Highlights from the T2K Experiment

Tetsuro Sekiguchi

KEK, IPNS

for T2K collaboration

Contents

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

Introduction of T2K

Neutrino Oscillation

- **Flavor oscillation described by Pentecorvo-Maki-Nakagawa-Sakata matrix.**
- **Parameterized by 3 mixing angles and CP-violating phase δ_{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"

θ_{23}

ν_μ disappearance

(SuperK, K2K, MINOS)

ν_τ 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"

θ_{12}

ν_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 δ_{CP}**

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

θ_{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

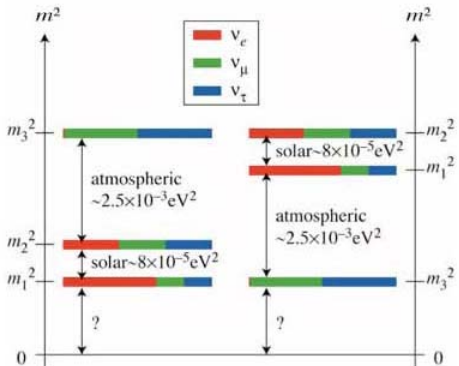
($\bar{\nu}_e$ disappearance)

Accelerator experiment

L=*O*(100km)

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

(ν_e appearance)



normal or inverted?

if θ_{13} is non-zero, open the possibility to measure
- *Mass Hierarchy*
- *δ_{CP}*

The T2K Experiment

- **<u>T</u>okai <u>to</u> <u>K</u>amioka 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 θ_{13} which controls this phenomena.**
  - **Precise measurement of the parameters θ_{23} and Δm_{23} in $\nu_\mu \rightarrow \nu_\mu$ oscillation.**

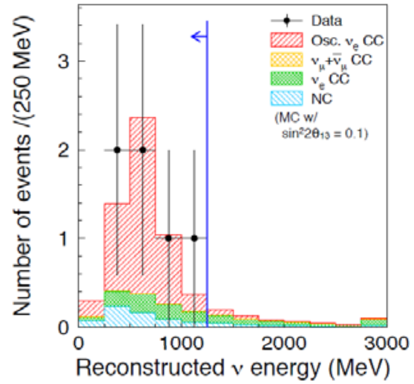
First T2K Results

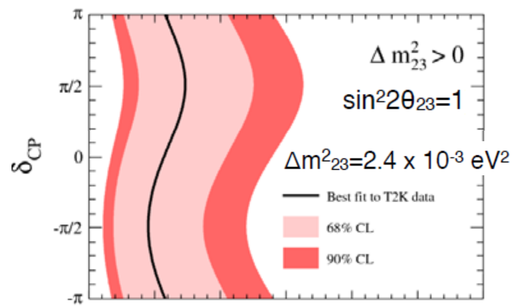
Data collected until Mar. 2011: 1.43 × 10^{20} POT

ν_e appearance result (15/June/2011) →PRL 107, 041801 (2011)

- **6 ν_e events observed !!** ↔ Background(BG): 1.5±0.3events
  - Probability to observe 6 or more BG events = **0.7% (2.5σ)**
- θ_{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 θ_{13}.

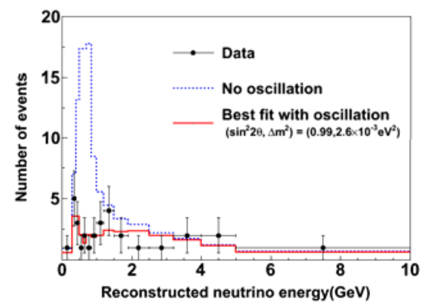


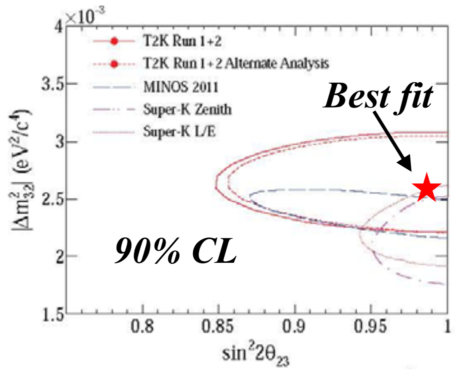


ν_μ disappearance result →PR D85, 031103(R) (2012)

- **31 ν_μ 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.

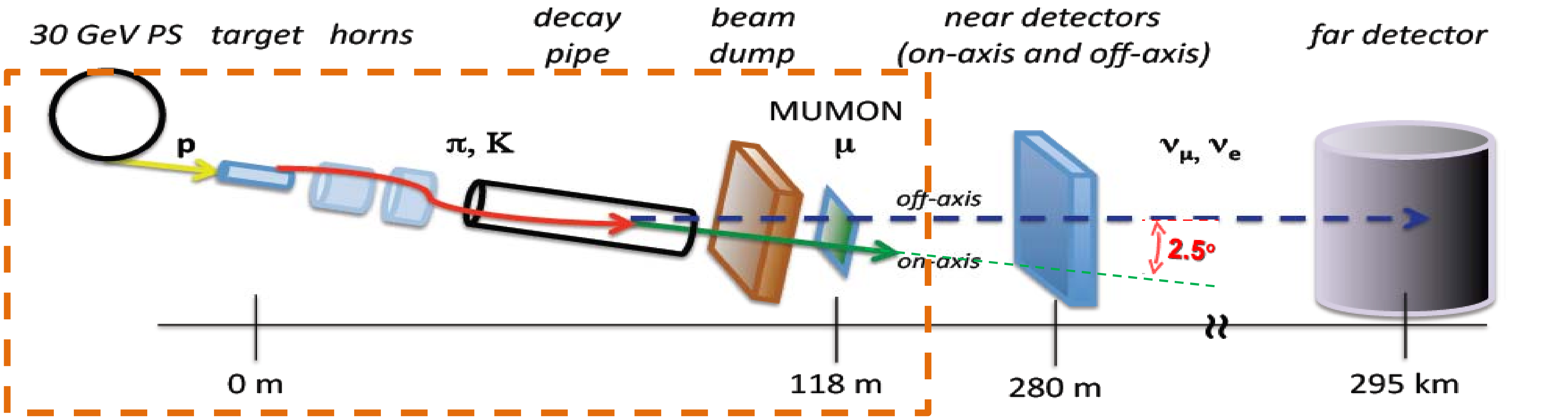




This talk = Updated ν_e appearance result

Experimental Setup

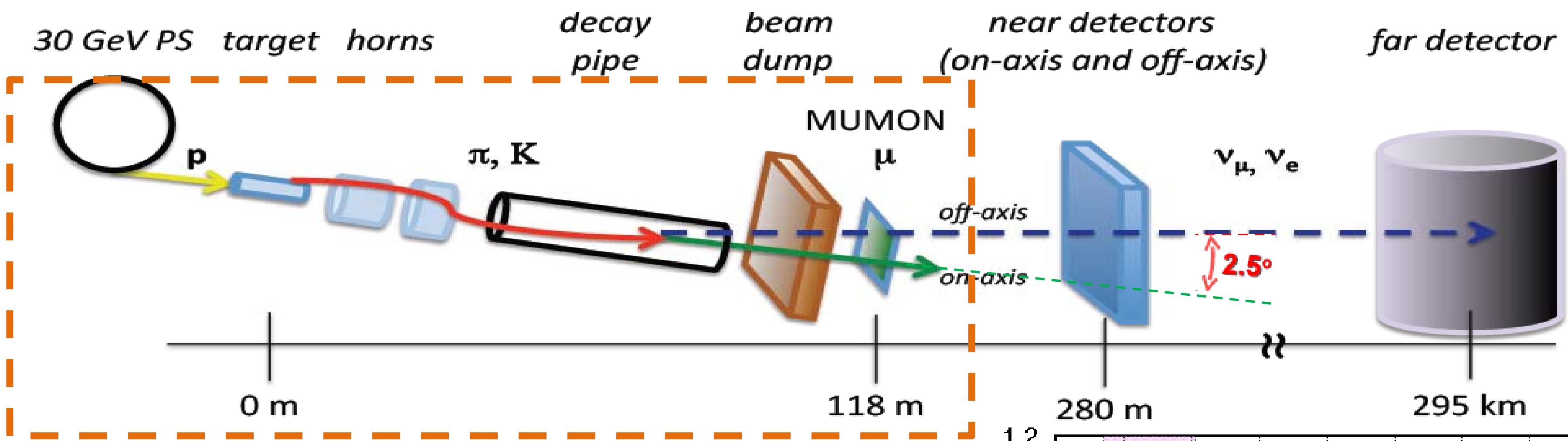
T2K Neutrino Beam

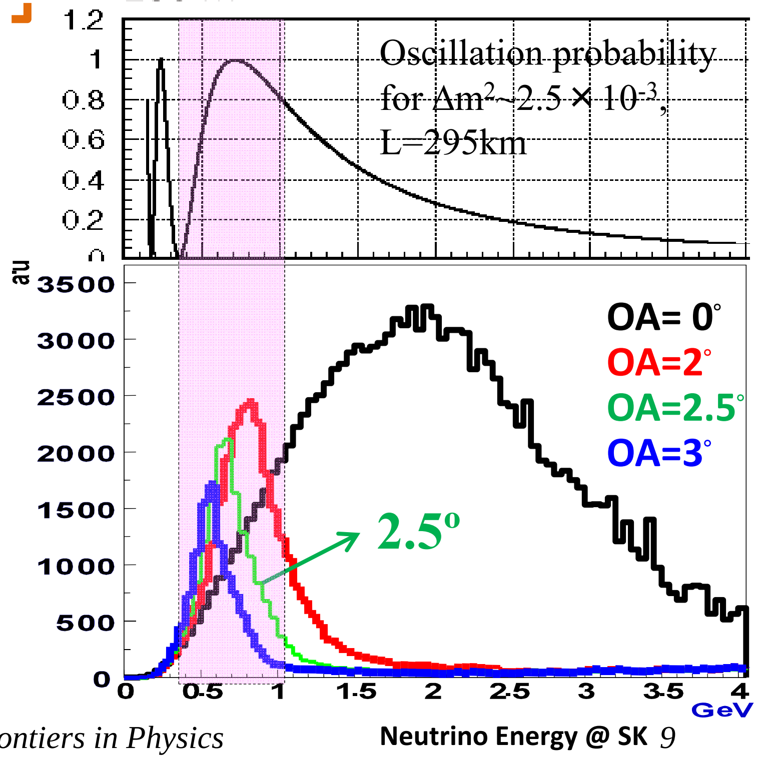


High intensity neutrino beam

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

T2K Neutrino Beam

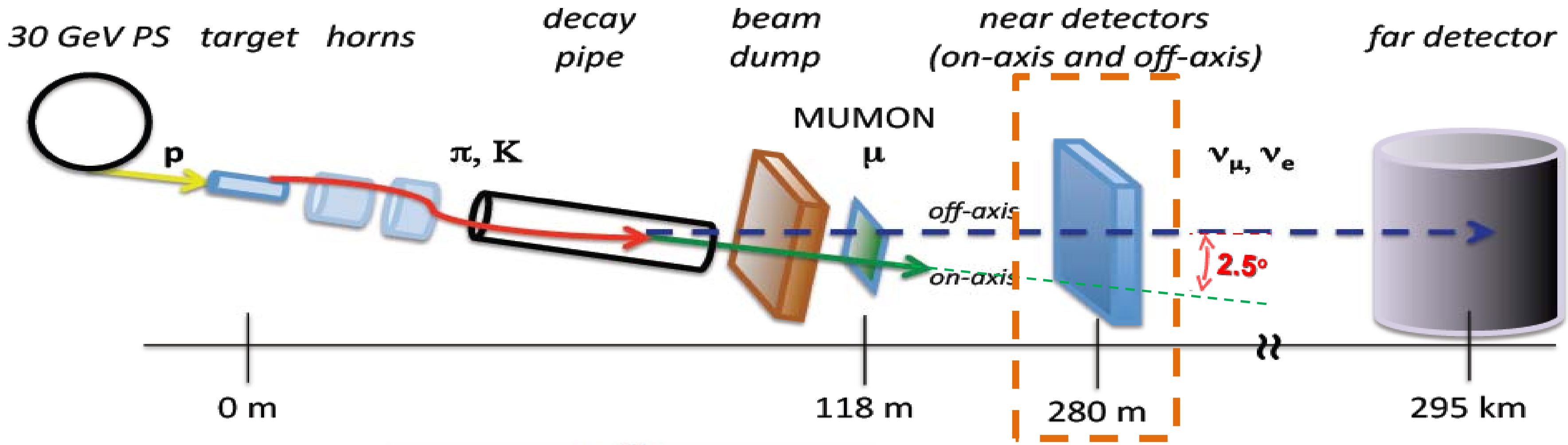




Off-Axis (2.5°) ν_μ beam

- Intense, low energy narrow-band.
- Peak E_ν tuned for oscillation max. (~0.6 GeV)
- Reduce BG from high energy tail.
- Small ν_e fraction (~1%).

Near Detectors

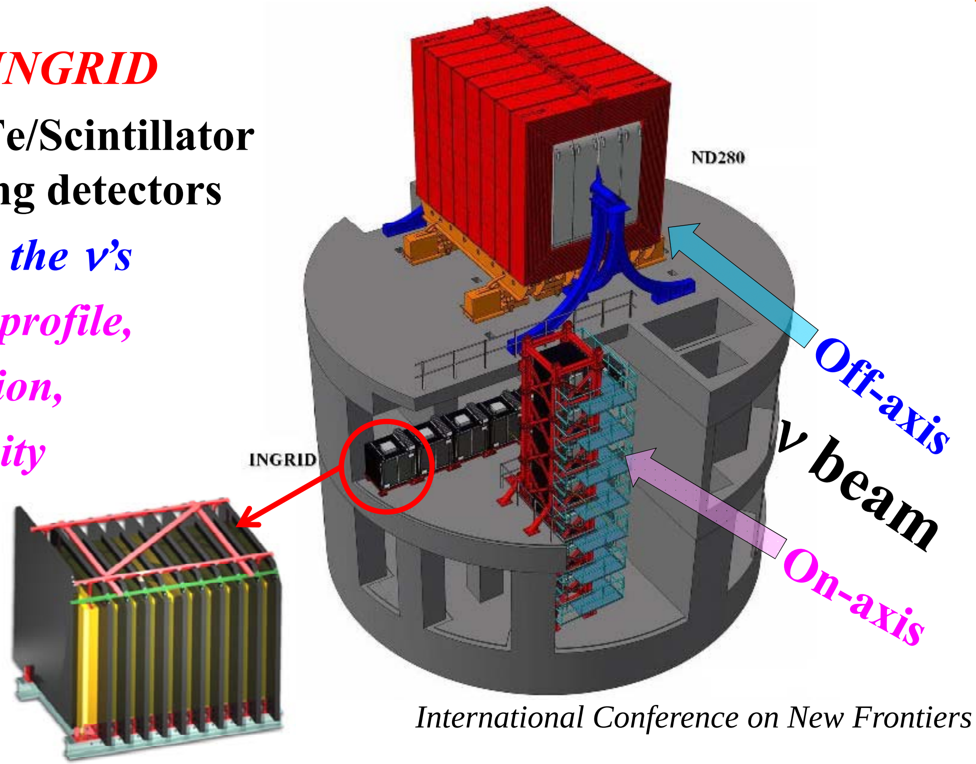


On-axis: INGRID

Array of Fe/Scintillator tracking detectors

→***Monitor the ν's***

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



Off-Axis: ND280

Fine grained detector complex in 0.2T magnetic field

→***Characterization of the ν beam before oscillations***

- ***ν_μ flux/Energy spectrum***
- ***ν_e contamination***
  →***bkg to ν_e appearance***

→***Measurement of ν_μ interactions***

- ***ν_μ induced π^0 production***
  →***bkg to ν_e appearance***

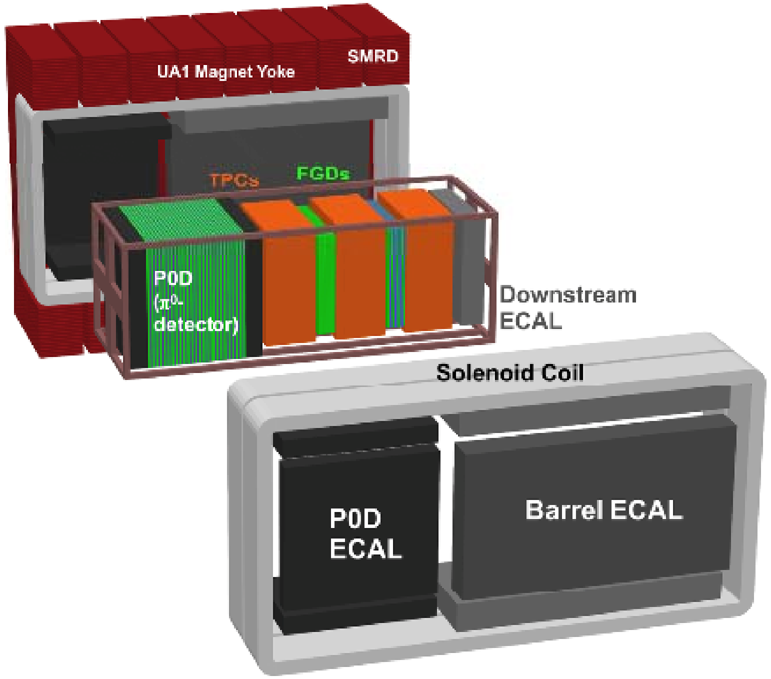
Near Detector ND280 (Off-Axis)

- **ND280 @ 2.5 degree off-axis**
- **ND280 consists of:**
  - Dipole magnet with 0.2T field
  - **F**ine **G**rain **D**etectors FGD's (× 2):

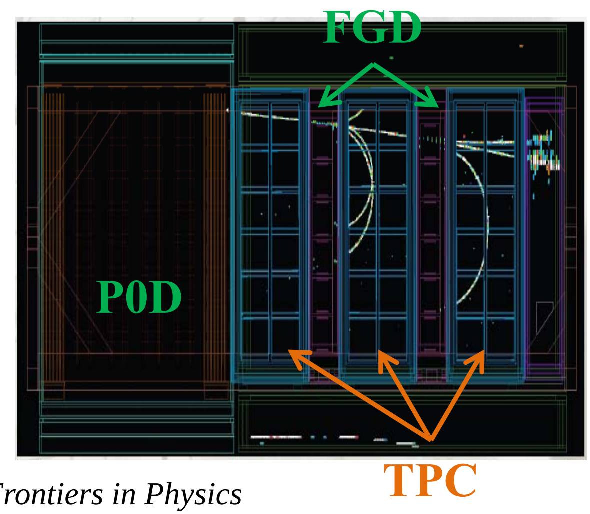
    2.2 tons scintillator bars active ν target
  - **T**ime **P**rojection **C**hambers TPC's (× 3):

    <10% dE/dx resolution

    <10% δp/p @ 1 GeV/c
  - P0D: π^0 Detector
  - ECAL (**E**lectromagnetic **CAL**orimeters)
  - SMRD (**S**ide **M**uon **R**ange **D**etector)



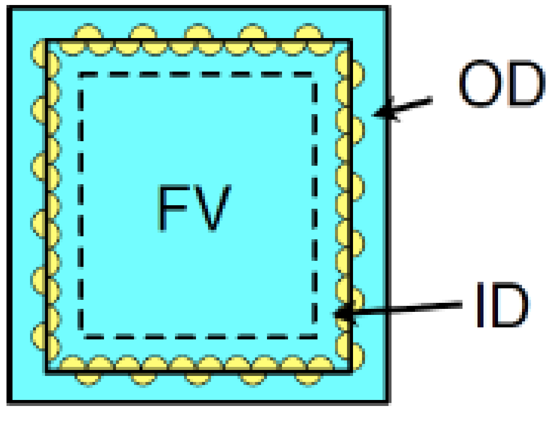
Example of ND280 ν event

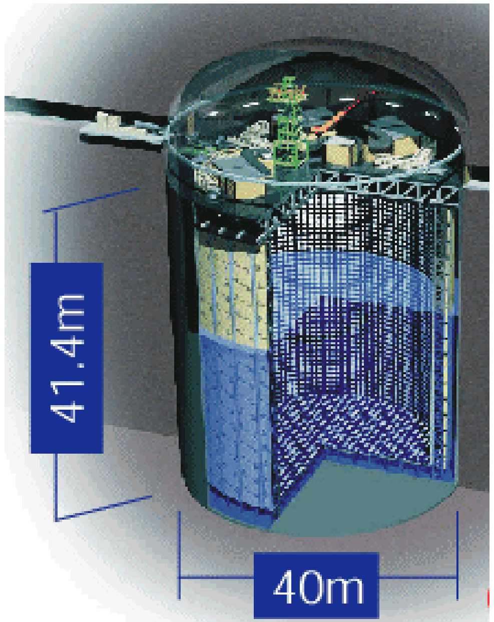


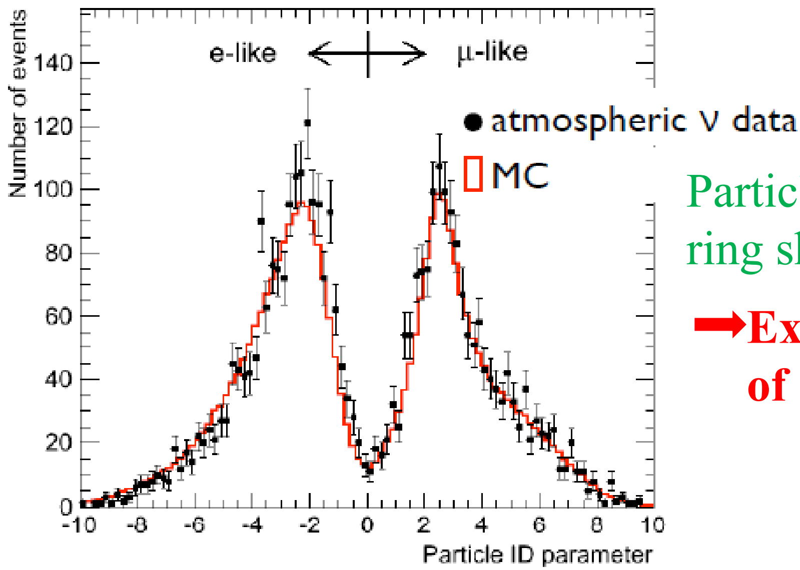
Super Kamiokande as T2K Far Detector

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







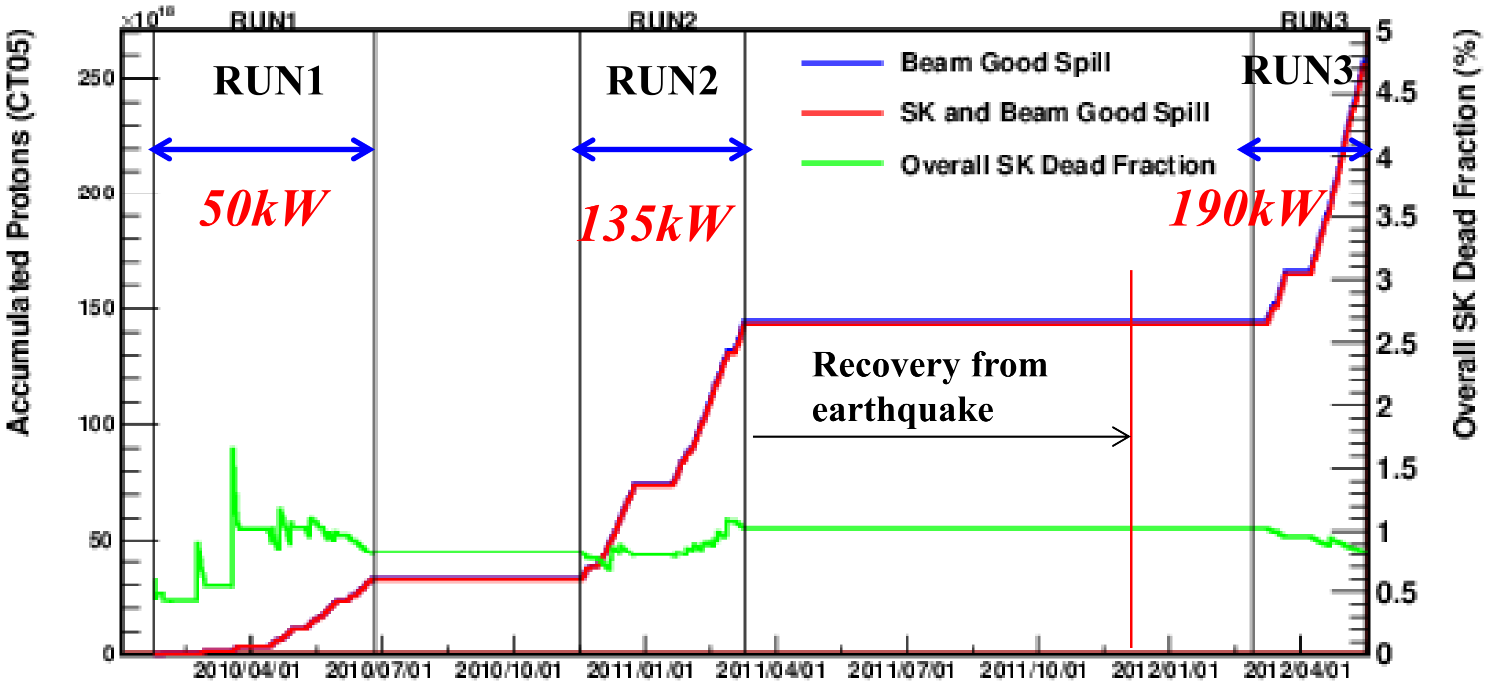
Particle ID using
ring shape & opening angle

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

Status of Experiment

Data Collected and Analyzed

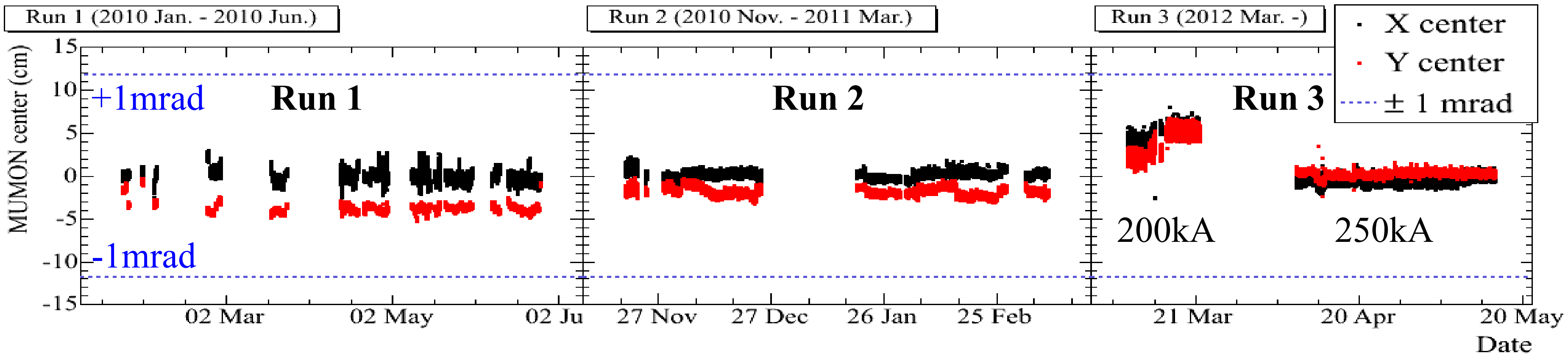
- **Beam Power increased up to 190kW w/ 1×10^14 protons per pulse (world record)**
- **Analyzed data: up to May 15th, 2012: 2.56×10^20 POT (Protons On Target)**
  - RUN1 (2010): 0.32×10^20 POT
  - RUN2 (2010-2011): 1.11×10^20 POT
    - ND280 RUN 1+2 data used for oscillation analysis
  - **RUN 3 (2012): 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



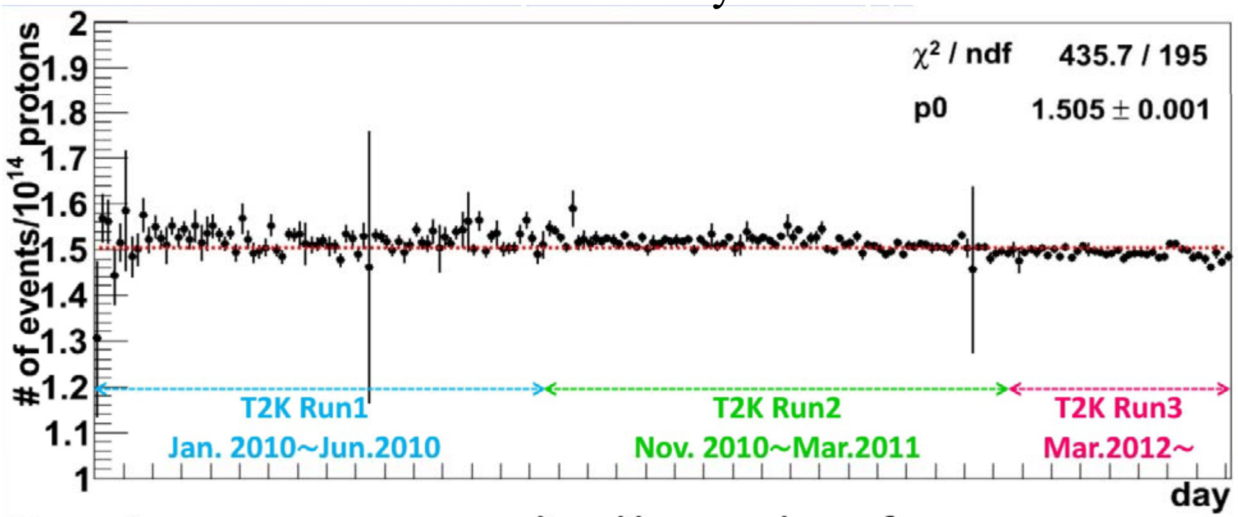
Neutrino Beam Quality

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

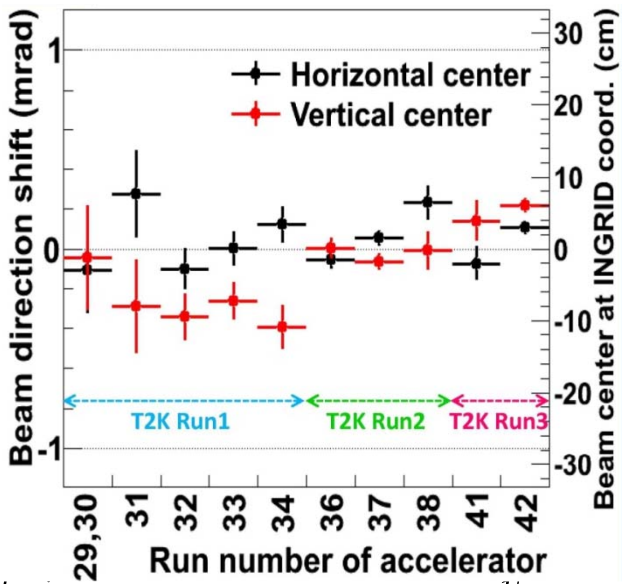
1 mrad shift of the beam direction = 2% shift of the E_ν peak at SK



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



INGRID: beam direction



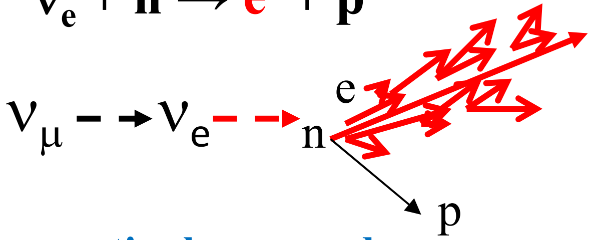
Analysis Results

Signal and Background for T2K ν_e Appearance Search

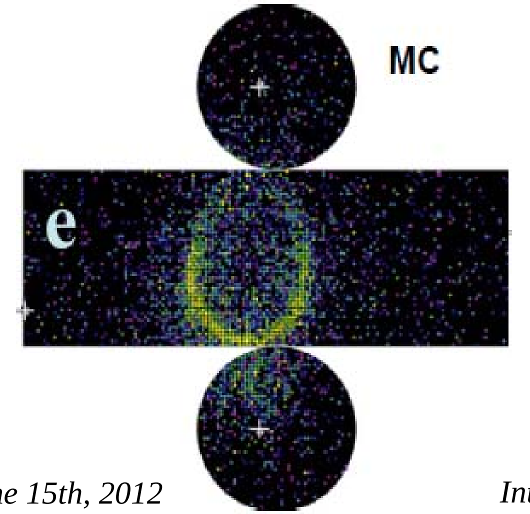
SIGNALS

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



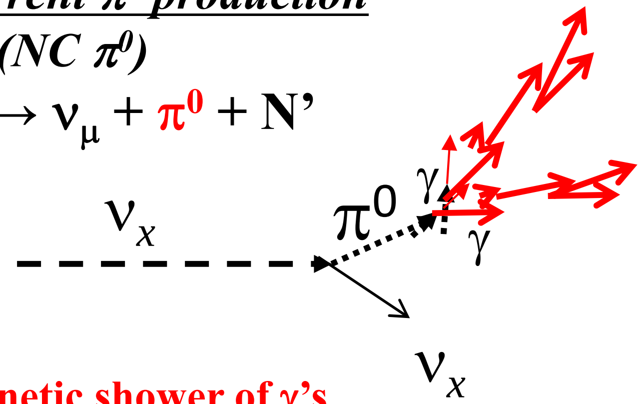
BACKGROUND

Intrinsic ν_e contamination in the beam (<1%)

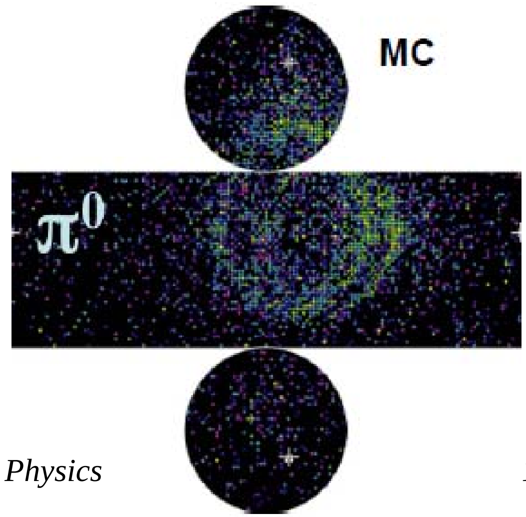
→wider energy dist.

Neutral current π^0 production (NC π^0)

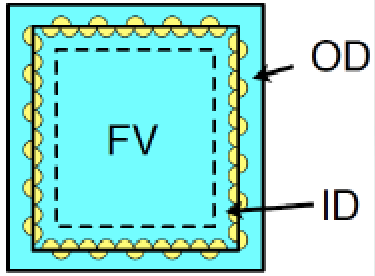
$$\nu_\mu + N \rightarrow \nu_\mu + \pi^0 + N'$$



Electromagnetic shower of γ's from π^0 can fake an electron



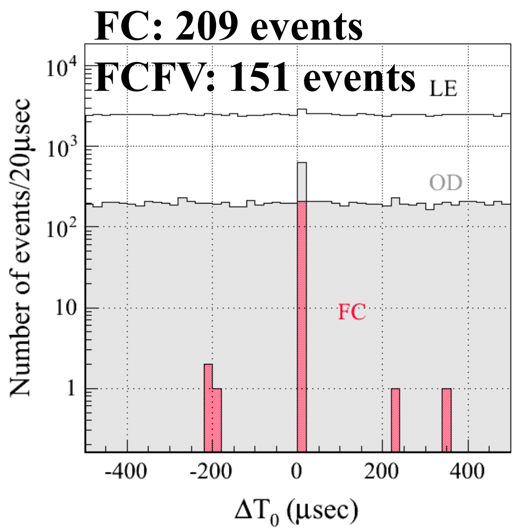
T2K Event Selection

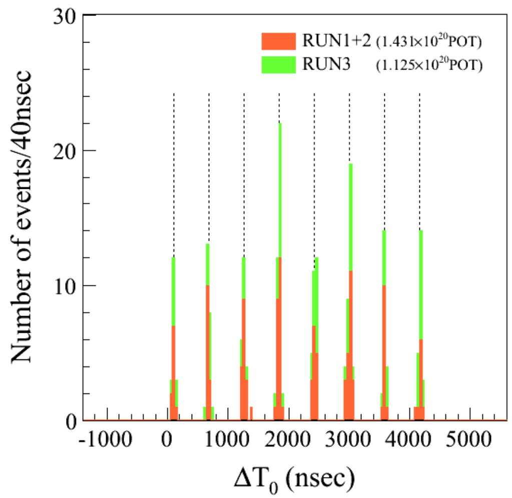


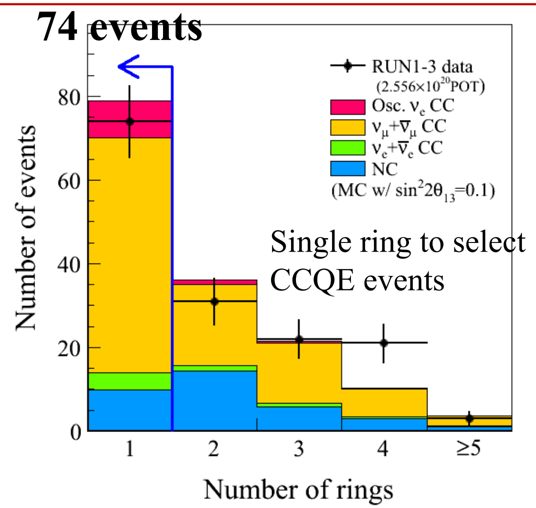
Selection Criteria

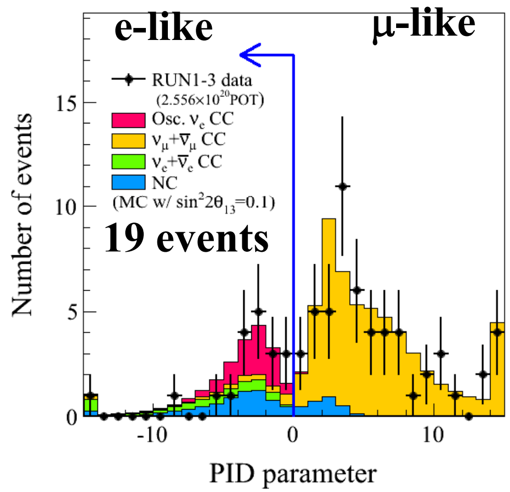
(*[determined before data analysis]*):

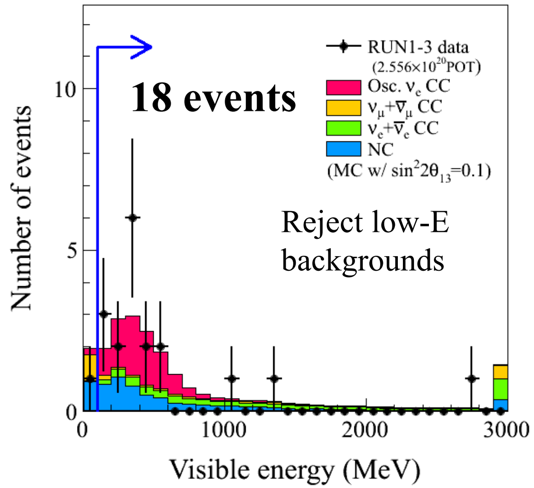
1. **T2K beam timing**
2. **Fully contained (FC) event,**
3. **Vertex is in Fiducial Volume (FV)**
4. **A single e-like Cherenkov ring**
5. **Visible energy > 100 MeV**
6. No decay electrons
7. π^0 mass cut, $M_{inv} < 105$ MeV/c^2
8. Reconstructed $E_\nu < 1250$ MeV











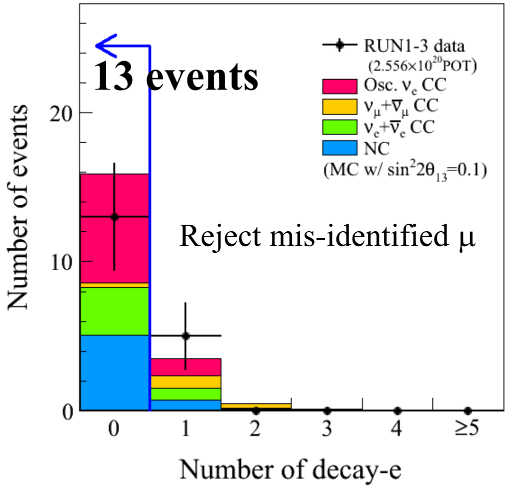
Further ν_e Selection

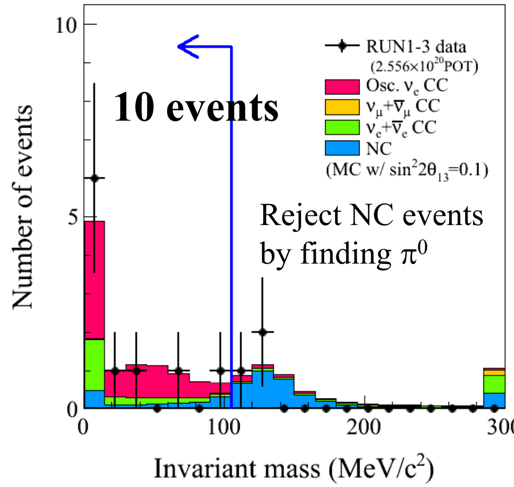
Selection Criteria

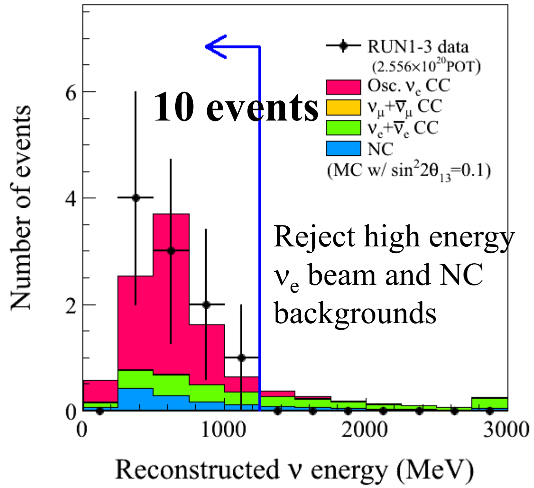
(*determined before data analysis*):

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. **π^0 mass cut, M_{inv} < 105 MeV/c^2**
8. **Reconstructed E_ν < 1250 MeV**

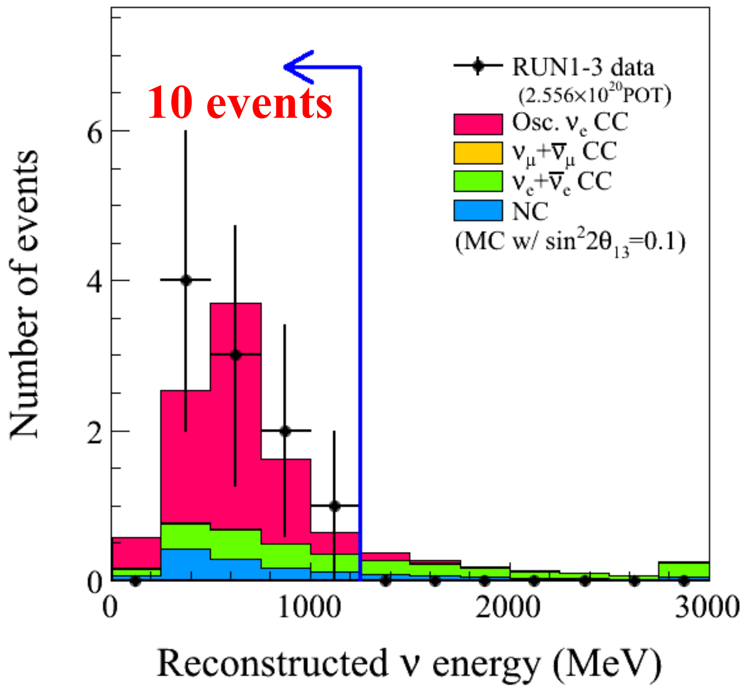
Run 1+2+3 2.56×10^{20} POT	Data	MC Expectation w/ $\sin^2 2\theta_{13}$=0.1				
		Signal $\nu_\mu\to\nu_e$	BG total	$\nu_\mu+\bar{\nu}_\mu$ CC	$\nu_e+\bar{\nu}_e$ CC	NC
e-like	19	8.70	13.23	2.30	4.07	6.86
E_{vis}>100MeV	18	8.50	11.47	1.49	4.03	5.94
No decay-e	13	7.31	8.56	0.28	3.19	5.09
π^0 mass cut	10	6.82	3.67	0.07	2.21	1.39
E_ν^{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

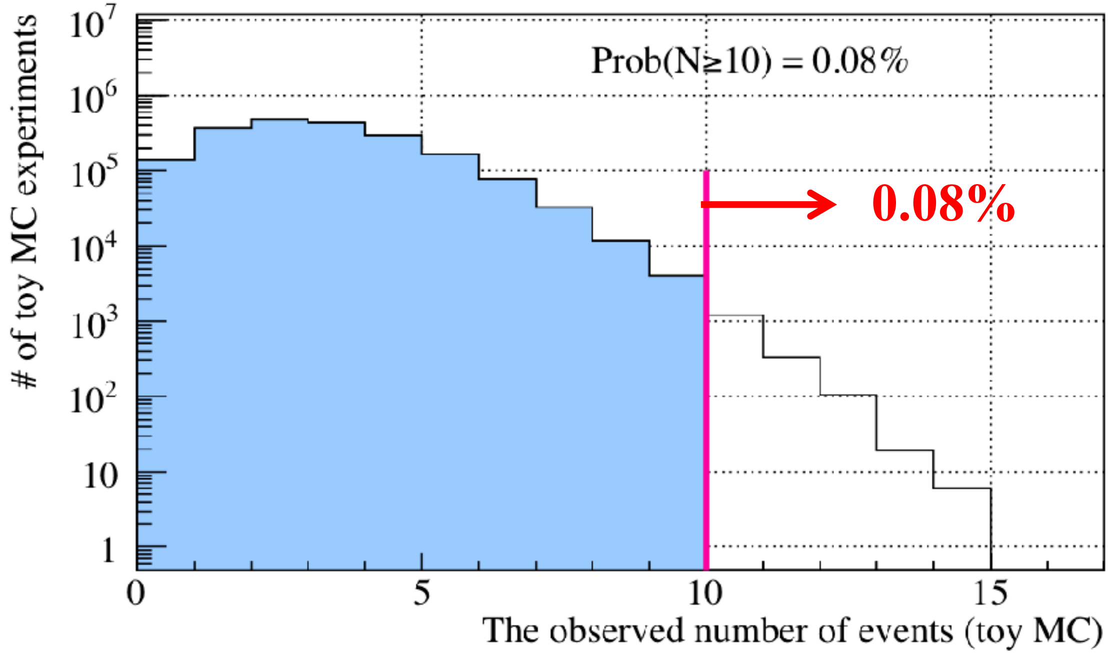






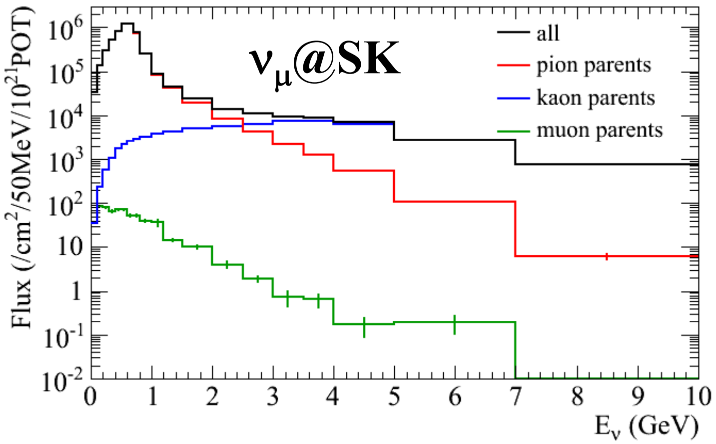
Evidence of ν_e Appearance



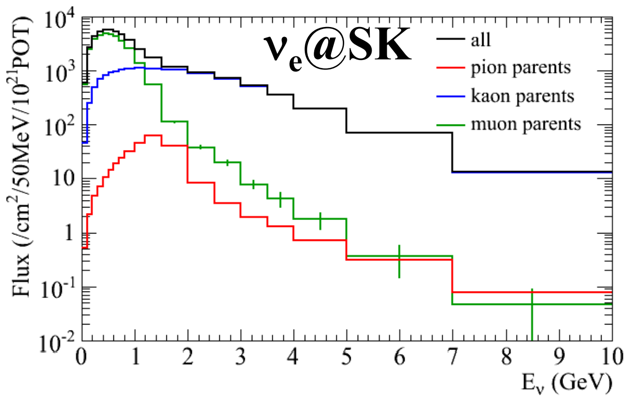


- **10 ν_e candidates found!**
- **Probability (p-value) to observe 10 or more events with 2.73±0.37(sys.) BG events is 0.08% (3.2 σ)**
  - *Confirm the T2K 2011 results [PRL 107, 041801 (2011)] !!*
  - **We find the Evidence of "Electron Neutrino Appearance".**

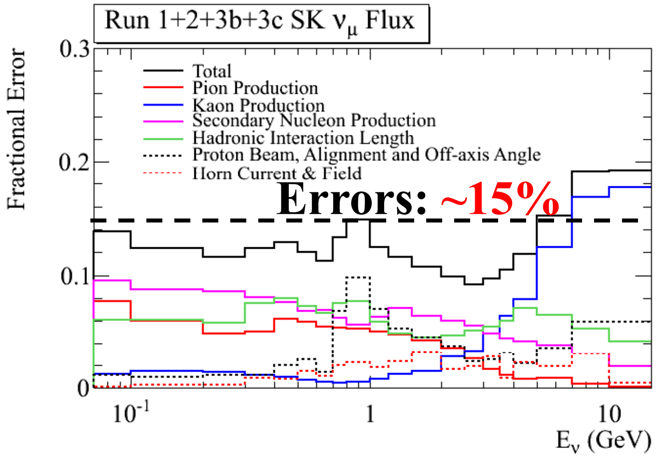
Neutrino Flux Prediction w/ CERN NA61

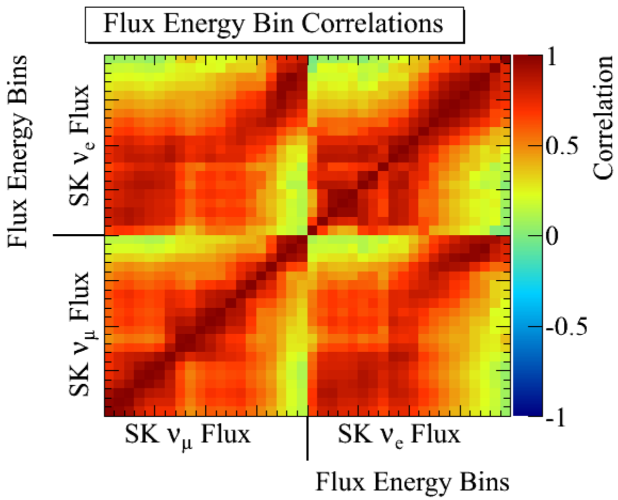


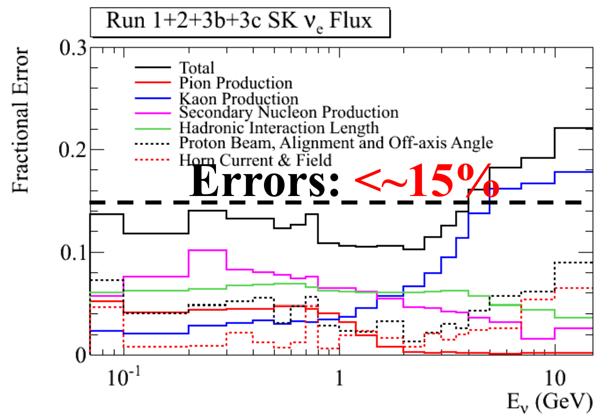
ν_μ, ν_e, anti-ν_μ, anti-ν_e energy dependent errors with full correlations @SK and @ND280 are taken in the FIT!



ν_μ and ν_e Flux Energy Correlations



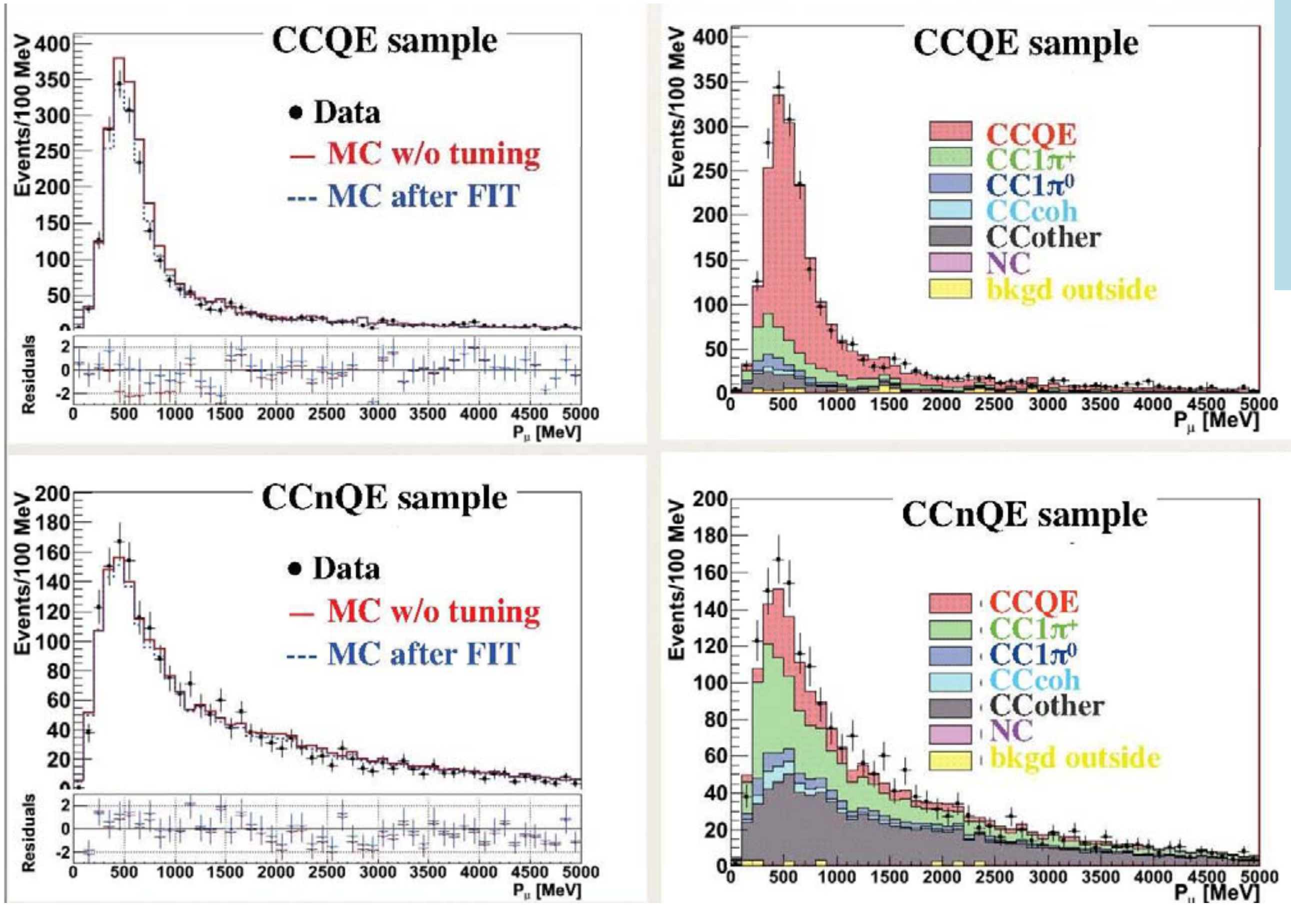




Errors: 10~15%

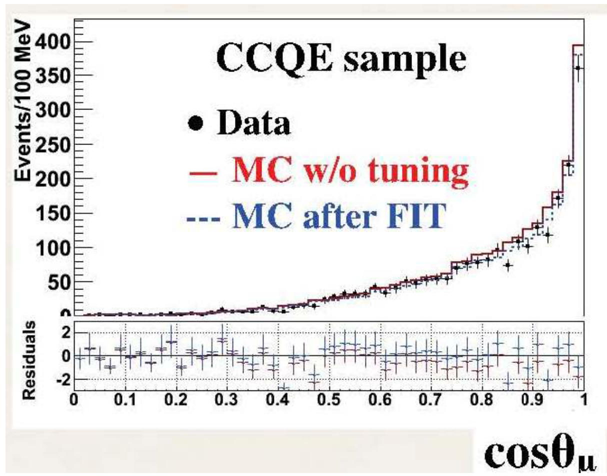
ND280 ν_μ Measurement (RUN1+2 Data)

# of Events in P_μ vs. θ_μ are used in FIT to constrain the flux and ν cross sections (MC predictions at ND280 and SK)

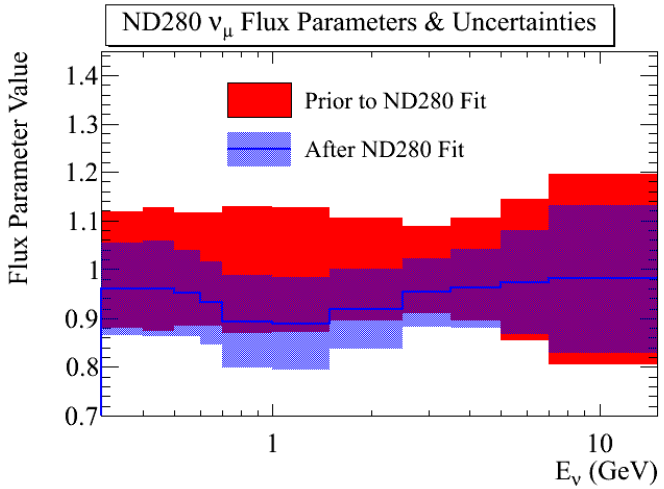


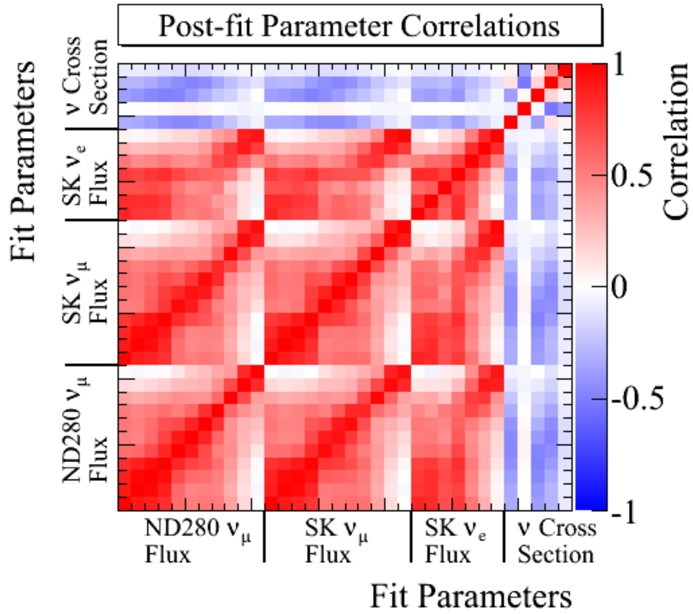
- Good negative track in FV
- Upstream TPC veto
- muon ID by TPC for CCQE
  - **1 FGD-TPC track**
  - **No decay-e FGD**

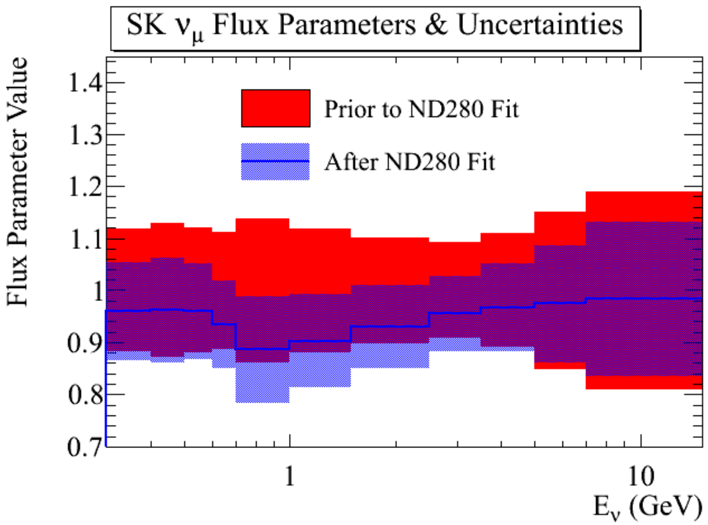
For CCQE selection 40% eff. w/ 72% purity.

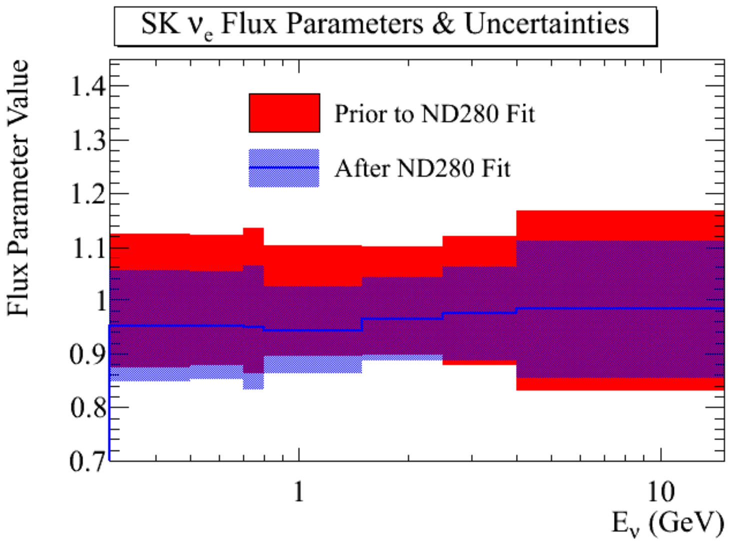


Flux + Cross Section FIT output



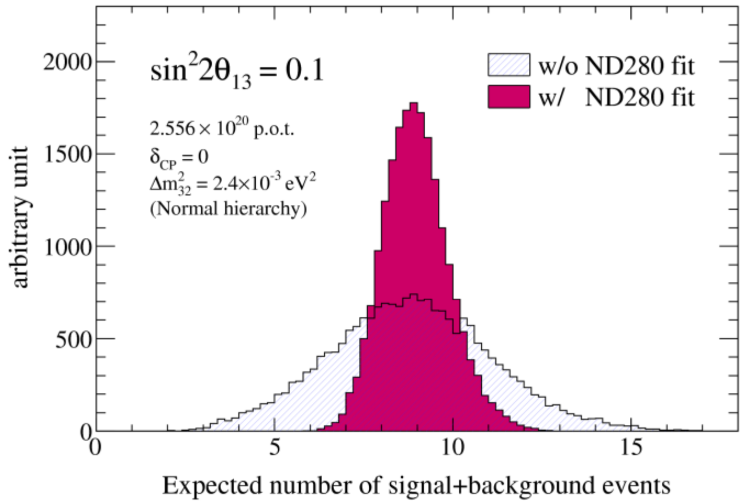


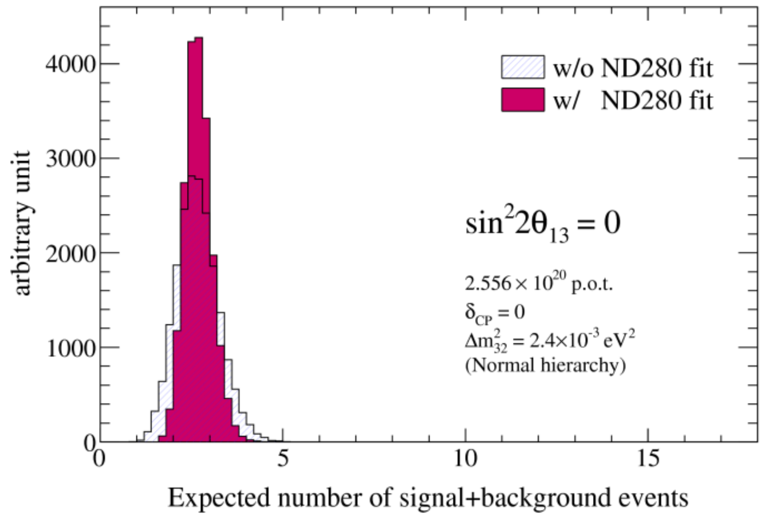




of Events Predictions at T2K w/ Sys. Error

(Note: 10 ν_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**
ν_e signal	6.60	0.15
ν_e bkg. (beam org.)	1.32	1.42
ν_μ bkg. (~NCπ^0)	1.02	1.02
anti-ν bkg.	0.13	0.14

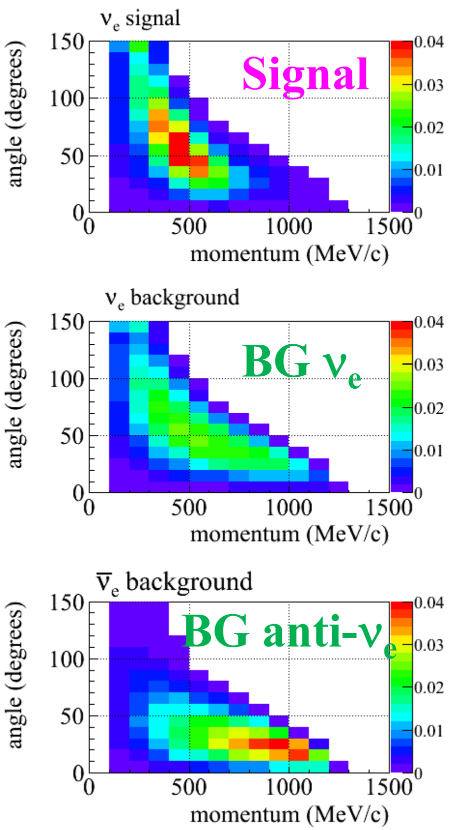
Systematic Errors

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, θ_e)**
- **Method-2: Maximum Likelihood Fit w/ Rate + reconstructed E_ν**
- **Method-3: Feldman&Cousins for Rate only (used in previous analysis)**

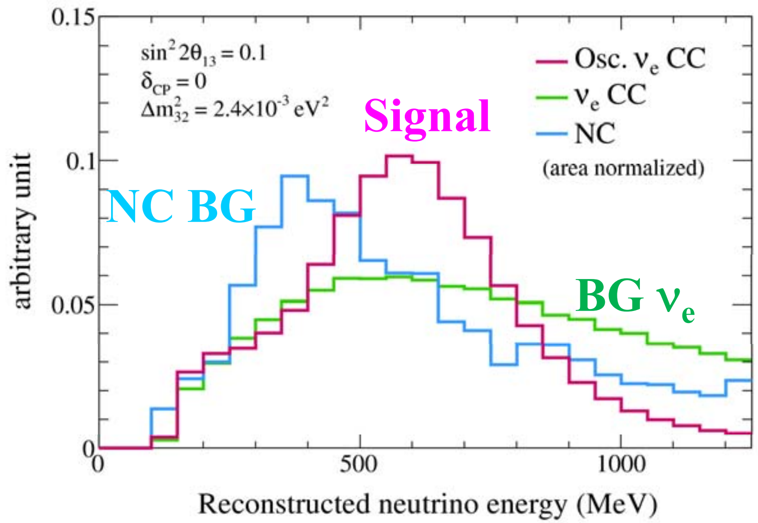
Method-1



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

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

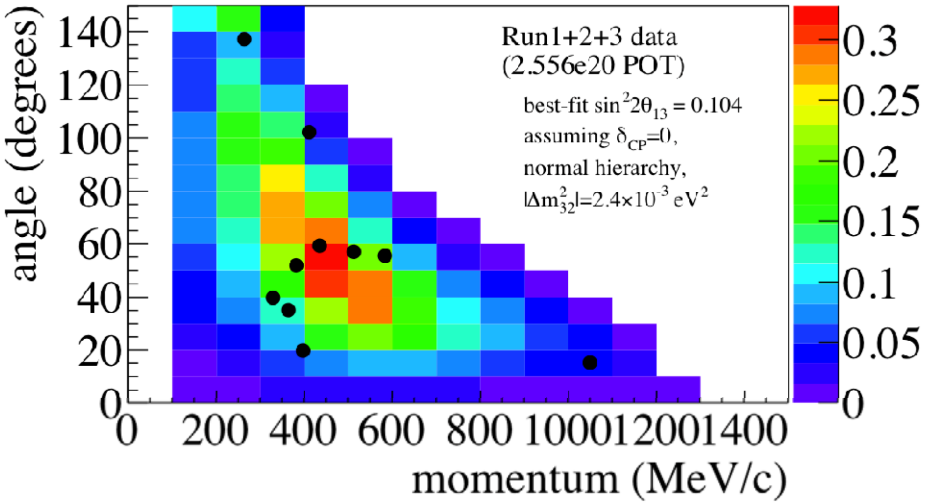
Method-2

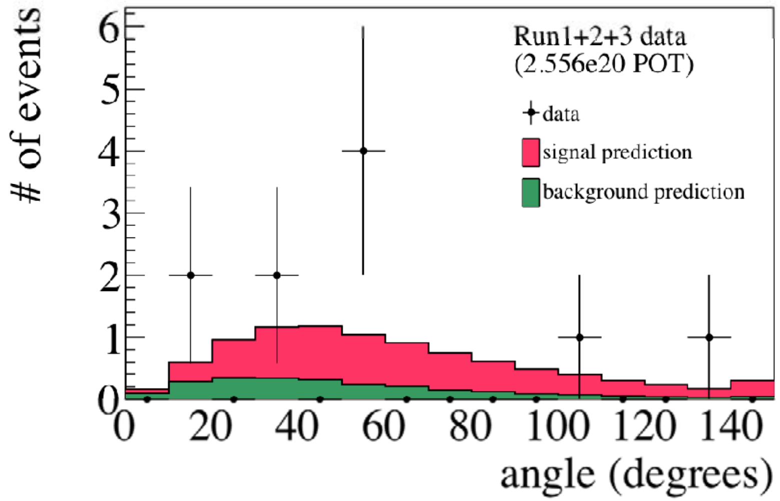


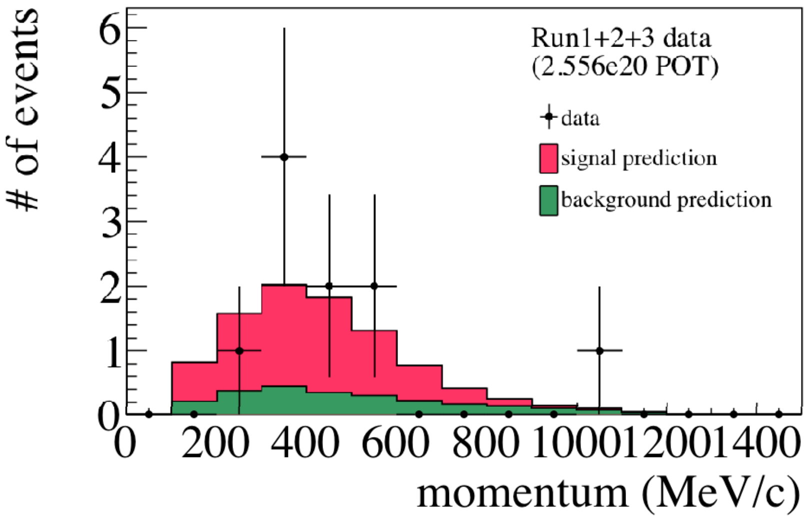
Data is fit to signal + 2 BG 1-D curves

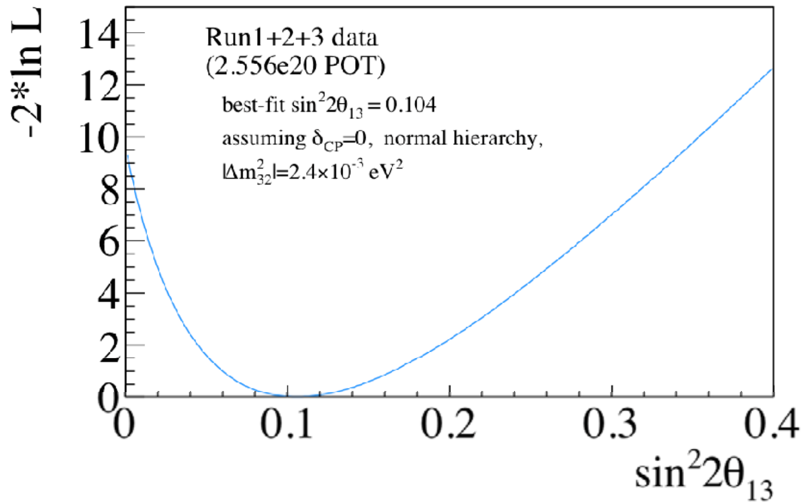
Method-1: Rate + (p_e, θ_e)

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







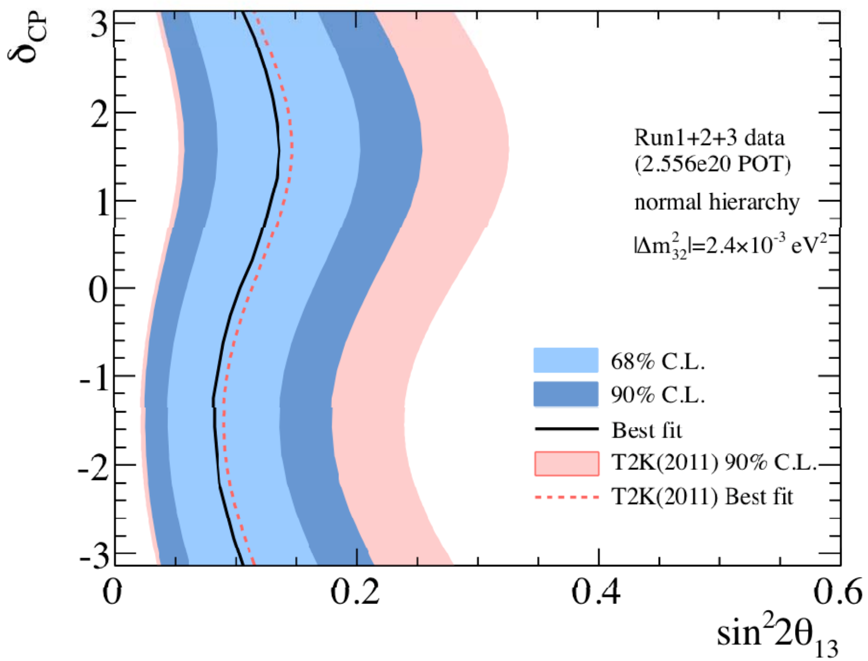


Method-1: Rate + (p_e, θ_e)

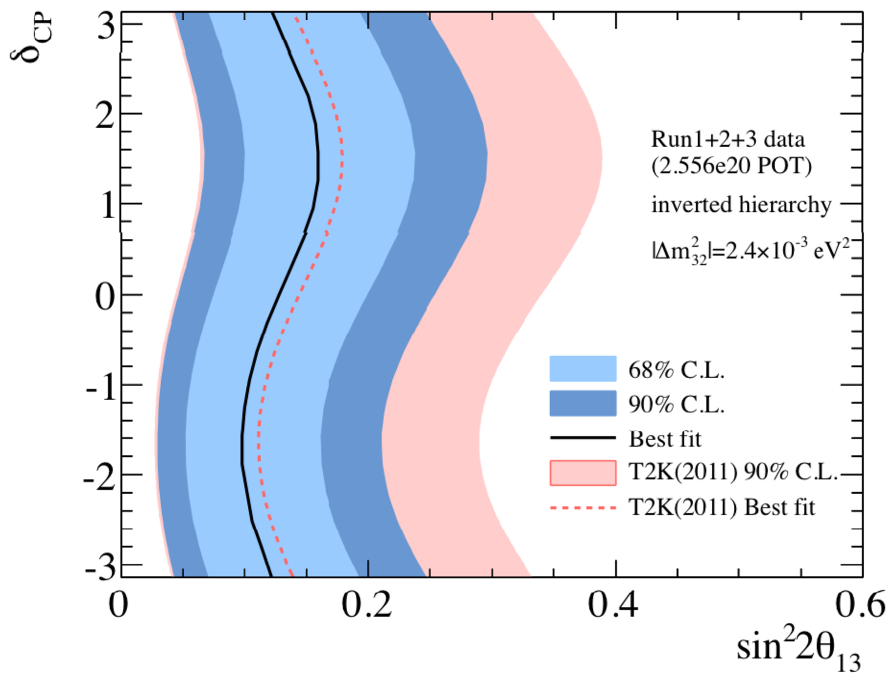
90% CL: $0.036 < \sin^2 2\theta_{13} < 0.211$ for Normal Hierarchy ($\Delta m^2_{23}>0$)

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

Normal Hierarchy



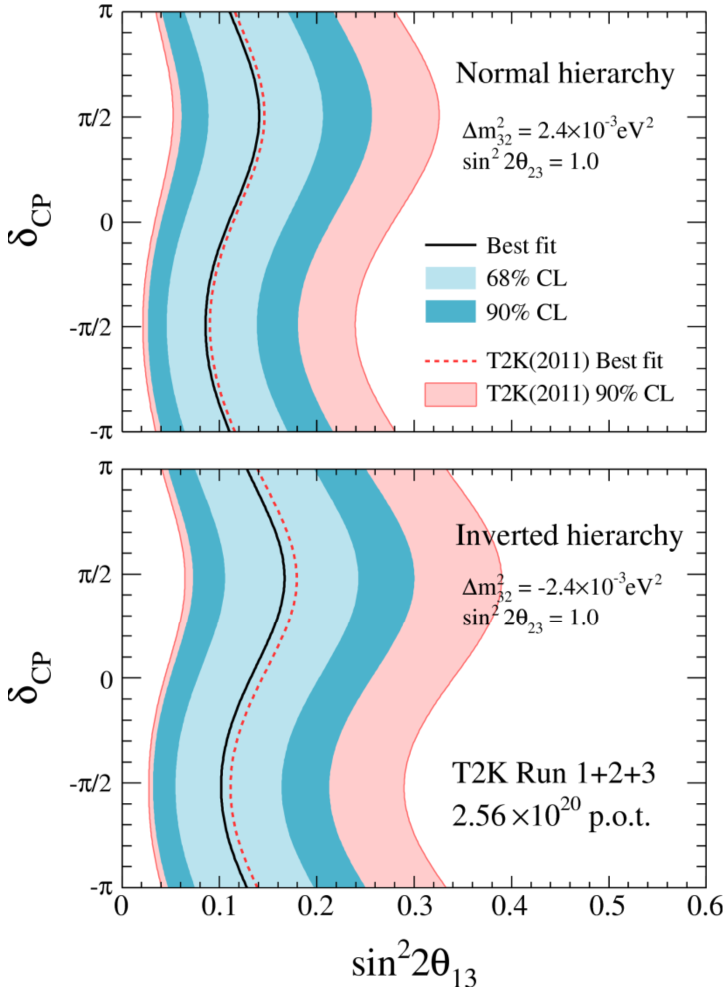
Inverted Hierarchy



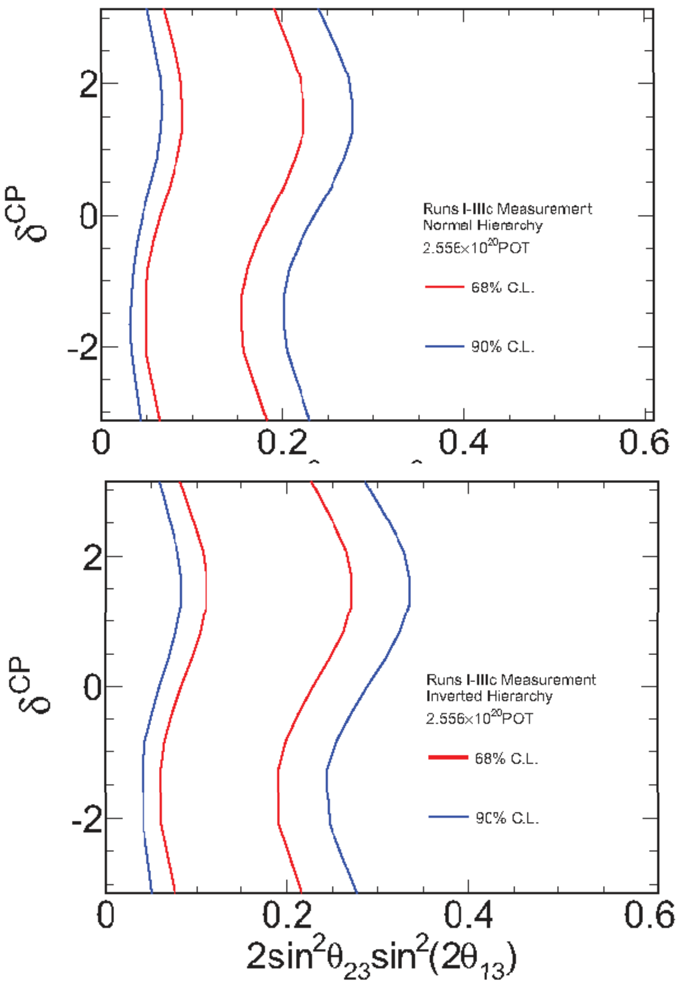
$\sin^2 2\theta_{13} = 0.104^{+0.060}_{-0.045}$ **@ $\delta_{CP}=0$** $\sin^2 2\theta_{13} = 0.128^{+0.070}_{-0.055}$

Method-2 and -3

Method-2: Rate + E_ν^{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 ν_μ disappearance result is coming soon for θ_{23} measurement.
  - The precision of θ_{23} with the reactor θ_{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 ν_e appearance.
- The data will increase in each new run with higher beam power.
  - **~8 × 10^{20} POT (2013)→~1.2 × 10^{21} POT (2014)→~1.8 × 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 ν_e appearance results with 2.56×10^{20} POT***
  - **Systematic uncertainties reduced from the previous analysis: 23%→13%.**
  - **10 ν_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 σ)**
  - **Evidence of ν_e appearance!!**
- ***θ_{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.***
  - ν_e appearance
  - ν_μ disappearance