# Highlights from the T2K Experiment

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**for T2K collaboration**

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- ***Introduction of T2K***
- ***Experimental Setup***
- ***Status of Experiment***
- ***Analysis Results***
- ***Future Prospects***
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# *Introduction of T2K*

# Neutrino Oscillation

- **Flavor oscillation described by Pentecorvo-Maki-Nakagawa-Sakata matrix.**
- **Parameterized by 3 mixing angles and CP-violating phase $\delta_{CP}$**

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

***"Atmospheric sector"***

**$\theta_{23}$**

$\nu_\mu$ disappearance

(SuperK, K2K, MINOS)

$\nu_\tau$ appearance

(OPERA, SuperK)

$0.92 < \sin^2 2\theta_{23} < 1.0$

$2.3 \times 10^{-3} < |\Delta m^2_{23}|$ ($eV^2$) $< 2.56 \times 10^{-3}$

***"Solar sector"***

**$\theta_{12}$**

$\nu_e$ disappearance

(SNO, KamLAND, SuperK and others)

$0.84 < \sin^2 2\theta_{12} < 0.89$

$7.38 \times 10^{-5} < |\Delta m^2_{12}|$ ($eV^2$) $< 7.80 \times 10^{-5}$

# *Neutrino Oscillation*

- **Flavor oscillation described by Pentecorvo-Maki-Nakagawa-Sakata matrix.**
- **Parameterized by 3 mixing angles and CP-violating phase $\delta_{CP}$**

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

**$\theta_{13}$**

only upper limit known

$\sin^2 2\theta_{13} < 0.13$ @90%CL (2010)

(CHOOZ, MINOS)

**Reactor experiment**

**L=~1km**

$\bar{\nu}_e \rightarrow \bar{\nu}_e$ oscillation

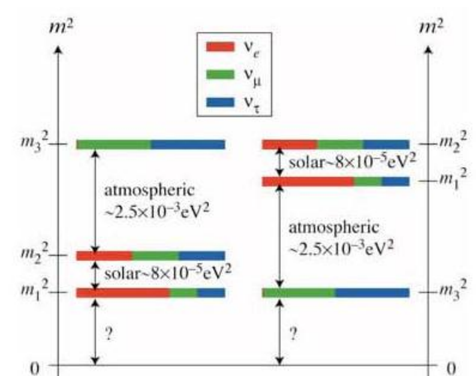
($\bar{\nu}_e$ disappearance)

**Accelerator experiment**

**L=*O*(100km)**

**Observation of $\nu_\mu \rightarrow \nu_e$ oscillation**

**($\nu_e$ appearance)**




***normal or inverted?***

*if $\theta_{13}$ is non-zero, open the possibility to measure*

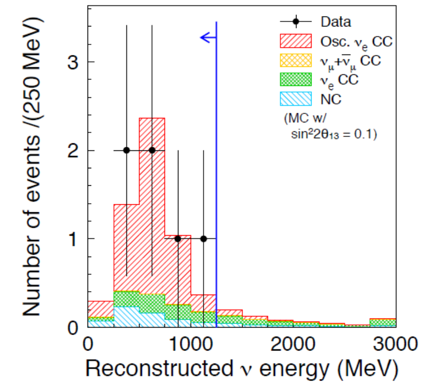
- *Mass Hierarchy*
- *$\delta_{CP}$*

# The T2K Experiment

- **Tokai to Kamioka Long Baseline Neutrino Oscillation Experiment**
  - Accelerator-based neutrino experiment.
- **Physics Motivation**
  - **Discovery of $\nu_\mu \rightarrow \nu_e$ conversion phenomena and the measurement of parameter $\theta_{13}$ which controls this phenomena.**
  - **Precise measurement of the parameters $\theta_{23}$ and $\Delta m_{23}$ in $\nu_\mu \rightarrow \nu_\mu$ oscillation.**

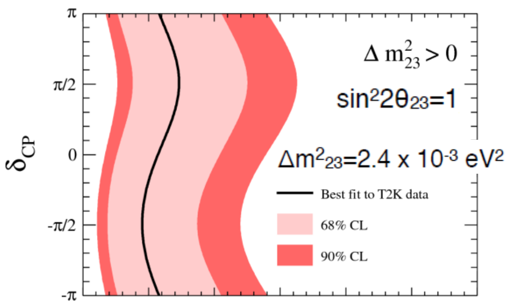
# First T2K Results

## Data collected until Mar. 2011: 1.43 ×10^20 POT



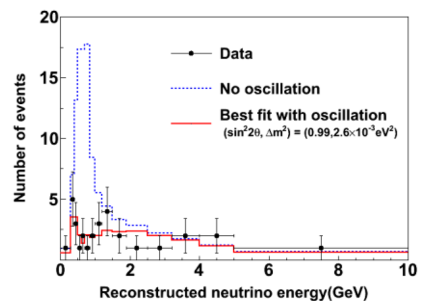

## $\nu_e$ appearance result (15/June/2011) →PRL 107, 041801 (2011)

- **6 $\nu_e$ events observed !!** ↔ Background(BG): 1.5±0.3events
  - Probability to observe 6 or more BG events = **0.7% (2.5σ)**
- $\theta_{13}$ measurement (90%CL)
  - **$0.03<\sin^2 2\theta_{13}<0.28$ (cent. val.=0.11)** for $\Delta m^2_{23}>0$, $\delta_{CP}=0$
  - **$0.04<\sin^2 2\theta_{13}<0.34$ (cent. val.=0.14)** for $\Delta m^2_{23}<0$, $\delta_{CP}=0$



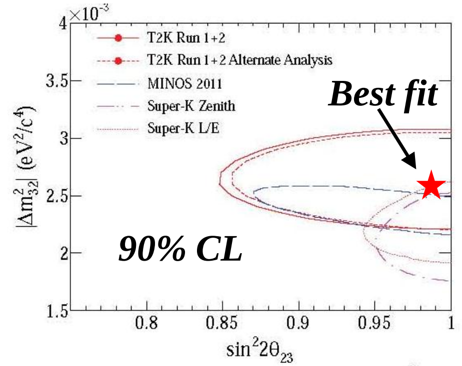

***→ First indication of non-zero $\theta_{13}$.***

## $\nu_\mu$ disappearance result →PR D85, 031103(R) (2012)




- **31 $\nu_\mu$ events observed** ↔ $103.6^{+13.8}_{-13.4}$(syst.) expected w/o oscillation.
- **$\sin^2 2\theta_{23}$ = 0.99, $|\Delta m^2_{23}|$ = 2.63 × 10^-3 eV^2 (best fit values)**

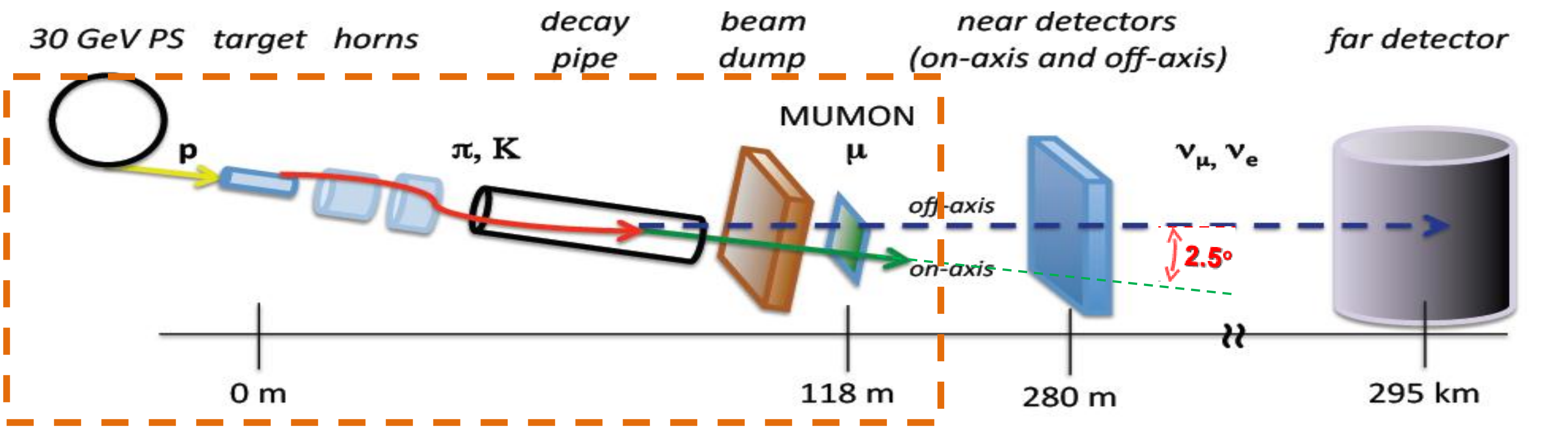
  →Consistent with MINOS and SK results.




**This talk = Updated $\nu_e$ appearance result**

# *Experimental Setup*

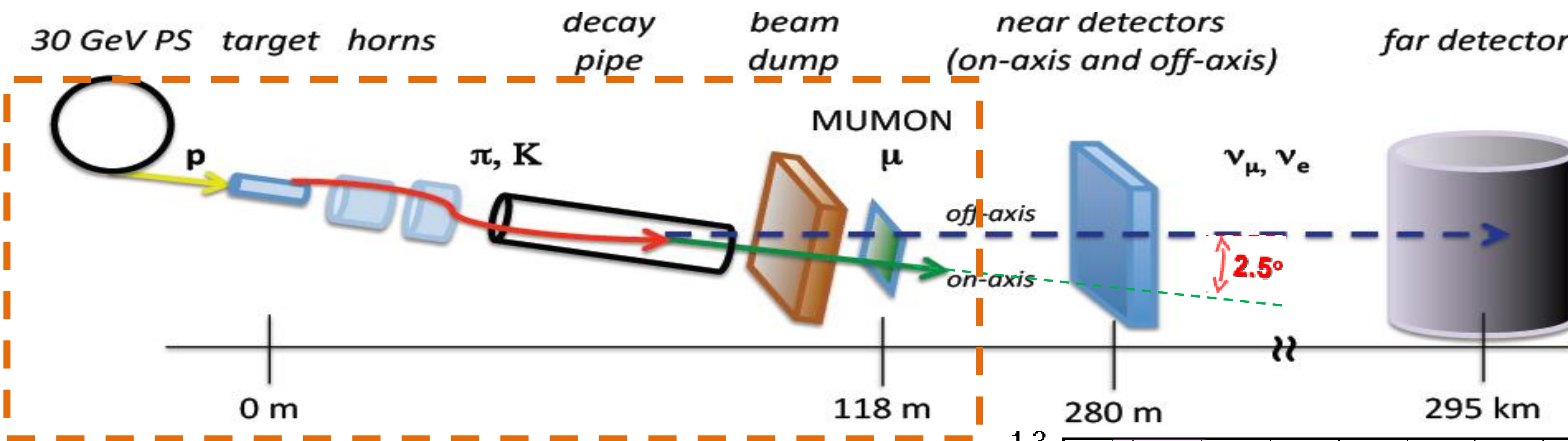
# T2K Neutrino Beam




***High intensity neutrino beam***

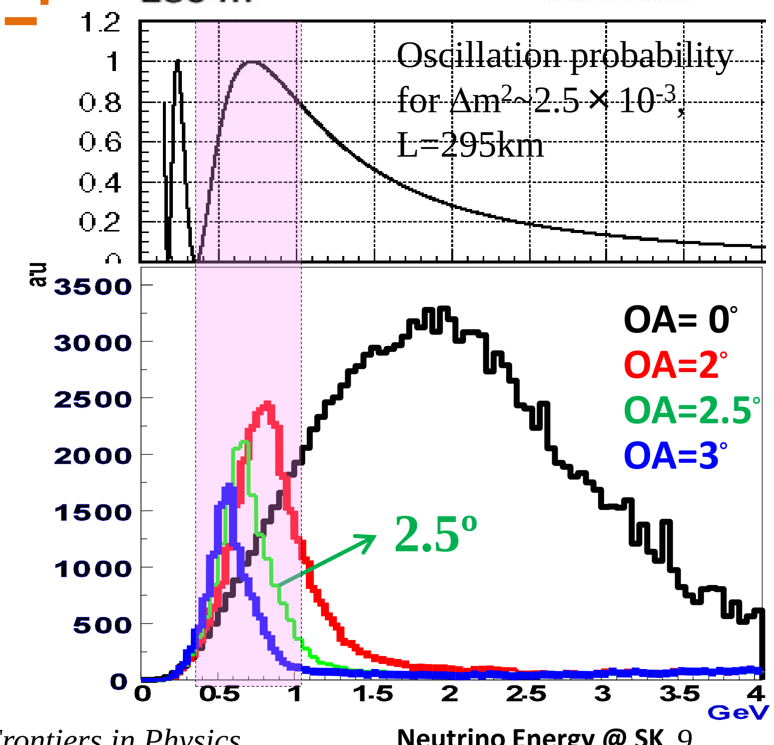
- 30 GeV **~10$^{14}$** protons extracted every 2.5sec.
- Protons hit the target: graphite rod (ϕ2.6cm × 90cm)
- Secondary $\pi^+$(and $K^+$) focused by three magnetic horns (250kA/200kA)
- Decay Volume (96m long, He~1atm.)
  - $\nu_\mu$ from mainly $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - $\nu_e$ in the beam come from K and μ decay
- Beam Dump: stop all the hadrons and muons with $p_\mu$<5GeV/c.
- Muon Monitors: measure the intensity and profile of the muons ($p_\mu$>5GeV/c) bunch by bunch

# T2K Neutrino Beam

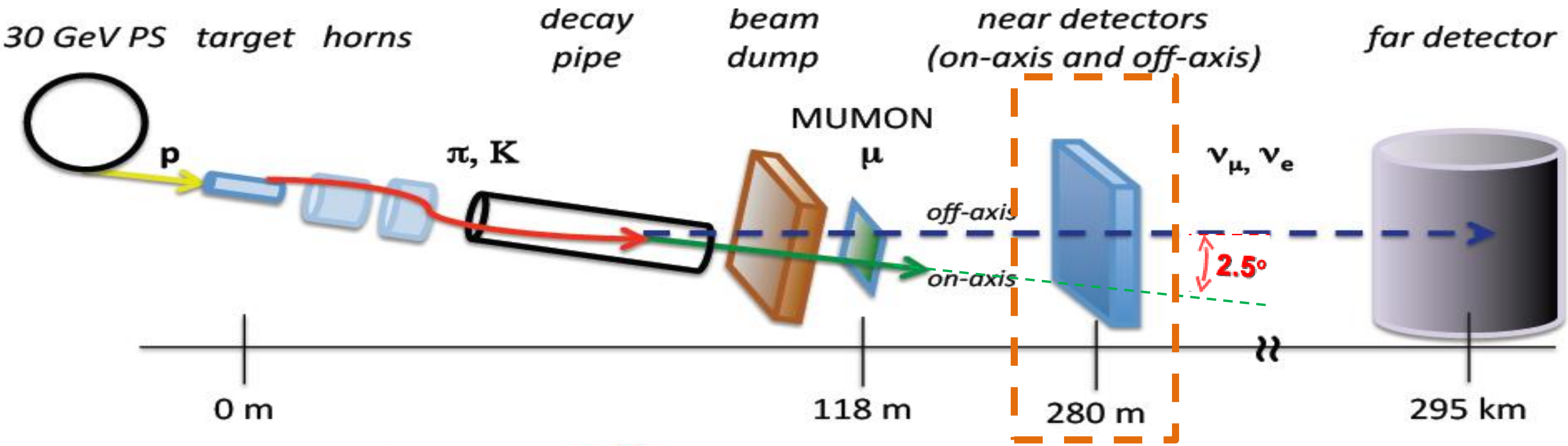



## *Off-Axis (2.5°) $\nu_\mu$ beam*

- Intense, low energy narrow-band.
- Peak $E_\nu$ tuned for oscillation max. (~0.6 GeV)
- Reduce BG from high energy tail.
- Small $\nu_e$ fraction (~1%).



# Near Detectors

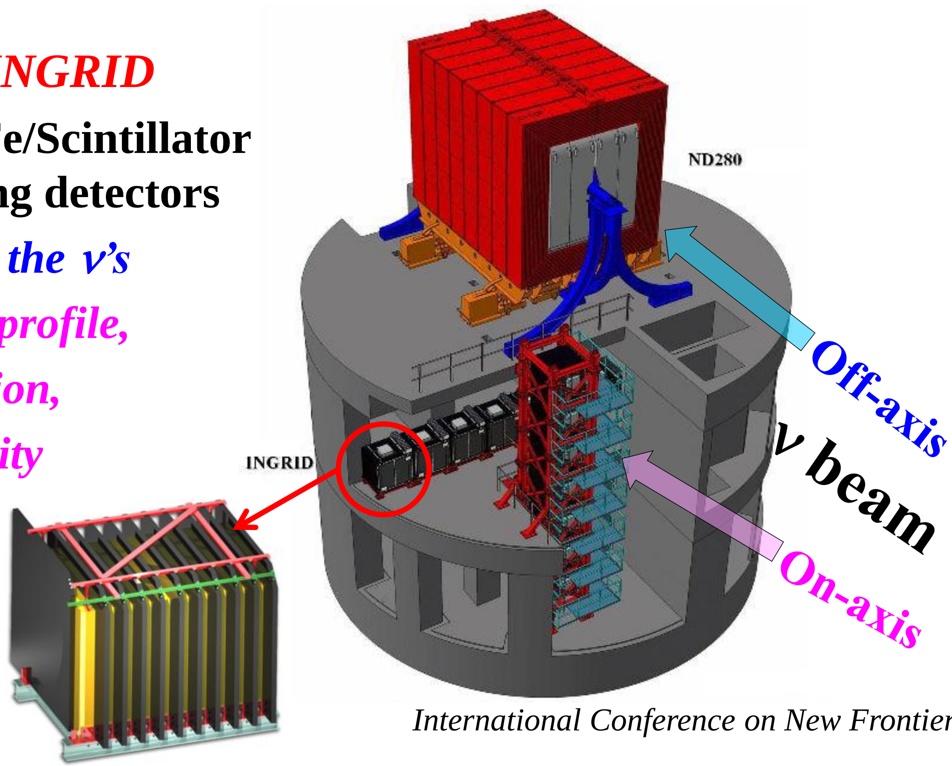



**On-axis: INGRID**

**Array of Fe/Scintillator tracking detectors**

→***Monitor the*** $\nu$***'s***

- *beam profile,*
- *direction,*
- *intensity*




**Off-Axis: ND280**

**Fine grained detector complex in 0.2T magnetic field**

→***Characterization of the*** $\nu$ ***beam before oscillations***

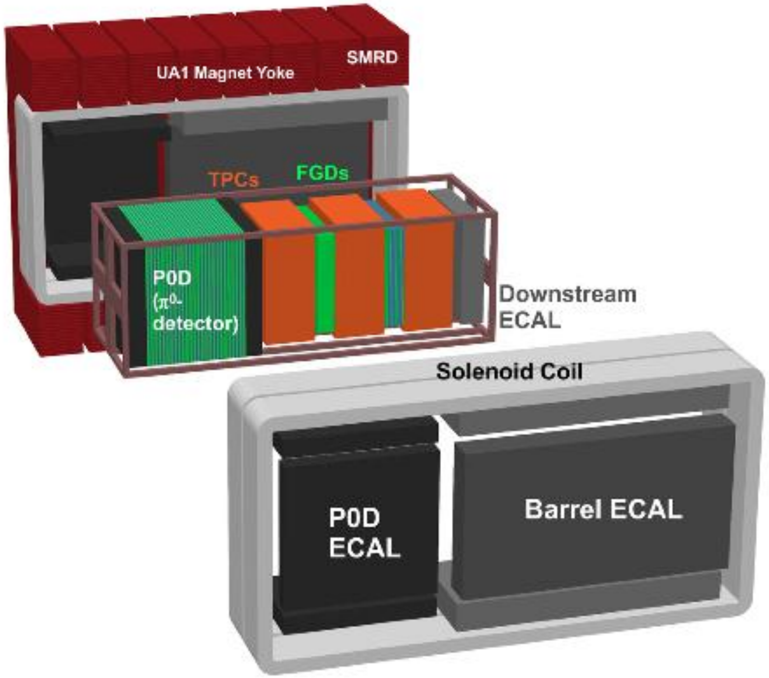
- $\nu_\mu$ *flux/Energy spectrum*
- $\nu_e$ *contamination*
  →*bkg to* $\nu_e$ *appearance*

→***Measurement of*** $\nu_\mu$ ***interactions***

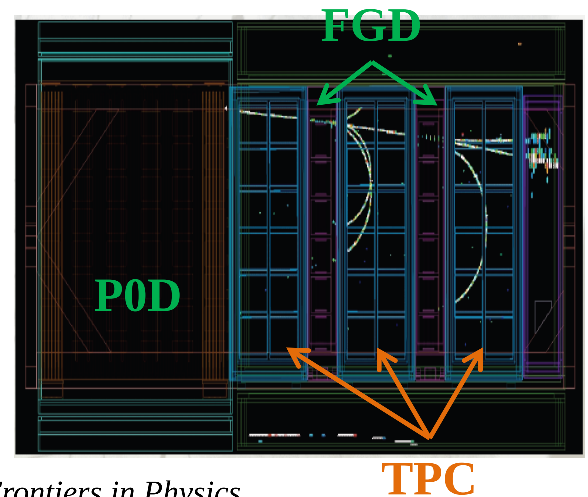
- $\nu_\mu$ *induced* $\pi^0$ *production*
  →*bkg to* $\nu_e$ *appearance*

# *Near Detector ND280 (Off-Axis)*

- **ND280 @ 2.5 degree off-axis**
- **ND280 consists of:**
  - Dipole magnet with 0.2T field
  - **F**ine **G**rain **D**etectors FGD's (×2):
    ***2.2 tons scintillator bars active ν target***
  - **T**ime **P**rojection **C**hambers TPC's (×3):
    ***<10% dE/dx resolution***
    ***<10% δp/p @ 1 GeV/c***
  - P0D: $\pi^0$ Detector
  - ECAL (**E**lectromagnetic **CAL**orimeters)
  - SMRD (**S**ide **M**uon **R**ange **D**etector)



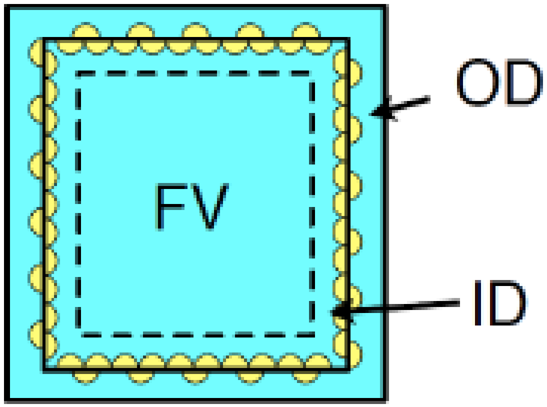

***Example of ND280 ν event***

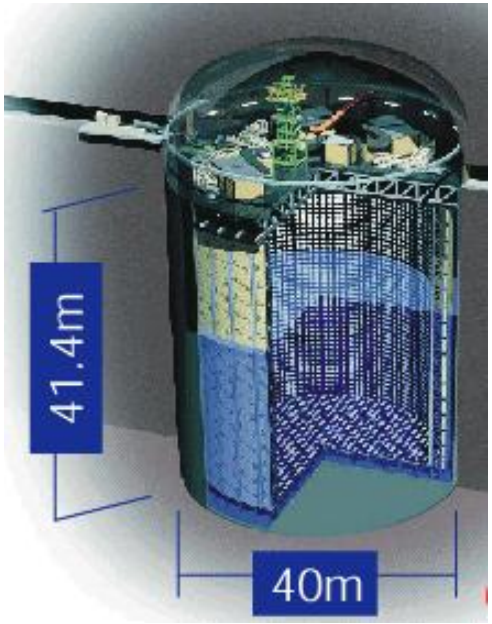


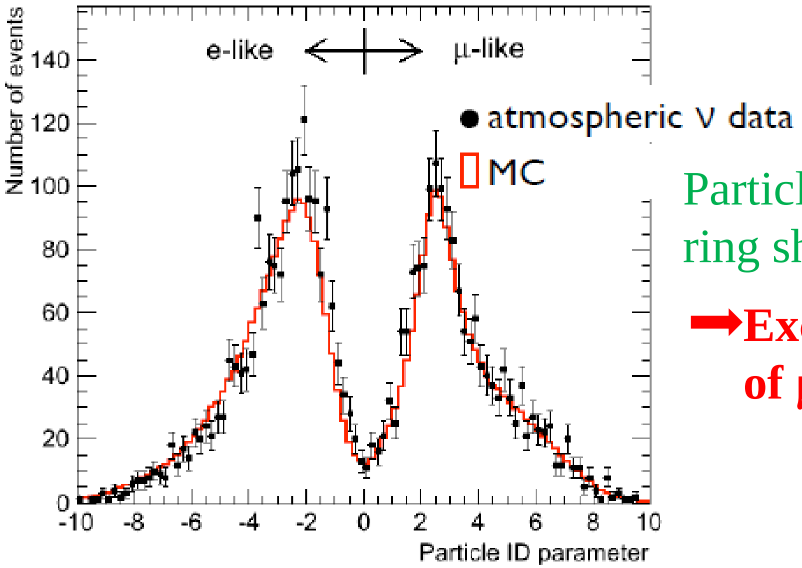
# Super Kamiokande as T2K Far Detector

**Super Kamiokande (SK)**

- **Water Cherenkov detector**
  - Total Mass: 50 kton
    - **Fiducial Volume: 22.5 kton**
  - Inner Detector(ID): ~11k PMTs facing inward
  - Outer Detector(OD): ~2k PMTs facing outward (OD)
    - veto for cosmic and background



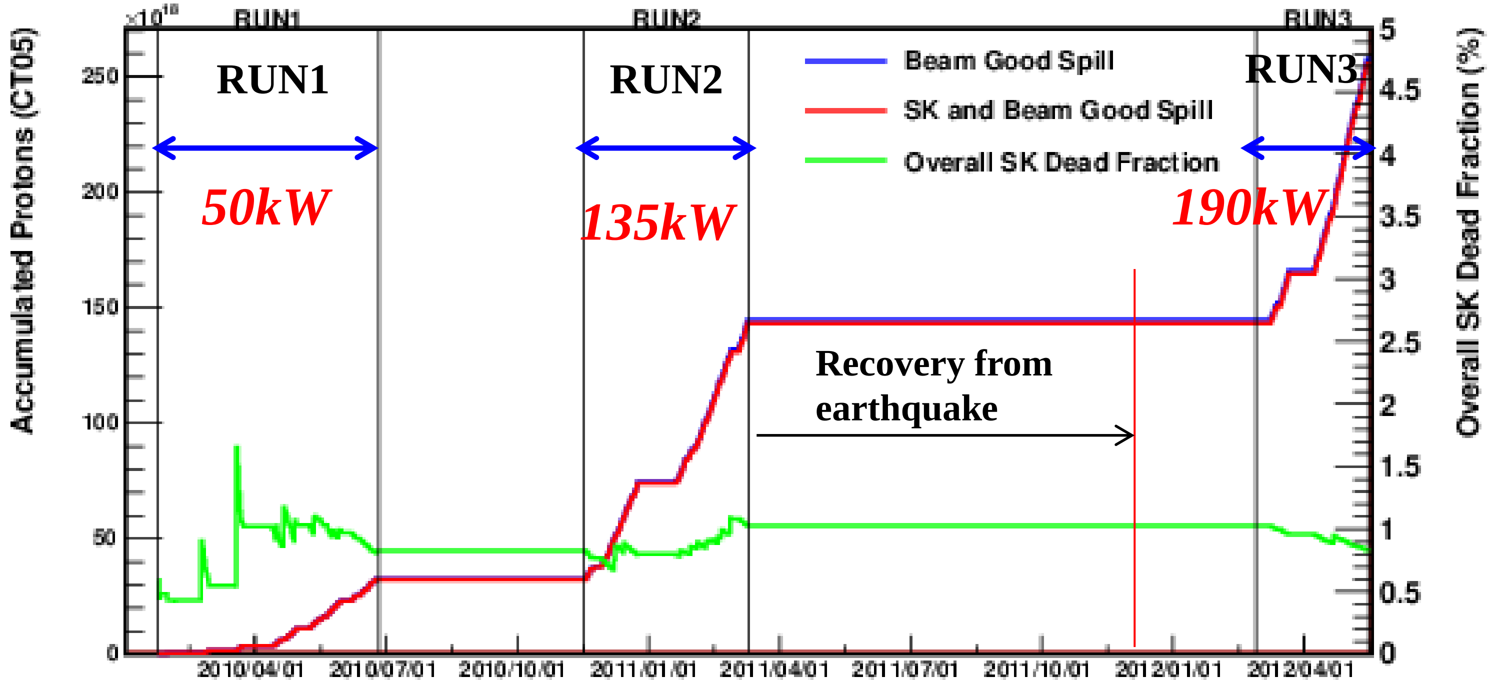

Particle ID using
ring shape & opening angle

➡**Excellent identification of μ/e: ~99% efficiency.**

# *Status of Experiment*

# *Data Collected and Analyzed*

- **Beam Power increased up to 190kW w/ 1×10$^{14}$ protons per pulse (world record)**
- **Analyzed data: up to May 15th, 2012: 2.56×10$^{20}$ POT (Protons On Target)**
  - RUN1 (2010): 0.32×10$^{20}$ POT
  - RUN2 (2010-2011): 1.11×10$^{20}$ POT
    - ND280 RUN 1+2 data used for oscillation analysis
  - **RUN 3 (2012): 1.14×10$^{20}$ POT**
    - including 0.21×10$^{20}$ POT with 200kA horn operation (13% flux reduction at peak)
    - ND280 RUN 3 data for checking the RUN 1+2 measurement

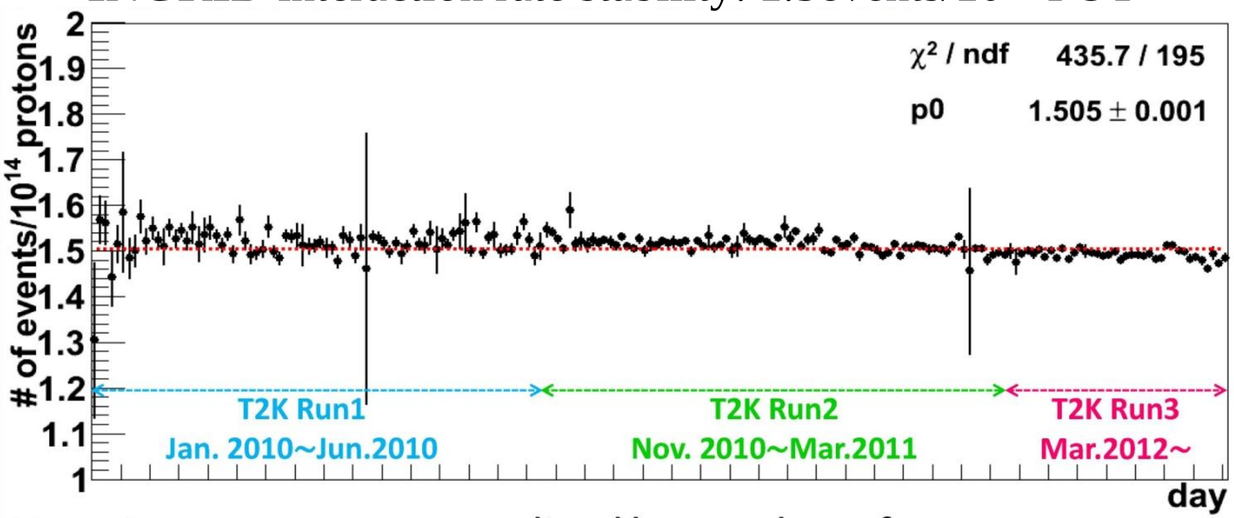


# *Neutrino Beam Quality*

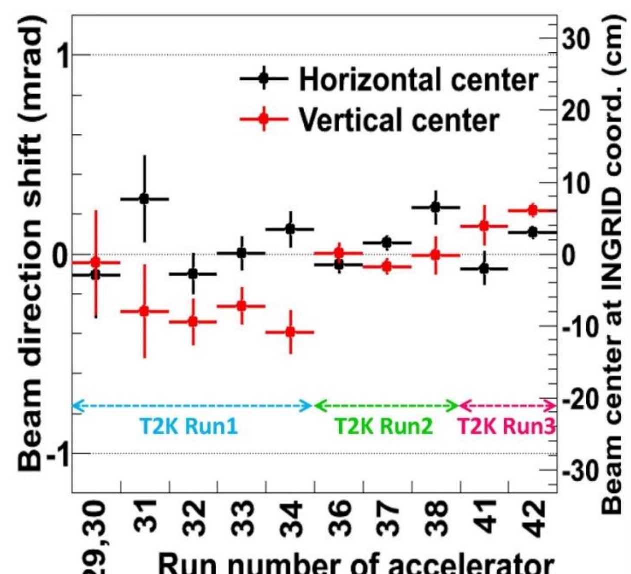
**Muon Monitor**: Beam center (X, Y) and direction stability (<1mrad)

1 mrad shift of the beam direction = 2% shift of the $E_\nu$ peak at SK


**INGRID** interaction rate stability: 1.5events/$10^{14}$ POT




**INGRID**: beam direction



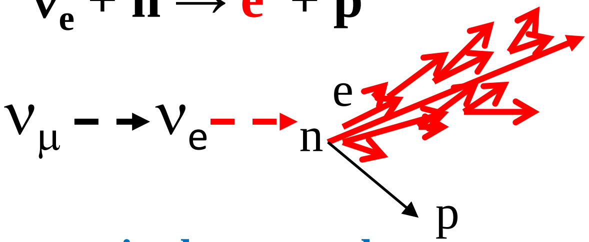
# *Analysis Results*

# *Signal and Background for T2K $\nu_e$ Appearance Search*

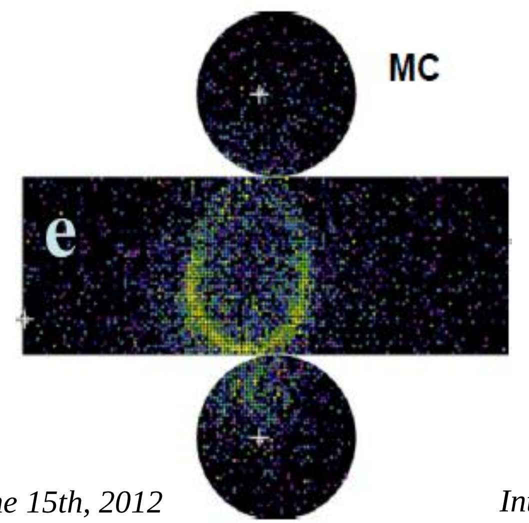
## SIGNALS

***Charged current quasi-elastic scattering* (CCQE)**

$$\nu_e + n \rightarrow e^- + p$$




- **Electromagnetic shower and multiple scattering**
  **→Ring has fuzzy edge**
- **Electron is relativistic**
  **→ Opening angle is maximal**



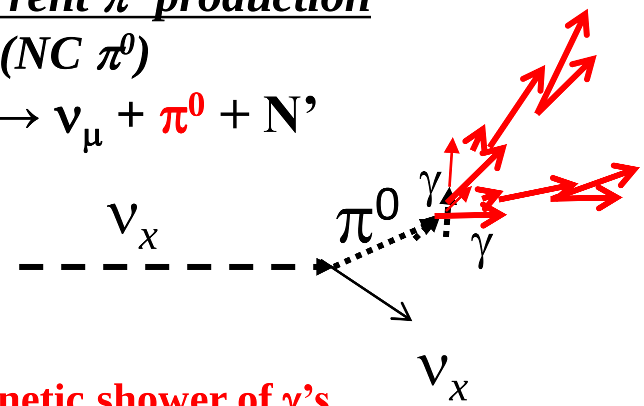

## BACKGROUND

***Intrinsic $\nu_e$ contamination in the beam (<1%)***

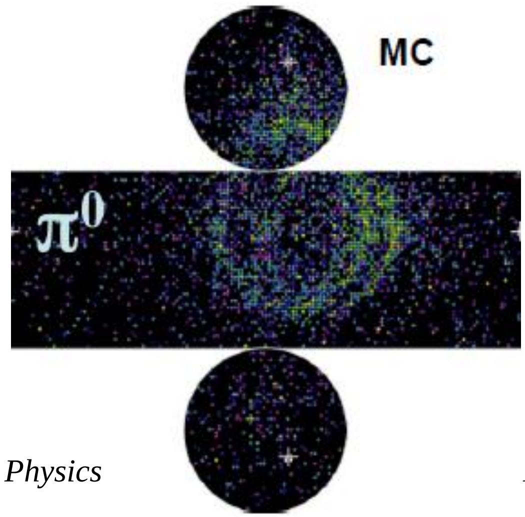
→wider energy dist.

***Neutral current $\pi^0$ production* (NC $\pi^0$)**

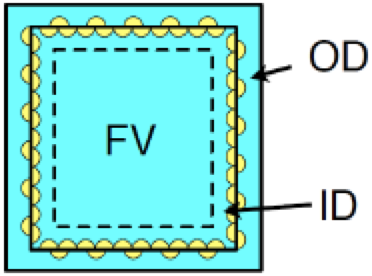
$$\nu_\mu + N \rightarrow \nu_\mu + \pi^0 + N'$$




**Electromagnetic shower of $\gamma$'s from $\pi^0$ can fake an electron**



# T2K Event Selection



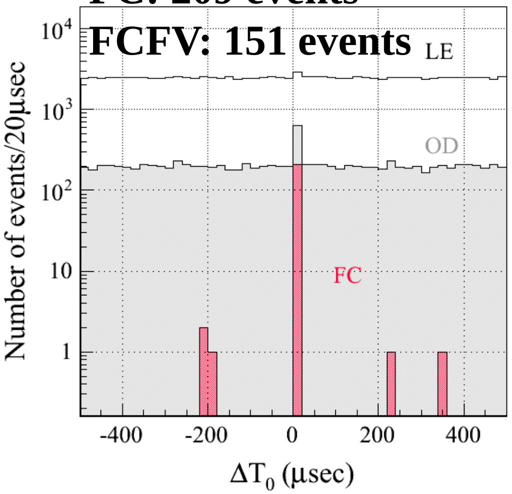

**Selection Criteria**

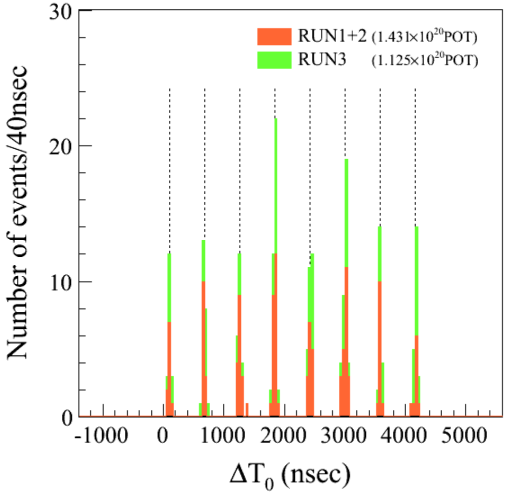
(*determined before data analysis*):

1. **T2K beam timing**
2. **Fully contained (FC) event,**
3. **Vertex is in Fiducial Volume (FV)**
4. **A single e-like Cherenkov ring**
5. **Visible energy > 100 MeV**
6. No decay electrons
7. $\pi^0$ mass cut, $M_{inv} < 105$ MeV/$c^2$
8. Reconstructed $E_\nu < 1250$ MeV

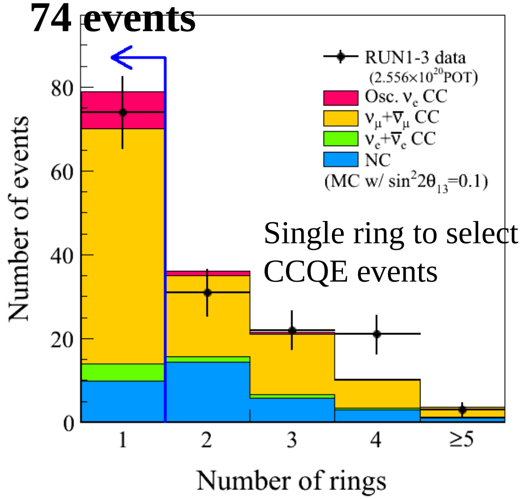
**FC: 209 events**

**FCFV: 151 events**



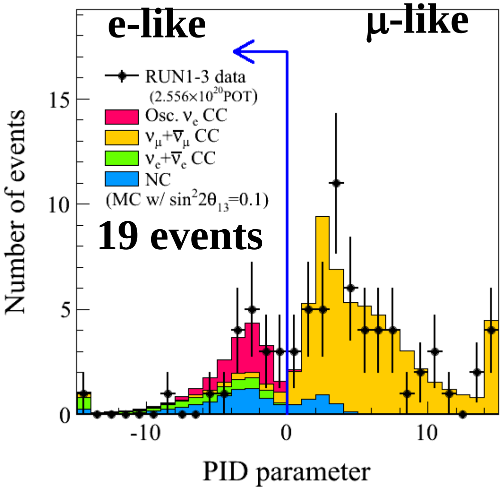




**74 events**

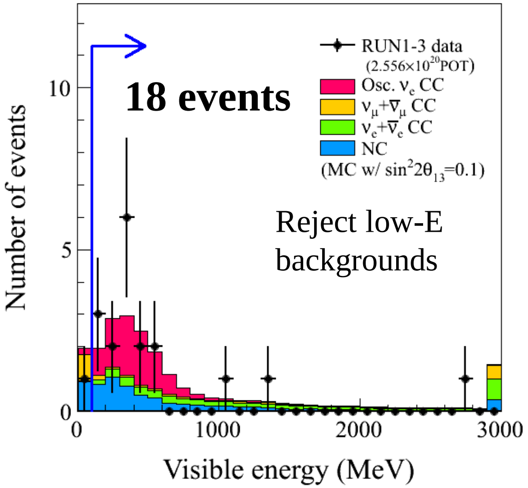



**e-like** **μ-like**

**19 events**




**18 events**



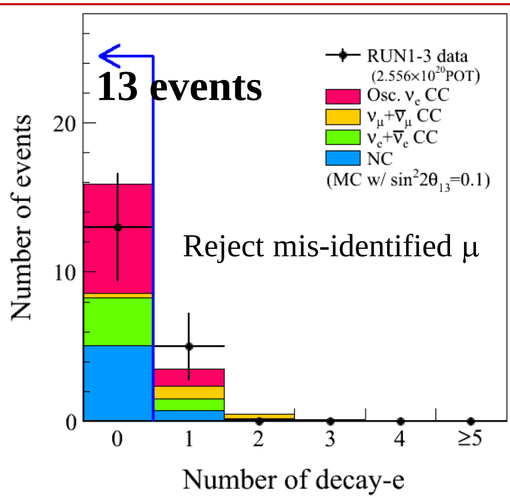
# Further $\nu_e$ Selection

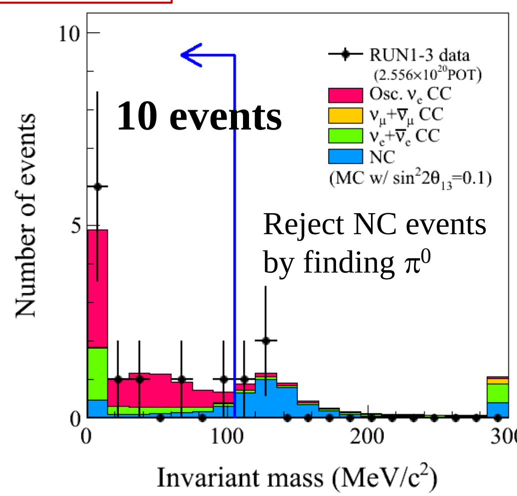
**Selection Criteria**

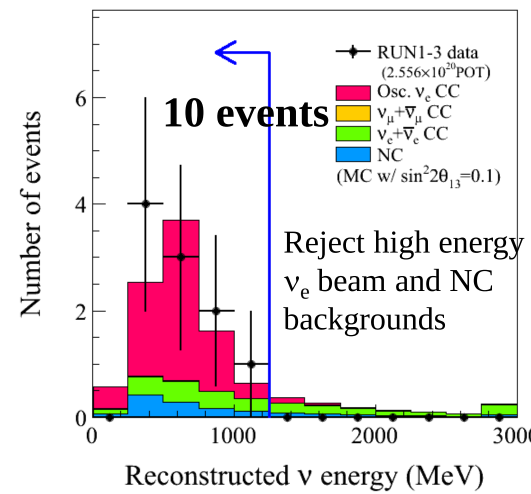
(*determined before data analysis*):

1. T2K beam timing
2. Fully contained (FC) event,
3. Vertex is in Fiducial Volume (FV)
4. A single e-like Cherenkov ring
5. Visible energy > 100 MeV
6. **No decay electrons**
7. **$\pi^0$ mass cut, $M_{inv}$ < 105 MeV/$c^2$**
8. **Reconstructed $E_\nu$ < 1250 MeV**

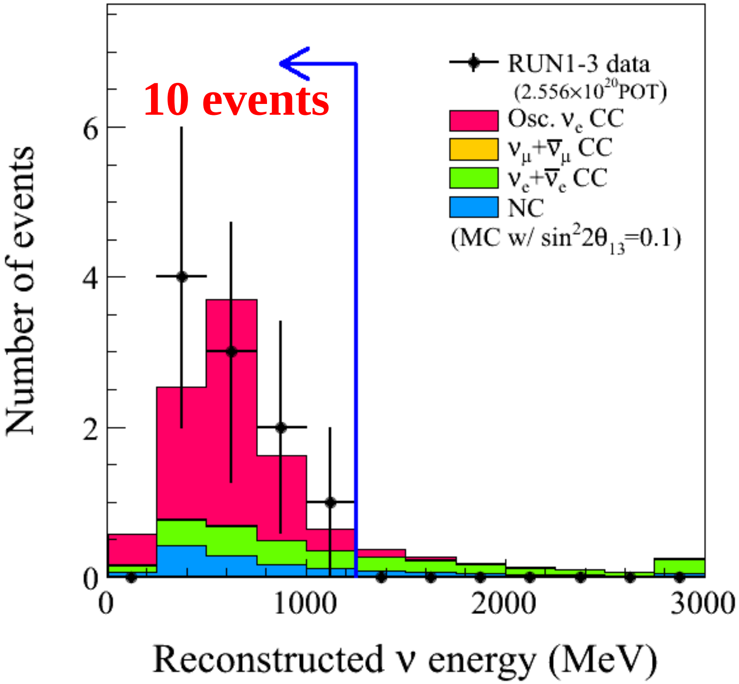
| Run 1+2+3 $2.56\times10^{20}$ POT | Data | MC Expectation w/ $\sin^2 2\theta_{13}$=0.1 | | | | |
|---|---|---|---|---|---|---|
| | | Signal $\nu_\mu\to\nu_e$ | BG total | $\nu_\mu+\bar{\nu}_\mu$ CC | $\nu_e+\bar{\nu}_e$ CC | NC |
| e-like | 19 | 8.70 | 13.23 | 2.30 | 4.07 | 6.86 |
| $E_{vis}$>100MeV | 18 | 8.50 | 11.47 | 1.49 | 4.03 | 5.94 |
| No decay-e | 13 | 7.31 | 8.56 | 0.28 | 3.19 | 5.09 |
| $\pi^0$ mass cut | 10 | 6.82 | 3.67 | 0.07 | 2.21 | 1.39 |
| $E_\nu^{rec}$<1250MeV (MC $\sin^2 2\theta_{13}$=0 case) | 10 | 6.61 (0.15) | 2.47 (2.58) | 0.05 (0.05) | 1.36 (1.47) | 1.06 (1.06) |
| Efficiency [%] | | 60.7 | 1.0 | 0.0 | 20.0 | 0.9 |

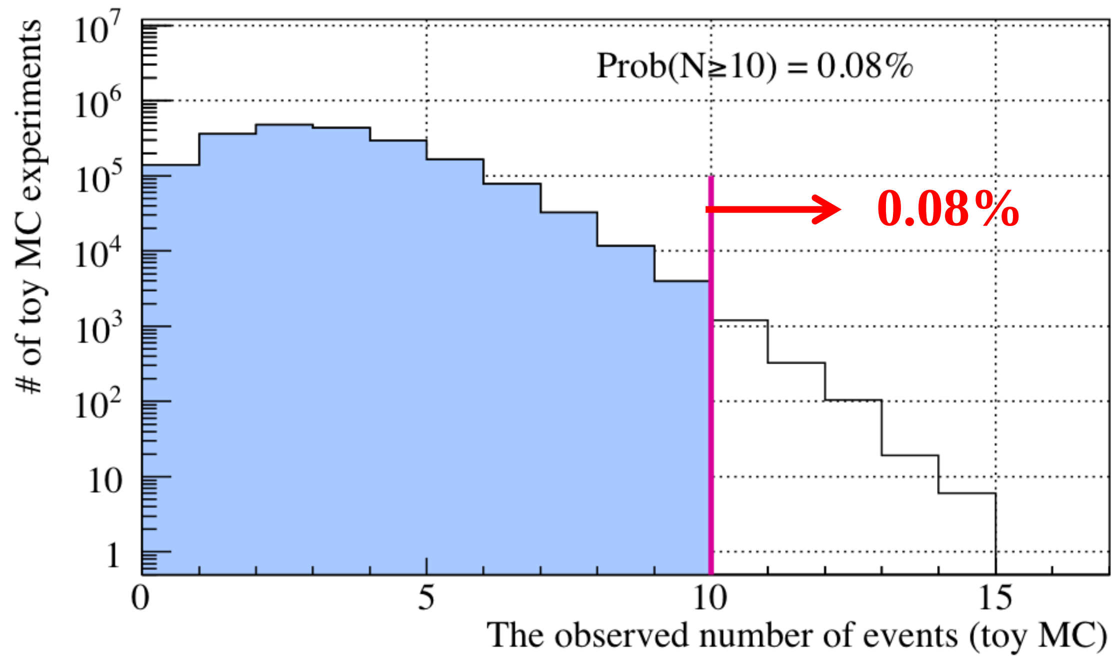


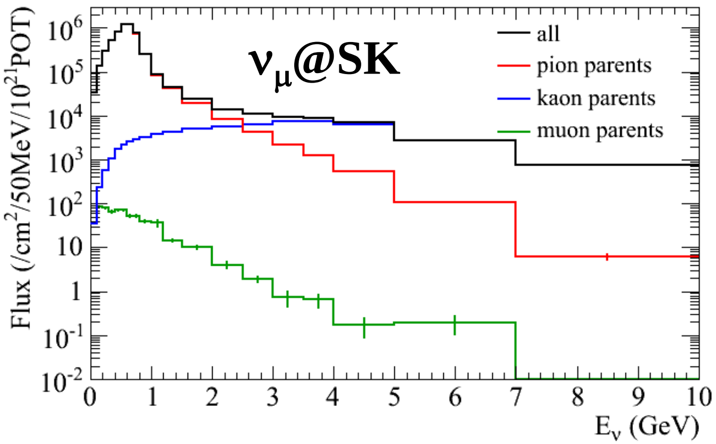
# *Evidence of $\nu_e$ Appearance*



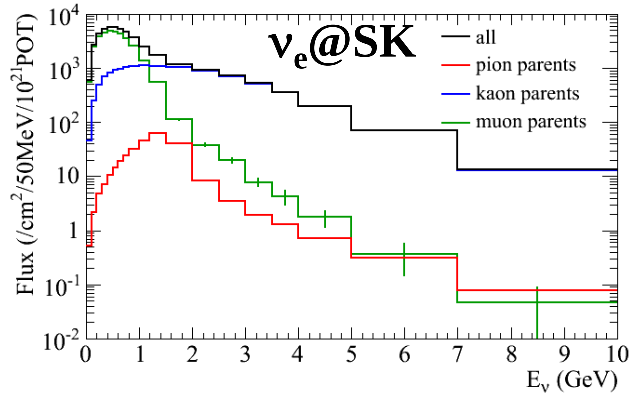




- **10 $\nu_e$ candidates found!**
- **Probability (p-value) to observe 10 or more events with 2.73±0.37(sys.) BG events is 0.08% (3.2 σ)**
  - *Confirm the T2K 2011 results [PRL 107, 041801 (2011)] !!*
  - **We find the Evidence of "Electron Neutrino Appearance".**

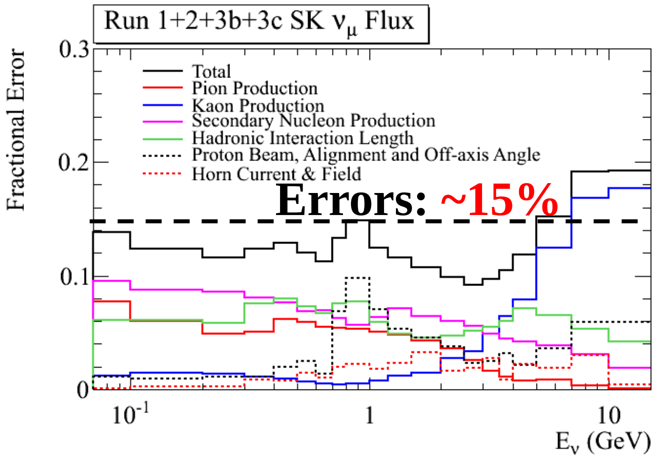
# *Neutrino Flux Prediction w/ CERN NA61*

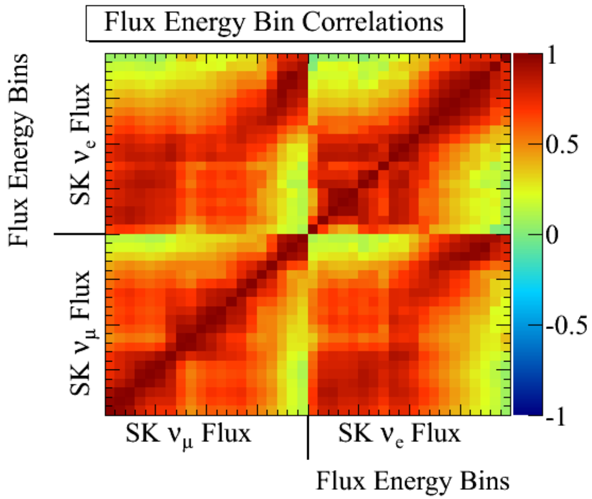


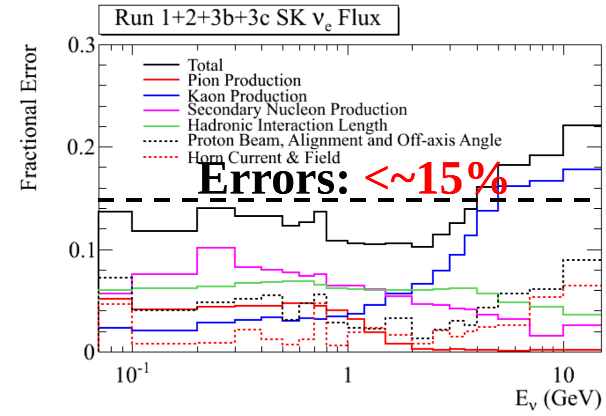

**$\nu_\mu$, $\nu_e$, anti-$\nu_\mu$, anti-$\nu_e$ energy dependent errors with full correlations @SK and @ND280 are taken in the FIT!**




**$\nu_\mu$ and $\nu_e$ Flux Energy Correlations**



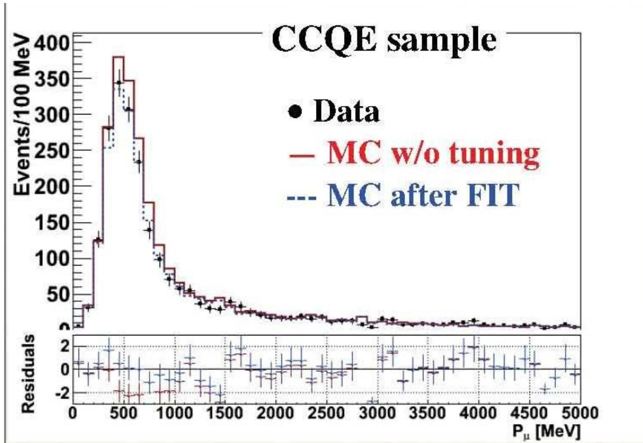



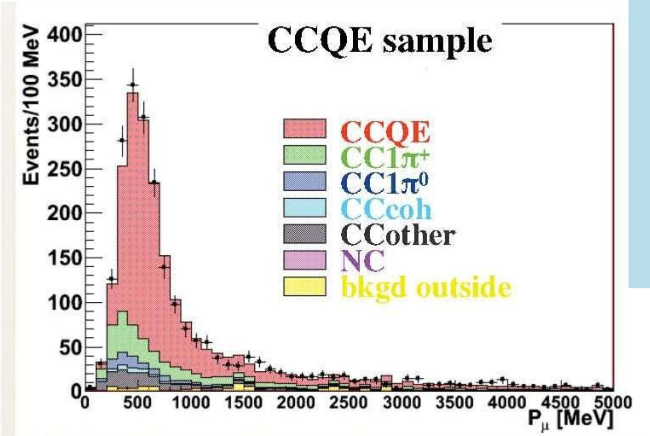




**Errors: 10~15%**

# *ND280 $\nu_\mu$ Measurement (RUN1+2 Data)*

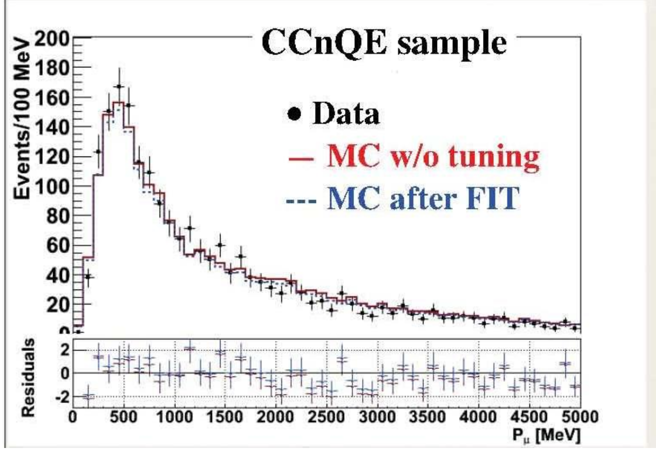
**# of Events in $P_\mu$ vs. $\theta_\mu$ are used in FIT to constrain the flux and $\nu$ cross sections (MC predictions at ND280 and SK)**

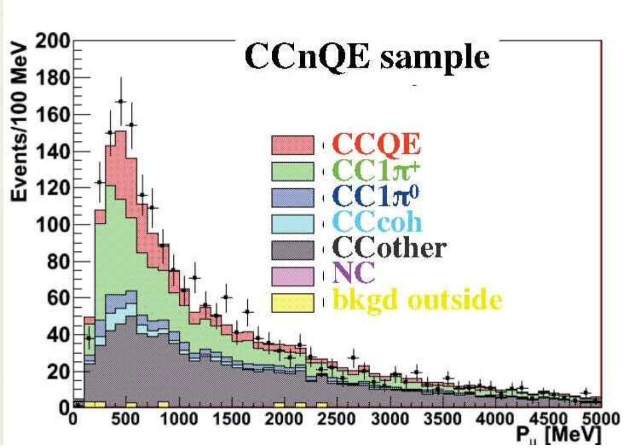


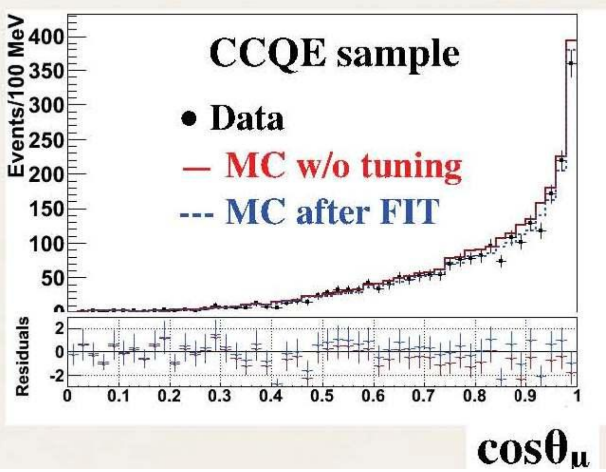




- Good negative track in FV
- Upstream TPC veto
- muon ID by TPC for CCQE
  - **1 FGD-TPC track**
  - **No decay-e FGD**

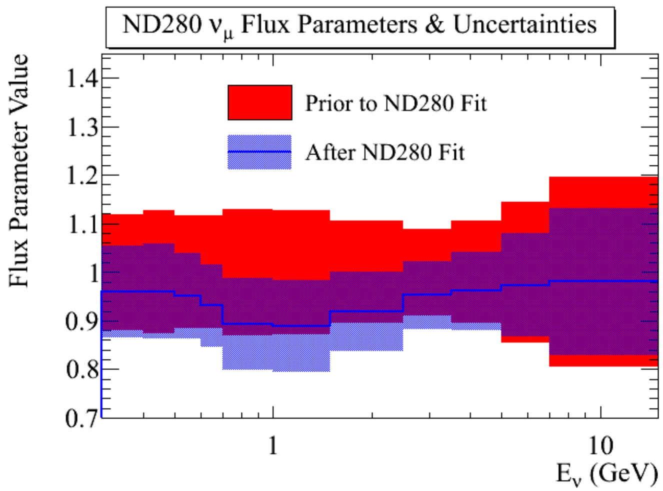
For CCQE selection
40% eff. w/ 72% purity.

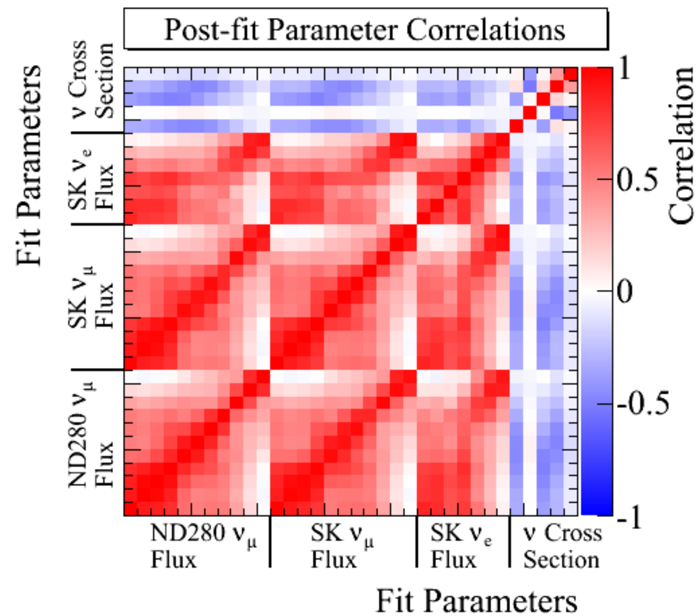


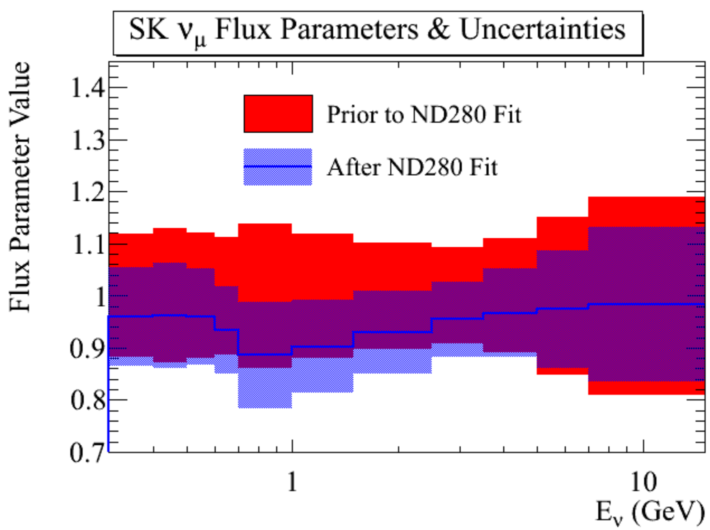



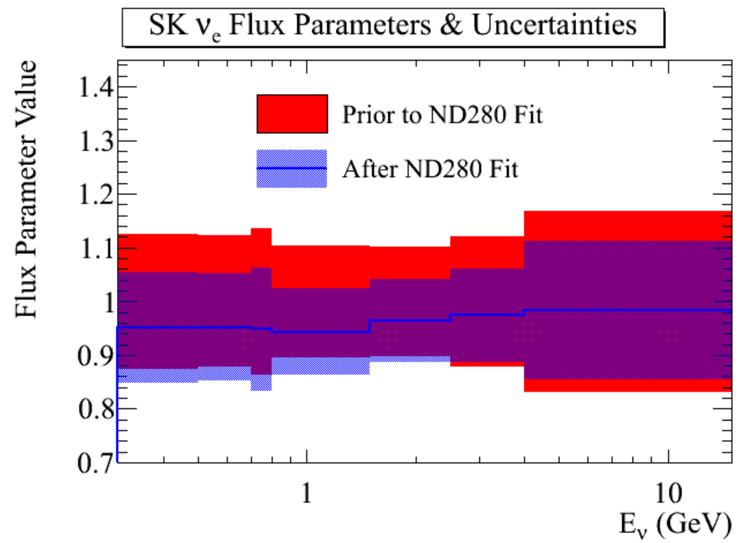



# *Flux + Cross Section FIT output*



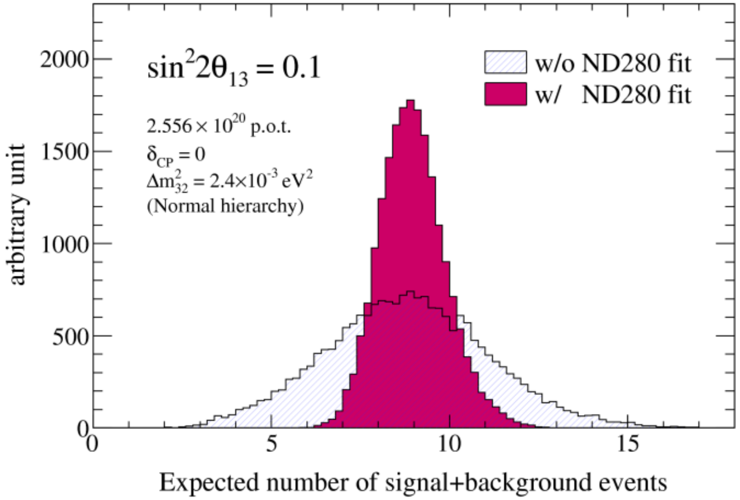



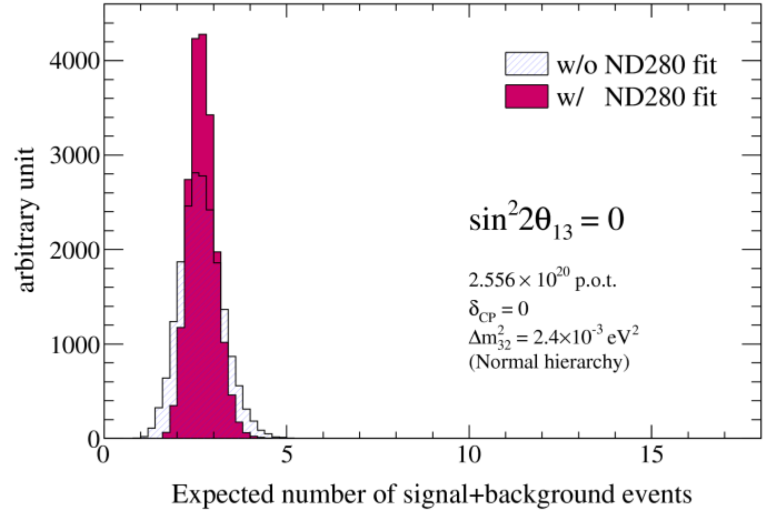



# # of Events Predictions at T2K w/ Sys. Error

(Note: 10 $\nu_e$ Candidates observed)




## # of Events prediction

| | $\sin^2 2\theta_{13} = 0.1$ | $\sin^2 2\theta_{13} = 0$ |
|---|---|---|
| **Total** | **9.07±0.93** | **2.73±0.37** |
| $\nu_e$ signal | 6.60 | 0.15 |
| $\nu_e$ bkg. (beam org.) | 1.32 | 1.42 |
| $\nu_\mu$ bkg. (~NC$\pi^0$) | 1.02 | 1.02 |
| anti-$\nu$ bkg. | 0.13 | 0.14 |

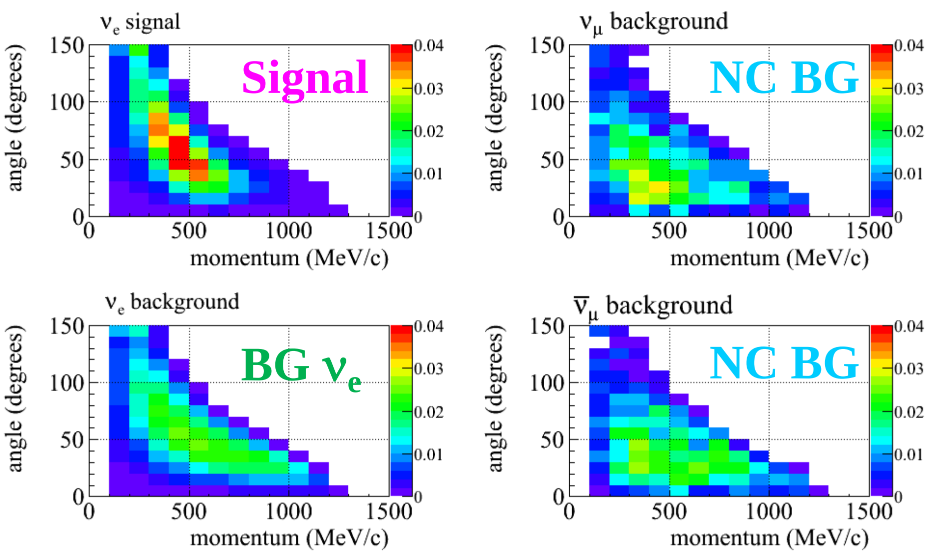
## Systematic Errors

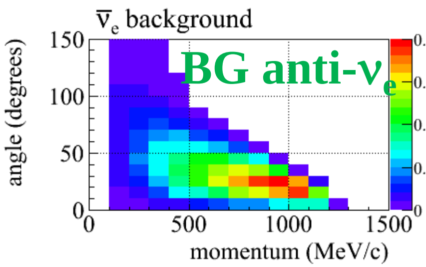
| Error Source | $\sin^2 2\theta_{13} = 0.1$ | $\sin^2 2\theta_{13} = 0$ |
|---|---|---|
| ND fit | 5.7% | 8.7% |
| Cross section (from other exp.) | 7.5% | 5.9% |
| SK + FSI | 3.9% | 7.7% |
| **Total** | **10.3%** | **13.4%** |
| Error (2011 result) | ~18% | ~23% |

# Oscillation Analysis FIT (3 methods)

- **Method-1: Maximum Likelihood Fit w/ Rate + ($p_e$, $\theta_e$)**
- **Method-2: Maximum Likelihood Fit w/ Rate + reconstructed $E_\nu$**
- **Method-3: Feldman&Cousins for Rate only (used in previous analysis)**

## Method-1

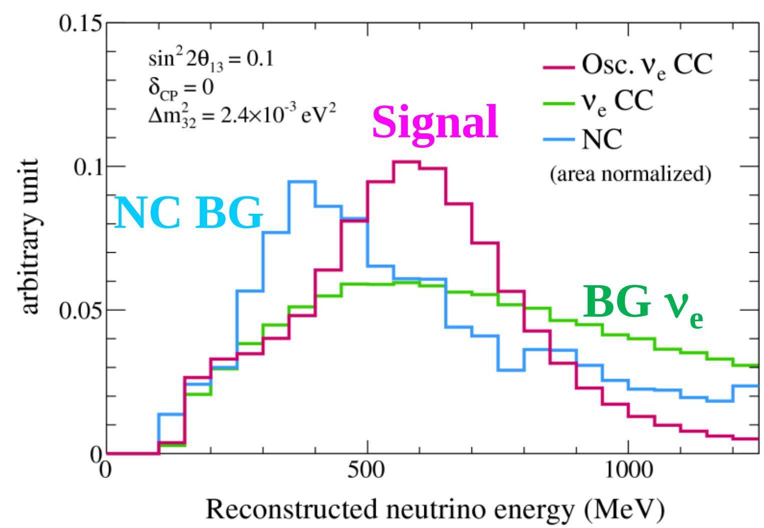



**Data is fit to signal + 4 BG 2-D curves**

$$E^{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e \cos\theta_e)}$$

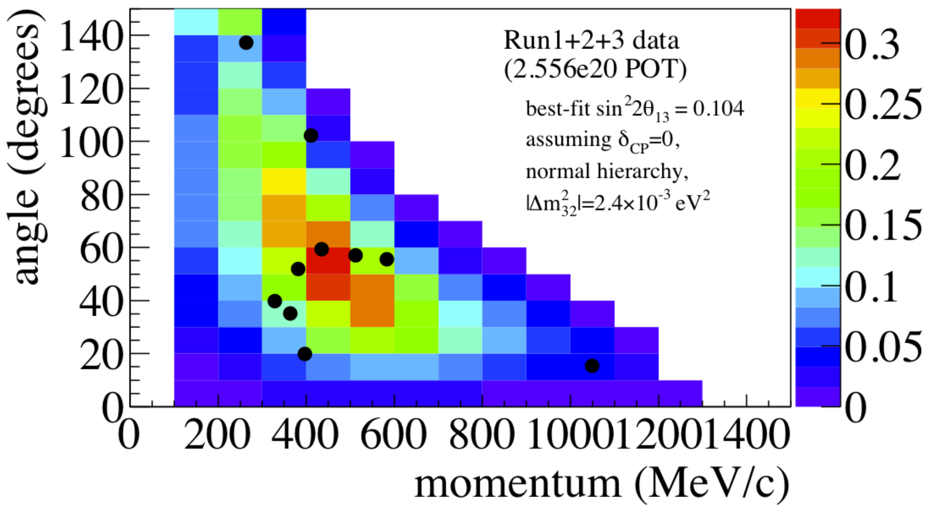
## Method-2

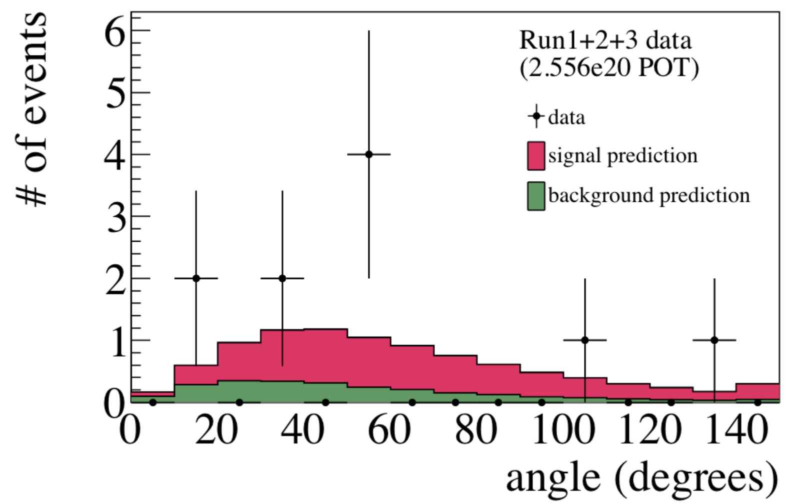


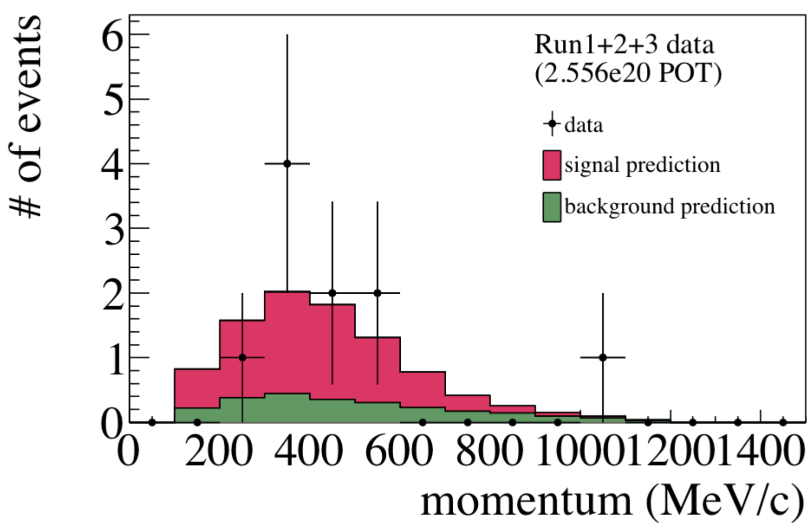

**Data is fit to signal + 2 BG 1-D curves**

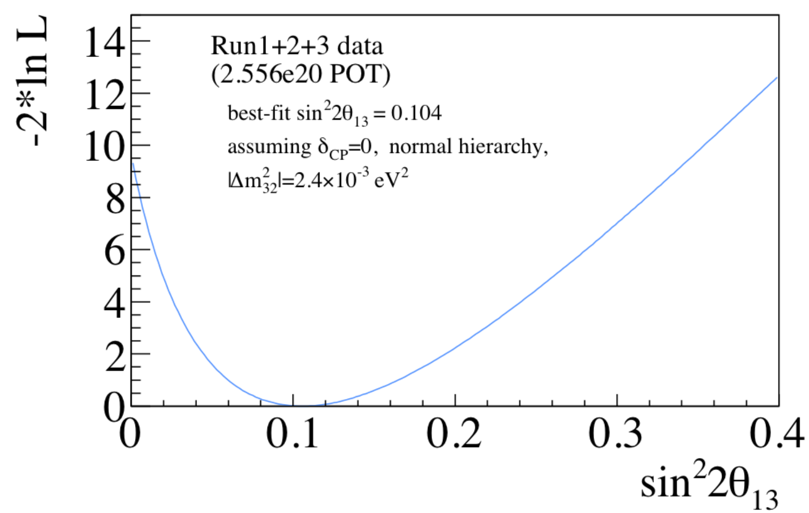
# *Method-1: Rate + ($p_e$, $\theta_e$)*

**Best fit: $\sin^2 2\theta_{13} = 0.104^{+0.060}_{-0.045}$**



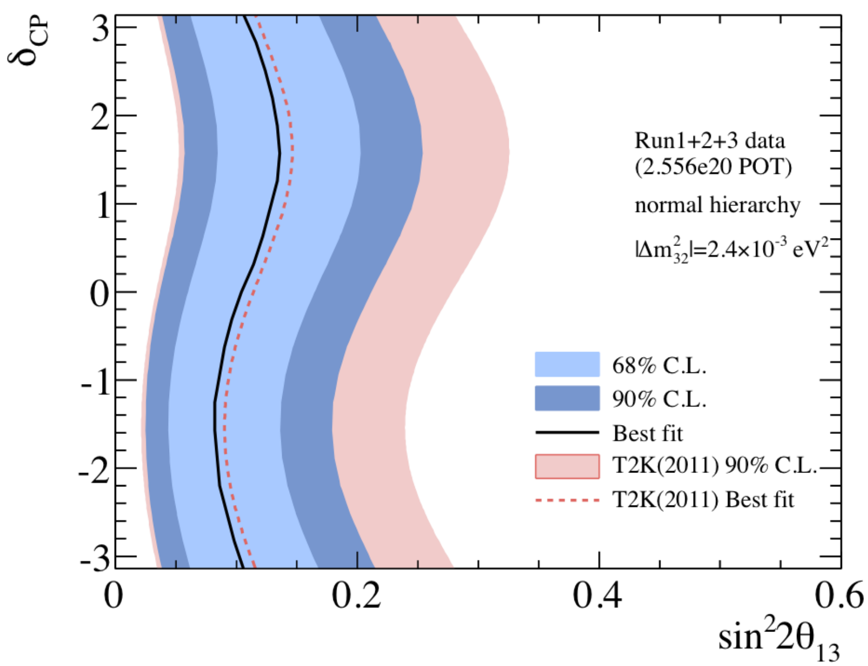



# *Method-1: Rate + ($p_e$, $\theta_e$)*

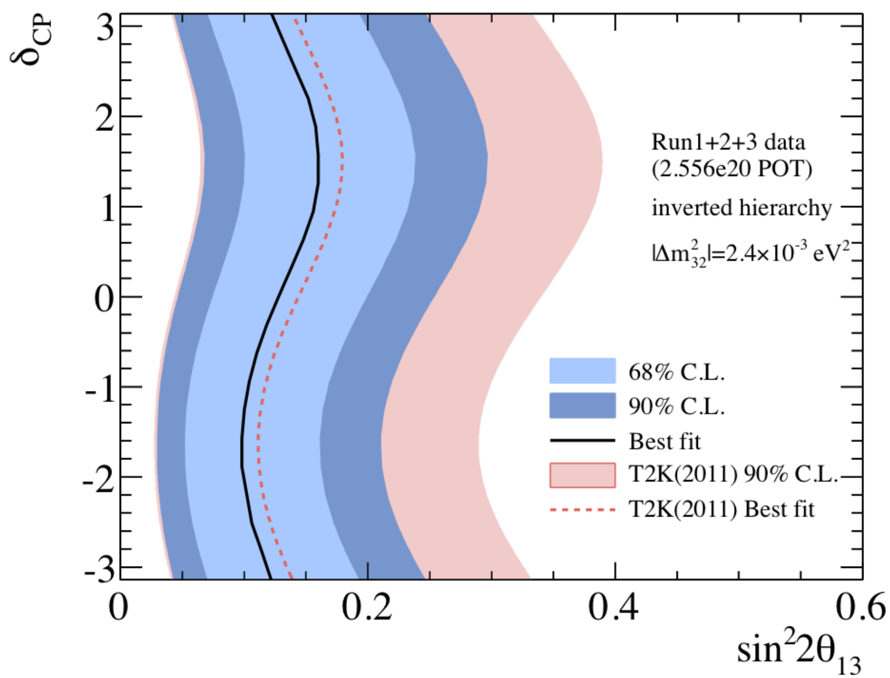
**90% CL: $0.036 < \sin^2 2\theta_{13} < 0.211$ for Normal Hierarchy ($\Delta m^2_{23} > 0$)**

**90% CL: $0.045 < \sin^2 2\theta_{13} < 0.253$ for Inverted Hierarchy ($\Delta m^2_{23} < 0$)**

**Normal Hierarchy**




**Inverted Hierarchy**



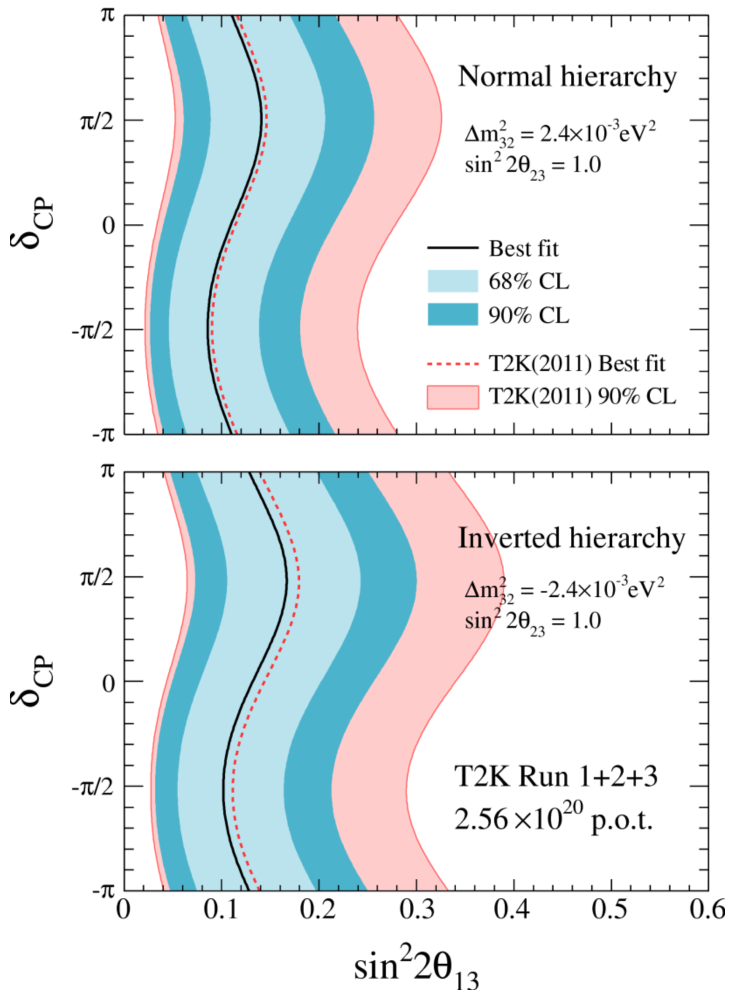

$$\sin^2 2\theta_{13} = 0.104^{+0.060}_{-0.045}$$

**@ $\delta_{CP}$=0**

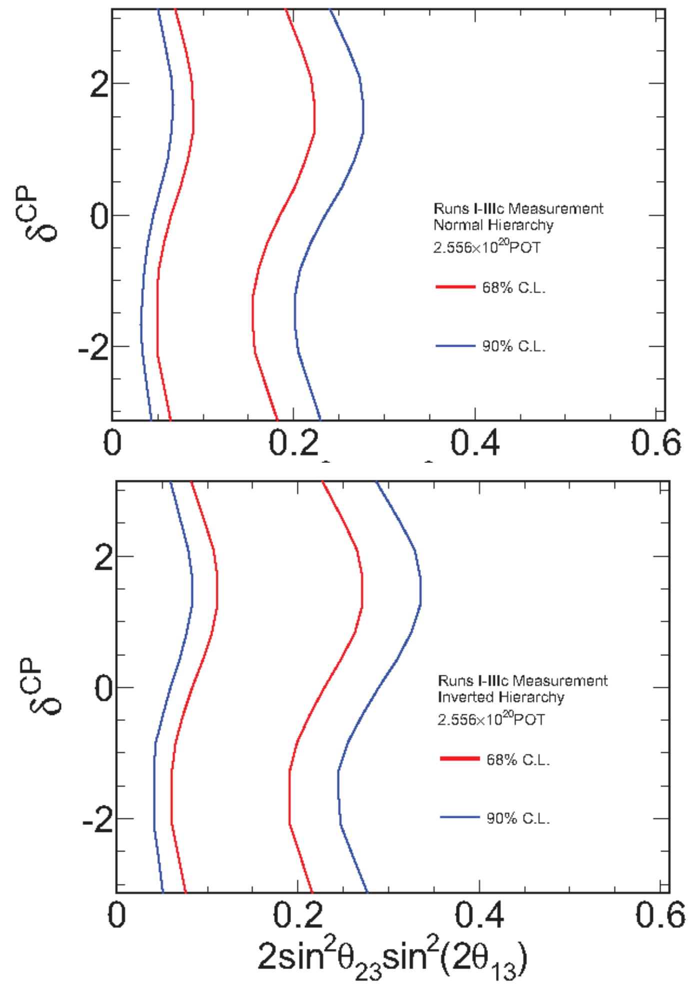
$$\sin^2 2\theta_{13} = 0.128^{+0.070}_{-0.055}$$

# *Method-2 and -3*

## Method-2: Rate + $E_\nu^{rec}$




## Method-3: Rate only




*All three results are consistent.*

# *Future Prospect*

# *Future Prospect*

- Results with all data collected by June 2012 is expected soon.
- Updated $\nu_\mu$ disappearance result is coming soon for $\theta_{23}$ measurement.
  - The precision of $\theta_{23}$ with the reactor $\theta_{13}$ value is also important to explore the sub-leading term.
- Precise measurement of $P(\nu_\mu \rightarrow \nu_e)$ is important to search for the sub-leading effects [ CP violation, matter effect, new physics, etc] in $\nu_e$ appearance.
- The data will increase in each new run with higher beam power.
  - **~$8 \times 10^{20}$ POT (2013)→~$1.2 \times 10^{21}$ POT (2014)→~$1.8 \times 10^{21}$ POT (2015)**

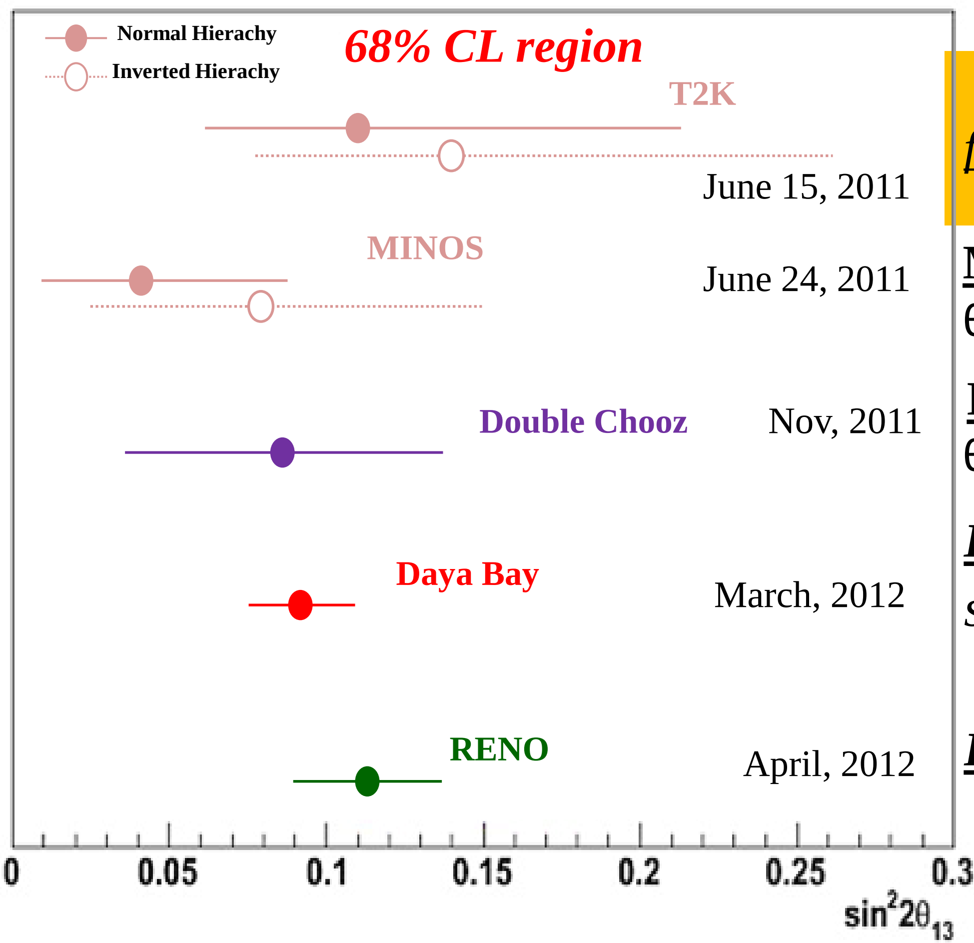
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(1.27\Delta m^2_{23}L/E) + \text{CPV} + \text{matter effect} + \ldots$$

# *Summary*

- ***Updated $\nu_e$ appearance results with 2.56 ×$10^{20}$ POT***
  - **Systematic uncertainties reduced from the previous analysis: 23%→13%.**
  - **10 $\nu_e$ candidates observed.**
  - **2.73±0.73 events with $\sin^2 2\theta_{13}$=0 assumption**
  - Probability to observe 10 or more events = **0.08% (3.2 $\sigma$)**
  - **Evidence of $\nu_e$ appearance!!**
- ***$\theta_{13}$ measurement***
  - **$\sin^2 2\theta_{13} = 0.104^{+0.060}_{-0.045}$ (normal hierarchy, $\delta_{CP}$=0)**
  - **$\sin^2 2\theta_{13} = 0.128^{+0.070}_{-0.055}$ (inverted hierarchy, $\delta_{CP}$=0)**
- ***Results with all the collected data by June 2012 will be coming soon.***
  - $\nu_e$ appearance
  - $\nu_\mu$ disappearance

# *Backup Slides*

# Neutrino Oscillations as of 2012 May




**T2K** $\nu_\mu \to \nu_e$

*first indication of* $\theta_{13} \neq 0$ with 2.5 σ significance

**MINOS** $\nu_\mu \to \nu_e$

$\theta_{13} = 0$ *disfavored @1.7 σ*

**Double Chooz** $\bar{\nu}_e \to \bar{\nu}_e$

$\theta_{13} \neq 0$ *@3σ combined with T2K and MINOS*

***Daya Bay*** $\bar{\nu}_e \to \bar{\nu}_e$

$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$

5.2σ significance

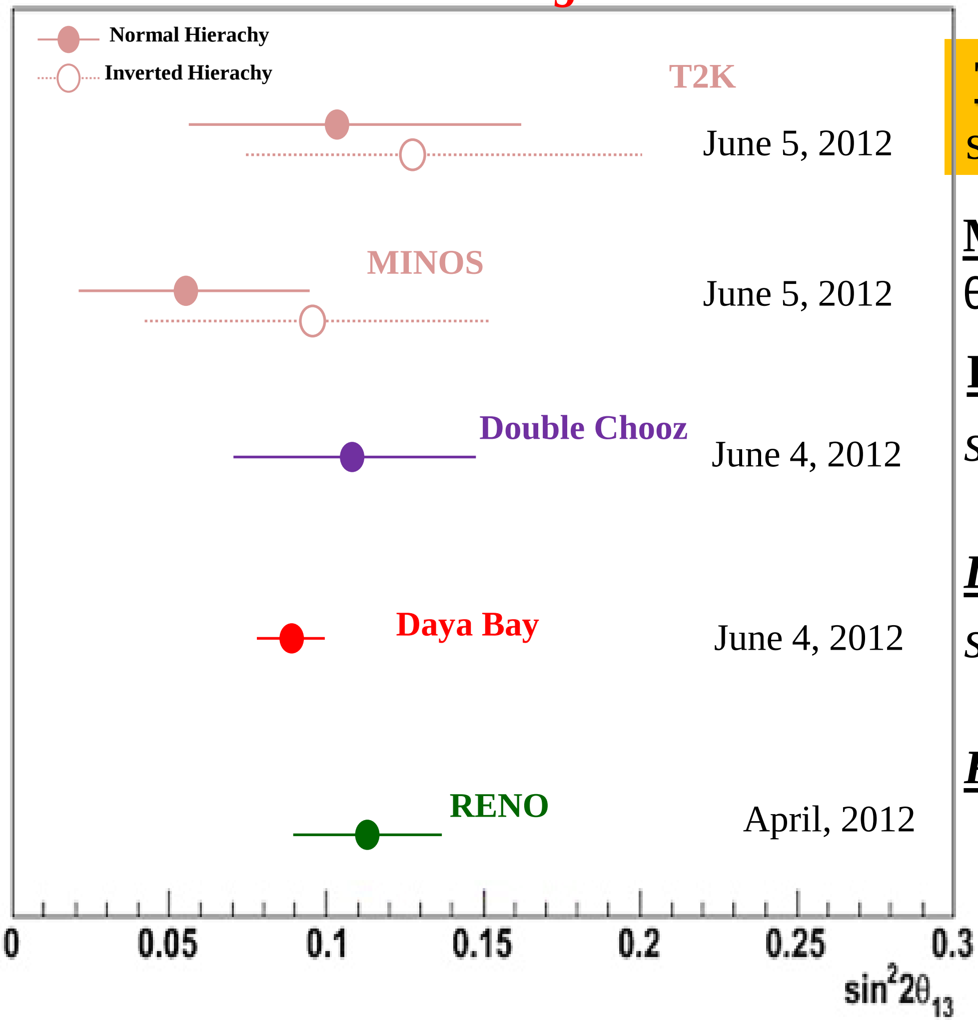
***RENO*** $\bar{\nu}_e \to \bar{\nu}_e$

$\sin^2 2\theta_{13} = 0.113 \pm 0.013(\text{stat}) \pm 0.019(\text{syst})$

4.9σ significance

# *Neutrino Oscillations as of 2012 June*

*68% CL region*




**T2K** $\nu_\mu \rightarrow \nu_e$

$\sin^2 2\theta_{13} = 0.104^{+0.060}_{-0.045}(NH),\ 0.128^{+0.070}_{-0.055}(IH)$

**MINOS** $\nu_\mu \rightarrow \nu_e$

$\theta_{13}=0$ *disfavored @96% CL*

**Double Chooz** $\bar{\nu}_e \rightarrow \bar{\nu}_e$

$\sin^2 2\theta_{13}=0.109 \pm 0.030(\text{stat}) \pm 0.025(\text{syst})$

***Daya Bay*** $\bar{\nu}_e \rightarrow \bar{\nu}_e$

$\sin^2 2\theta_{13}=0.089 \pm 0.010(\text{stat}) \pm 0.005(\text{syst})$

***RENO*** $\bar{\nu}_e \rightarrow \bar{\nu}_e$

$\sin^2 2\theta_{13}=0.113 \pm 0.013(\text{stat}) \pm 0.019(\text{syst})$

# $\nu_\mu \rightarrow \nu_e$ Oscillation Probability

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) = \; & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} && \text{Leading term} \\
& + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} && \text{CPC} \\
& - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} && \text{CPV} \\
& + 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} && \text{Solar} \\
& - 8C_{13}^2 S_{12}^2 S_{23}^2 \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} && \text{Matter} \\
& + 8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2} (1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31} && \text{Matter}
\end{aligned}
$$

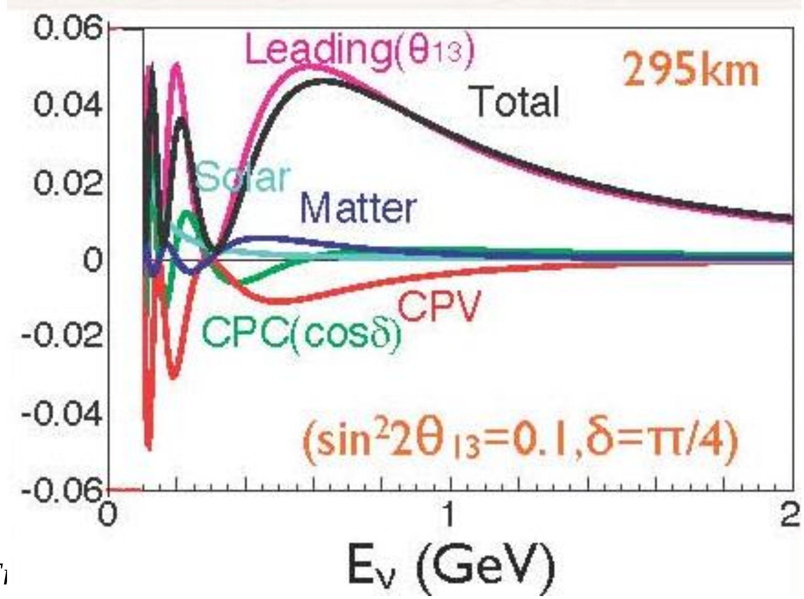
CP violating

Matter effect

For $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$, $\delta \rightarrow -\delta$, $a \rightarrow -a$

$$\frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \approx \frac{\Delta m_{12}^2 L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

***$\theta_{13} \neq 0$ is necessary for CP violation.***

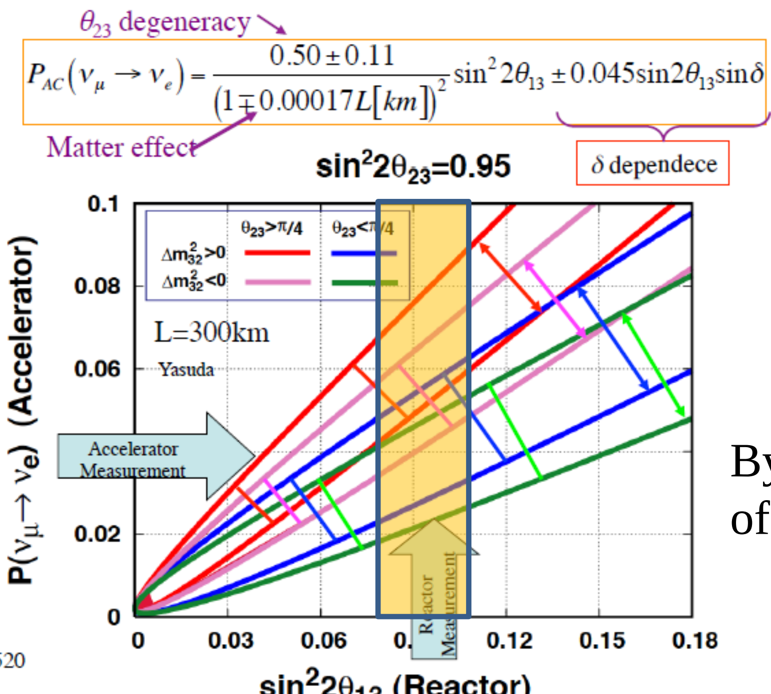


# *Future Neutrino Physics*

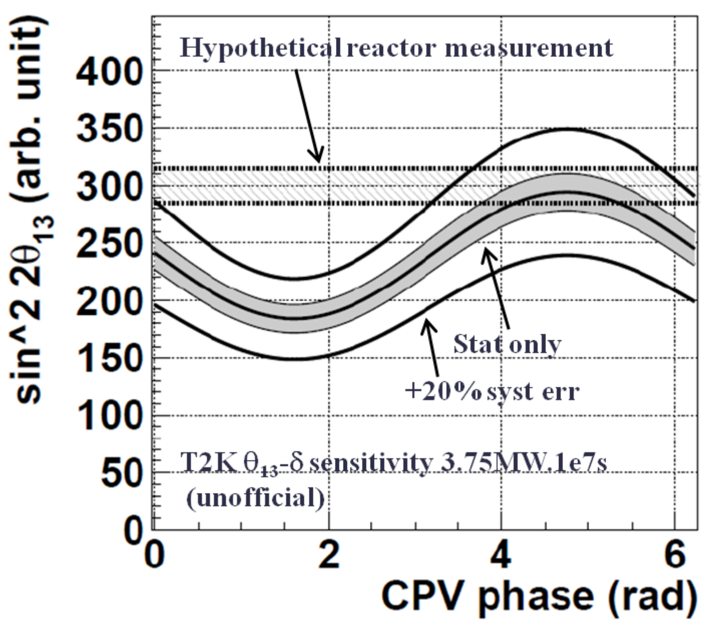
- **Search for CP violation & mass hierarchy**
  - $\theta_{13}$ from reactor measurement : higher precision
  - Precise measurement of $\nu_e$ appearance
  - **Comparison with reactor measurement**

***→ hint for CP phase δ & Mass Hierarchy***

**Complementarity of Reactor-accelerator $\theta_{13}$ measurement**




By courtesy of Suekane



# T2K Neutrino Event Category

| RUN1+2+3 $2.56\times10^{20}$ POT | Data | MC Expectation | | | Accidental (12μs window) |
|---|---|---|---|---|---|
| | | $\sin^2 2\theta_{13}$=0.1 | $\sin^2 2\theta_{13}$=0 | No Osc. | |
| FC | 209 | 213.6 | 199.7 | 429.6 | 0.034 |
| FCFV | 151 | 150.7 | 140.9 | 297.0 | 0.0042 |
| Single ring | 74 | 79.0 | 70.6 | 205.4 | - |
| μ-like ($p_\mu$>200MeV/c) | 55(54) | 57.0(56.7) | 57.0(56.7) | 185.7(184.6) | - |
| e-like ($p_e$>100MeV/c) | 19(18) | 21.9(20.0) | 13.6(11.8) | 19.7(13.6) | - |
| Multi ring | 77 | 71.8 | 70.3 | 91.5 | - |

***Observation is consistent with $\sin^2 2\theta_{13}$=0.1 case.***

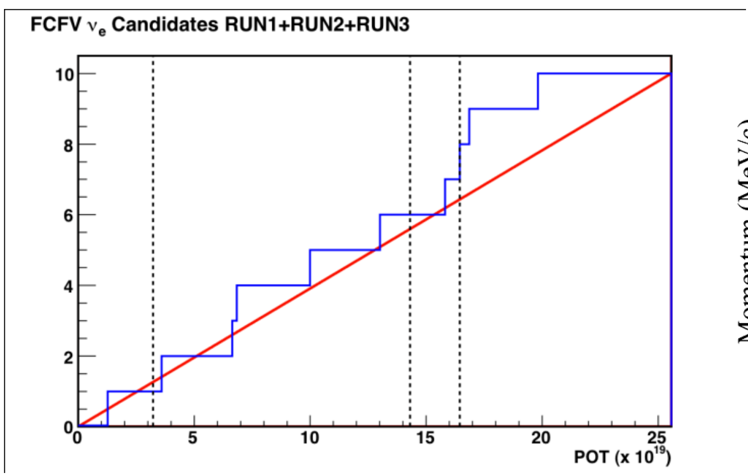
# MC Expectation for Signal and Background

| RUN1+2+3 $2.56 \times 10^{20}$POT | MC Expectation with $\sin^2 2\theta_{13}=0.1$ | | | | | Data |
|---|---|---|---|---|---|---|
| | $\nu_\mu+\bar{\nu}_\mu$ CC | $\nu_e+\bar{\nu}_e$ CC | NC | BG total | Signal | |
| True FV | 130.99 | 6.82 | 112.61 | 250.41 | 10.89 | - |
| FCFV | 99.43 | 6.51 | 34.31 | 140.26 | 10.46 | 151 |
| One-ring | 56.27 | 4.09 | 9.78 | 70.15 | 8.81 | 74 |
| e-like | 2.30 | 4.07 | 6.86 | 13.23 | 8.70 | 19 |
| $E_{vis}$>100MeV | 1.49 | 4.03 | 5.94 | 11.47 | 8.50 | 18 |
| No decay-e | 0.28 | 3.19 | 5.09 | 8.56 | 7.31 | 13 |
| $M_{inv}$<105MeV | 0.07 | 2.21 | 1.39 | 3.67 | 6.82 | 10 |
| $E_\nu^{rec}$<1250MeV | 0.05 | 1.36 | 1.06 | 2.47 | 6.61 | 10 |
| Efficiency [%] | 0.0 | 20.0 | 0.9 | 1.0 | 60.7 | - |

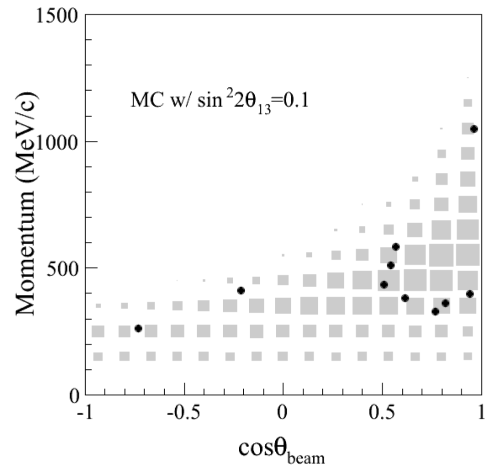
# $\nu_e$ Appearance Candidates

- **Check for candidate events**
  - Candidate event observation rate vs. POT
    - **Kolmogorov-Smirnov (KS) test →probability = 53.3%**
  - Momentum vs. angle between electron and incident ν for candidates
    →**consistent with signal.**
  - Timing difference from nearest bunch
    →**all candidates are inside bunch width.**

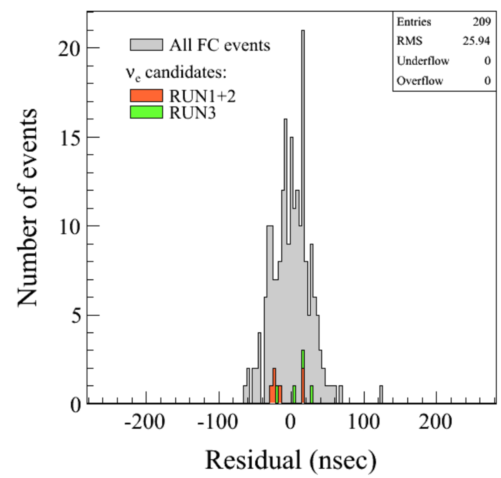
**Candidate event rate vs POT**




**angle vs. momentum**



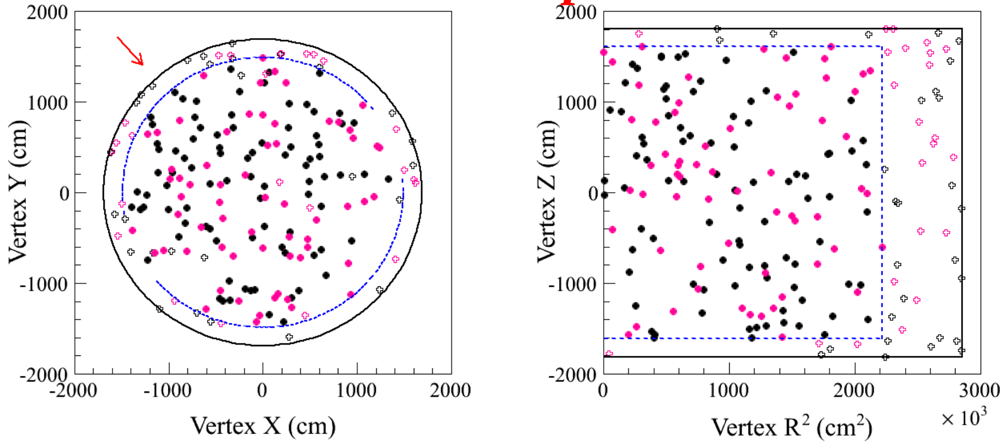

**Timing distribution**



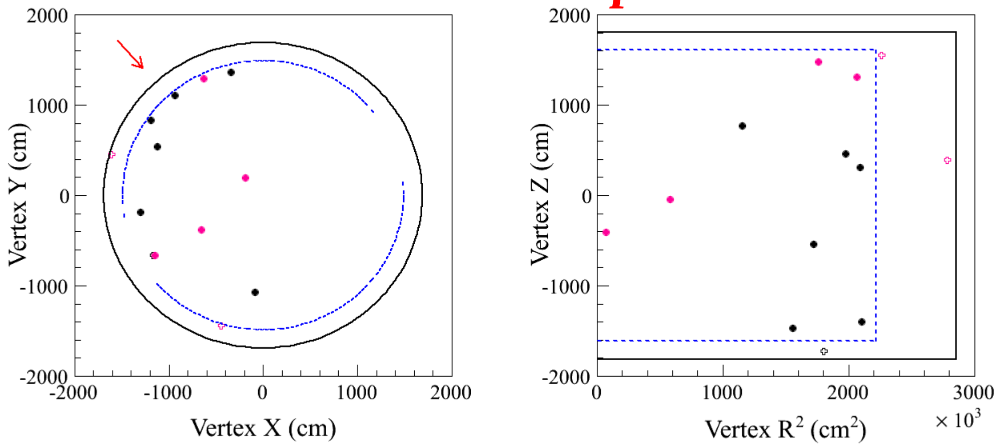
# Vertex Distribution

- **Vertex distribution of FC sample and final sample**

*FC sample*




*Final sample*




***Event vertex evenly distributed.***

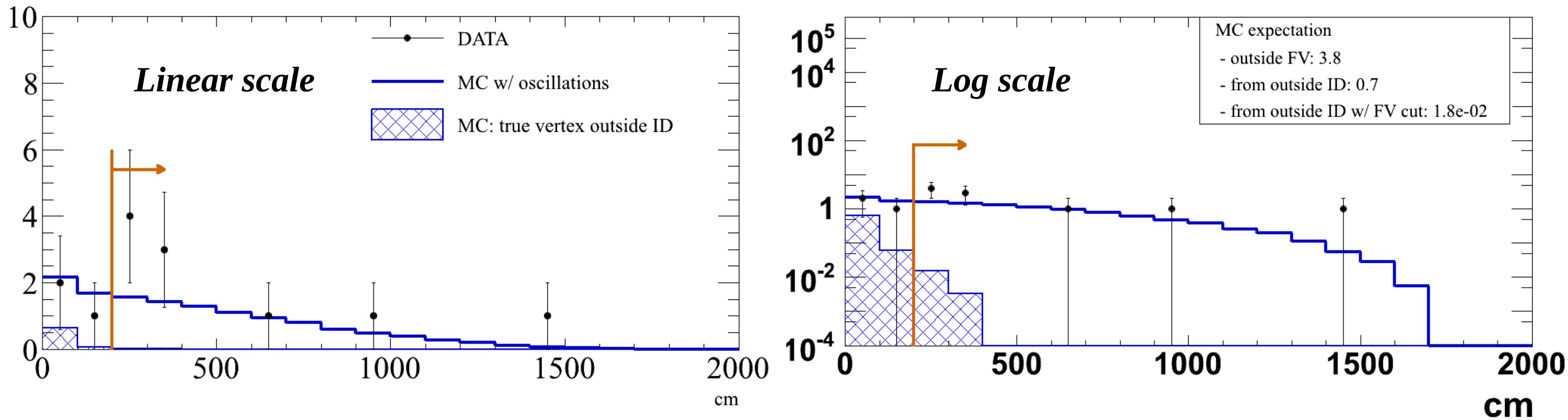
***→No event cluster near the edge of ID***

# *Contamination from Outside ID*

- **MC estimation to check contamination of events with true vertex outside ID**

  **→MC expectation = 0.018 events inside FV.**

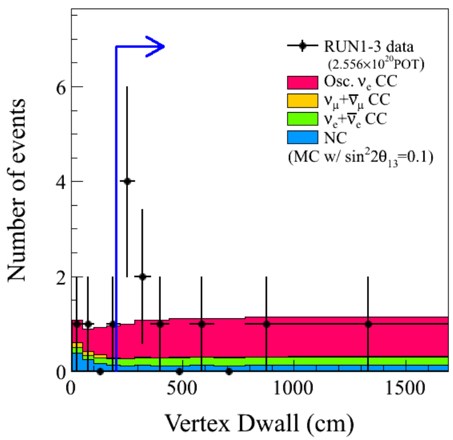
**Distance from vertex to ID wall**

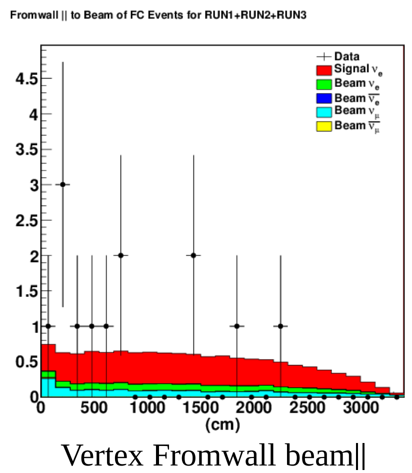


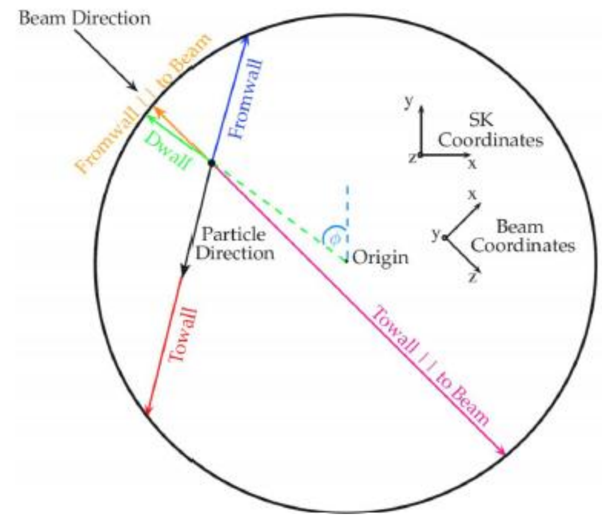

***BG contamination from outside ID is very small***

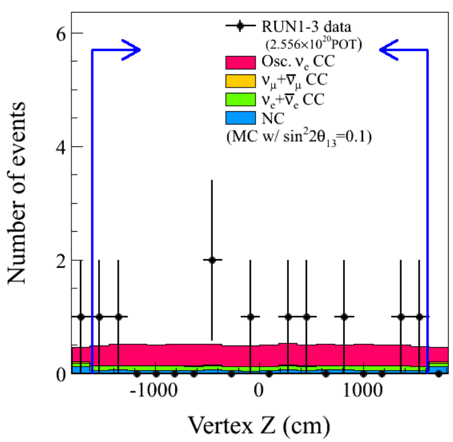
# *Vertex Distribution Test*

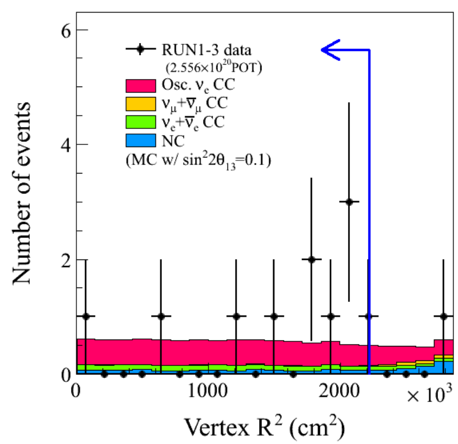
- **KS test for vertex distributions of candidate events.**
  - Low probability for distance from wall parallel to beam.
  - Low probability from RUN1+2. ↔RUN3 looks fine.



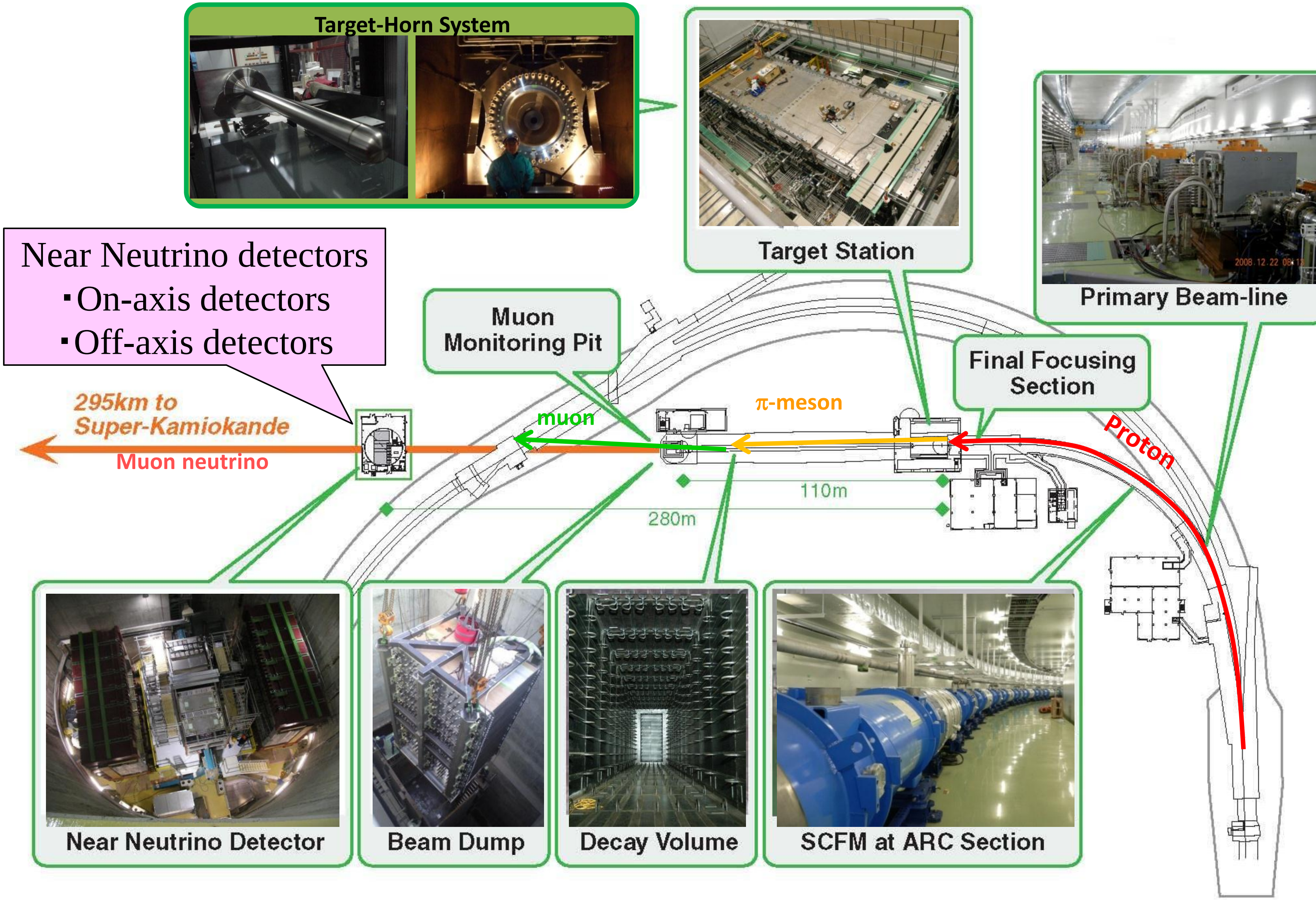




| | RUN1+2 | RUN3 | RUN1+2+3 |
|---|---|---|---|
| $Dwall$ | 22.9% | 80.7% | 21.5% |
| $Fromwall$ beam$_{\|\|}$ | 1.34% | 47.3% | 2.64% |
| $R^2 + Z$ | 10.5% | 66.1% | 17.2% |

***Need to check with more statistics***

# T2K Neutrino Beamline Facility



# *Recovery from Earthquake*

- **Subsidence outside buildings → Many water pipes and cables damaged.**
- **All the functionality were back after recovery work.**

***→Beam operation resumed on Dec. 9th, 2011 after 9 months recovery work.***

**Subsidence around Beam Dump**

**After Earthquake (Mar. 24th)**

**After recovery (May 13th)**

# Realignment of Beamline Magnets

- **Beamline magnets moved by ~10mm**
  - **Realignment was done.**

***→All the magnets aligned within 1mm.***


**Residual from ideal beam orbit**