The latest results from T2K on the neutrino oscillation

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for T2K collaboration

TAUP 2013

Outline

- Introduction to Neutrino oscillations
- Introduction to T2K
- ν_e appearance result with Run 1-4 data
- ν_μ disappearance result with Run 1-3 data

The T2K Collaboration

~500 members, 59 Institutes, 11 countries

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

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

•Germany
•Aachen U.

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

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

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

Russia
INR

Spain
IFAE, Barcelona
IFIC, Valencia

Switzerland
ETH Zurich
U. Bern
U. Geneva

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

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

Neutrino flavors and mixing and neutrino oscillation

(Maki-Nakagawa-Sakata-Pontecorvo Matrix)

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

Flavor eigenstates

Atmospheric ν,
Accelerator ν experiments
(K2K, MINOS, T2K..)

$\theta_{23} = 45^o \pm 6^o$

$\Delta m^2_{23} \sim 2.4\times10^{-3}(eV^2)$

Reactor ν,
Accelerator ν,
Atm. ν

$\theta_{13} = 9.1^o \pm 0.6^o$

First non-zero θ_{13} is indicated by T2K,2011.

Solar ν,
Reactor ν

$\theta_{12} = 33.6^o \pm 1.0^o$

$\Delta m^2_{12} \sim 8\times10^{-5}(eV^2)$

Mass eigenstates

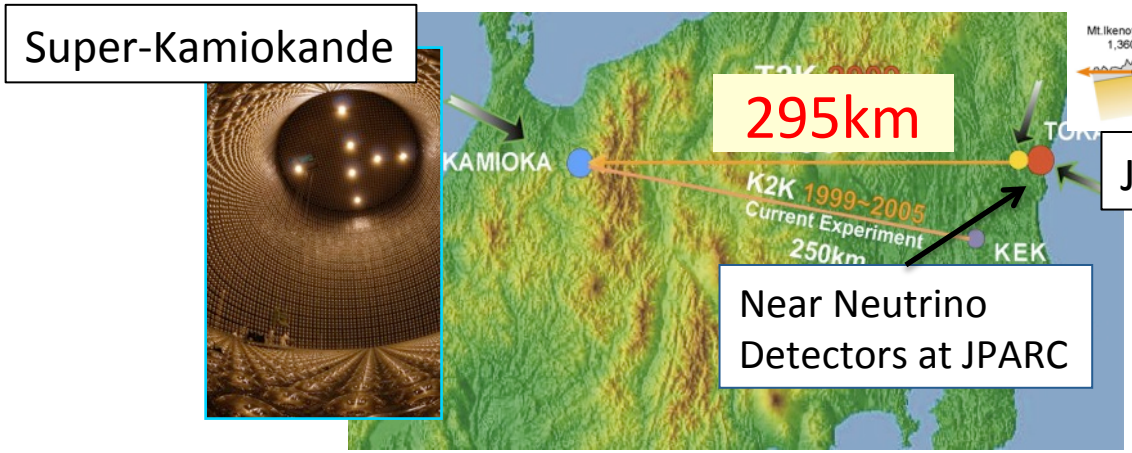
$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\cdot\sum_{i>j}\mathrm{Re}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\cdot\sin^2\Phi_{ij} \pm 2\cdot\sum_{i>j}\mathrm{Im}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\cdot\sin^2 2\Phi_{ij}$$

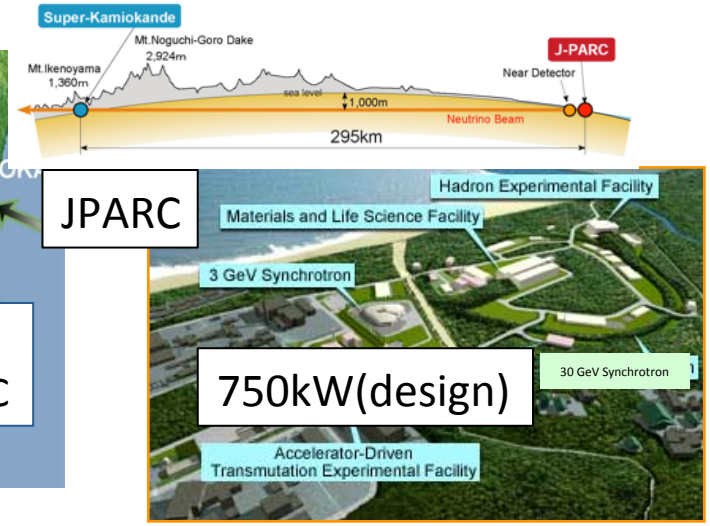
$$\Phi_{ij} = \Delta m^2_{ij}L/4E$$

- δcp, mass hierarchy is unknown
- Imaginary part can only accessible by appearance channel (α≠β)

T2K (Tokai to Kamioka) Long-Baseline Neutrino Oscillation Experiment

First Long baseline experiment with Intensive off-axis ν_μ beam





59 Institute, ~500 physicists.

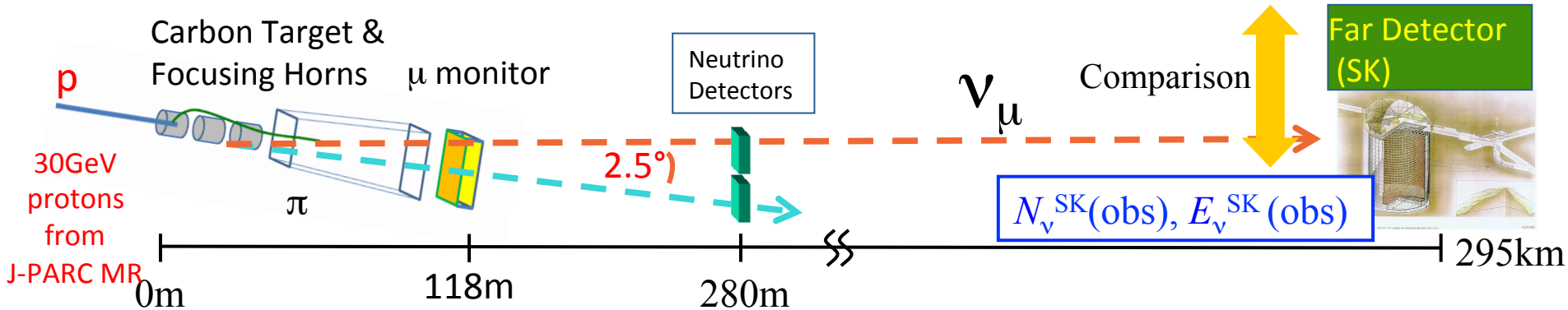
Physics Goals:

- Discovery of $\nu_\mu \rightarrow \nu_e$ appearance
- Precise measurement of ν_μ disappearance

$$\delta(\Delta m^2_{23}) \sim 1\times10^{-4}\ \mathrm{eV}^2\ ,\ \delta(\sin^2 2\theta_{23}) \sim 0.01$$

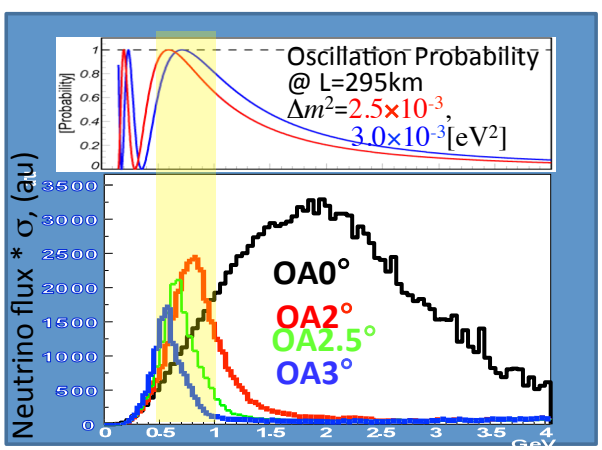
Flux & spectrum measurement at Near Neutrino detectors → Constraint on Model

extrapolation → Expectation



Off-axis ν beam

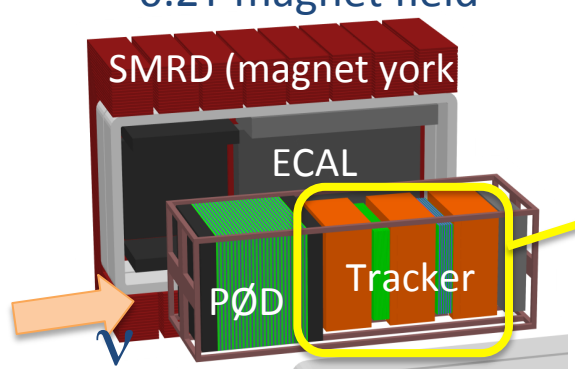
- Quasi-Monochromatic (peaked at 600MeV)
- Main interaction is Charged Current Quasi-Elastic (CCQE, $\nu + n \rightarrow l^- + p$)



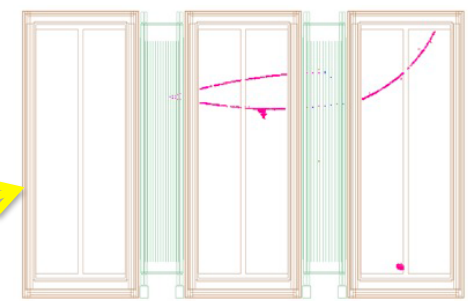
Off Axis = 2.5° is selected.

Off-axis ν detector (ND280)

0.2T magnet field



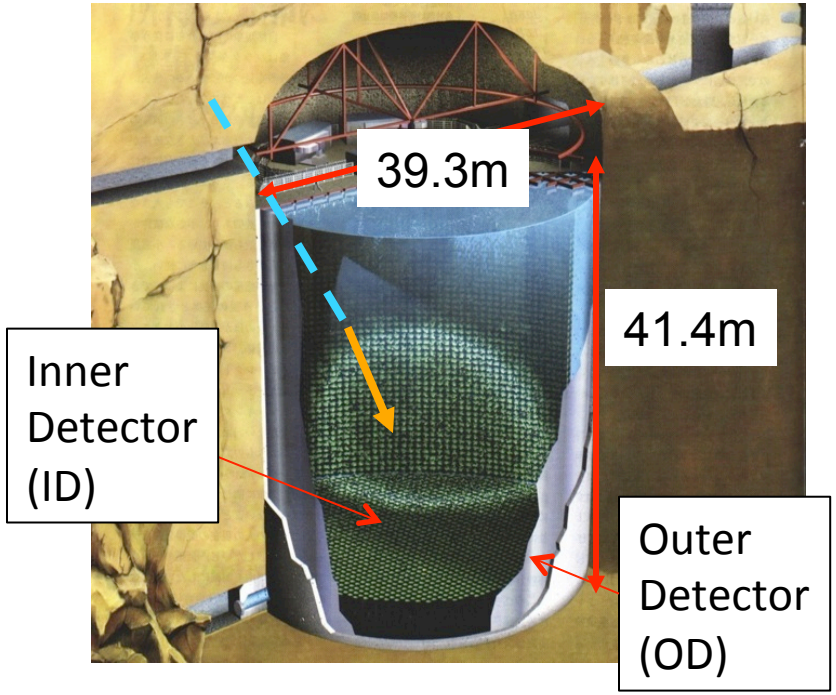
event display

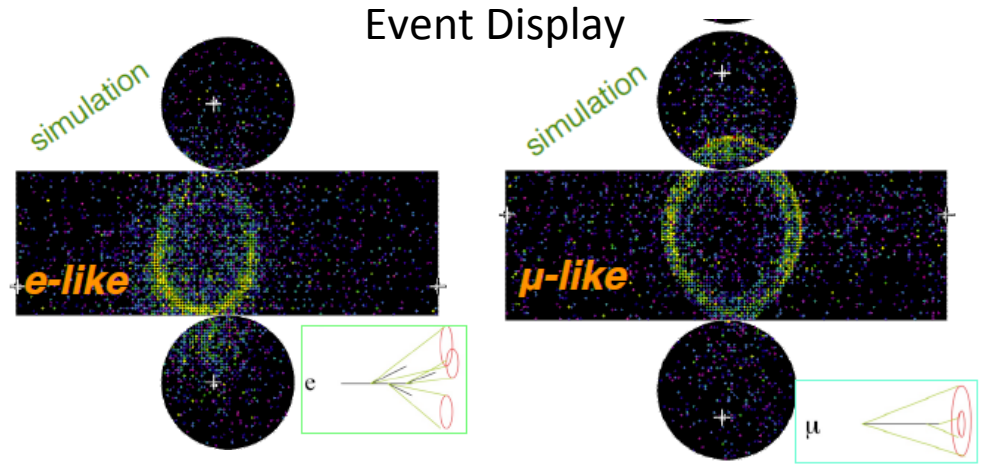


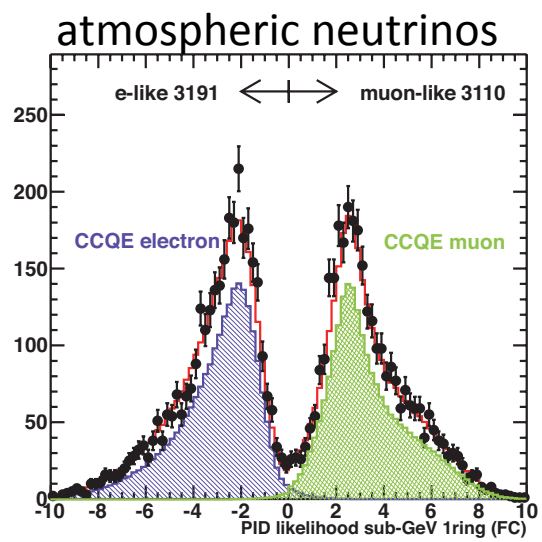
TPC FGD

- 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

T2K Far detector: Super-Kamiokande IV





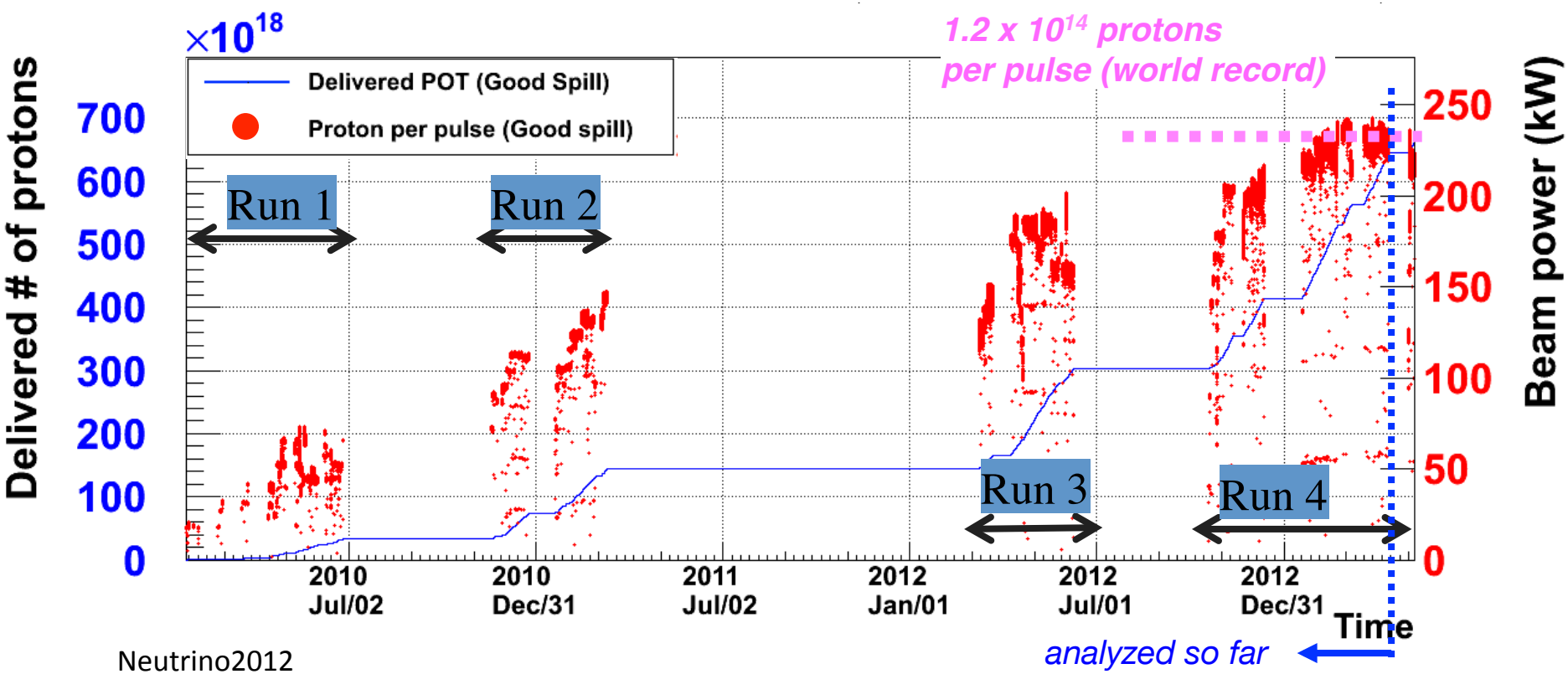


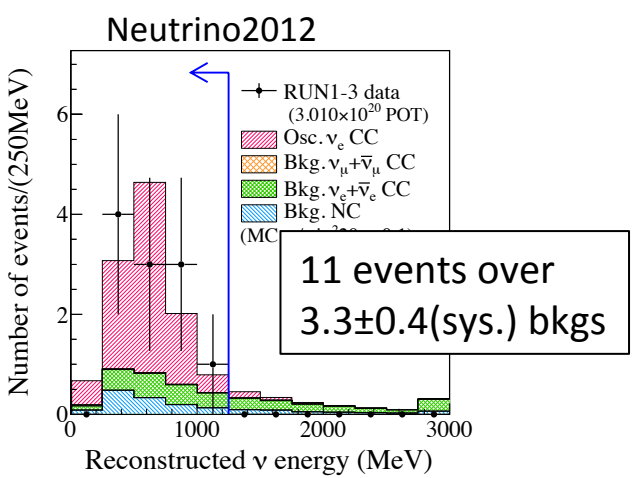
Particle Identifier

- Ring-imaging Water Cherenkov Detector, located at 1000m underground, Kamioka-Mine, Gifu-pref. Japan
- 22.5kton Fiducial Volume.
- SK-I had started 1996, over 10yr operation.
- SK-IV with deadtime-less DAQ : 2008~

- 4π acceptance, very efficient π^0/e separation.
- High Particle ID (μ/e) power (~99% at 600MeV/c)
- Good energy reconstruction.

T2K Data Taking





- JPARC has been stably running.
- Beam power reached at 235kW.

- Very stable operation of neutrino detectors.
- Previous appearance result (2013) is based on 3.01×10^{20} POT. → 6.39×10^{20} POT

T2K Analysis Strategy

ν Flux Prediction

- Based on Hadron int. model with NA61/SHINE measurements
- T2K beamline measurement

ν Interaction Model

- *NEUT* as a baseline
- Uncertainties are estimated from external data

ND280 Measurement

- ν_μCC enhanced samples are utilized to constraint model parameters.
- Intrinsic ν_e and NC π^0 measurements as cross-check

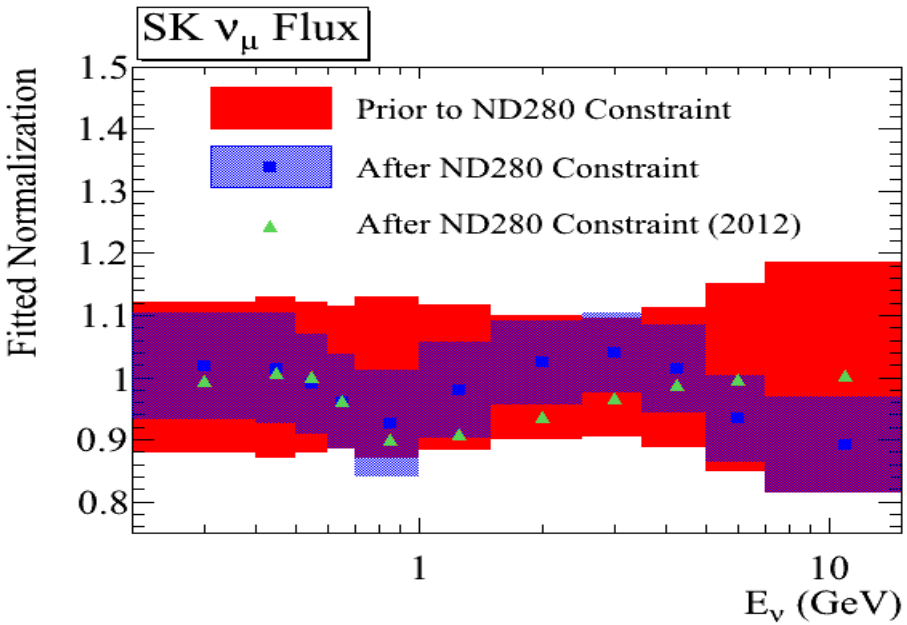
Constraint on Model Parameters

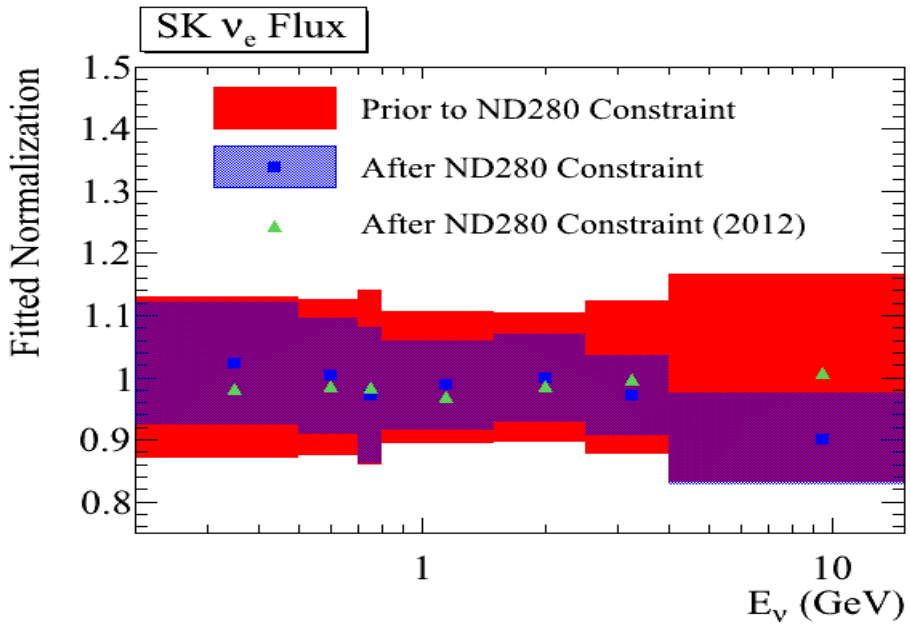
Prediction at T2K far Detector
Tuned by ND280 Measurements

Comparison & extract ν osc. parameters

Observation at Super-Kamiokande

Constrained ν Flux at Far Detector and ν Cross Section Parameters





Parameter	Prior to ND280 Constraint	After ND 280 Constraint	After ND280 Constraint (2012)
M_A^{QE} (GeV)	1.21 ± 0.45	1.22 ± 0.07	1.27± 0.19
M_A^{RES} (GeV)	1.41 ± 0.22	0.96 ± 0.06	1.22± 0.13
CCQE norm.	1.00 ± 0.11	0.96 ± 0.08	0.95± 0.09
CC1π norm.	1.15 ± 0.32	1.22 ± 0.16	1.37± 0.20

- Uncertainty of the ν flux & cross sections reduces by utilizing ND280 T2K neutrino data.
- Improvement from 2012 analysis is achieved.

ν_e appearance analysis

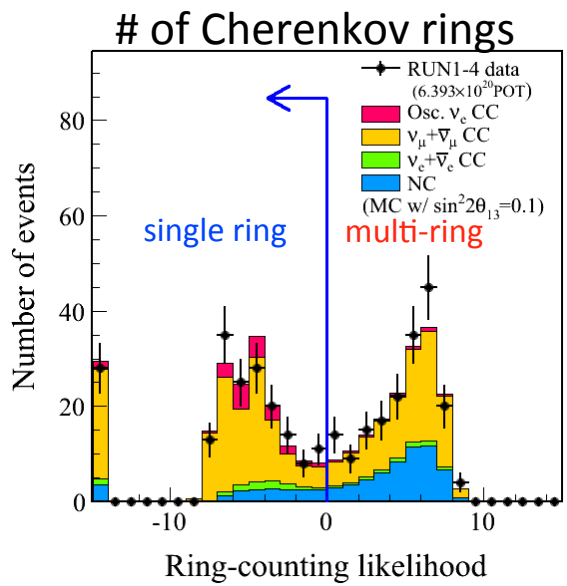
T2K ν_e event selection at Far Detector

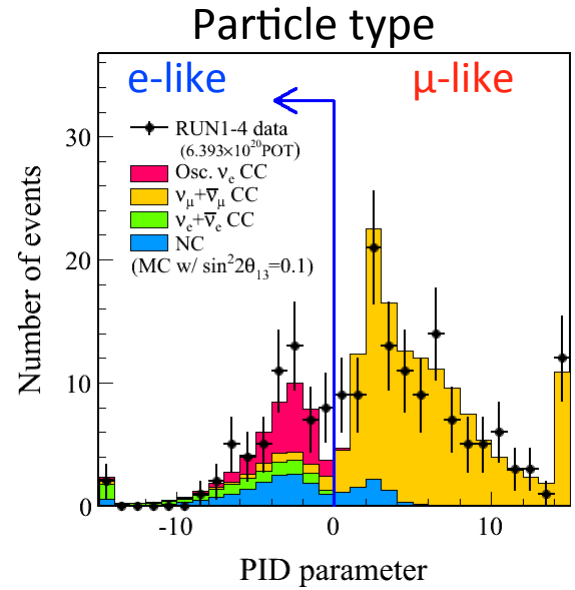
- Enrich ν_e CCQE events:
  $\nu_e + n \rightarrow e^- + p$

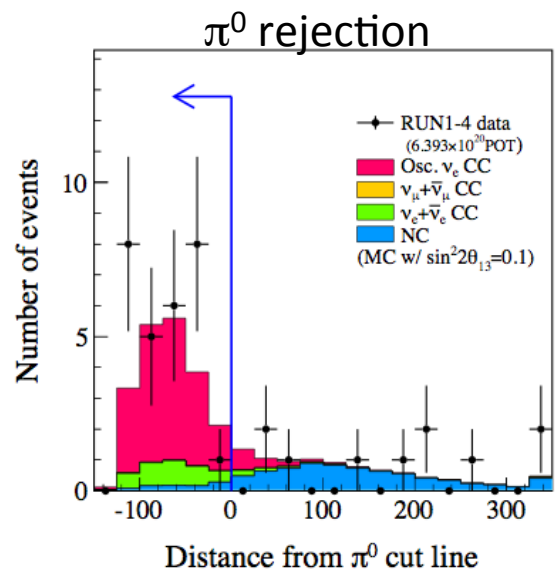
- Beam on-timing & Fully-contained (FC) in ID
- Vertex in the fiducial volume
- One Cherenkov ring
- Particle is identified as electron
- Visible energy > 100MeV
- No delayed electron signal
  - ✓ rejects events with invisible μ, π
- Reconstructed ν energy < 1.25GeV
  - ✓ rejects intrinsic beam ν_e at high energy
- Non-π^0-like ← New algorithm

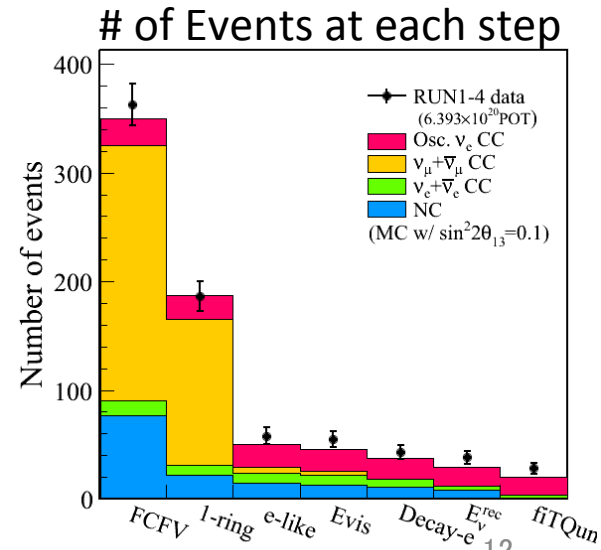
- We developed new algorithm of π^0 rejection, and reduce background events:

6.36 events → 4.64 events
(for this dataset)









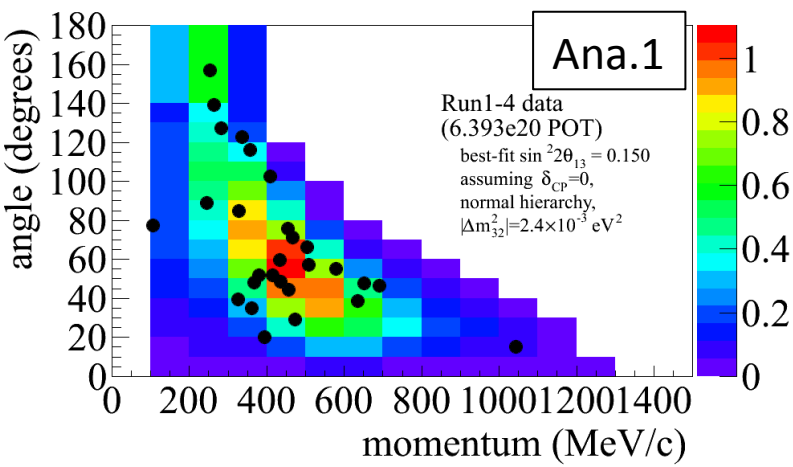
ν_e Appearance Analyses

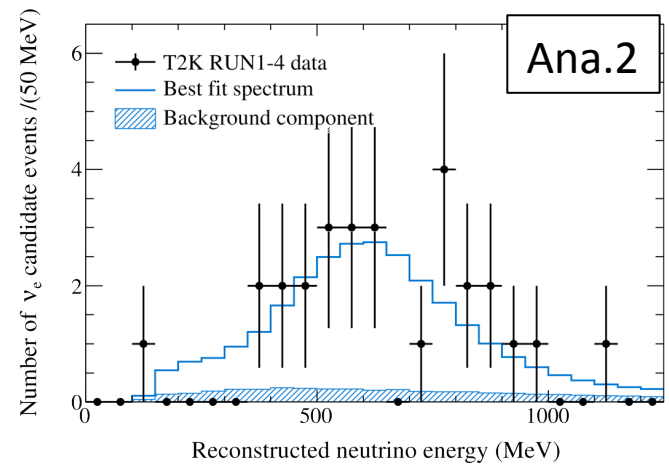
Two type of the analyses are carried out:

1. Maximum likelihood fit w/ Rate + (p_e , θ_e) shape
2. Maximum likelihood fir w/ Rate + reconstructed E_ν

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

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





For Run 1-4 data (6.63×10^{20} POT),

4.64 ± 0.53 background events

20.4 ± 1.8 events expected For $\sin^2 2\theta_{13}$=0.1, $\sin^2 2\theta_{23}$=1, δ_{CP}=0, normal mass hierarchy

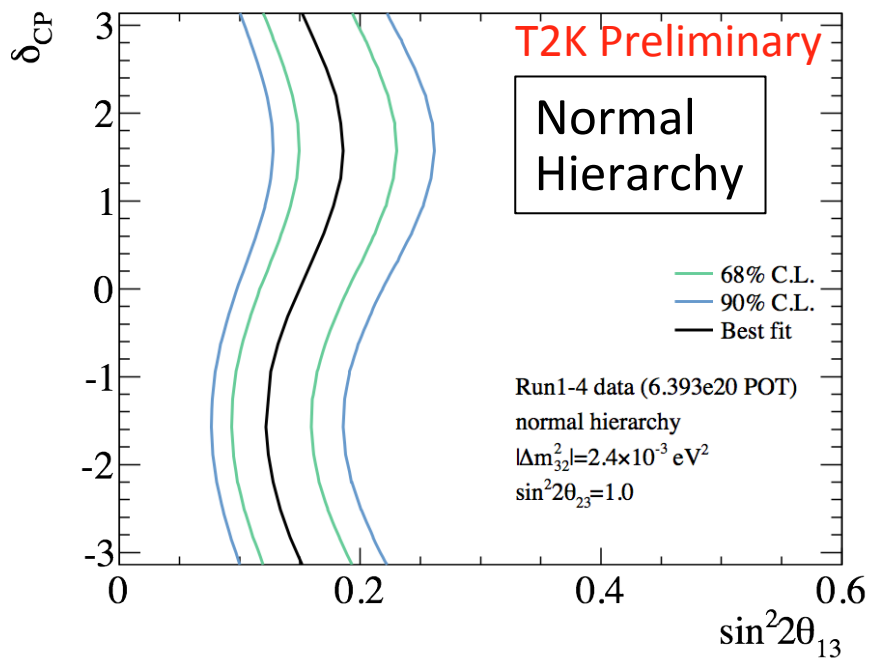
5.5σ sensitivity to exclude θ_{13} = 0

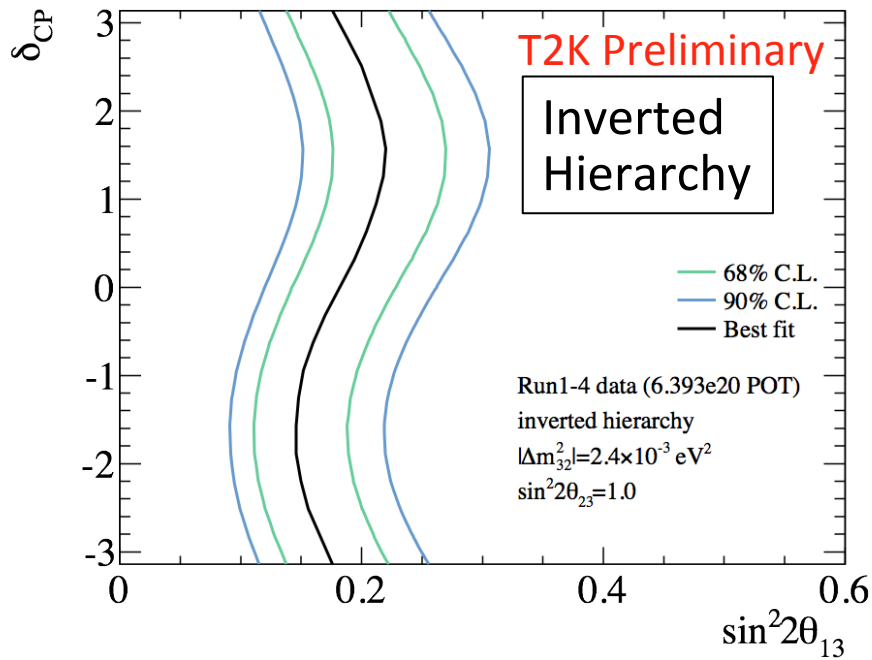
ν_e Appearance Analyses

- **Observed 28 events** (expected 20.4 ± 1.8 for $\sin^2 2\theta_{13}$=0.1)
- Comparing the best p-θ fit likelihood to null hypothesis (Analysis 1) gives a **7.5σ significance for non-zero θ_{13}**

(For $\sin^2 2\theta_{23}$=1, δ_{CP}=0, and normal mass hierarchy)

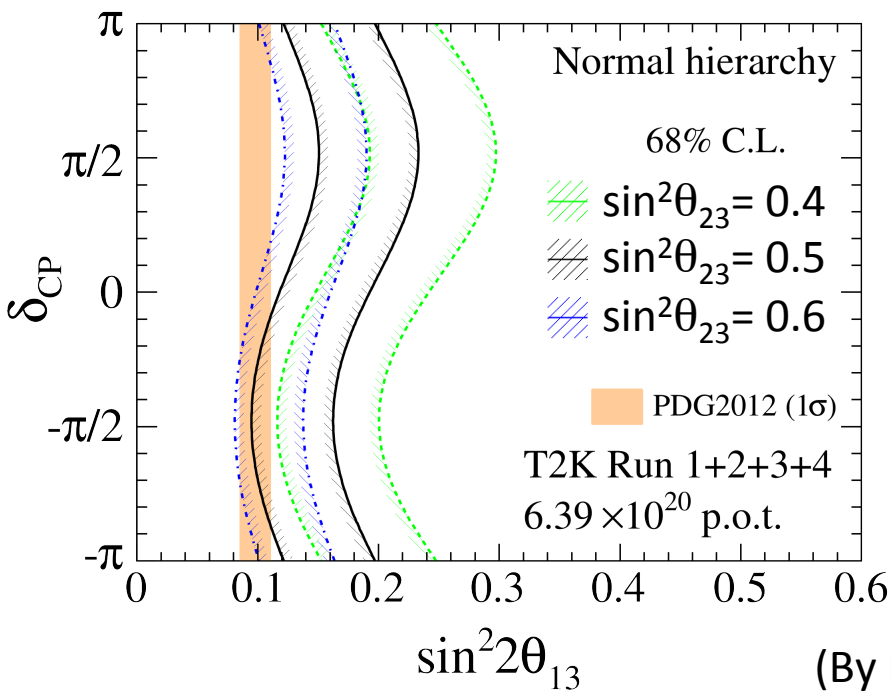
Definitive observation of electron neutrino appearance !

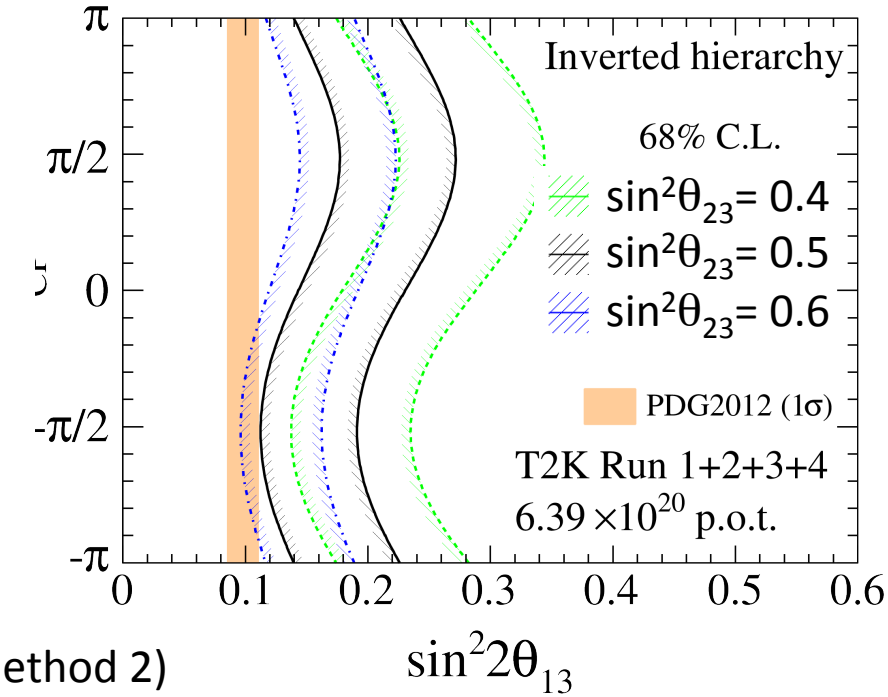




NOTE: These are 1D contours for various value of δcp, not 2D contours

Effect of θ_{23} Uncertainty





(By Method 2)

- ν_e appearance probability also depends on the value of θ_{23}

  $P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(\Delta m^2_{31} L/4E)$
- Future improved measurements of θ_{23} will be important to extract information about other oscillation parameters (including δ_{CP}) in long-baseline experiments
- A T2K combined $\nu_e+\nu_\mu$ analysis is underway

NOTE: These are 1D contours for various value of δcp, not 2D contours

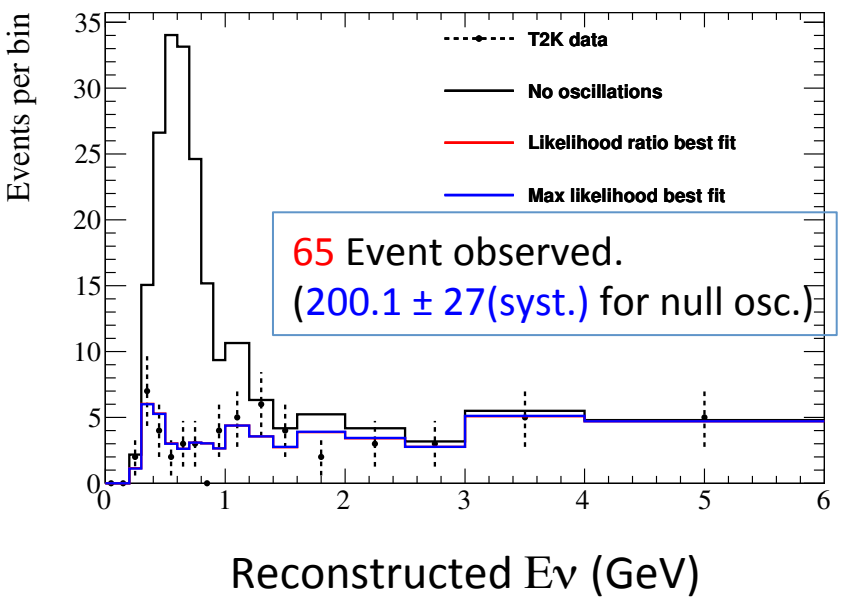
ν_μ disappearance analysis

Recent result of ν_μ disappearance analysis

- We reported the preliminary results using Run 1-3 data ($3.01*10^{20}$ POT) earlier this year.
- Previously we gave allowed region on $\sin^2 2\theta_{23}$ assumed $\theta_{23} < \pi/4$ (first octant). It is realized that results depends on the choice of the 1st/2nd octant.

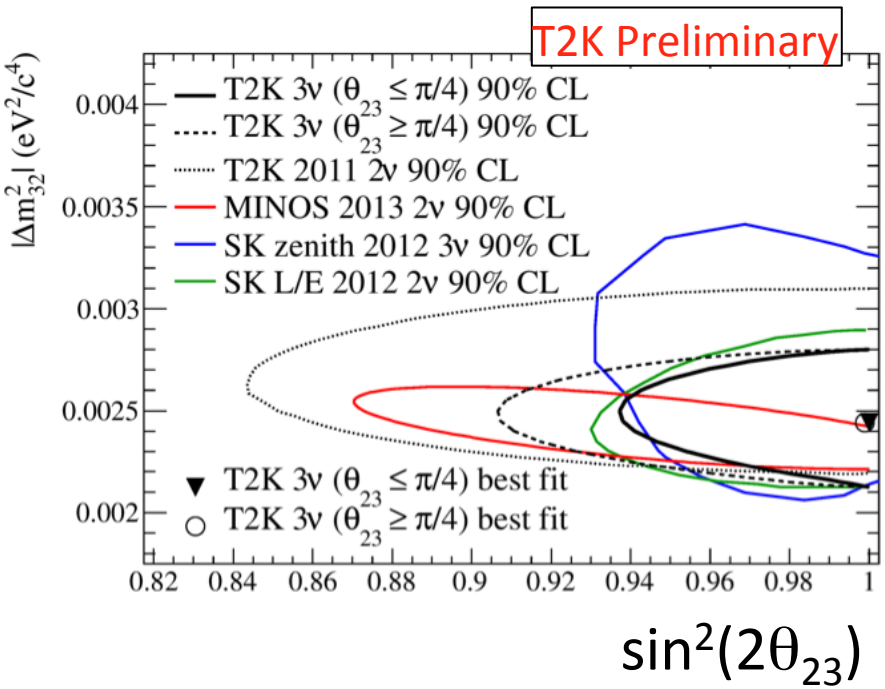
$$P(\nu_\mu \to \nu_\mu) \sim 1 - \left(\cos^4\theta_{13}\cdot\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\cdot\sin^2\theta_{23}\right)\sin^2\frac{\Delta m_{31}^2\cdot L}{4E}$$

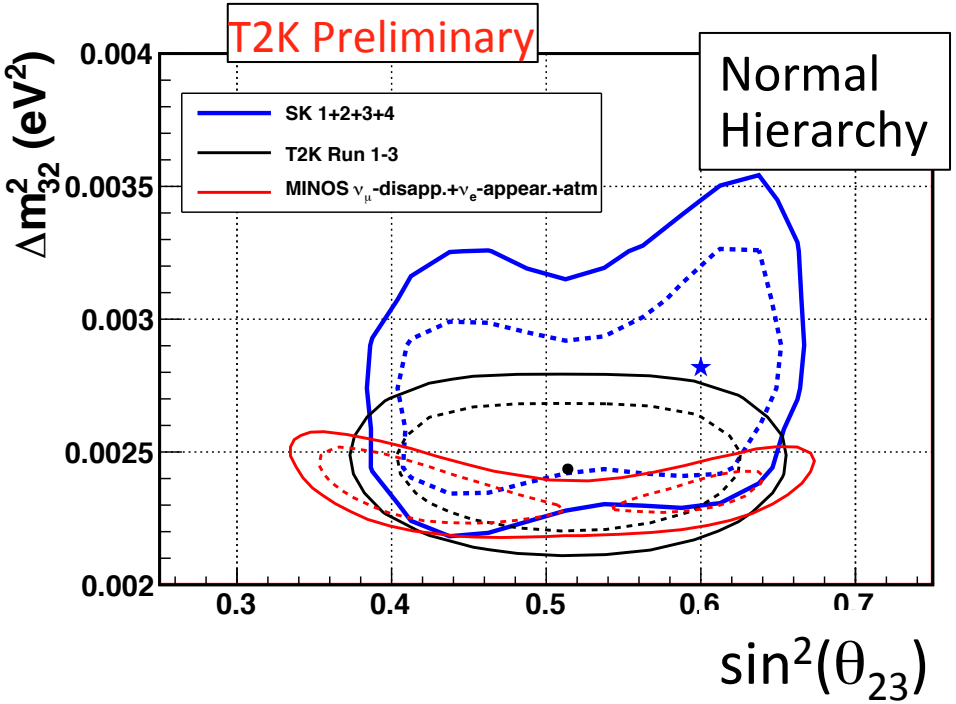
Leading Next-to-leading



ν_μ disappearance is studied using normalization information & spectrum shape.

ν_μ disappearance analysis with 3.01×10^{20} P.O.T. data





MINOS: taken from DPF 2013 (Alexander Radovic)

- Octant choice can significantly affect the shape of the 90% C.L. contour in ($\sin^2 2\theta_{23}$, Δm^2_{32}) plane in previous results.
- We construct allowed region on ($\sin^2\theta_{23}$, Δm^2_{32})plane.
- Best fit point was found slightly in 2nd octant.
- Allowed region on $\sin^2\theta_{23}$ is consistent with other experiments.

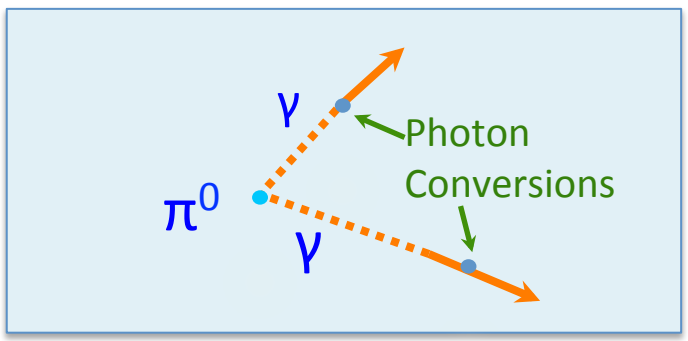
Summary

- T2K has made the definitive observation of ν_e appearance from the ν_μ beam
  - Using 6.39×10^{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 π^0 background rejection at Super-K Far ν Detector, etc.
  - 28 candidate events over 4.6±0.5(sys.) backgrounds
  - $\theta_{13}=0$ is excluded at 7.5σ
- We start constructing allowed region on ($\sin2\theta_{23}$, Δm^2_{32}) from ν_μ disappearance analysis.
- We had reported the allowed region of the ($\sin2\theta_{23}$, Δm^2_{32}) plane via ν_μ disappearance analysis in early this year, but we realize the dependency on the choice of the 1st/2nd octant of $\sin2\theta_{23}$.

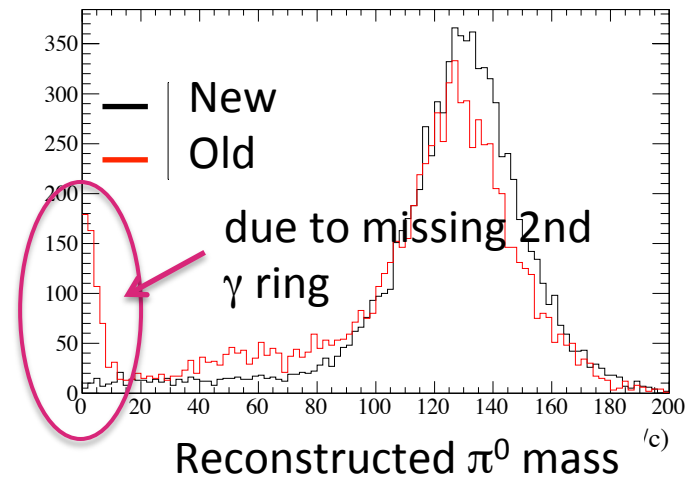
back up slides

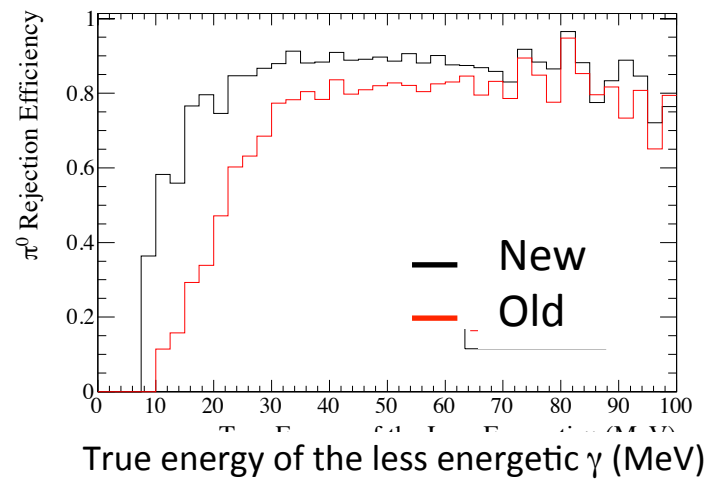
Improved π^0 Background Rejection

- New event reconstruction algorithm has been developed based on likelihood with multi-parameters (event vertex, direction, momentum, etc.). The parameters are fitted simultaneously. (cf. Previous tool is search the parameter space step-by-step.)



"π^0 particle guns" MC (0-500MeV/c)

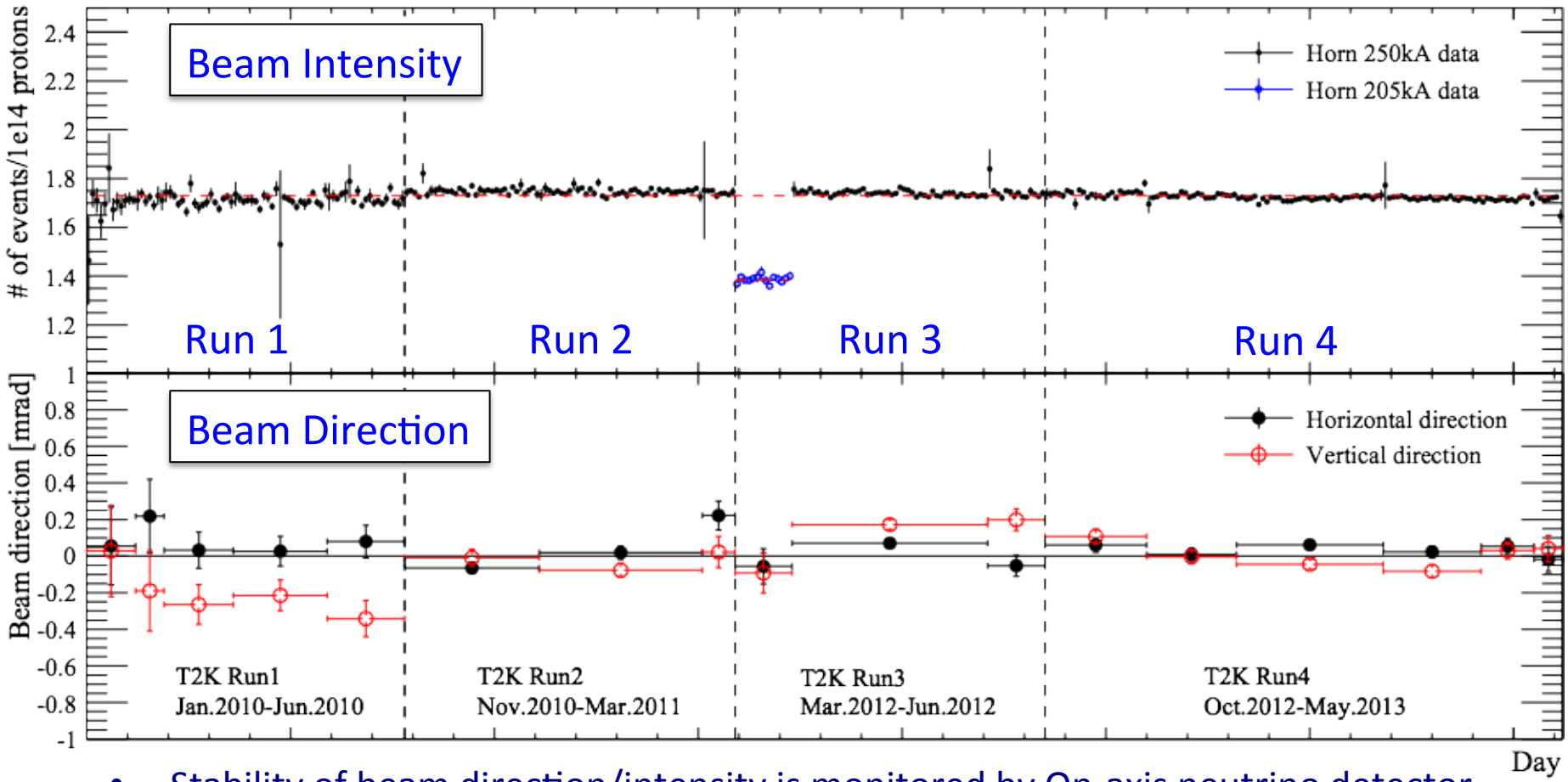




- New algorithm has more sensitivity for lower energy γ's.
- Apply cut in 2D space of (likelihood ratio of electron-like/π^0 -like) vs π^0 inv. mass.
- Better rejection power is achieved. Total B.G. reduces:

6.36 events → 4.64 events (for this dataset)

Beam stability



- Stability of beam direction/intensity is monitored by On-axis neutrino detector (INGRID)
- 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)

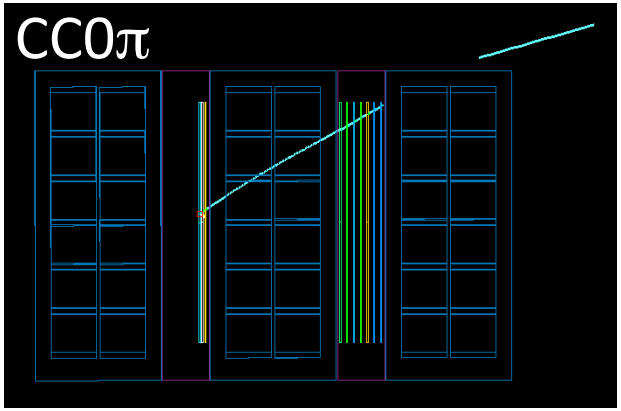
ND280 constraint

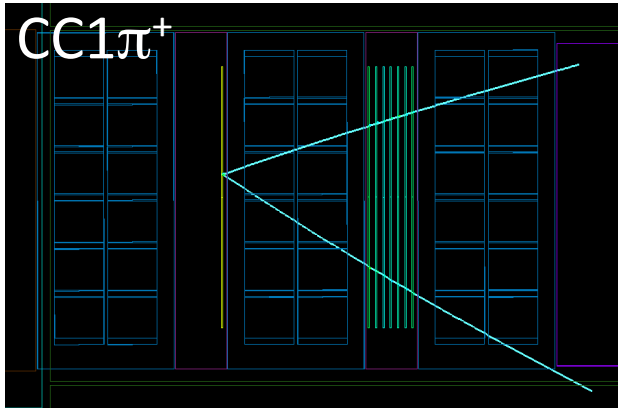
ν_μCC sample classification : CC0π, CC1π^+, Ccother

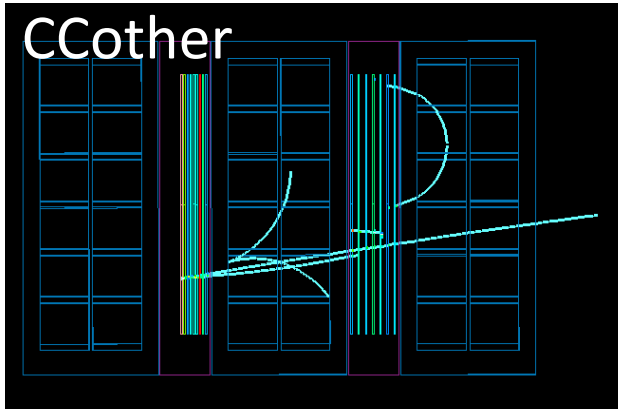
- In 2012 analysis, 2 categories : CCQE-like (1 track) & CCnonQE-like (2 tracks)
- Much better samples for constraining CCQE & CC1π cross section parameters

Data are binned in two dimensions : μ momentum (p) and angle (cosθ)

- 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 %

Predicted Number of ν_e Candidate Events

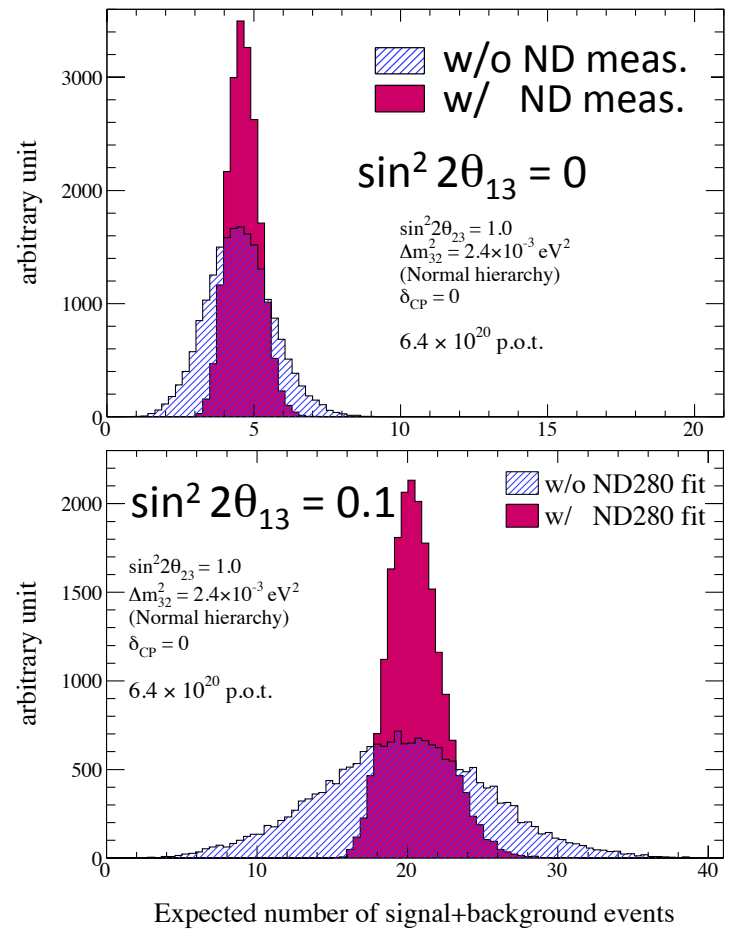
Predicted # of events w/ 6.393×10^{20} p.o.t.

Category	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
ν_e signal	0.38	16.42
ν_e BG	3.17	2.93
ν_μ 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 + ν int. (ND meas.)	4.9 %	3.0 %
ν 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 %

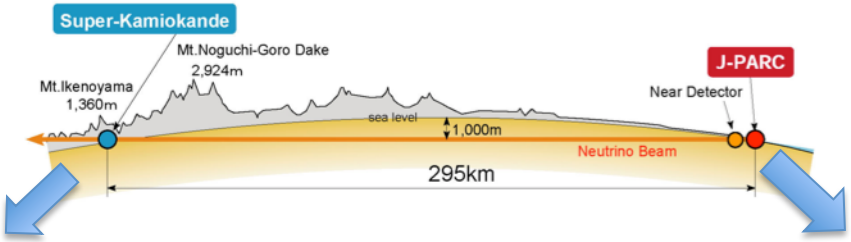
Predicted # of events w/ sys. error



Uncertainty reduced much by the ND measurement

Selection of T2K beam neutrino event at Super-Kamiokande

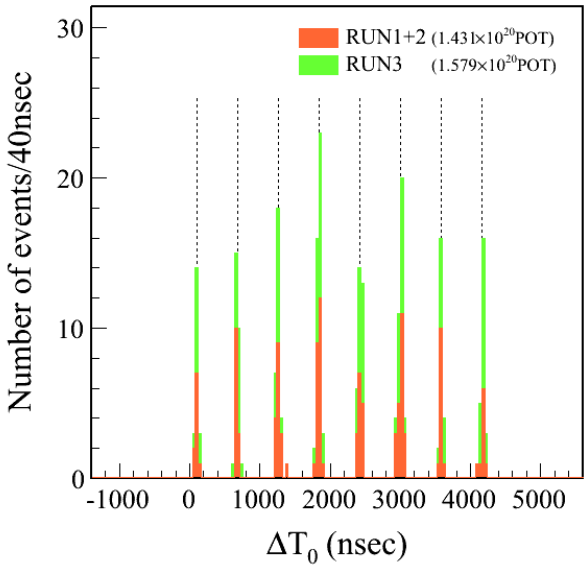
- Select PMT signals in a interval (1ms) at expected arrival time of beam neutrinos.



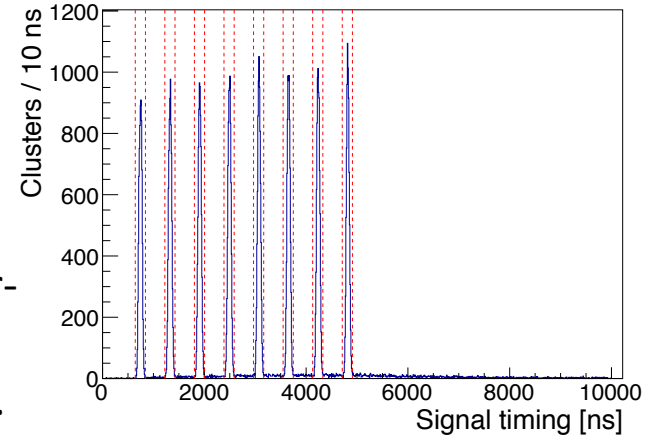
Observed SK event timing
(relative to beam arrival time)

Accelerator issues time stamp to ND280, and to Super-K delivered via Network

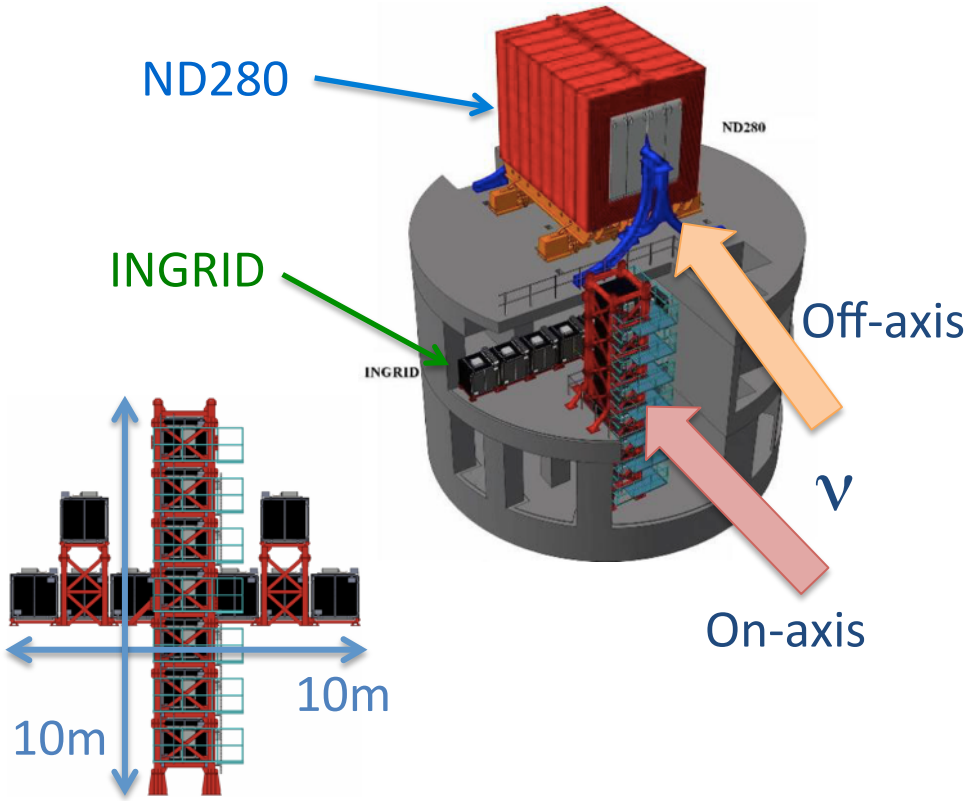
Observed ND280 event timing
(relative to beam time)

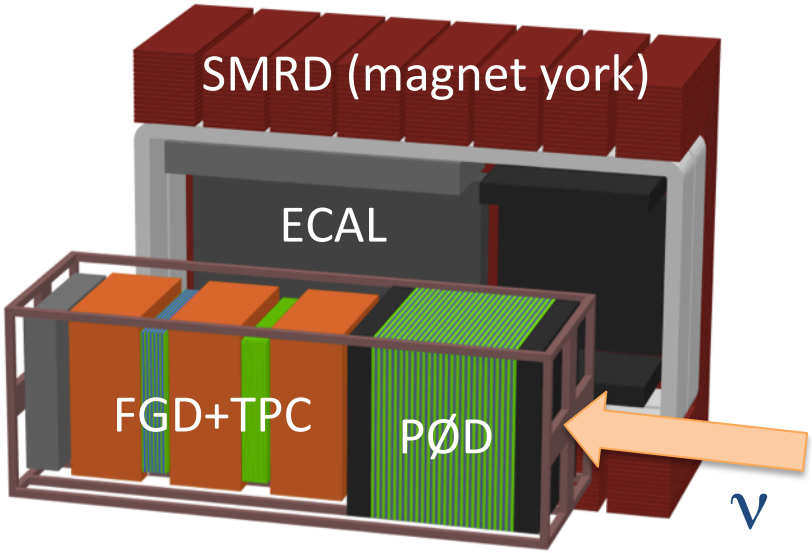


Clearly micro-bunch structure observed in Super-K and ND280.
→ Timing is well controlled.



3. Near neutrino detectors (@280m downstream)





On-axis detector (INGRID)

- direct ν beam day-by-day monitoring (direction, intensity and profile)
- 16 cubic modules. Sandwich of iron plates and scintillator planes

Off-axis detector (ND280)

- measures ν flux/spectrum before oscillations @2.5° off-axis angle
- 0.2T dipole magnet
- Fine Grained Detectors (FGDs) x2
  1.6ton fiducial mass target + tracking
- Time Projection Chambers (TPCs) x3
  PID by dE/dx in gas, resolution <10%
- PØD (π^0 detector)
  ECAL (Electromagnetic calorimeters)
  SMRD (Side Muon Range Detector)

Predicted Number of Events at Each Cut

		ν_μCC	ν_eCC	NC	BG all	Sig. ν_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_ν^{rec} <1.25GeV	0.2	3.5	8.0	11.8	17.9
(8)	fiTQun π^0 cut	0.06	3.1	0.9	4.0	16.4
	Efficiency	<0.1%	20%	0.3%	0.7%	64%
(8)'	POLfit π^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

Old Cut

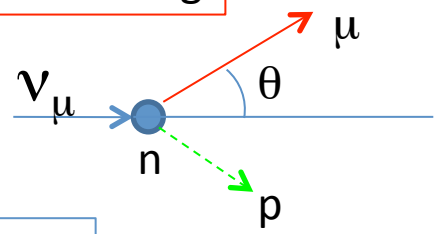
NC BG reduced to ~40% compared to previous ν_e selection

with keeping signal efficiency high

ν_μ disappearance ($\nu_\mu \rightarrow \nu_x$ oscillation) in T2K

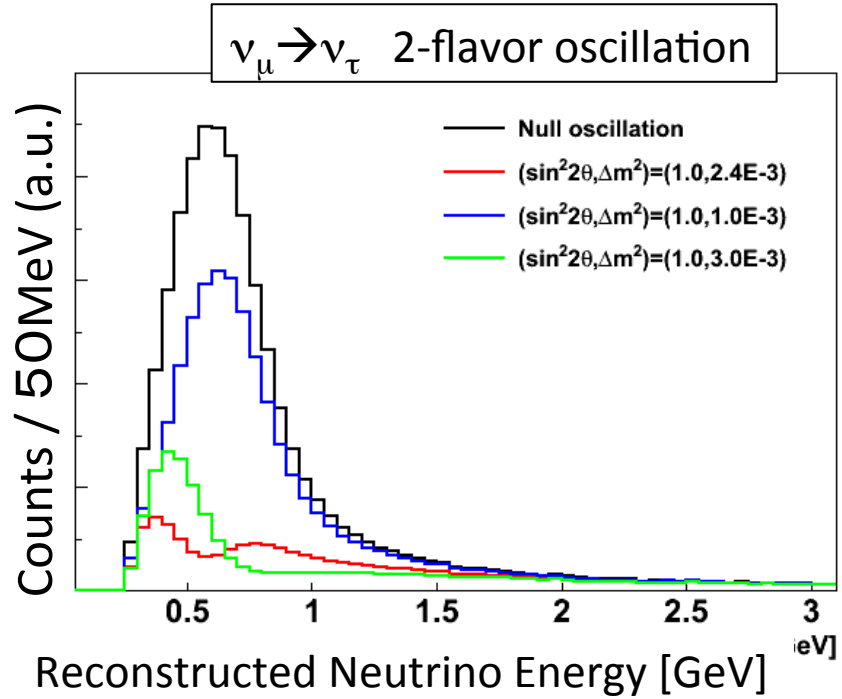
Investigate skew of energy spectrum of ν_μ with CCQE ν_μ enriched sample

CCQE scattering



Selection Criteria:

- T2K beam timing & FCFV
- 1 Cherenkov ring
- muon-like
- one or 0 delayed electron signals .
- Muon equivalent momentum > 200MeV/c



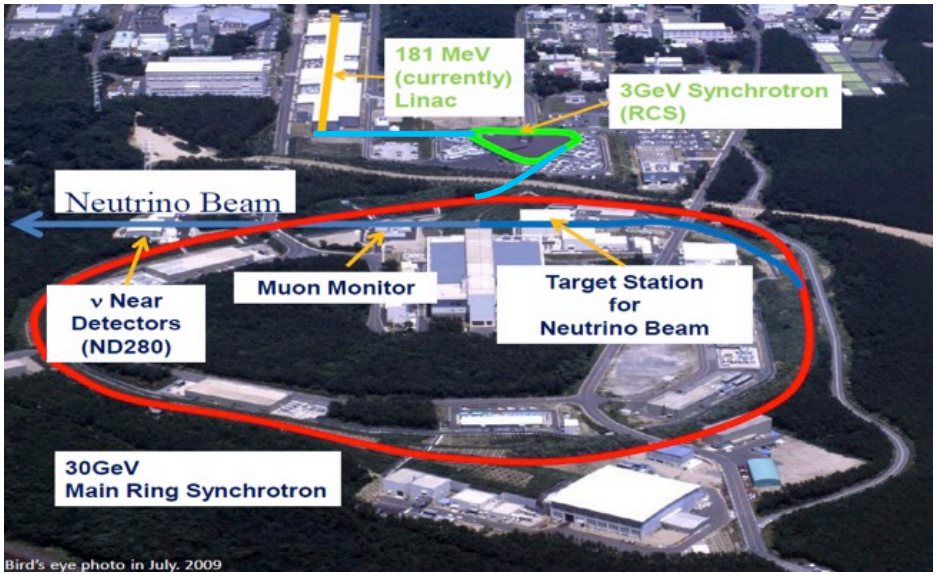
CCQE ~ 50%, (after ν osc.)

CC1π (ν+N$\rightarrow\mu$+$\Delta\rightarrow\mu$+N'+π) ~ 30%,

NC ~ 6% (mainly π+- and proton)

$$E_\nu = \frac{m_N \cdot E_l - m_l^2/2}{m_N - E_l + p_l \cdot \cos\theta_l}$$

Experimental Setup:
1. J-PARC Accelerator and Experimental Facility

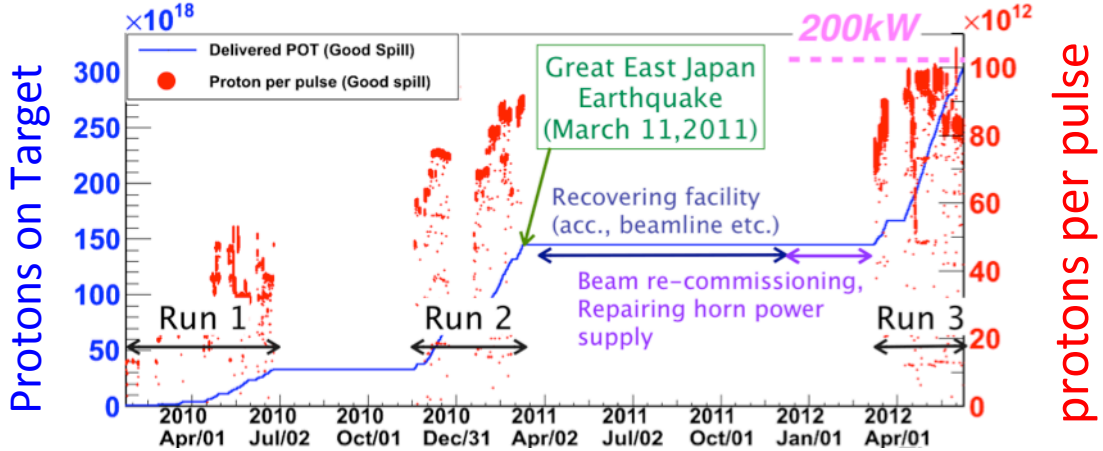


- 30GeV Proton synchrotron
- 6 bunch (before Autumn 2010)
- 8 bunch (2010 Autumn -)

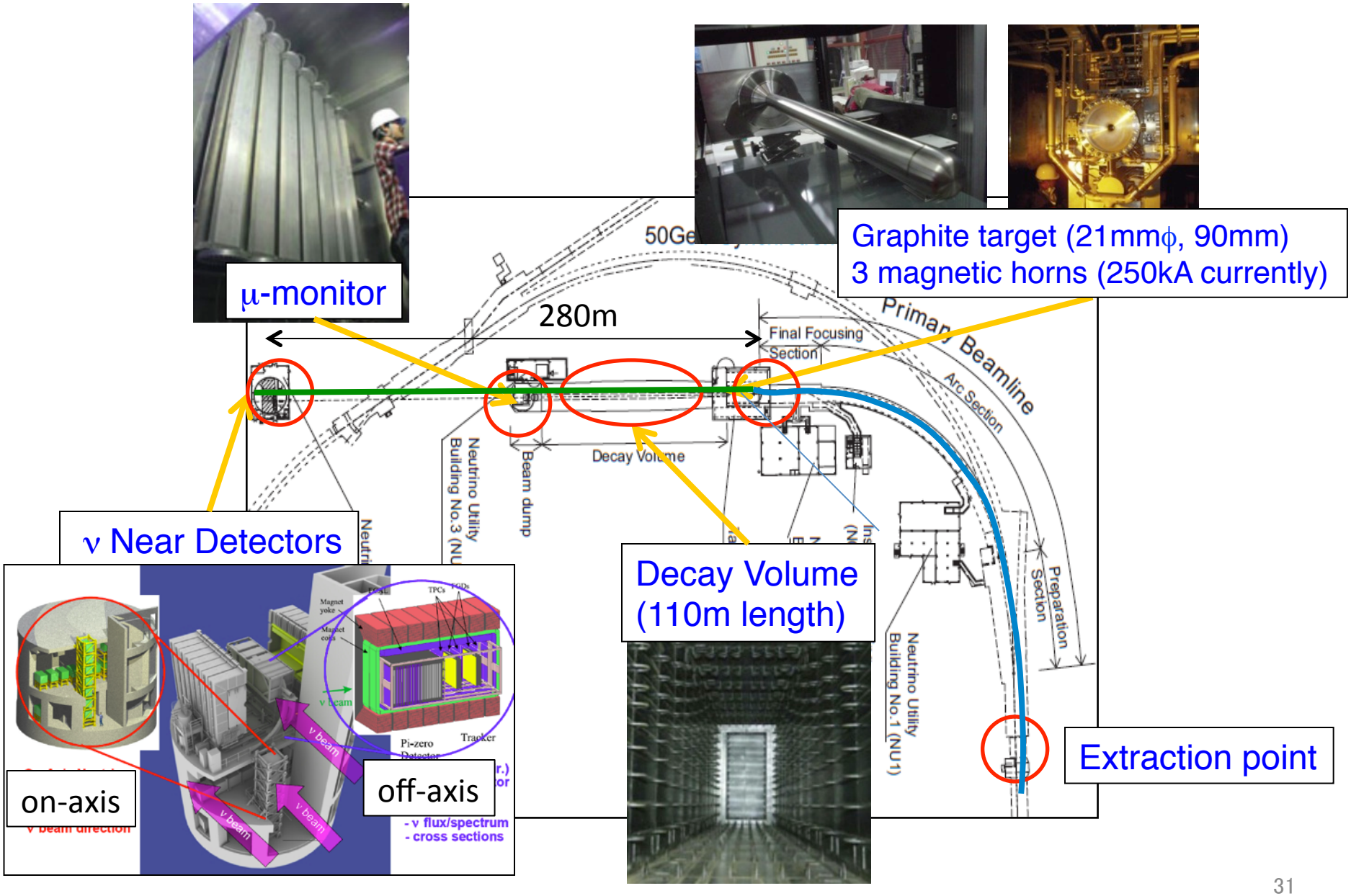
- 581ns interval
- ~ 0.3 Hz repetition rate
- Construction finished 2008 JFY

Fast Extraction
→ pulsed neutrino beam

- Accelerator facility, beam monitors, neutrino detectors are stably running
- Today's reults based on before last summer (3.01×10^{20} P.O.T.)

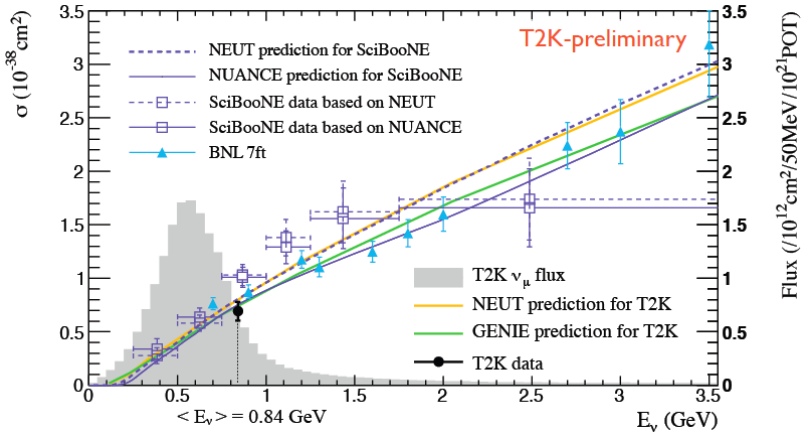


2. Neutrino Beam line



Other studies in T2K

- Cross section measurements
  - Preliminary results from the flux averaged ν_μCC inclusive cross section measurement



- Nuclear g-rays from de-excitation of residual nuclei (^{15}O, ^{16}N,..) induced by Neutral Current scattering of ν.

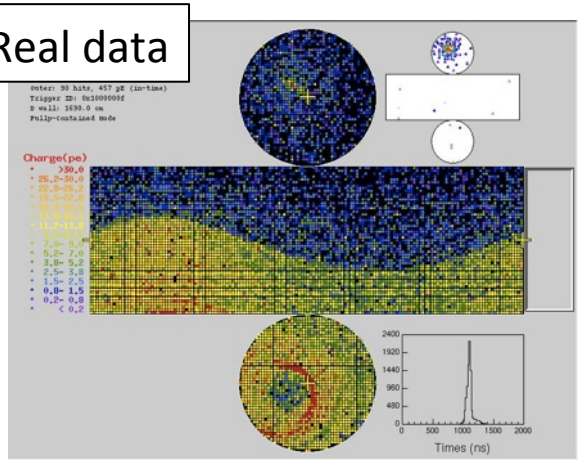
ex.) $\nu + {}^{16}O \rightarrow \nu + p + {}^{15}O^* \rightarrow \gamma(6\text{MeV})$ + residuals.

- Sterile neutrino search at T2K using NC nuclear de-excitation γ-rays
  - Preliminary results w/ Run1+2 data

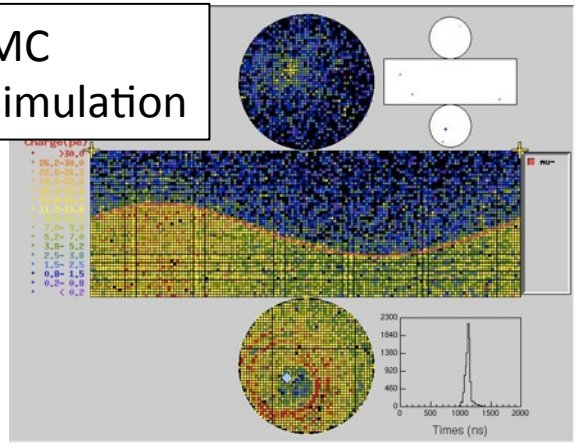
and more …

Calibration of the detector

Real data



MC simulation

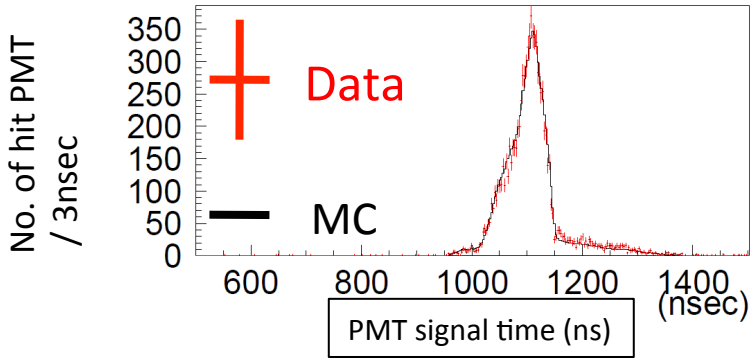


Detailed Calibration works has been done intensively with in-situ & ex-situ sources: (pulse laser, CRμ, electron LINAC, ..)

- Timing response of PMTs
- Gain of PMTs
- Water transparency measurement
- Detector Uniformity …

Well test the event reconstruction performance

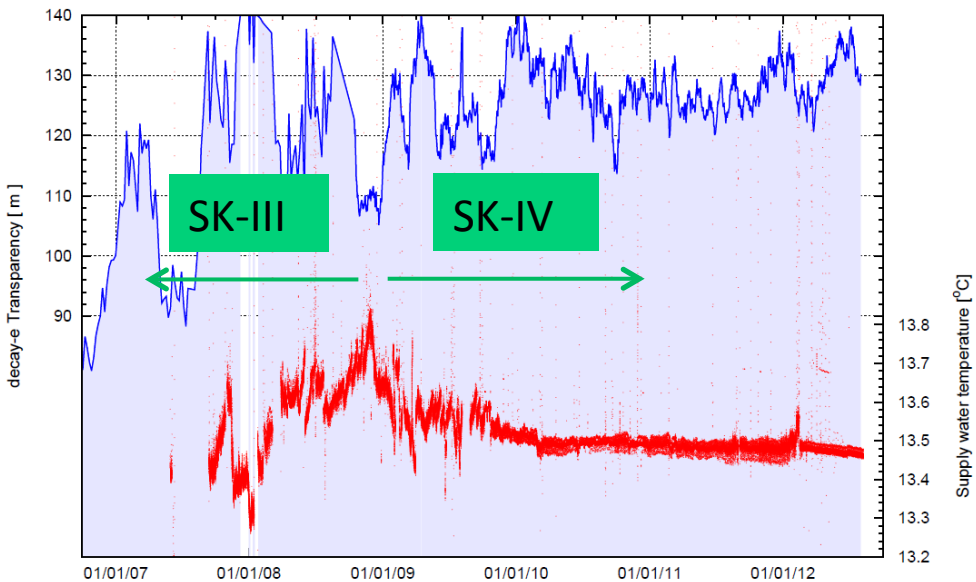
- Vertex, direction
- Particle identification
- Energy reconstruction, …

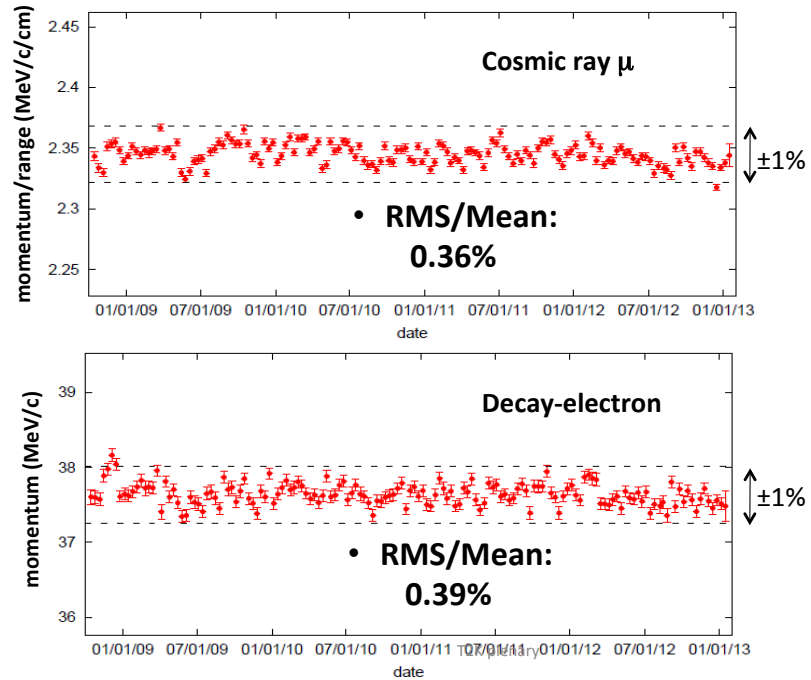


Full Monte Carlo (MC) simulation has been developed based on measurements of fundamental parameters & available models.

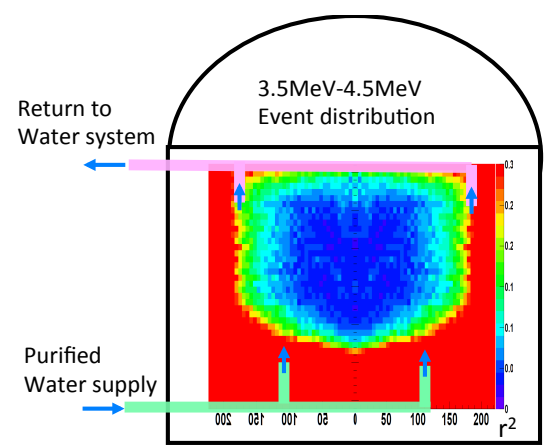
Stability

Key issue is a water quality.



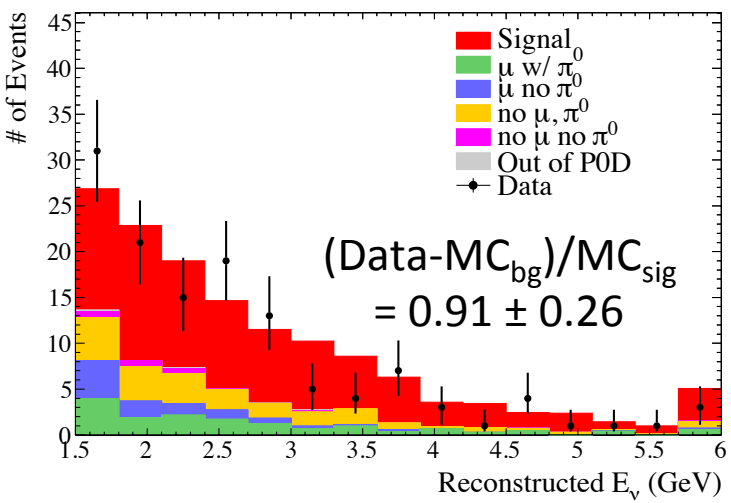


- Keep water quality by continuous purification of the water.
- Carefully control the flow inside Super-K
- Water transparency is continuously monitored and taken into account in event reconstruction.
- 1% level stability of energy estimation.

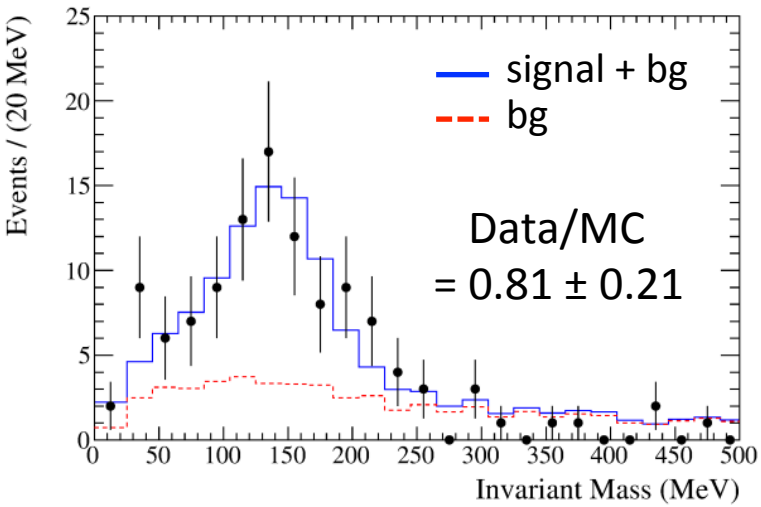


ND280 ν_eCC and NC π^0 checks

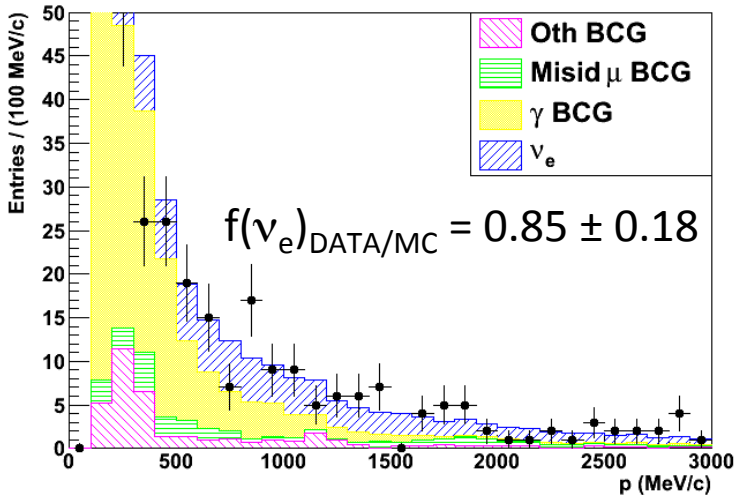
High energy ν_e events (PØD)



NC π^0 events (PØD)



Enhanced ν_e events (Tracker)



- Dominant BG for ν_e appearance search are measured at ND280
  - Intrinsic beam ν_eCC
  - NC π^0
- Data consistent with MC prediction

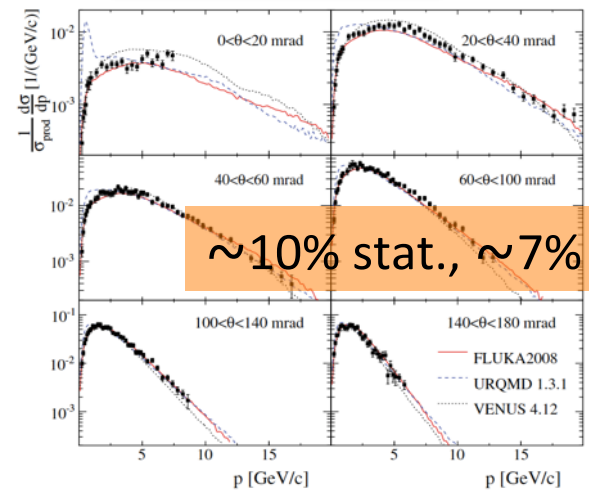
Flux prediction

Full simulation based on measurements:

- T2K proton beam profile measured by beam monitors
- π, K production cross section tuned mainly by NA61/SHINE(@CERN) measurements: hadron (π/K) production with 30GeV protons and a graphite target

NA61 π^+ data

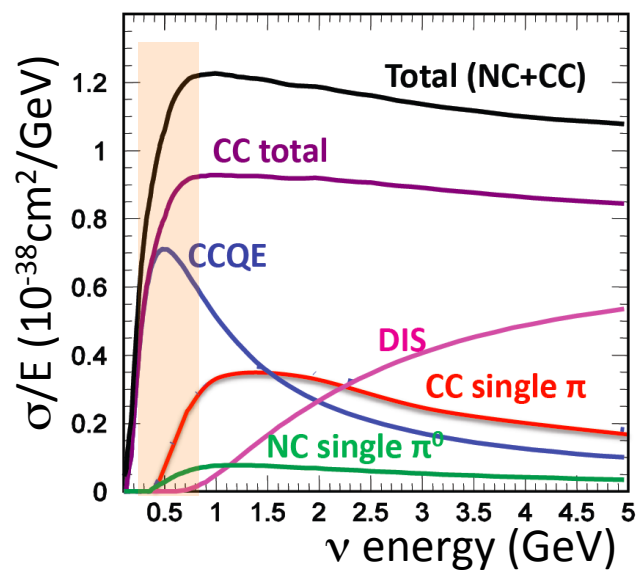
Phys.Rev.C 84, 034604 (2011)



~10% stat., ~7% sys.

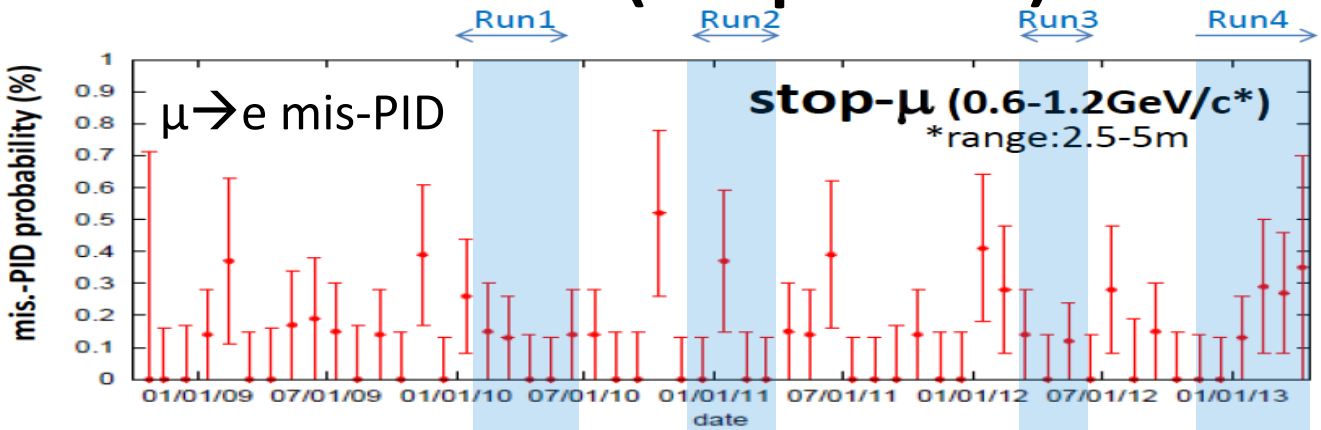
Neutrino interactions

- NEUT model is used as a baseline.
- Uncertainties are set from fits to MiniBooNE data
  - Similar ν energy, multiple differential cross-section
  - K2K, SciBooNE data sets used as cross check
- Pion interactions in nuclei
  - Semi-classical cascade model



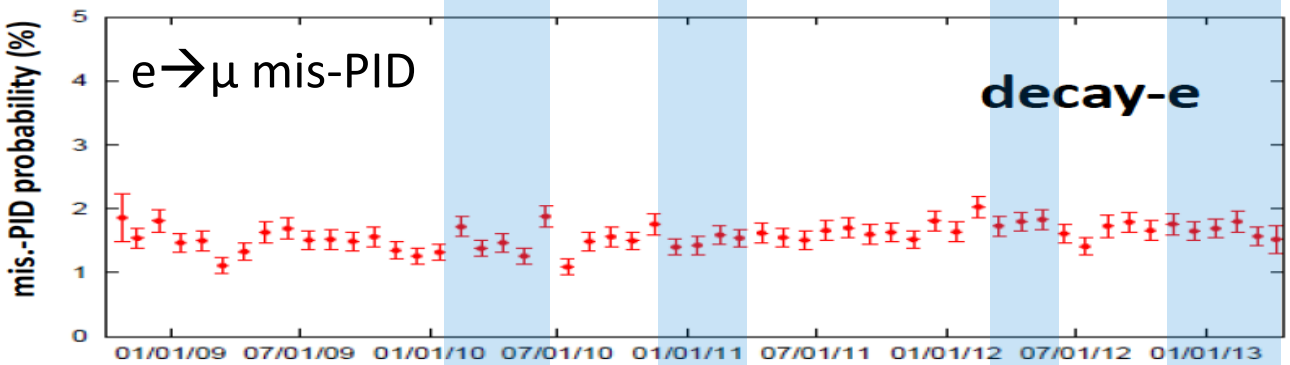
Far Detector (Super-K) Stability

mis-PID prob.



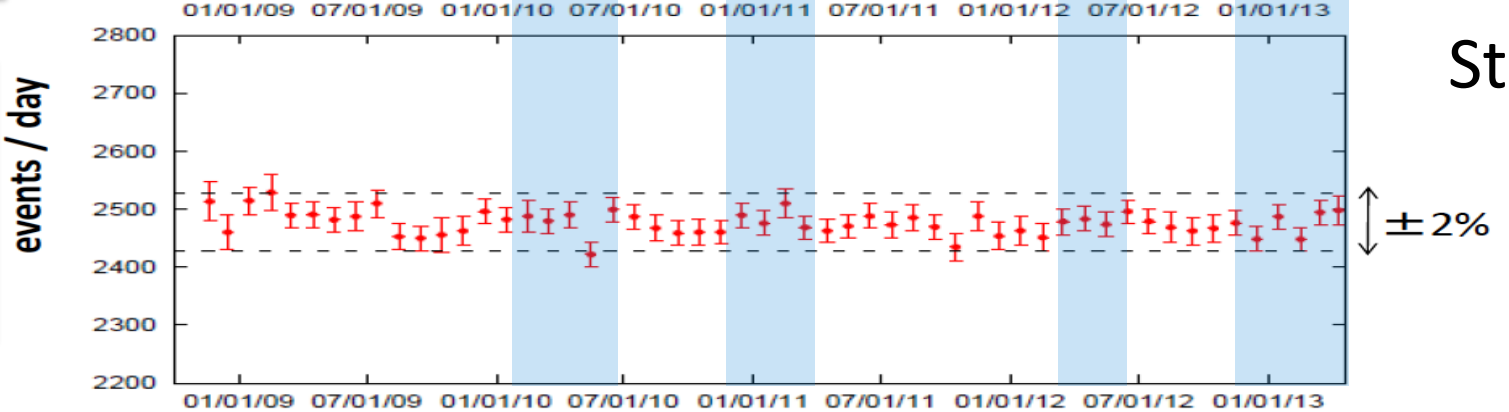
- RMS: 0.14%

mis-PID prob.



- RMS: 0.19%

Decay-e tagging eff.



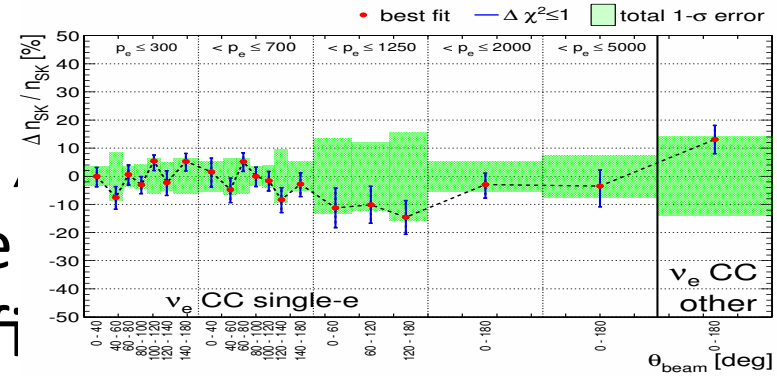
Stable

Far Detector (Super-K) Systematics

Dominant error coming from the ring-counting, PID, π^0 rejection cuts

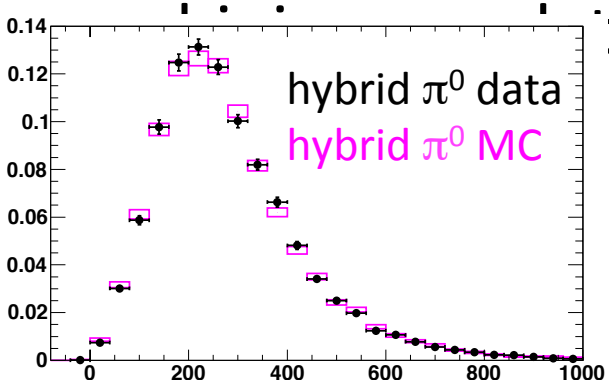
Error for ν_eCC components :

– Number of events in each (p_e …
atmospheric ν control sample …
evaluate the sys. errors on effi…



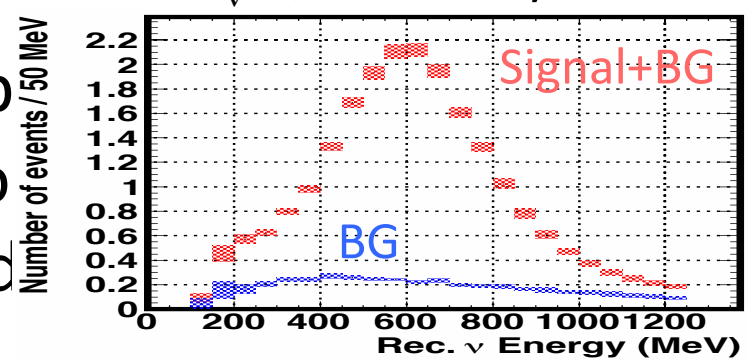
Error for π^0 BG components :

– π^0 topological control samp…
…a electro…
…γ (hybrid…



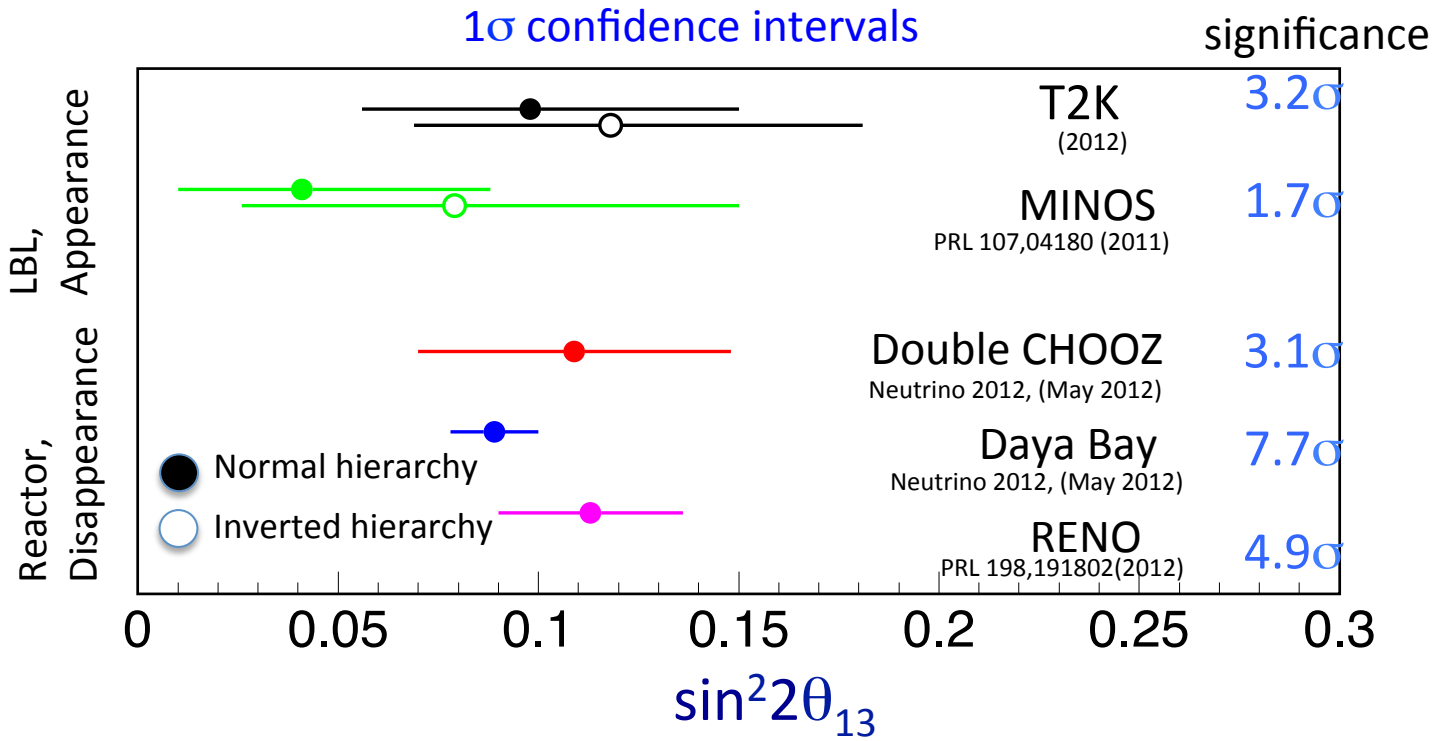
fiTQun π^0/e likelihood ratio

Rec. E_ν w/ total SK sys. errors



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

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

Non-zero θ_{13} search

- In 2011 June, T2K reported the first indication of $\theta_{13} \neq 0$ (2.5σ) using the data before the earthquake. PRL 107, 041801 (2011)
- A solid confirmation of $\theta_{13} \neq 0$ had been given by reactor neutrino experiments.
- Establishment of ne appearance is very important for CP violation & mass hierarchy problem