Recent Results From T2K

Xth Rencontres du Vietnam

Flavour Physics Conference

ICISE, Quy Nhon,VN

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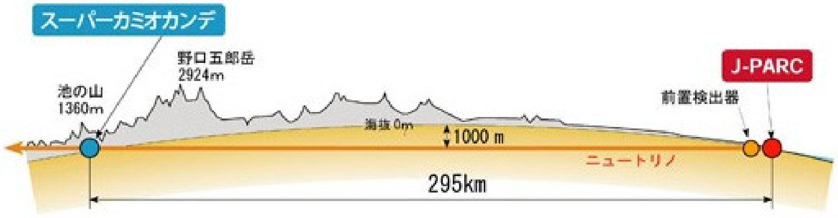
(Representing the T2K collaboration)

Outline

- Motivation
- T2K Experimental Overview
- Physics Results
  - Electron Neutrino Appearance
  - Muon Neutrino Disappearance
- Summary and Outlook



Motivation

- 3-flavor mixing describes (almost) all neutrino oscillation phenomena (3 mixing angles, 2 independent mass splittings, 1 CPV phase)

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{+i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric & accelerator:
θ_{23} ~ 45°
$(\Delta m_{23})^2$ ~2.4x10^{-3} eV^2

Interference:
θ_{13}~ 9° and δ_{CP}=??

Solar & reactor:
θ_{12}~ 34°
$(\Delta m_{12})^2$ ~8x10^{-5} eV^2

Anti-electron neutrino disappearance ($\bar{\nu}_e \rightarrow \bar{\nu}_e$):

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1-\sin^2 2\theta_{13}\ \sin^2\frac{\Delta m^2_{31}L}{4E}$$

→ **Reactors Sensitive to: θ_{13}, $|\Delta m^2_{31}|$**

Electron neutrino appearance ($\nu_\mu \rightarrow \nu_e$):

Appearance

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

Expanded under small θ_{13},α

$$A=\pm 2\sqrt{2}G_F n_e E\Delta m^2_{31} \qquad \Delta=\frac{\Delta m^2_{31}L}{E} \qquad \alpha=\frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

Hierarchy?

CP Violation!

→ **T2K (+NOνA, MINOS) Sensitive to: θ_{13}, δ_{CP}, θ_{23}, Δm^2_{31}**

What We Don't Know?

- **Value CP Violating Phase:** δ
- **θ_{23} Maximal? Octant? (< or > 45^0)**
- **Sign of the mass difference:** Δm^2_{31}
  - **Normal Hierarchy (NH) > 0**
  - **Inverted Hierarchy (IH) < 0**
- **Are there any more ν's? (sterile)**
- **Are Neutrinos Dirac or Majorana?**

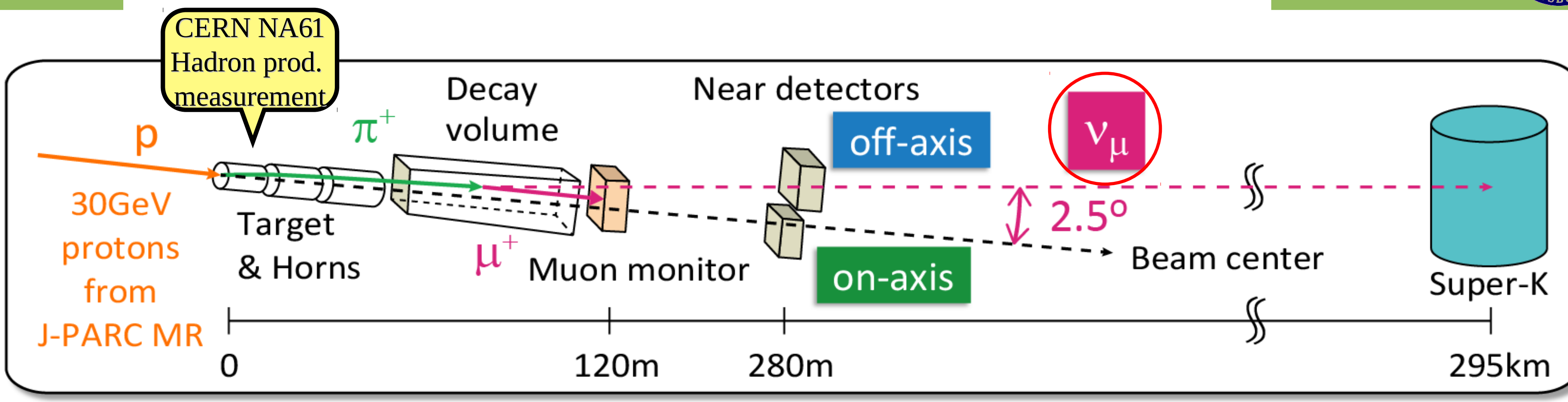
The T2K Experiment
(Tokai to Kamioka)

Goals:

- Study electron neutrino appearance ($\nu_\mu \to \nu_e$): Explore δ_{CP} and $\theta_{13, 23}$
- Precision measurement of ν_μ disappearance: Explore θ_{23}

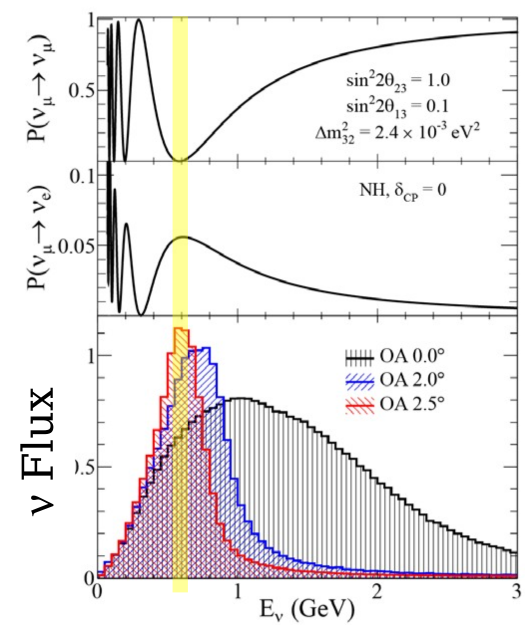
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{32} L}{E}$$

Overview of T2K: Beam

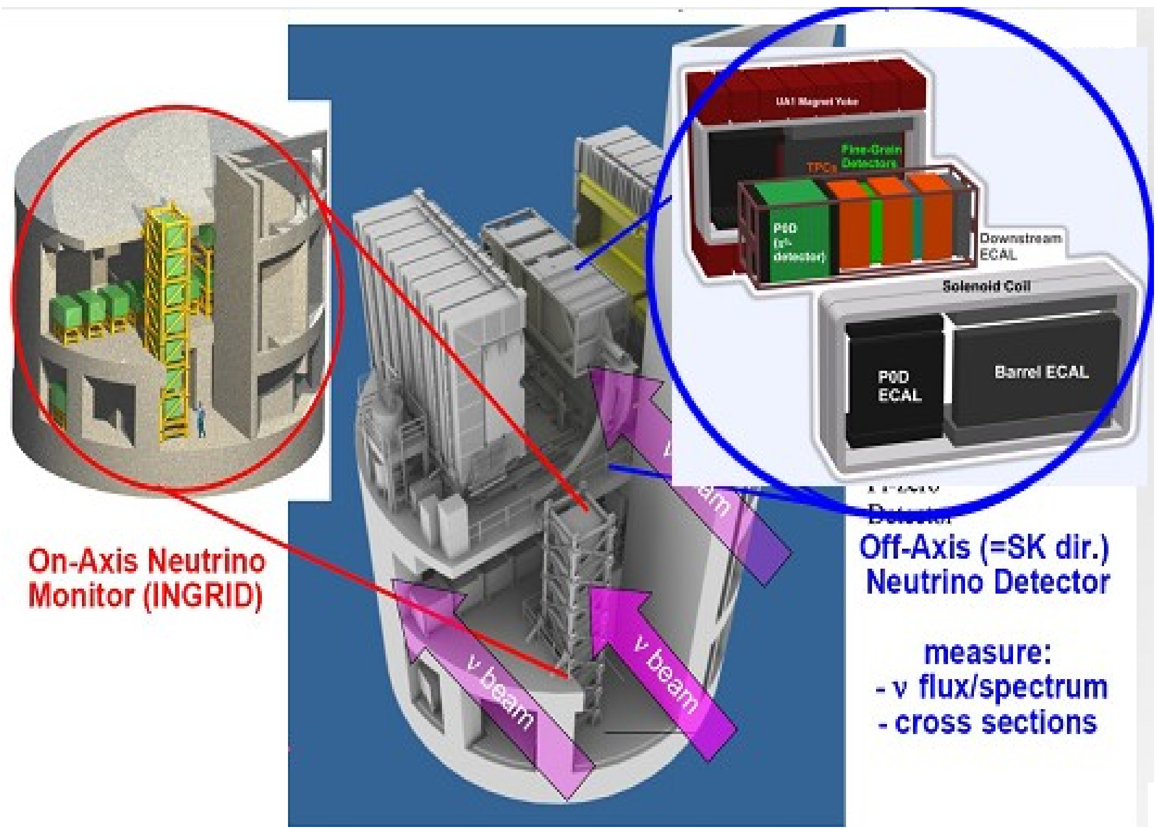


First Use of Off-axis ν_μ Beam:

- Intense & high quality beam (Beam direction stability < 1mrad)
  - ~1 mrad shift corresponds to ~2% energy shift at peak
- Low energy narrow band beam
- E_ν peak around oscillation maximum (~0.6GeV)
- Small high energy tail → reduces feed-down background events
- π,K production at target was measured using CERN NA61 exp.
  - See Alexis Haesler's talk



Overview of T2K: Near Detectors(ND280)

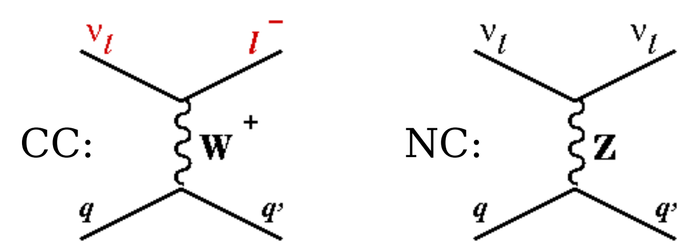


On-Axis Detector (INGRID) Monitor ν:

- **Beam direction**
- **Beam Intensity**

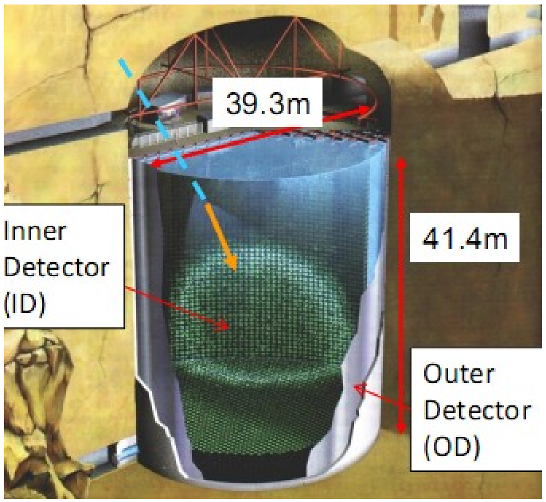
Off-Axis Detector:

- **In SK Direction**
- **Measure:**
  - **ν flux**
  - **Cross sections measurements using water targets to reduce Systematic errors on oscillation parameters**

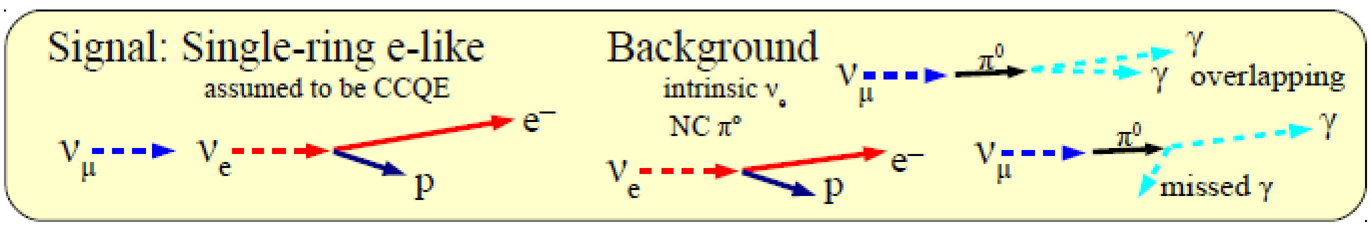


→ Used for monitoring of beam and systematic error reduction

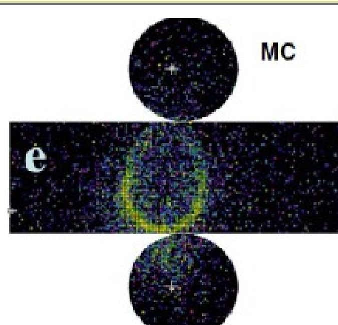
The T2K Far Detector: Super-Kamiokande



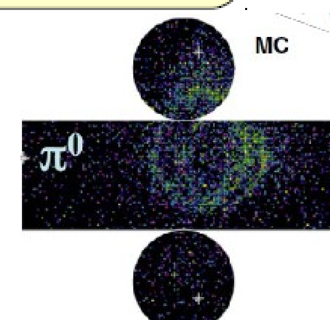
- 50 kiloton Water Cherenkov detector 1 km underground
- Performance well matched to sub-GeV neutrinos
- High ν_e signal efficiency plus high π^0 rejection
  - 32 kiloton inner volume (22.5 kiloton fiducial)
  - 2 meter wide outer region to identify entering particles
- Probability to misidentify muon as electron is small
- GPS time recorded in real-time for every spill
  - Associate events with JPARC (beam)



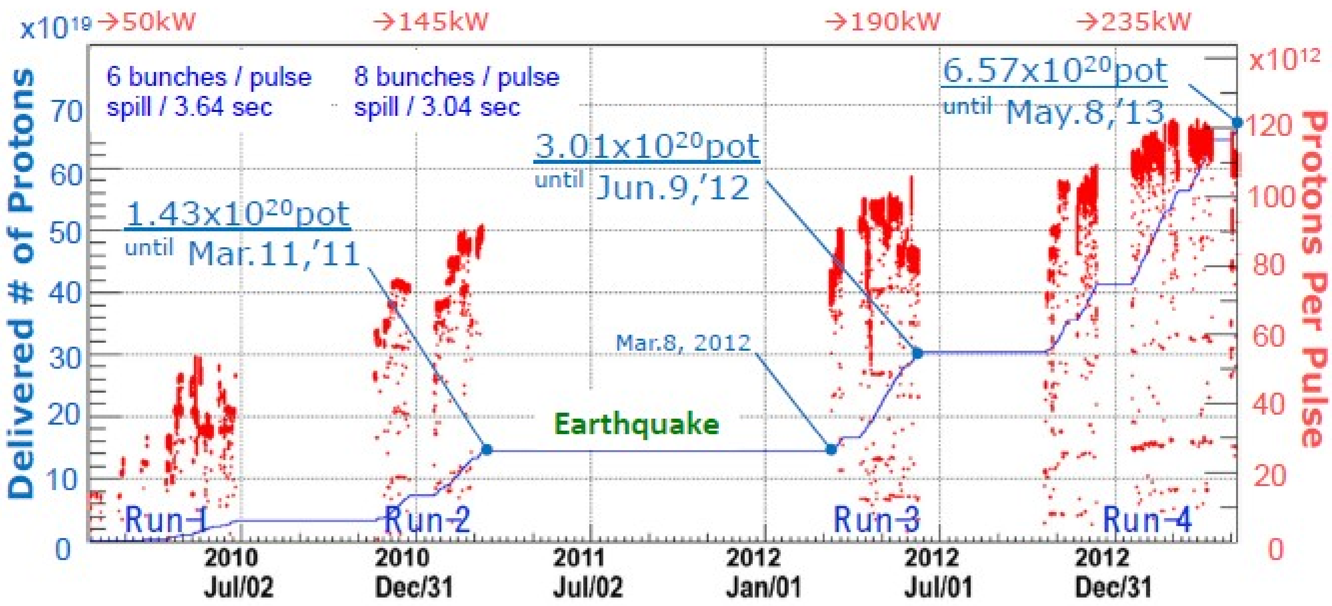
1 EM Shower:
1 Fuzzy Ring



2 EM Showers:
2 or 1 Fuzzy Ring

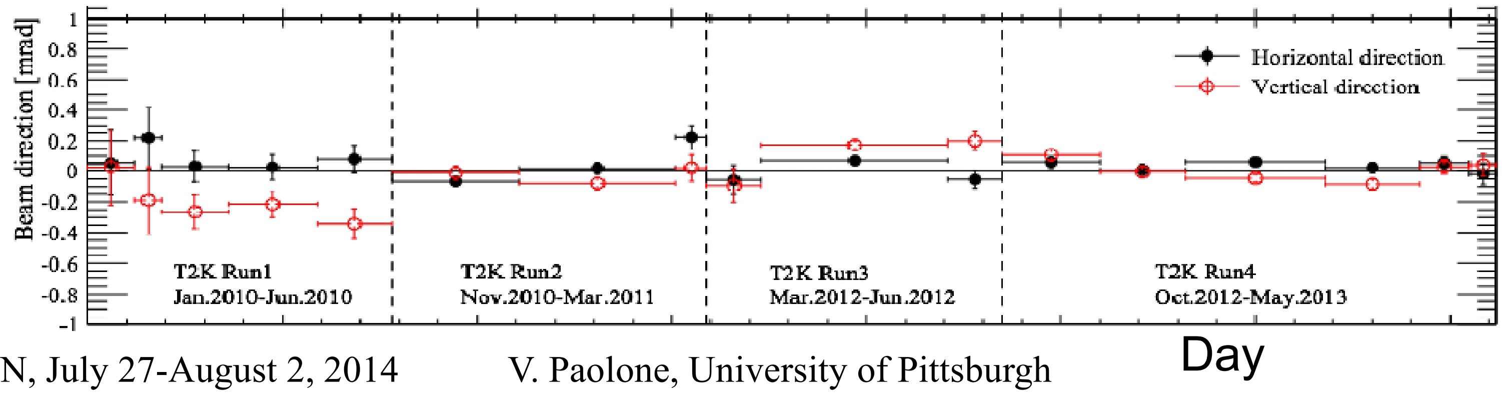


Analyzed Data: Run 1-4

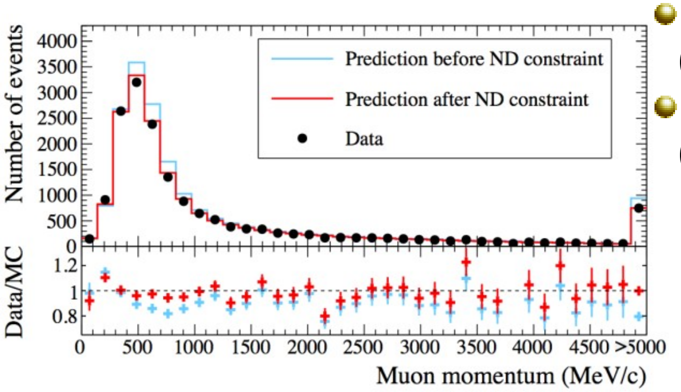


- **Total: 6.57 x 10^{20} POT**
- **Intensity:**
  - ~235 kW stable operation for Run 4
- **Run 5** Started in May 2014 – ***with anti-ν's!***

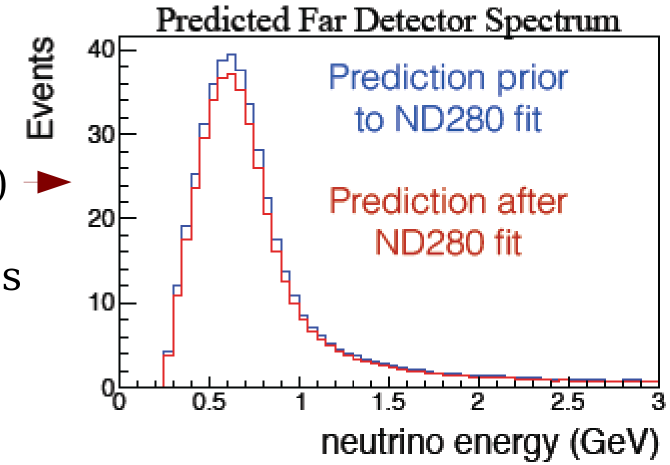
Required Beam direction stability achieved (< 1mrad)
(Many thanks to the accelerator group and beam-line group)



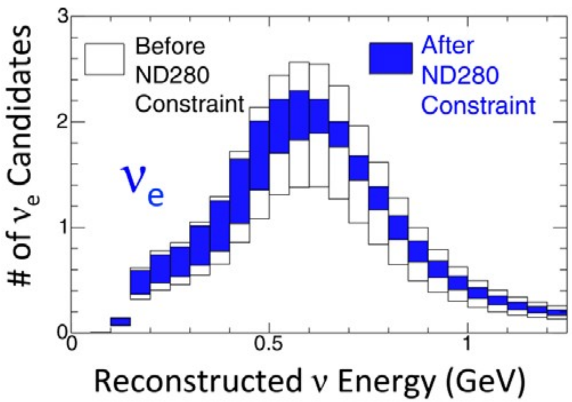
Flux & ν Background Constraints using ND280



- Select charged-current (CC) events in ND280
- Separate into 3 categories (CCQE, CC Resonance, CC DIS)
  - Parameters from simultaneous fit of 3 samples
  - Used for prediction of Super-K neutrino spectrum w/o oscillation

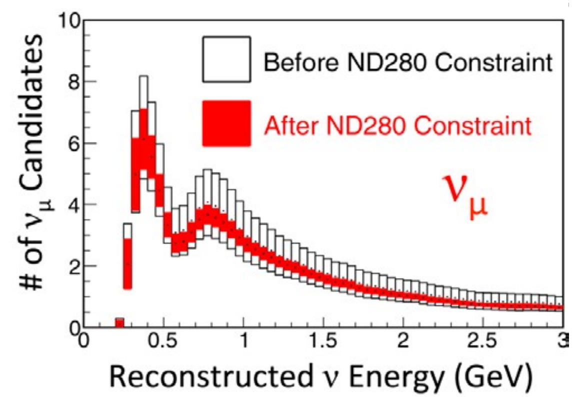


ND280 constraint provides significant reduction of uncertainty at Super-K:



(Appearance)

Systematic Source	Relative Uncertainty in # of ν_e Candidates (%)	Relative Uncertainty in # of ν_μ Candidates (%)
Flux + cross section (ND280 constrained)	3.1	2.7
Cross section (ND280-independent)	4.7	5.0
π Hadronic Interactions	2.3	3.5
SK Detector	2.9	3.6
Total	**6.8**	**7.6**



(Disappearance)

T2K: SK Event Selection

ν_μ event selection (disappearance):

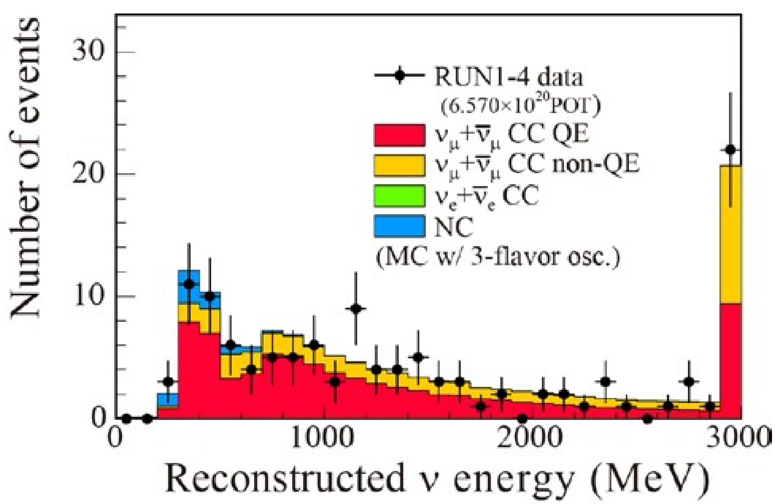
- Fully contained fiducial volume
- Single-ring μ-like event
- p_μ > 200 MeV/c
- # of decay electron ≤ 1

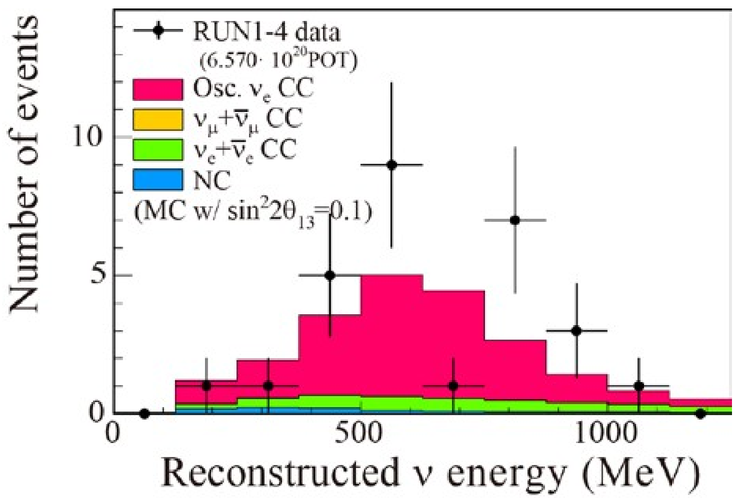
$N_{observed}$ = 120
$N_{expected}$ (w/o osc.) = 446±23(syst.)

ν_e event selection (appearance):

- Fully contained fiducial volume
- Single-ring e-like event
- $E_{visible}$ > 100 MeV, E_{rec} < 1250 MeV
- # of decay electron = 0
- π^0 rejection cut

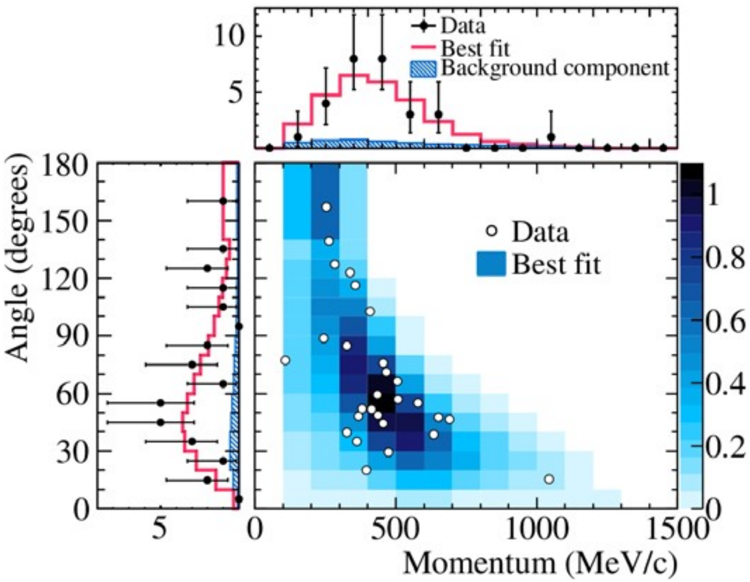
$N_{observed}$ = 28
$N_{expected}(\sin^2 2\theta_{13}=0.1)$ = 21.6
$N_{expected}$(bkg.) = 4.9±0.6(syst.)





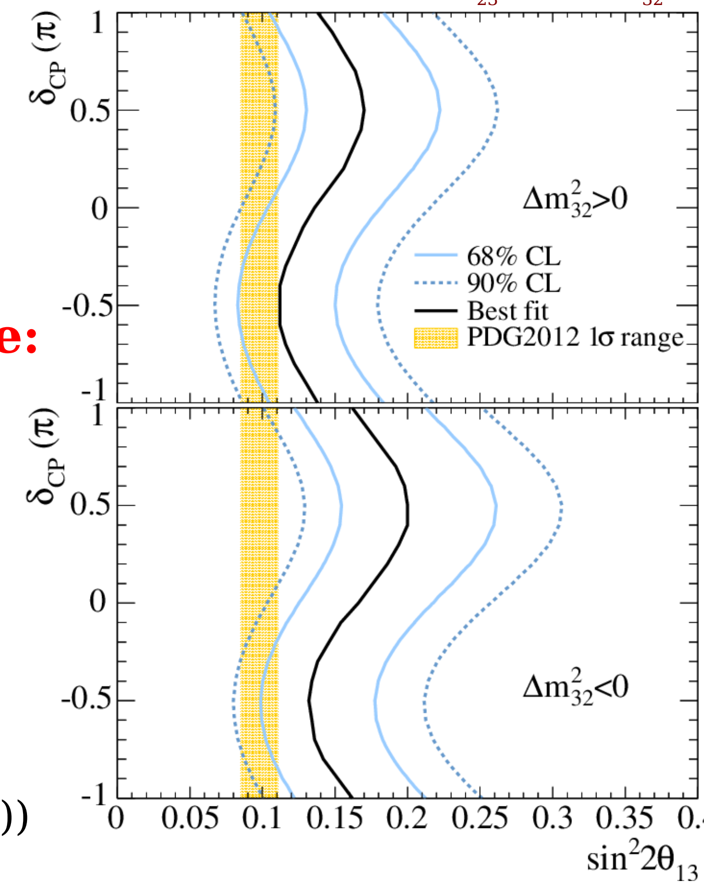
Results: Observation of ν_e Appearance

Using Maximum likelihood fit in (p_e, θ_e):



7.3σ significance: $\theta_{13} \neq 0$!

(Marginalized over θ_{23} and Δm^2_{32})



	Best-fit value
NH	$\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$
IH	$\sin^2 2\theta_{13} = 0.170^{+0.045}_{-0.037}$

for $\sin^2\theta_{23} = 0.5$, $|\Delta m^2_{32}| = 2.4 \times 10^{-3}$ eV^2, $\delta_{CP} = 0$

(Result Published:
PRL 112, 061802 (2014))

When combining T2K with reactor results, some values of δ_{CP} are disfavored

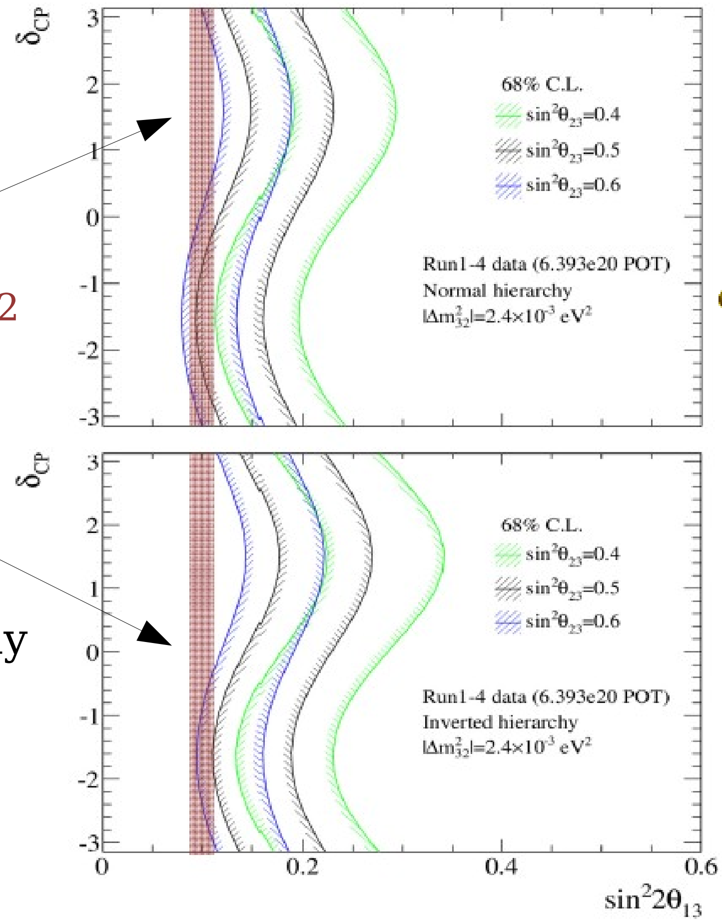
θ_{13} vs δ_{CP} scan for $\theta_{23} \neq \pi/4$

- Significant dependence on value of θ_{23}
- Need to increase the value of θ_{23} to account for T2K's observed number of events

(NOTE: These are 1D contours for values of δ_{CP}, not 2D contours in δ_{CP}- θ_{13} space)

Pink band represents PDG2012 reactor average value of $\sin^2 2\Theta_{13}$=(0.098±0.013)

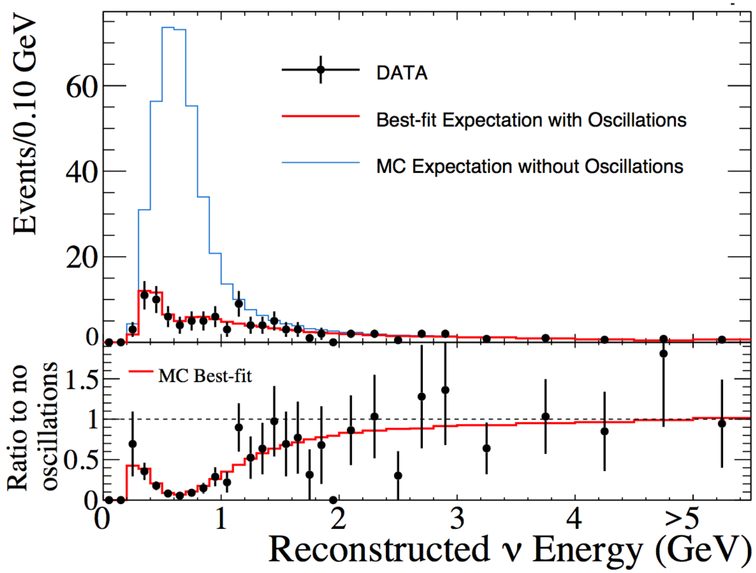
Best overlap with reactor results is normal hierarchy And δ_{CP} = $-\pi/2$



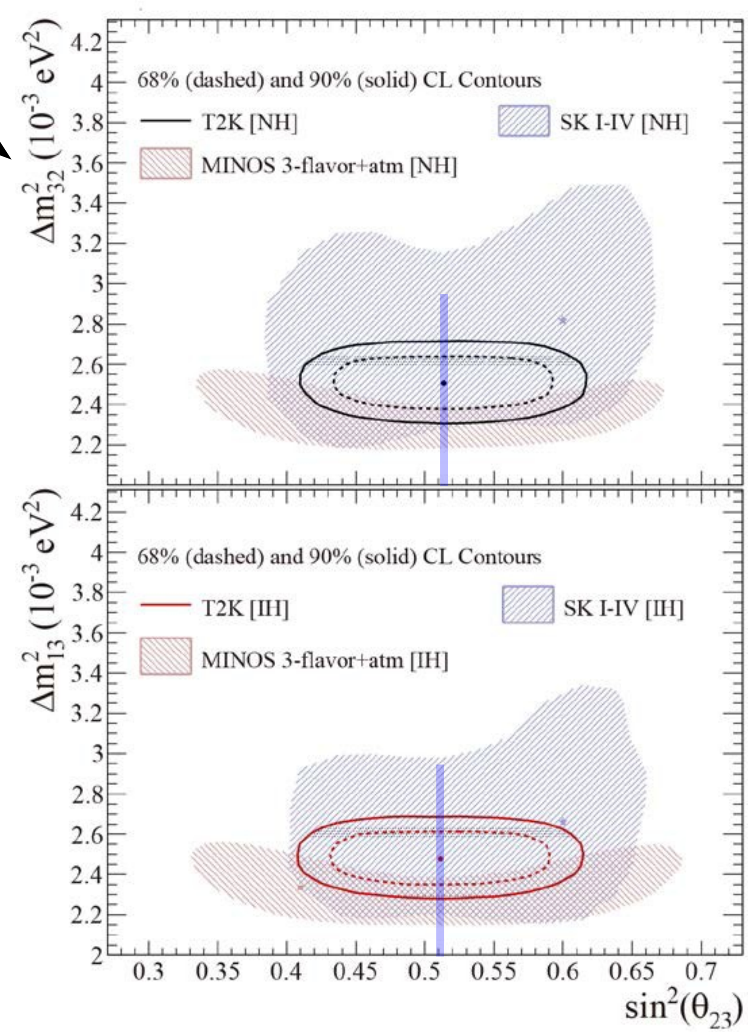
- Improved measurements of θ_{23} are important!

ν_μ Disappearance Result

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{32} L}{E}$$



Presently the best measurement of θ_{23}

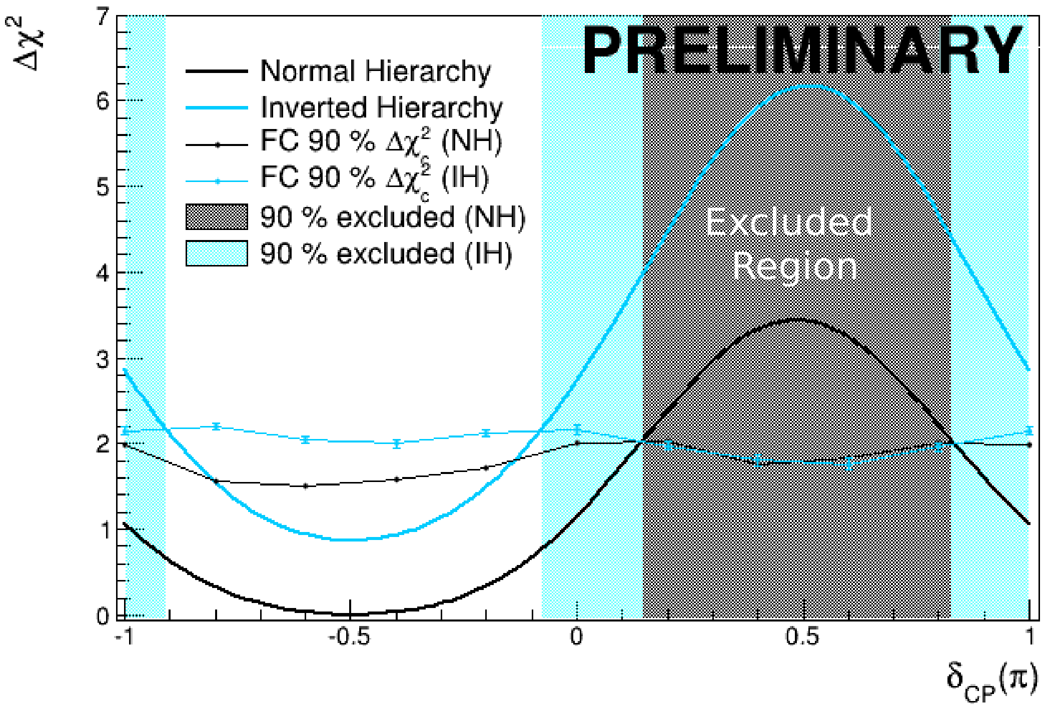


Oscillation parameters		Best-fit value
NH	$\sin^2(\theta_{23})$	$0.514^{+0.055}_{-0.056}$
	Δm^2_{32} (10^{-3} eV^2)	2.51 ± 0.10
IH	$\sin^2(\theta_{23})$	0.511 ± 0.055
	Δm^2_{13} (10^{-3} eV^2)	2.48 ± 0.10

(Published result:
PRL 112, 181801 (2014))

Joint $\nu_\mu+\nu_e$ Analysis Fit: Preliminary

- **Likelihood ratio fit of ν_μ and ν_e events from T2K**
  - Confidence interval performed with Feldman-Cousins
  - Include constraint from reactor experiments



- **Preference for Normal Hierarchy and a value of δ_{CP} around $-\pi/2$**

Using a Markov Chain Monte Carlo (MCMC):

(%)	NH	IH	Sum
$\sin^2\theta_{23} \leq 0.5$	18	8	26%
$\sin^2\theta_{23} > 0.5$	50	24	74%
Sum	68%	32%	

PRELIMINARY

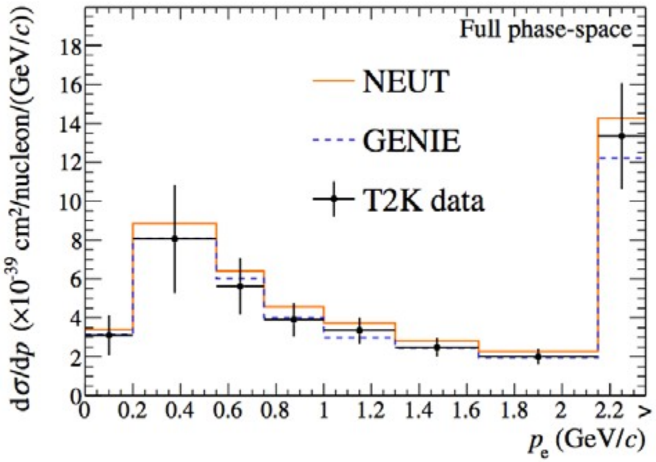
- Comparing the probabilities for each Mass Hierarchy (MH) and θ_{23} octant combination in the posterior probabilities.

T2K ν Cross Section Measurements

- Important in their own right
  - Understand how ν's interact with matter
- Needed to reduce the systematic errors in oscillation analyses
  - Extract the fundamental properties of ν's

Good Agreement with MC's!

- ND280:
  - ν_e CC Inclusive Cross Section
    - arXiv:1403.2552 [hep-ex]
  - ν_μ Cross Section on Fe/CH(INGRID)
  - ν_μ CC inclusive cross section on carbon
    - Result published in PRD 87, 092003 (2013)



- SK:
  - ν + Oxygen NCQE interaction followed by nuclear de-excitation γ ray
    - arXiv:1403.3140 [hep-ex]

- **More to Come**

Summary and Outlook

- Presented T2K results based on 6.57×10^{20} POT (neutrino mode):
  - ν_e appearance :
    - Observation of non-zero θ_{13} in appearance channel at 7.3σ significance
  - ν_μ disappearance
    - World's most precise measurement of θ_{23}
- Using reactor constraint in conjunction with T2K results:
  - Hints of a favored region for δ_{CP} centered at $-\pi/2$
- Continue to combine T2K results with other experiments:
  - Including Reactors and NOνA to provide improved constraints on: δ_{CP}, Mass hierarchy (normal or inverted ?), θ_{23} octant
- T2K will continues to take data with the ultimate goal of 7.8×10^{21} POT:
  - Current data : 8% → 12 times more data
  - Future runs will include significant fraction of anti-ν running
  - J-PARC accelerator upgrades to accelerate POT rate
    - MR beam power : 235 kW (current) → 750kW (designed)
- T2K data taking has restarted (with anti-neutrinos)
- **Stay Tuned: More results to come**

The T2K Collaboration Thanks You

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
U. Aachen

Italy
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INFN, U. Napoli
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Colorado S.U.
Duke U.
Louisiana S.U.
Stony Brook U.
U.C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

~500 members from 11 countries

Backup Slides

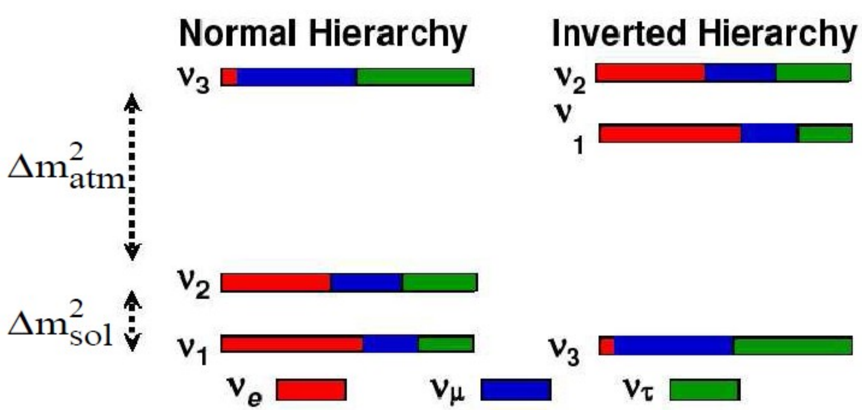
What Do We Know?

Solar+KamLAND → $\theta_{12} \sim 34^0$

SK, MINOS, T2K → $\theta_{23} \sim 45^0$

Daya Bay, Reno, Double Chooz → $\theta_{13} \sim 9^0$

(T2K: $\theta_{13} \neq 0$ → In Appearance Channel)



$\Delta m^2_{21} = (7.65 + \pm 0.23) \times 10^{-5}$ eV^2

sign of the mass difference, $\Delta m^2_{21} > 0$.

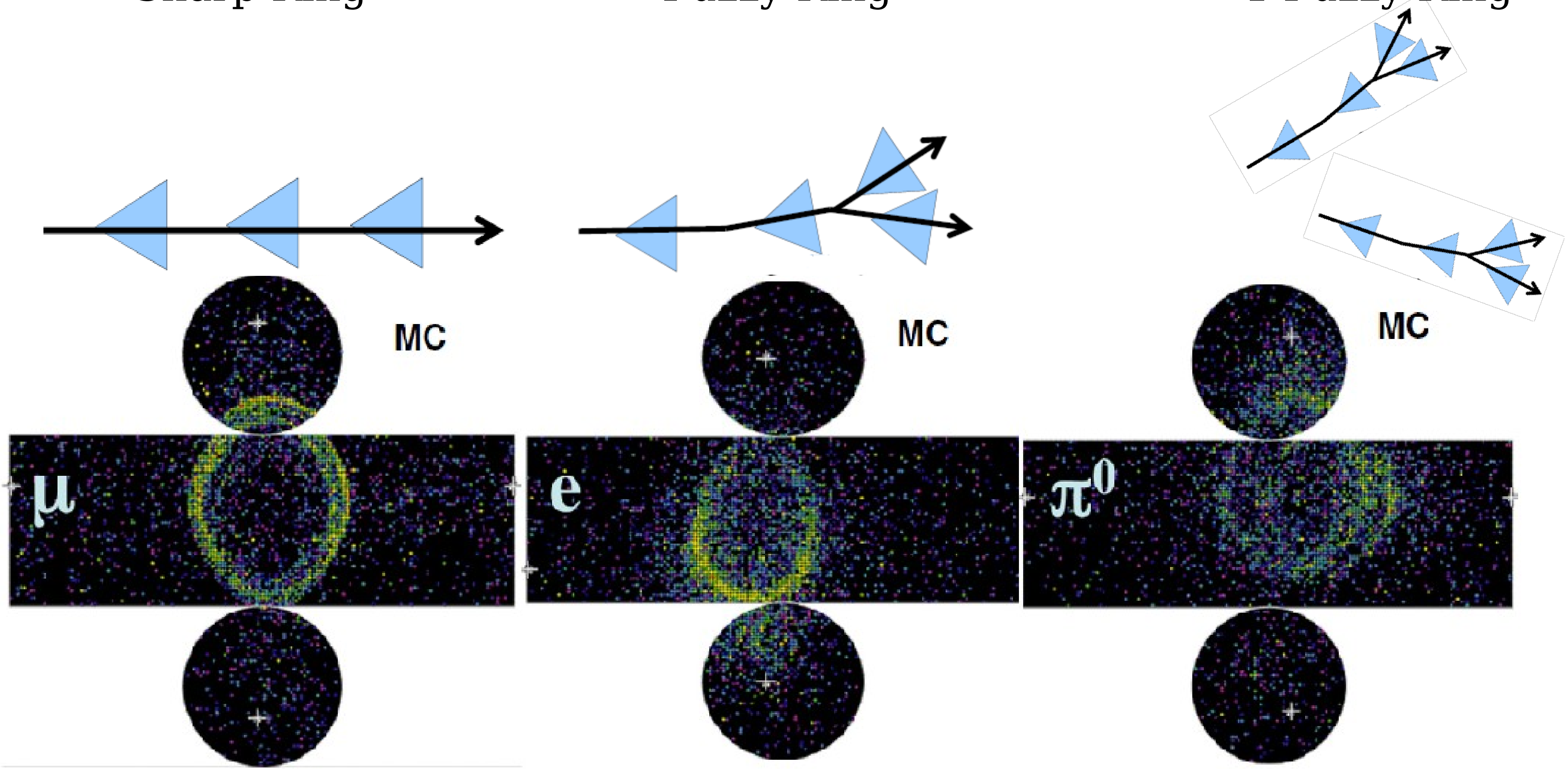
$\Delta m^2_{32} (\approx \Delta m^2_{31}) = (2.40 \pm 0.12) \times 10^{-3}$ eV^2

Far Detector: Particle ID

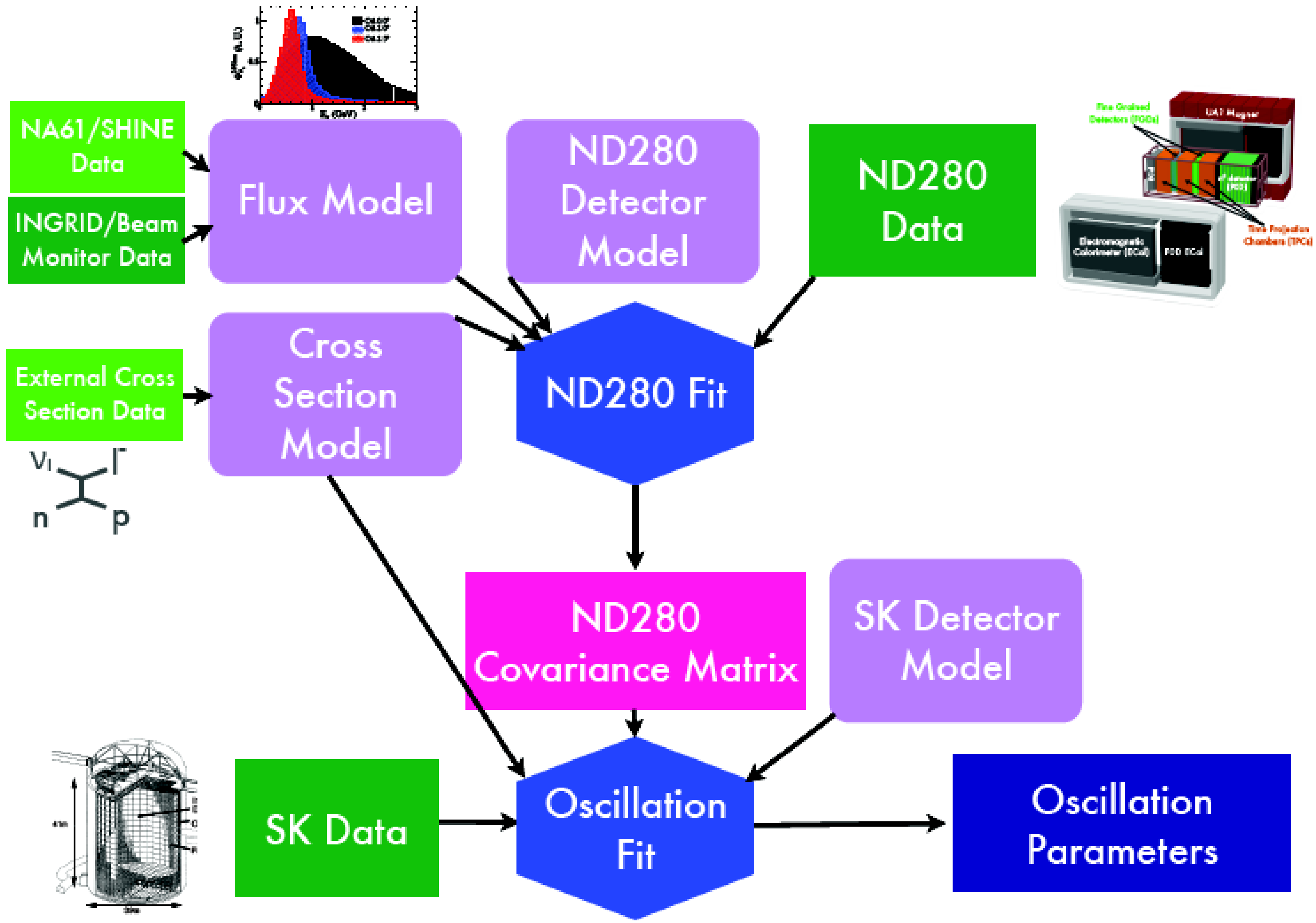
MS Small:
Sharp Ring

EM Shower:
Fuzzy Ring

2 EM Showers:
> 1 Fuzzy Ring



Oscillation Parameter Fitting Procedure



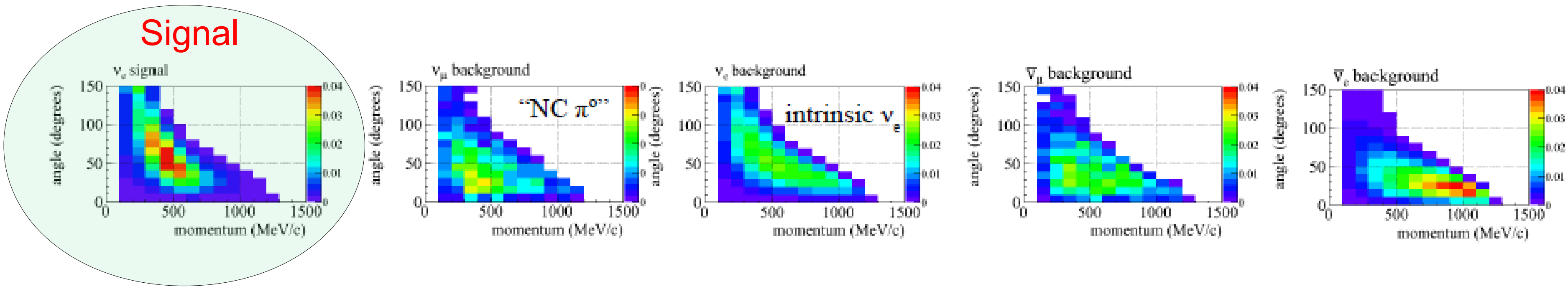
$\nu_\mu \rightarrow \nu_e$: Oscillation Parameters

Three analysis methods used:

- Maximum likelihood Fit using 2D-distributions of electron momentum & angle → Result presented here
- Maximum likelihood Fit using reconstructed neutrino energy distribution
- “Rate Only” analysis → Single energy bin using Feldman-Cousins technique

→ All three methods result in consistent values

Using method 1: Differences in electron momentum and angle distributions allow signal and background separation and exploits detector measured variables:

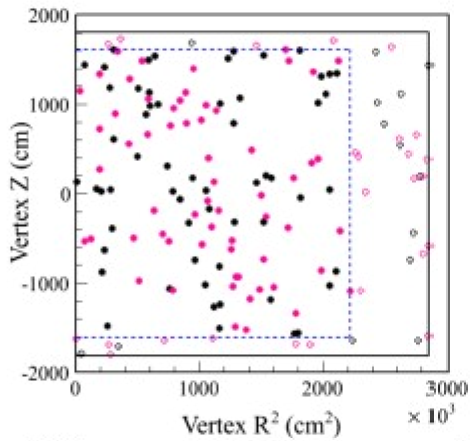


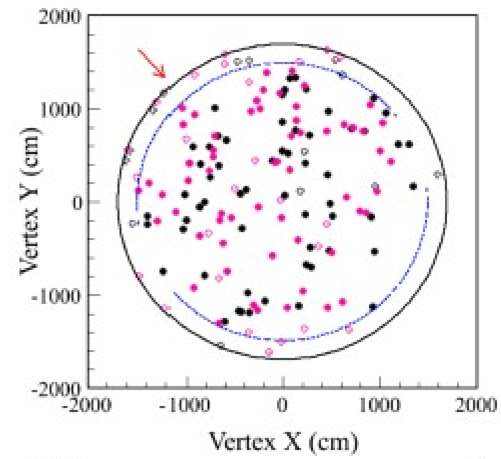
SK Vertex Distributions

RUN 1-3

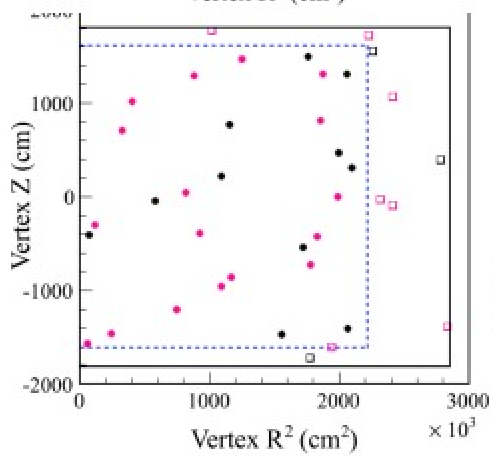
RUN 4

ν_μ:

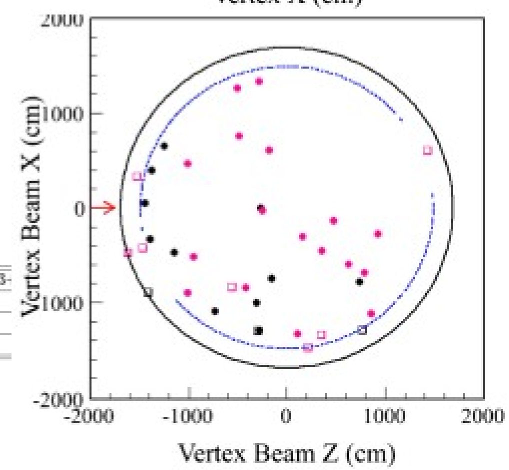




ν_e:



	RUN1+2+3	RUN4	RUN1+2+3-
Dwall	34.4%	44.4%	15.0%
Fromwall beam$_{\parallel}$	6.04%	76.7%	8.4%
$R^2 + Z$	32.4%	98.1%	64.4%



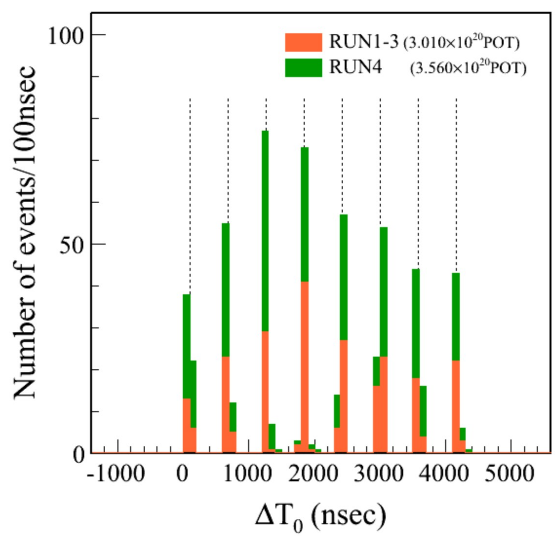
Present Accelerator Upgrade Plans

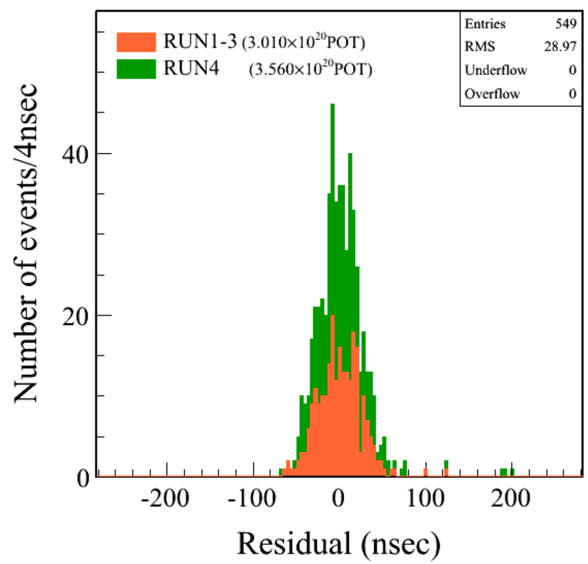
- High repetition rate scheme (~1.3 s) will be used to achieve design power: 750 kW
- Magnet Power Supplies and RF cavities to be replaced.
  - The new PS require additional budget funds – request sent to Japanese government for 2015-2017 FY
- Collimators have been updated from 2 kW to 3.5 kW in present JFY.
- Injection kicker power supplies are being improved and septum will be replaced for high rep rate running.

JFY	2011	2012	2013	2014	201 5	2016	2017
			Li. upgrade				
FX power [kW] SX power : User op. (study) [kW]	150 3 (10)	200 10 (20)	240 ~ (300) 25 (30)	~ 400 50 (100)			750 100
Cycle time of main magnet PS New magnet PS for high rep.	3.04 s	2.56 s R&D	2.4 s		Manufacture installation/test		1.3 s
Present RF system New high gradient rf system	Install. #7,8	Install. #9 R&D			Manufacture installation/test		
Ring collimators	Additional shields	Add.collimators and shields (2kW)	Add.collimators (3.5kW)				
Injection system FX system	New injection kicker	Kicker PS improvement, Septum 2 manufacture /test LF septum, PS for HF septa manufacture /test					

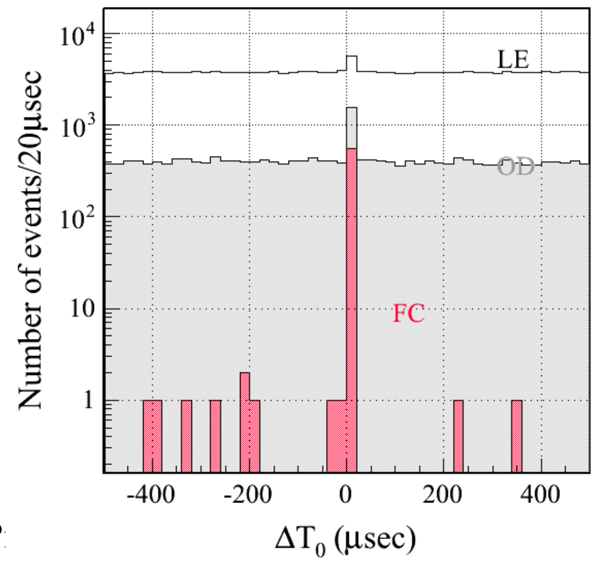
Far Detector: Event Timing

(JPARC:
8 bunches/spill)





- T2K beam timing
  - Time window of (−2μs, +10μs)
- Fully Contained (FC) definition
  - No signal in Outer Detector (OD)
- Fiducial volume definition:
  - Vertex > 2 m from wall



(LE – Low Energy events)