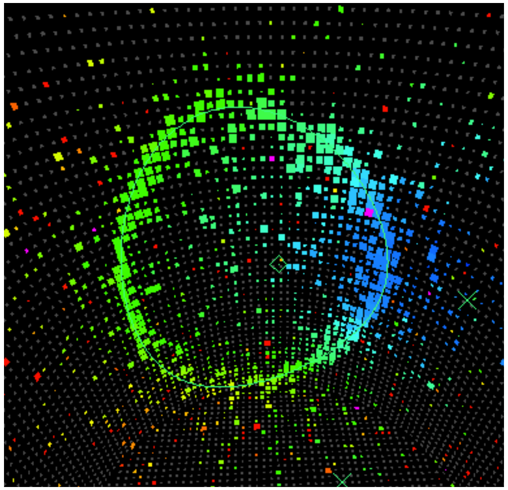
# Latest Results from T2K

## *Observation of Electron Neutrino Appearance from a Muon Neutrino Beam*




Shoei Nakayama

Kamioka Observatory, ICRR


July 19, 2013

ICRR seminar

Official release of this result is to be at EPS conference in Stockholm.

Strict press embargo time : 21:30 (JST) on July 19th, 2013

No e-mails, no phone calls, no blogs, no tweets, … until 21:30

# Summary

- T2K has made the definitive observation of $\nu_e$ appearance from the $\nu_\mu$ beam
  - Using $6.39 \times 10^{20}$ Protons-On-Target beam data (×2.1 of 2012 analysis) obtained by the stable beam and detector operations
  - Analysis improvements also contributed : Improved Near ν Detector analysis, Improved $\pi^0$ background rejection at Super-K Far ν Detector, …
  - 28 candidate events over 4.6±0.5(sys.) backgrounds
  - $\theta_{13}=0$ is excluded at 7.5σ

  → We have entered the era of $\nu_e$ appearance "measurement" for exploring the leptonic CPV and ν mass hierarchy !

- Now is the time to realize a new project in Japan
  - Hyper-K has great potential for discovering new physics
  - Need your strong support to the project

# Neutrino Oscillation

- Flavor eigenstate ($\nu_e, \nu_\mu, \nu_\tau$) ≠ Mass eigenstate ($\nu_1, \nu_2, \nu_3$)

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

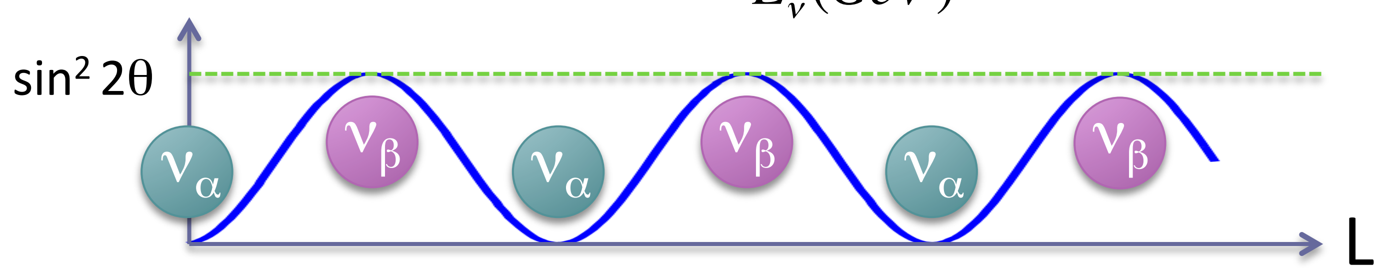
Two-flavor case

$\alpha$, $\beta$ = Flavor states
1, 2 = Mass states

- Probability that a neutrino originally generated as $\nu_\alpha$ will later be observed as $\nu_\beta$ after traveling a distance of L :

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2(eV^2)L(km)}{E_\nu(GeV)}\right)$$

$\Delta m^2 = m_2^2 - m_1^2$




ν oscillation experiments
- measure the disappearance of $\nu_\alpha$
- measure the appearance of $\nu_\beta$

# Unknowns in Neutrino Oscillation Parameters

$c_{ij} = \cos\theta_{ij}, \; s_{ij} = \sin\theta_{ij}$

CP phase

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

- $\theta_{12} = 33.6^\circ \pm 1.0^\circ$ Solar ν, KamLAND
- $\theta_{23} = 45^\circ \pm 6^\circ$ (90%CL) Atm. ν, Acc. ν

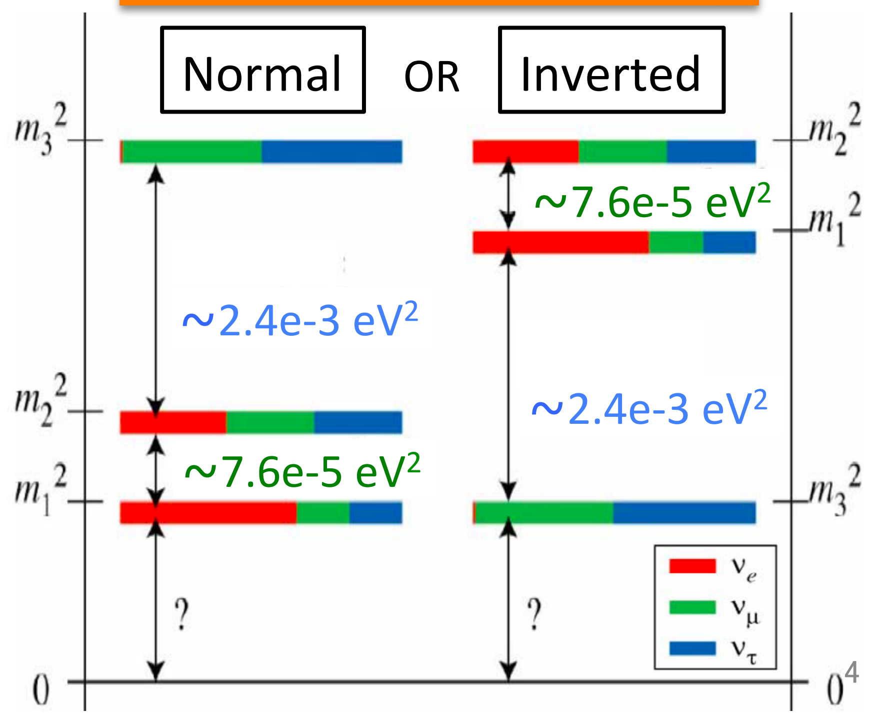
**$\theta_{23}$ : How close to 45° ?**
**Octant? (<45°, >45° ?)**

- $\theta_{13} = 9.1^\circ \pm 0.6^\circ$

Indication of $\theta_{13} \neq 0$ by T2K
PRL107, 041801 (2011)

Later precise measurements by reactor ν experiments

## Neutrino Mass Hierarchy



NOTE: solar/atmospheric ν data are also sensitive to $\theta_{13}$

# $\theta_{13}$ Measurements

- Reactor neutrino experiments : $\overline{\nu}_e$ disappearance

$$P(\overline{\nu}_e \to \overline{\nu}_e) \approx 1 - \boxed{\sin^2(2\theta_{13})} \sin^2\left(\frac{1.27\Delta m^2_{31} L(m)}{E_\nu(MeV)}\right)$$

*Pure $\theta_{13}$ measurement*

Complementary

- Accelerator neutrino experiments : $\nu_e$ appearance

$$P(\nu_\mu \to \nu_e) \approx \boxed{\sin^2(2\theta_{13})} \sin^2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{31} L(km)}{E_\nu(GeV)}\right)$$

Sub-leading terms

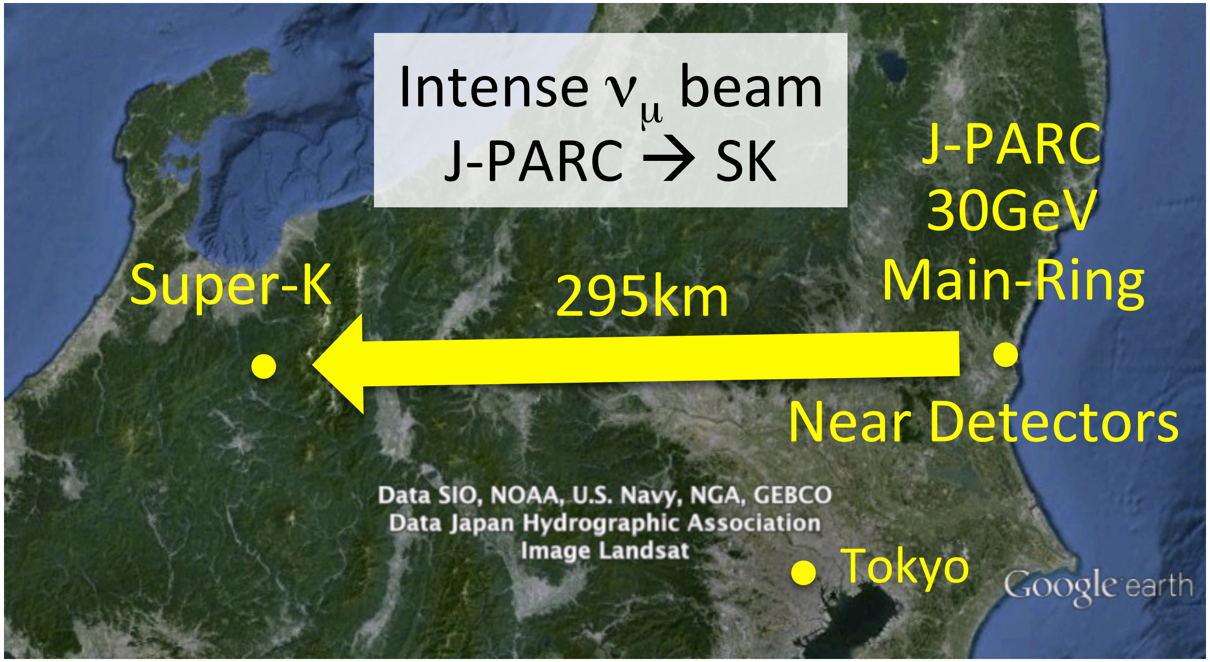
$$\begin{cases} +8C^2_{13}S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\ -8C^2_{13}C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\ +4S^2_{12}C^2_{13}(C^2_{12}C^2_{23} + S^2_{12}S^2_{23}S^2_{13} - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta) \cdot \sin^2\Delta_{21} \\ -8C^2_{13}S^2_{13}S^2_{23} \cdot \frac{aL}{4E_\nu}(1-2S^2_{13}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\ +8C^2_{13}S^2_{13}S^2_{23} \cdot \frac{a}{\Delta m^2_{31}}(1-2S^2_{13}) \cdot \sin^2\Delta_{31} \end{cases}$$

$\delta \to -\delta$
$a \to -a$
for $P(\overline{\nu}_\mu \to \overline{\nu}_e)$

*Sensitive to CPV phase $\delta$ and ν mass hierarchy*

Opens the possibility to explore CPV in the lepton sector

# T2K (Tokai-to-Kamioka) Experiment




International Collaboration

~500 members
from 11 nations

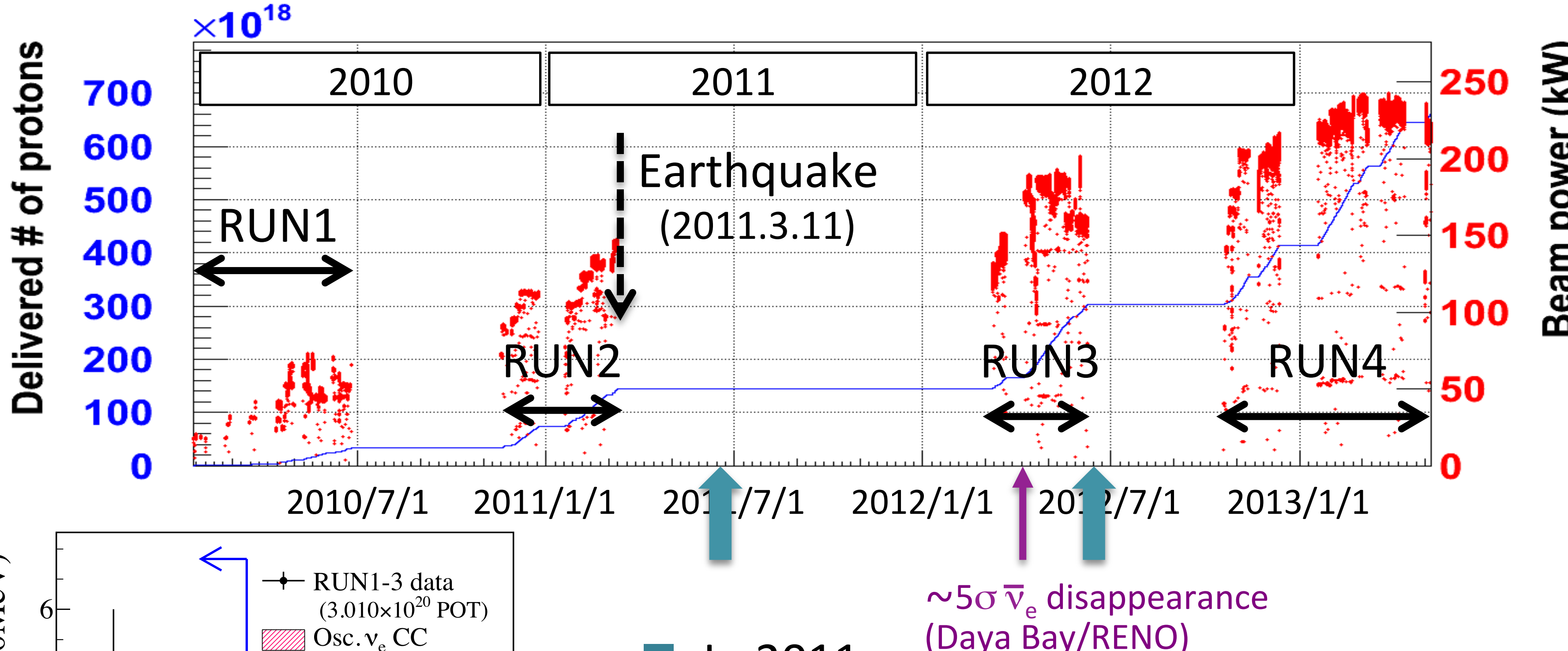
## Discovery of $\nu_e$ appearance ($\nu_\mu \rightarrow \nu_e$ oscillation)

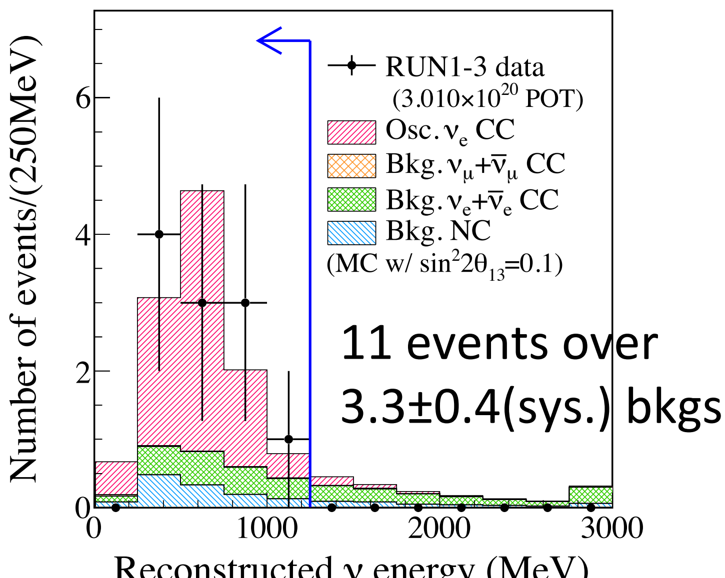
- Direct detection of $\nu$ flavor mixing ($\theta_{13} \neq 0$) by an "appearance" channel
- Opens the possibility to probe the leptonic CP violation

## Precision measurement of $\nu_\mu$ disappearance

- $\delta(\Delta m^2_{32}) \sim 1\text{x}10^{-4}\ \text{eV}^2$ , $\delta(\sin^2 2\theta_{23}) \sim 0.01$

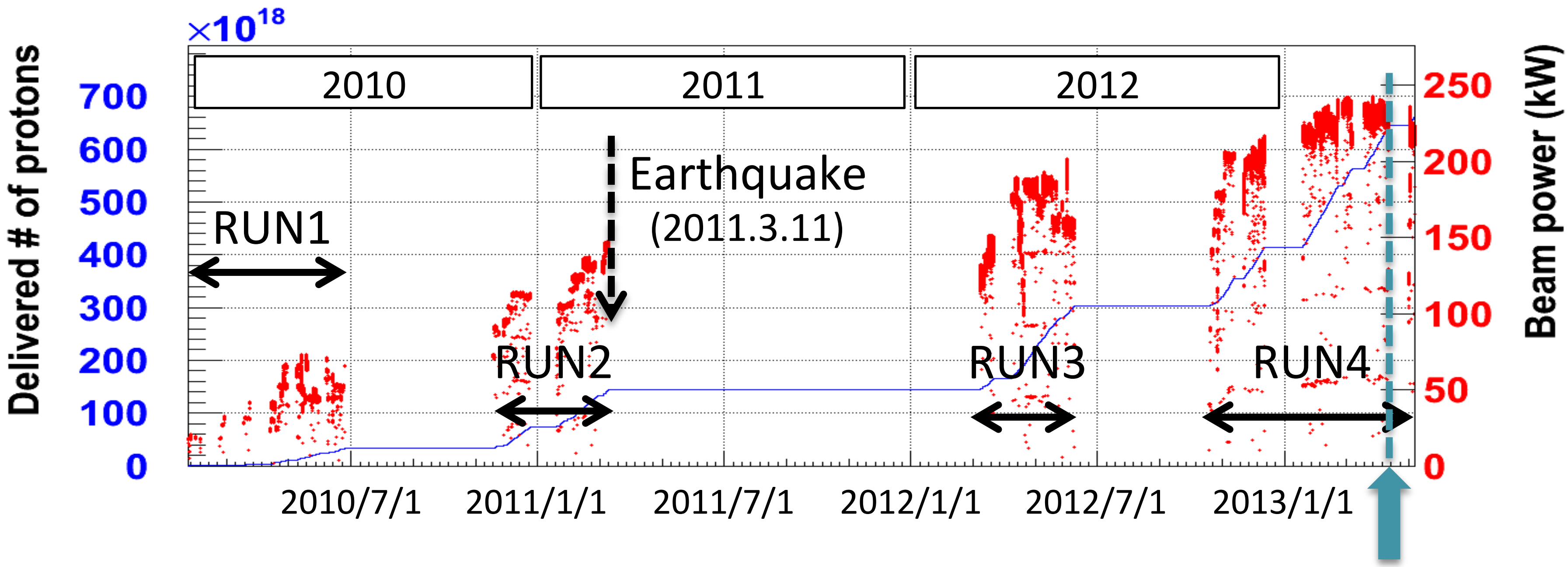
# T2K Data-Taking and $\nu_e$ Search History




- In 2011
  First indication of $\nu_e$ appearance ($2.5\sigma$) using RUN1-2 data (2% of T2K full stat.)
- In 2012
  $>3\sigma$ signal of $\nu_e$ appearance using RUN1-3 data (4% of T2K full stat.)

# Data Set in this Talk




Analyzed up to April 12th, 2013

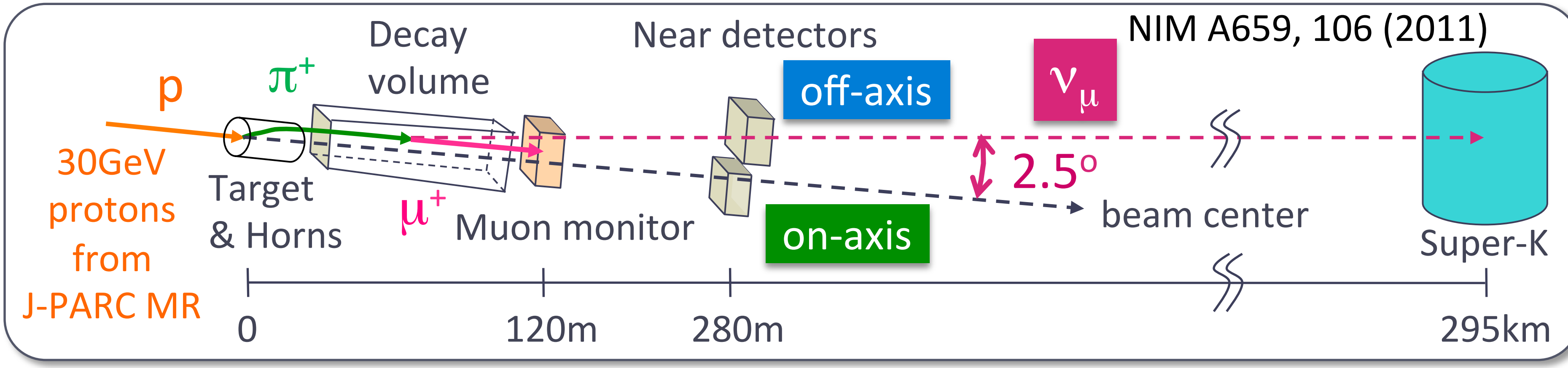
Steady beam data accumulation during T2K RUN4

- Beam power reached 235kW
- Very stable Super-K operation : livetime ~99%

Previous analysis (2012) : RUN1+2+3, $3.010\times10^{20}$ POT (Protons-On-Target)

More than ×2

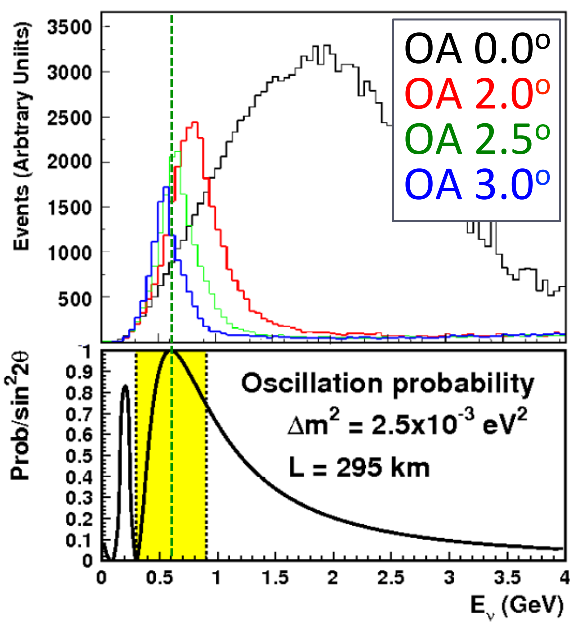
This analysis (2013) : RUN1+2+3+4 (by April 12th), $6.393\times10^{20}$ POT




## *Off-axis ν beam*

Intense narrow-band @osc. max. (~0.6GeV)

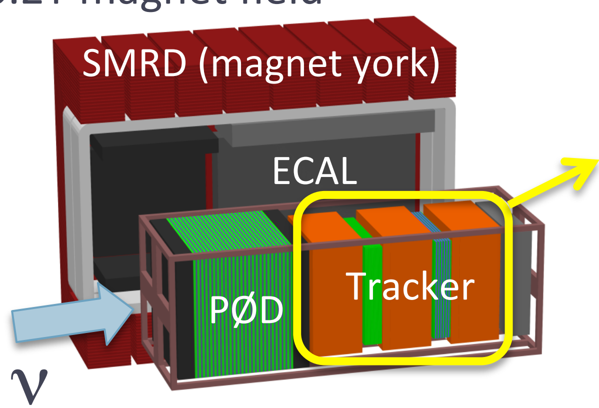
- Reduce high energy tail which creates BG

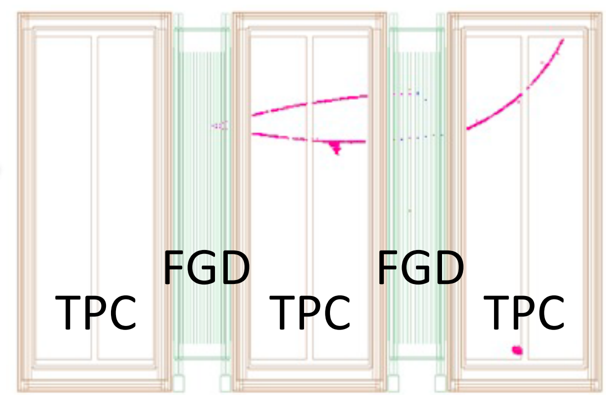



## *Off-axis ν detector (ND280)*

measures ν flux/spectrum before oscillations @2.5° OA

0.2T magnet field




Fine-Grained Detectors (FGDs)

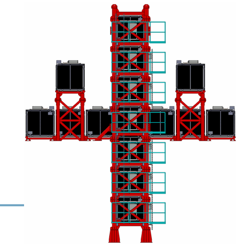
Scintillator strips, 1.6t fiducial target, Detailed vertex info.

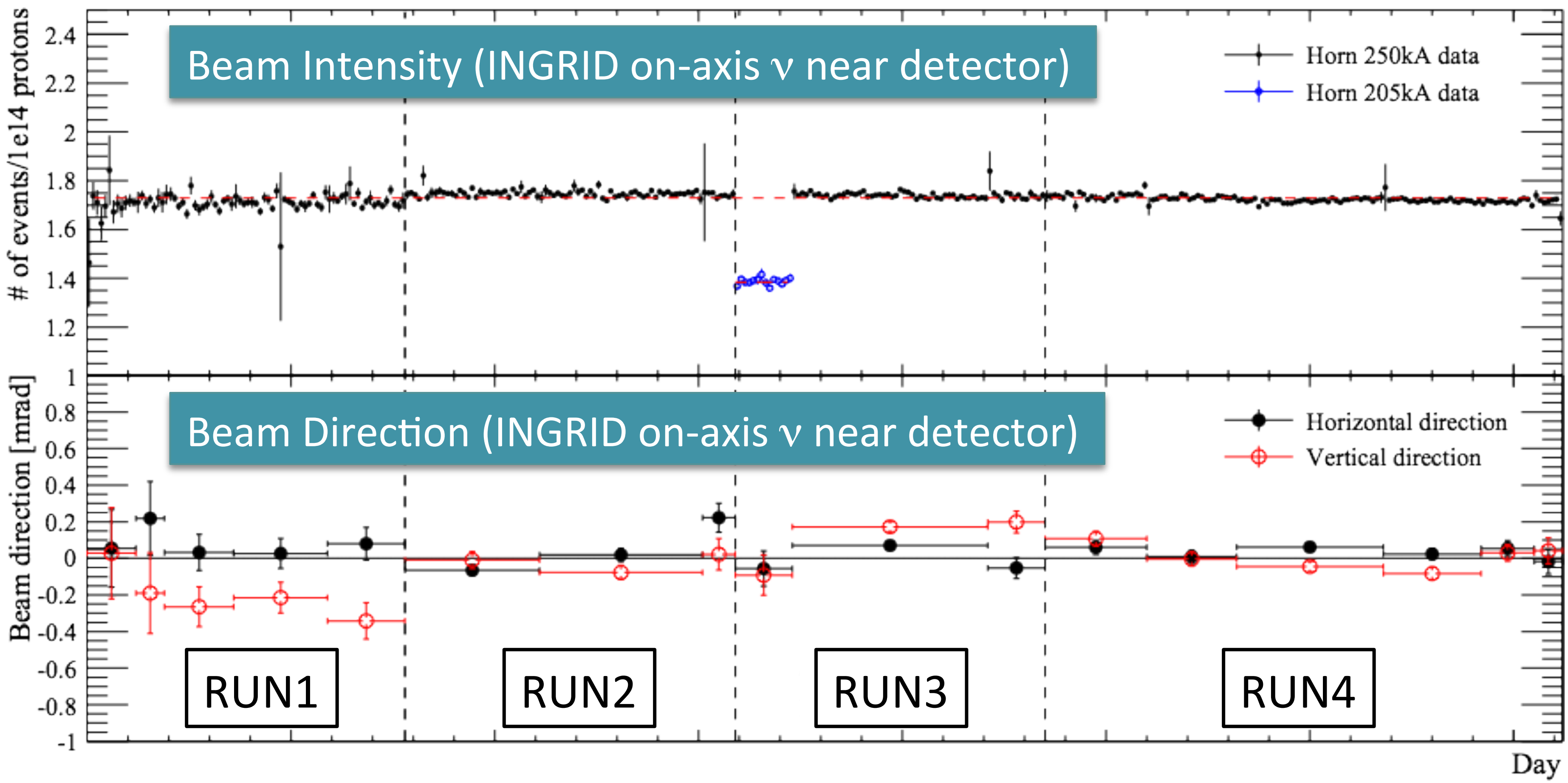
Time Projection Chamber (TPCs)

Gas ionization, Momentum by curvature, PID by dE/dx

# Beam Stability

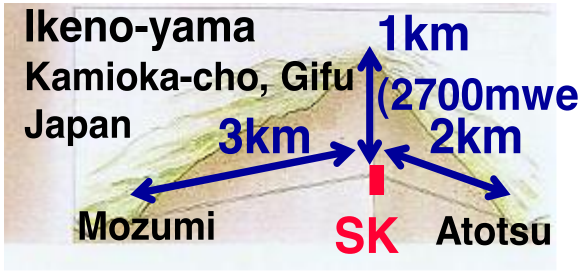
INGRID on-axis ν detector monitors beam intensity, direction, and profile

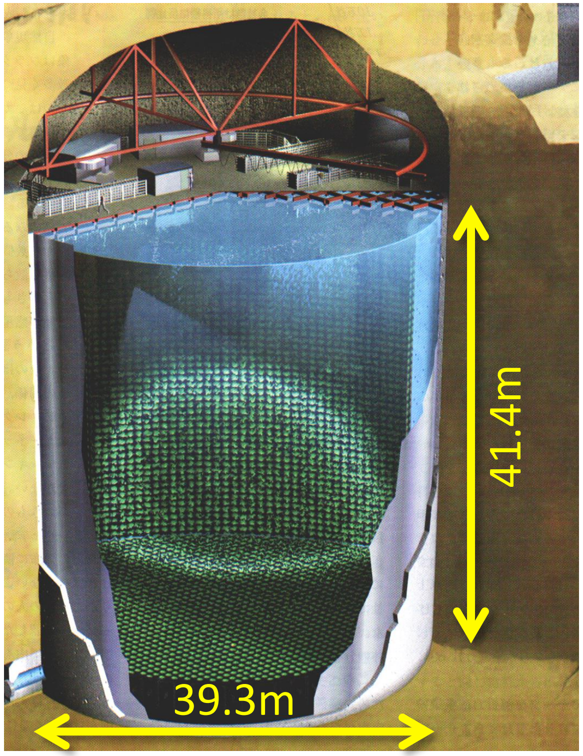





- POT normalized ν event rate is very stable (<1%)
- Beam direction is controlled well within the design requirement of 1mrad (→ 2% shift in the peak energy of ν spectrum)

# T2K Far ν Detector : Super-Kamiokande

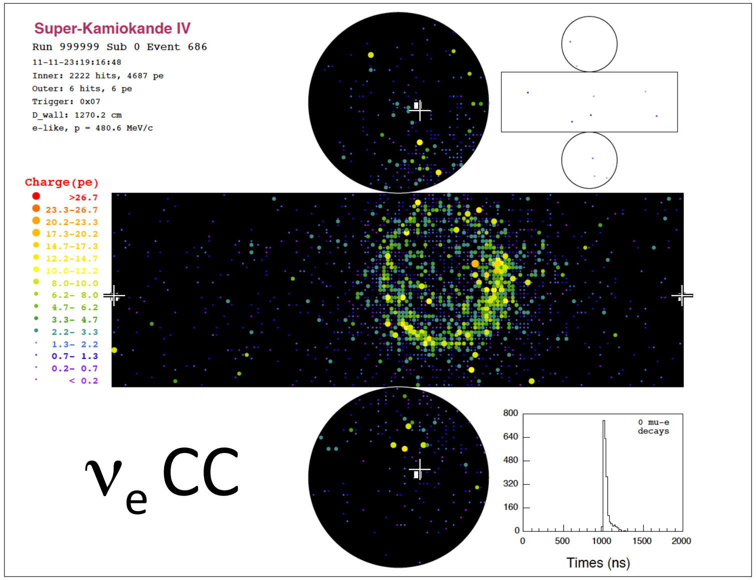


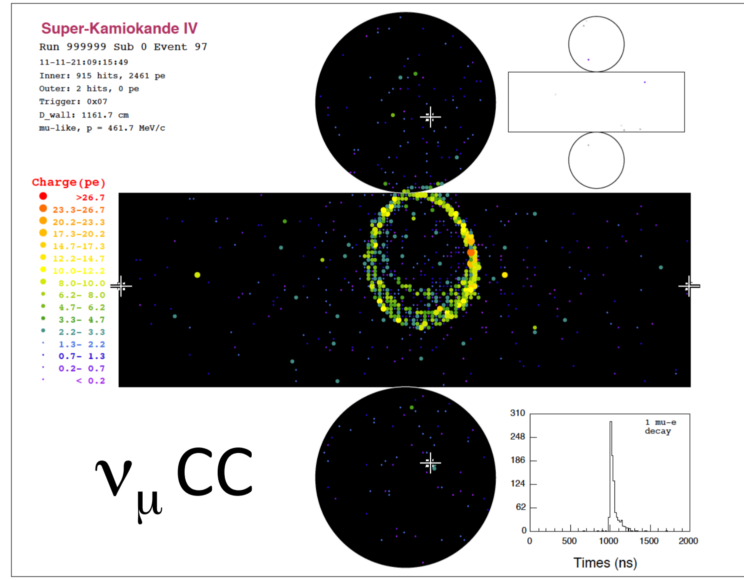



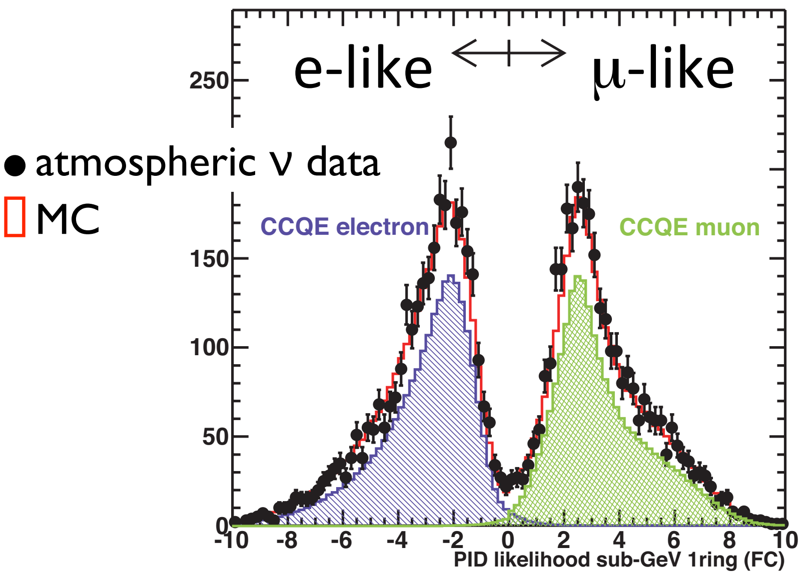



- 50kton Water Cherenkov detector
  - 22.5kton fiducial mass
  - World largest ”ν & proton-decay” detector
- Located in the Kamioka Observatory
  - 295km from J-PARC
- Excellent detection capability
  - Ring-shaped pattern on the detector wall
- Atmospheric ν data as control samples to study detector performance
- T2K trigger records all the PMT hits within ±500μs of the beam arrival time
  - Time synchronization by GPS

# Electron/Muon PID at Super-K



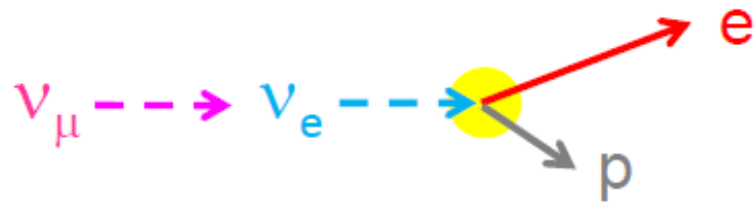

- Particle identification using ring shape and opening angle
- Probability that a muon is mis-identified as an electron is <1%
  - Very small $\nu_\mu$ CC background for $\nu_e$ appearance search

# Signal and BG for T2K $\nu_e$ appearance search

## Signals

Single electron event by CC interaction of $\nu_e$ oscillated from $\nu_\mu$

- Mainly CCQE : $\nu_e + n \rightarrow e^- + p$
- Protons mostly have momenta below Cherenkov threshold

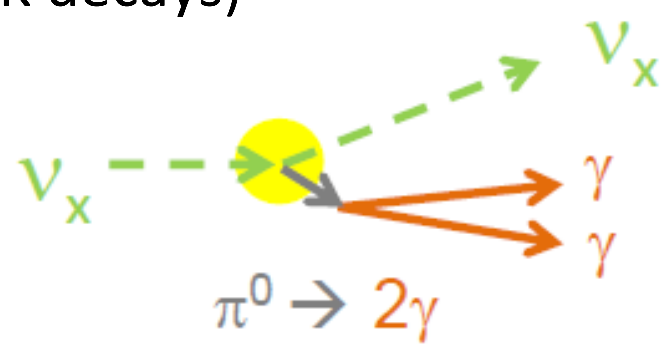



## Backgrounds

(1) intrinsic $\nu_e$ in the beam (from $\mu$, K decays)

(2) NC single $\pi^0$ events

- overlap of 2 $\gamma$ rings
- asymmetric decay
  (one of the $\gamma$ has very low energy)



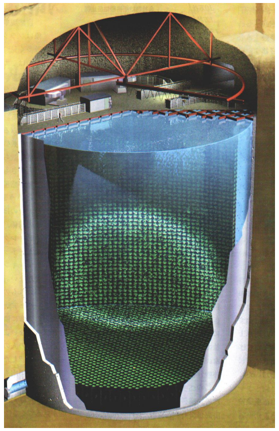
# Oscillation Analysis Strategy

**Neutrino Flux**
MC simulation of beamline based on hadron production meas. (NA61/SHINE) and beam monitor meas.

**Neutrino Interaction**
Model (NEUT) tuned/constrained with external data

**ND280 Measurements**
- $\nu_\mu$CC enhanced samples ($CC0\pi$, $CC1\pi^+$, and CCother)
- Intrinsic $\nu_e$ and NC $\pi^0$ measurements as cross-check

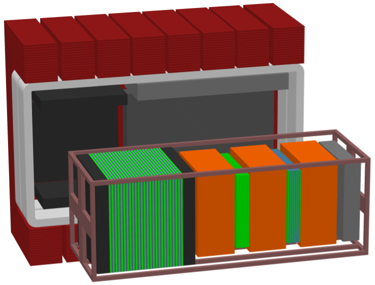
Constraint on flux & cross section



**SK Prediction**

Oscillation parameter fit

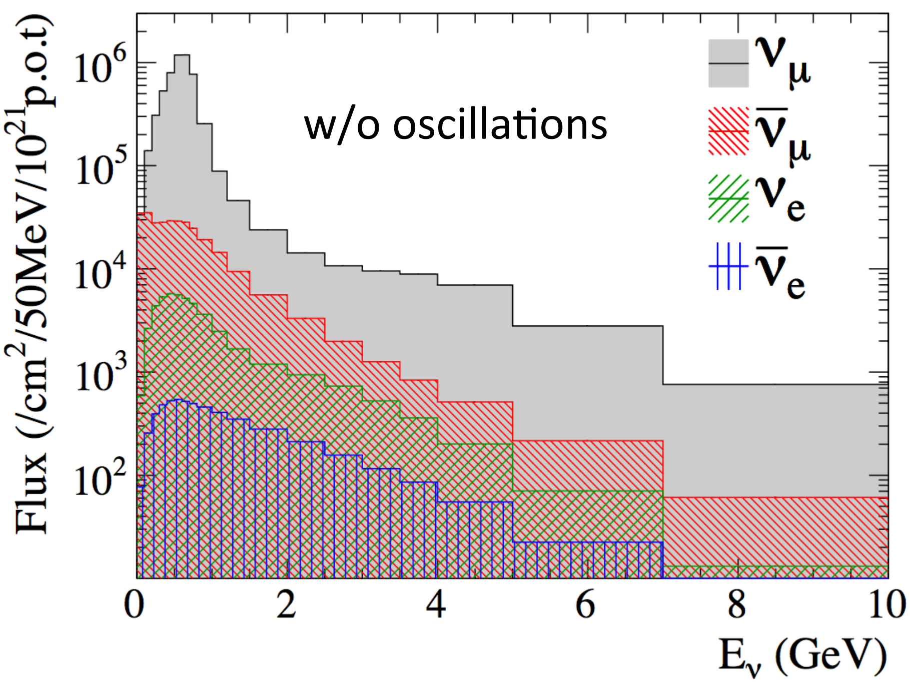
**SK Data : $\nu_e$ candidates**



PRD 87, 012001 (2013)

# Predicted Neutrino Flux

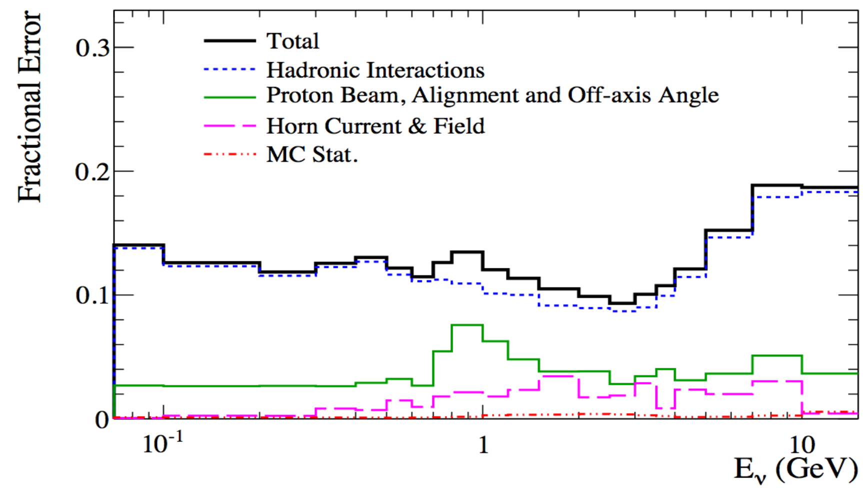
## Predicted Neutrino Flux @SK



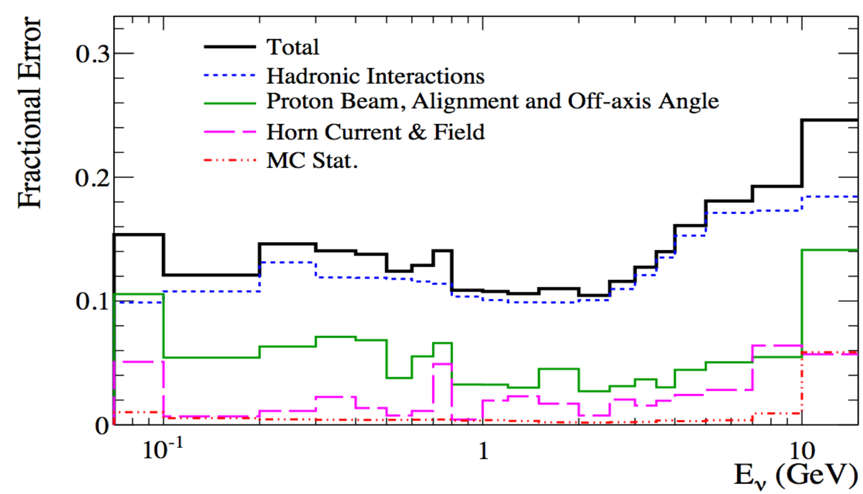

$\nu_e$ fraction : <1% @$E_\nu$ peak

Total flux error : 10~15%

## Fractional Error on $\nu_\mu$ flux @SK

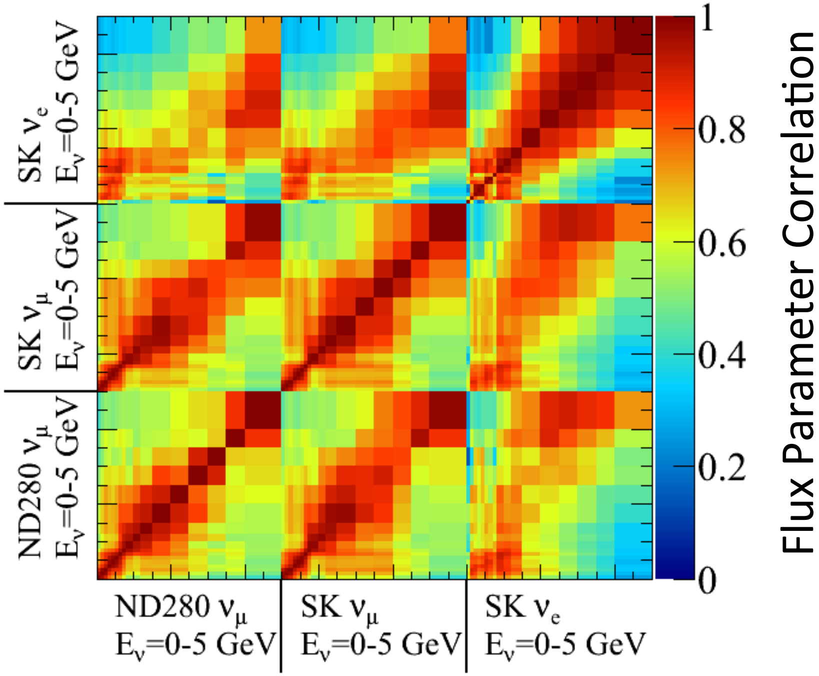



## Fractional Error on $\nu_e$ flux @SK

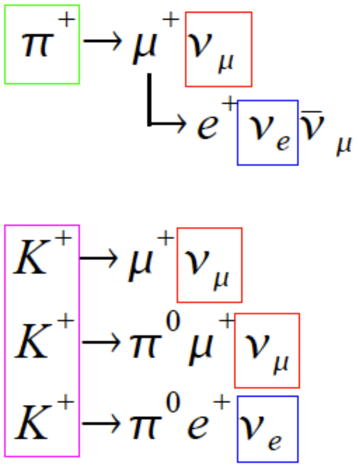


# Near Detector Constraint on SK Prediction

- SK flux parameters are constrained through their prior correlations with the ND280 $\nu_\mu$ flux parameters




$\nu_e$ and $\nu_\mu$ fluxes are correlated through parent hadrons




- Subset of cross section parameters are correlated at near & far detectors : $M_A^{QE}$, $M_A^{RES}$, CCQE/CC1$\pi$/NC1$\pi^0$ normalizations

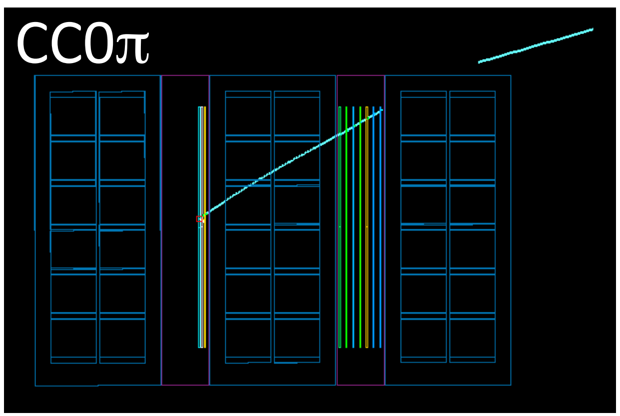
# ND Fit Data Inputs

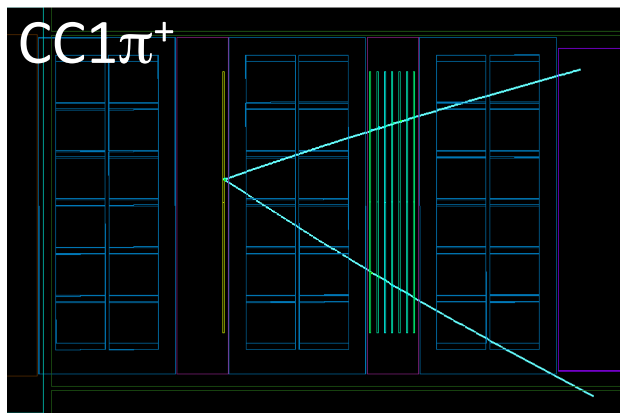
New $\nu_\mu$CC sample classification : CC0$\pi$, CC1$\pi^+$, CCother

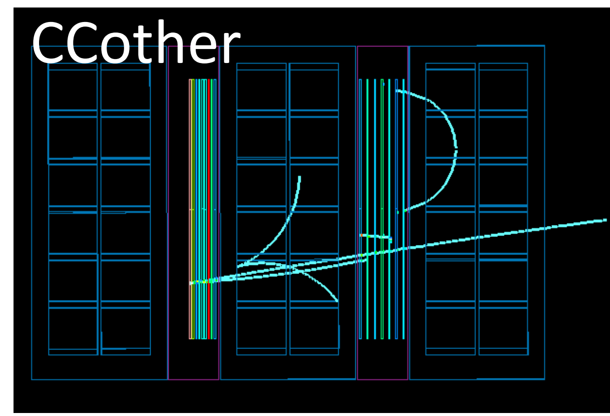
- In 2012 analysis, 2 categories : CCQE-like (1 track) & CCnonQE-like (2 tracks)
- Much better samples for constraining CCQE & CC1$\pi$ cross section parameters

Data are binned in two dimensions : $\mu$ momentum (p) and angle (cos$\theta$)

- Finer binning than 2012 analysis




Composition

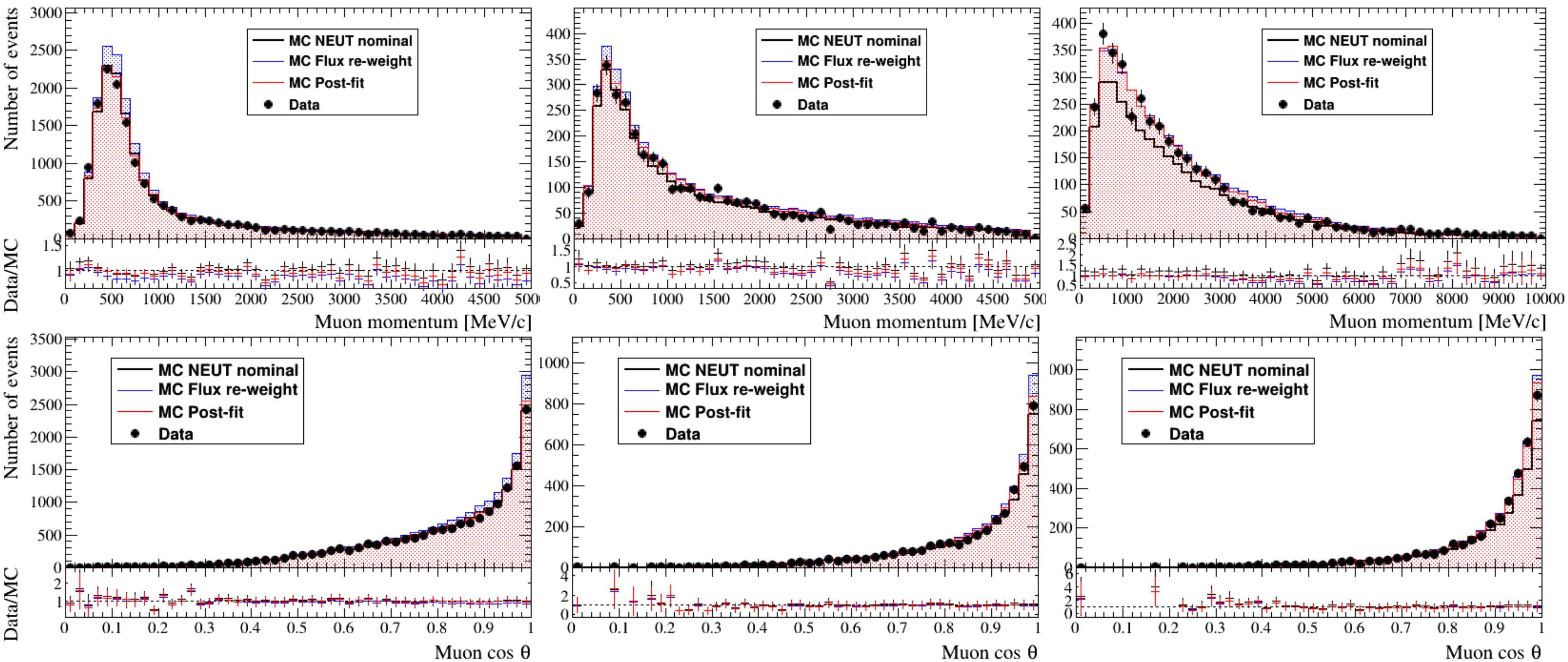
| | |
|---|---|
| CCQE | 63.5 % |
| Resonant | 20.2 % |
| DIS | 7.5 % |
| Coherent | 1.4 % |
| Other | 7.4 % |

| | |
|---|---|
| CCQE | 5.3 % |
| Resonant | 39.5 % |
| DIS | 31.3 % |
| Coherent | 10.6 % |
| Other | 13.3 % |

| | |
|---|---|
| CCQE | 3.9 % |
| Resonant | 14.3 % |
| DIS | 67.8 % |
| Coherent | 1.4 % |
| Other | 12.6 % |

# Near Detector Distributions after the Fit

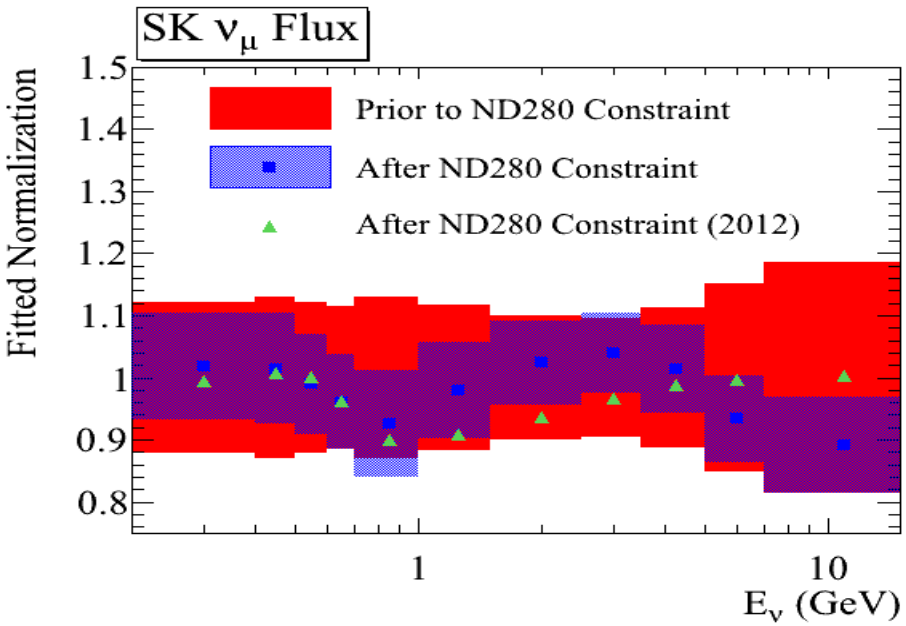
CC0π CC1$\pi^+$ CCother

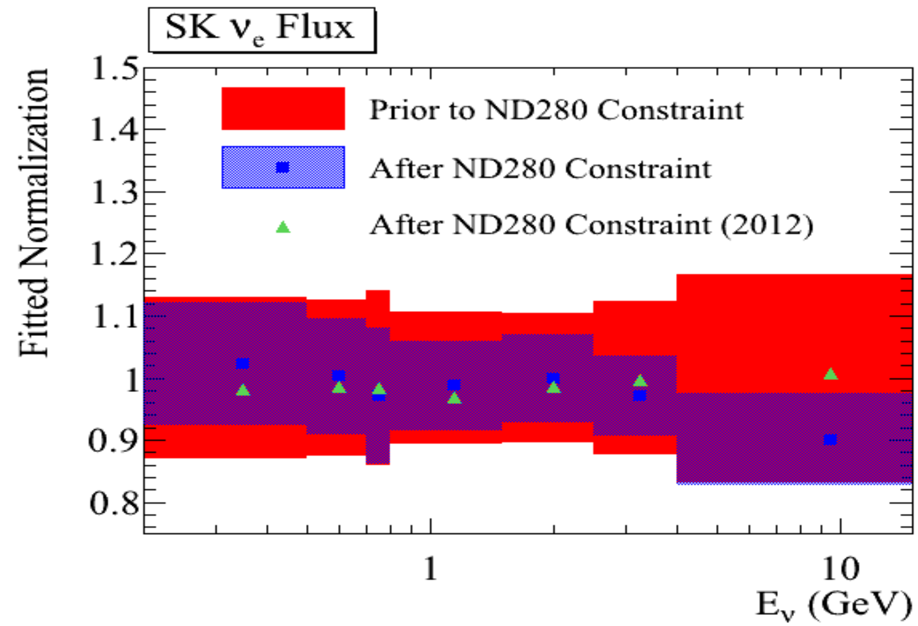



| (# of events) | CC0π | CC1$\pi^+$ | CCother |
|---|---|---|---|
| Data | 16912 | 3936 | 4062 |
| Unconstrained MC | 20016 | 5059 | 4602 |
| Constrained MC | 16803 | 3970 | 4006 |

Improved agreement after the fit

# Constrained SK Flux and Cross Section Params




| Parameter | Prior to ND Constraint | After ND Constraint |
|---|---|---|
| $M_A^{QE}$ (GeV) | 1.21 ± 0.45 | 1.22 ± 0.07 |
| $M_A^{RES}$ (GeV) | 1.41 ± 0.22 | 0.96 ± 0.06 |
| CCQE norm. | 1.00 ± 0.11 | 0.96 ± 0.08 |
| CC1π norm. | 1.15 ± 0.32 | 1.22 ± 0.16 |

Significant error reduction

# T2K $\nu_e$ event selection at Super-K

1. Beam on-timing & Fully-contained (FC) in the inner detector
2. Vertex in the fiducial volume
3. Number of rings = 1
4. Electron-like PID
5. Visible energy > 100MeV
   - ✓ rejects low energy NC events and electrons from invisible $\mu$, $\pi$ decays
6. No delayed electron signal
   - ✓ rejects events with invisible $\mu$, $\pi$
7. Reconstructed $\nu$ energy < 1.25GeV
   - ✓ rejects intrinsic beam $\nu_e$ at high energy
8. Non-$\pi^0$-like ← Improved by New Algorithm

Developed new $\pi^0$ rejection algorithm. The other cuts unchanged.

# A New Event Reconstruction Tool : fiTQun

i-th PMT's charge, time

$$L(\mathbf{x}) = \prod_i^{\text{unhit}} P(i\text{unhit}|\mathbf{x}) \prod_i^{\text{hit}} P(i\text{hit}|\mathbf{x}) f_q(q_i|\mathbf{x}) f_t(t_i|\mathbf{x})$$

Unhit probability Hit probability Charge likelihood Time likelihood

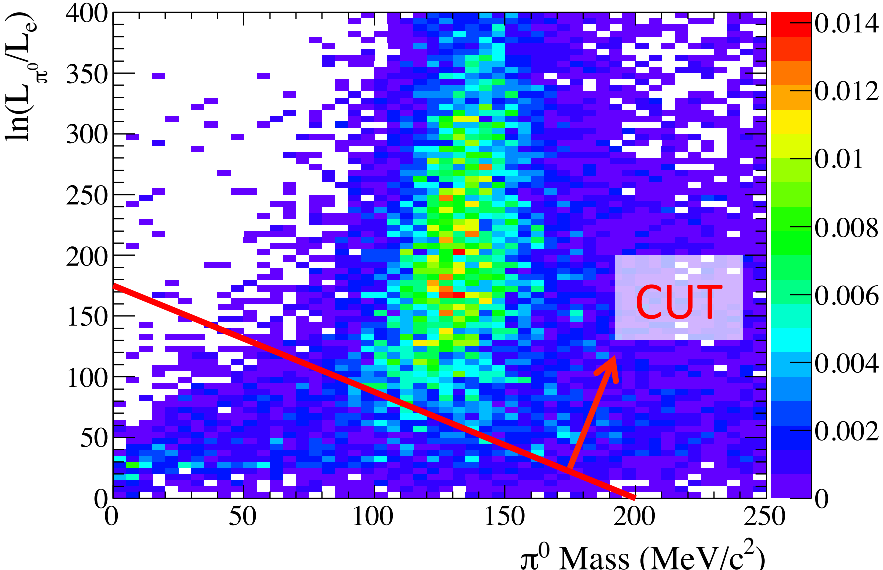
- A maximum likelihood fitter
- For a given track(s) hypothesis, a charge and time PDF is produced for every PMT
  - Charge PDF can be factorized into predicted charge and PMT response
- Track parameters $\mathbf{x}$ (vertex, direction, momentum, …) are fit simultaneously to maximize the likelihood
  - ↔ Step-by-step reconstruction in the previous algorithm
  - For PID, compare final likelihoods for $\pi^0$ and electron assumptions

# $\pi^0$ Background Rejection by fiTQun

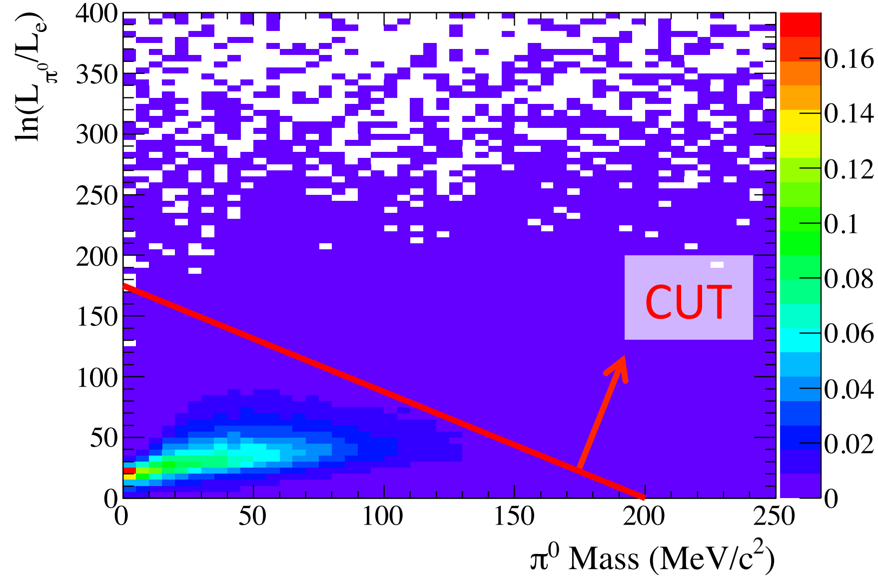
This time, we use the fiTQun reconstruction only at the $\pi^0$ rejection cut

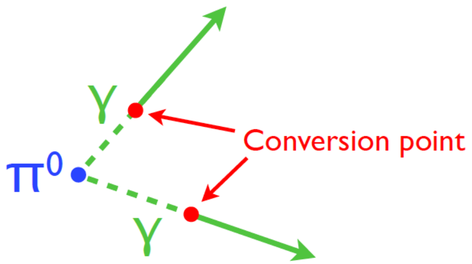
(fiTQun will also improve vertex/angle/momentum resolutions, PID, etc.)

T2K MC events with ≥1 $\pi^0$




T2K MC $\nu_e$CC signal events




Horizontal : Reconstructed $\pi^0$ mass

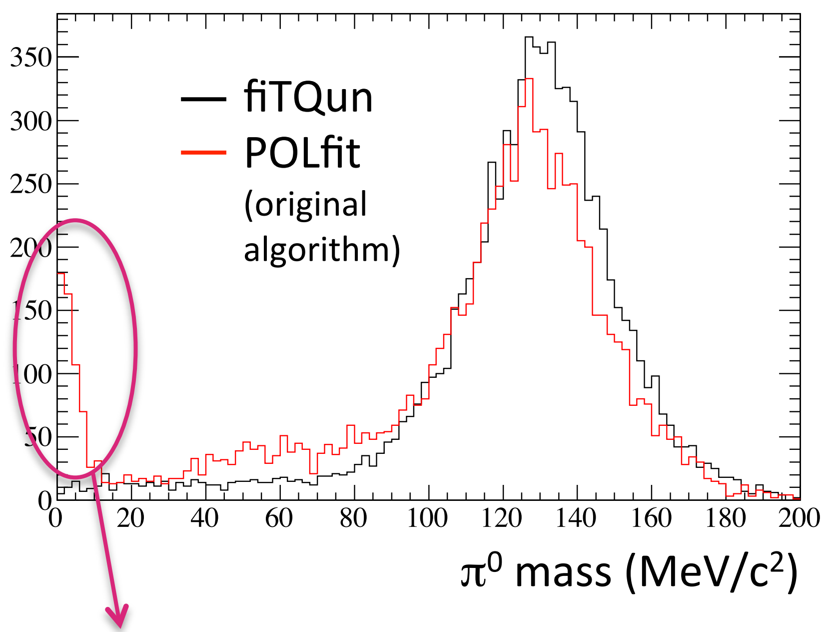
Vertical : Likelihood ratio of $\pi^0$ and 1-ring electron hypotheses

Clear separation

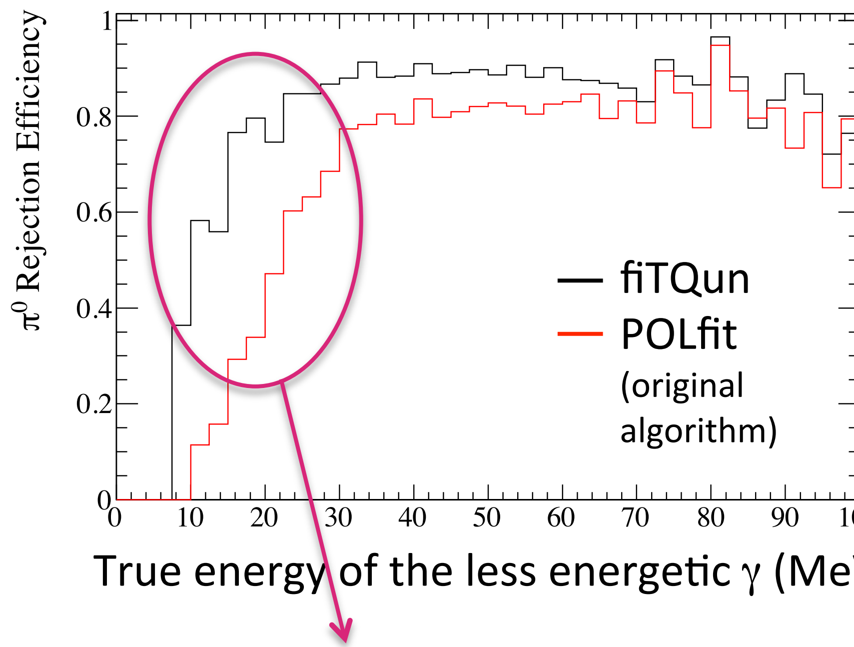
# $\pi^0$ Background Rejection by fiTQun

Performance evaluation using "$\pi^0$ particle guns" MC
(with a flat momentum 0-500MeV/c)

Reconstructed $\pi^0$ mass




$\pi^0$ rejection efficiency




The 2nd $\gamma$ ring is missed by POLfit.

fiTQun doesn't have such a pileup at zero, and the low mass tail is lower than POLfit.

fiTQun is more sensitive to lower energy photons than POLfit

Improved performance

# Predicted Number of Events at Each Cut

| | $\nu_\mu$CC | $\nu_e$CC | NC | BG all | Sig. $\nu_e$ |
|---|---|---|---|---|---|
| True FV | 308 | 15.0 | 272 | 594 | 25.6 |
| (2) FCFV | 234 | 14.4 | 76.5 | 325 | 24.8 |
| (3) 1 ring | 135 | 9.2 | 21.6 | 166 | 21.5 |
| (4) e-like | 5.3 | 9.1 | 14.9 | 29.3 | 21.2 |
| (5) $E_{vis}$ >100MeV | 3.5 | 9.1 | 12.7 | 25.2 | 20.9 |
| (6) No decay-e | 0.7 | 7.4 | 10.6 | 18.7 | 18.6 |
| (7) $E_\nu^{rec}$ <1.25GeV | 0.2 | 3.5 | 8.0 | 11.8 | 17.9 |
| (8) fiTQun $\pi^0$ cut | 0.06 | 3.1 | 0.9 | 4.0 | 16.4 |
| Efficiency | <0.1% | 20% | 0.3% | 0.7% | 64% |
| (8)' POLfit $\pi^0$ cut | 0.12 | 3.2 | 2.3 | 5.6 | 16.8 |
| Efficiency | <0.1% | 21% | 0.8% | 0.9% | 66% |

w/ $\sin^2 2\theta_{13}$=0.1

6.393×$10^{20}$ POT

unit = events

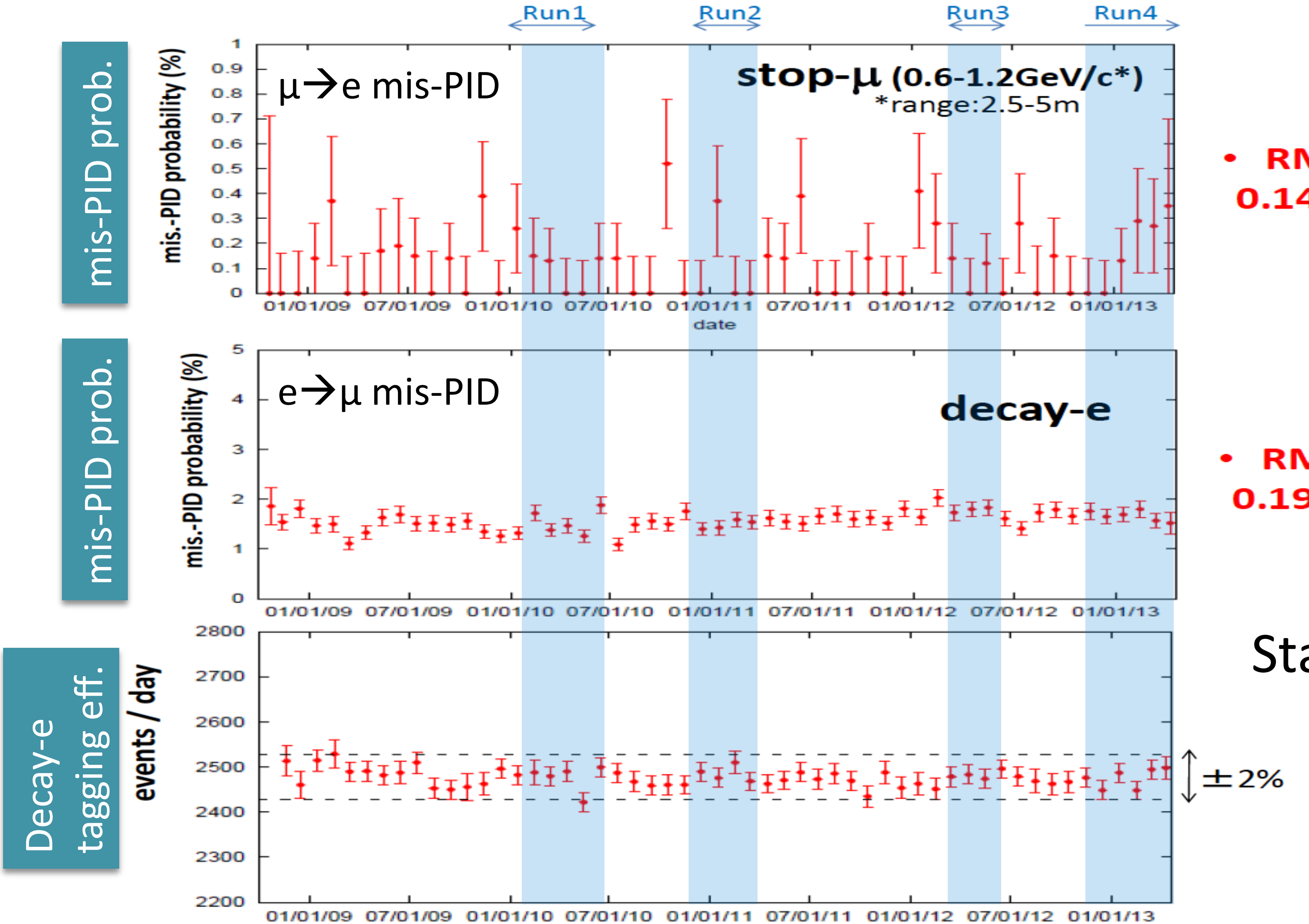
New Cut: (7) → (8)

Old Cut: (7) → (8)'

NC BG reduced to ~40% compared to previous $\nu_e$ selection

with keeping signal efficiency high

# Far Detector (Super-K) Stability




- RMS: 0.14%
- RMS: 0.19%

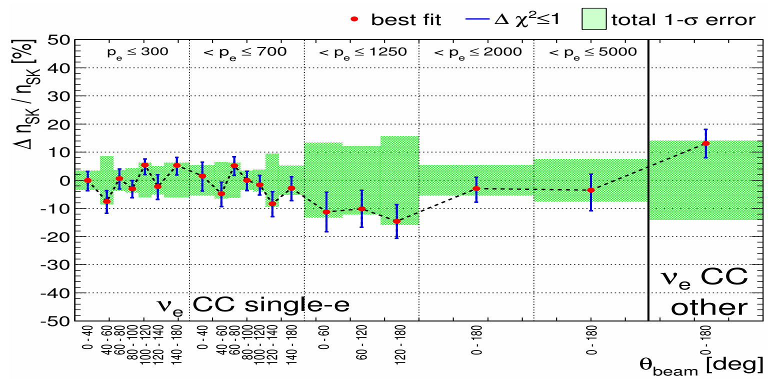
Stable

# Far Detector (Super-K) Systematics

Dominant error coming from the ring-counting, PID, $\pi^0$ rejection cuts

## Error for $\nu_e$CC components :

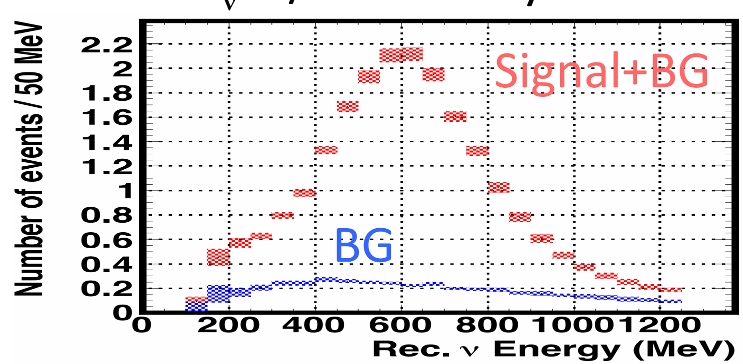
- Number of events in each ($p_e$ , $\theta_e$) in the atmospheric $\nu$ control sample is fit to evaluate the sys. errors on efficiencies

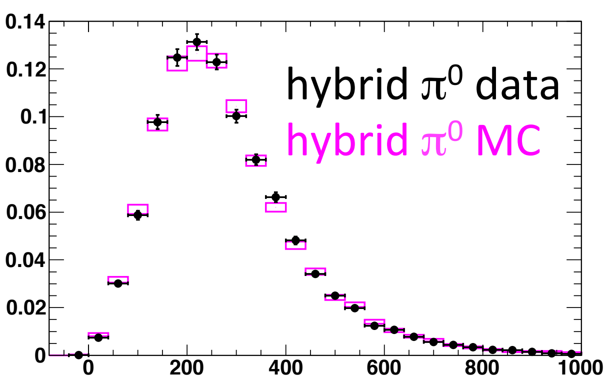



## Error for $\pi^0$ BG components :

- $\pi^0$ topological control sample combining one data electron and one simulated $\gamma$ (hybrid $\pi^0$)

Rec. $E_\nu$ w/ total SK sys. errors




fiTQun $\pi^0$/e likelihood ratio

SK systematic error on predicted # of ne candidates is reduced (thanks to the new $\pi^0$ rejection)

3.0% (2012) → 2.4% @$\sin^2 2\theta_{13}$=0.1

# Predicted Number of $\nu_e$ Candidate Events

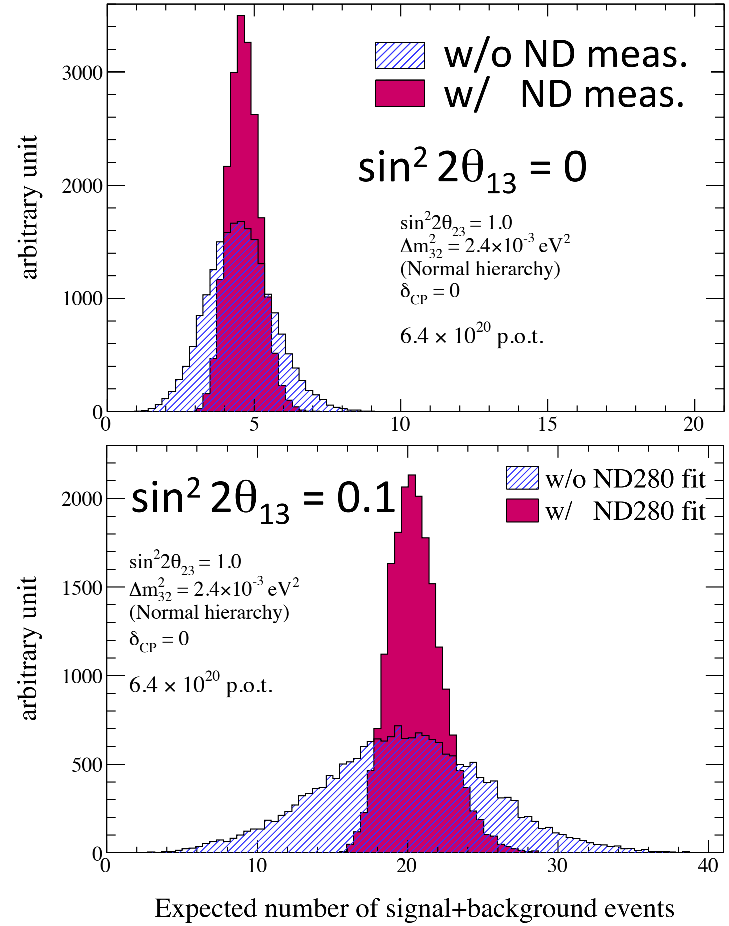
**Predicted # of events w/ $6.393\times10^{20}$ p.o.t.**

| Category | $\sin^2 2\theta_{13} = 0$ | $\sin^2 2\theta_{13} = 0.1$ |
|---|---|---|
| $\nu_e$ signal | 0.38 | 16.42 |
| $\nu_e$ BG | 3.17 | 2.93 |
| $\nu_\mu$ BG | 0.89 | 0.89 |
| $\bar{\nu}_\mu+\bar{\nu}_e$ BG | 0.20 | 0.19 |
| Total | 4.64 ± 0.52 | 20.44 ± 1.80 |

**Systematic Uncertainties**

| Source | $\sin^2 2\theta_{13} = 0$ | = 0.1 |
|---|---|---|
| Flux + $\nu$ int. (ND meas.) | 4.9 % | 3.0 % |
| $\nu$ int. (from other exp.) | 6.7 % | 7.5 % |
| Super-K +FSI+SI+PN | 7.3 % | 3.5 % |
| Total | 11.1 % | 8.8 % |
| Total (2012) | 13.0 % | 9.9 % |

Predicted # of events w/ sys. error

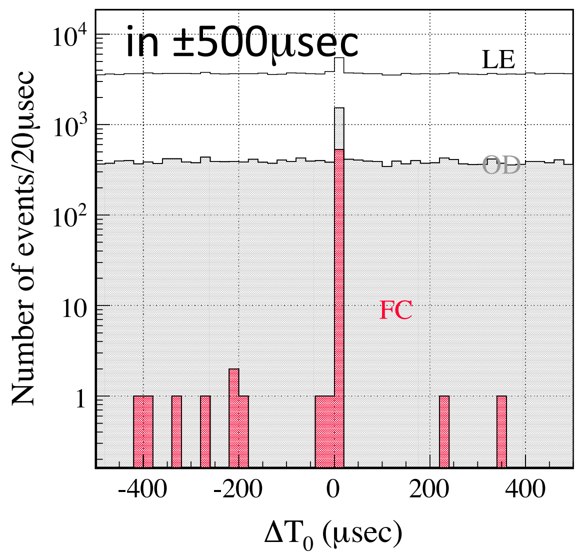


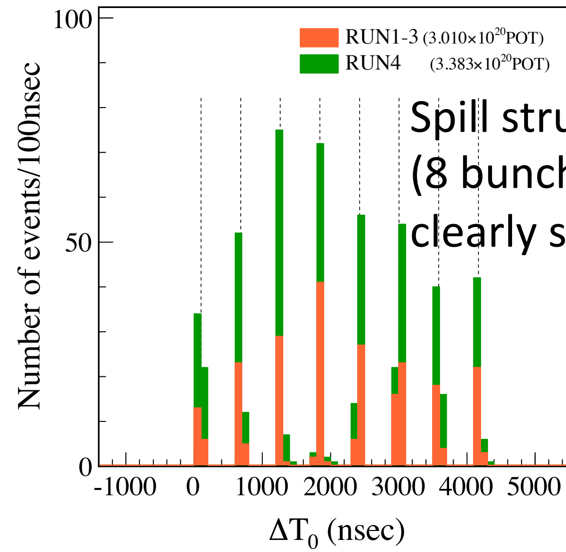

Uncertainty reduced much by the ND measurement

# T2K Event Selection at Super-K

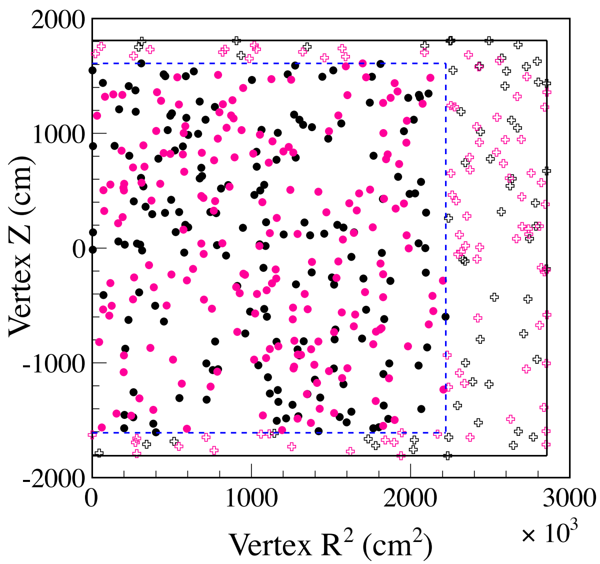
1.
Event timing relative to the beam arrival timing

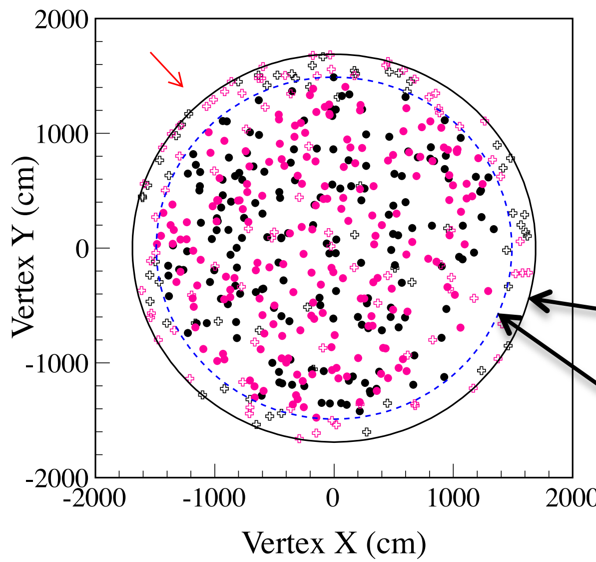
FC = Fully-Contained events




Spill structure (8 bunches) is clearly seen




2. Fiducial volume cut

Inner detector wall

FV boundary (2m from wall)

# T2K $\nu_e$ Event Selection at Super-K

3. Number of rings = 1

   186 events

4. Electron-like PID

   58 events

5. Visible energy >100MeV

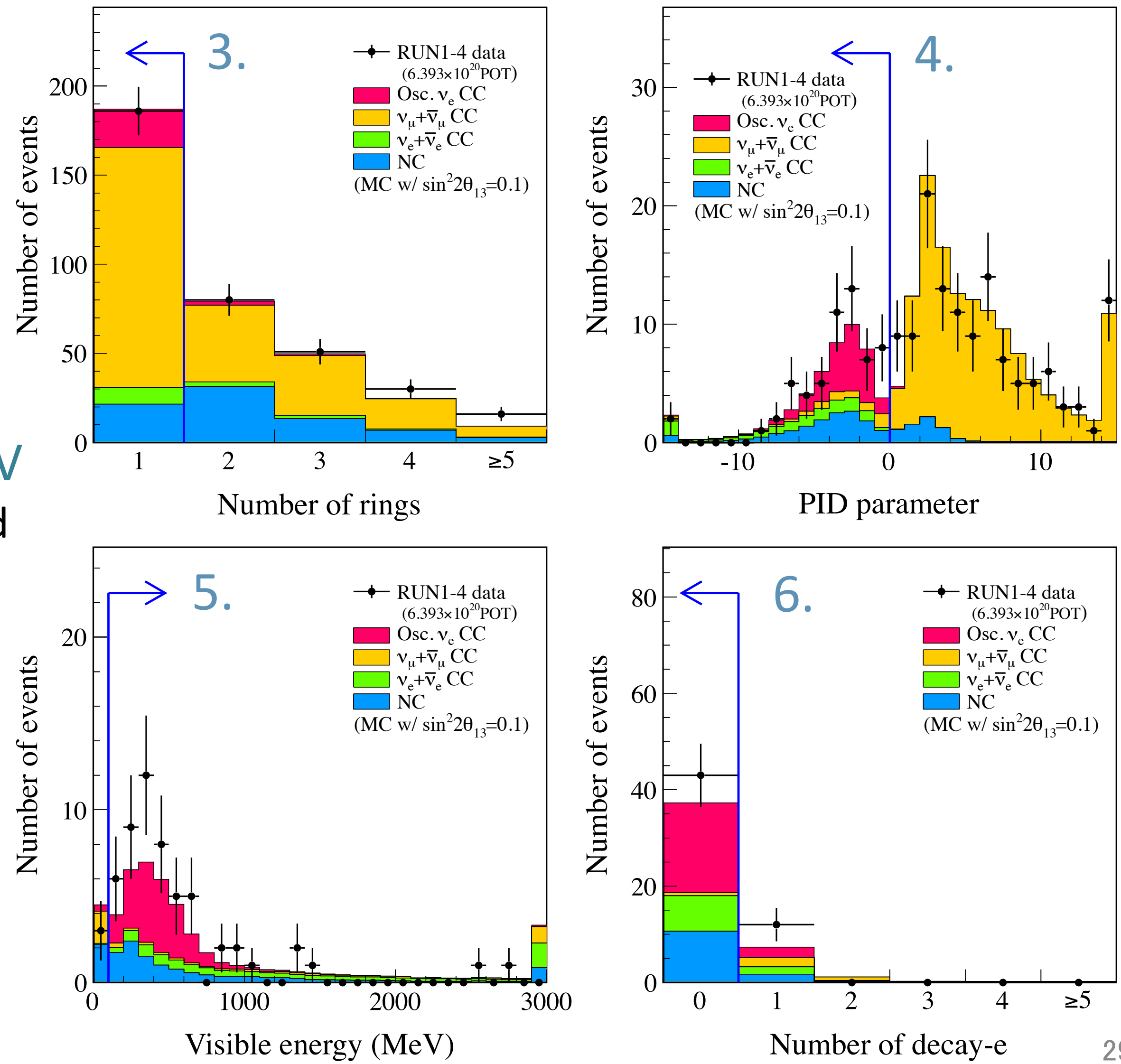
   Rejects low-E NC events, and electron from invisible $\mu$, $\pi$

   55 events

6. No $\mu$ decay electron

   Rejects events with invisible $\mu$, $\pi$

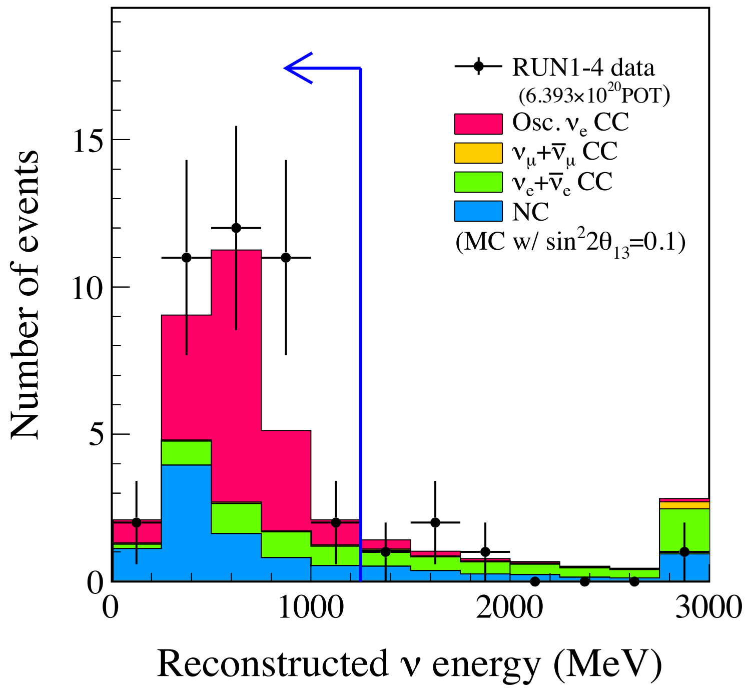
   43 events



# T2K $\nu_e$ Event Selection at Super-K (cont'd)

7. Reconstructed $E_\nu$ <1.25 GeV

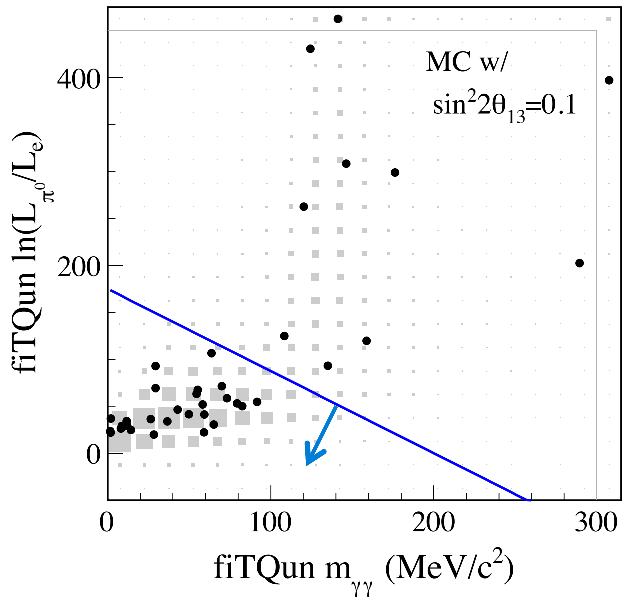
Reject intrinsic $\nu_e$ in the beam
(high energy $\nu_e$ mainly from K)

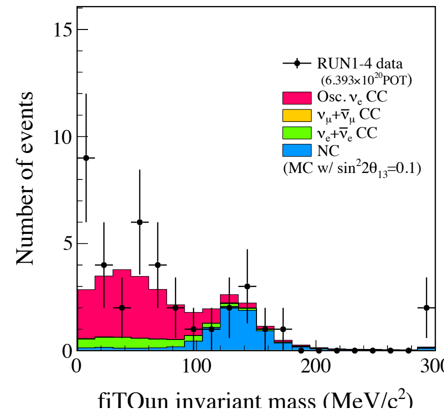


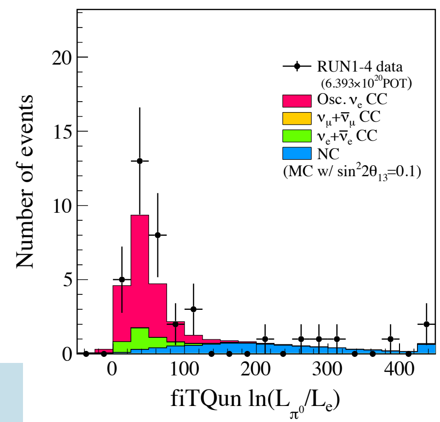

38 events

8. fiTQun $\pi^0$ rejection cut

Reject events with $\pi^0$



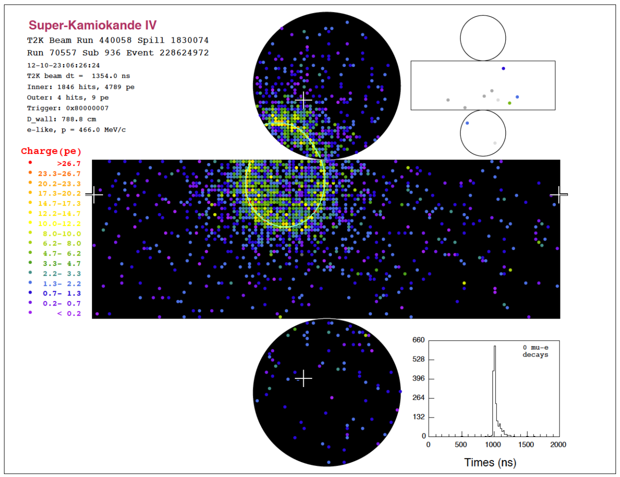



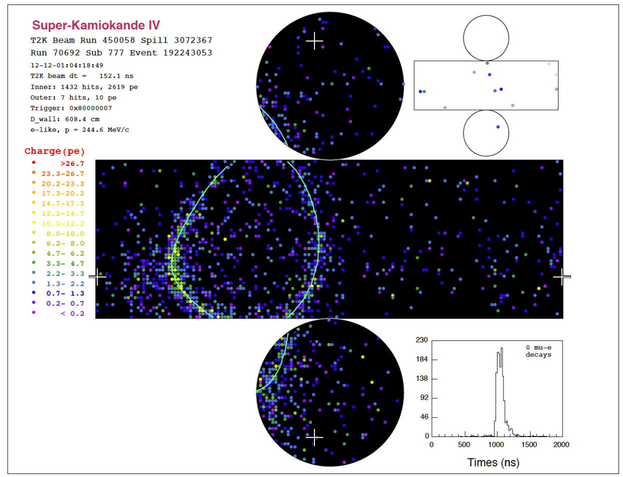



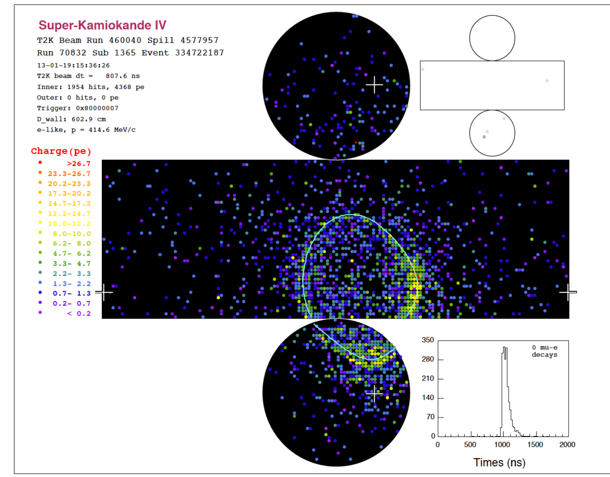

28 events after all cuts

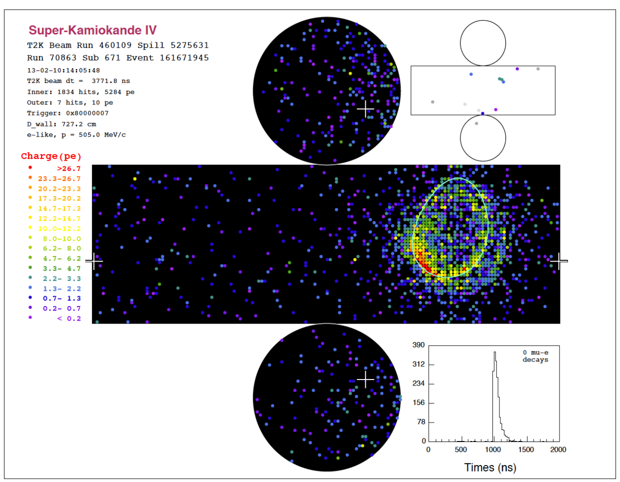
4.64 ± 0.52 events expected for $\sin^2 2\theta_{13}$=0
20.44 ± 1.80 events expected for $\sin^2 2\theta_{13}$=0.1

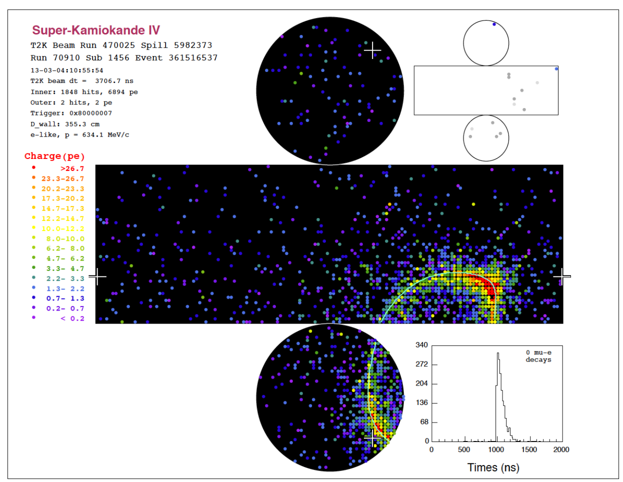
# Observed $\nu_e$ Candidate Events (Several Examples)

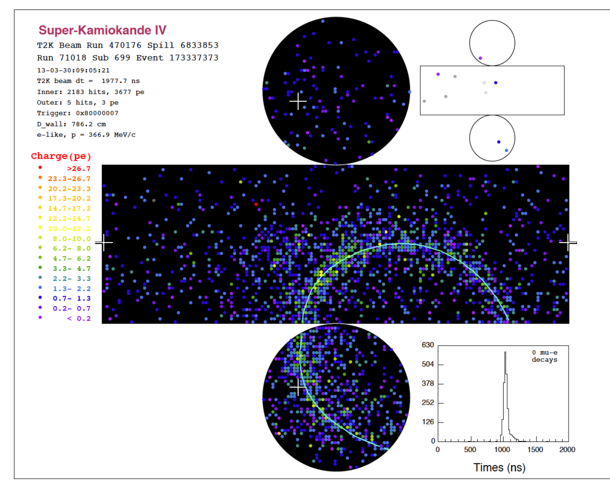


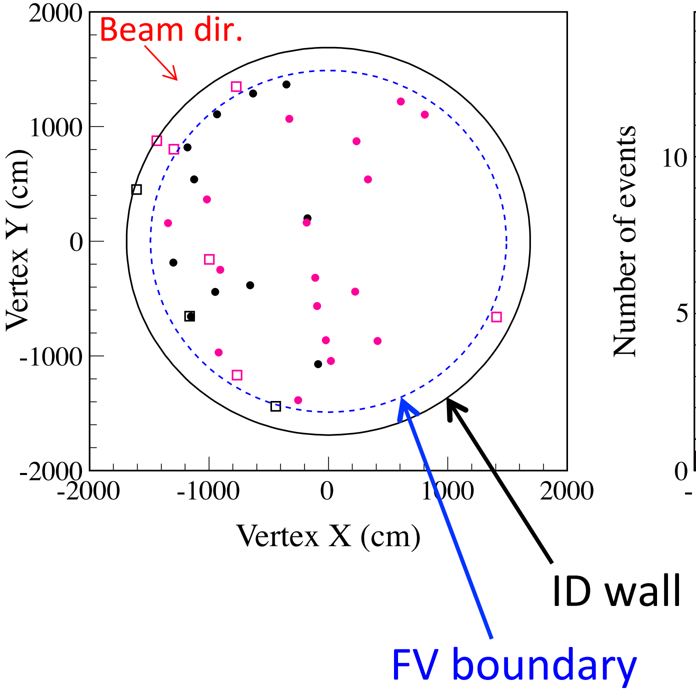



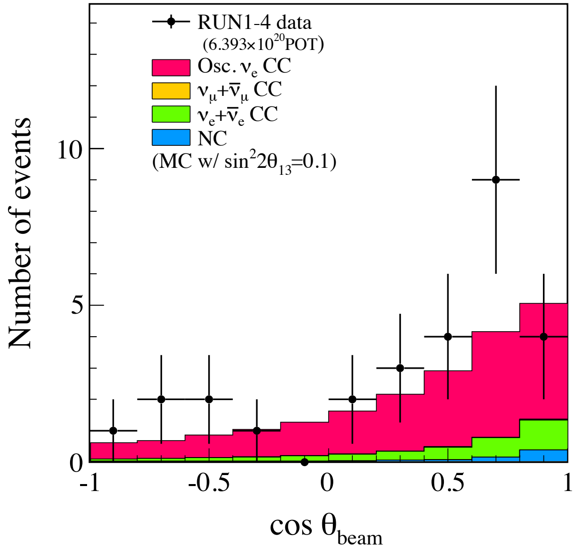

All events have a clear showering ring

# $\nu_e$ Candidate Event Distributions

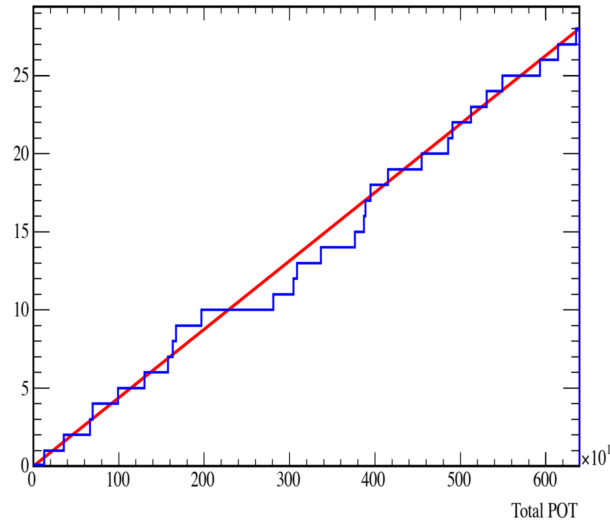
## Vertex X-Y




## Direction ($\cos\theta_{beam}$)



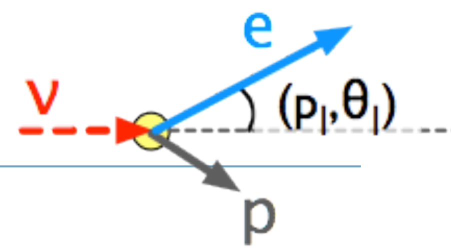

## Cumulative # of $\nu_e$ candidates vs. POT




KS probability to the constant event rate assumption = 97%

**Reasonable distributions**

# Oscillation Parameter Fits



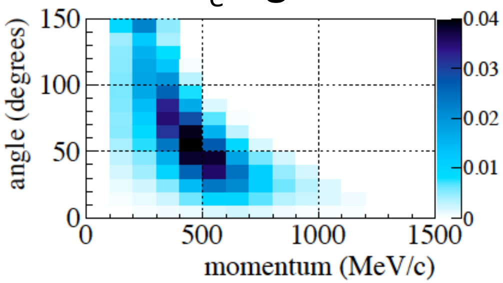

- Method 1 : Maximum likelihood fit w/ Rate + ($p_e$ , $\theta_e$) shape
- Method 2 : Maximum likelihood fir w/ Rate + reconstructed $E_\nu$

$$\mathcal{L}(\underline{N_{obs.}}, \underline{x}; o, f) = \mathcal{L}_{norm}(N_{obs.}; \underline{o}, f) \times \mathcal{L}_{shape}(x; o, f) \times \mathcal{L}_{syst.}(\underline{f})$$

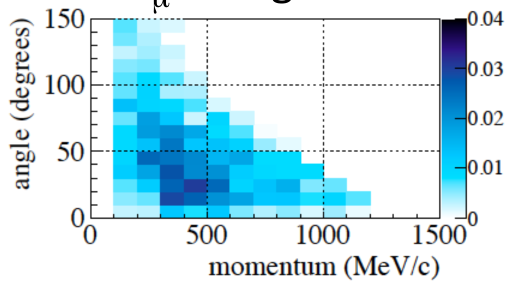
measurement variables | oscillation parameter | systematic parameters (prior: ND280 results)

Method 1

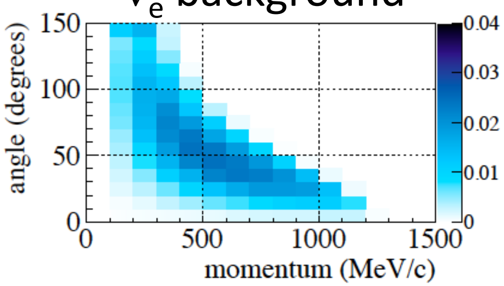
$\nu_e$ signal




$\nu_\mu$ background

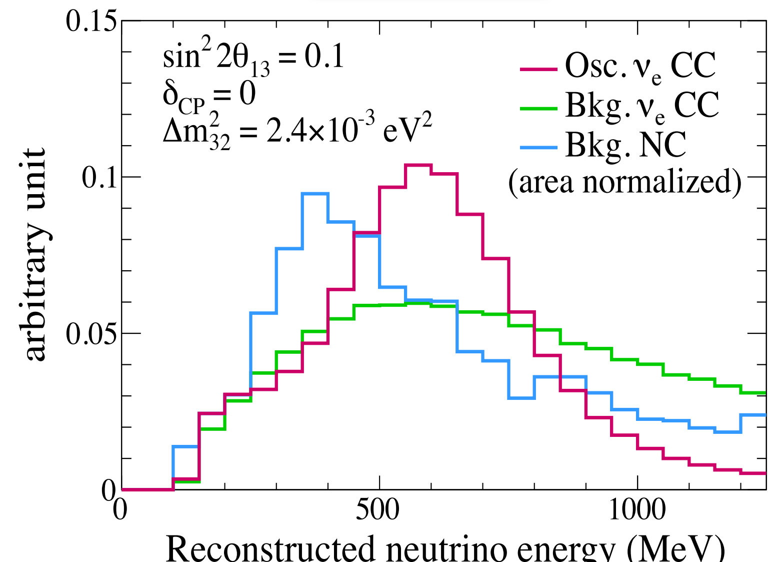



$\nu_e$ background




Shape difference allows to have a better discrimination of signal events from background

Method 2

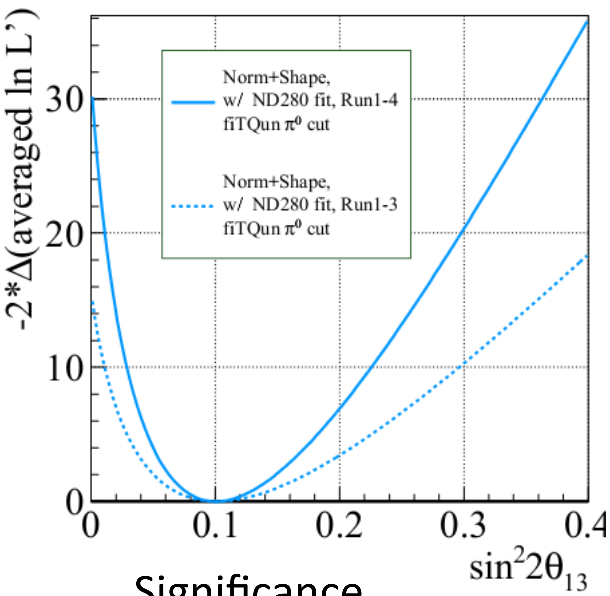


# Sensitivity (Expected Significance to Exclude $\theta_{13}=0$)

Averaged log likelihood curve over many toy data with true $\sin^2 2\theta_{13}=0.1$

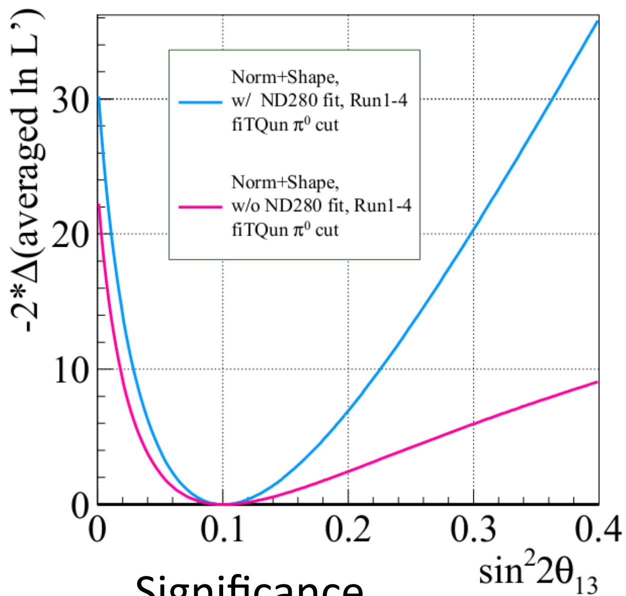
(Assuming $\delta_{CP}=0$, $\sin^2 2\theta_{23}=1.0$, and normal mass hierarchy)

RUN1-4 vs. RUN1-3 POT



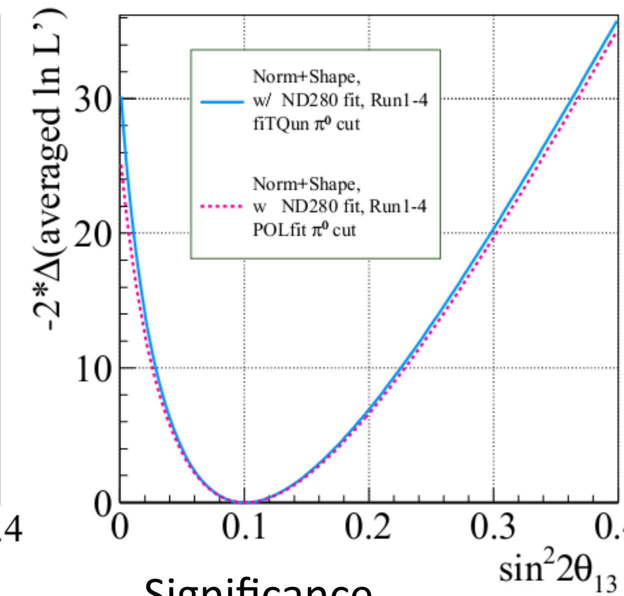

Significance
RUN1-4 POT : 5.5σ
RUN1-3 POT : 3.9σ

w/ vs. w/o ND Constraint




Significance
w/ ND info. : 5.5σ
w/o ND info. : 4.7σ

NEW vs. OLD SK Selection



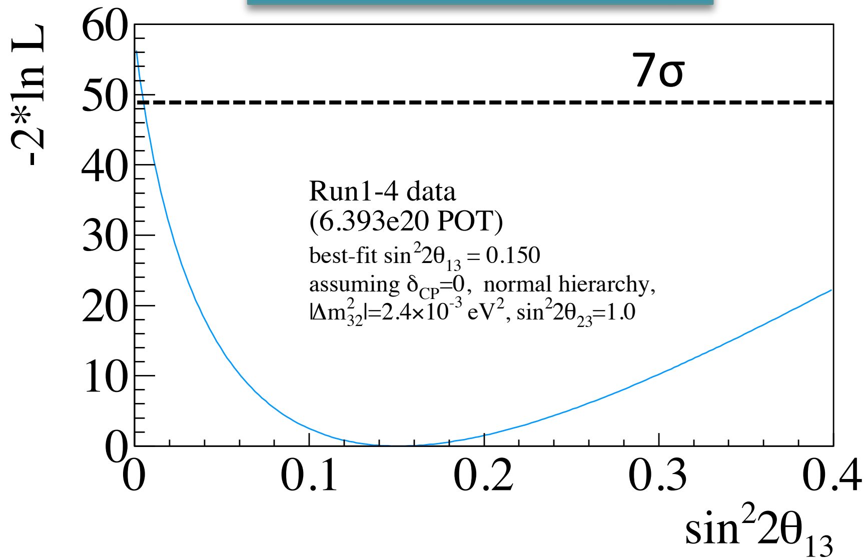

Significance
NEW (fiTQun) : 5.5σ
OLD (POLfit) : 5.0σ

Significance = $\sqrt{-2\Delta \ln L_{\theta 13=0}}$

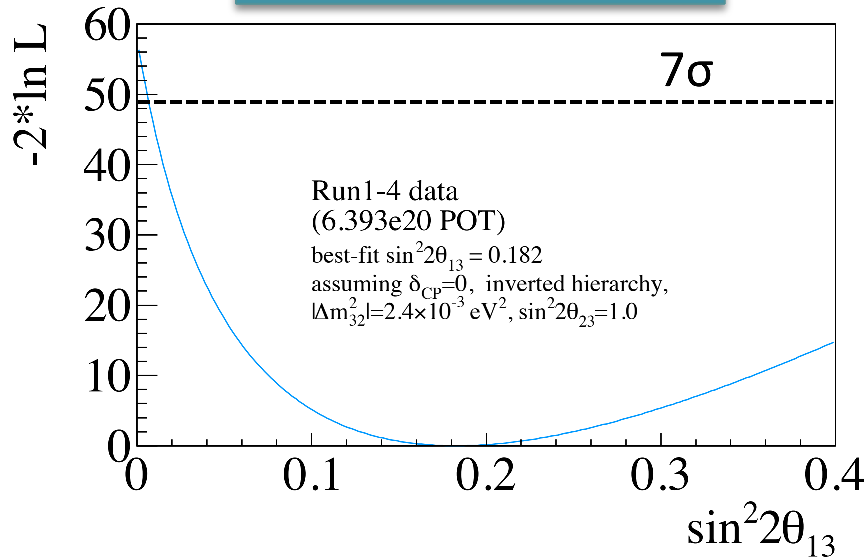
T2K preliminary

# RUN1-4 Data Fit Results : Method 1 (p-θ)

**Normal Hierarchy**




**Inverted Hierarchy**




Assuming $\delta_{CP}=0$, $\sin^2 2\theta_{23}=1.0$

$\sin^2 2\theta_{13}$ = $0.150^{+0.039}_{-0.034}$ Best-fit values w/ 68% confidence intervals $0.182^{+0.046}_{-0.040}$

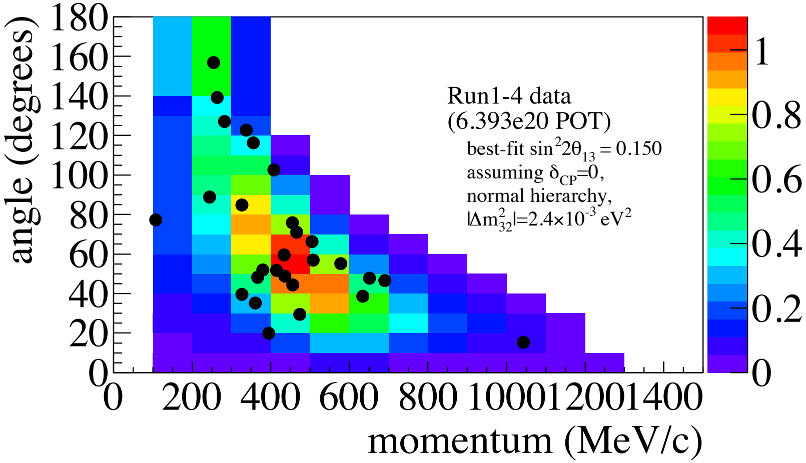
$\theta_{13}=0$ is excluded at 7.5σ

→ Definitive observation of electron neutrino appearance !

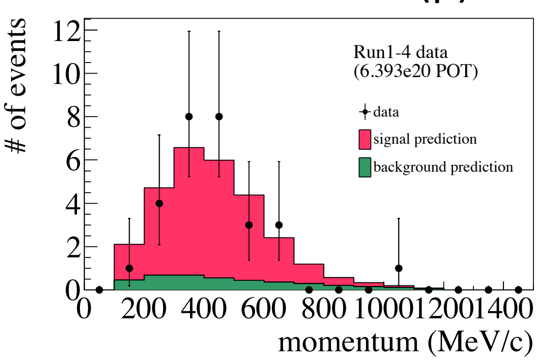
# RUN1-4 Data Fit Results : Method 1 (p-θ)

## Data and best-fit MC distributions

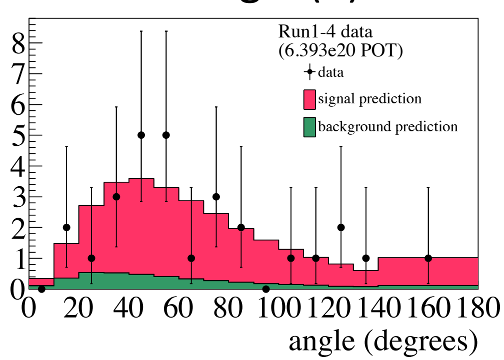
### Momentum vs. Angle (p-θ)



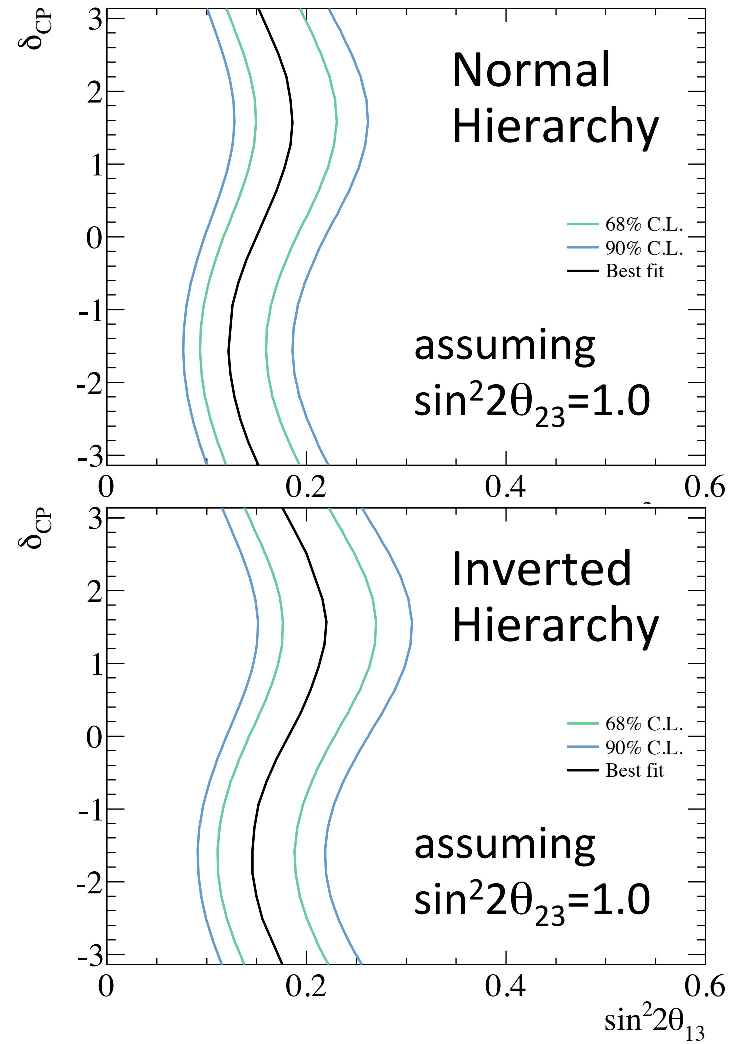

### Momentum (p)




### Angle (θ)



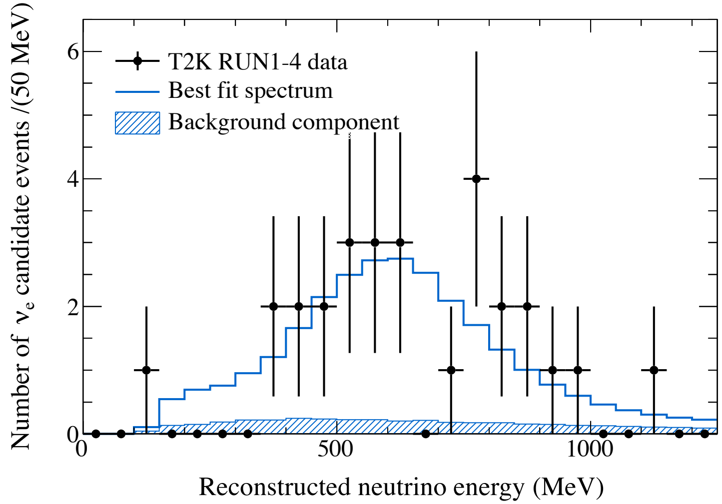

## 68%/90% C.L. regions for $\sin^2 2\theta_{13}$ for each value of $\delta_{CP}$



T2K preliminary

# RUN1-4 Data Fit Results : Method 2 (rec. $E_\nu$)

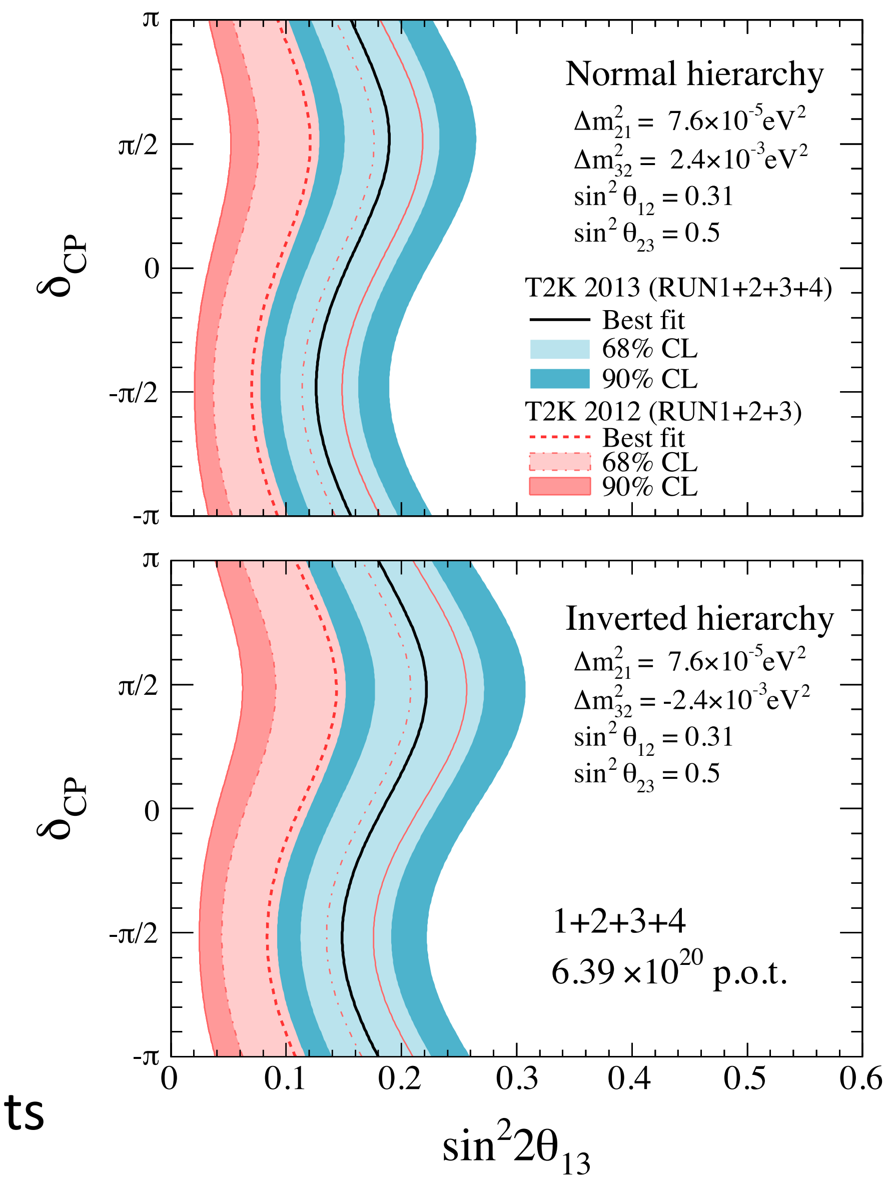
Data and best-fit MC :
Reconstructed $E_\nu$ distribution




Assuming $\delta_{CP}$=0, $\sin^2 2\theta_{23}$=1.0

$$\sin^2 2\theta_{13} = 0.152^{+0.041}_{-0.034} \quad \text{(NH)}$$

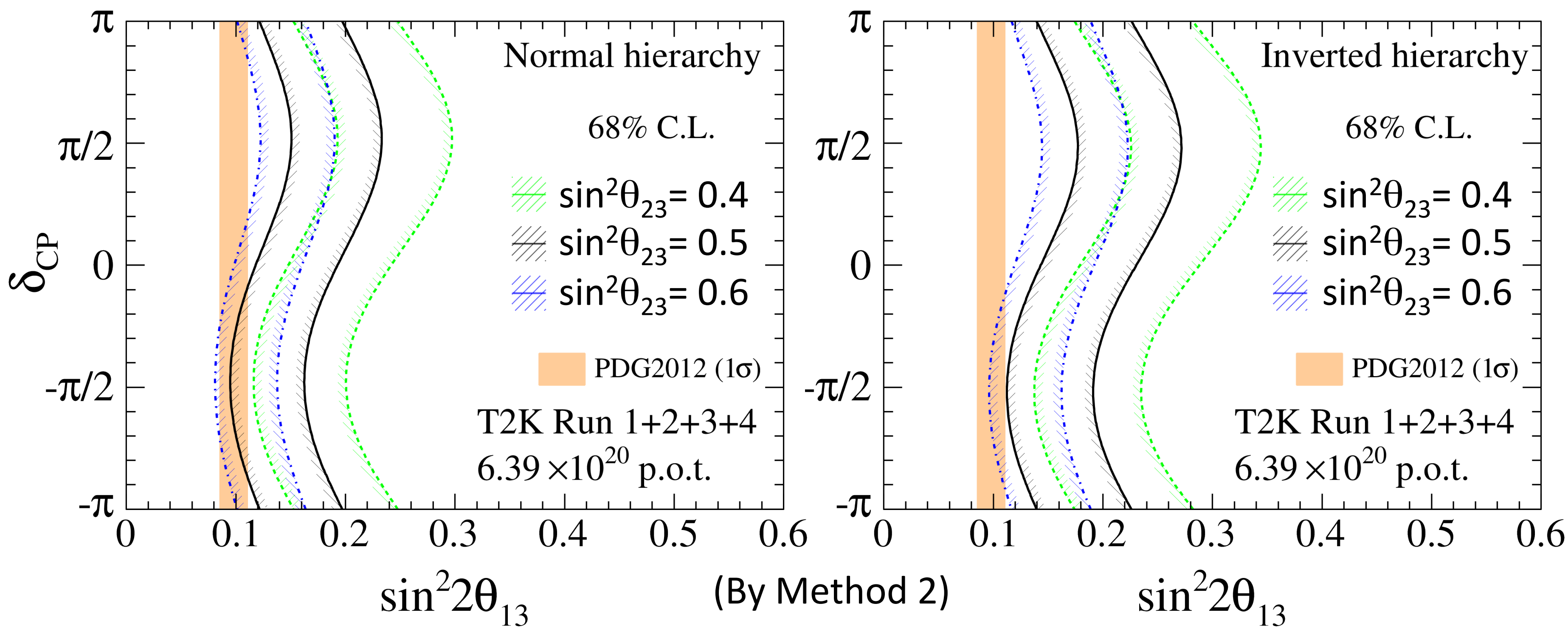
$$\sin^2 2\theta_{13} = 0.184^{+0.046}_{-0.041} \quad \text{(IH)}$$




Consistent with Method 1 results

# Effect of $\theta_{23}$ Uncertainty

T2K preliminary




(By Method 2)

- $\nu_e$ appearance probability also depends on the value of $\theta_{23}$

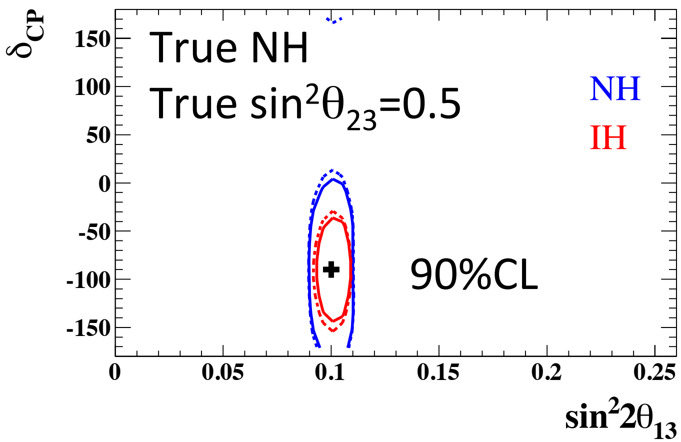
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \boxed{\sin^2\theta_{23}} \sin^2(\Delta m^2_{31} L/4E)$$

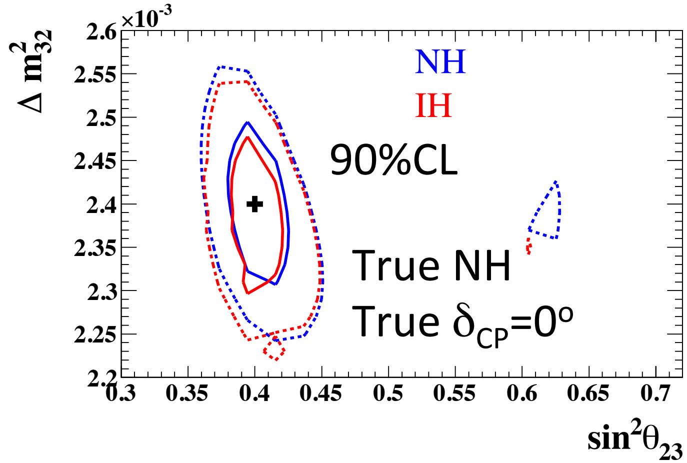
- T2K $\nu_e$ appearance measurement in cooperation with other experiments may give some hint on $\theta_{23}$ octant

# T2K Next Step :

# Can T2K measure $\delta_{CP}$/Mass Hierarchy/$\theta_{23}$ Octant ?

Detailed sensitivity studies are ongoing



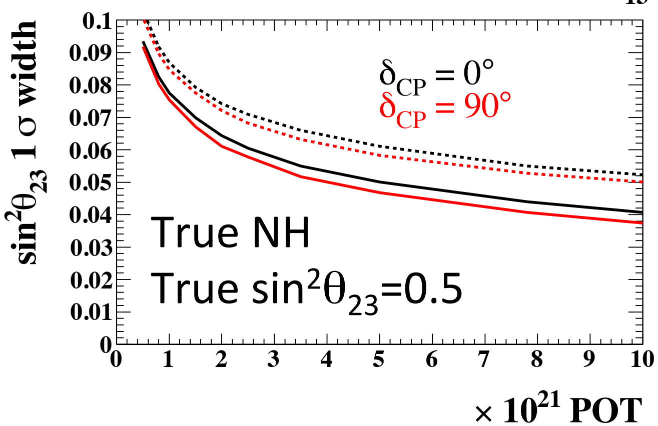



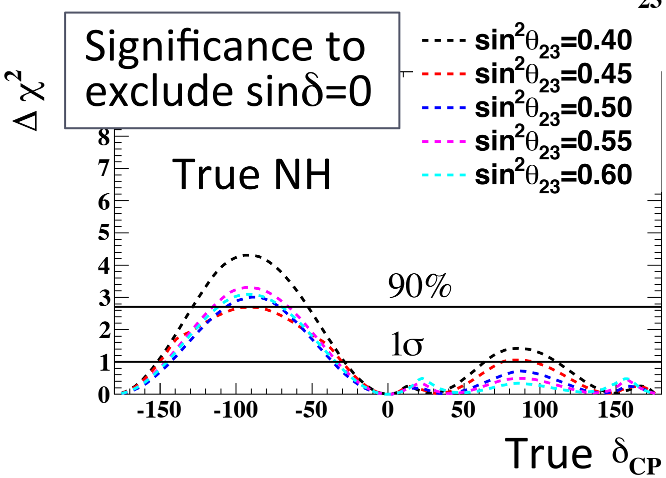

50% ν + 50% anti-ν

Full T2K stat.

w/ ultimate $\theta_{13}$ meas.

w/o NOvA




Solid : stat. error only

Dashed : current sys.

T2K will make run plans (anti-ν run, …) based on these studies

Observation of $\nu_e$ appearance has just been made by T2K

→ We've entered the era of $\nu_e$ appearance "measurement"

T2K may constrain $\delta_{CP}$, mass hierarchy, and $\theta_{23}$ octant
(in cooperation with reactor experiments, NOvA, and SK)

But, significance may not be large

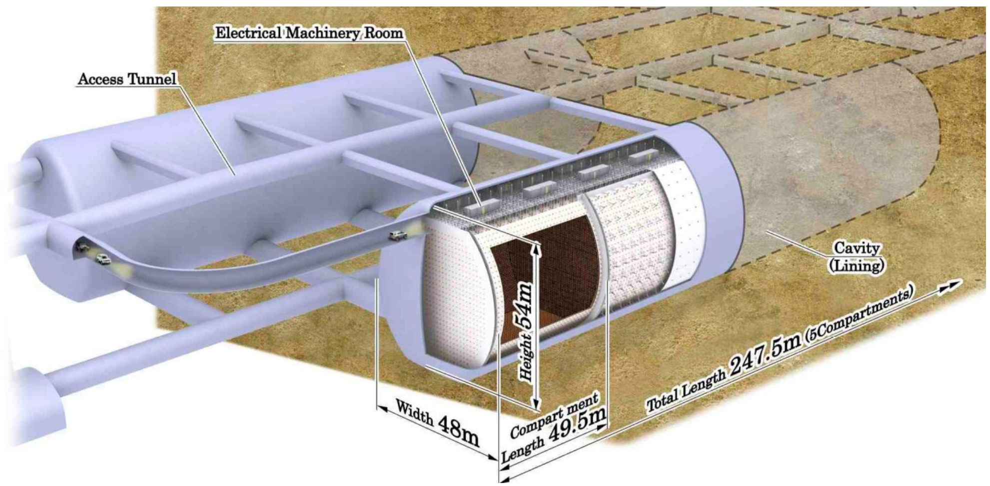
To get a definitive conclusion on CPV and to measure $\delta_{CP}$,
next generation long-baseline experiments are indispensable

Higher intensity beam + Larger neutrino detector

NOW IS THE TIME to realize a new project in Japan

# Hyper-Kamiokande Project

arXiv:1109.3262




Total Mass : 0.99 Mton
Fiducial Mass : 0.56 Mton
( x25 of Super-K )

## Next generation Mega-ton scale Water Cherenkov detector

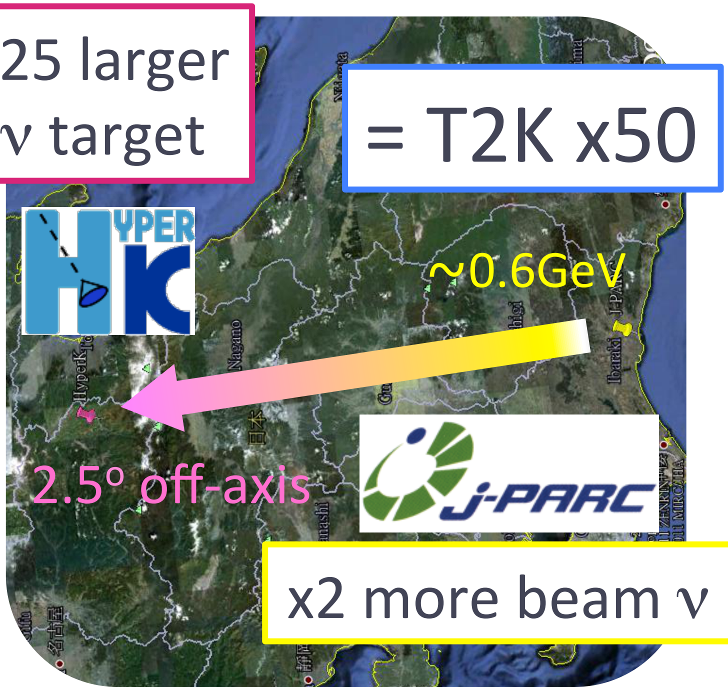
- Exploring full picture of neutrino oscillation
  - w/ Higher intensity ν beam from J-PARC, Atmospheric ν
- Astrophysical neutrinos
  - Solar ν, Supernova, WIMP, solar flare, …
- Neutrino geophysics
- Proton decay search

# $\delta_{CP}$ Measurement (Accelerator ν)

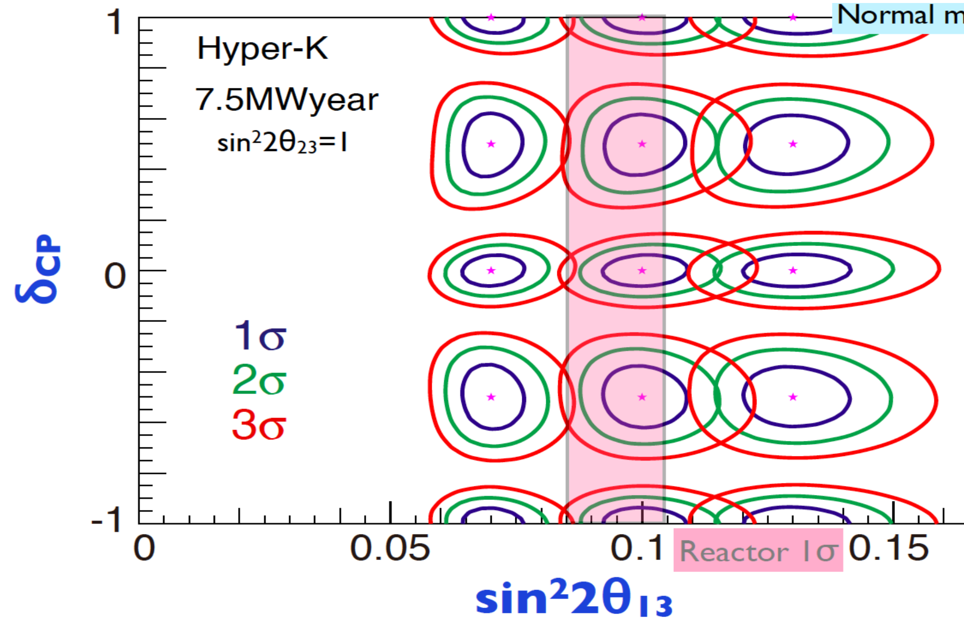
x25 larger ν target

= T2K x50

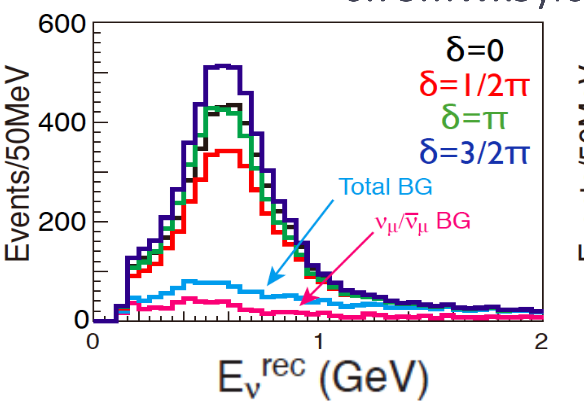
x2 more beam ν



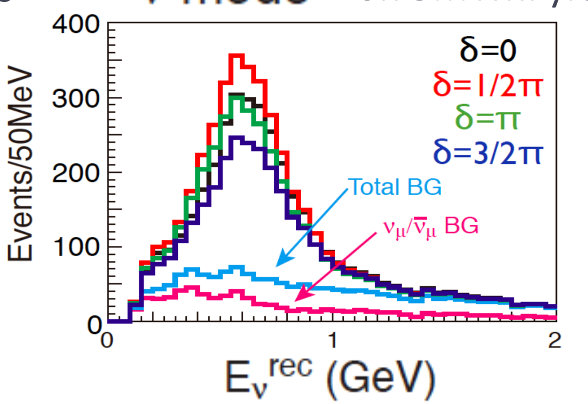

7.5MWyear, ν:anti-ν = 3:7, NH (known)




ν mode 0.75MWx3yrs




$\bar{\nu}$ mode 0.75MWx7yrs

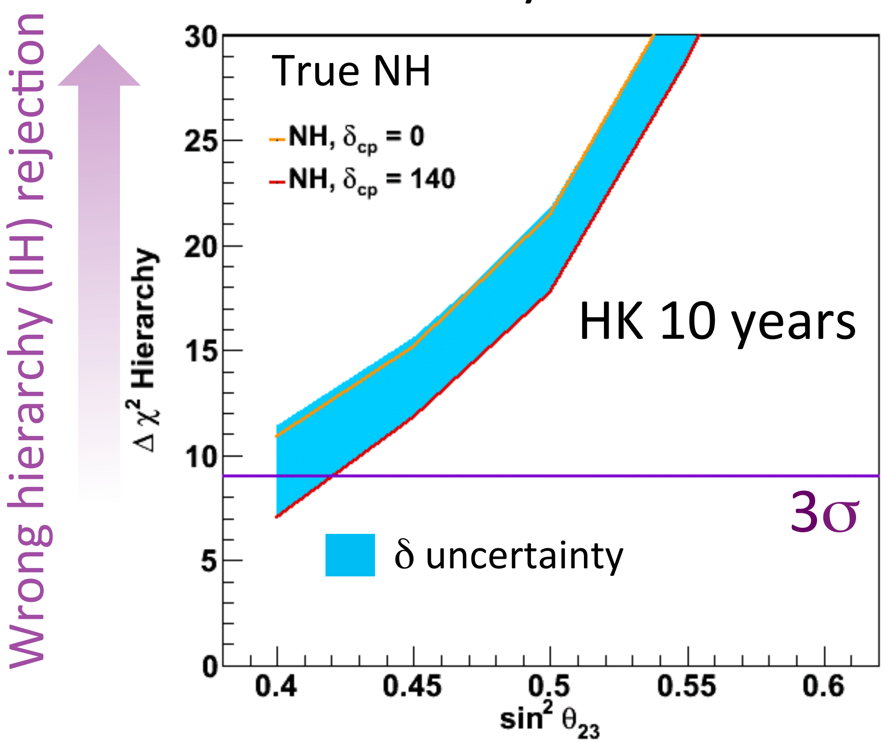



δ precision (1σ error size)
< 20° at δ=90°
< 10° at δ=0°

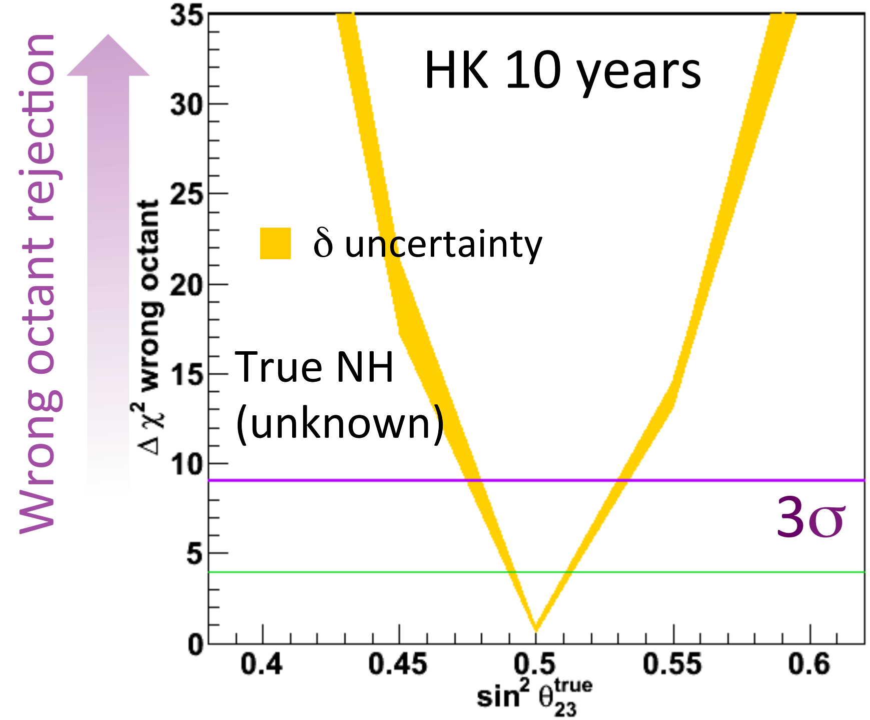
For 74% of δ, sinδ=0 is excluded with >3σ

# Mass Hierarchy & $\theta_{23}$ Octant Sensitivity (Atm. $\nu$)

## Mass Hierarchy Determination




## $\theta_{23}$ Octant Determination




- <10 years HK atmospheric $\nu$ data can determine the MH w/ $3\sigma$.

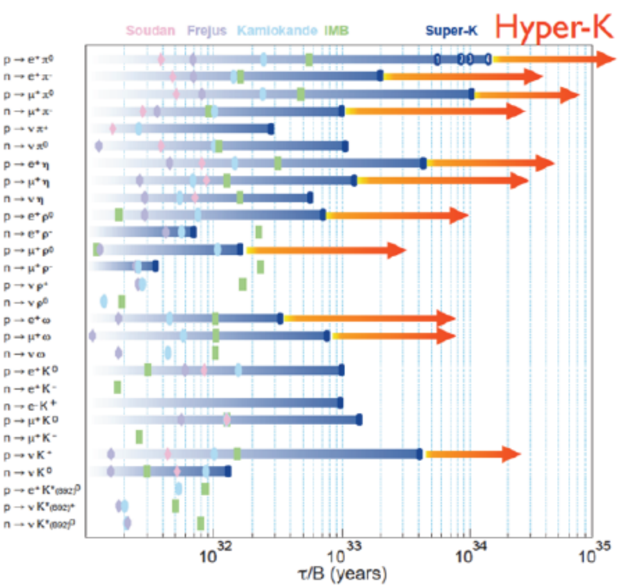
  (Higher significance and earlier in larger $\theta_{23}$ case)

- If $\sin^2 2\theta_{23}$ <0.99 ($\sin^2\theta_{23}$ <0.45 or >0.55), $\theta_{23}$ octant can be determined at >$3\sigma$ using 10 years of HK atmospheric $\nu$ data.

# More Hyper-K Physics

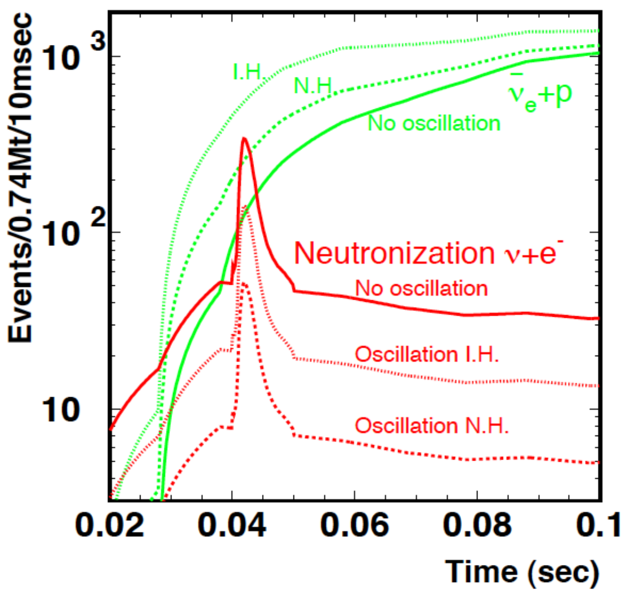
## Nucleon decay search

- x10 better sensitivity than SK
- >3σ discovery is possible for lifetime beyond SK limits



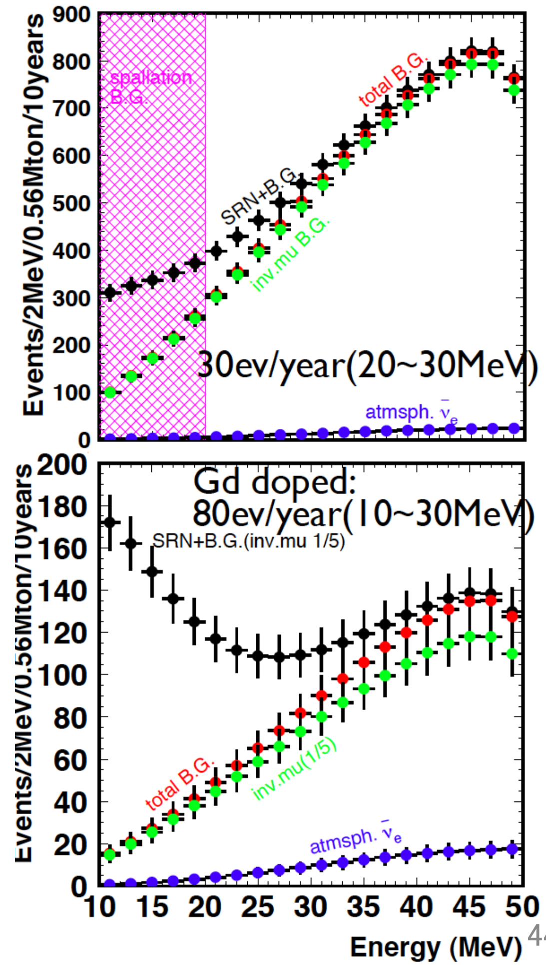

## Supernova burst ν

- 250,000 ν (SN@10kpc)
- Variation of ν luminosity, temperature, flavor, …
- MH determination ?




## Relic supernova ν

- 80events/year (w/ Gd)

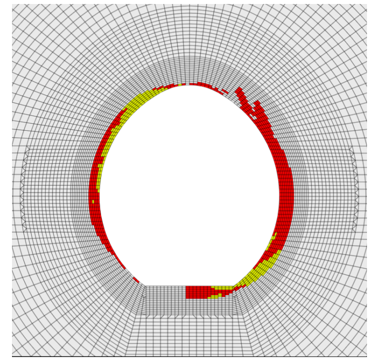


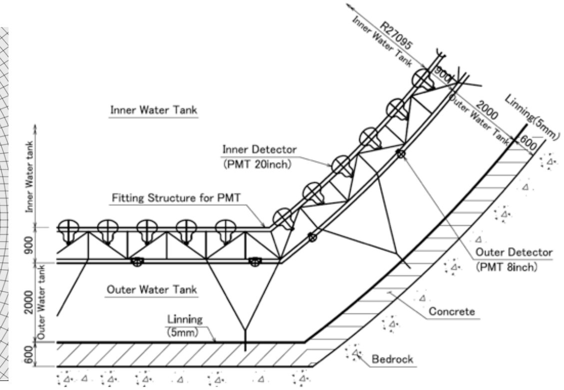

- 200 solar ν /day → ~3σ day/night asym.
- WIMP ν, Solar flare ν, …

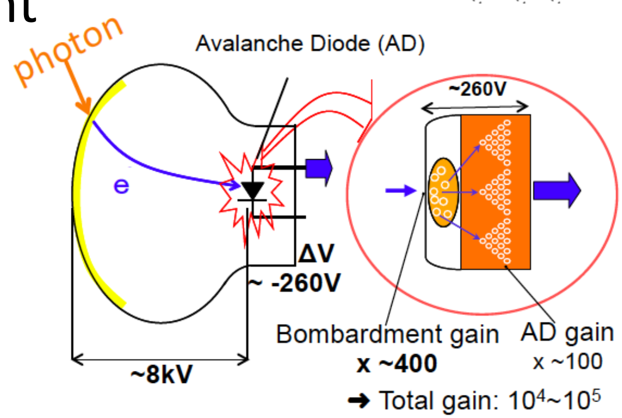
# R&D Work and Studies ongoing

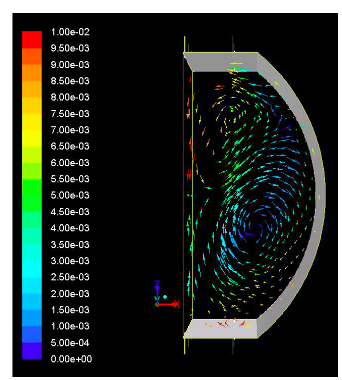
- Detector design optimization
  - Cavern stability, Tank shape, Number of compartments, PMT support structure, …
- New photo-sensor development
  - Hybrid Photo Detector (HPD), Higher QE photo-cathode
- Water purification system
- Electronics/DAQ system
  - Electronics immersed in water ?
- Software development
- Physics potential studies
  - Requirements for near detectors

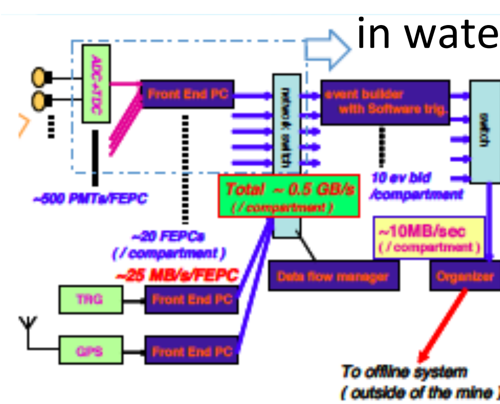
Better performance w/ lower cost







# International Hyper-K Working Group

- Hyper-K is open to the international community
- Three open meetings at IPMU (Kashiwa)
  - 1st mtg in August 2012 http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=7
  - 2nd mtg in January 2013 http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=10
  - 3rd mtg in June 2013 http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=23
  - ~100 participants at each mtg.
    ~50% from abroad
- Formed international WG
  - Canada, Spain, Switzerland, Russia, U.K., U.S., and Japan

You are VERY WELCOME to join us !

# Summary

- T2K has made the definitive observation of $\nu_e$ appearance from the $\nu_\mu$ beam
  - Using $6.39\times10^{20}$ Protons-On-Target beam data (×2.1 of 2012 analysis) obtained by the stable beam and detector operations
  - Analysis improvements also contributed : Improved Near ν Detector analysis, Improved $\pi^0$ background rejection at Super-K Far ν Detector, …
  - 28 candidate events over 4.6±0.5(sys.) backgrounds
  - $\theta_{13}=0$ is excluded at 7.5σ

  → We have entered the era of $\nu_e$ appearance "measurement" for exploring the leptonic CPV and ν mass hierarchy !

- Now is the time to realize a new project in Japan
  - Hyper-K has great potential for discovering new physics
  - Need your strong support to the project

# Supplement