Evidence of Electron Neutrino Appearance in a Muon Neutrino Beam

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Neutrino physics for its oscillation

The behave of their mixing is explained by PMNS matrix (Pontecorvo-Maki-Nakagawa-Sakata).

$$|\nu_\alpha(t)> = \sum_i U_{\alpha i} |\nu_i(t)>$$

Flavor eigenstates ≠ **Mass eigenstates**

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

$$\Delta m^2 = |m_e^2 - m_\mu^2|$$

The oscillation of 2-flavor case:

$$P(\nu_e \rightarrow \nu_\mu) = \underbrace{\sin^2 2\theta}_{\text{mixing}} \sin^2\left(\frac{\Delta m^2}{4E}L\right)$$

+ CP phase

If the neutrino mixing exits (θ≠0) and neutrinos have masses (Δm≠0), the neutrino oscillation occurs.

Neutrino oscillation

The oscillation of neutrinos occur by the mixing of massive neutrinos.

- Θ_{12} : Solar ≈ 34°

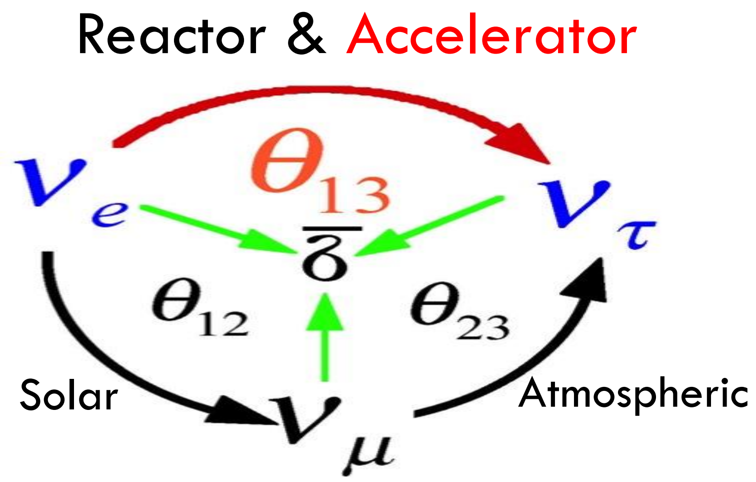
$$4\mathrm{P} \rightarrow {}^{4}\mathrm{He} + 2e^{-} + 2\bar{\nu}_{e}$$

- Θ_{23} : Atmospheric ≈ 45°

$$\pi^{-} \longrightarrow \mu^{-} + \overline{\nu_{\mu}}$$
$$\hookrightarrow e^{-} + \overline{\nu_{e}} + \nu_{\mu}$$

- Θ_{13} : Reactor and Accelerator

⇒ today's topic



$$P_{\nu_{\mu}\rightarrow\nu_{e}} \approx \sin^{2}\theta_{23}\ \sin^{2}\theta_{13}\ \sin^{2}\frac{\Delta m_{32}^{2}L}{4E_{\nu}} + \text{CP phase}$$

θ_{13}

reactor

$$P(\bar{\nu}_e \nrightarrow \bar{\nu}_e) = \underline{P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu) + P(\bar{\nu}_e \rightarrow \bar{\nu}_\tau)}$$

- Θ_{13} can be measured directly since Θ_{23} and CP phase are canceled.
- Event control is difficult.
- For the short distance, the there is no sensitivity for appearance.

accelerator

$$P_{\nu_\mu \rightarrow \nu_e} \approx \sin^2\theta_{23}\ \sin^2\theta_{13}\ \sin^2\frac{\Delta m^2_{32}L}{4E_\nu}$$

- Since the oscillation depends many parameter, the measurement of Θ_{13} is indirect.
- Event control is not difficult.
- Canceling the CP phase in the same way as upper blue line, θ_{23} is measurable.

At the accelerator, the direct measurement of Θ13 is hopeless,
but the measurement of CP has sensitivity.
⇒ **The complementarity of reactor and accelerator is very important !!**

The formula of the neutrino oscillation of $\nu_\mu \rightarrow \nu_e$

$$
\begin{aligned}
P_{\nu_\mu \to \nu_e} = & \frac{1}{(A-1)^2} \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 [(A-1)\Delta] \\
& -(+) \frac{\alpha}{A(1-A)} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \times \\
& \sin\delta_{CP} \sin\Delta \sin A\Delta \sin[(1-A)\Delta] \\
& + \frac{\alpha}{A(1-A)} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \times \\
& \cos\delta_{CP} \cos\Delta \sin A\Delta \sin[(1-A)\Delta] \\
& + \frac{\alpha^2}{A^2} \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2 A\Delta
\end{aligned}
$$

Here $\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{32}} << 1$, $\Delta = \frac{\Delta m^2_{32} L}{4E_\nu}$ and $A = 2\sqrt{2} G_F N_e \frac{E_\nu}{\Delta m^2_{32}}$, where N_e is the electron density of the Earth's crust.

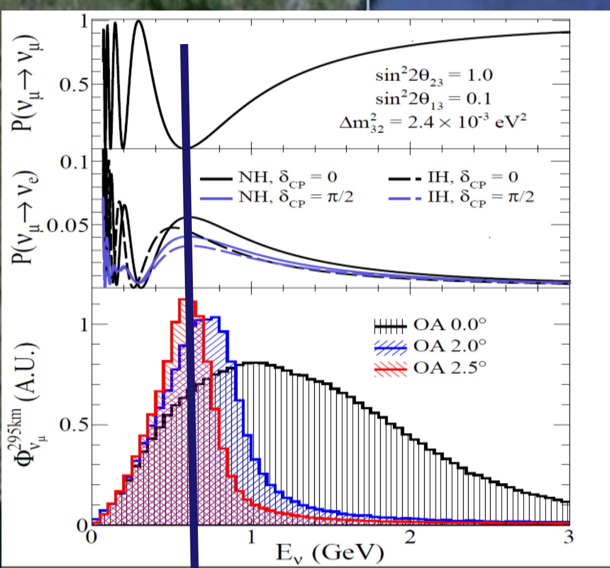
T2K

Run Period	Dates	Integrated POT by SK
Run 1	Jan. 2010-Jun. 2010	0.32×10^{20}
Run 2	Nov. 2010-Mar. 2011	1.11×10^{20}
Run 3	Mar. 2012-Jun. 2012	1.58×10^{20}

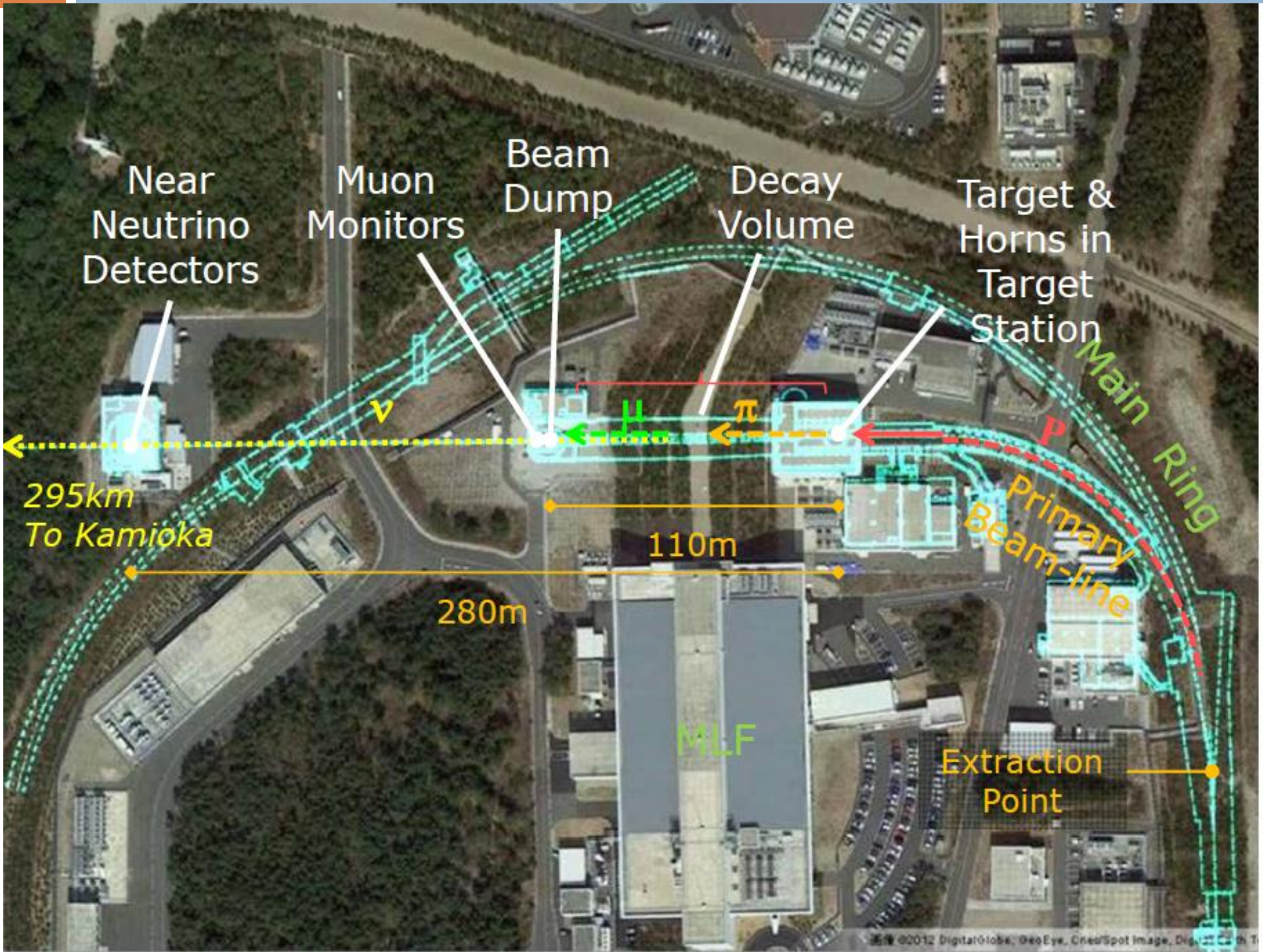
295km is the oscillation maximum point.
For obtaining the maximum of neutrino mixing (n=1), the length and the neutrino energy were set.

$\Delta m^2_{23} \sim 2.4 \times 10^{-3} eV^2$: L = 295km

$$1.27 \times \frac{\Delta m^2_{23} L}{E_\nu} = \frac{(2n-1)\pi}{2} \quad (1)$$



Accelerator



Experimental equip – Accelerator -

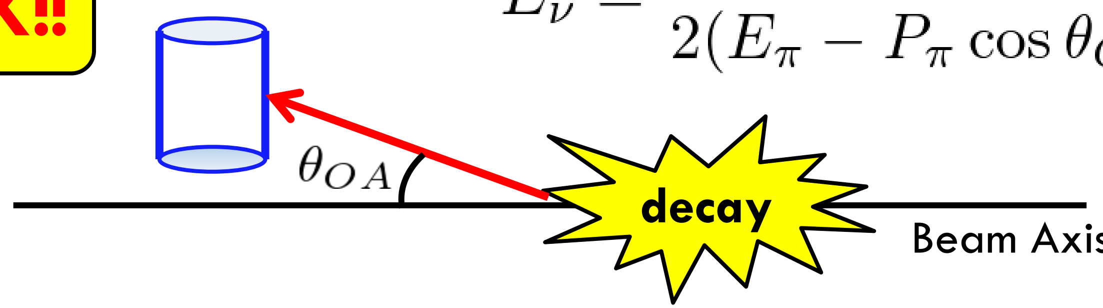
By striking the protons to the targets (Carbon), K and π mesons are generated. At this time, positive charged ones are selected and they decay into μ^+ and ν_μ.

The muon neutrino beam generated in J-PARC (Tokai-Mura) penetrate to the near detector which is placed in 280 m from the target and the far detector, Super Kamiokande (SK) which is placed in 295 km from that.

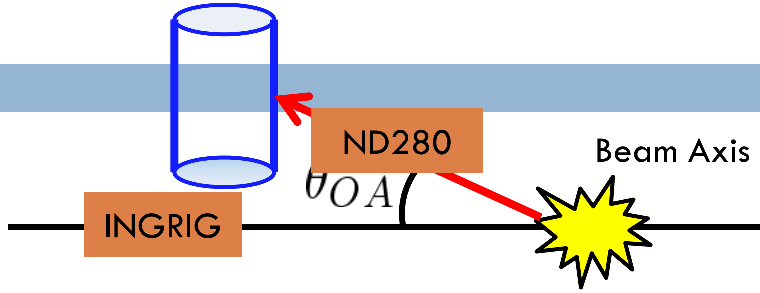
In particular, narrow band beam is obtain using off-axis configuration (OA) for optimizing the neutrino energy spectrum at the T2K.

Only T2K!!

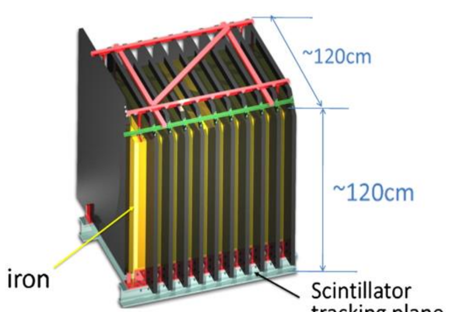
$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - P_\pi \cos\theta_{OA})}$$



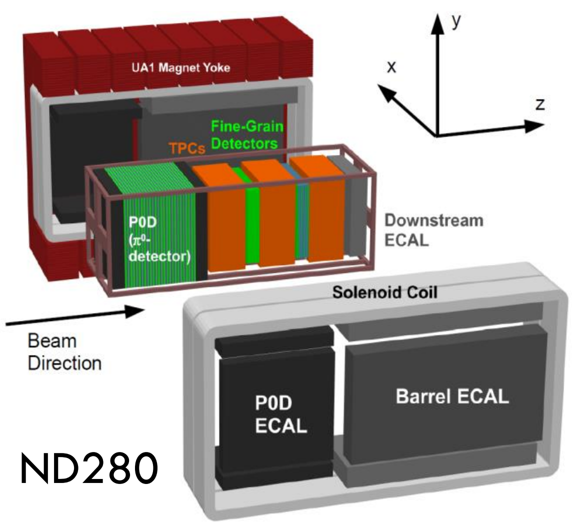
Experimental equip – Near Detector-



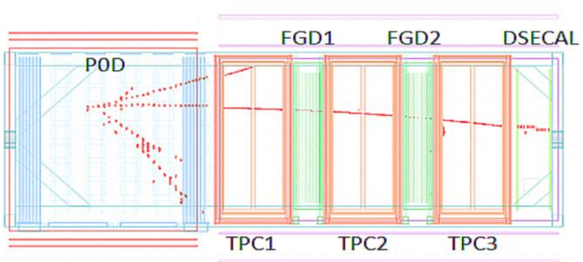
- INGRID – on-axis
  - 280 m downstream of the proton target.
  - Measuring the neutrino beam direction within 1 mrad uncertainty for suppressing the systematic error by2%.
  - A module is a sandwich of 9 iron target plates and 11 scintillator tracking planes
  - The charged particle from neutrino interaction at iron is detected.
- ND280 – off axis = same direction as SK
  - measuring the ν energy spectrum, kind of ν, ν cross section before oscillation
  - 0.2 T magnetic field, ECAL, π^0detector, fine-grained scintillator …



INGRID



ND280



The event display at ND280

Neutrino model

- Charged Current Quasi-Elastic (CCQE)

$$\nu_l + N \rightarrow l + N'$$

- Charged Current interaction (CC1π)

$$\nu_l + N \rightarrow l + N' + \pi$$

- Neutral Current interaction (NC1π)

$$\nu_l + N \rightarrow \nu + N' + \pi$$

Muon finding at ND280

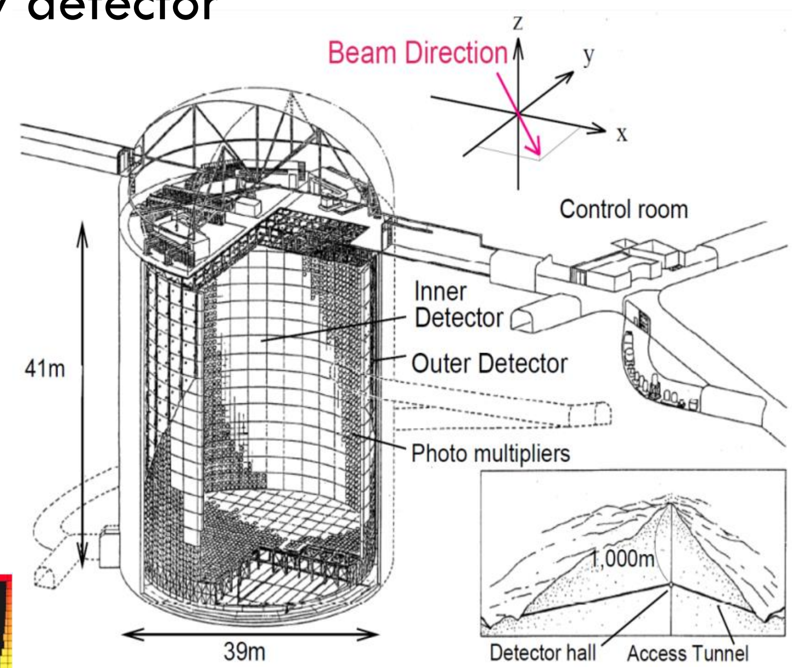
- Geant4-based MC simulation using neutrino flux describe.
- 2.66×10^{20} POT (proton on target)
- Muons were selected for creating CC ν_μ .
  - The highest momentum negatively lepton was found for each event.
  - Muon which was detected at both TPC1 and FGD1 was rejected.
  - Only one muon-like track in the final state.
  - No additional tracks which pass through both FGD1 and TPC2.
  - No Michel electrons. (low energy or stopped, PID by time-delay)
  - Other condition such as momentum and $\cos\theta_\mu$(the angle between z-axis and muon direction)
- For measuring ν_e appearance, they had to know how many ν_e they had in beam.
  - The cut condition is almost all same to muon

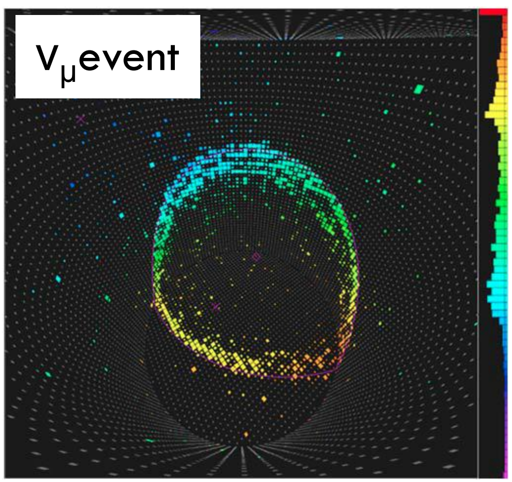
TABLE VII: Number of data and predicted events for the ND280 CC-inclusive selection criteria.

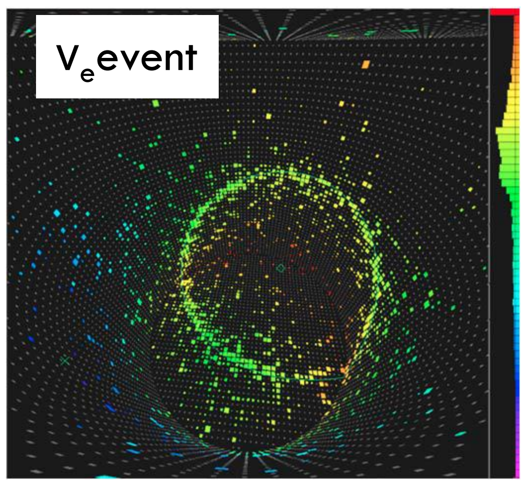
	Data	MC
Good negative track in FV	21503	21939
Upstream TPC veto	21479	21906
μ PID	11055	11498

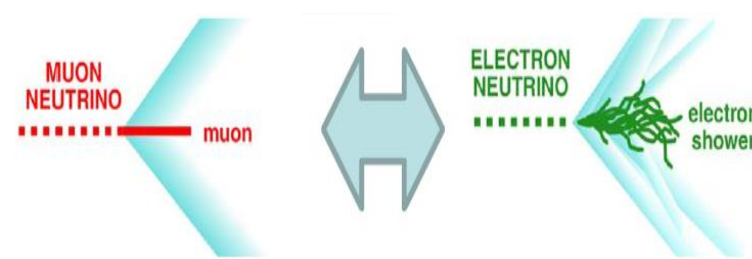
Experimental equip – SK(Super Kamiokande) - far Detector-

- 50 kt water world largest Cherenkov detector
- ID(inner detector)
  - 11129 PMT (20 inch)
  - for obtaining the signals
- OD(outer detector)
  - 1885 PMT (8 inch)
  - for bkg.(cosmic ray and rocks)
- PID using the ring image









SK detector simulation

- Detector simulation
  - Using SKDETSIM which is based on GEANT3 far detector simulation was applied.
- Neutrino event selection for detector bkg.
  - Obviously hit on OD (more than 15 hits)
  - For suppressing the low energy background, at 300ns time window measurement, they required 200 photonelectrons and Evis > 20MeV.
  - If half of total charge are detected on 1 PMT, that event was rejected.
  - Rejection for “Flasher events”, charge deposit near dynode
    - Although the ring of Neutrino event is larger than that of Flasher event, since signals are sometimes generated near ID, they are easy to misidentify.

Event selection

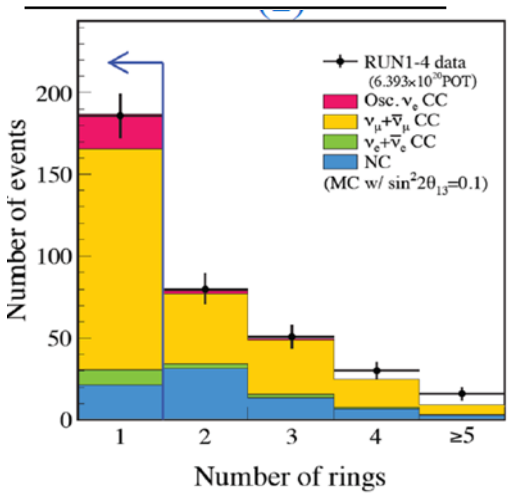
Cut table at $\theta_{13}=0$ (top table) and $\theta_{13}\neq 0$(bottom one)

	Data	MC total	CC ν_μ	CC ν_e	NC	CC $\nu_\mu \to \nu_e$
(0) interaction in FV	n/a	299.0	158.5	8.6	131.6	0.3
(1) fully contained in FV	174	168.5	119.8	8.2	40.2	0.3
(2) single ring	88	85.4	68.5	5.3	11.4	0.2
(3) e-like	22	16.1	2.7	5.2	8.0	0.2
(4) $E_{\text{vis}} > 100$ MeV	21	14.1	1.8	5.2	6.9	0.2
(5) no delayed electron	16	10.6	0.3	4.2	5.9	0.2
(6) not π^0-like	11	4.8	0.09	2.9	1.6	0.2
(7) $E_\nu^{\text{rec}} < 1250$ MeV	11	3.3	0.06	1.8	1.2	0.2

	Data	MC total	CC ν_μ	CC ν_e	NC	CC $\nu_\mu \to \nu_e$
(0) interaction in FV	n/a	311.4	158.3	8.3	131.6	13.2
(1) fully contained in FV	174	180.5	119.6	8.0	40.2	12.7
(2) single ring	88	95.7	68.4	5.1	11.4	10.8
(3) e-like	22	26.4	2.7	5.0	8.0	10.7
(4) $E_{\text{vis}} > 100$ MeV	21	24.1	1.8	5.0	6.9	10.4
(5) no delayed electron	16	19.3	0.3	4.0	5.9	9.1
(6) not π^0-like	11	13.0	0.09	2.8	1.6	8.5
(7) $E_\nu^{\text{rec}} < 1250$ MeV	11	11.2	0.06	1.7	1.2	8.2

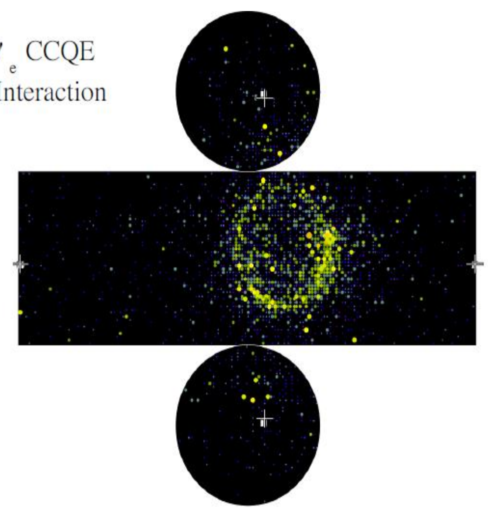
Event selection

- (0) interaction in FV
- (1) fully contained in FV
- (2) single ring
- (3) e-like
- (4) $E_{\mathrm{vis}} > 100$ MeV
- (5) no delayed electron
- (6) not π^0-like
- (7) $E_{\nu}^{\mathrm{rec}} < 1250$ MeV

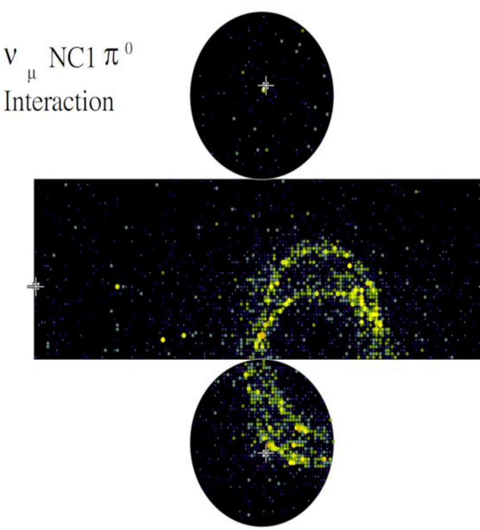


- (0) means all events which were interaction to ID.
- (1) is the selection to reject the detector bkg. such as flasher.
- (2) is suppress the beam background such as neutral hadrons like $\pi^0$and K^0. the cut criteria is decided by MC study.

b) ν_e CCQE Interaction



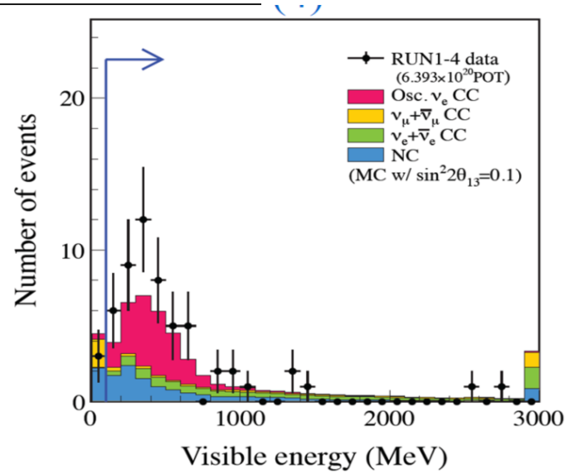
c) ν_μ NC1 π^0 Interaction

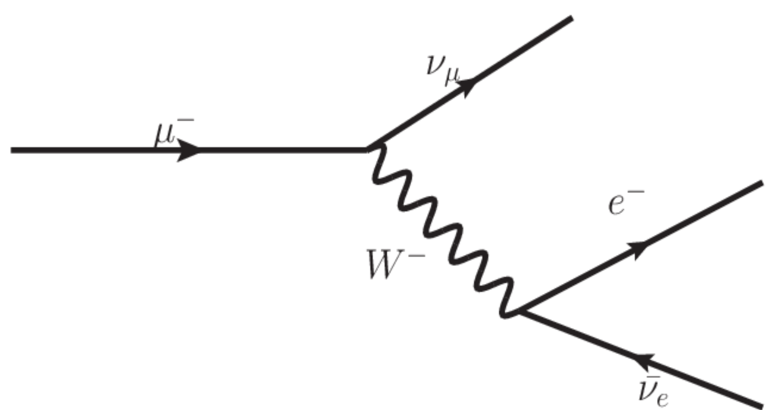


Event selection

(0) interaction in FV
(1) fully contained in FV
(2) single ring
(3) e-like
(4) $E_{\rm vis} > 100$ MeV
(5) no delayed electron
(6) not π^0-like
(7) $E_\nu^{\rm rec} < 1250$ MeV

- (3) is the selection for e or μ neutrino.
  The cut criteria is also determined by MC study.
- (4) Visible energy
  - the energy of an electromagnetic shower that produces the observed amount of Cherenkov light
  - Cosmic ray muon, pion
- (5) The electron decayed from μ

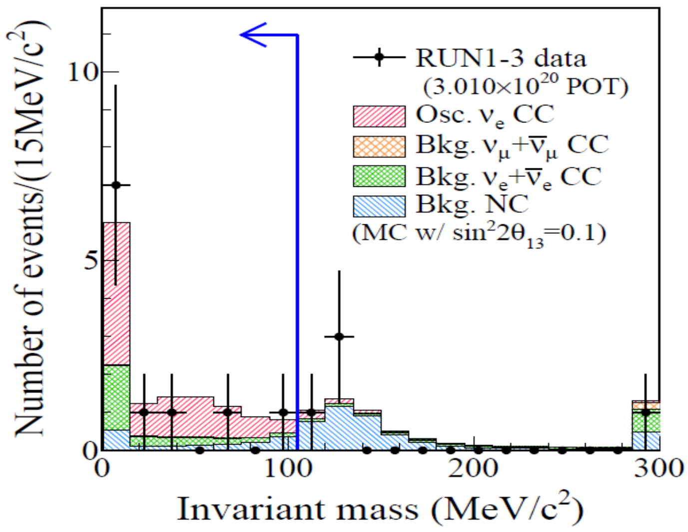


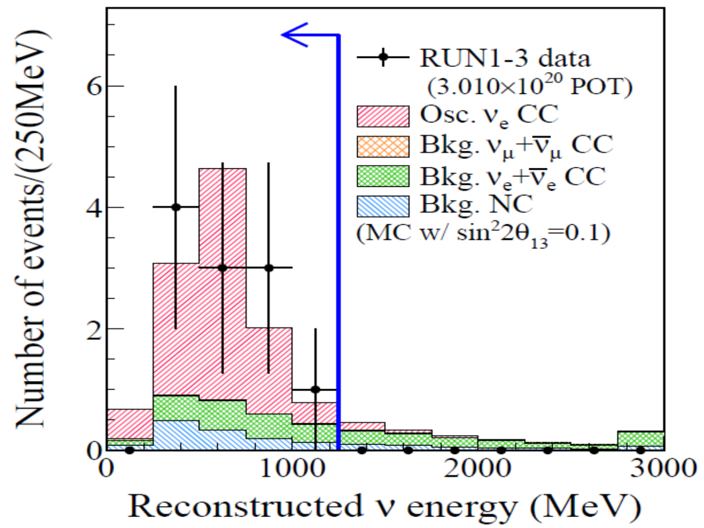


Event selection

(0) interaction in FV
(1) fully contained in FV
(2) single ring
(3) e-like
(4) $E_{\rm vis} > 100$ MeV
(5) no delayed electron
(6) not π^0-like
(7) $E_\nu^{\rm rec} < 1250$ MeV

- (6) Likelihood which is based on light pattern and ring image. And using invariant mass M_{inv} > 105 MeV
- (7) they can separate atmospheric mass splitting and signal. And in high energy region, background are dominant.





Conclusion

- The evidence of electron neutrino appearance in a muon neutrino beam with a baseline.
  - 11 candidate ν_e events were observed (bkg. 3.3±0.4 syst.).
- Future measurements od appearance probability for antineutrinos will provide a future constraint on δ_{CP} and the mass hierarchy.

$$\sin^2\theta_{13} = 0.088^{+0.049}_{-0.039}$$ (normal hierarchy)

$$\sin^2\theta_{13} = 0.108^{+0.059}_{-0.046}$$ (inverted hierarchy)

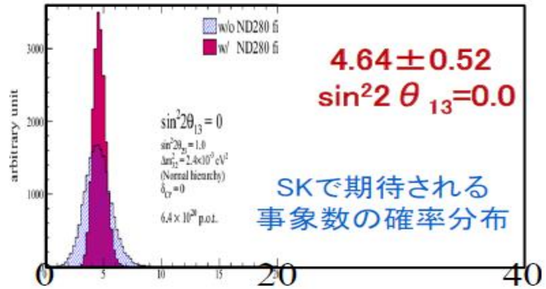
New result

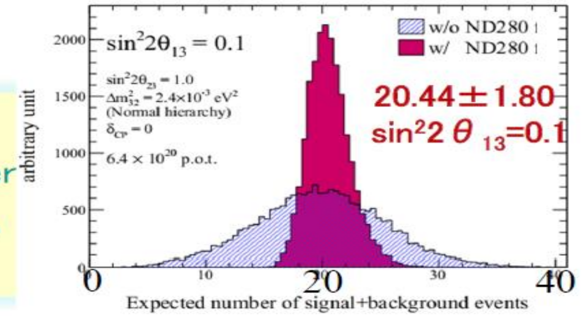
Candidate event summary

Data	28	
MC	$\sin^2 2\theta_{13}=0$	$\sin^2 2\theta_{13}=0.1$
Osci. $\nu_\mu \rightarrow \nu_e$	0.38	16.42
ν_e BG (Beam)	3.17	2.93
ν_μ BG (NC π^0 etc)	0.89	0.89
$\bar{\nu}_e + \bar{\nu}_\mu$ BG	0.20	0.19
MC Total	4.64	20.44
Sys.Err(%)	(11.1%)	(8.8%)
Sys.Err(#)	±0.52	±1.80
Sys.Err(%)-2012	(13.0%)	(9.9%)

Parameter	Value
Δm^2_{21}	7.6×10^{-5}eV^2
Δm^2_{32}	2.4×10^{-3}eV^2
$\sin^2 2\theta_{12}$	0.8495
$\sin^2 2\theta_{23}$	1.0
$\sin^2 2\theta_{13}$	0.1 (or 0)
δ_{CP}	0
Mass hierarchy	Normal
ν travel length	295 km
Earth density	2.6g/cm^3

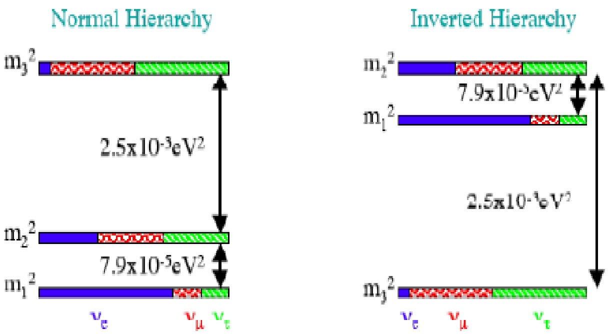
w/o ND280 fit
w/ ND280 fit





- N_{exp}=20.4 at $\sin^2 2\theta_{13}$=0.1, while we observe 28 events
- ν_μ background significantly reduced by new NC π^0 fitter
- Systematic uncertainties are reduced from 2012 release, mainly thanks to the near detector analysis

New result



δ_{CP} vs. $\sin^2 2\theta_{13}$ contours

- Allowed region of $\sin^2 2\theta_{13}$ for each value of δ_{CP}
- Best fit w/ 68% C.L. error @ $\delta_{CP}=0$
  - normal hierarchy

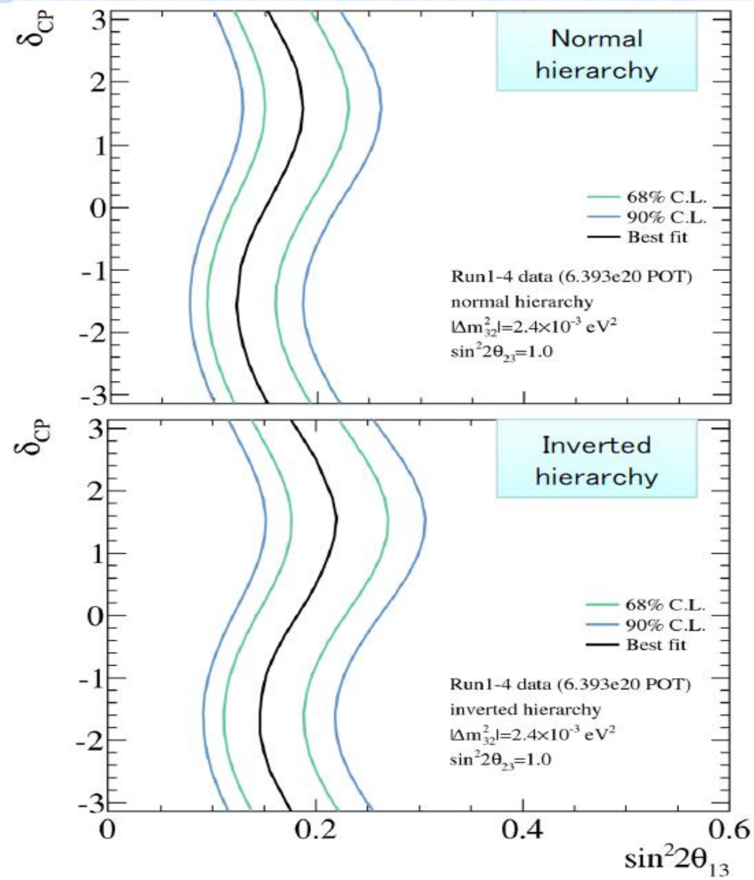
$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$$

  - inverted hierarchy:

$$\sin^2 2\theta_{13} = 0.182^{+0.046}_{-0.040}$$

Assuming
$|\Delta m^2_{32}|=2.4\times10^{-3}\ eV^2$
$\sin^2 2\theta_{23}=1.0$

Cf. $\sin^2 2\theta_{13}$: 0.098±0.013 (PDG2012)



New result

Citation from JPS 23aSE01

サマリー

- 6.39 x 10^{20}個の陽子を使って、SKでのν_eアピアランス事象を探し、28個を観測。
- 電子のp−θ分布をもっとも再現するのは、δ=0の場合、

normal hierarchy: $\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$

inverted hierarchy: $\sin^2 2\theta_{13} = 0.182^{+0.046}_{-0.040}$

- 28個観測されているのにニュートリノ振動がない $\sin^2 2\theta_{13}$=0.0であるのは、$\Delta\chi^2$ =56.3となり、7.5σで棄却。

⇒我々T2Kは、7.5σの有意性で、ν_eアピアランス事象を発見した。

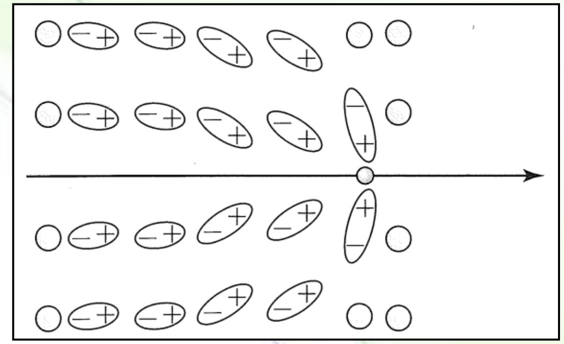
Backup

- These are written in Japanese for my scamped work
  - チェレンコフ光の検出
  - こころのさけび

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

1.6 チェレンコフ光 (粒子と物質の相互作用)

荷電子が物質中を”その物質の
光速を超える速度”で通過するとき
放出する微弱な光



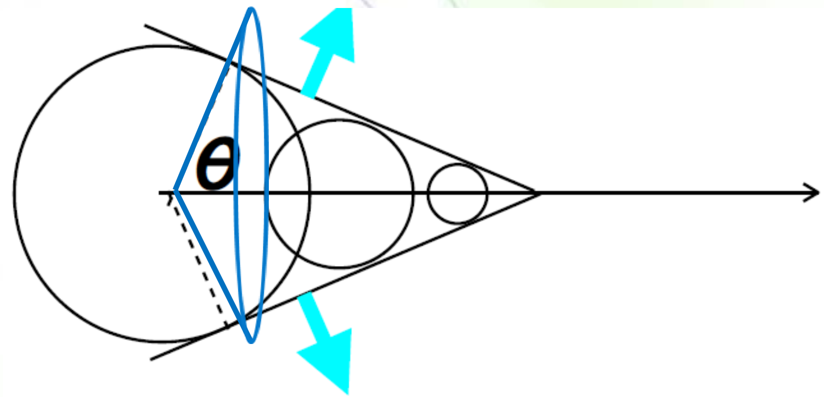
物質中での
分極の様子

放出速度の
閾値

$$\beta > \frac{1}{n}$$

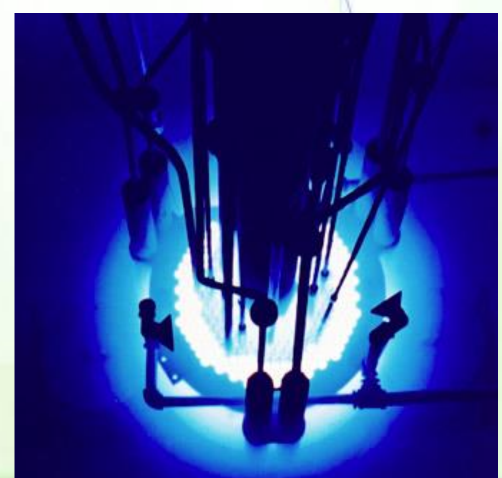
放出角度
(チェレンコフ角)

$$\cos\theta_c = \frac{1}{n\beta}$$



□屈折率によって閾値が変化する
□放出角は粒子の速度βに依存する

例)石英の場合n=1.47 で閾値はβ>0.68
　　水の場合n=1.33で閾値はβ>0.75



こころのさけび

論文講読の素材はあまり長いものを選ぶべきではない。

(T_T)