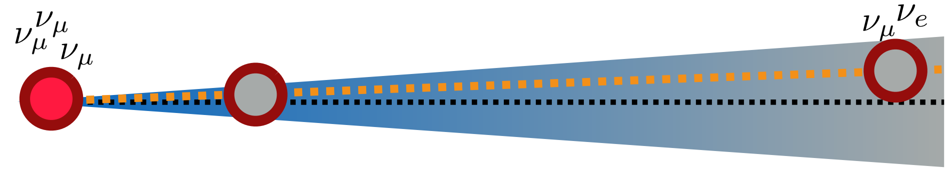


Far Detector **Super-Kamiokande**

detects muon
and electron neutrinos and
measures oscillations



J-PARC Beam



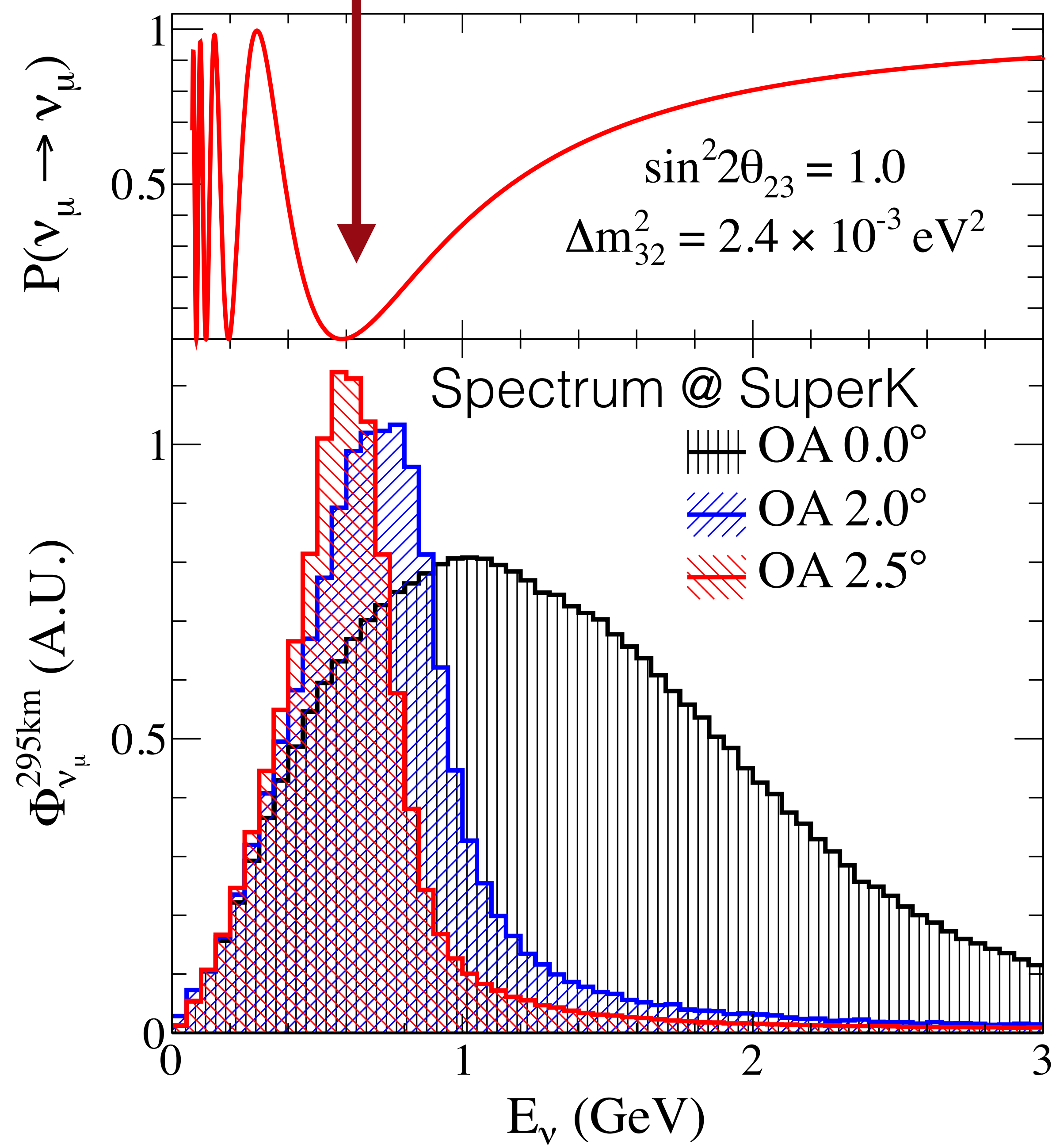
2.5° Off-axis beam from JPARC
maximizes oscillation effect at SuperK

Previous experiments suggest largest oscillation dip near 600 MeV

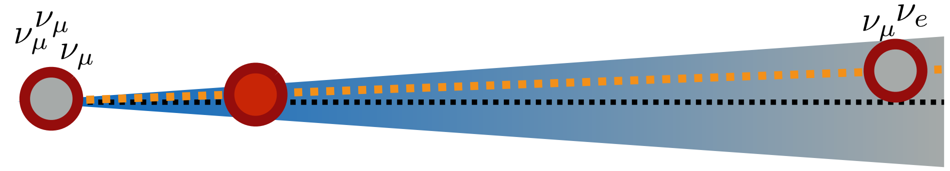
On-axis beam spectrum broad

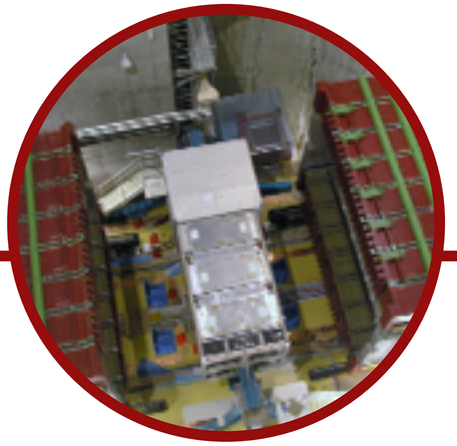
Neutrino energy spectrum at 2.5° off-axis is narrow and peaked right at dip

At 2.5° off-axis, maximum fraction of spectrum oscillates, improving analysis sensitivity



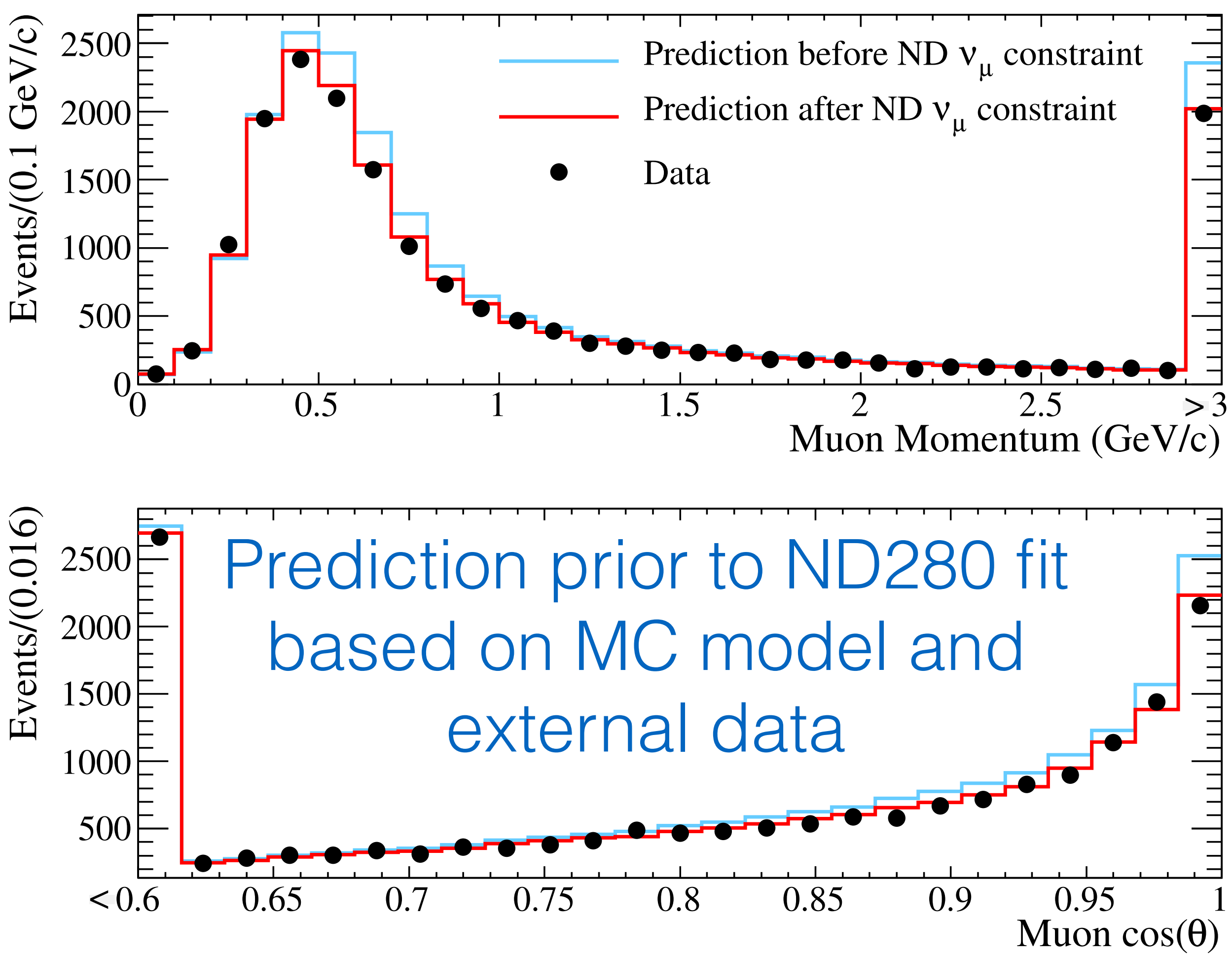
ND280



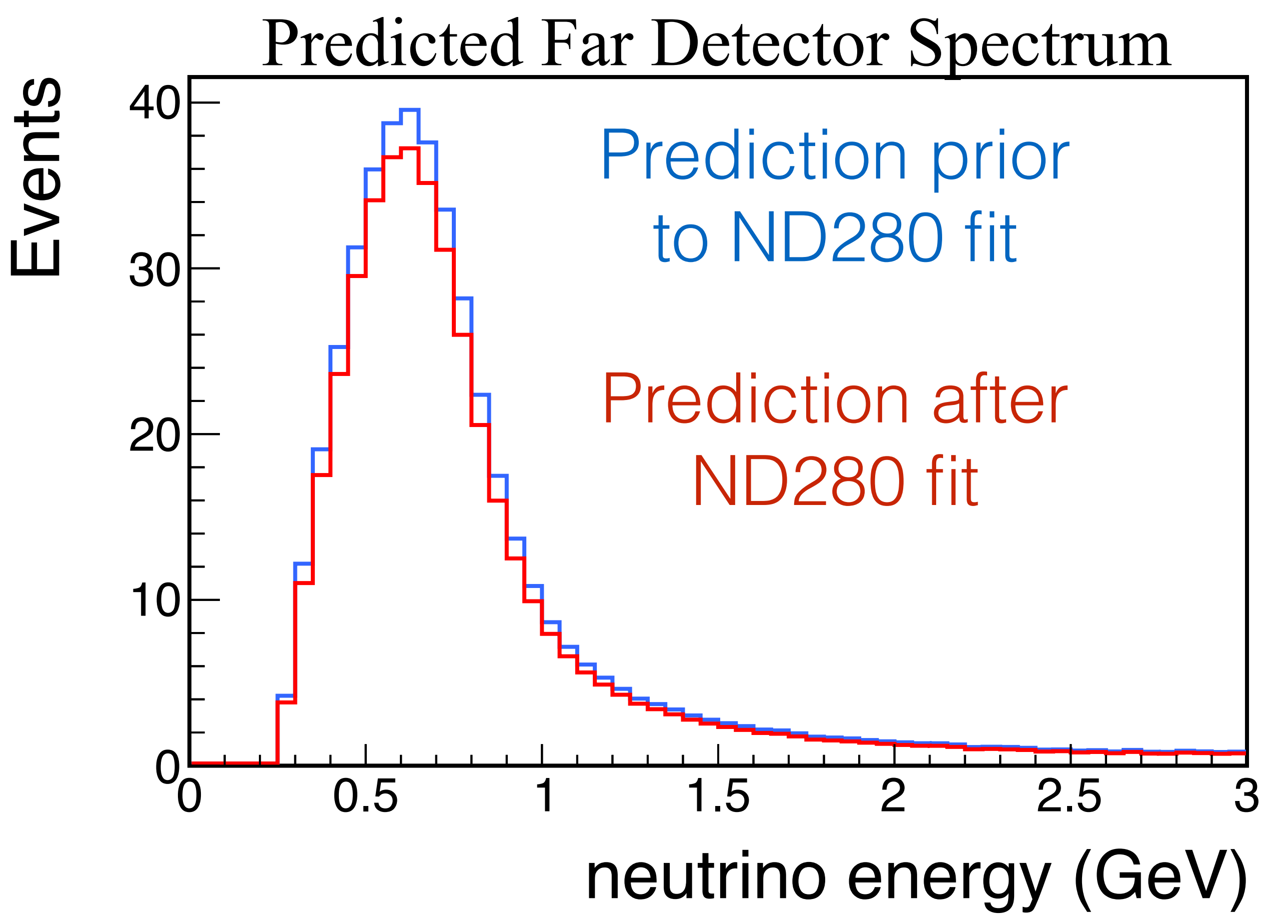


Fit of near detector data tunes parameters of flux and xsec model for both near and far detectors

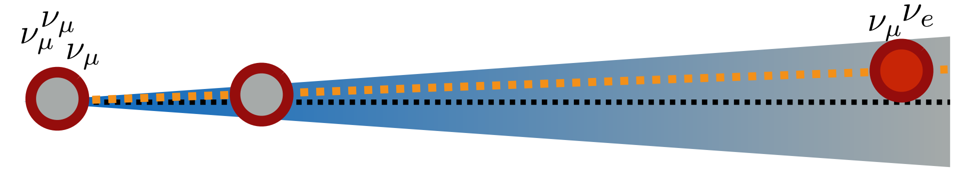
model of ND280 spectrum is fit to ND280 data (CC 0π sub-sample)

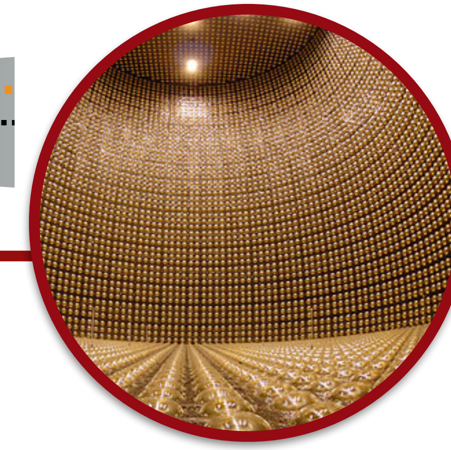


Parameters from ND fit passed to model of far detector spectrum



SuperK



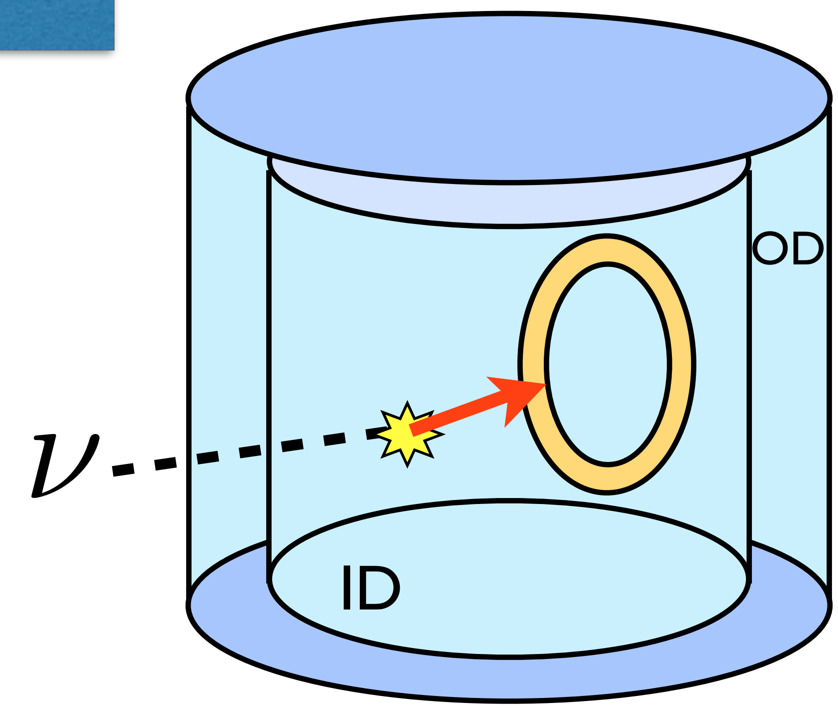


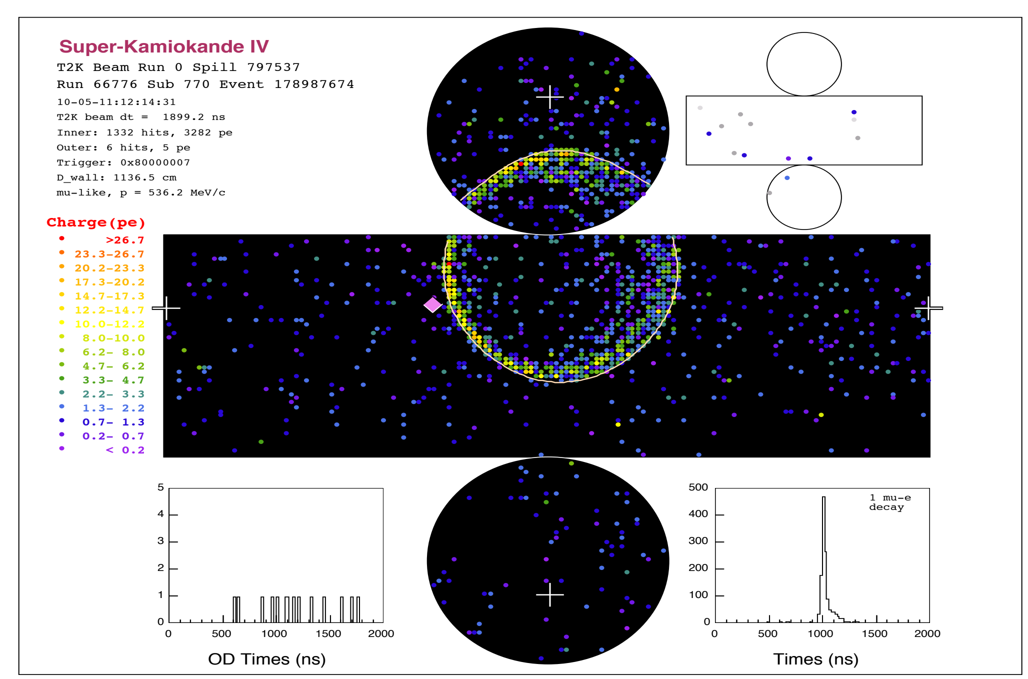
Neutrinos at SuperK used for Osc. Analysis

Large water Cherenkov detector with 22.5 ktonne of fiducial mass instrumented with 13K PMTs

Charge particles travel through water and produce Cherenkov light — leaves ring of PMT hits on wall

PMT hit pattern gives information for reconstructing momentum and for <u>lepton flavor ID, i.e μ vs. e</u>





Oscillation Analyses

Oscillation Analyses

- ν_μ disappearance
- ν_e appearance

Oscillation Analyses

Muon Neutrino Disappearance

New result — released last week

ν_μ Disappearance: goal to measure **θ_{23} and Δm^2_{32}**

$$P(\nu_\mu \to \nu_\mu) = 1 - (\cos^4 \theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23}) \sin^2 \left(\frac{\Delta m^2_{32} L}{4E} \right) + ...$$

External Constraint Used

θ_{13} constraint according to PDG2012

Combined from recent measurements *Daya Bay, Double Chooz, RENO*

Oscillation Analyses

Muon Neutrino Appearance

New result — released last week

ν_μ Disappearance: goal to measure **θ_{23} and Δm^2_{32}**

$$P(\nu_\mu \to \nu_\mu) = 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) + \ldots$$

Note: T2K Analyses use full oscillation formula

External Constraint Used

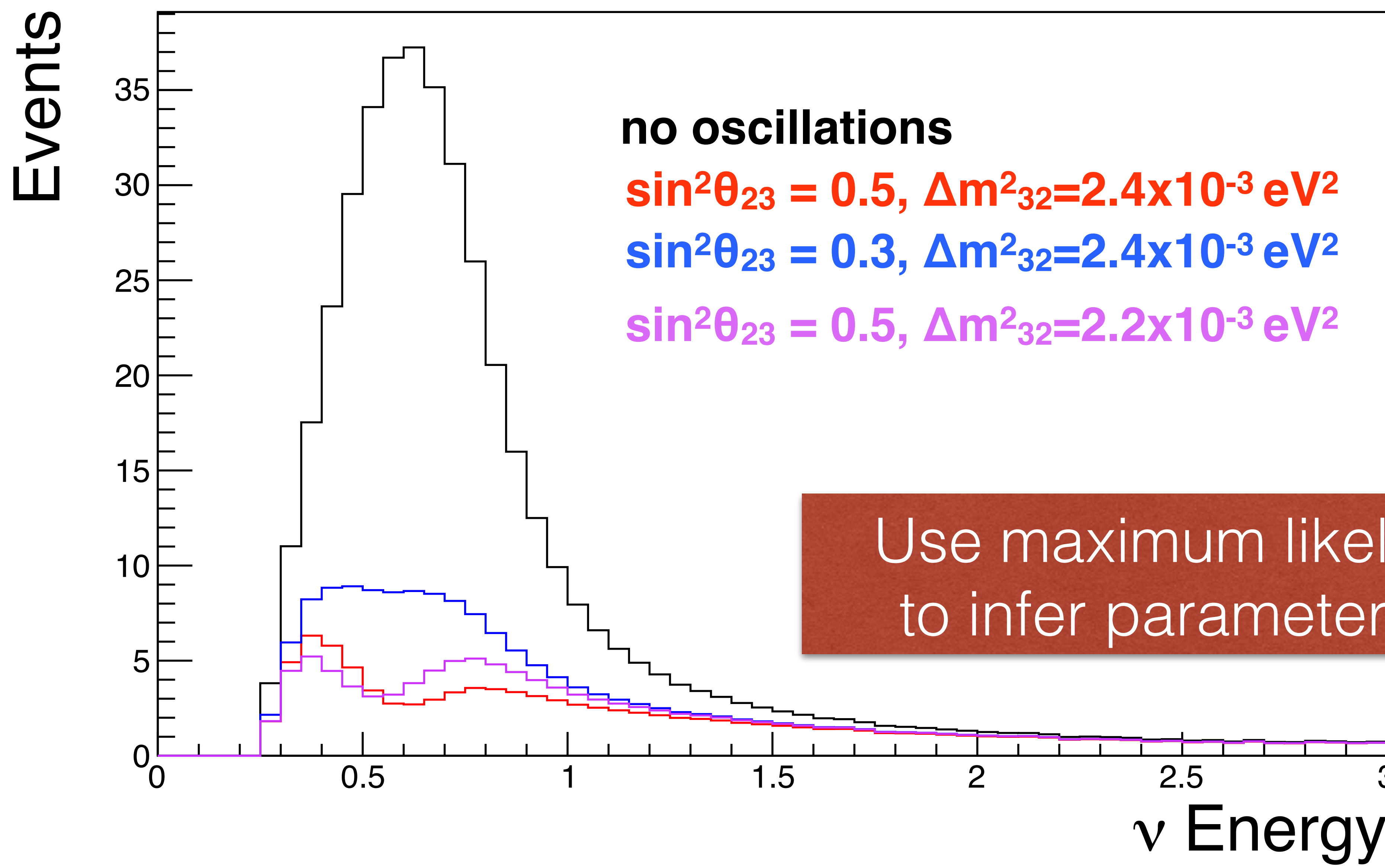
θ_{13} constraint from reactor experiments

Using recent measurements several reactor neutrino experiments *Daya Bay, Double Chooz, RENO*

ν_μ Disappearance

Oscillation parameters extracted from observed neutrino energy spectrum at SuperK

MC Spectrum at SuperK for different oscillation values



Use maximum likelihood fit to infer parameter values

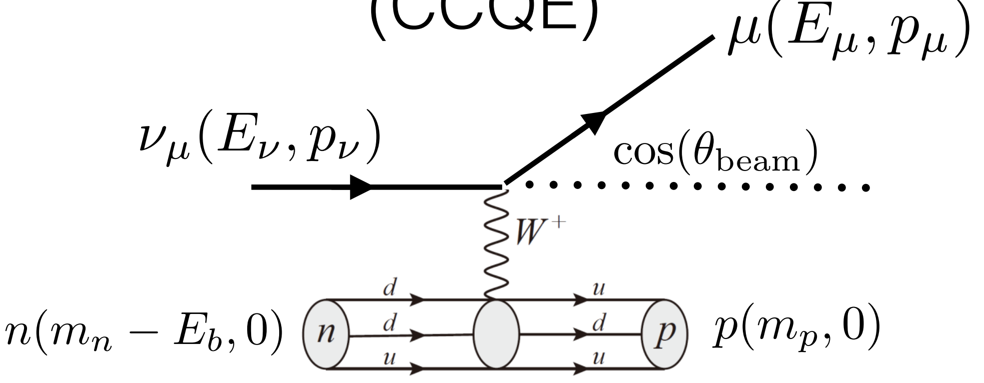
ν_μ Disappearance

Event Selection

Choose events with most reliable reconstruction of neutrino energy

Aim is to select events from CCQE channel

Signal Channel
charged current quasi-elastic (CCQE)



E_b = nucleus binding energy

For CCQE, single muon mom. + beam direction gives neutrino energy

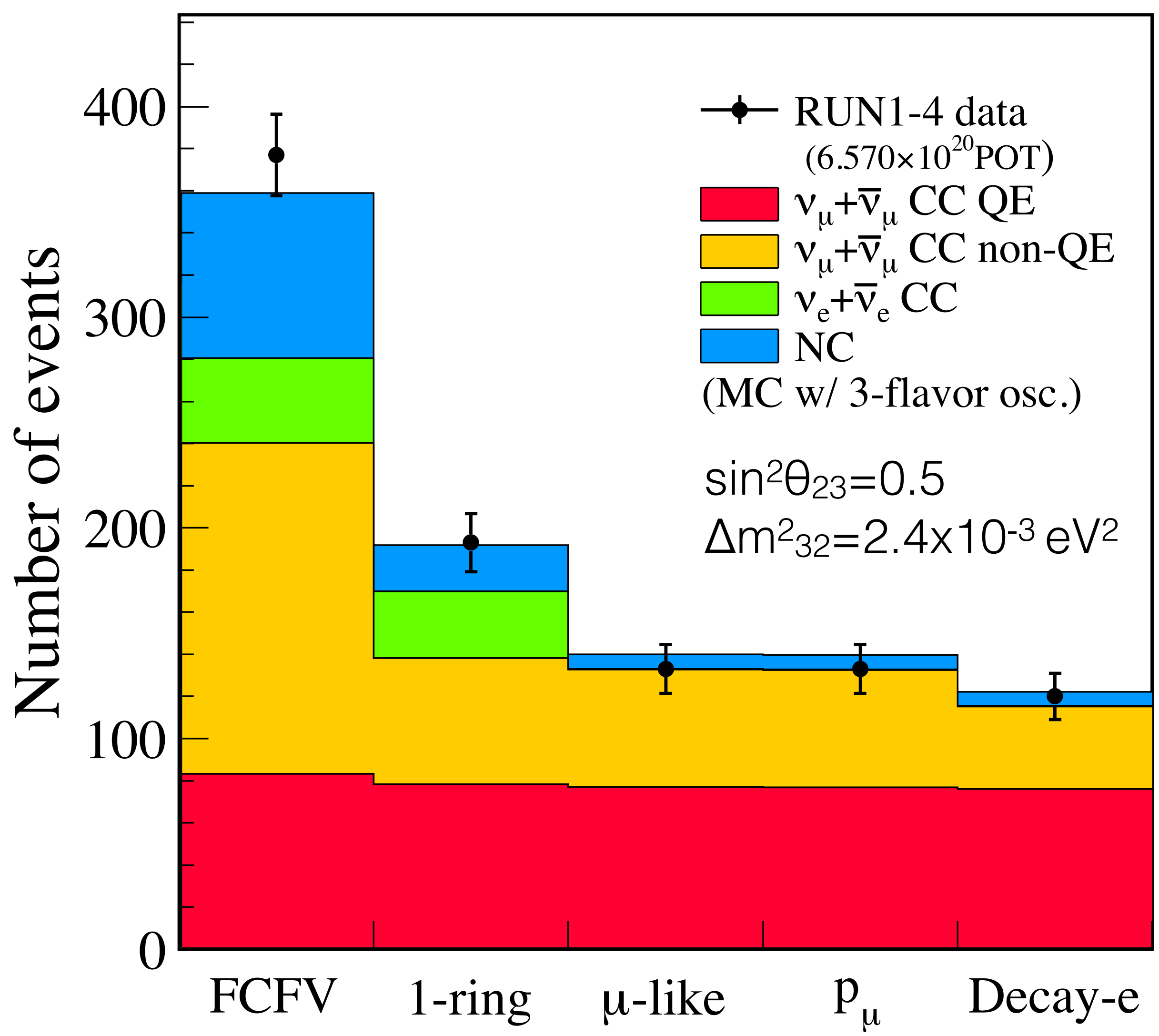
$$E_{\text{reco}} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_{\text{beam}})}$$

At SuperK, select events with single muon

ν_μ Disappearance

Event Selection

From data, **choose single muon events** in far detector



Each stage of selection agrees well with MC

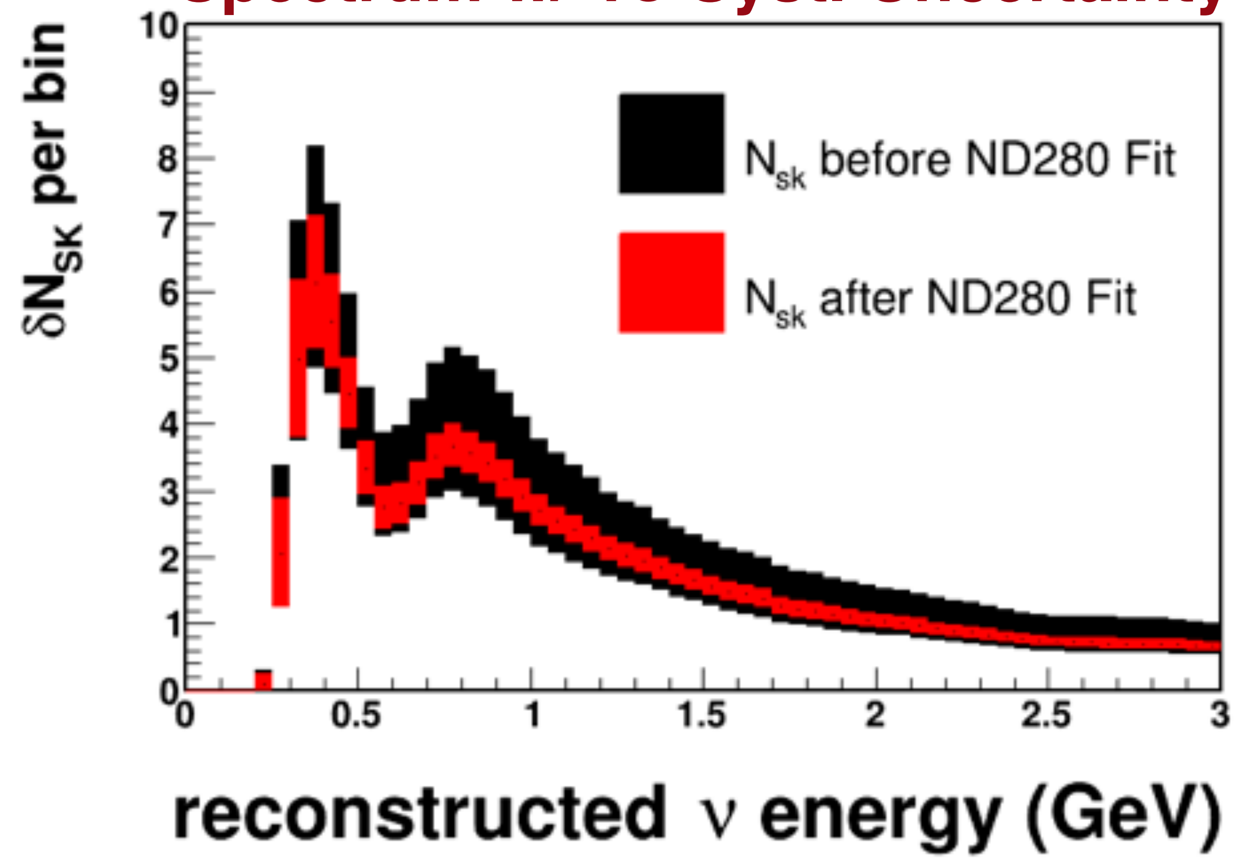
- **FCFV:** Fully contained in detector and event inside fiducial volume
- **1-ring:** 1 particle in Super-K
- ***μ*-like:** track using flavor ID
- **p_μ:** momentum >200 MeV
- **Decay e:** Decay electrons <= 1

ν_μ Disappearance

Analysis includes systematic uncertainties in spectrum from flux, interaction models, and SuperK detector errors

Spectrum Uncertainties	**% Variation of # of Events due to systematic error**
Flux/xsec constrained by ND280	2.7
Super-K only xsec	4.9
Super-K Efficiencies/Hadronic interactions in water	5.6
$\sin^2(\theta_{12})$, $\sin^2(\theta_{13})$, Δm^2_{12}, Δm^2_{13}, δ_{CP}	0.2
Total	**8.1**

Spectrum w/ 1σ Syst. Uncertainty



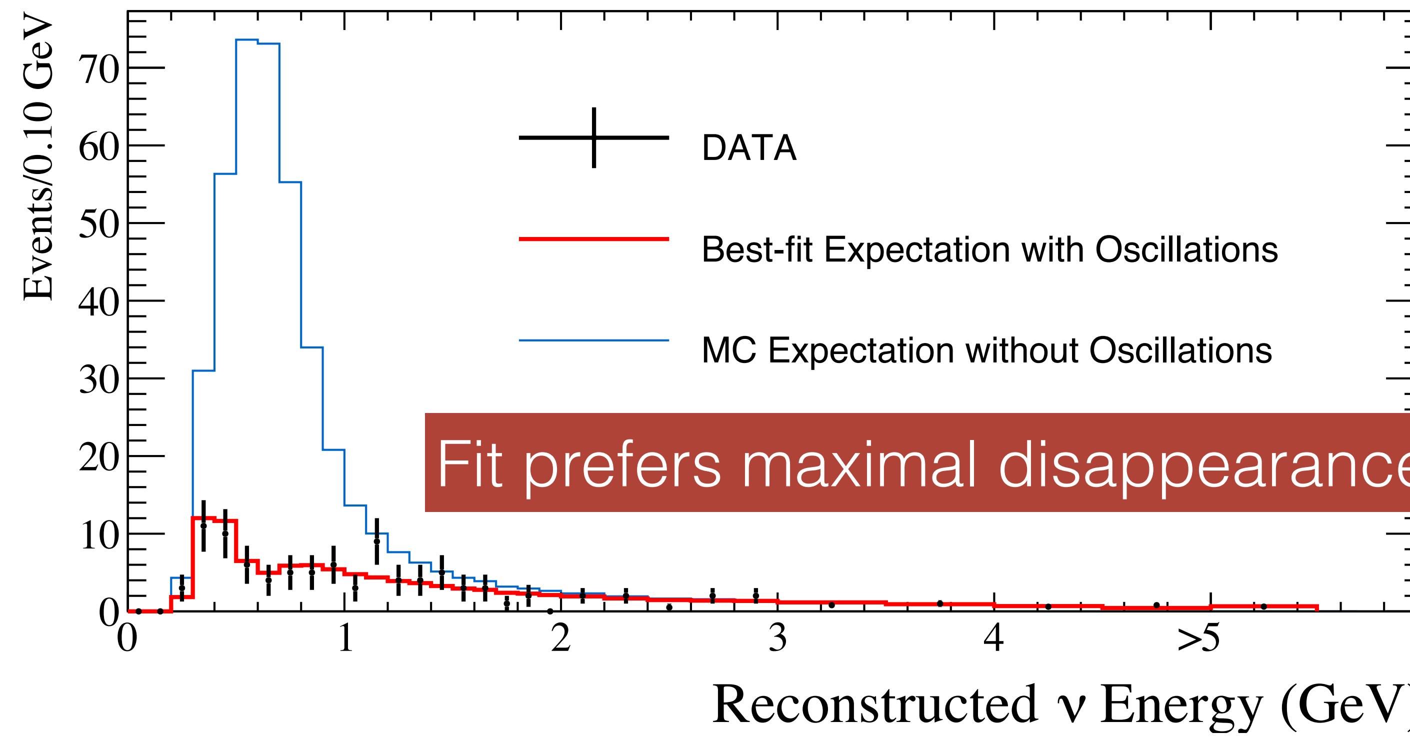
ND280 fit gives large reduction in spectrum uncertainty from flux and some xsecs δN_{SK} from ~**21% → 2.7%!**

ν_μ Disappearance

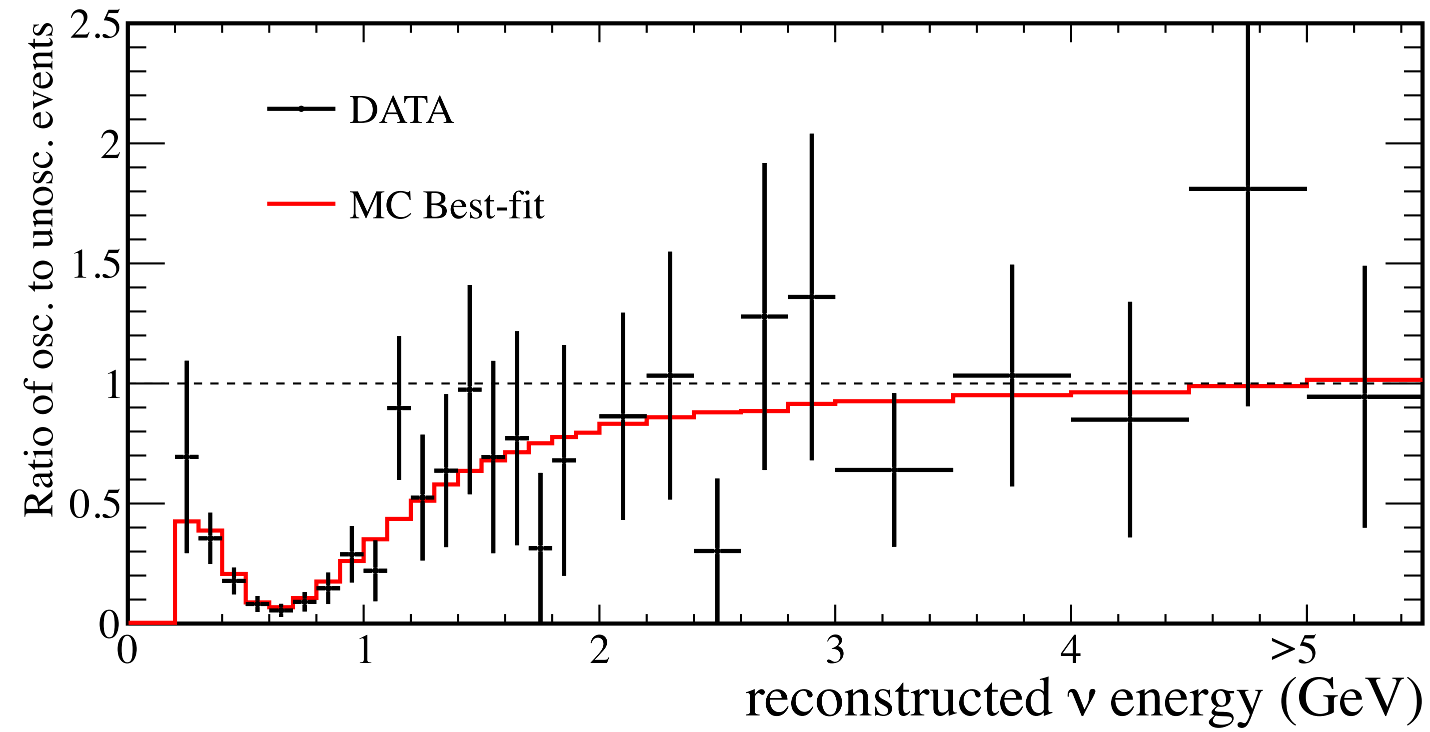
Fit to 120 Single Muon Events

$\sin^2\theta_{23}$ [NH] ([IH])	$0.514^{+0.055}_{-0.056}$ (0.511 ± 0.055)
Δm^2_{32} [NH] (Δm^2_{13} [IH])	$(2.51 \pm 0.1) \times 10^{-3}$ eV^2 $((2.48 \pm 0.1) \times 10^{-3}$ eV$^2)$
N_{exp} [NH] ([IH])	121.41 (121.39)

Fit run twice with different hierarchy assumption
[NH] Normal
[IH] Inverted



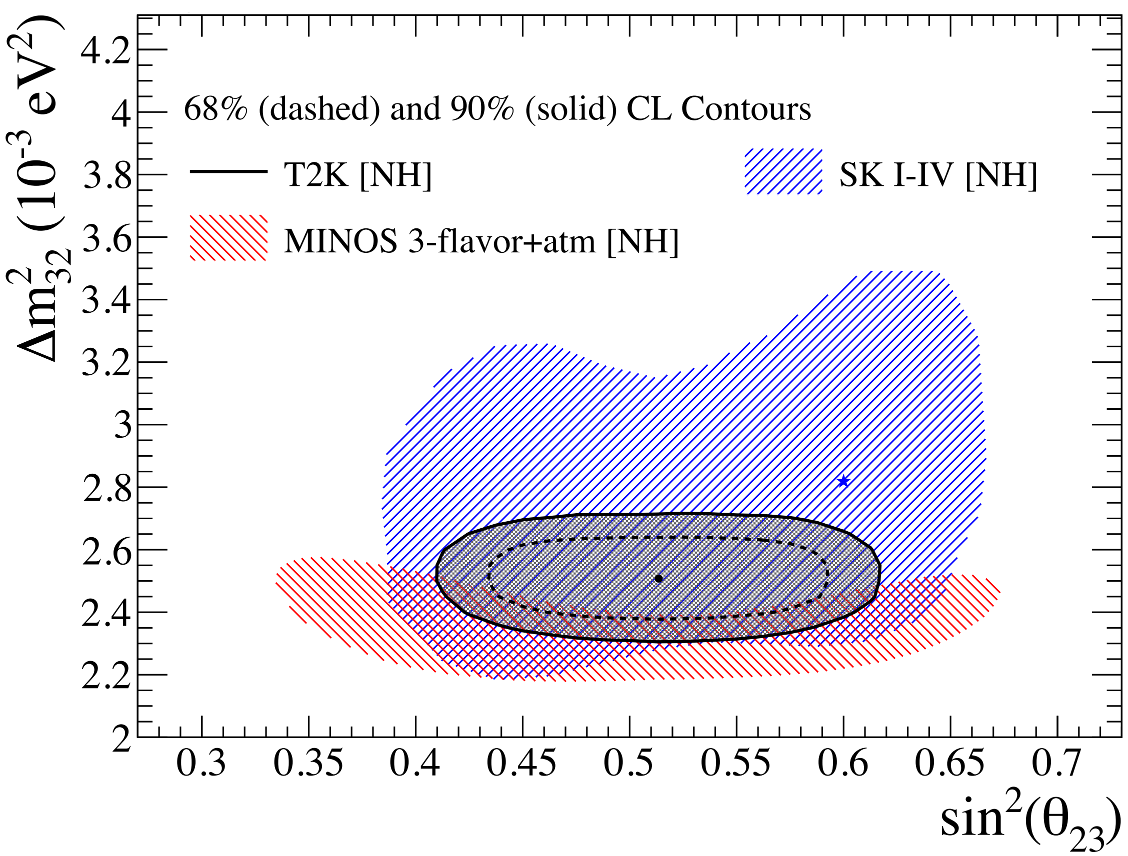
Fit prefers maximal disappearance



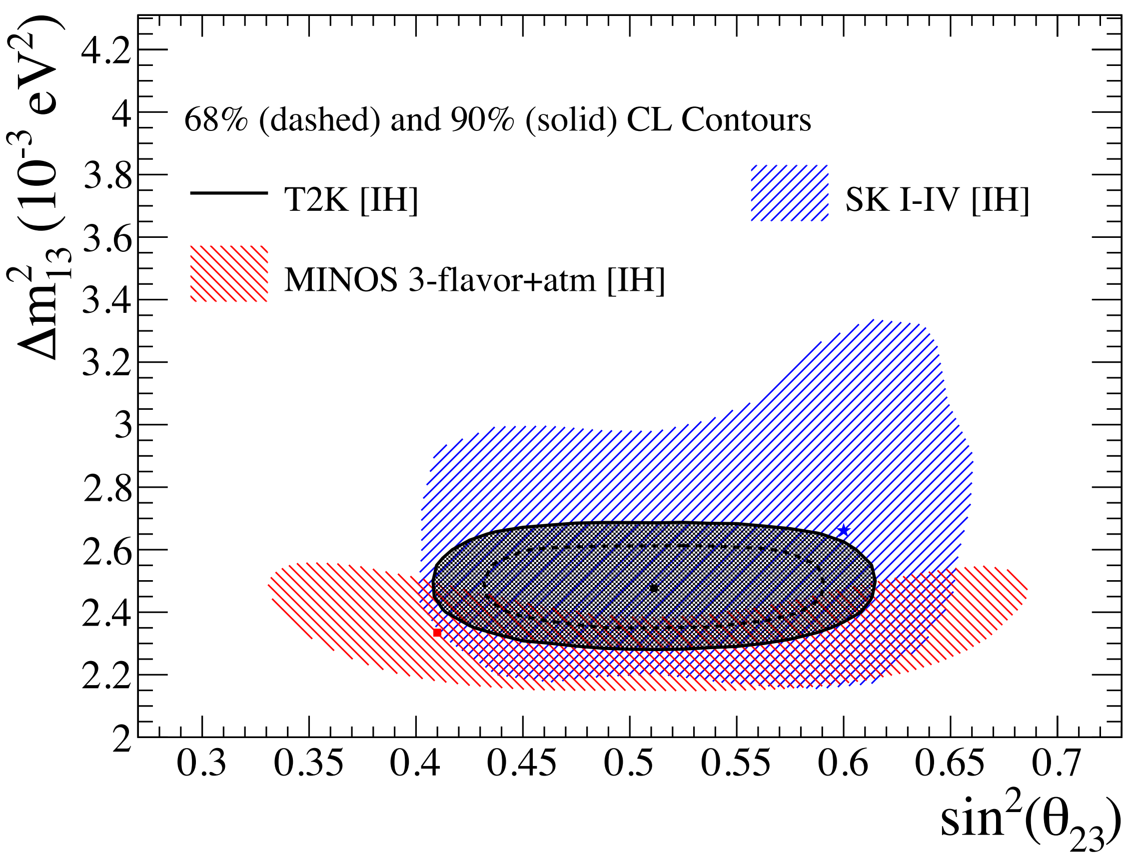
ν_μ Disappearance Result

T2K has the current best 90% CL constraint on $\sin^2(\theta_{23})$

Normal Hierarchy Fit



Inverted Hierarchy Fit



T2K contours made with Feldman-Cousins prescription

θ_{23} ~ **41°± 7.5°**

T2K → **45.8°± 6.4°**

$\delta\theta_{13}$ ~**7%** $\delta\theta_{12}$ ~**3%** $\delta\Delta m^2_{21}$~**3%** $\delta\Delta m^2_{32/13}$~**4%**

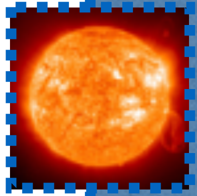
Oscillation Analysis

Electron Neutrino Appearance

ν_e Appearance: measurement of **θ_{13}** and constrain **δ_{CP}**

$$P(\nu_\mu \to \nu_e) = (\sin^2\theta_{23}\sin^2\theta_{13}$$
$$- \sin\delta_{CP}\sin\theta_{13}\cos\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\sin\frac{\Delta m^2_{21}L}{4E})\sin^2\frac{\Delta m^2_{31}L}{4E} + \ldots$$

External Constraints Used



θ_{12} and Δm^2_{21} constrained by solar experiments

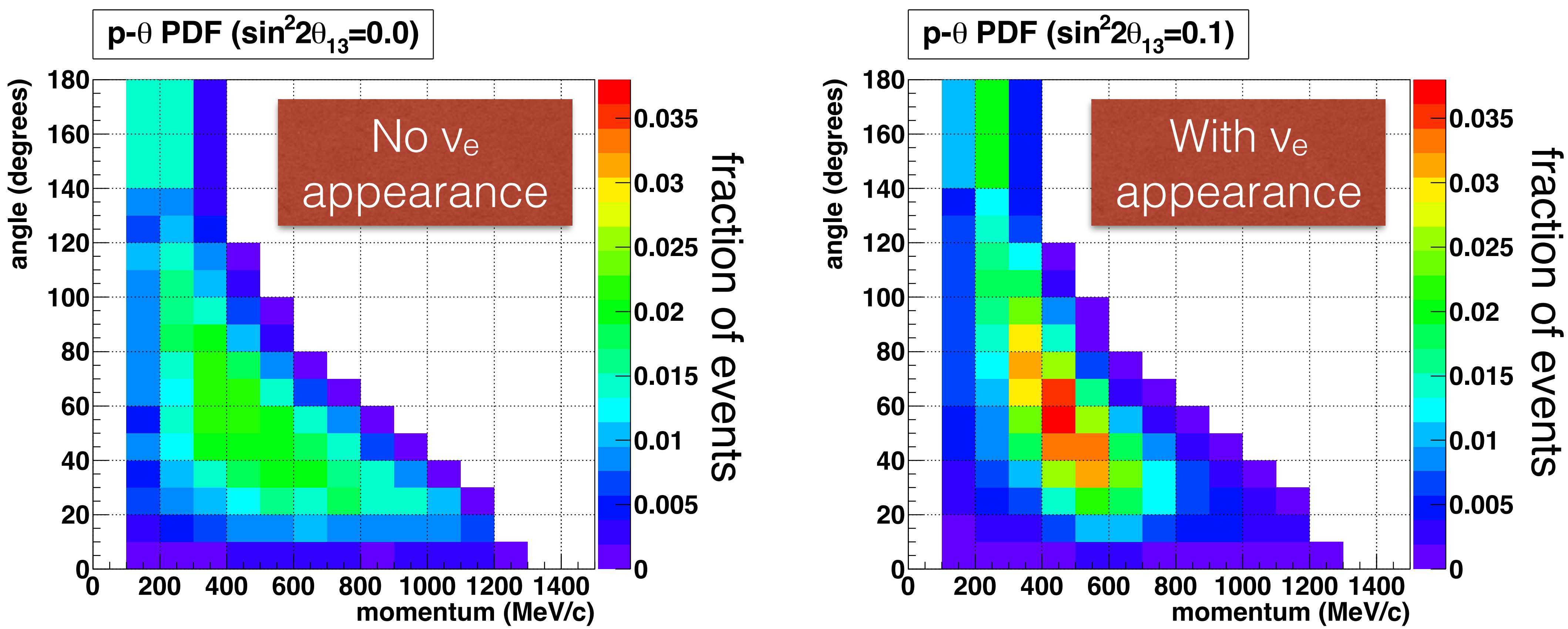
θ_{23} and Δm^2_{32} constrained by previous T2K measurement

ν_e Appearance

ν_e appearance uses (p,θ) distribution for fit

Using CCQE interactions for signal (like ν_μ disappearance)

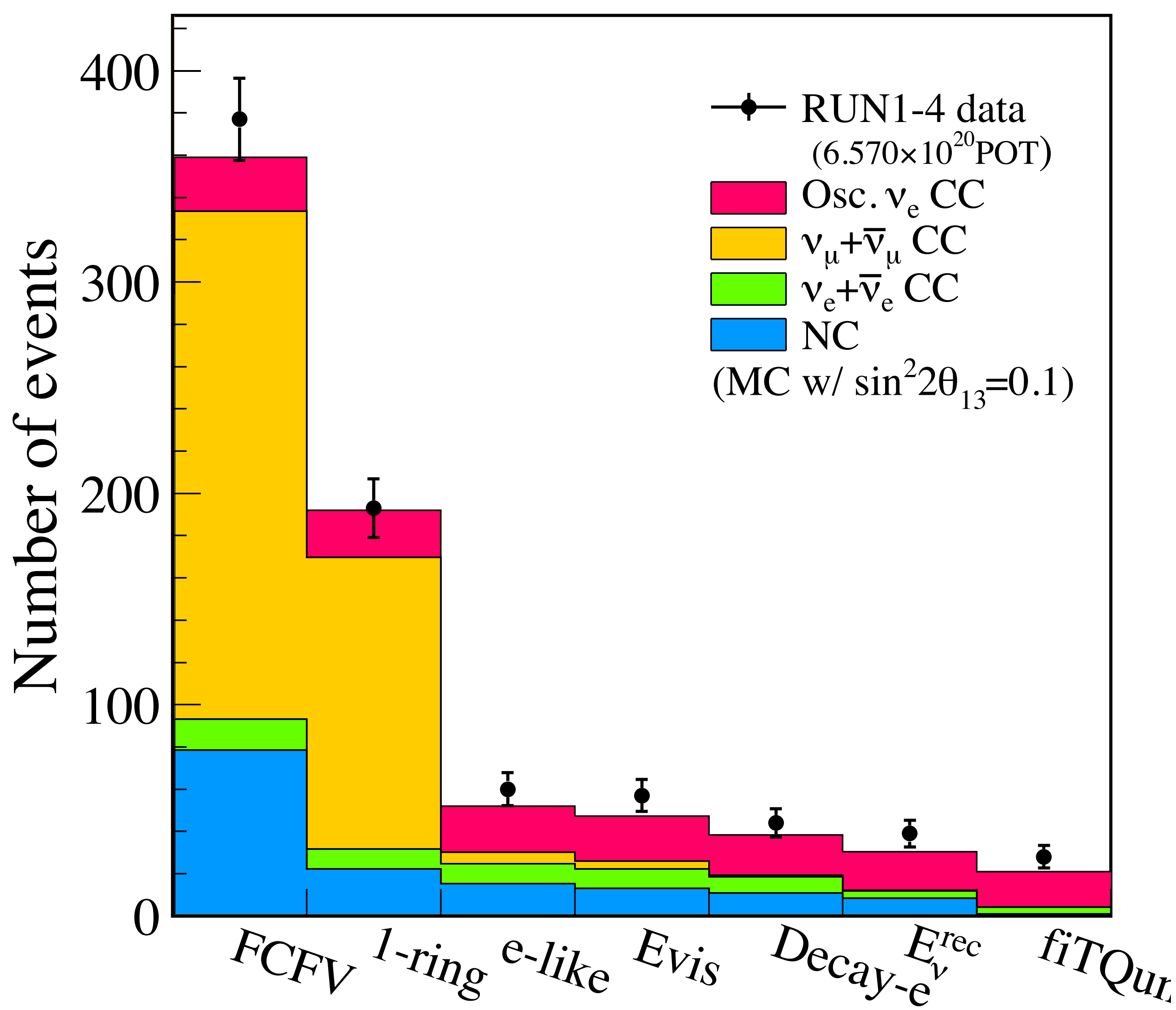
- Selected events are single electron tracks at SuperK
- Reliable particle reconstruction
- (p,θ) used to help separate signal and background



ν_e Appearance

Event Selection

From data, choose single electron events in far detector

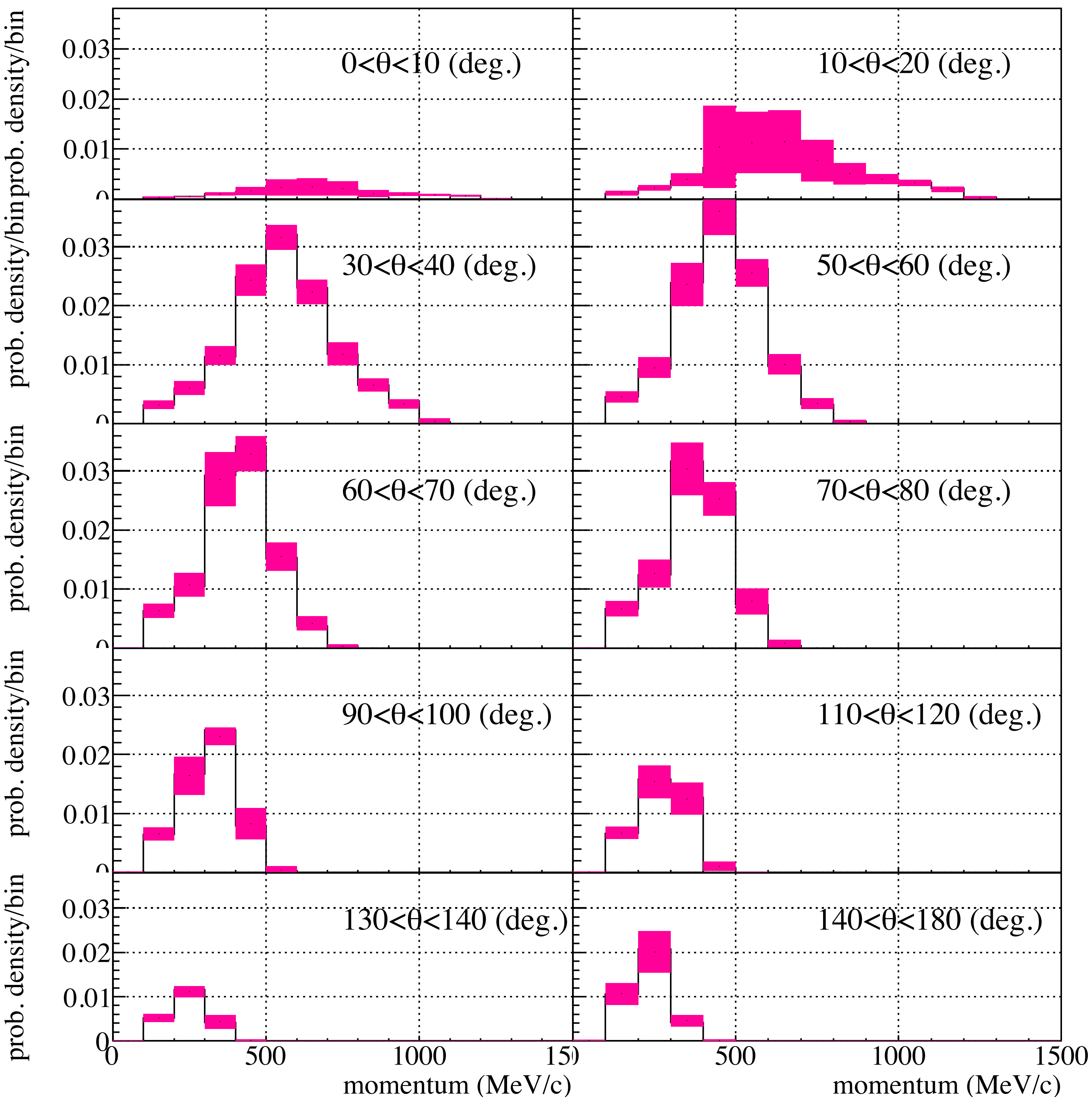


Each stage of selection agrees well with MC

- **FCFV:** Fully contained in fiducial volume
- **1-ring:** Single ring found
- **e-like:** track electron like
- **Evis:** light seen equal to 100 MeV electron
- **Decay-e:** no decay electrons seen
- **E^{rec}_ν:** energy below 1250 MeV
- **fiTQun:** Events pass π^0 rejection algorithm

ν_e Appearance

Probability density per (p,θ) bin with uncertainties in density shown



Uncertainty in (p,θ) Bins

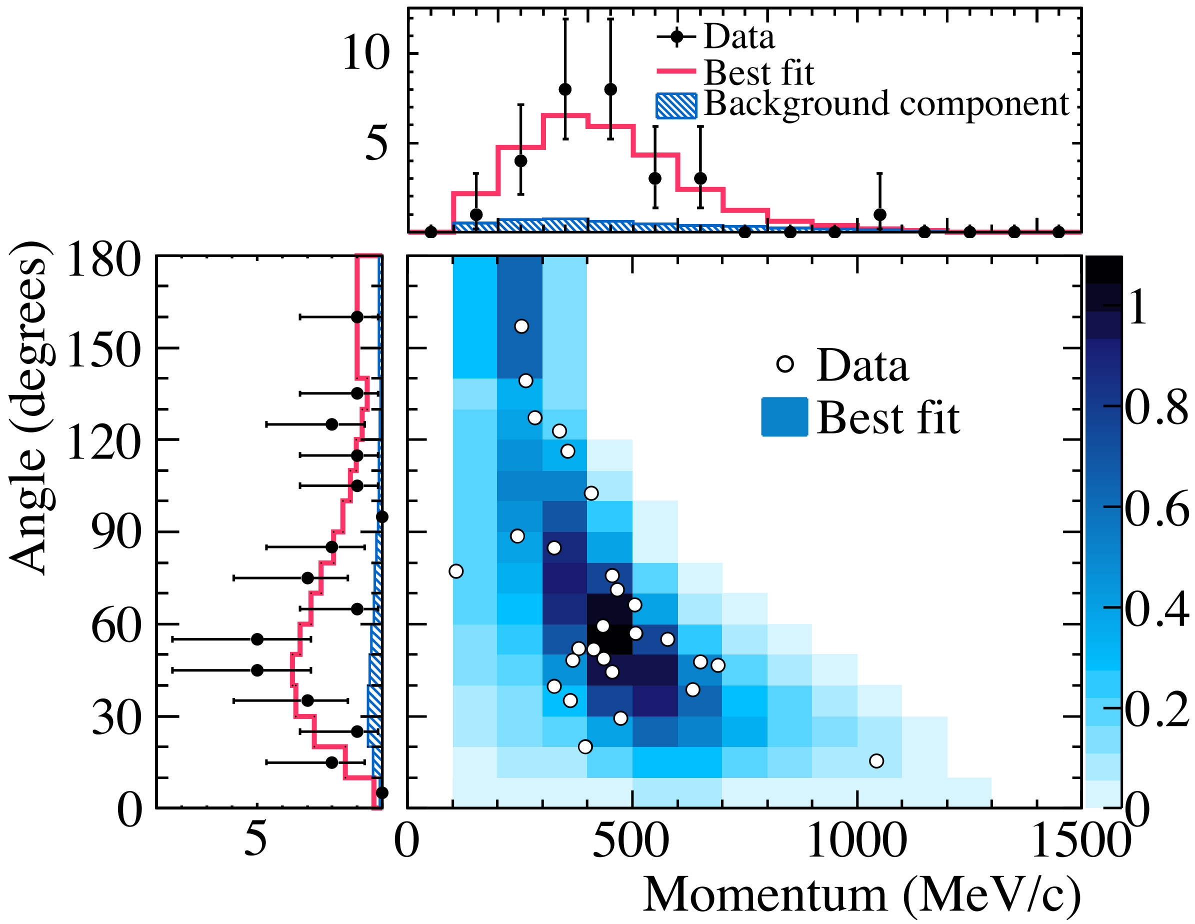
Systematic Uncertainties	% Variation of # of Events due to systematic error
Flux/xsec contrained by ND280	2.9
SuperK-only xsecs	13.8
SuperK Efficiencies/ Hadronic interactions in water	9.9
Total	**18.3**

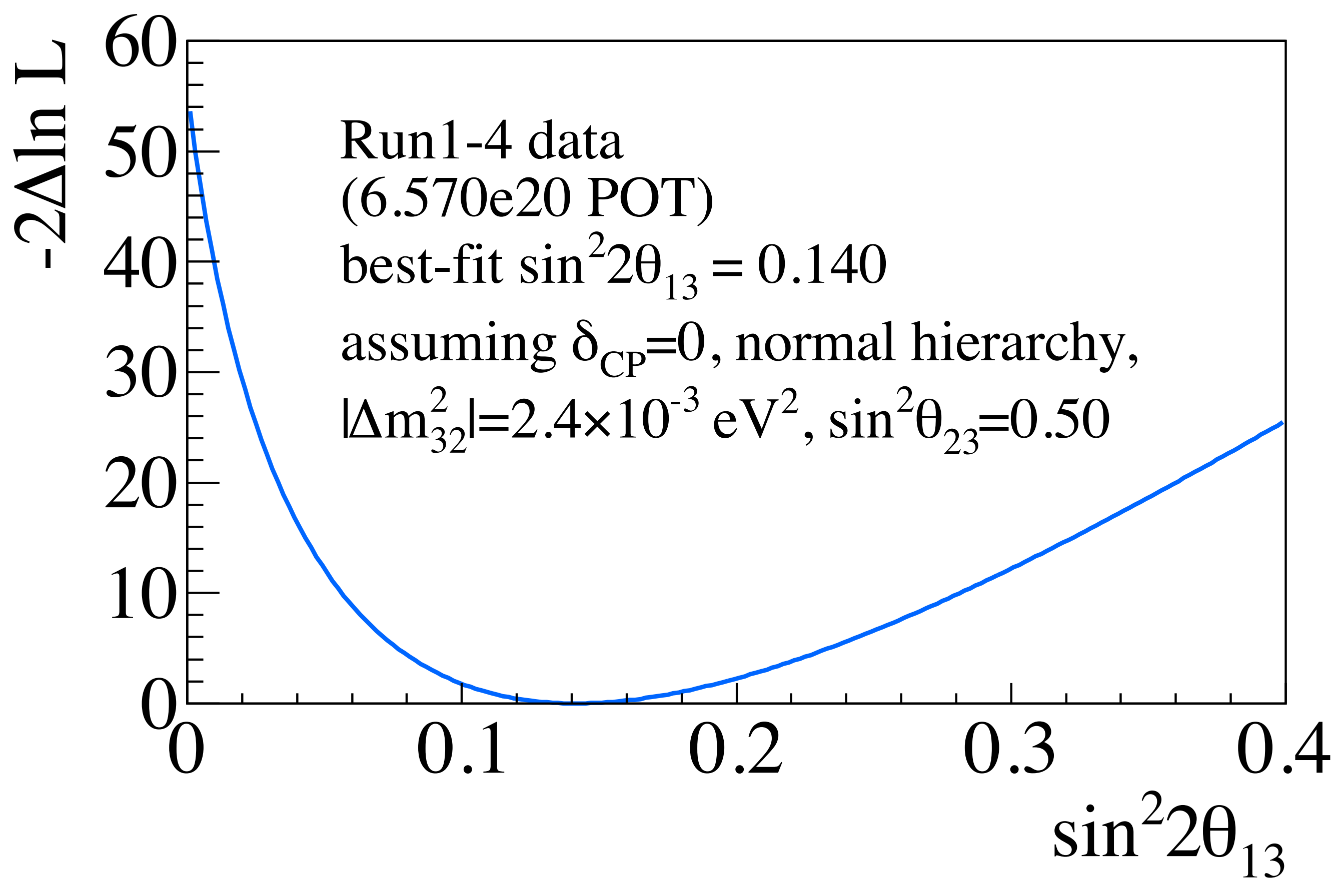
ν_e Appearance

Fit to 28 Single Electron Events

$\sin^2 2\theta_{13}$ [NH] ([IH]) [assuming δ_{CP}=0]	$0.140^{+0.038}_{-0.032}$ ($0.170^{+0.045}_{-0.037}$)

Exclude zero $\sin^2 2\theta_{13}$ to 7.3σ

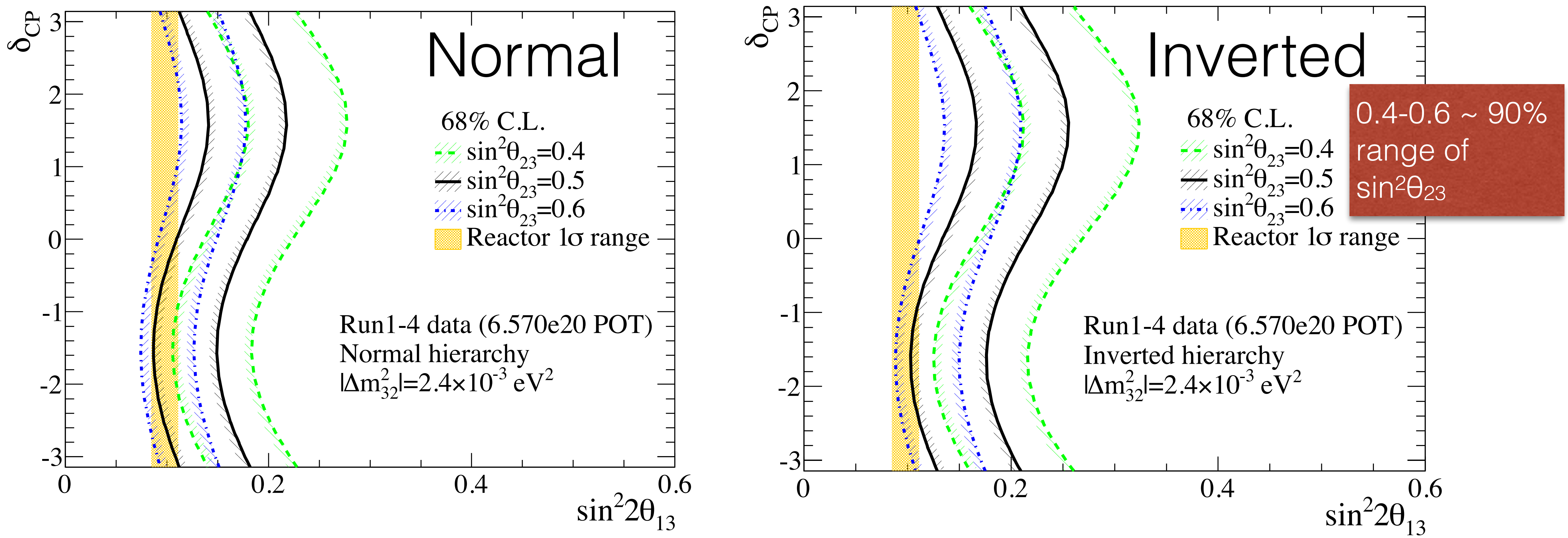




ν_e Appearance

Comparison to reactor measurements of $\sin^2 2\theta_{13}$

Overlay of reactor measurement (via $\bar{\nu}_e$ disappearance) and T2K allowed regions for $\sin^2(2\theta_{13})$ as a function of δ_{CP}



T2K regions shown with different values of assumed $\sin^2\theta_{23}$

Note: These are 1D allowed regions as a function of δ_{CP}

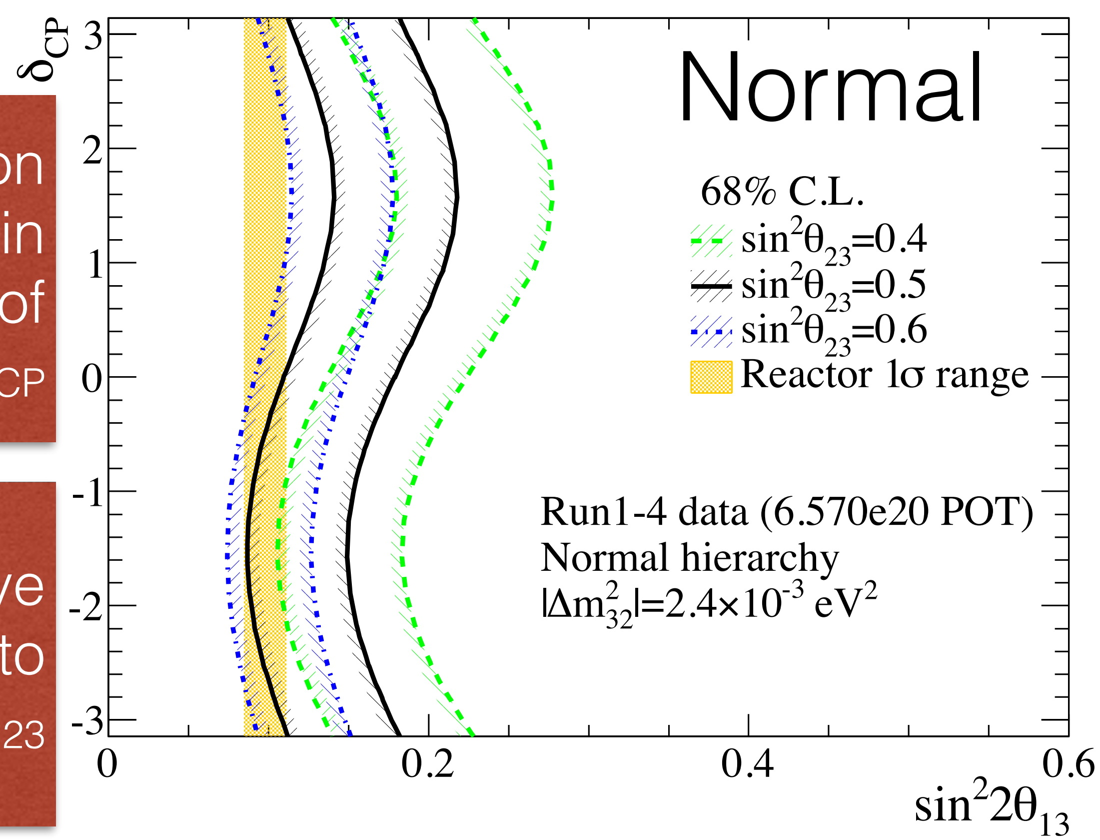
ν_e Appearance

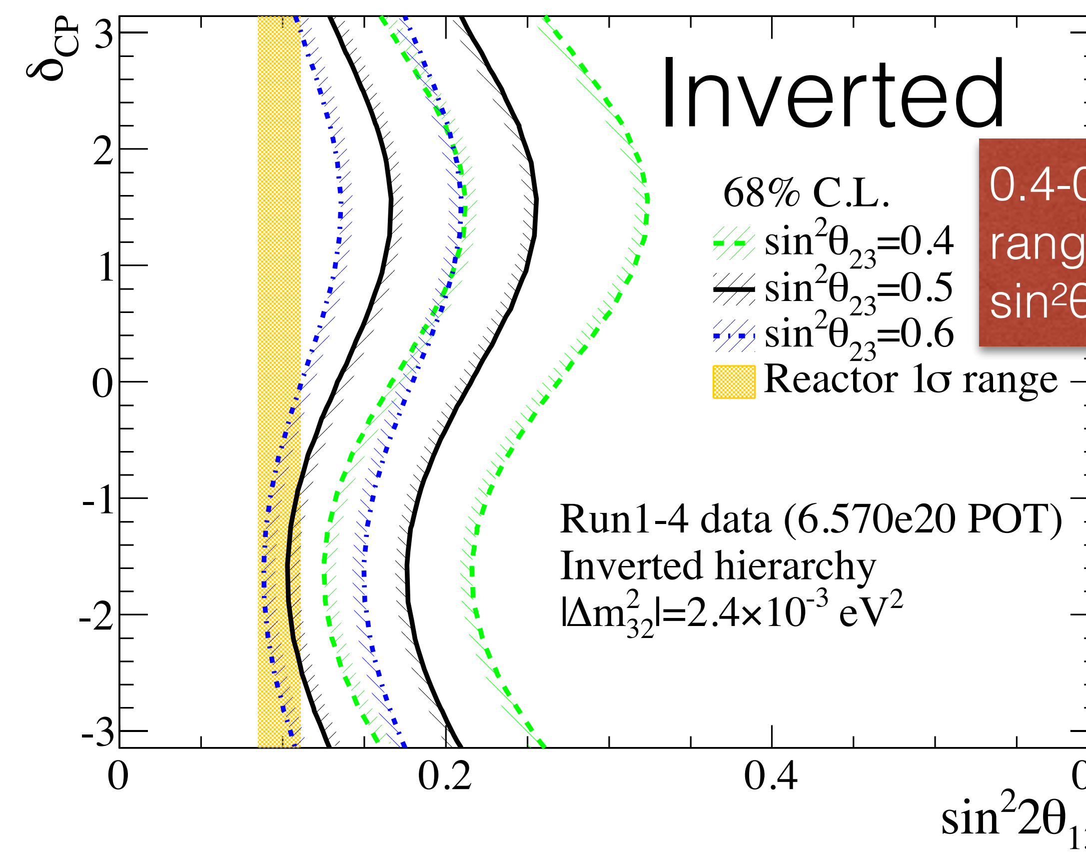
Comparison to reactor measurements of $\sin^2 2\theta_{13}$

Overlay of reactor measurement (via $\bar{\nu}_e$ disappearance) and T2K allowed regions for $\sin^2(2\theta_{13})$ as a function of δ_{CP}

Tension for certain values of δ_{CP}

sensitive to $\sin^2\theta_{23}$





0.4-0.6 ~ 90% range of $\sin^2\theta_{23}$

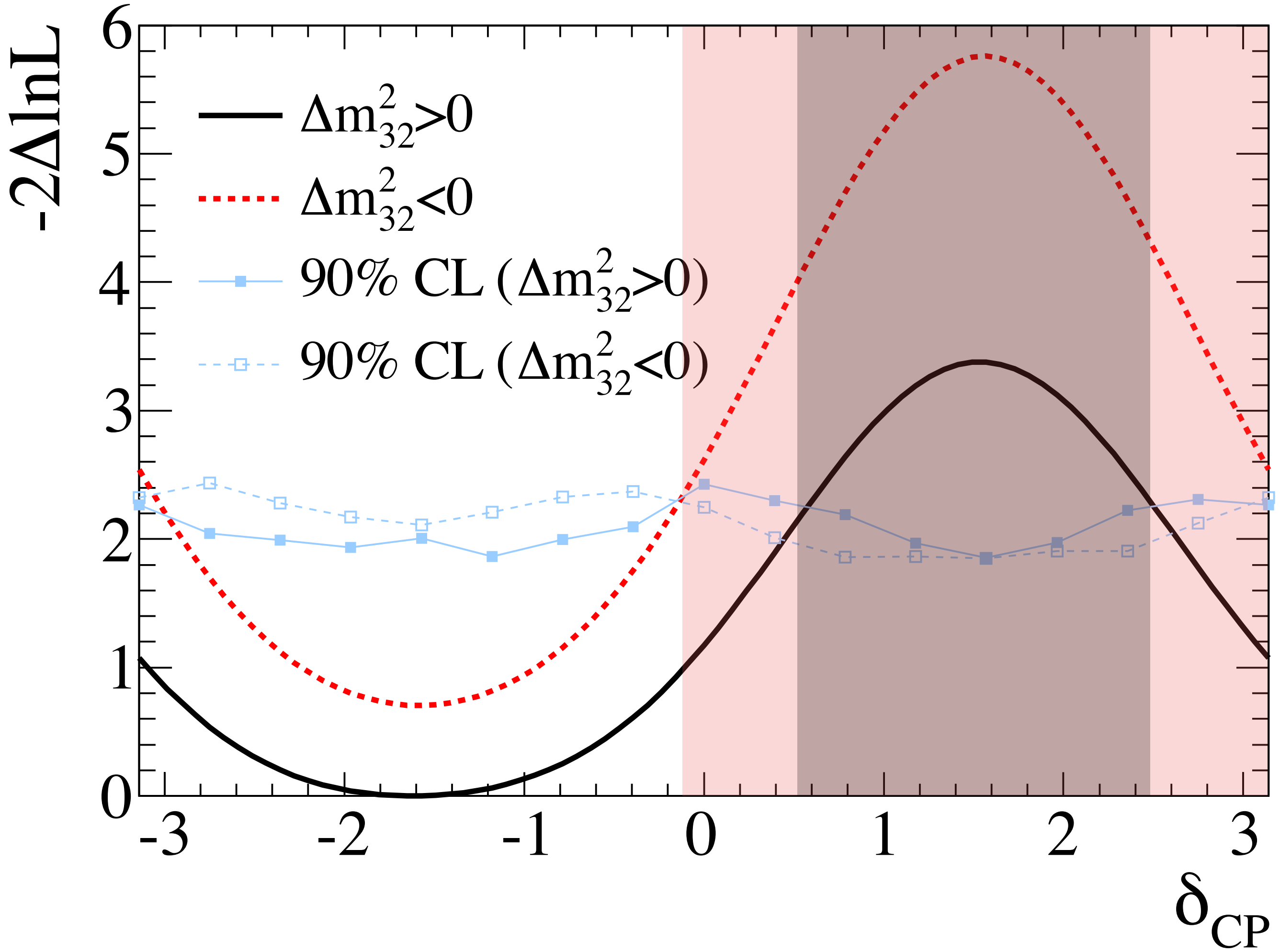
T2K regions shown with different values of assumed $\sin^2\theta_{23}$

Note: These are 1D allowed regions as a function of δ_{CP}

ν_e Appearance

Use reactor experiments to constrain $\sin^2 2\theta_{13}$

And use T2K to fit δ_{CP}



Blue line with dots give Feldman-Cousins critical values for 90% CL

90% CL Excluded Region

[NH]: 0.19π - 0.80π

[IH]: -0.04π - 1.03π

includes marginalization of $\sin^2(2\theta_{13})$, $\sin^2(\theta_{23})$ and Δm^2_{32}

Intriguing first step towards investigating CP violation in the lepton sector!

What's Next for T2K

Update ν_e appearance with latest ν_μ disappearance constraints on $\sin^2(\theta_{23})$ and Δm^2_{32}

Will do this through a combined ν_e appearance and ν_μ disappearance analysis coming soon (as opposed to applying as external constraint)

Also, expect first anti-neutrino data run in 2014

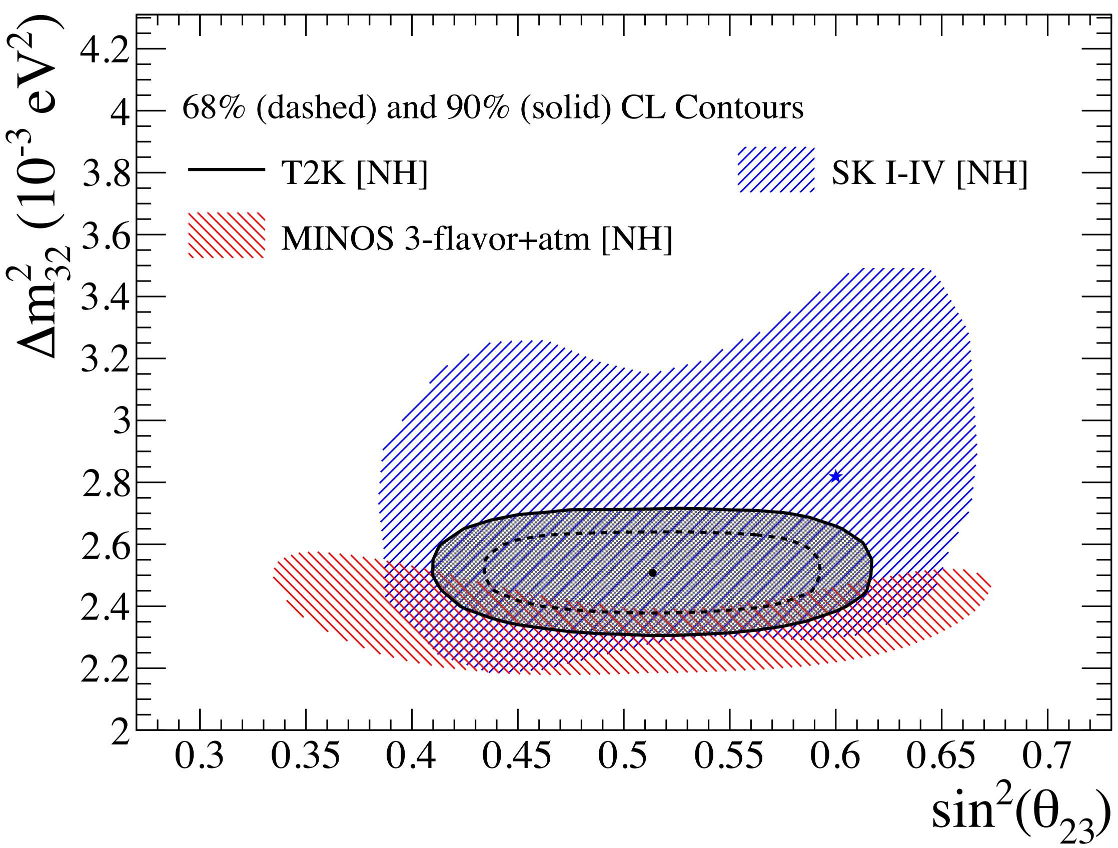
Conclusions

Just released the current best constraints on $\sin^2(\theta_{23})$

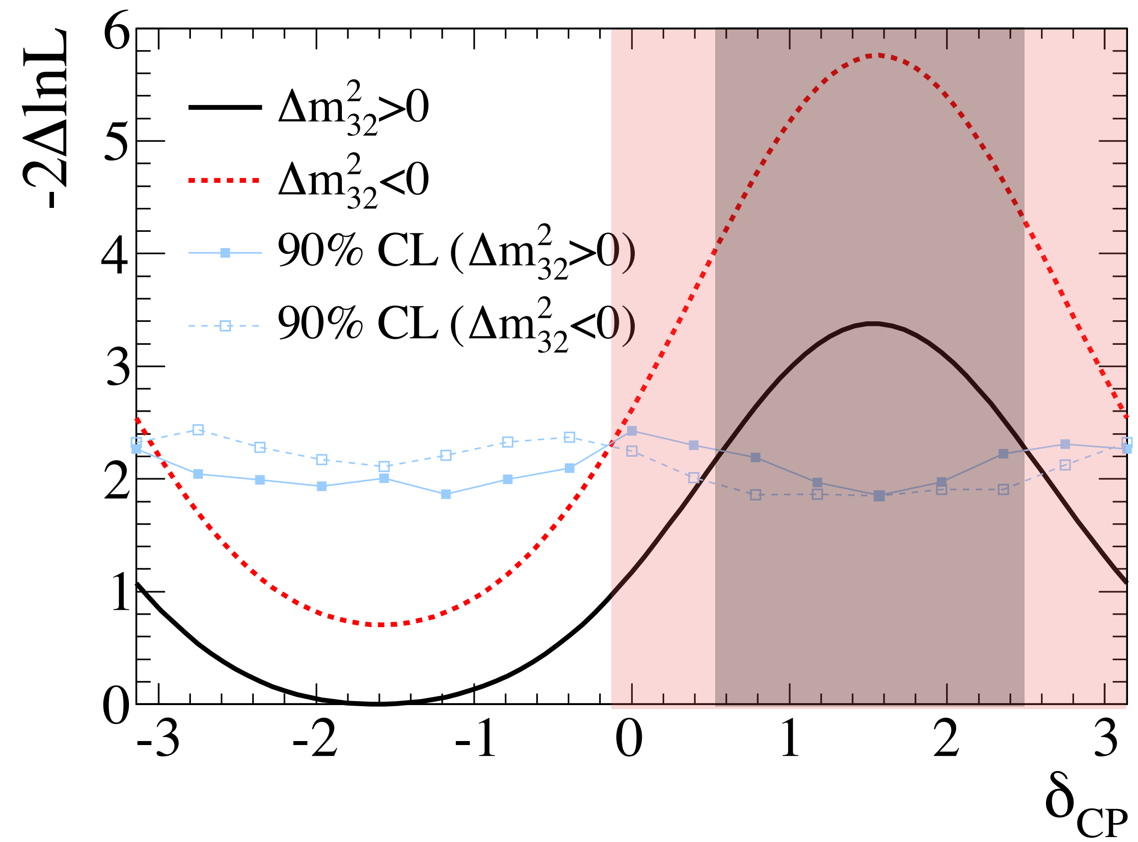
ν_e appearance measured at discovery level significance (i.e. zero θ_{13} at 7.3σ)

Combined with reactor measurements of θ_{13},
T2K is able to exclude some values of δ_{CP} to 90% CL

From ν_μ disappearance



From ν_e appearance



T2K Collaboration

On behalf of T2K, thank you for your attention

Canada
TRIUMF
U. Alberta
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
Aachen U.

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Osaka City U.
Okayama U.
Tokyo Metropolitan U.
U. Tokyo

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroklaw U.

Russia
INR

Spain
IFAE, Barcelona
IFIC, Valencia

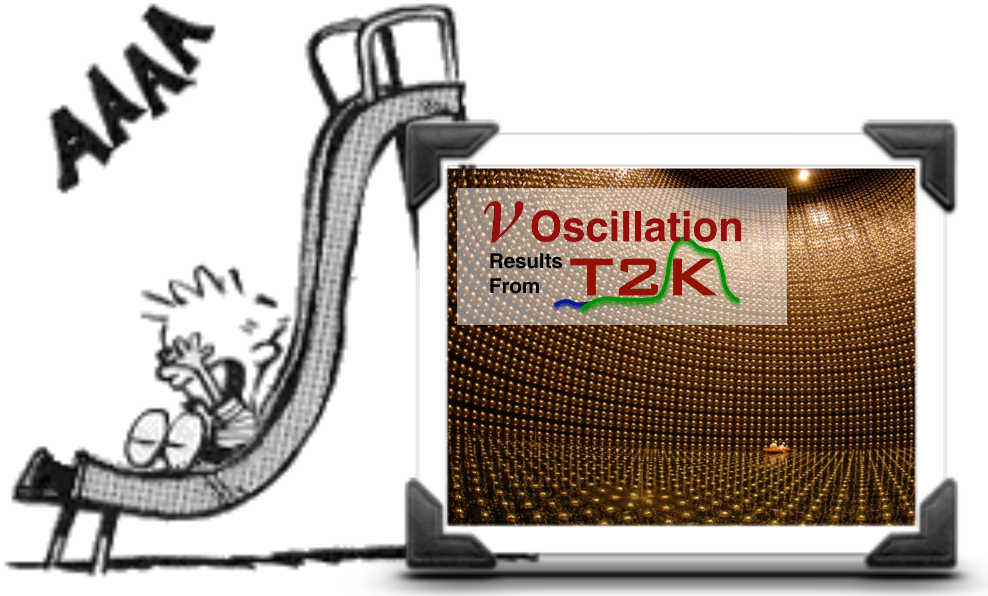
Switzerland
ETH Zurich
U. Bern
U. Geneva

United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

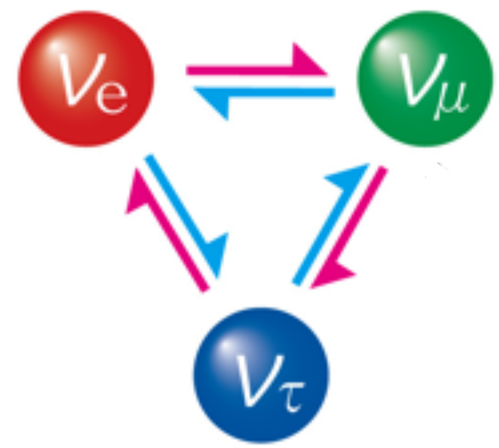
~500 members, 59 Institutes, 11 countries

Support Slides

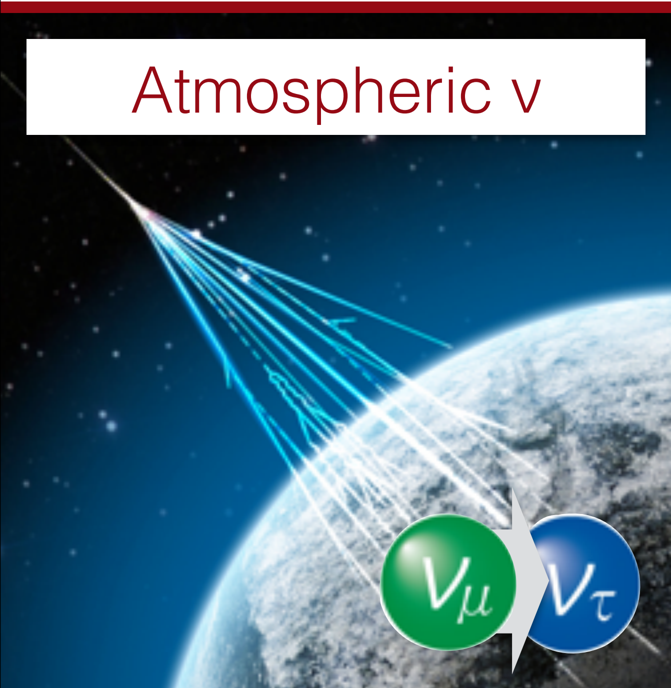


Neutrino Oscillations Review

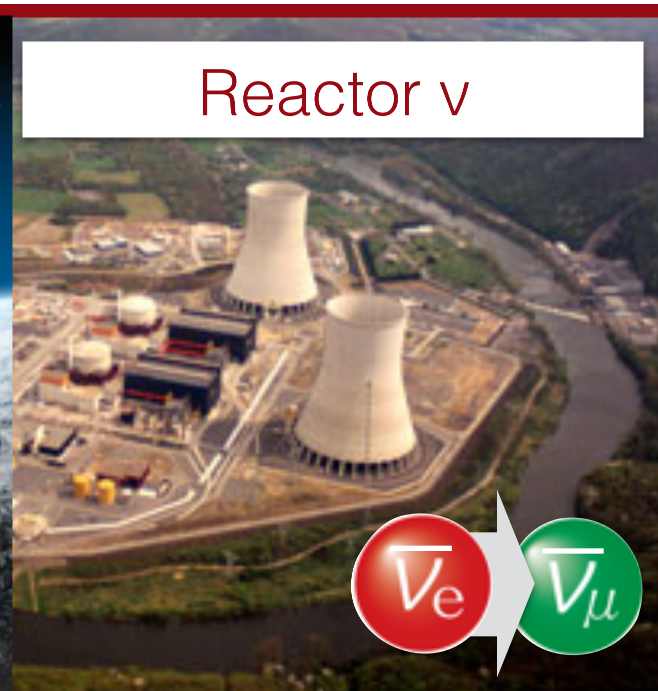
Neutrinos can change from one flavor to another



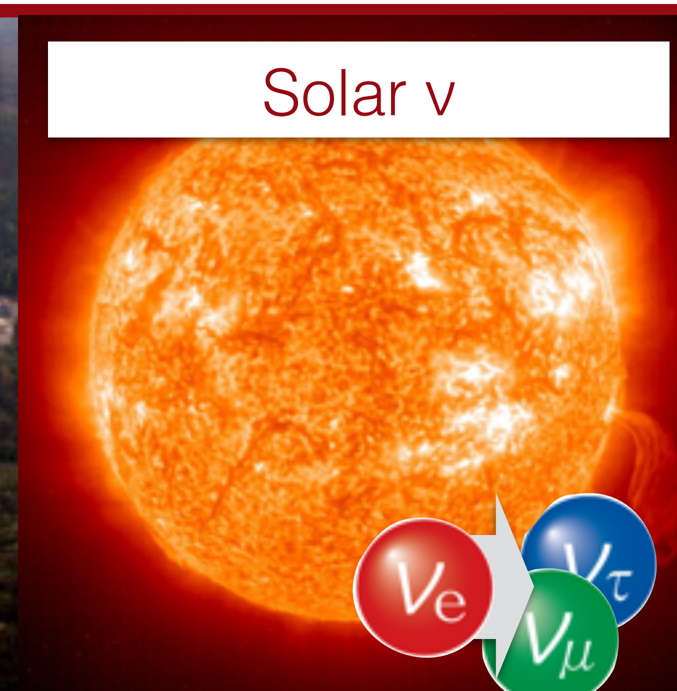
Observed by many experiments measuring neutrinos of all different sources and flavors



SuperK MINOS IceCUBE ANTARES BDUNT



KamLAND Daya Bay RENO Double Chooz LSND



SuperK KamLAND SNO SAGE Borexino Homestake GALLEX

MINOS NOvA OPERA K2K T2K MiniBooNE

Neutrino Oscillations Review

Neutrino oscillations occur because

- neutrinos have mass
- flavor states are mixture of mass states

Example 2 ν model

Flavor States | Mixing Matrix | Mass States

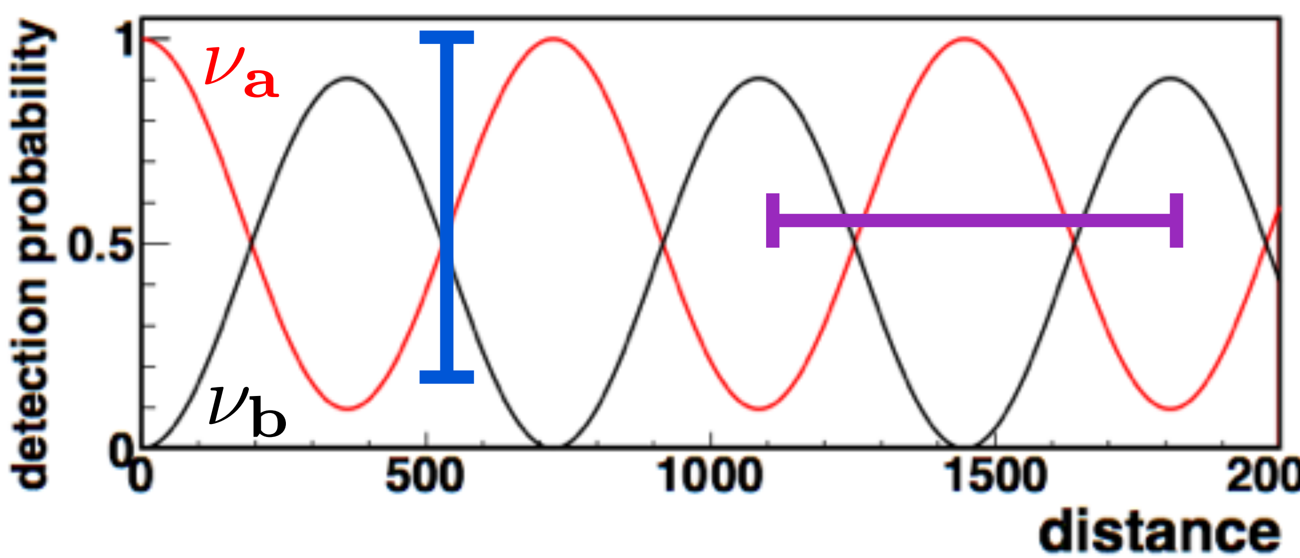
$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \quad \begin{matrix} \text{w/mass } m_1 \\ \text{w/mass } m_2 \end{matrix}$$

For a neutrino, ν_a, with energy, *E*, traveling a distance, *L*,

$$P_{a\to b} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2}{4\hbar c}\frac{L}{E}\right)$$

where $\Delta m^2 = m^2_1 - m^2_2$

Get oscillating probability as function of L/E



mixing angle, θ, governs amplitude

mass splitting, Δm^2, governs frequency

Experiments report $\theta, \Delta m^2$ values

State of Oscillation Measurements

3 Neutrino mixing matrix using the standard parameterization and
List of current parameter values

Flavor States

Note: $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$

Mass States

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1}/2 & 0 & 0 \\ 0 & e^{i\alpha_2}/2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

atmospheric/
accelerator

$\theta_{23} \sim$ **41°± 7.5°**

From Global Fits
MINOS/SK

reactor/
accelerator

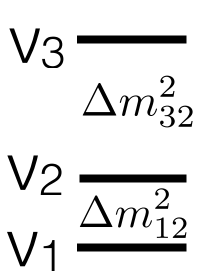
$\theta_{13} \sim$ **9.1°± 0.6°**

$\delta\theta_{13} \sim$ **7%**

δ_{CP} **not measured**

Lots of progress on θ_{13} over last few years
T2K saw first indication that non-zero and
Reactor experiments have measured well

Mass
Splittings

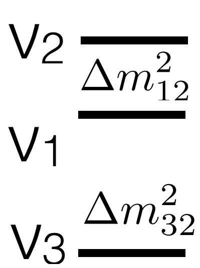


$\Delta m^2_{32} \approx 2.5 \times 10^{-5}\ \mathrm{eV}^2/c^4$

$\Delta m^2_{12} = 7.5 \times 10^{-5}\ \mathrm{eV}^2/c^4$

Normal Hierarchy

OR



$\Delta m^2_{12} = 7.5 \times 10^{-5}\ \mathrm{eV}^2/c^4$

$\Delta m^2_{32} \approx 2.5 \times 10^{-5}\ \mathrm{eV}^2/c^4$

Inverted Hierarchy

$\delta\Delta m^2_{32/13} \sim$ **4%**

$\delta\Delta m^2_{21} \sim$ **3%**

State of Oscillation Measurements

3 Neutrino mixing matrix using the standard parameterization and
List of current parameter values

Flavor States

Note: $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$

Mass States

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1}/2 & 0 & 0 \\ 0 & e^{i\alpha_2}/2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

atmospheric/ accelerator	reactor/ accelerator	solar	Majorana phases
$\theta_{23} \sim 41^\circ \pm 7.5^\circ$	$\theta_{13} \sim 9.1^\circ \pm 0.6^\circ$	$\theta_{12} \sim 34^\circ \pm 1^\circ$	not yet observed
From Global Fits MINOS/SK	$\delta\theta_{13} \sim$ **7%**	$\delta\theta_{12} \sim$ **3%**	
	δ_{CP} **not measured**		

Mass Splittings

ν_3

$\Delta m^2_{32} \approx 2.5 \times 10^{-5}\ \mathrm{eV}^2/c^4$

ν_2

$\Delta m^2_{12} = 7.5 \times 10^{-5}\ \mathrm{eV}^2/c^4$

ν_1

Normal Hierarchy

OR

ν_2

$\Delta m^2_{12} = 7.5 \times 10^{-5}\ \mathrm{eV}^2/c^4$

ν_1

$\Delta m^2_{32} \approx 2.5 \times 10^{-5}\ \mathrm{eV}^2/c^4$

ν_3

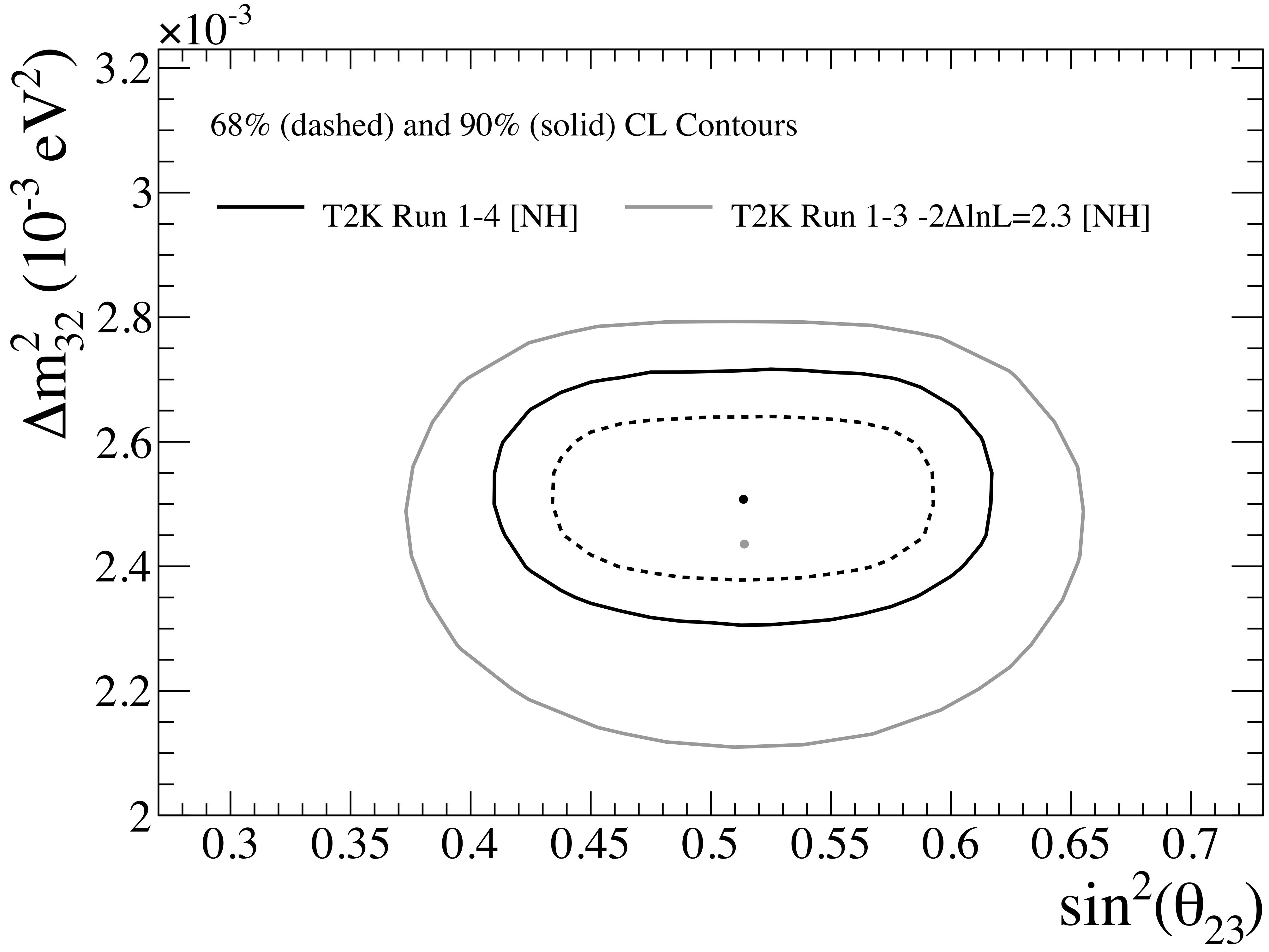
Inverted Hierarchy

$\delta\Delta m^2_{32/13} \sim$ **4%**

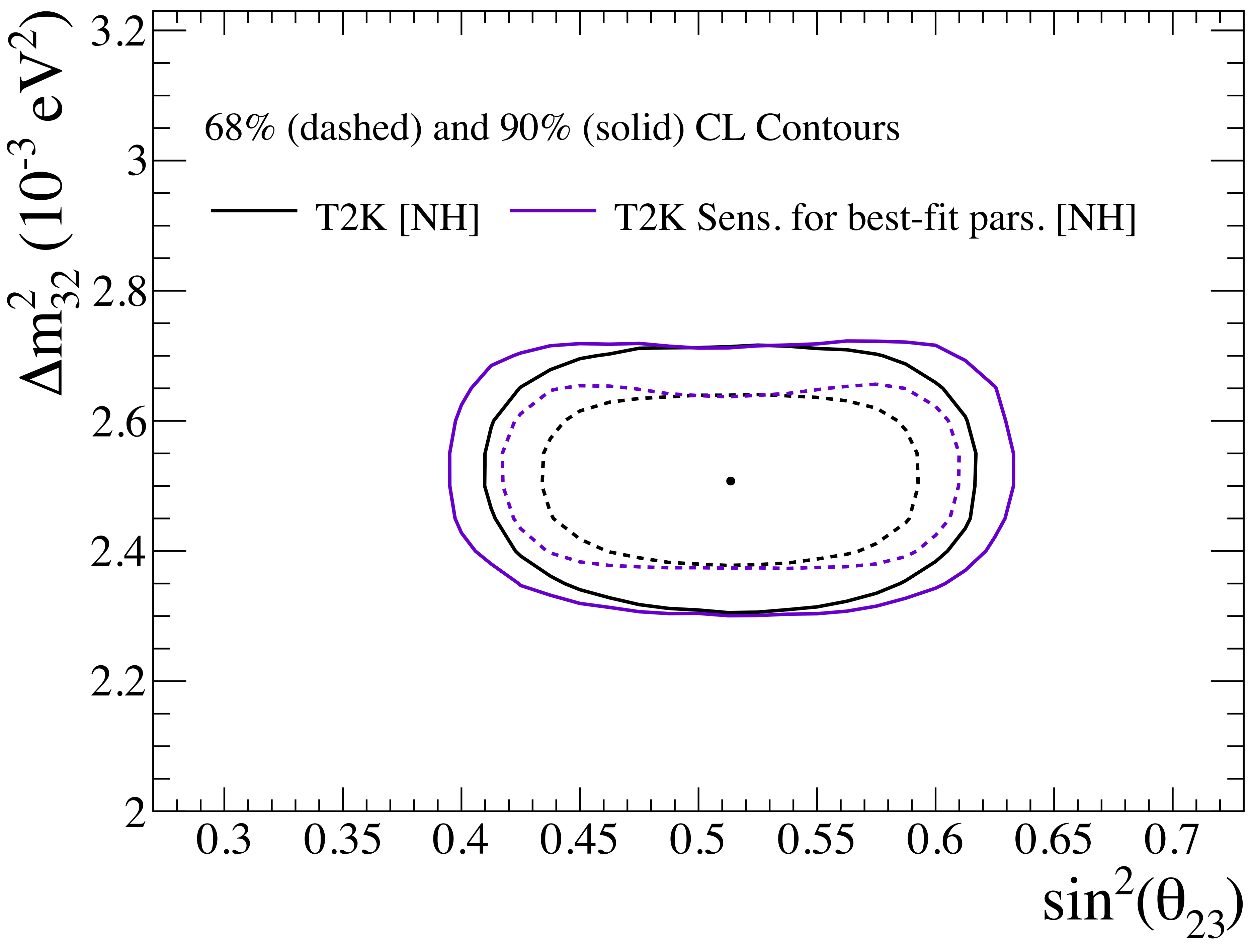
$\delta\Delta m^2_{21} \sim$ **3%**

Hierarchy ambiguity because oscillations depend only on Δm^2

Comparison to last T2K result



Comparison to Sensitivity



Maximal Mixing/Disappearance

Because θ_{13} is non-zero:
Maximal Mixing and Maximal Disappearance is not the same!

Maximal Mixing when $\sin^2\theta_{23}=0.5$

$$P(\nu_\mu \to \nu_\mu) = 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) + \ldots$$

Expression gives maximum amount of disappearance when
$\sin^2\theta_{23} = 1/(2\cos^2\theta_{13})$

$\sin^2\theta_{23}=0.5$
when $\sin^2\theta_{13}=0$

$\sin^2\theta_{23}=0.513$
when $\sin^2\theta_{13}=0.098$
(PDG2012 Value)

Actual maximal disappearance value is 0.514 [NH], 0.511 [IH]
(the terms past next-leading order causes small shift)

MC Model

ν_μ ν_e

Beam Simulation

- Hadronic interactions due to proton slamming into carbon target
- Tracking of resulting particles through target and magnetic field
- Tuning of hadron production to external measurements (NA61/SHINE)

Neutrino Flux

Interaction Generator

- Model and Cross sections from theory
- Detector Geometry

Neutrino Events

Detector Simulation

- Electronics
- Particle Propagation

MC data

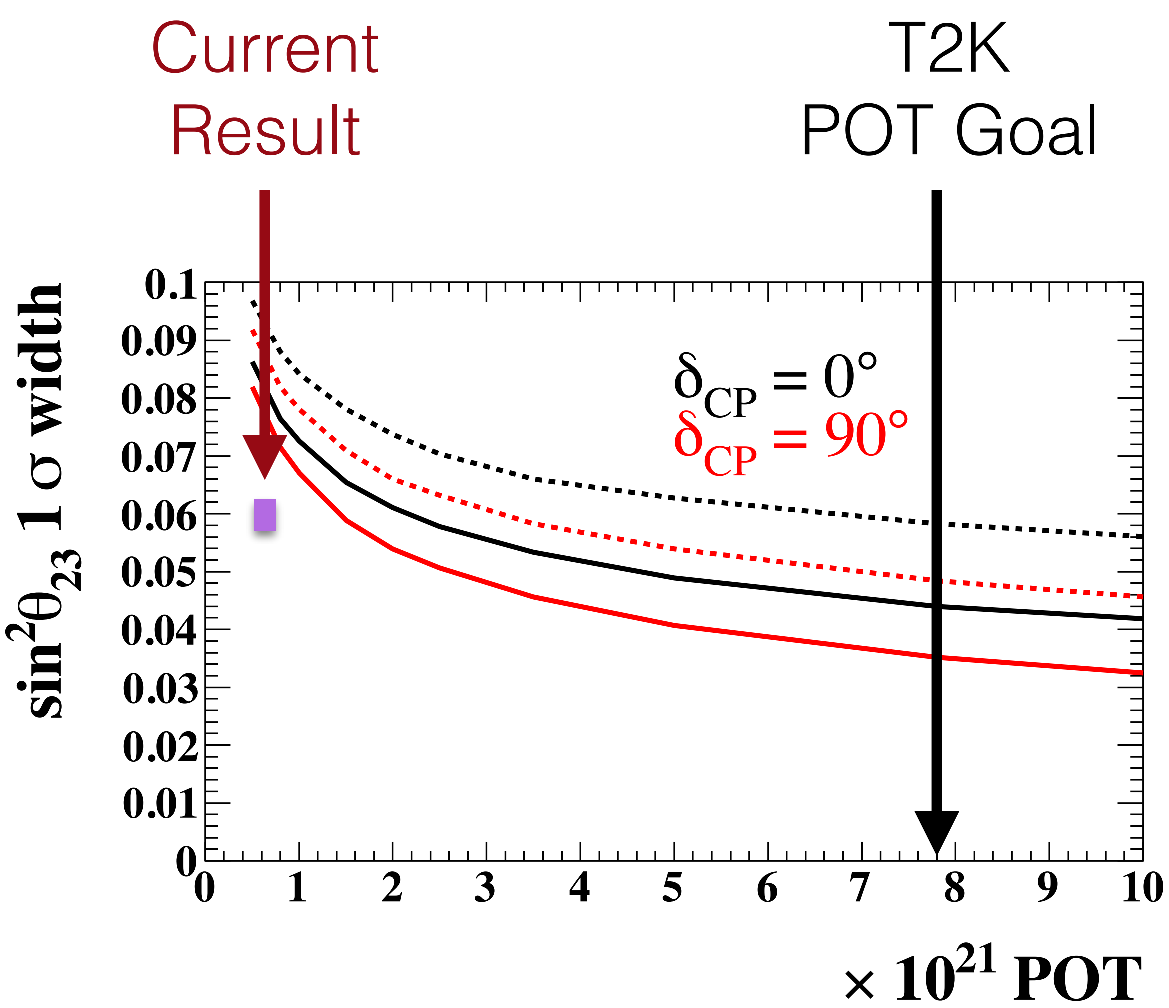
Reconstruction/ Selection

- Same as data
- Source of efficiencies

Predictions for distributions of observables

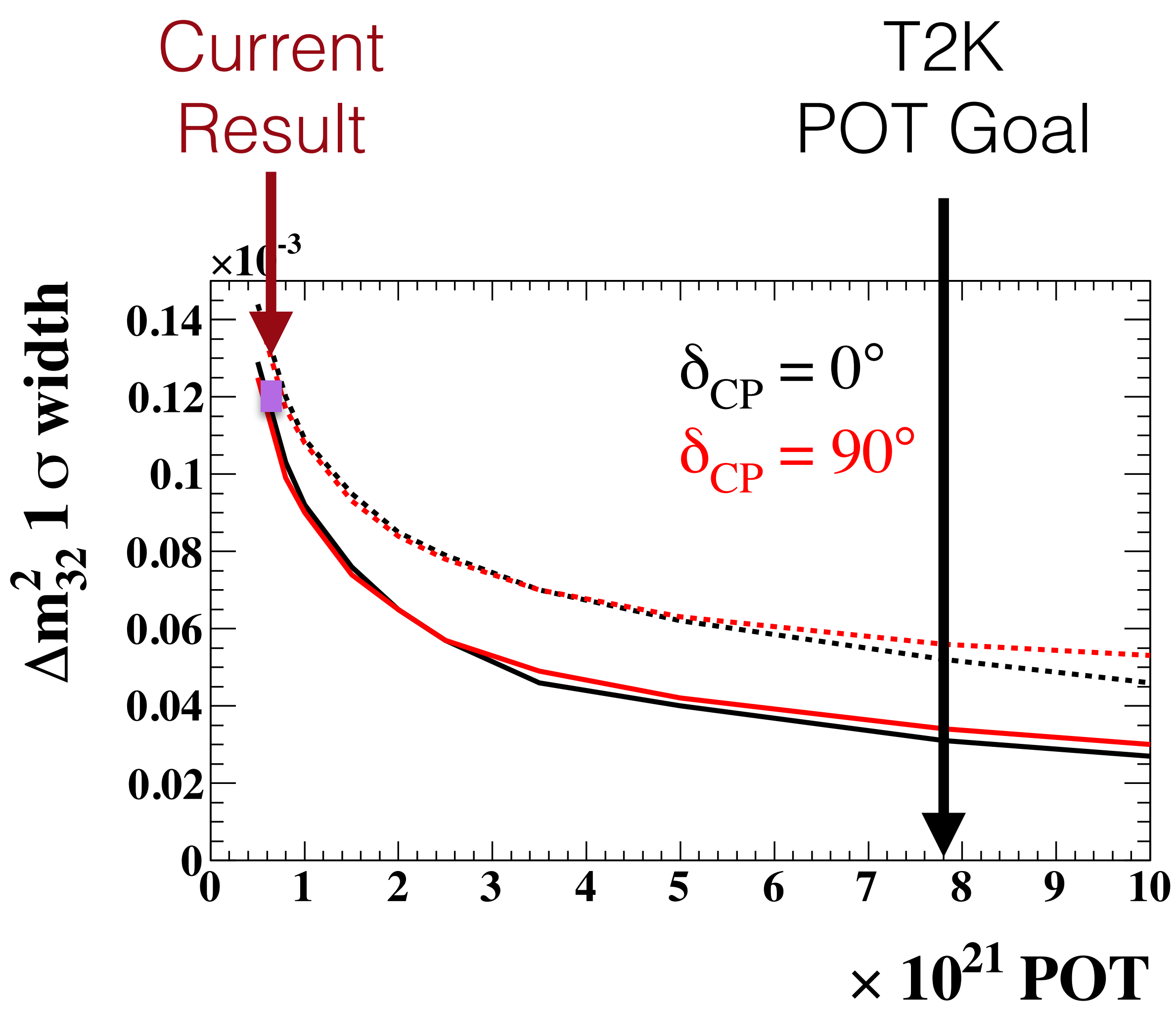
Future Sensitivity

$\sin^2\theta_{23}$



(a) 100% ν-running.

Δm^2_{32}

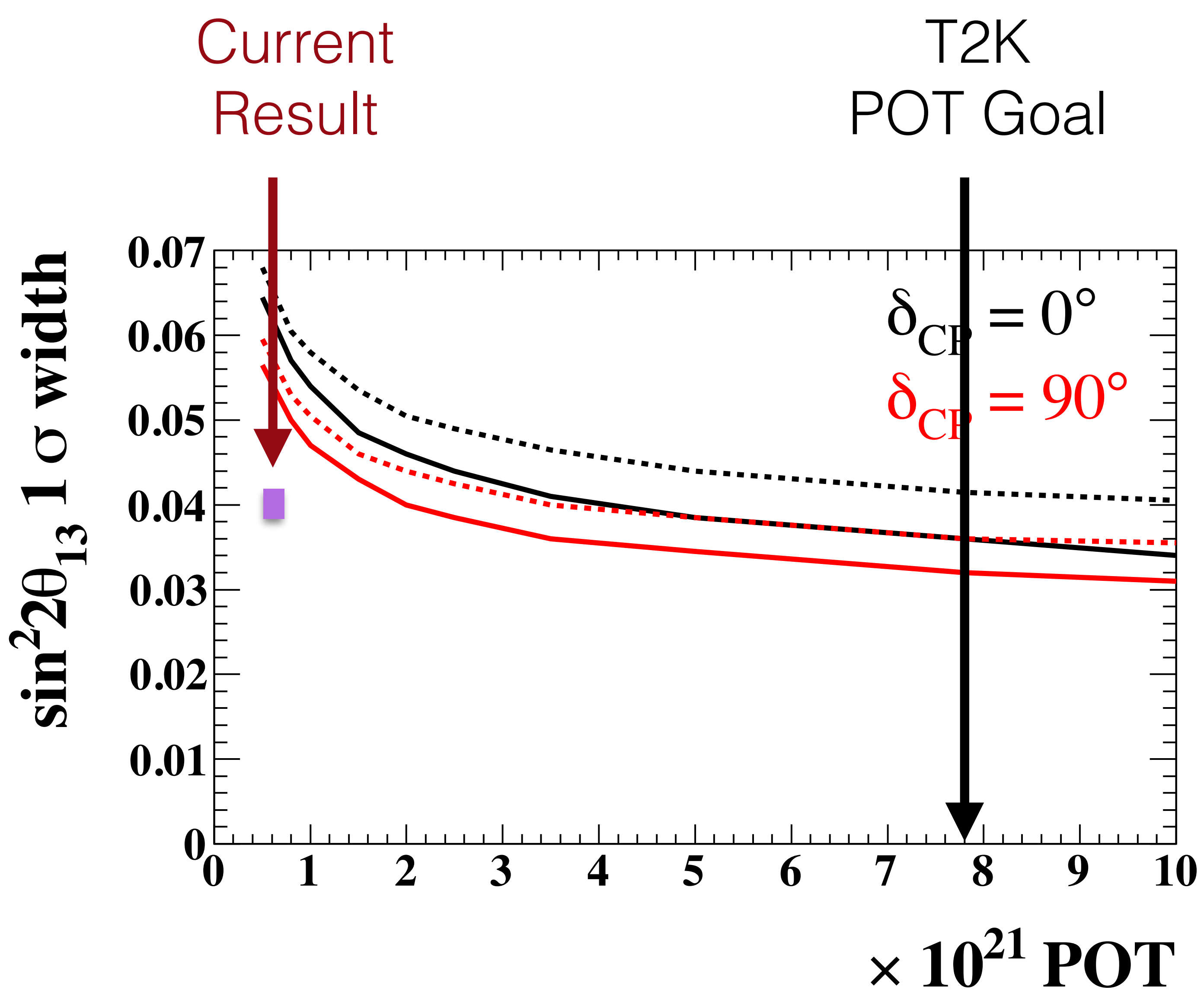


(a) 100% ν-running.

Better because events at dip slightly less than predicted by maximal disappearance

Future Sensitivity

$\sin^2\theta_{13}$



(a) 100% ν-running.

Plot assumes $\sin^2\theta_{13}$=0.1

Measured $\sin^2\theta_{13}$=0.14 so more events that expected

Future Sensitivity

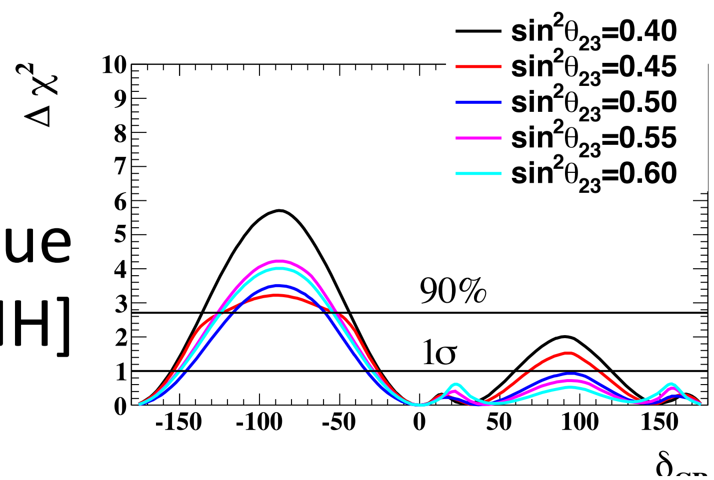
[NH] Normal hierarchy, [IH] Inverted hierarchy

Sensitivity for Resolving $\sin\delta_{CP}\neq 0$

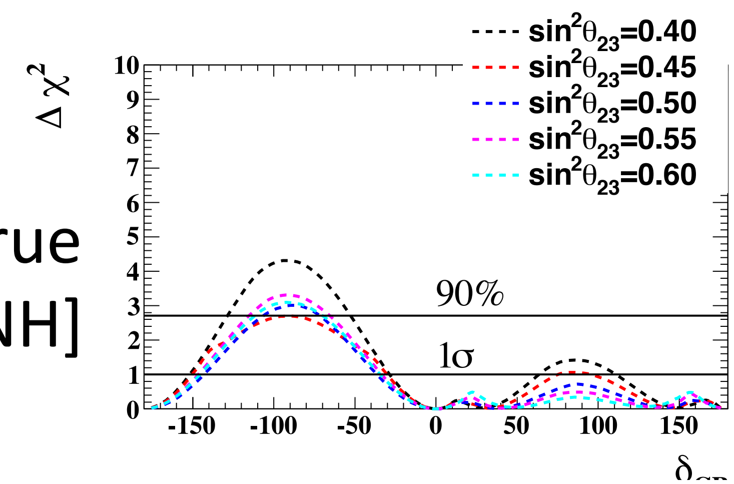
7.8×10^{21} POT (50% POT ν + 50% POT anti-ν)

No sys. err.	w/ 2012 sys. err. (~10% ν_e, ~13% ν_μ)

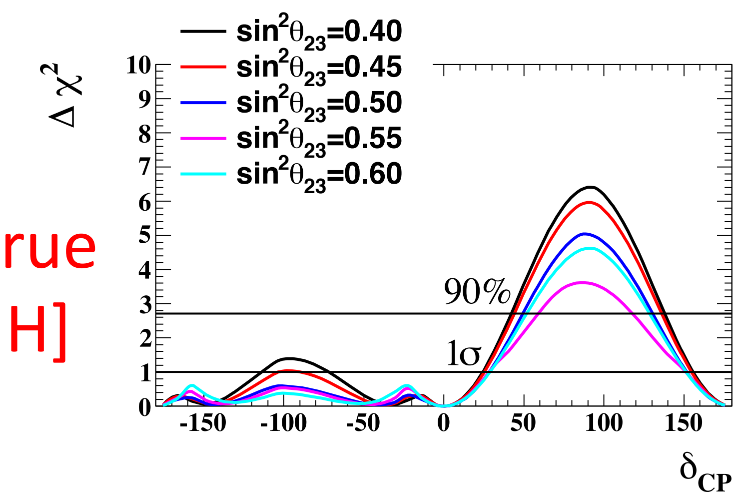
True [NH]



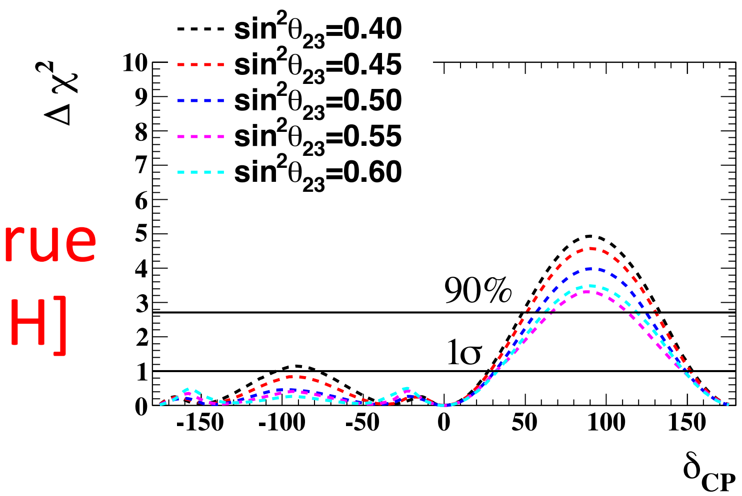
True [NH]



True [IH]



True [IH]



Assuming true: $\sin^2 2\theta_{13}=0.1$, $\Delta m^2_{32}=2.4\times10^{-3}$ eV^2
θ_{13} constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$

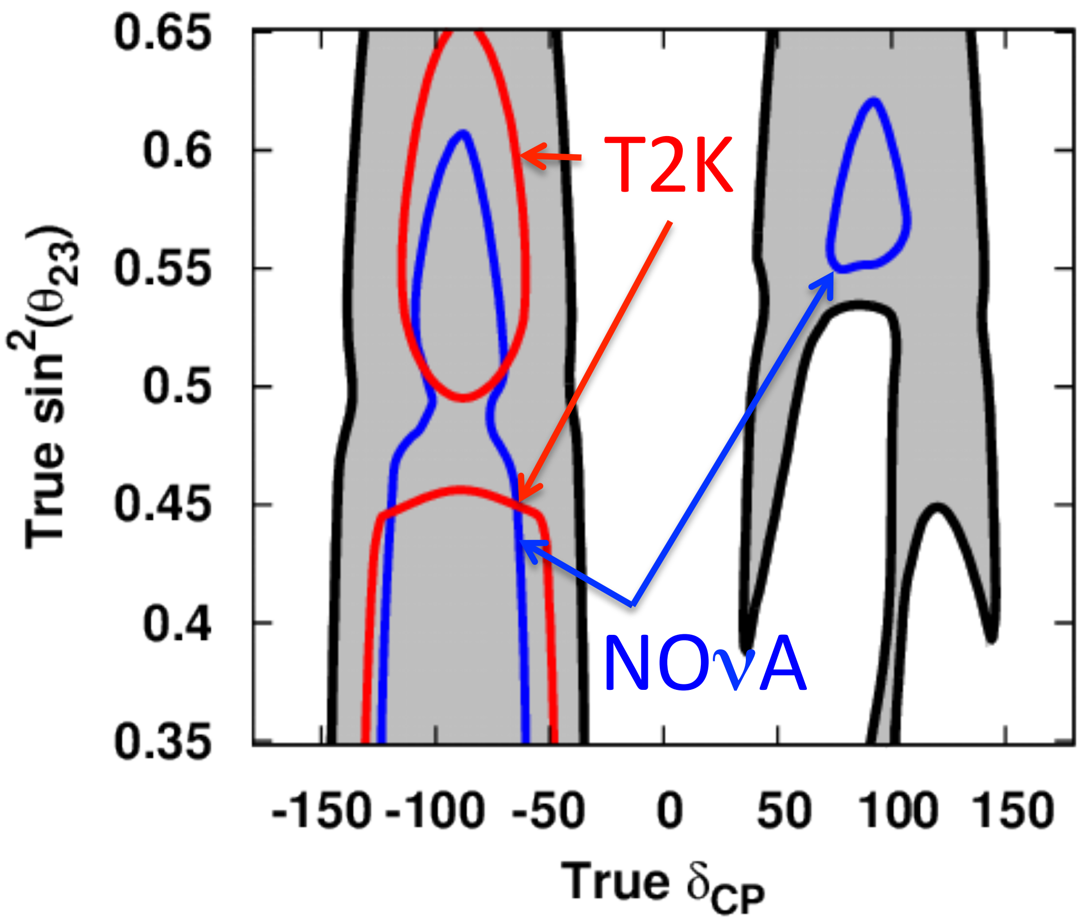
Future Sensitivity

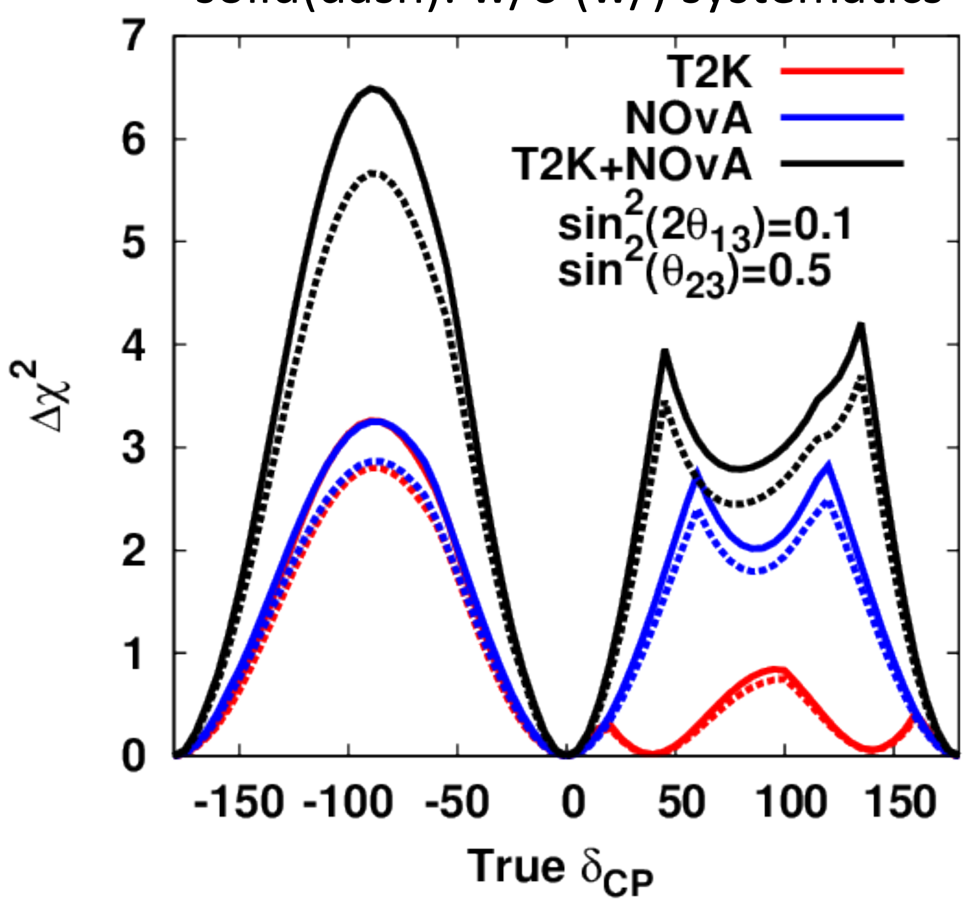
[NH] Normal hierarchy, [IH] Inverted hierarchy

T2K + NOνA Sensitivity for Resolving $\sin\delta_{CP} \neq 0$

Both T2K/NOνA -> full POT (50% POT ν + 50% POT anti-ν)
Shown in [NH] case.

solid(dash): w/o (w/) systematics





Region where $\sin\delta=0$ can be excluded by 90% C.L.

Sensitivity to resolve $\sin\delta=0$

Assuming 5% (10%) normalization uncertainty on signal (background)

Assuming true: $\sin^2 2\theta_{13}=0.1$, $\Delta m^2_{32}=2.4\times10^{-3}$ eV^2, θ_{13} constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$

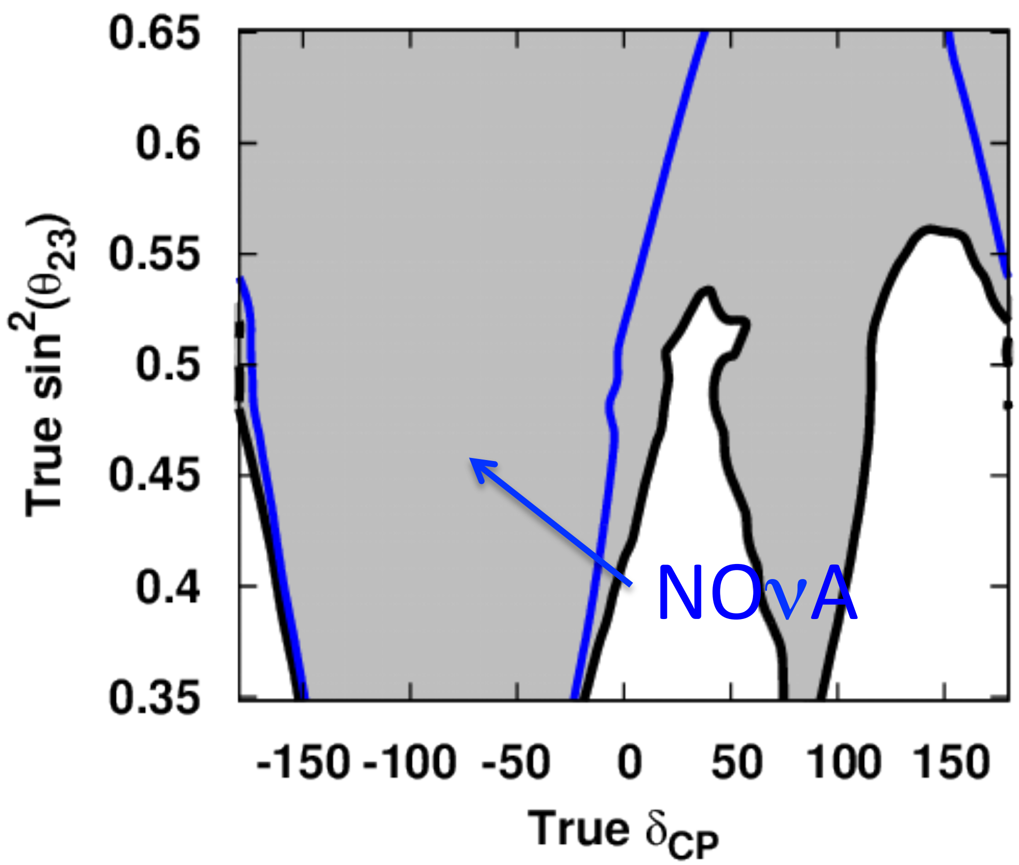
Future Sensitivity

[NH] Normal hierarchy, [IH] Inverted hierarchy

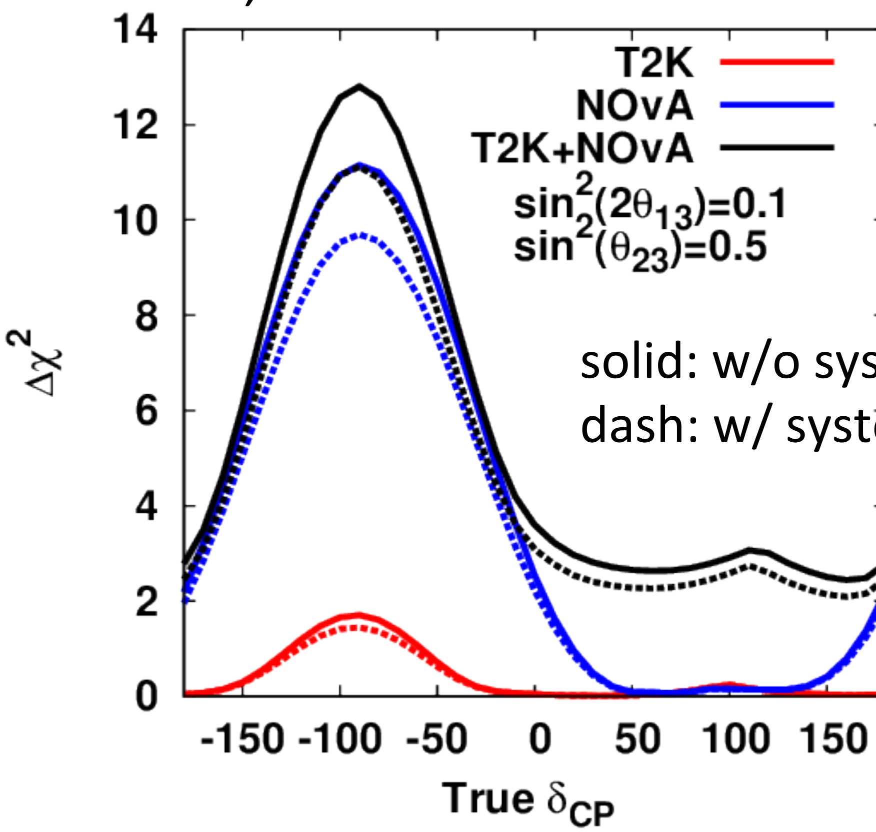
T2K + NOνA Sensitivity to Mass Hierarchy

Both T2K/NOνA -> full POT (50% POT ν + 50% POT anti-ν)
Shown in [NH] case.

Red: T2K alone, Blue: NOνA alone, Black: T2K + NOνA



Region where MH can be distinguished by 90% C.L.



Sensitivity to resolve MH

Assuming true: $\sin^2 2\theta_{13}=0.1$, $\Delta m^2_{32}=2.4\times10^{-3}$ eV^2, θ_{13} constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$

Multi-Nucleon Interactions

There has been considerable interest lately in multi-nucleon interactions for neutrino-nucleus scattering

Involves processes where neutrino interact occurs with 2 or more nucleons

Contrasts to interactions with a single nucleon, which is what our generator encodes

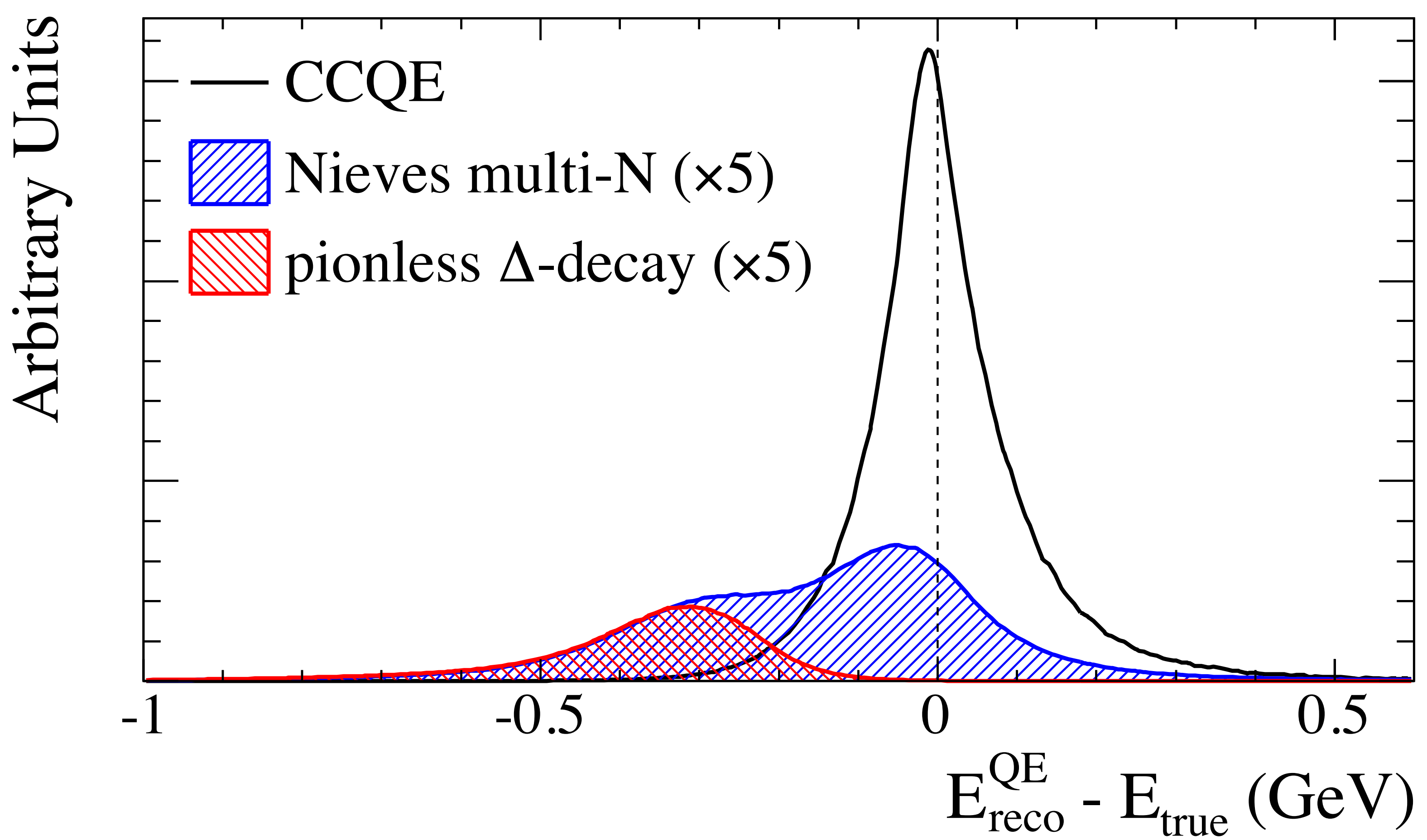
Such interactions gained interest when they were seen to be able to possible explain the disagreement between the CCQE cross section measurement and prediction by MiniBooNE — data was low

Offer a new mode of interaction to explain deficit seen

Multi-Nucleon Interactions

Note that there would not only be a missing mode in model, but that the energy bias would be different

We do have an interaction mode in our model, pionless delta-decay, that seems to cover some of the ams regions of energy bias as multi-nucleon events would (according to Nieves model)



Multi-Nucleon Interactions

If such interactions exist and are a sizable channel in comparison to CCQE interactions, then for interactions in T2K, this would be a missing channel in our neutrino interaction model

In order to investigate the size of such an effect we performed MC fake experiments:

1. We added to the MC events from multi-nucleon interactions as described in the model by Nieves (note this not a statement on model preference, but was just the easiest model to implement at the time as it was available in the NuWro generator)

2. We then simulated a full analysis — starting with the near detector fit all the way to the far detector fit — with our normal analysis

3. Our goal was to ask: if we left out this interaction channel, what is the average change in our measurement of $\sin^2\theta_{23}$ and Δm^2_{32}

Multi-Nucleon Interactions

For each toy fake experiment

1. We generated a fake data set for both the near and far detector that was made with a random throw in our current model parameters. The variation was within the uncertainty of the parameters

2. We performed the full analysis (near and far fits) twice:
   - Once without the multi-nucleon interactions [Nominal Fit]
   - Once with the multi-nucleon interactions added [Multi-N Fit]

3. Note that for both fits above — we use our current analysis which does NOT include the multi-nucleon interaction in its fit of the spectrum to the data

Our goal was to ask: if we left out this interaction channel, what is the average change in our measurement of $\sin^2\theta_{23}$ and Δm^2_{32}?

Multi-Nucleon Interactions

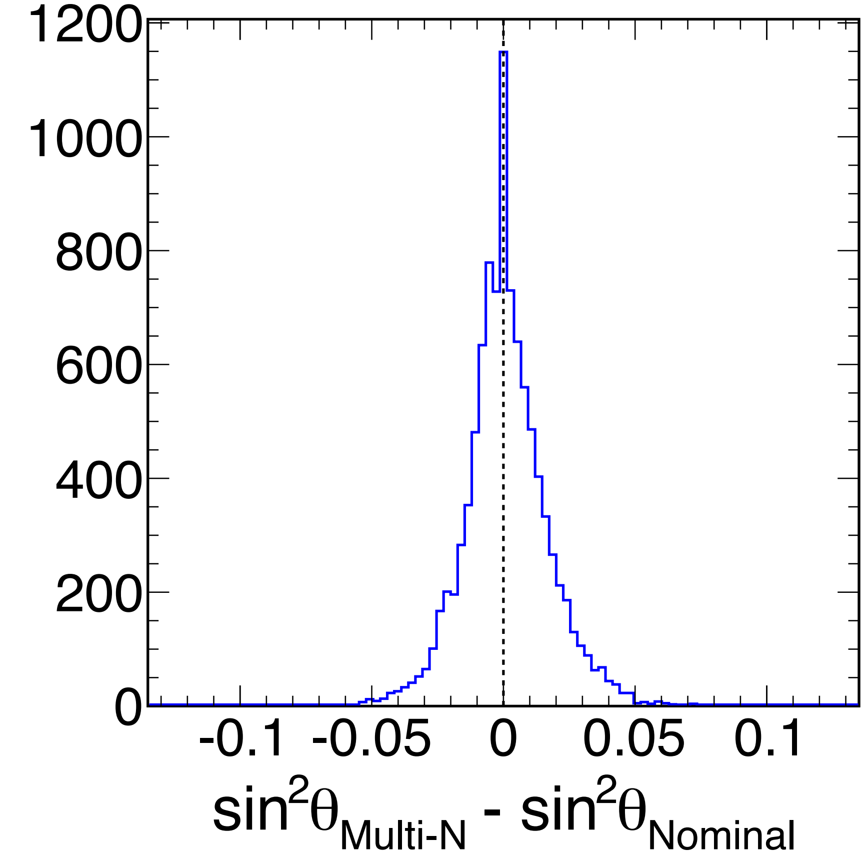
Result of our toy fake experiments:

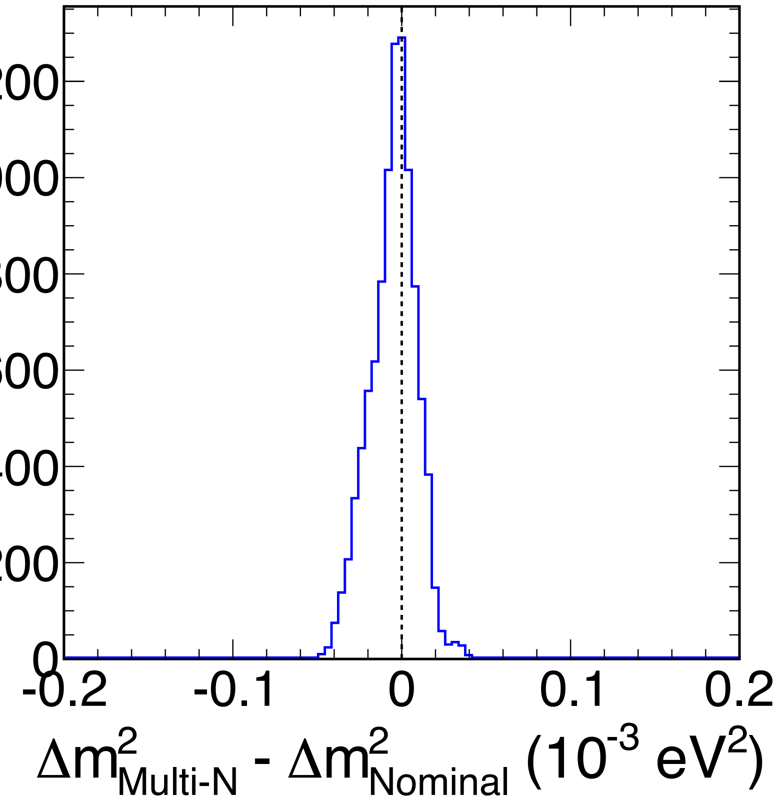
1. The bias in due to Multi-N's is small (<1%) compared to existing uncertain tie in both the mixing angle and mass splitting squared

2. However, the added variation in the bias due to the Multi-N's is comparable to our current systematics but small relative to current statistical error

3. Our conclusion is that at our current statistics, the effect is negligible for now. But the future, we will want to add these interactions into model

4. There is existing effort to do so





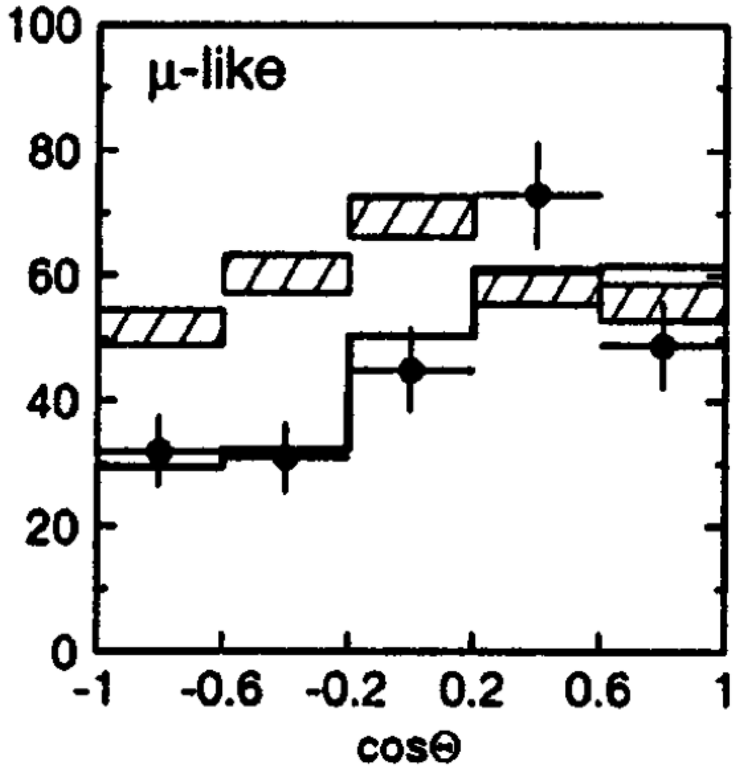
Neutrino Oscillations

In 1998, Super-Kamiokande measured the rate of neutrinos originating from the atmosphere as a function of direction

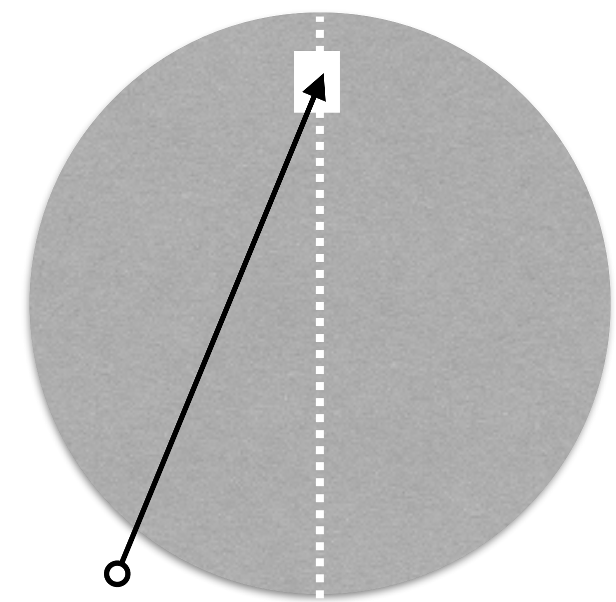
Observed that the rate of upward-going neutrinos (which traveled through the earth) was less than expected

First discovery of *neutrino oscillations*: neutrinos created as one flavor can later be detected as another flavor!

First evidence that at least one neutrino has mass (albeit a very small one)



cosθ=+1



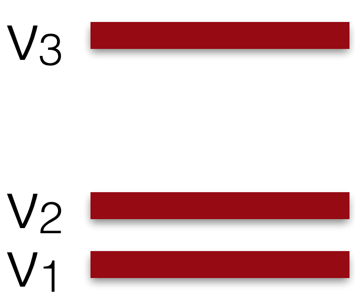
cosθ=-1

Neutrino Oscillations

For three flavors, expression much more complicated

But it turns out that one mass splitting is larger than the other

[Normal Hierarchy]

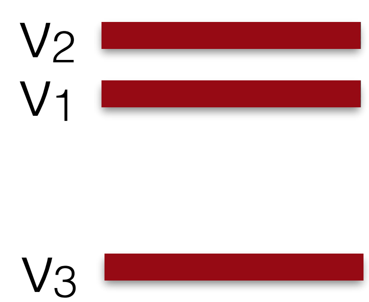


$\Delta m^2_{32} \approx 2.5 \times 10^{-5}\ \mathrm{eV}^2/c^4$

$\Delta m^2_{12} = 7.5 \times 10^{-5}\ \mathrm{eV}^2/c^4$

or

[Inverted Hierarchy]



$\Delta m^2_{12} = 7.5 \times 10^{-5}\ \mathrm{eV}^2/c^4$

$\Delta m^2_{13} \approx 2.5 \times 10^{-5}\ \mathrm{eV}^2/c^4$

(ambiguity because oscillations only measure mass differences)

This <u>allows for useful approximations</u> of the oscillation probability

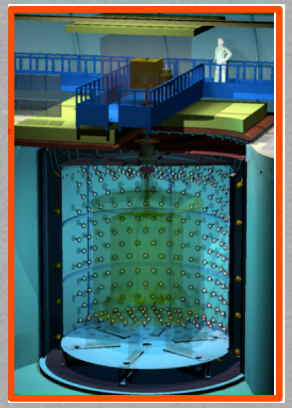
Note that when T2K does analyses, we use the full 3-flavor formula including matter effects

Neutrino Oscillations

Useful 3-flavor approximations (neglecting matter effects)
(when T2K does the analyses we use the full formula)

ν_e Disappearance

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$ [at *L*~1 km]



Measured most recently by several reactor neutrino experiments

Daya Bay, Double Chooz, RENO

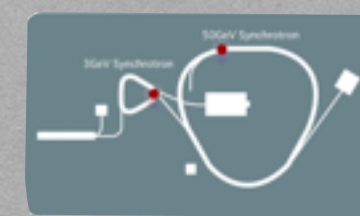
Notes:

- Appearance and Disappearance distinction useful
- θ_{13} and θ_{23} occur together often
- ν_e appearance has δ_{CP} term

Neutrino Oscillations

Useful 3-flavor approximations (neglecting matter effects)
(when T2K does the analyses we use the full formula)

Measured by accelerator experiments: *T2K, MINOS, NOvA*



ν_μ Disappearance

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

ν_e Appearance

$$P(\nu_\mu \to \nu_e) = (\sin^2\theta_{23}\sin^2\theta_{13} - \sin\delta_{CP}\sin\theta_{13}\cos\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\sin\frac{\Delta m^2_{12}L}{4E})\sin^2\frac{\Delta m^2_{13}L}{4E}$$

Notes:

- Appearance and Disappearance distinction useful
- θ_{13} and θ_{23} occur together often
- ν_e appearance has δ_{CP} term

What can we learn?

Many open questions related to neutrino oscillations,
but briefly discuss two that are most relevant to current T2K results

- Is $\sin^2(2\theta_{23})=1.0$?
- Do neutrinos exhibit CP-violation?
- Is our oscillation model complete?

Is This Everything?

Flavor States

Note: $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$

Mass States

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1}/2 & 0 & 0 \\ 0 & e^{i\alpha_2}/2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

"Atmospheric ν"	"Reactor/Acc. ν"	"Solar ν"	Majorana phases;
$\sin^2 2\theta_{23} > 0.95$ (90% C.L.)	$\sin^2 2\theta_{13} = 0.098 \pm 0.013$	$\sin^2 2\theta_{12} = 0.857 \pm 0.024$	Not yet observed

Besides CP violation, we want to know if this is the whole story.

Another long term goal of the field is precision measurements of the mixing angles and tests of "unitarity"

In other words, can all our measurements of oscillations be explained by the three standard model neutrinos? E.g. might there be additional neutrinos?

Oscillation Analysis

ν_μ ν_e

Culmination of the work of hundreds of collaborators

Circa 2010. Many members not shown.

Oscillation Analysis

ν_μ ν_e

Beam Simulation

- Hadronic interactions due to proton slamming into carbon target
- Tracking of resulting particles through target and magnetic field
- Tuning of hadron production to external measurements (NA61/SHINE)

Neutrino Flux

Interaction Generator

- Model and Cross sections from theory
- Detector Geometry

Neutrino Events

Detector Simulation

- Electronics
- Particle Propagation

MC data

Reconstruction/ Selection

- Same as data
- Source of efficiencies

Predictions for distributions of observables

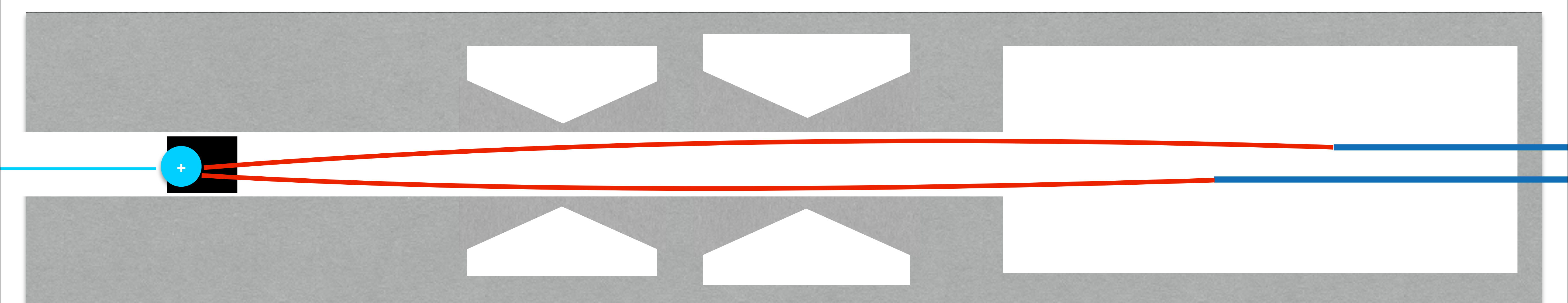
J-PARC Beam

Beam produced by:

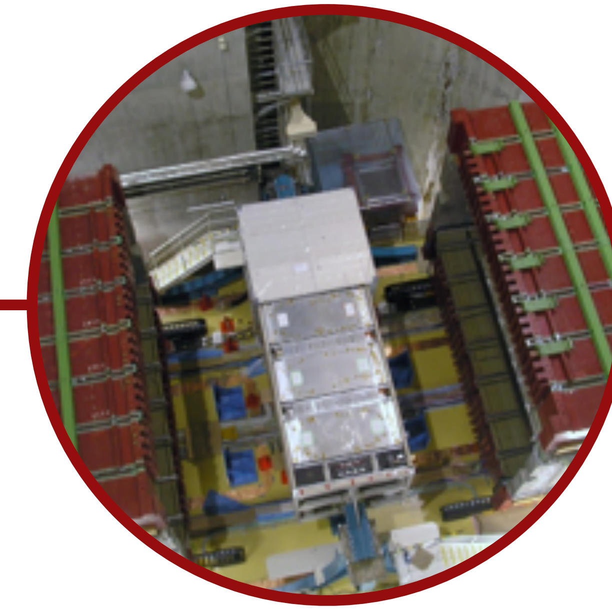
30 GeV proton impacting graphite target.

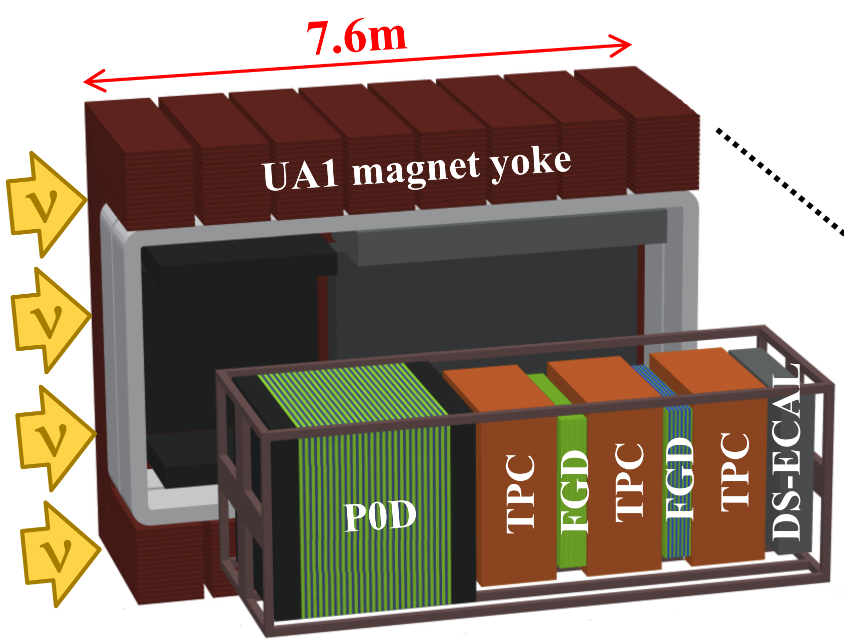
Resulting mesons focused by magnetic fields via “horns”.

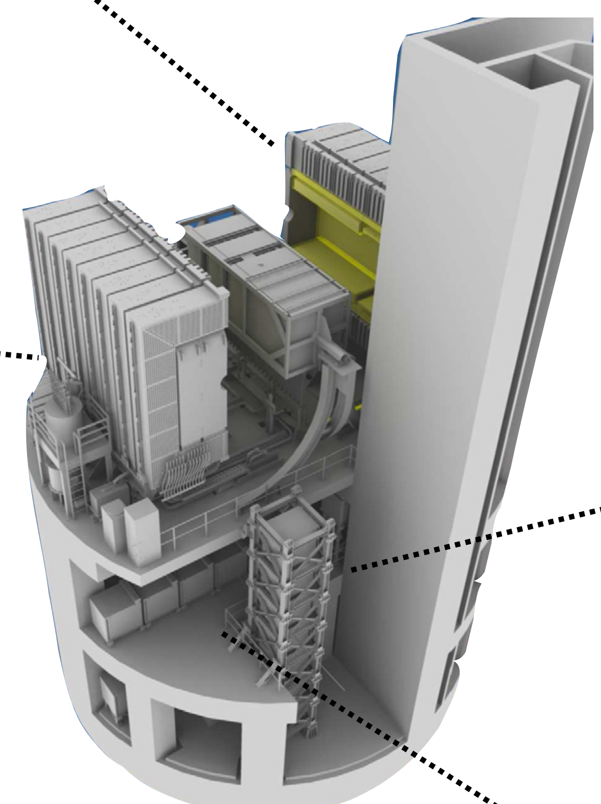
Mesons decay into neutrinos in “decay hall”.

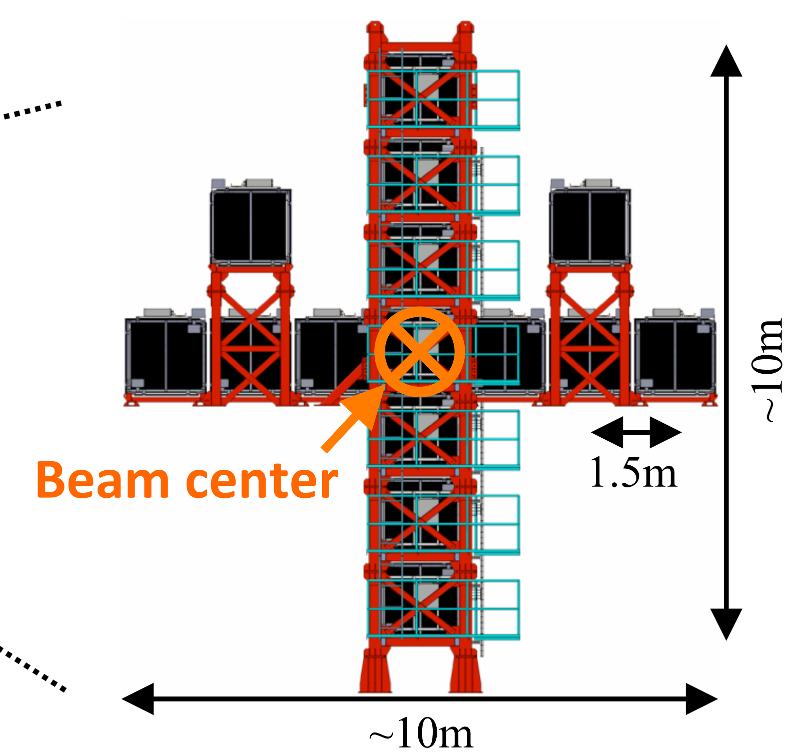


ND280 Complex









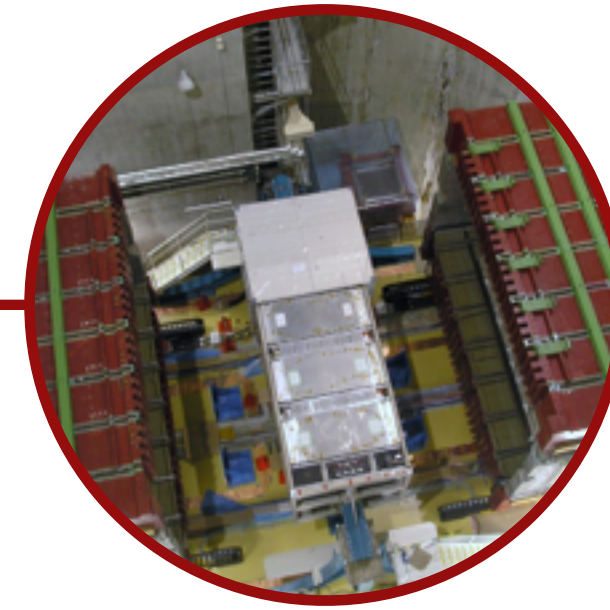
<u>ND280 Off-axis</u>

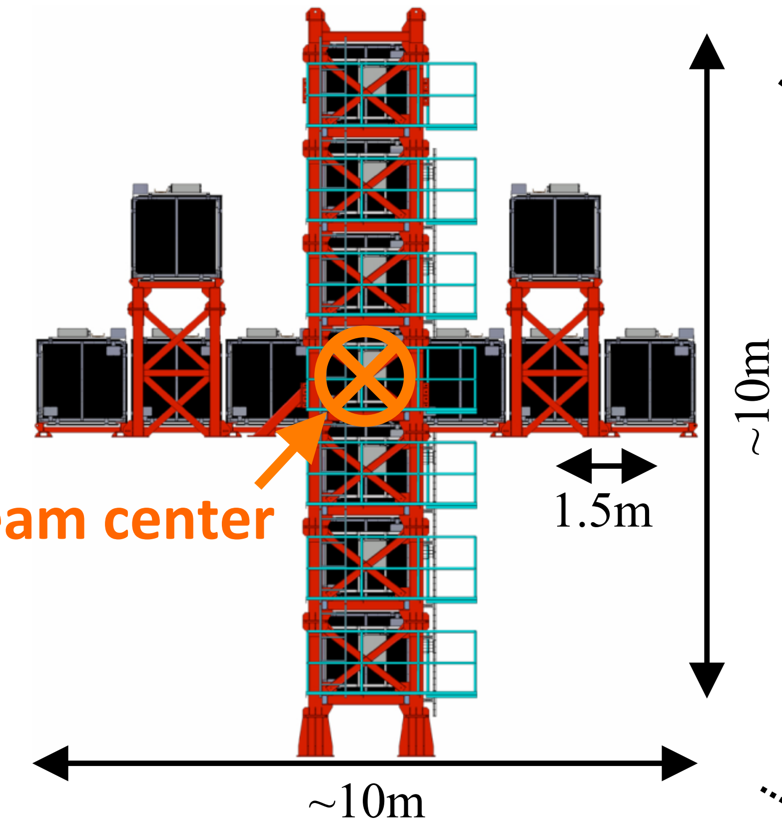
2.5° off-axis.

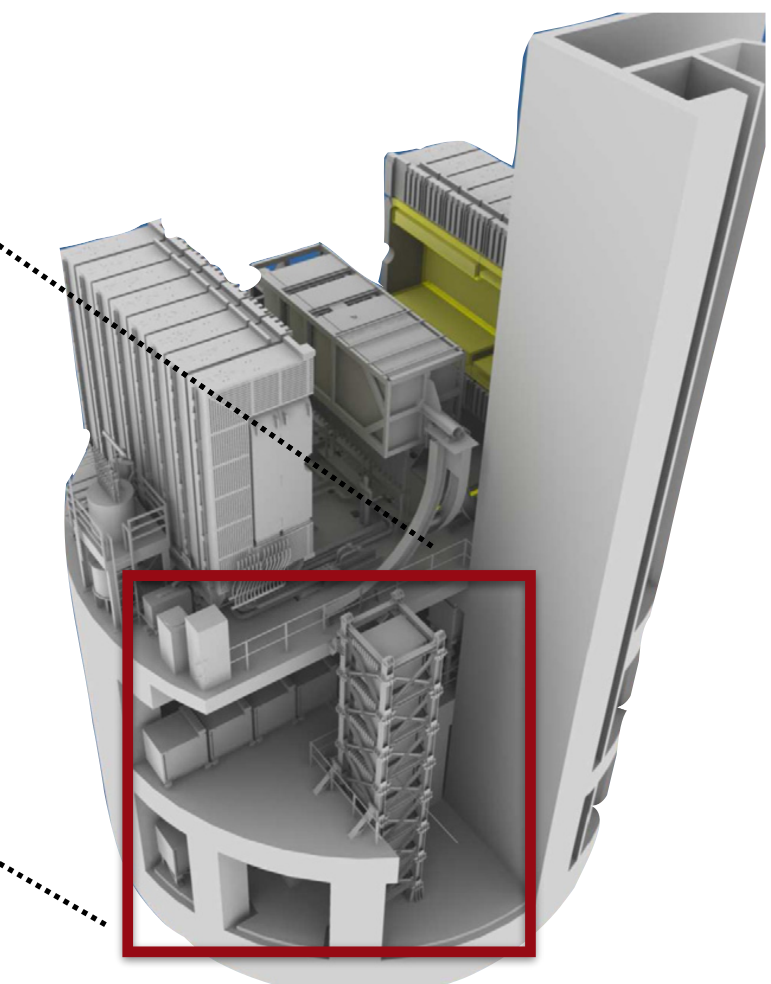
Collection of fine-grain trackers and calorimeter

Measures ν Flux/Spectrum

ND280 Complex







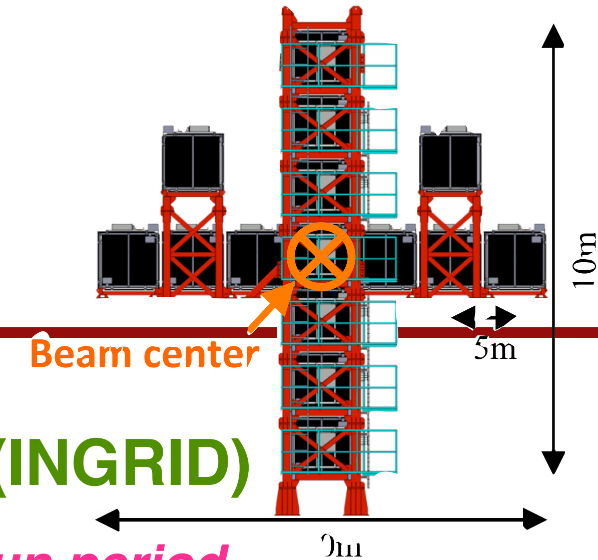
INGRID Detector

Located on-axis

Iron/Scintillator Layers

Measures rate and beam position/profile

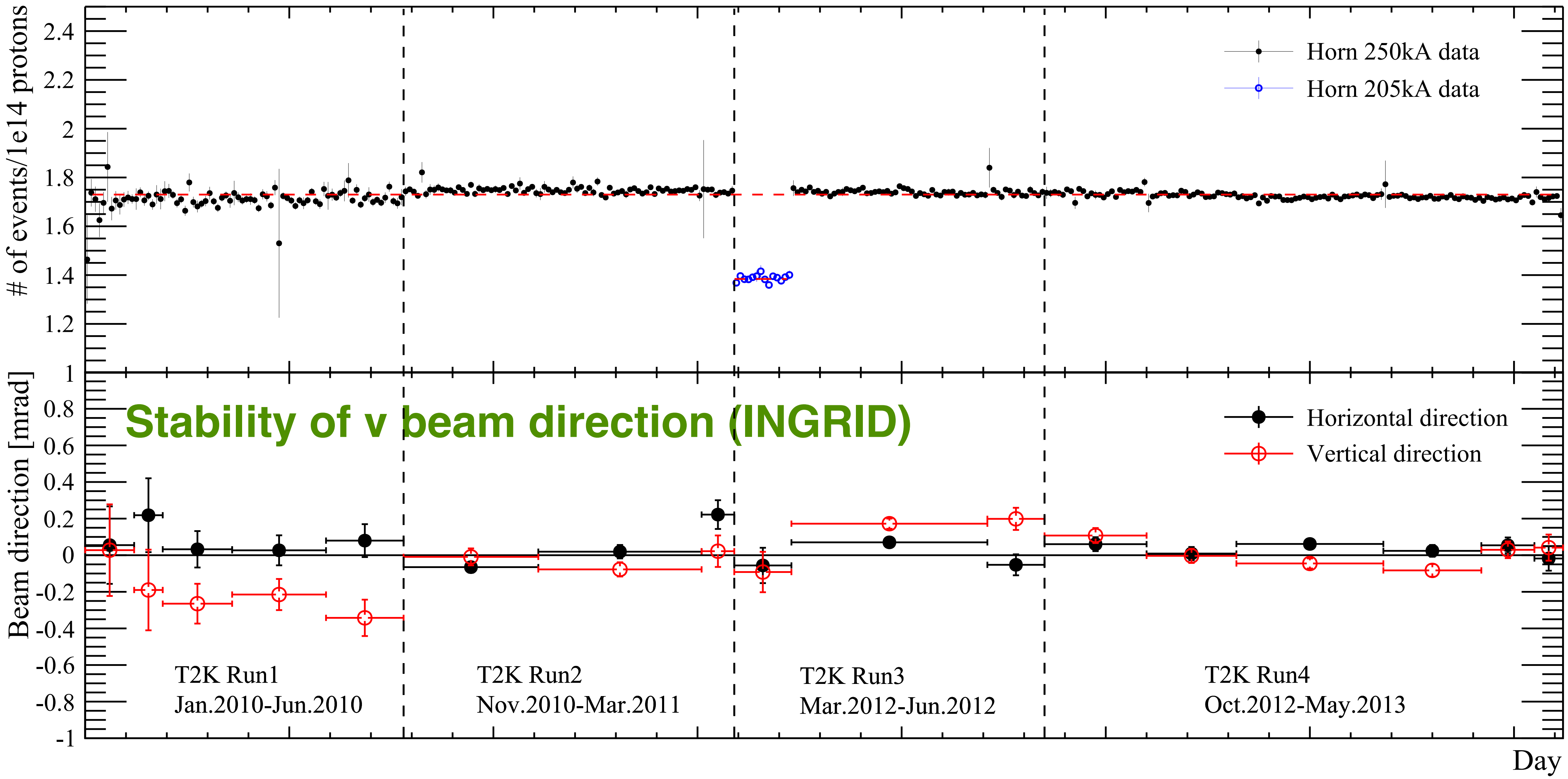
ND280 Complex



Stability of ν interaction rate normalized by # of protons (INGRID)

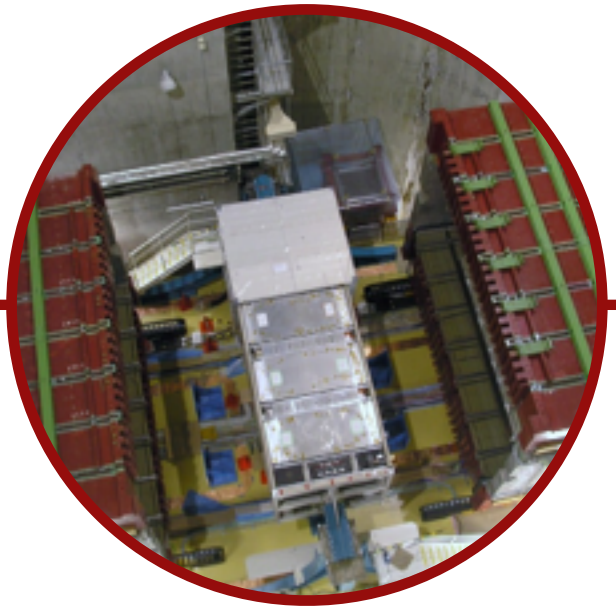
Fluctuation of ν interaction rate (/10^{19}p.o.t) is less than 0.7% whole run period

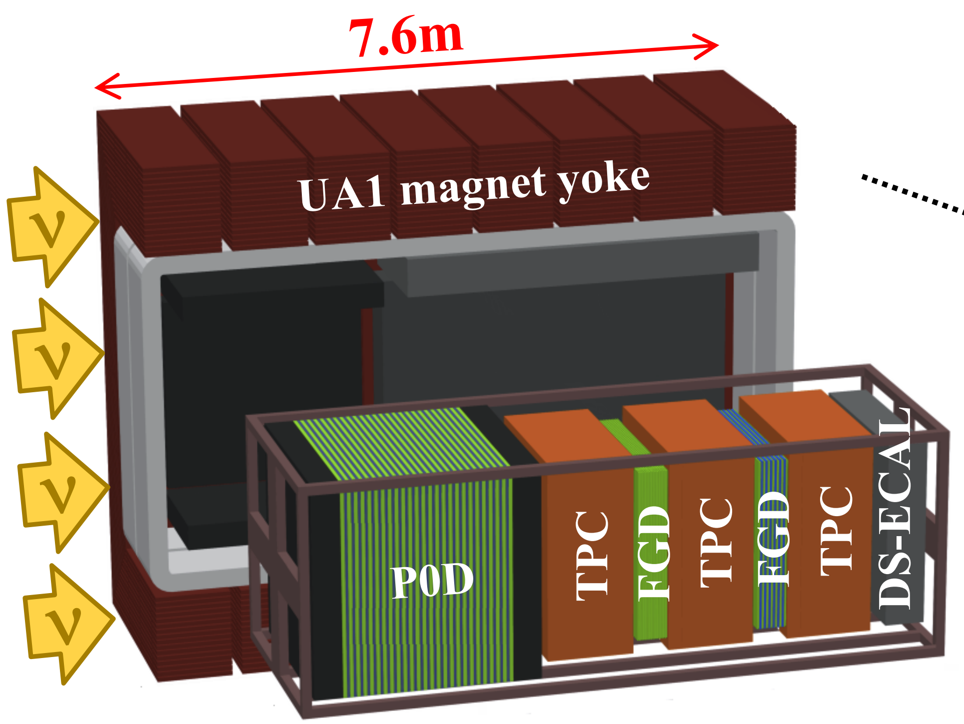
Stability of ν beam direction (INGRID)

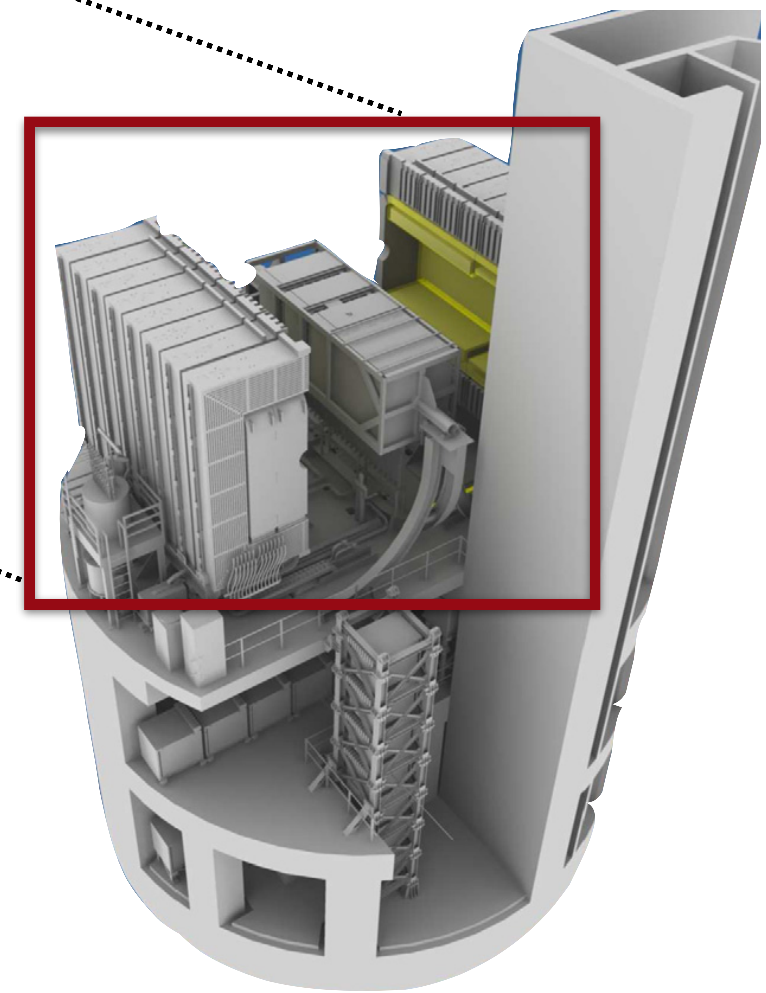


Stability of beam direction is much better than 1mrad during whole run period

ND280 Complex







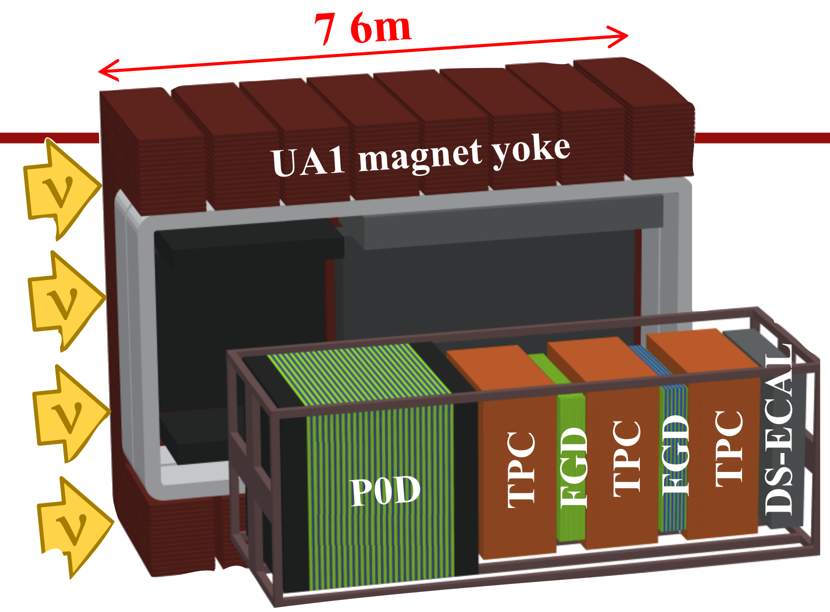
<u>ND280 Off-axis</u>

2.5° off-axis.

Collection of detectors for calorimetry and fine-grained particle tracking

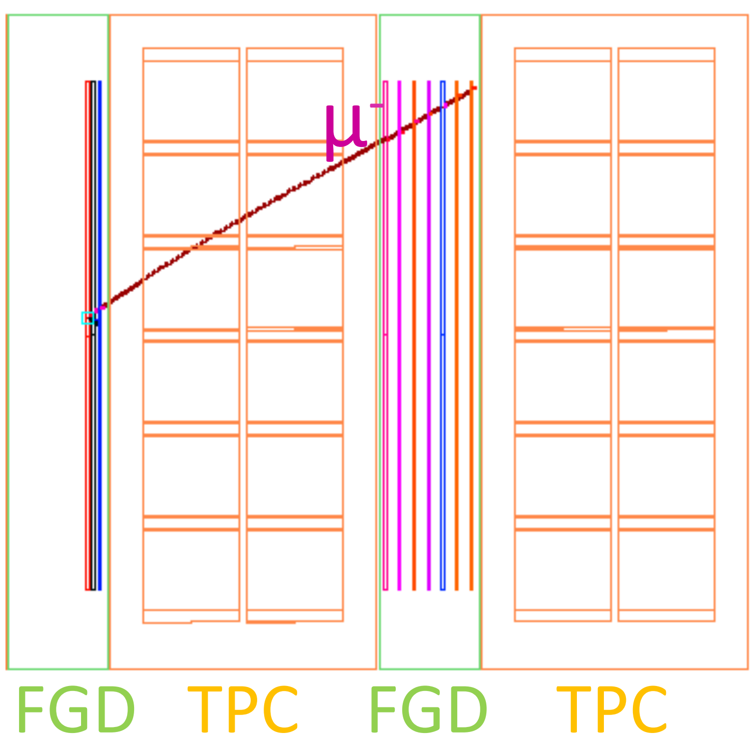
Measures ν Flux/Spectrum

ND280 Measurement

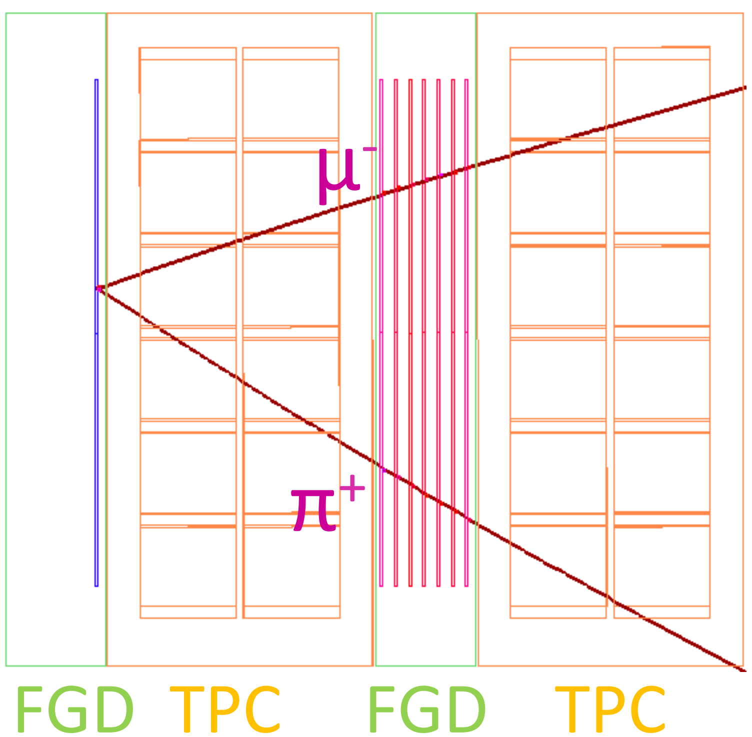


Fit of ND280 events constrains flux and xsec models

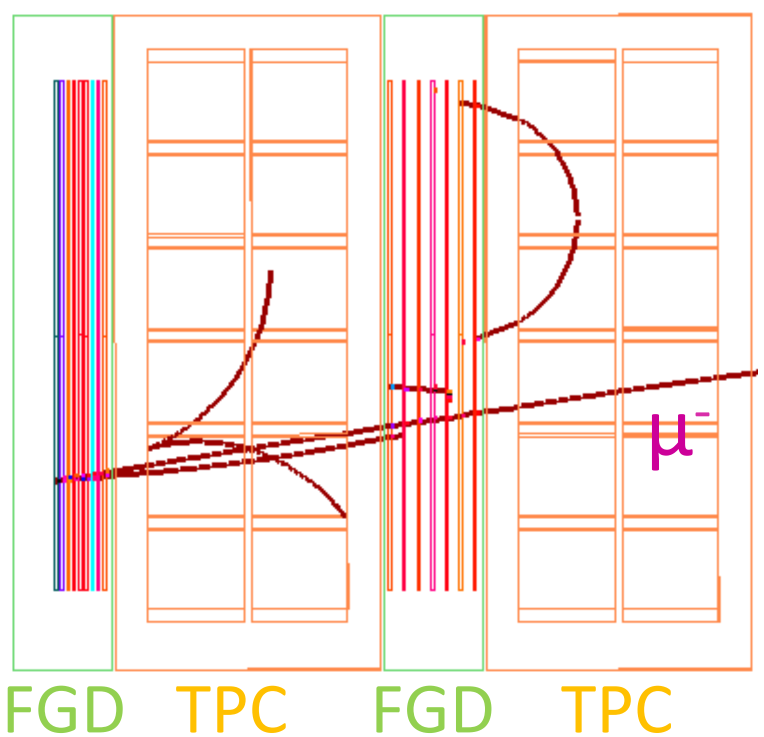
For oscillation analyses, events split into 3 classes based on final state topology.



Charged Current zero charged pions



Charged Current one charged pion



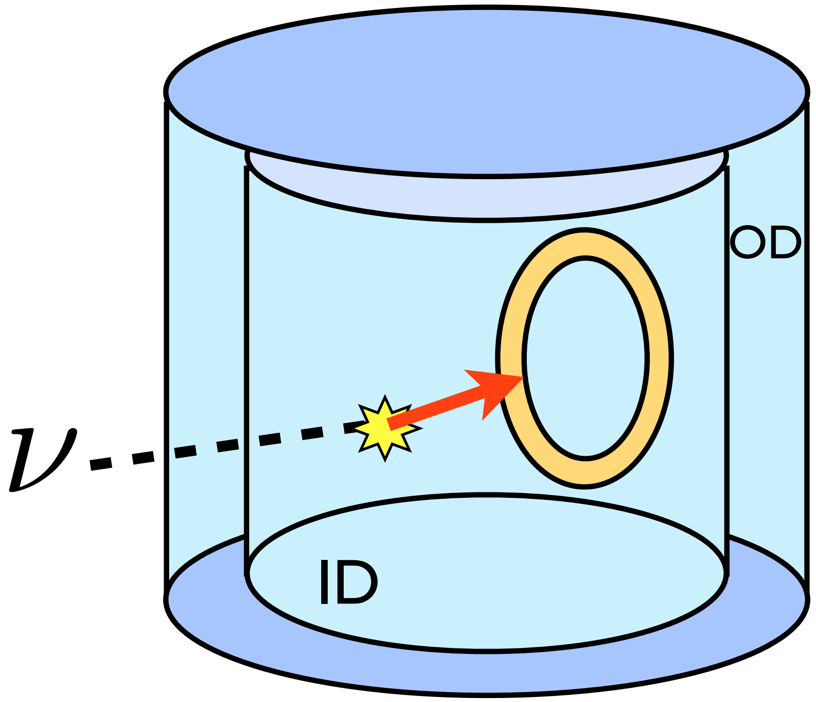
Charged Current Other

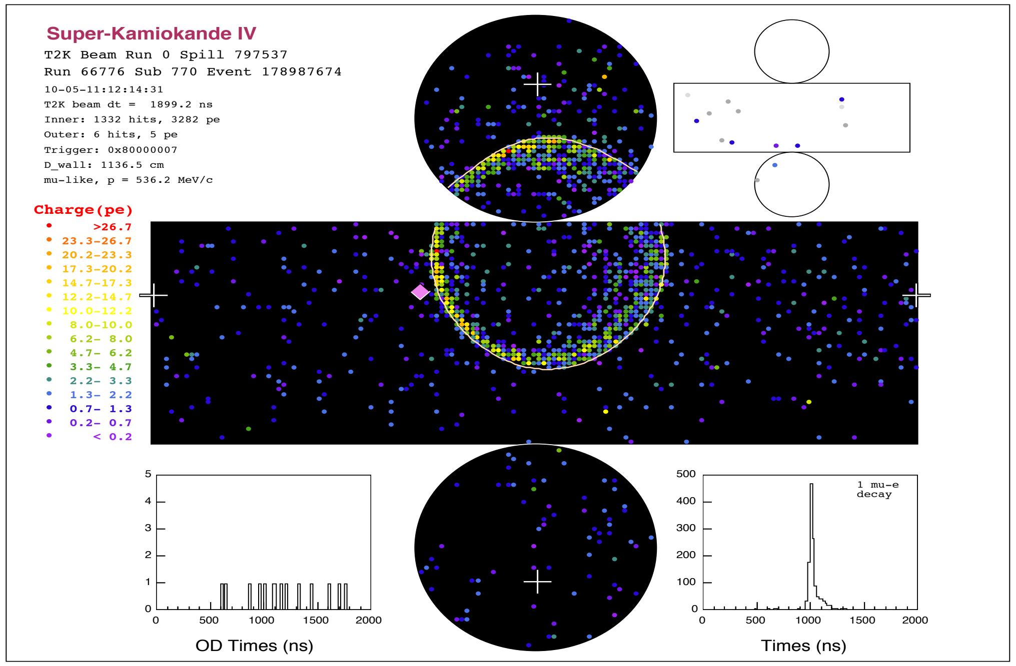
Super-Kamiokande

Super-K detects charged particle tracks traveling through water

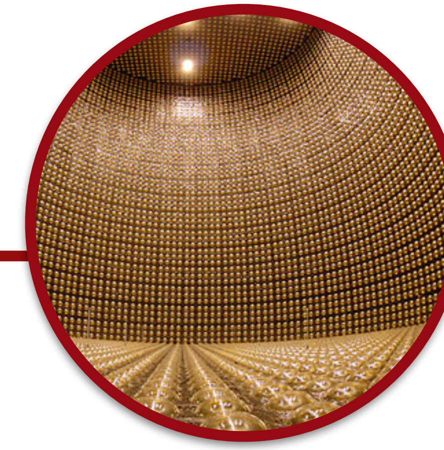
Charged particles produce cone of Cherenkov light observed by PMTs. Particles leave ring-shaped hit pattern on wall

Time and charge information from hits allows momentum reconstruction



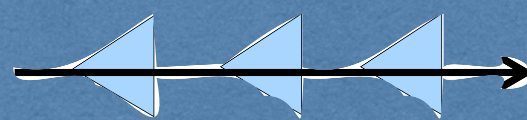


Super-Kamiokande



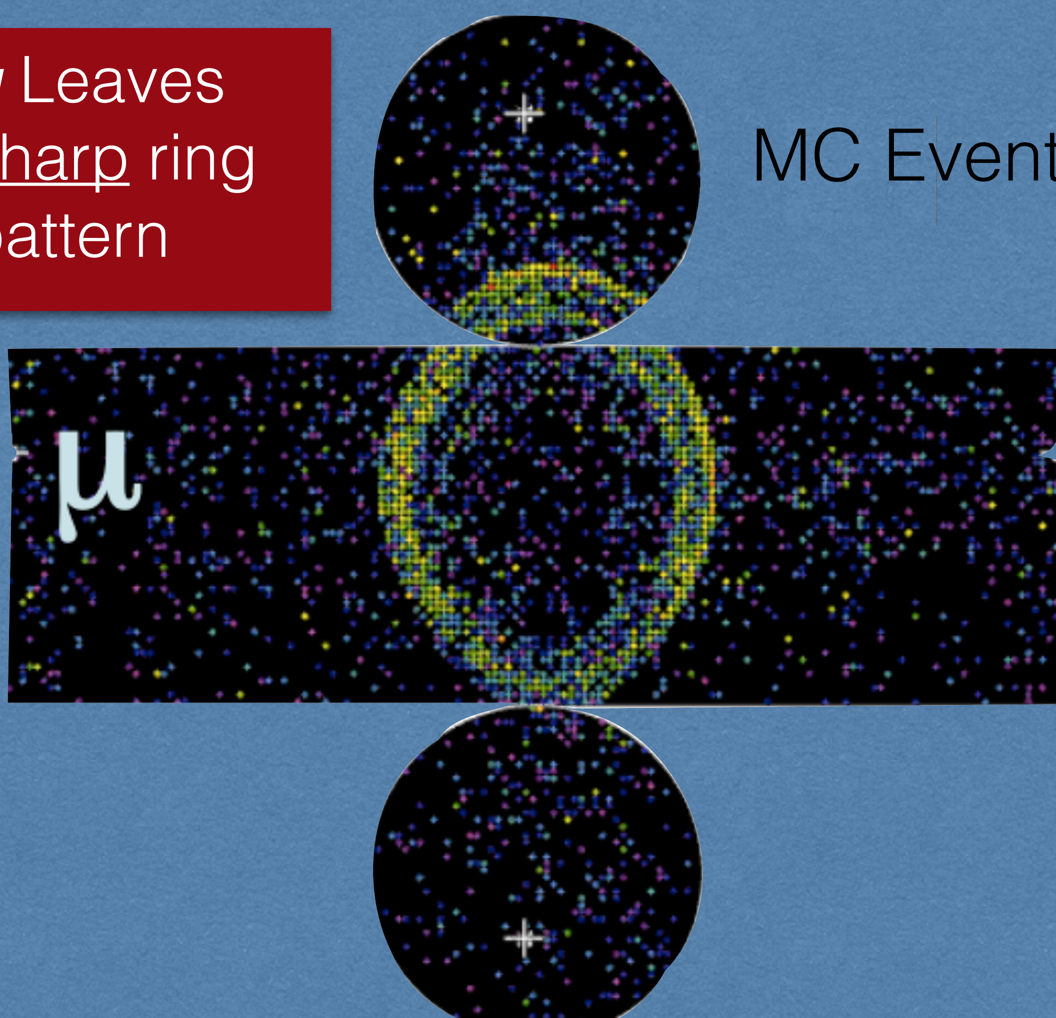
Lepton Flavor ID from Hit Pattern

<u>Muons</u> scatter minimally in water

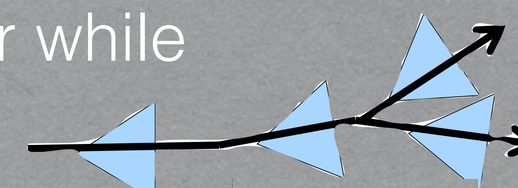


μ Leaves <u>sharp</u> ring pattern

MC Event

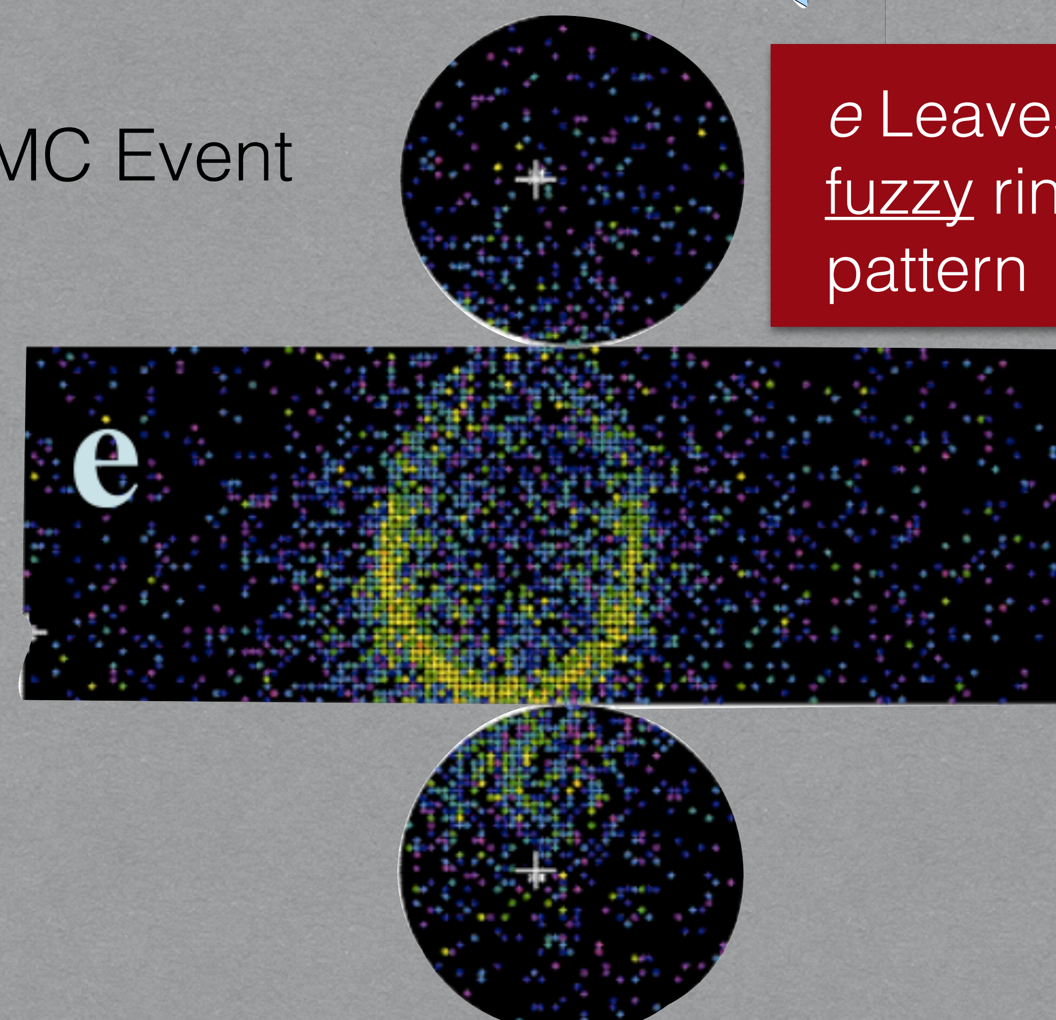


<u>Electrons</u> scatter/shower while traveling through water



MC Event

e Leaves <u>fuzzy</u> ring pattern



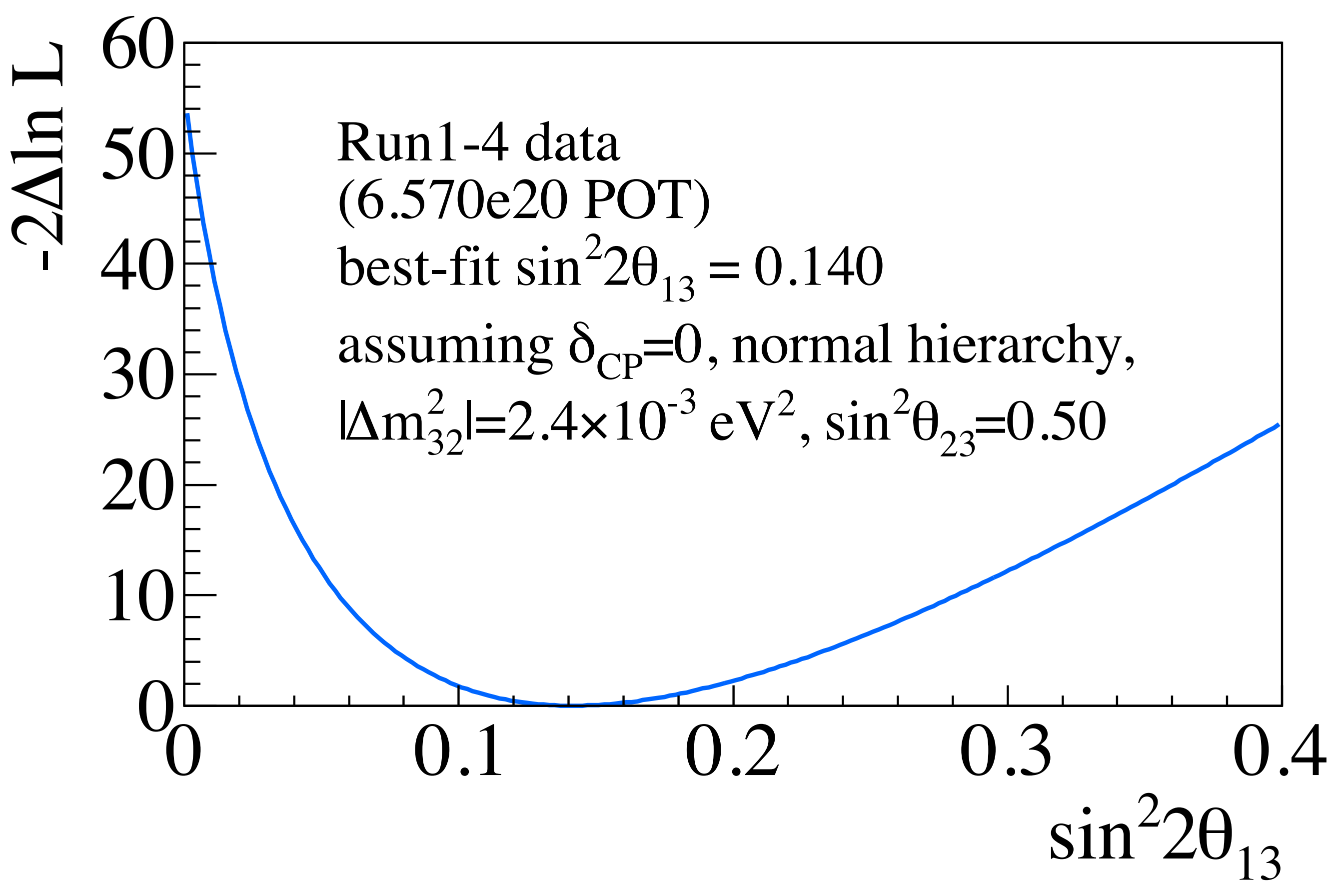
ν_e Appearance

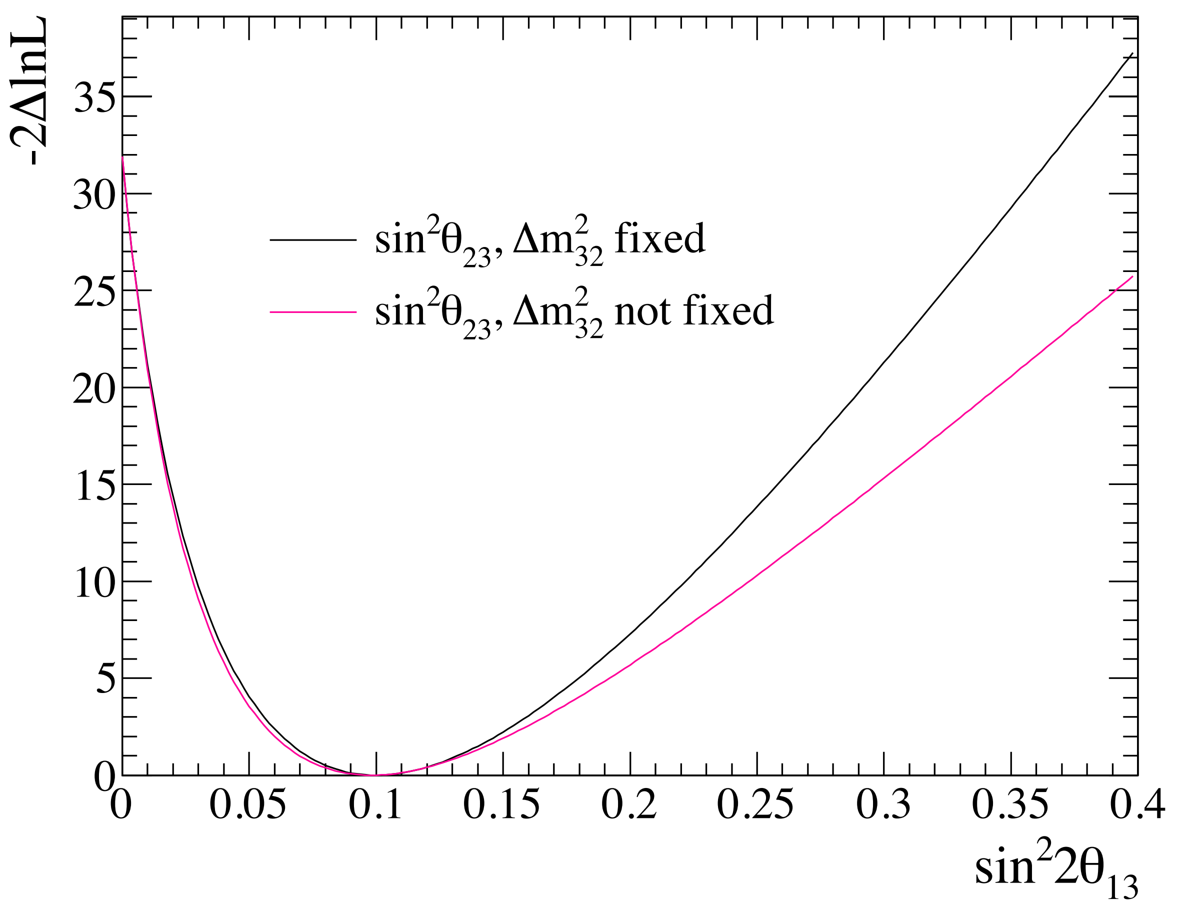
Effect of $\sin^2\theta_{23}$ and Δm^2_{32} on fit

Marginalized parameters using previous T2K constraint

Significance of ν_e appearance discovery not changed: Exclude zero $\sin^2 2\theta_{13}$ to 7.3σ

Best fit changes to
0.140 → 0.133 [NH]
0.170 → 0.166 [IH]





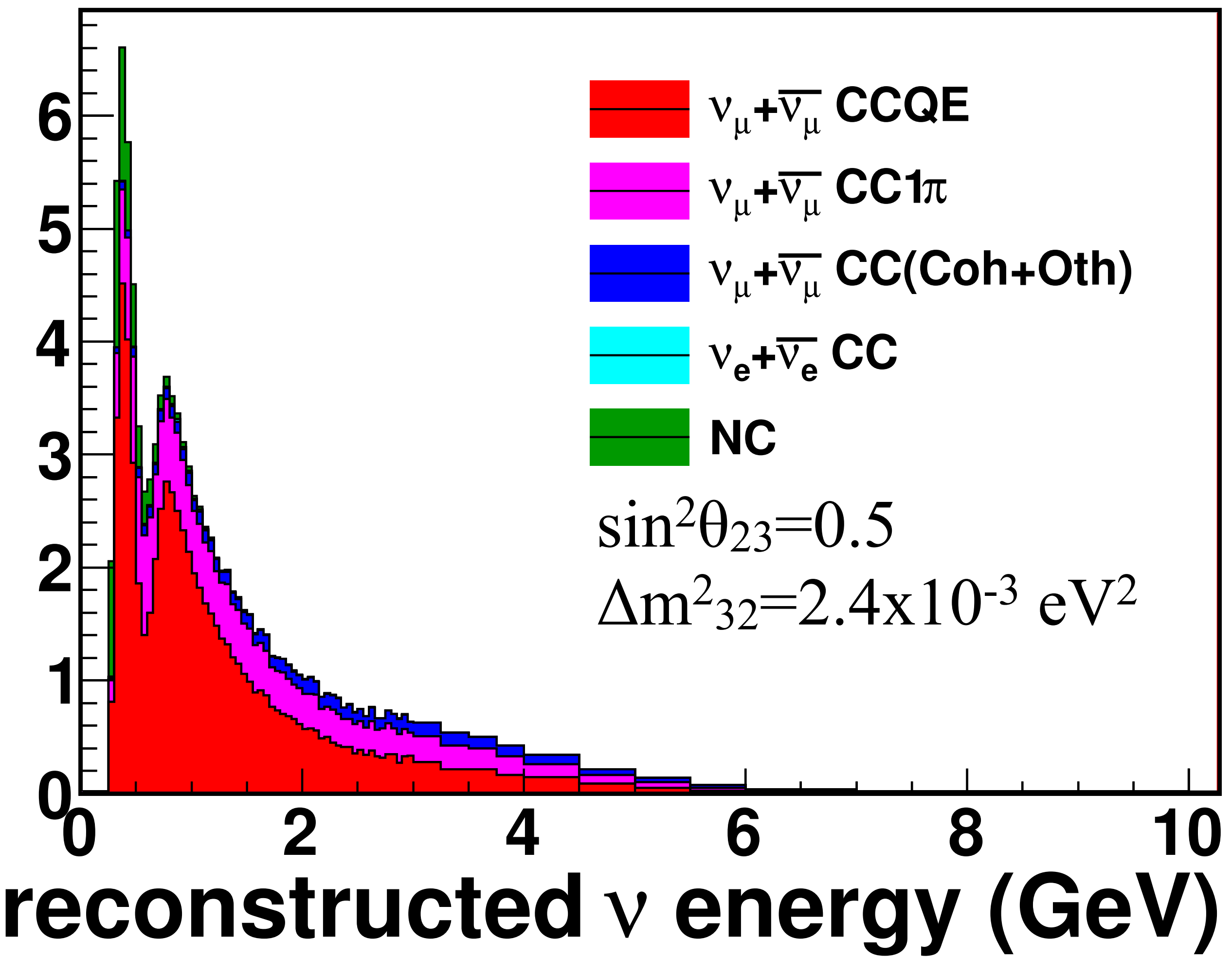
ν_μ Disappearance

Event Selection

Signal purity is high, even after a significant amount of oscillations

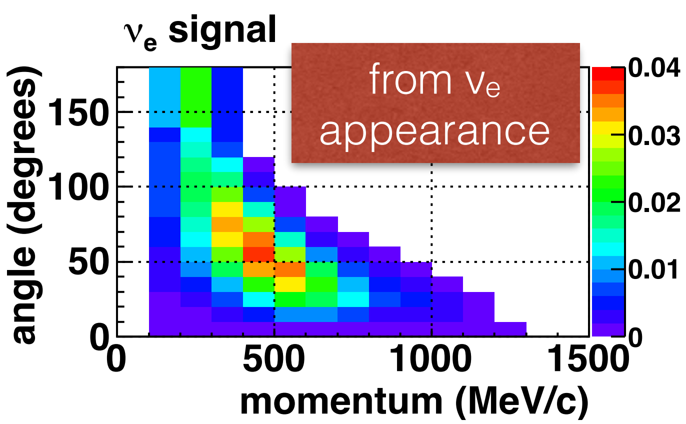
Event breakdown by interaction categories from MC

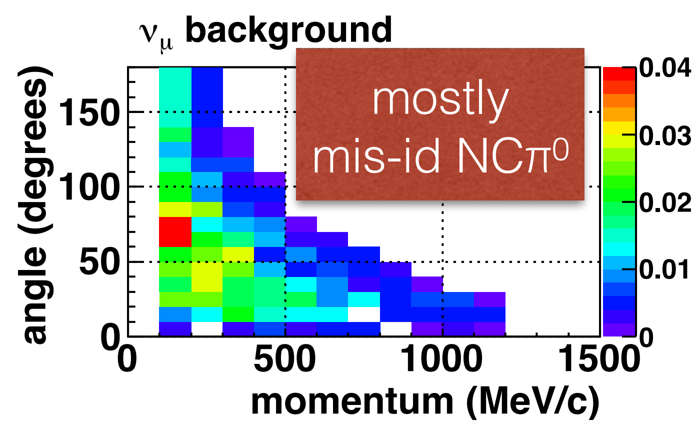
Event Type	Predicted Events $\sin^2(\theta_{23})=0.5$
$\nu_\mu + \bar{\nu}_\mu$ CCQE (signal)	77.93
$\nu_\mu + \bar{\nu}_\mu$ non-CCQE	40.78
$\nu_e + \bar{\nu}_e$ interactions	0.35
neutral current interactions	6.78
Total	**125.85**

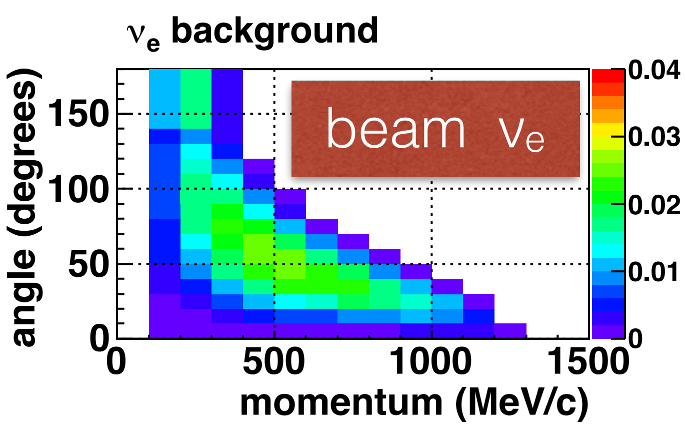


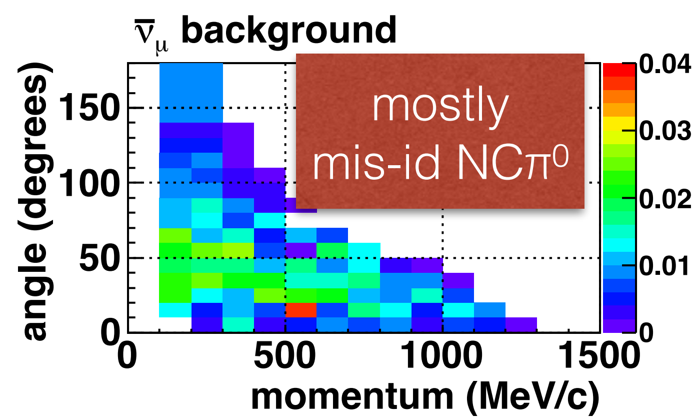
ν_e Appearance

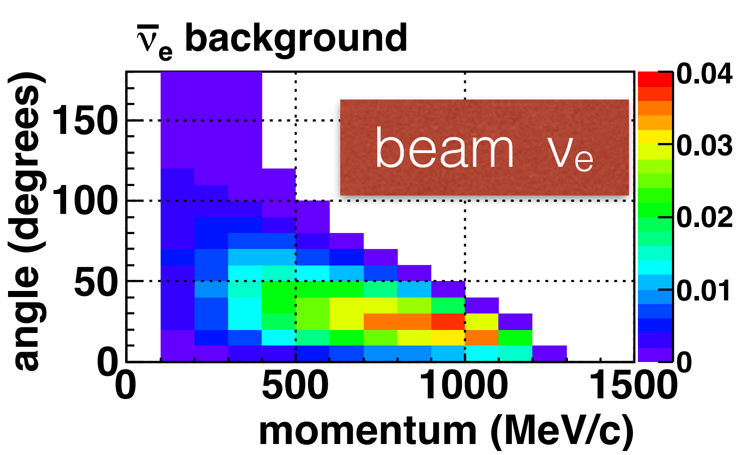
(p,θ) helps separate background from signal



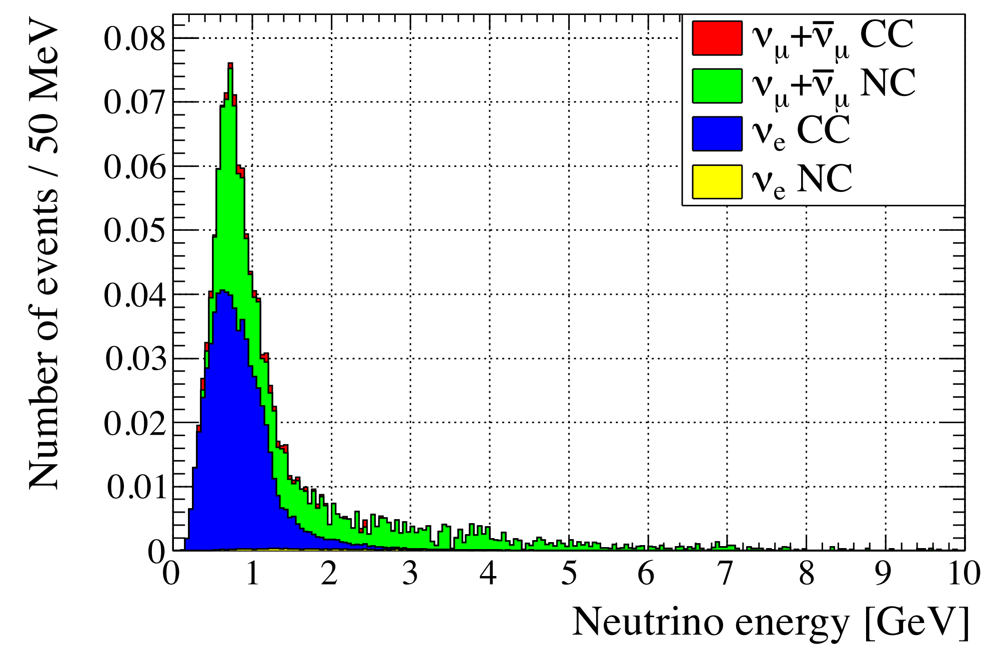








(p,θ)
Fraction of events for each category
$\sin^2\theta_{13}=0.1$, $\delta_{CP}=0$



Neutrino energy distribution
$\sin^2\theta_{13}=0.1$, $\delta_{CP}=0$

ν_e CC from appearance and from beam combined in blue region