

Neutrino oscillation

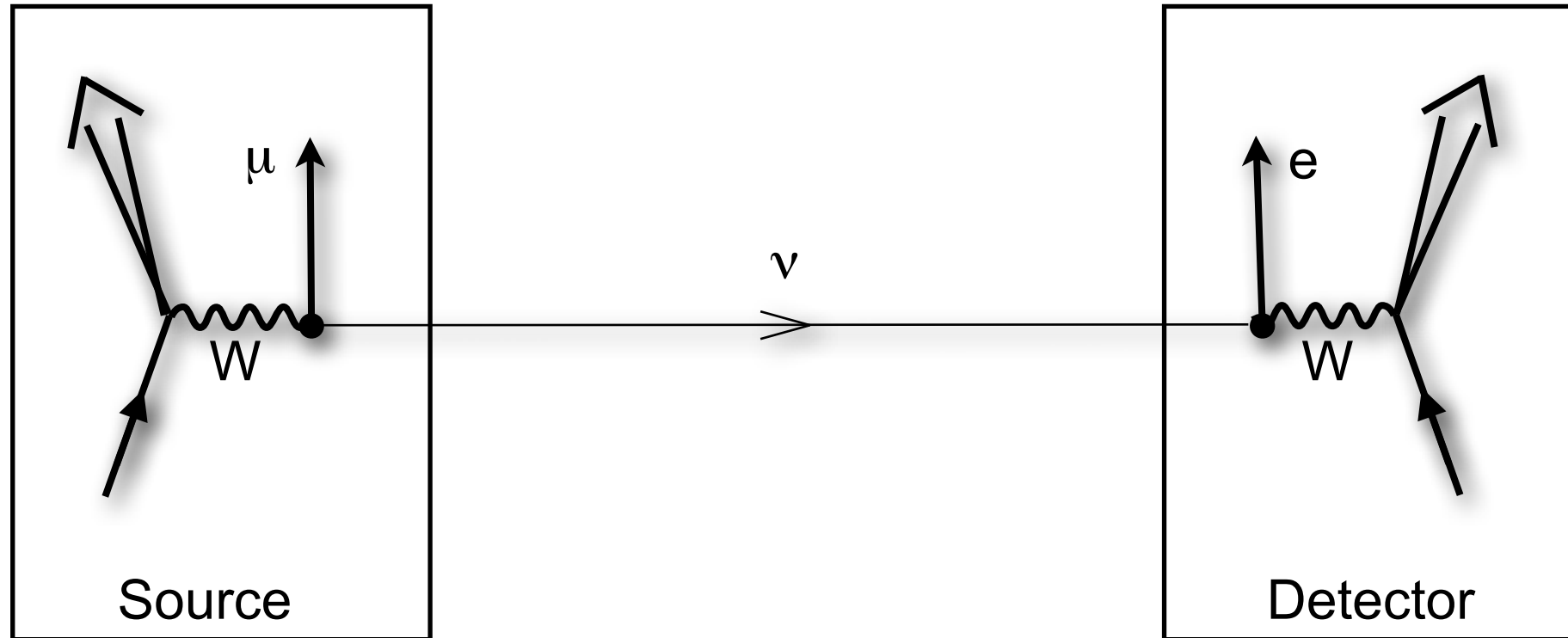


Бруно Понтекорво

Pontecorvo

[Sov.Phys.JETP](#)
6:429,1957

[Sov.Phys.JETP](#)
26:984-988,1968

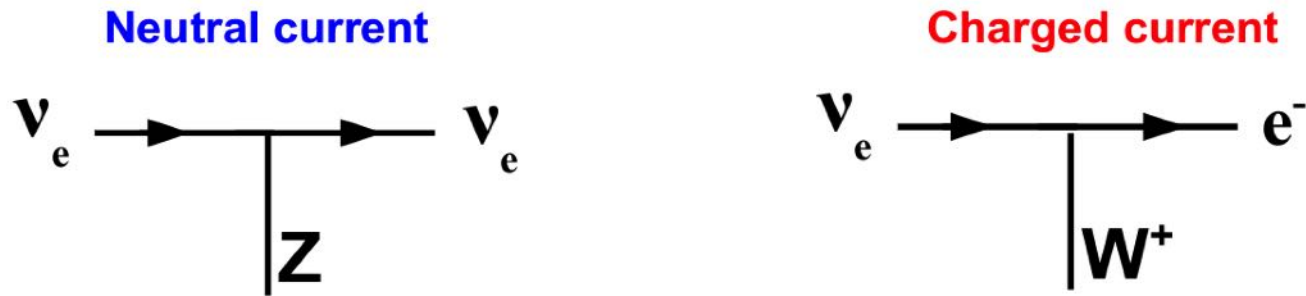


Maki,
Nakagawa,
Sakata

[Prog.Theor.Phys. 28,](#)
870 (1962)

- if neutrinos have mass...
 - a neutrino that is produced as a ν_μ
 - (e.g. $\pi^+ \rightarrow \mu^+ \nu_\mu$)
 - might some time later be observed as a ν_e
 - (e.g. $\nu_e n \rightarrow e^- p$)

- Weakly interacting isospin partners of charged leptons



- Standard model includes three massless stable neutrinos, but...

a) The weak neutrinos must be re-defined by a relation

$$\left. \begin{aligned} \nu_e &= \nu_1 \cos \delta - \nu_2 \sin \delta, \\ \nu_\mu &= \nu_1 \sin \delta + \nu_2 \cos \delta. \end{aligned} \right\} \quad (2.18)$$

As early as fifty-two years ago, discussions of massive neutrinos and oscillations had begun!



Maki, Nakagawa, Sakata
(June 1962)

The leptonic weak current (2.9) turns out to be of the same form with (2.1). In the present case, however, weak neutrinos are *not stable* due to the occurrence of a virtual transmutation $\nu_e \rightleftharpoons \nu_\mu$ induced by the interaction (2.10). If the mass difference between ν_2 and ν_1 , i.e. $|m_{\nu_2} - m_{\nu_1}| = m_{\nu_2}^{*})$ is assumed to be a few Mev, the transmutation time $T(\nu_e \rightleftharpoons \nu_\mu)$ becomes $\sim 10^{-18}$ sec for fast neutrinos with a momentum of $\sim \text{Bev}/c$. Therefore, a chain of reactions such as¹⁰⁾

$$\pi^+ \rightarrow \mu^+ + \nu_\mu, \quad (2.19a)$$

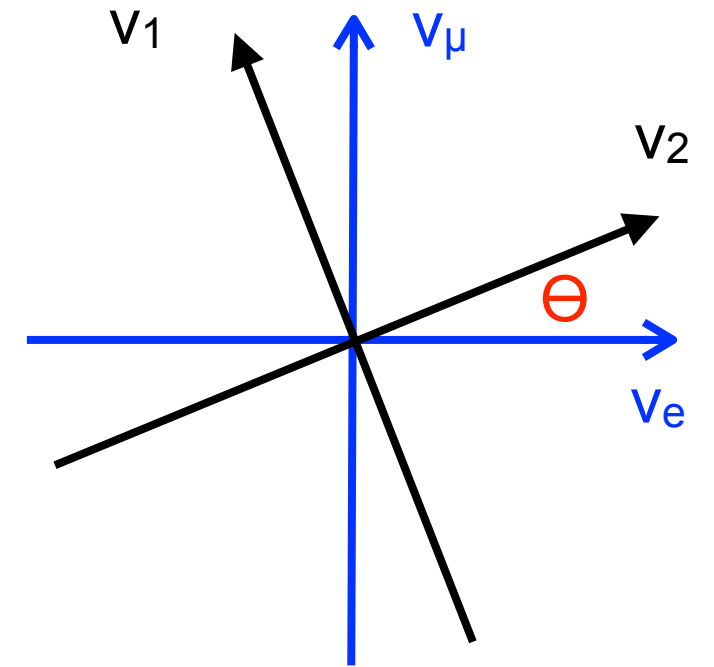
$$\nu_\mu + Z(\text{nucleus}) \rightarrow Z' + (\mu^- \text{ and/or } e^-) \quad (2.19b)$$

is useful to check the two-neutrino hypothesis only when $|m_{\nu_2} - m_{\nu_1}| \lesssim 10^{-6} \text{ Mev}$

Neutrino oscillation

In a world with 2 neutrinos,
if the weak eigenstates (ν_e, ν_μ)
are different from the mass eigenstates (ν_1, ν_2):

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



The weak states are mixtures of the mass states:

$$|\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

$$|\nu_\mu(t)\rangle = -\sin\theta (|\nu_1\rangle e^{-iE_1t}) + \cos\theta (|\nu_2\rangle e^{-iE_2t})$$

The probability to find a ν_e when you started with a ν_μ is:

$$P_{oscillation}(\nu_\mu \rightarrow \nu_e) = |\langle \nu_e | \nu_\mu(t) \rangle|^2$$

If a neutrino has mass, we expect that the weak eigenstate could be different from the mass eigenstate, as analogous to the quark system [10]. For simplicity, consider the two flavor case at first. The flavor eigenstates, ν_α and ν_β , is written by

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \equiv U \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \quad (1.1)$$

where ν_1 and ν_2 are the mass eigenstates and θ is the mixing angle. After traveling with a certain time period t , each component of the mass eigenstate gets a different phase:

$$\begin{pmatrix} \nu_1(t) \\ \nu_2(t) \end{pmatrix} = \begin{pmatrix} e^{-iE_1 t} & 0 \\ 0 & e^{-iE_2 t} \end{pmatrix} \begin{pmatrix} \nu_1(0) \\ \nu_2(0) \end{pmatrix} \quad (1.2)$$

Detection of neutrinos by the charged current interaction projects these new states back onto the flavor eigenstates:

$$\begin{pmatrix} \nu_\alpha(t) \\ \nu_\beta(t) \end{pmatrix} = U \begin{pmatrix} e^{-iE_1 t} & 0 \\ 0 & e^{-iE_2 t} \end{pmatrix} U^{-1} \begin{pmatrix} \nu_\alpha(0) \\ \nu_\beta(0) \end{pmatrix} \quad (1.3)$$

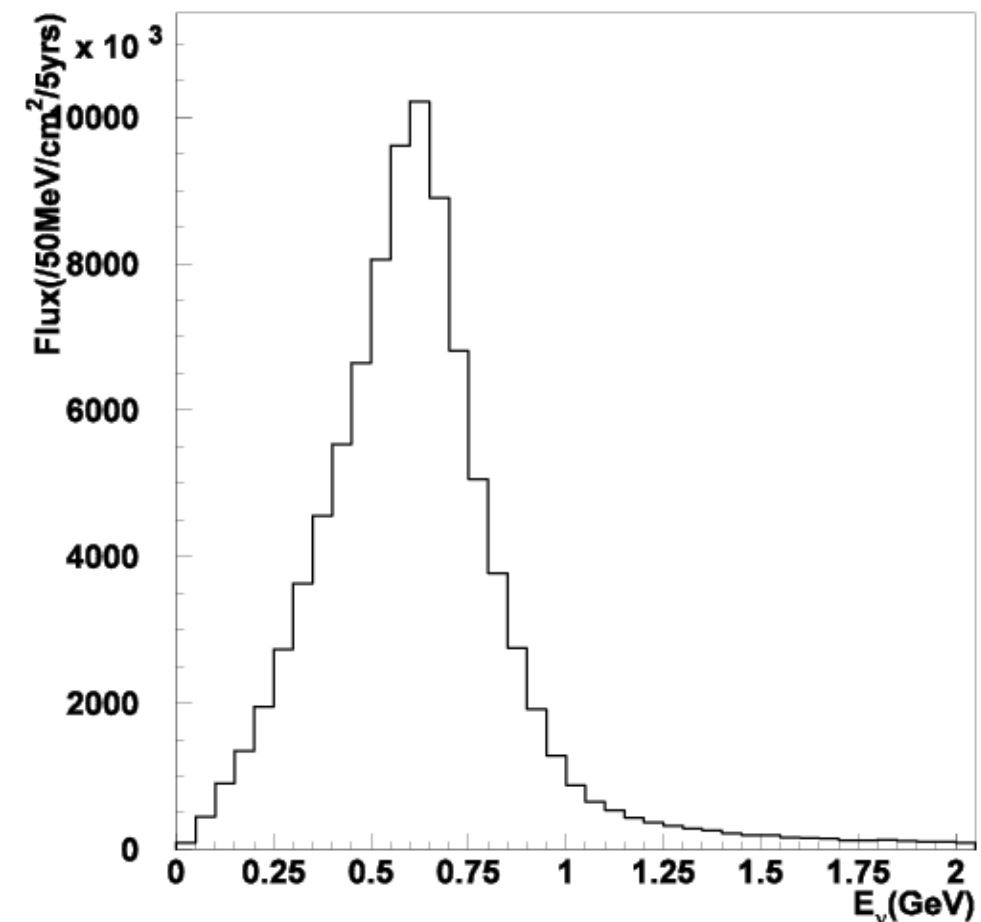
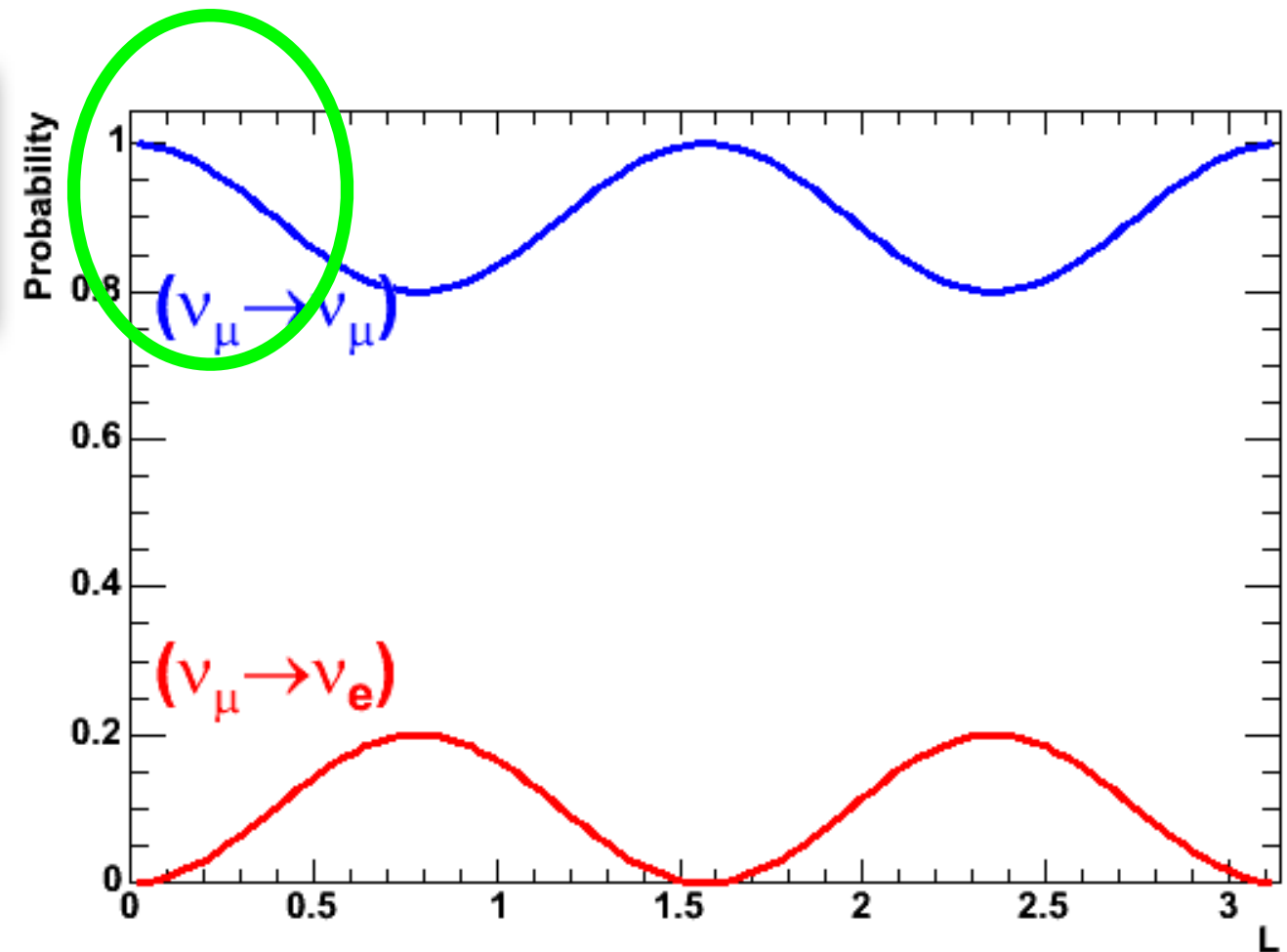
Supposing a neutrino is generated as ν_α (*i.e.* $\nu_\alpha(0) = 1$ and $\nu_\beta(0) = 0$), its surviving probability in the same flavor eigenstate after traveling a certain distance L is obtained as

$$P(\nu_\alpha \rightarrow \nu_\alpha) = |\nu_\alpha(t)|^2 = 1 - \sin^2 2\theta \cdot \sin^2 \left(1.27 \Delta m^2 [\text{eV}^2/\text{c}^4] \frac{L[\text{km}]}{E[\text{GeV}]} \right) \quad (1.4)$$

when m_i is very small compared to E_i ($E_i \simeq p + m_i^2/2p$). Here $\Delta m^2 \equiv m_2^2 - m_1^2$. Thus the flavor of neutrinos oscillates as a function of L/E .

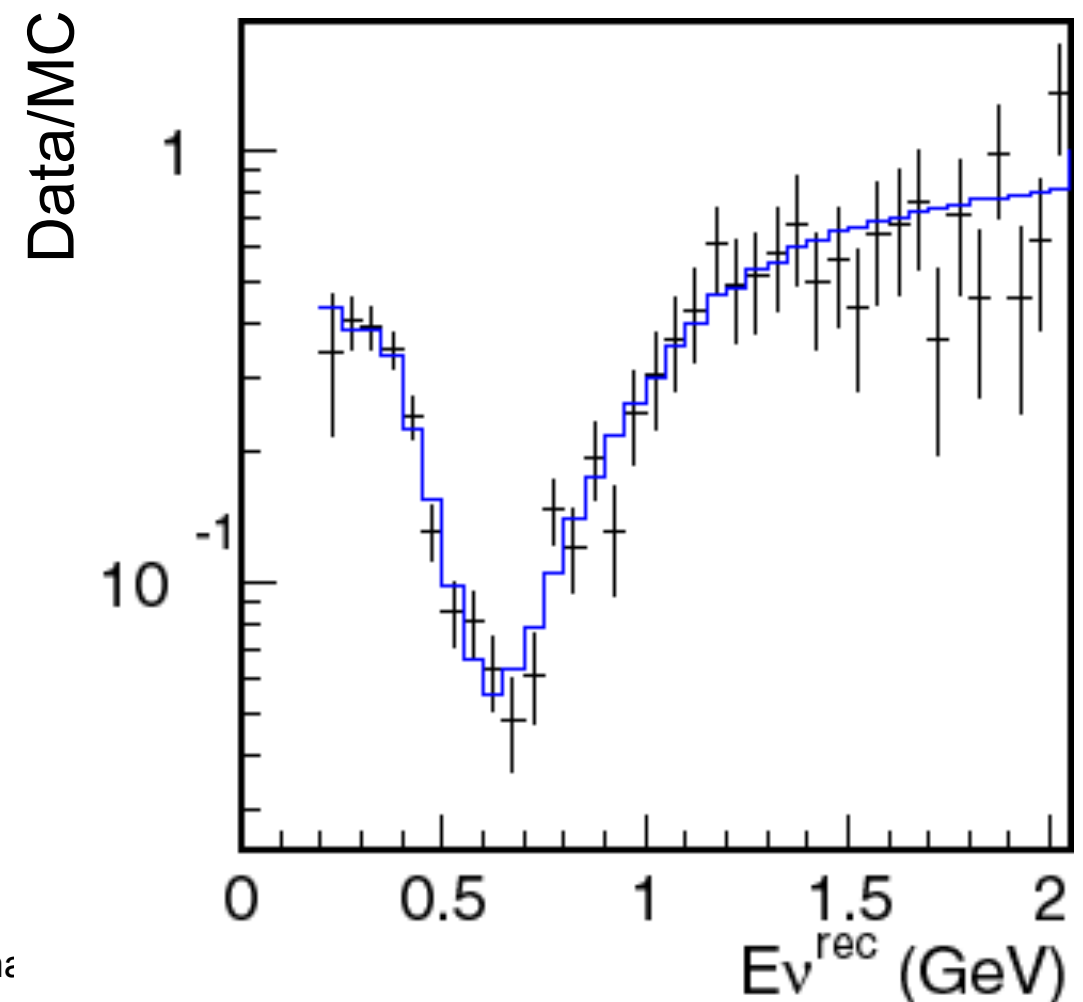
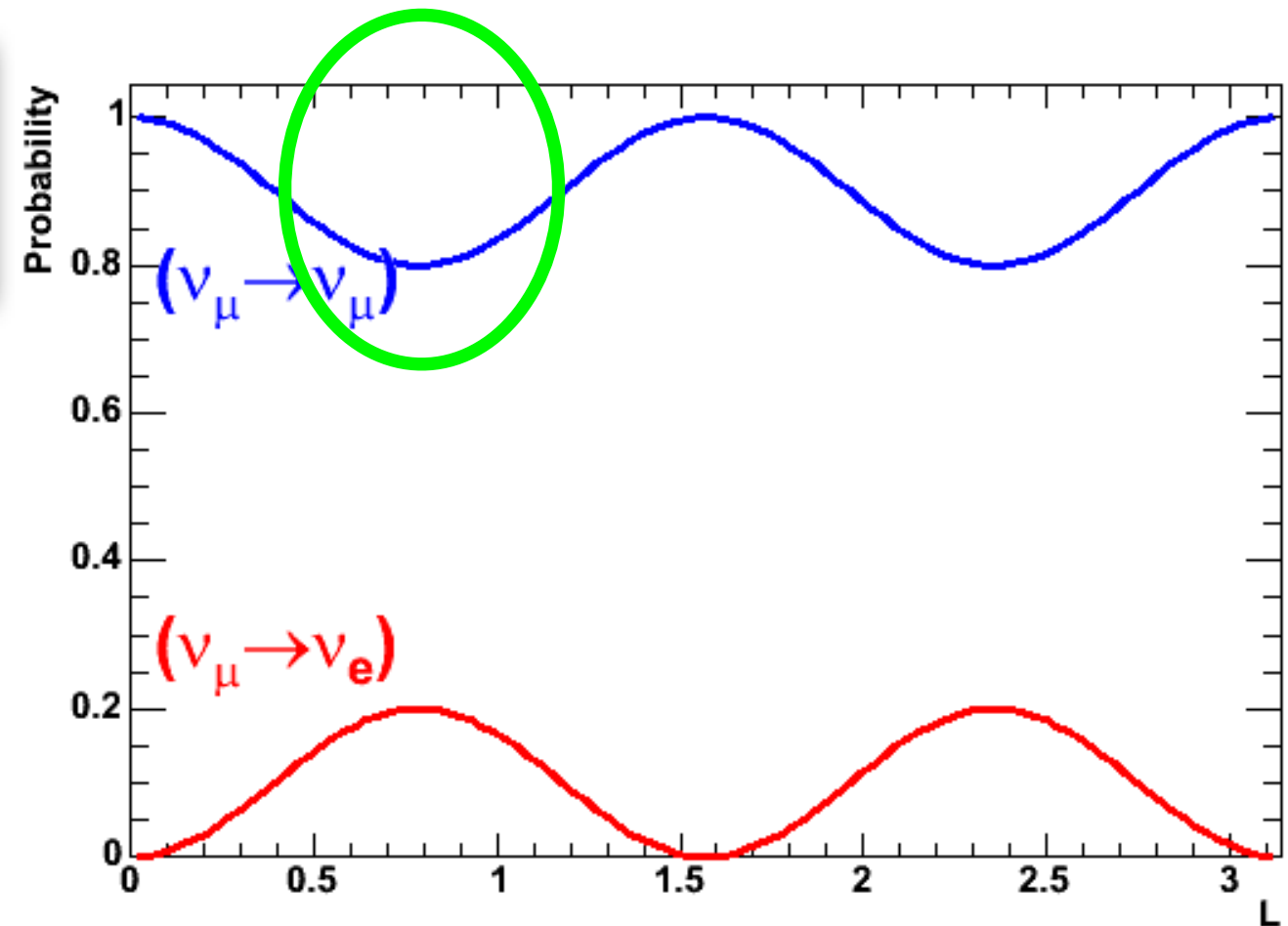
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \sin^2 \left(1.27 \Delta m_{12}^2 \frac{L}{E} \right)$$

- 2 fundamental parameters
 - $\Delta m^2 \leftrightarrow$ period
 - $\theta_{12} \leftrightarrow$ magnitude
- 2 experimental parameters
 - $L =$ distance travelled
 - $E =$ neutrino energy
- Choose L & E to target ranges of Δm^2 and θ
- Neutrinos disappear and appear



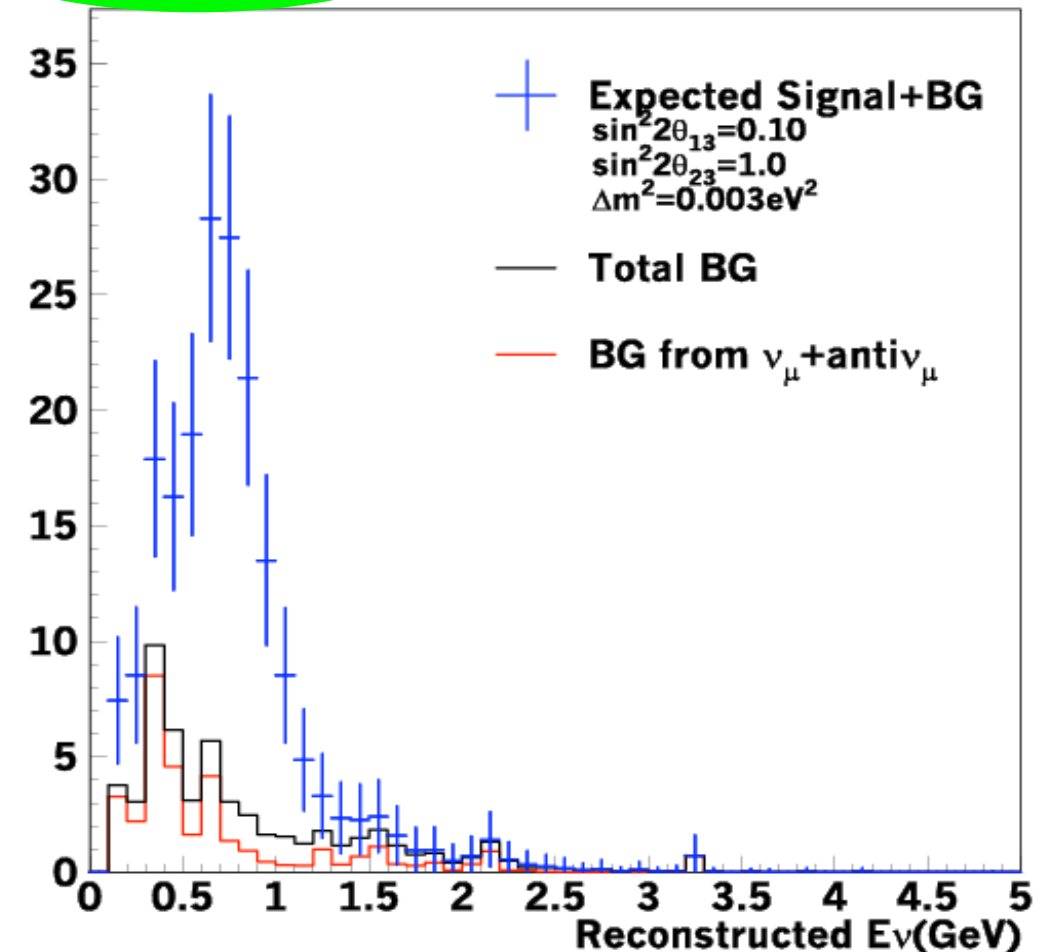
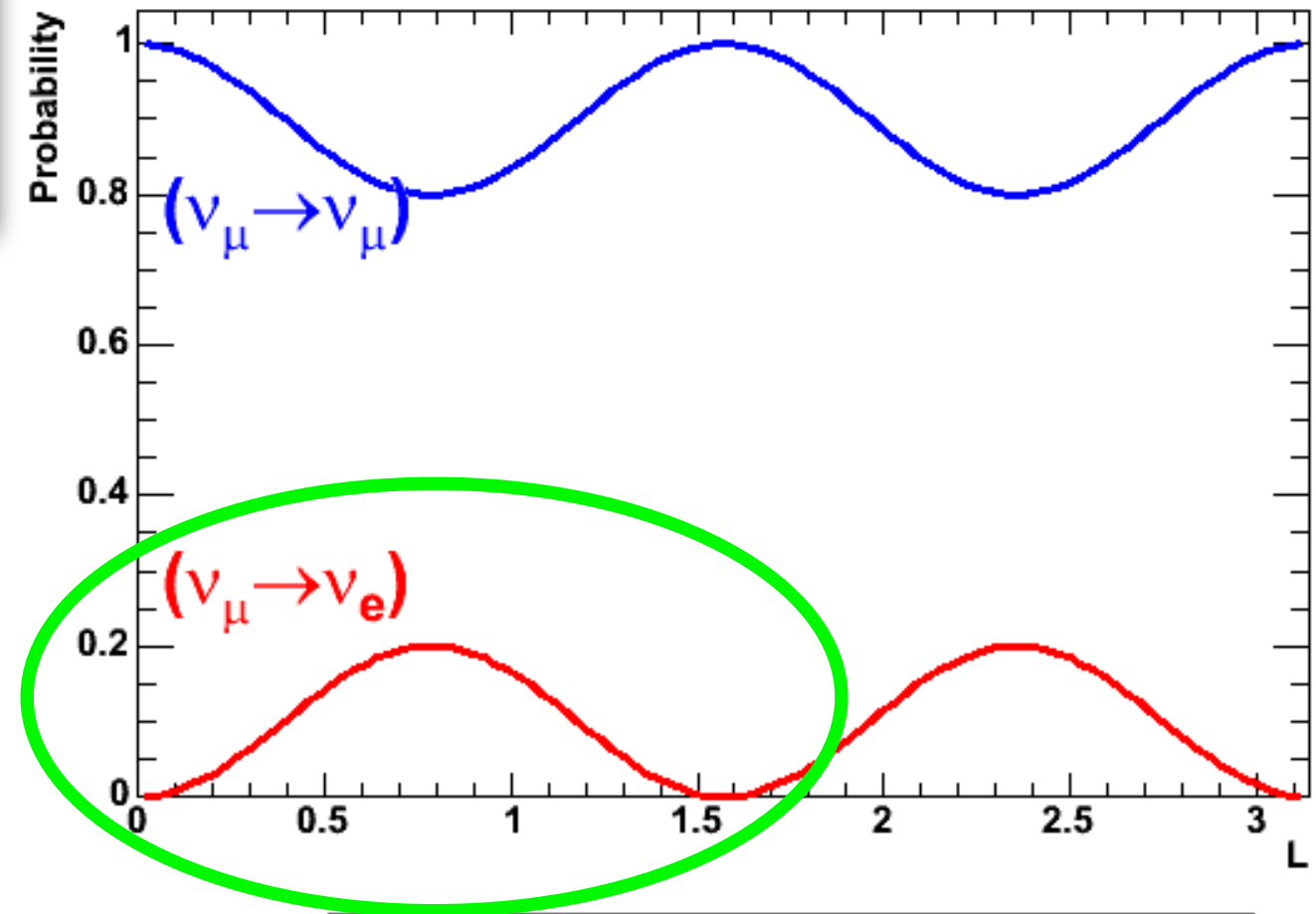
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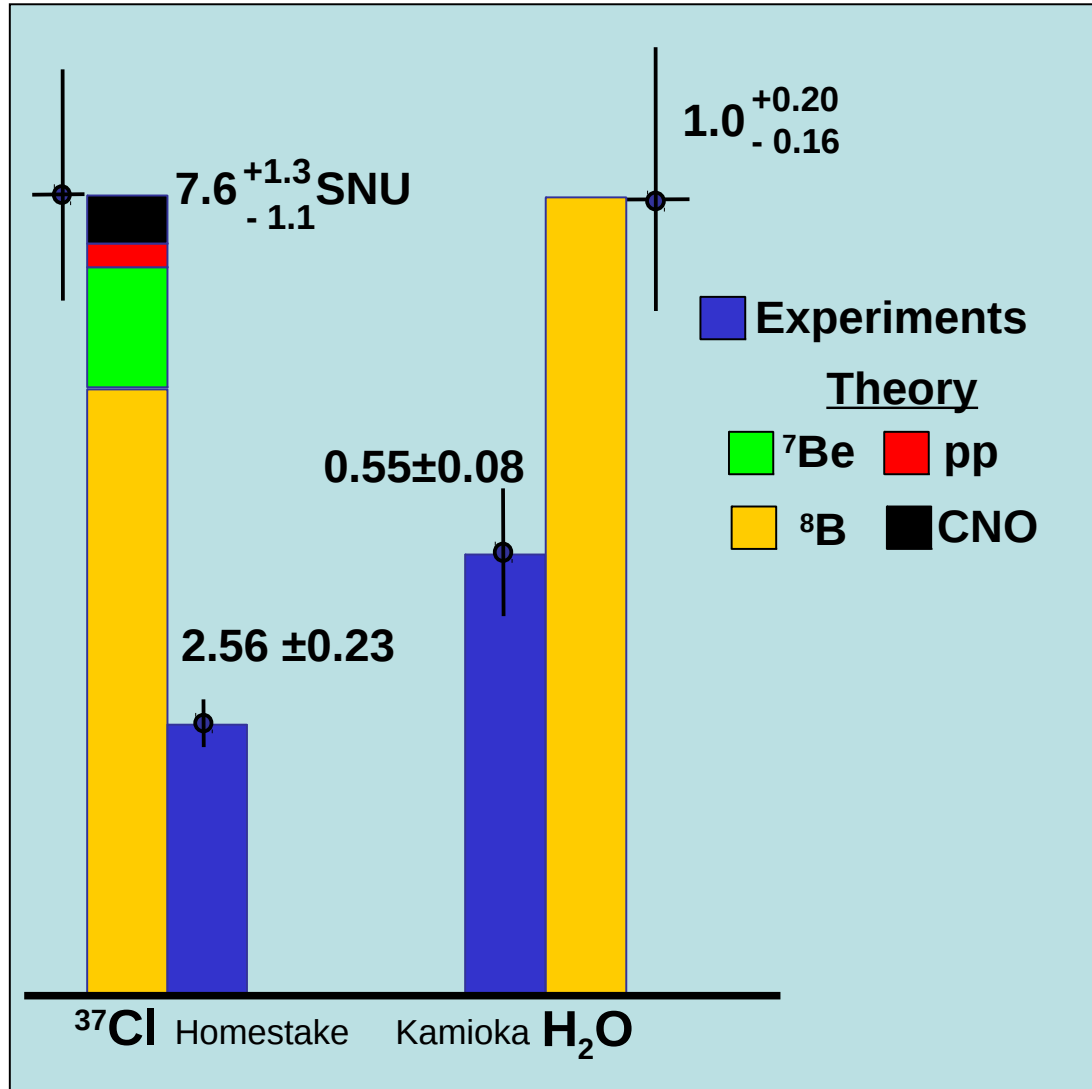
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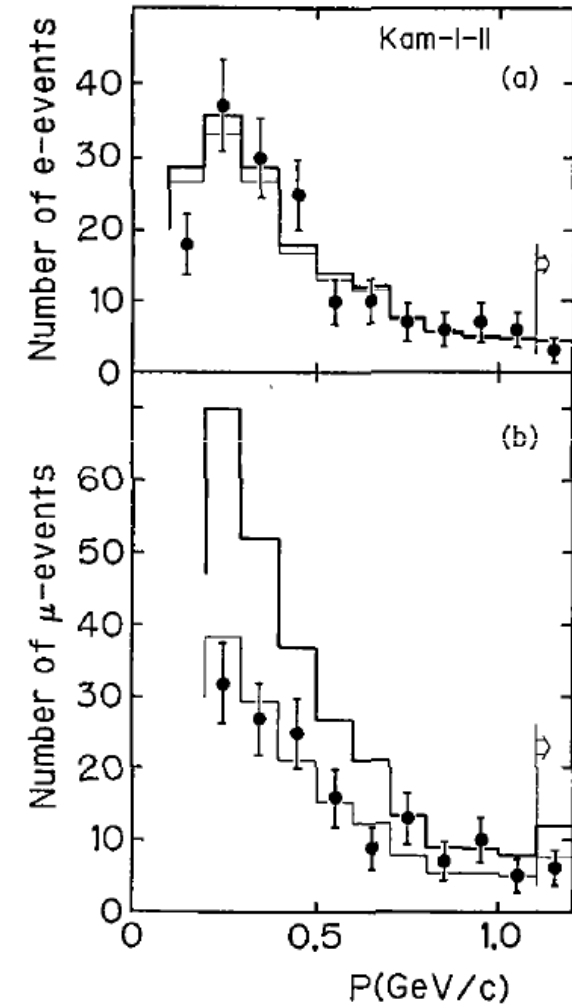
Early Hints of Oscillation



Solar Neutrinos



Atmospheric Neutrinos

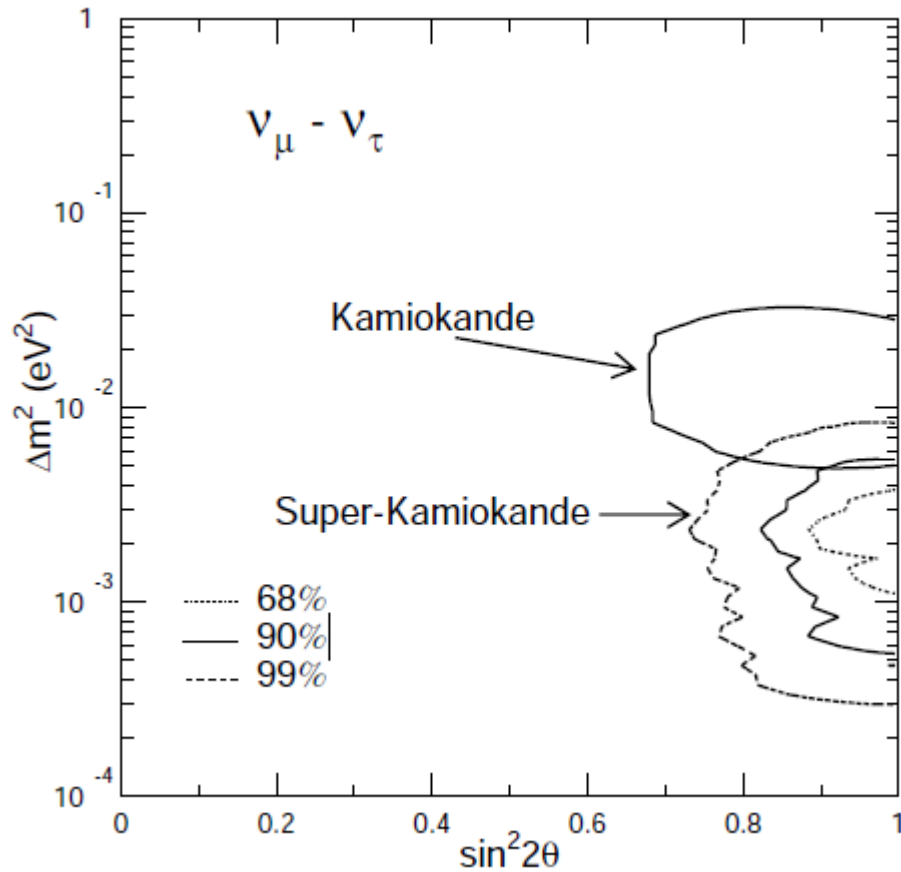


Kamiokande (1992)

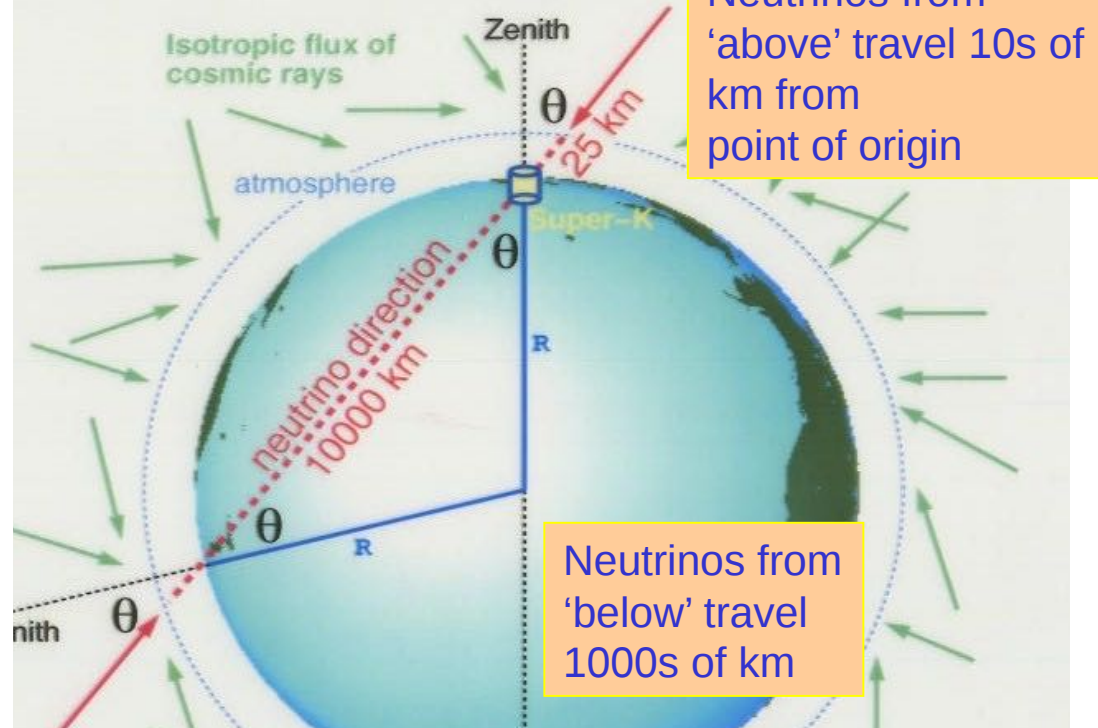
1998: Neutrino Mass!



ATMOSPHERIC NEUTRINOS



Ratio of $\nu_\mu/\nu_e \sim 2$
(for $E_\nu < \text{few GeV}$)



Neutrinos from 'above' travel 10s of km from point of origin

Neutrinos from 'below' travel 1000s of km

Super-Kamiokande (1998)

~530 days data-taking \rightarrow ~400 ν events

Up-Down Symmetric Flux
(for $E_\nu > \text{few GeV}$)

- Neutrinos have mass!

Flavour eigenstates: ν_e, ν_μ, ν_τ

Mass eigenstates: ν_1, ν_2, ν_3

$$|\nu_l\rangle = \sum_{i=1}^3 U_{li} |\nu_i\rangle$$

- Produced and interact as flavour eigenstates;

propagate as mass eigenstates: $|\nu_l(L)\rangle = \sum_{i=1}^3 U_{li} e^{-im_i^2 L/2E} |\nu_i(0)\rangle$

where:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino Mixing



- For Dirac neutrinos, standard parameterization of the PMNS matrix U_{li} (for Dirac neutrinos) has:

3 mixing angles, 2 mass square differences, 1 CP phase

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

1998 onwards:
Probed with atmospheric neutrinos,
long baseline accelerator neutrinos
(SK, K2K, MINOS)

First measured recently! (2011 – 2012)
Short baseline reactor neutrinos
(Daya Bay, RENO, DoubleChooz);
Long baseline accelerator neutrinos
(T2K, MINOS, NOvA)

2001 onwards:
Probed with solar neutrinos,
long baseline reactor neutrinos
(SK, SNO, KamLAND)

Experimental Probes



- For Dirac neutrinos, standard parameterization of the PMNS matrix U_{li} (for Dirac neutrinos) has:

3 mixing angles, 2 mass square differences, 1 CP phase

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

$\sin^2(2\theta_{23}) > 0.95$ (90% C.L.)
 $|\Delta m^2_{32}| = 2.43 \pm 0.13 \times 10^{-3} \text{ eV}^2$

$\sin^2(2\theta_{12}) = 0.857 \pm 0.024$
 $\Delta m^2_{12} = 7.59 \pm 0.20 \times 10^{-5} \text{ eV}^2$

$\sin^2(2\theta_{13}) = 0.098 \pm 0.013$

What is the octant of θ_{23} ?

What is the mass hierarchy?

What is the CP violating phase δ ?

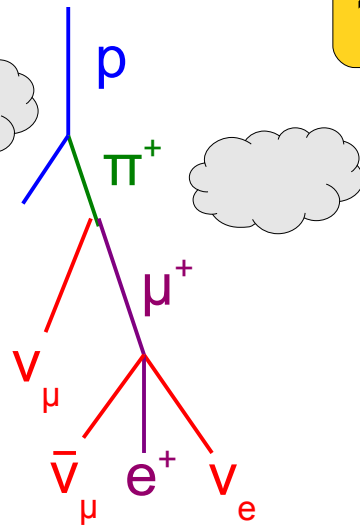
Neutrino Sources



Where do the neutrinos that experiments measure come from?

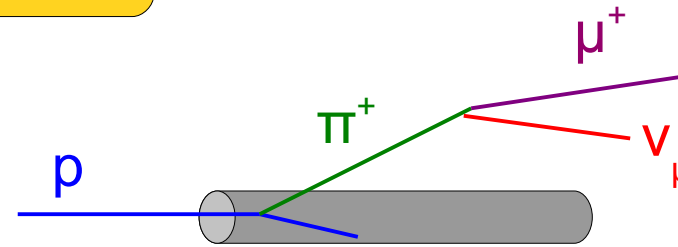
Atmospheric

Cosmic ray showers produce pions and muons that decay to neutrinos



~1-10 GeV

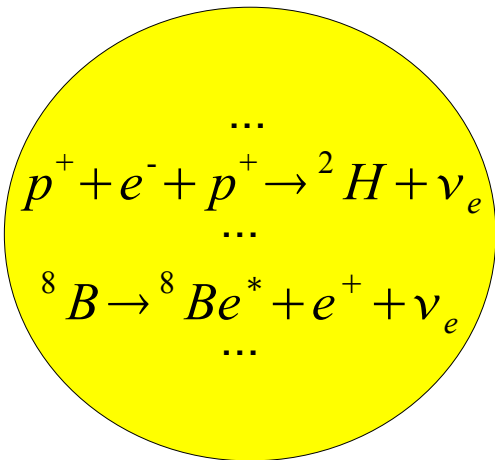
Accelerator



Proton beam from accelerator collides with fixed target

Most muons absorbed before decaying

Solar



Produced in fusion reactions inside sun.

Energy thresholds matter for experiments

~ 10 MeV

Reactor



$\bar{\nu}_e$ From β decay of isotopes in nuclear reactors

[Some] Open Questions

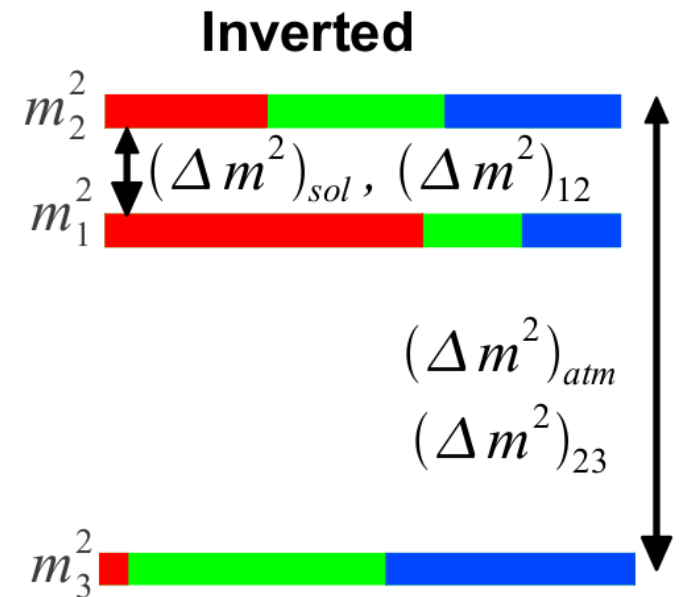
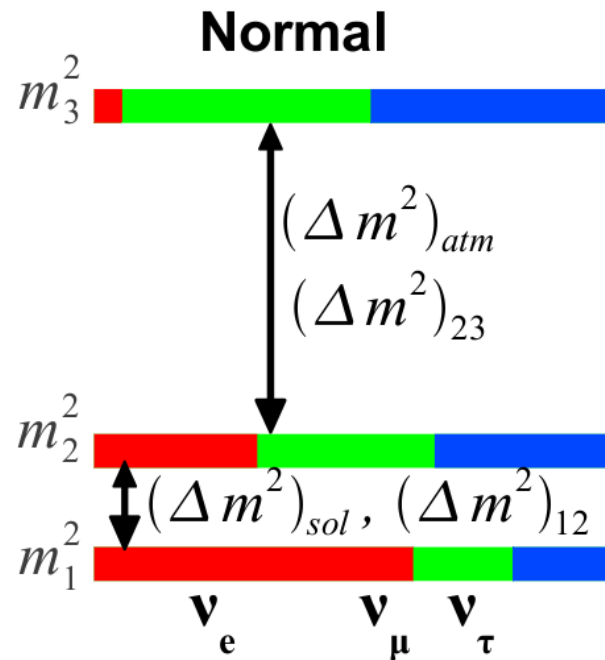


- 1) What is the CP violating phase δ ?
- 2) What is the mass hierarchy?

Ambiguity in sign of

$$m_3^2 - m_2^2$$

Two possible mass hierarchies



→ Electron neutrino appearance can help answer both questions!

θ_{13} measurements (other than solar- ν and atm- ν)

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

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{1.27\Delta m_{31}^2 L(m)}{E_\nu(MeV)}\right) \quad \text{pure } \theta_{13} \text{ measurement}$$

- Accelerator neutrino experiments : ν_e appearance

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13}) \sin^2\theta_{23} \sin^2\left(\frac{1.27\Delta m_{31}^2 L(km)}{E_\nu(GeV)}\right) \quad \text{leading term}$$

sub-leading terms

$$\begin{aligned} \delta &\rightarrow -\delta \\ a &\rightarrow -a \end{aligned}$$

for $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

$$\begin{aligned} &+ 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \cdot \sin\Phi_{31} \cdot \sin\Phi_{21} \quad \text{CPC} \\ &- 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \cdot \sin\Phi_{31} \cdot \sin\Phi_{21} \quad \text{CPV} \\ &+ 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2\Phi_{21} \quad \text{solar} \\ &- 8C_{13}^2 S_{13}^2 S_{23}^2 (1 - 2S_{13}^2) \frac{aL}{4E_\nu} \cos\Phi_{32} \sin\Phi_{31} \cdot \quad \text{matter effect} \end{aligned}$$

ν_e appearance : sensitive to δ and the mass hierarchy

→ Non-zero θ_{13} opens the possibility to probe the CP violation in the lepton sector !

Measuring θ_{13}



Long baseline accelerator: Sensitive to θ_{13} , δ , mass hierarchy

$$P(\nu_\mu \rightarrow \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos \delta - S_{12} S_{13} S_{23}) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin \delta \cdot \sin \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} + 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos \delta) \cdot \sin^2 \Delta_{21} - 8C_{13}^2 S_{12}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} + 8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2} (1 - 2S_{13}^2) \sin^2 \Delta_{31}$$

CP violating (flips sign for anti- ν)

Solar

Matter

where:

$$C_{ij} = \cos(\theta_{ij})$$

$$S_{ij} = \sin(\theta_{ij})$$

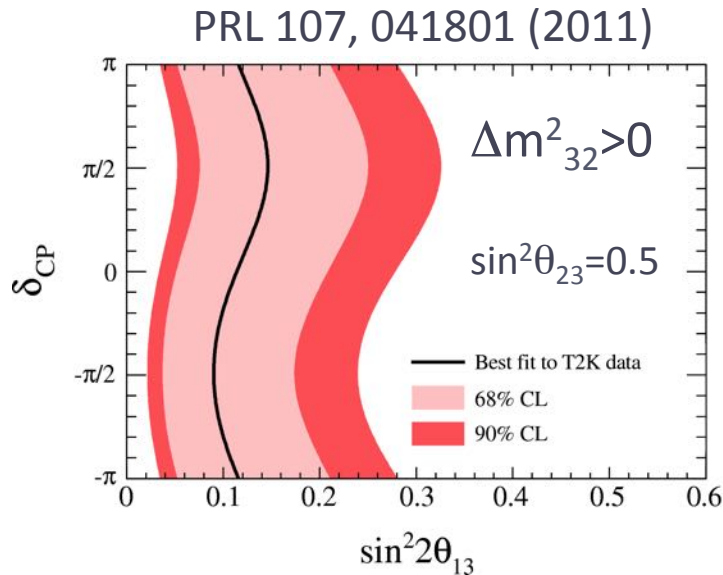
$$\Delta_{ij} = \Delta m_{ij} (L/4E)$$

Short baseline reactor: Sensitive only to θ_{13}

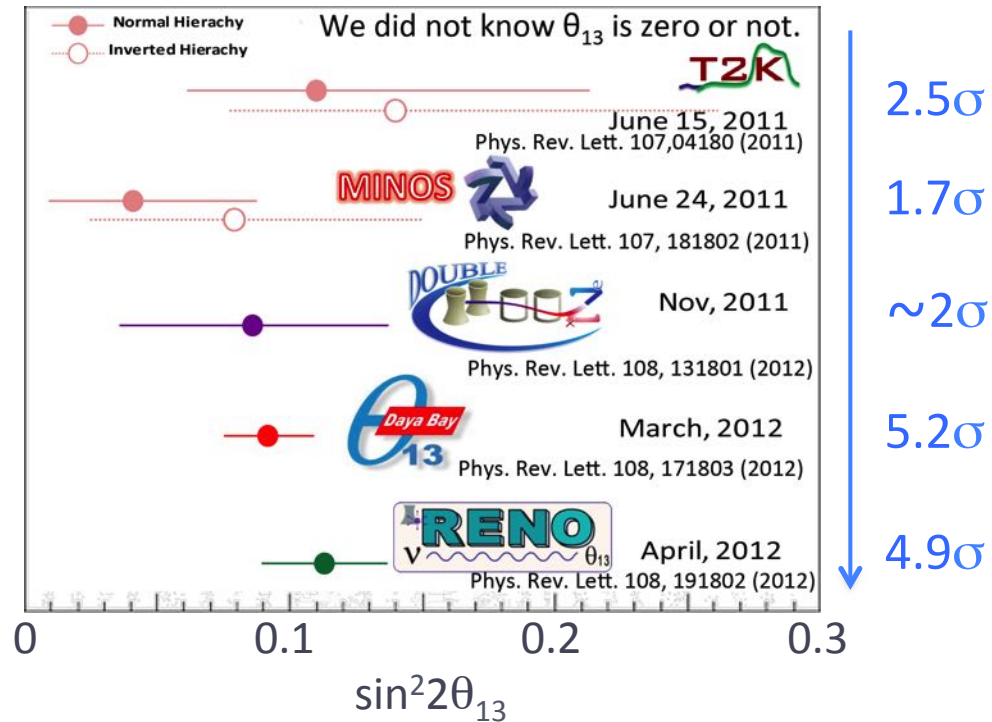
$$P_{\text{sur}} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.267 \Delta m_{31}^2 L/E)$$

Breakthrough of non-zero θ_{13} search (2011~)

- In 2011 June, T2K reported the first indication of $\theta_{13} \neq 0$ (2.5σ) using the data before the earthquake.



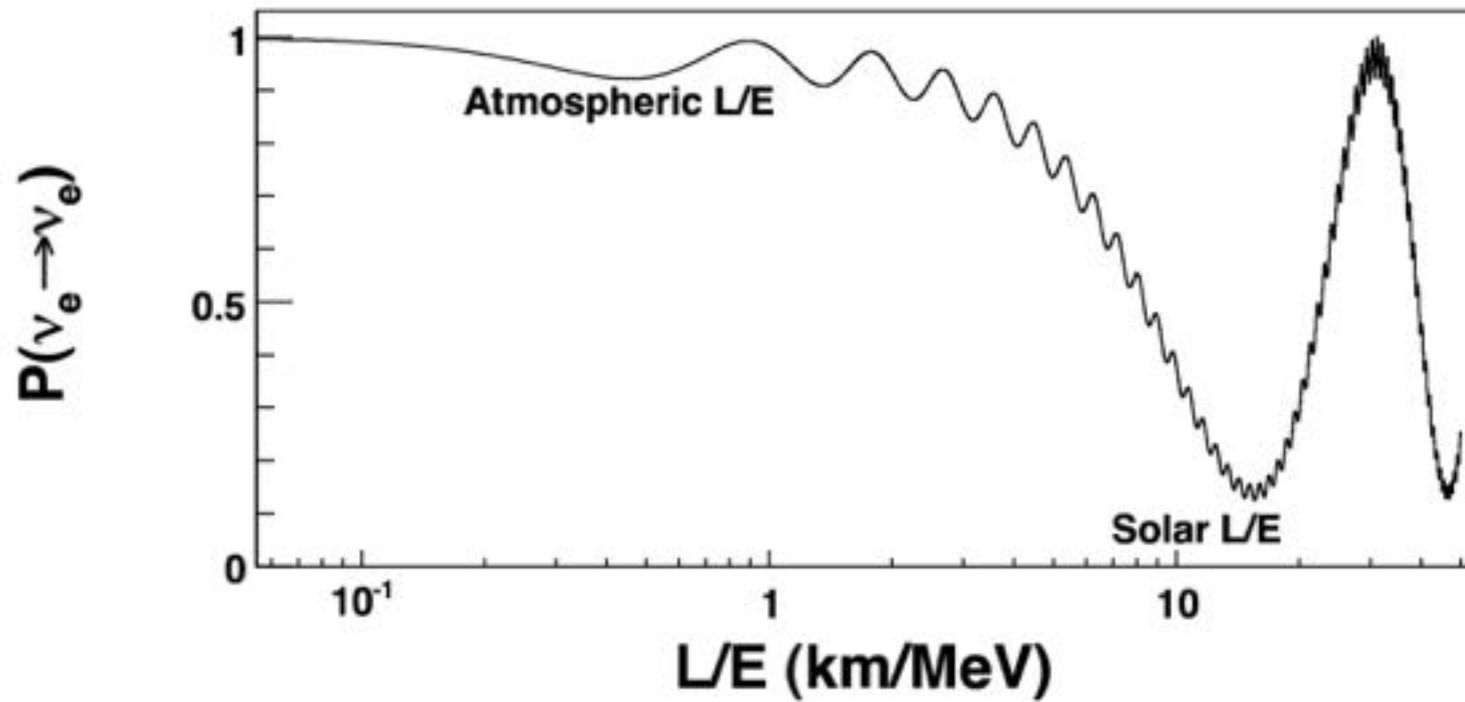
1σ confidence intervals (before Neutrino2012)



- In 2012, solid confirmation by reactor experiments.

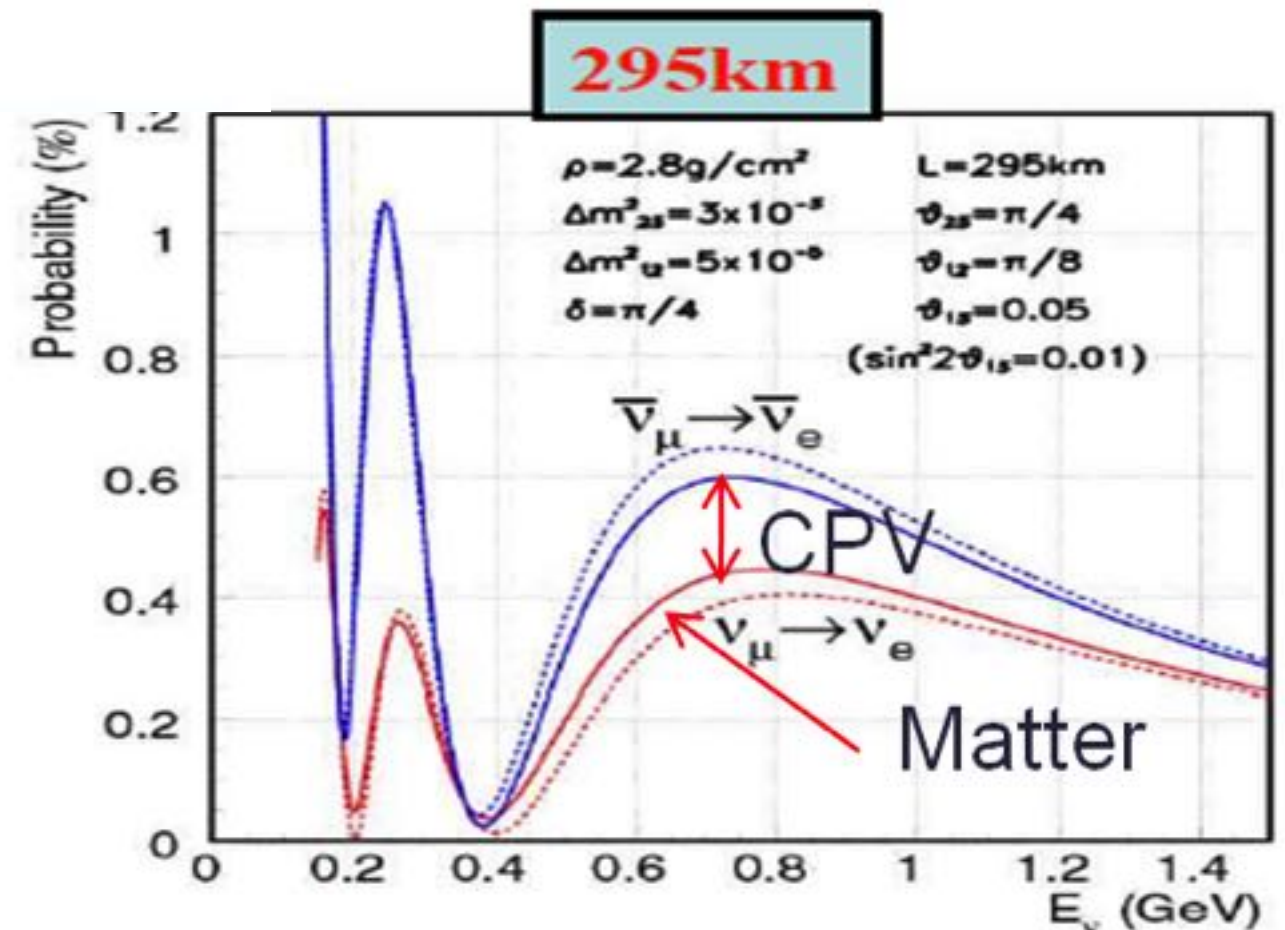
This talk : Updated ν_e appearance analysis using the full T2K data set

How to measure θ_{13}

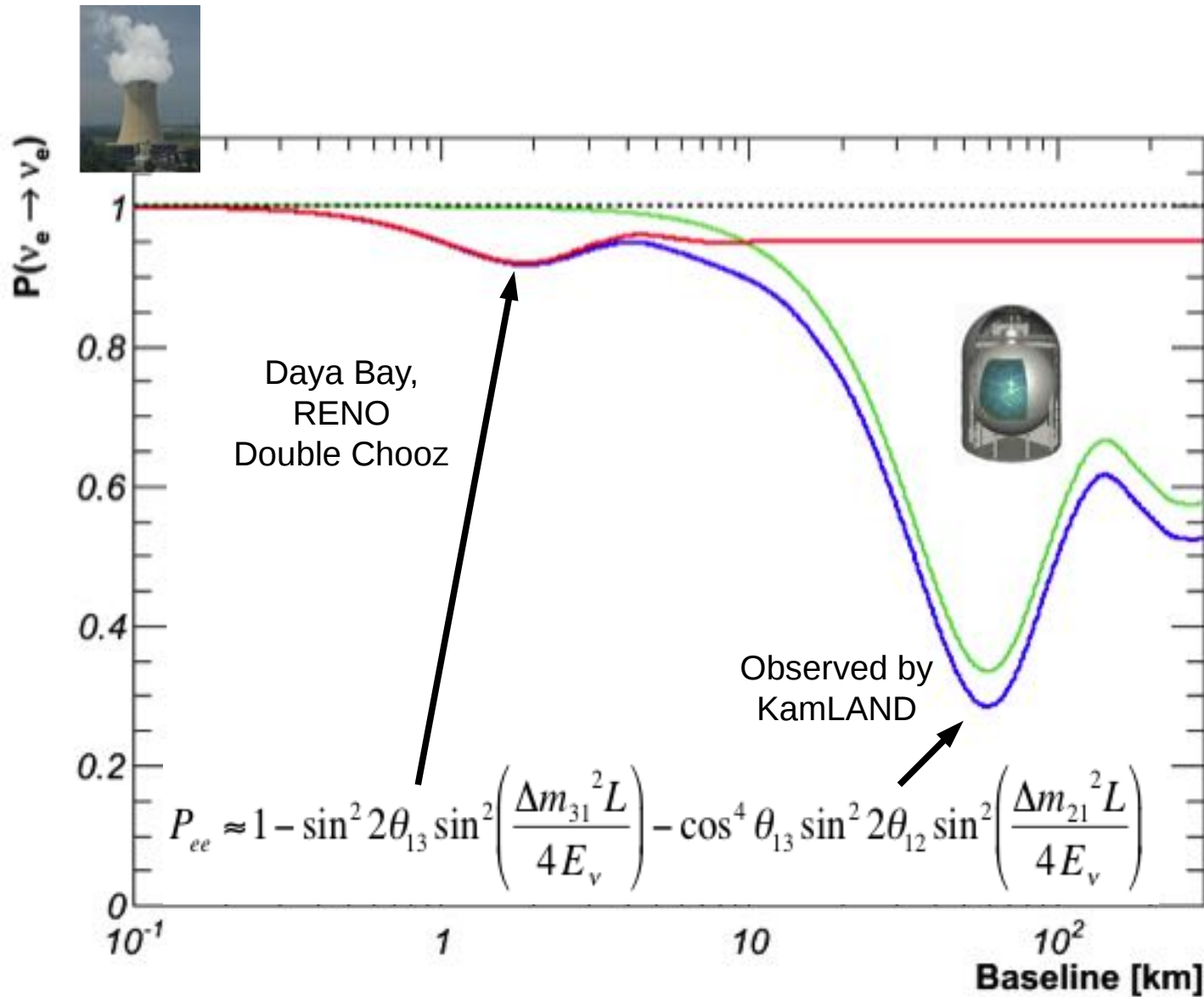


θ_{13} can cause $\bar{\nu}_e$ disappearance in reactor neutrinos

θ_{13} can cause $\nu_\mu \rightarrow \nu_e$ appearance in long baseline experiments



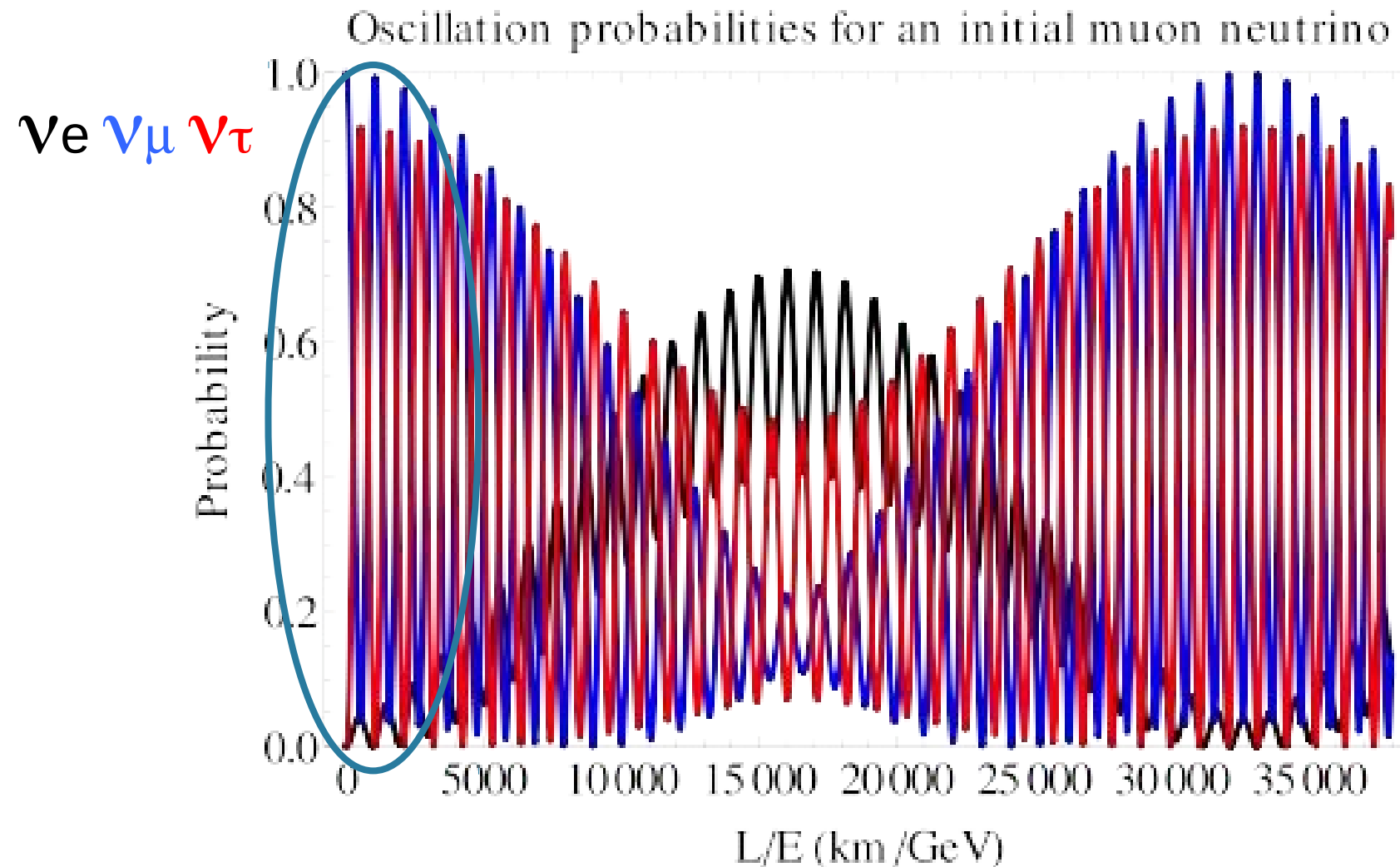
Oscillation @Reactors



Oscillation @Accelerators



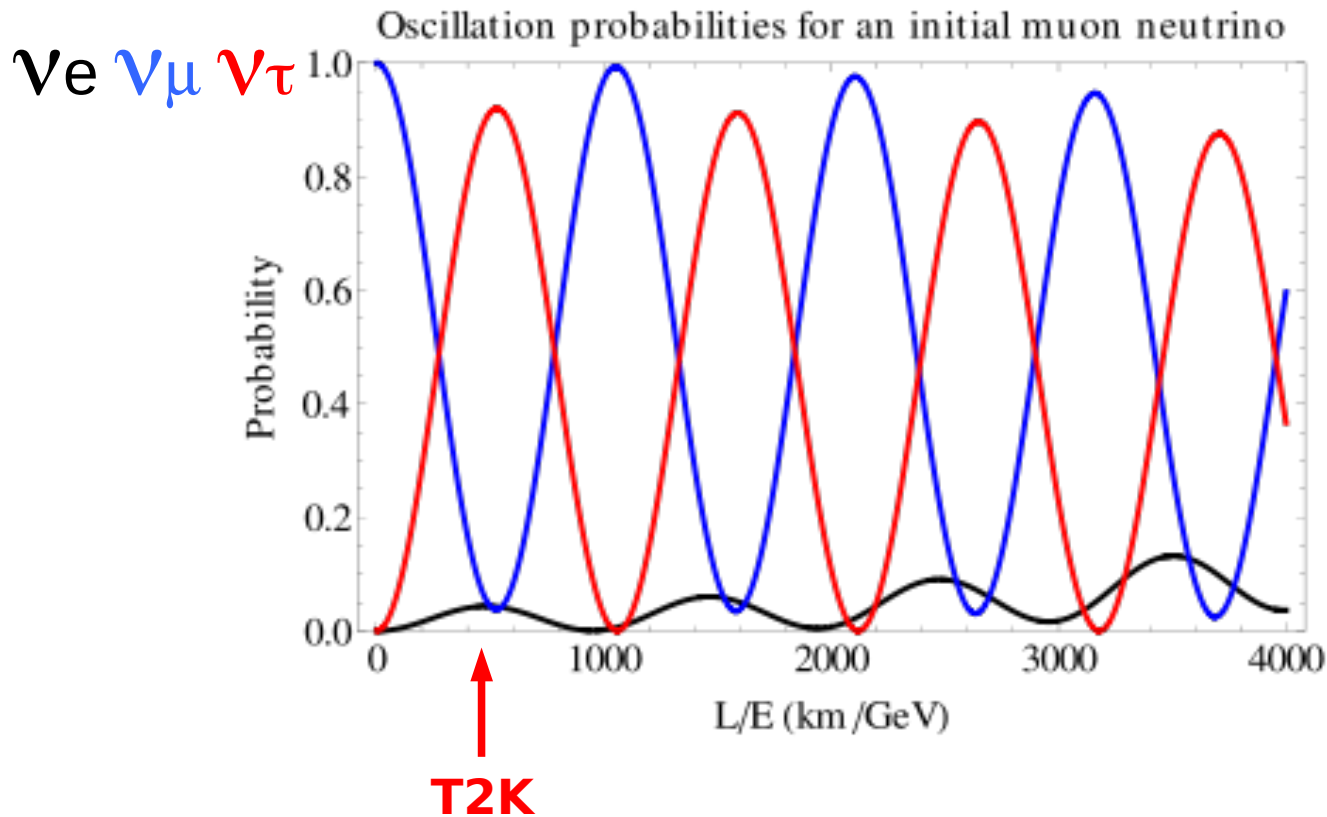
Long baseline accelerator: Sensitive to θ_{13} , θ_{23} , δ , mass hierarchy



Oscillation @Accelerators



Long baseline accelerator: Sensitive to θ_{13} , θ_{23} , δ , mass hierarchy



$$P_{\mu \rightarrow \mu} \approx 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

$$P_{\mu \rightarrow e} \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

A large, curved, perforated metal structure, possibly a tunnel or a large-scale scientific instrument, with a person visible in the distance.

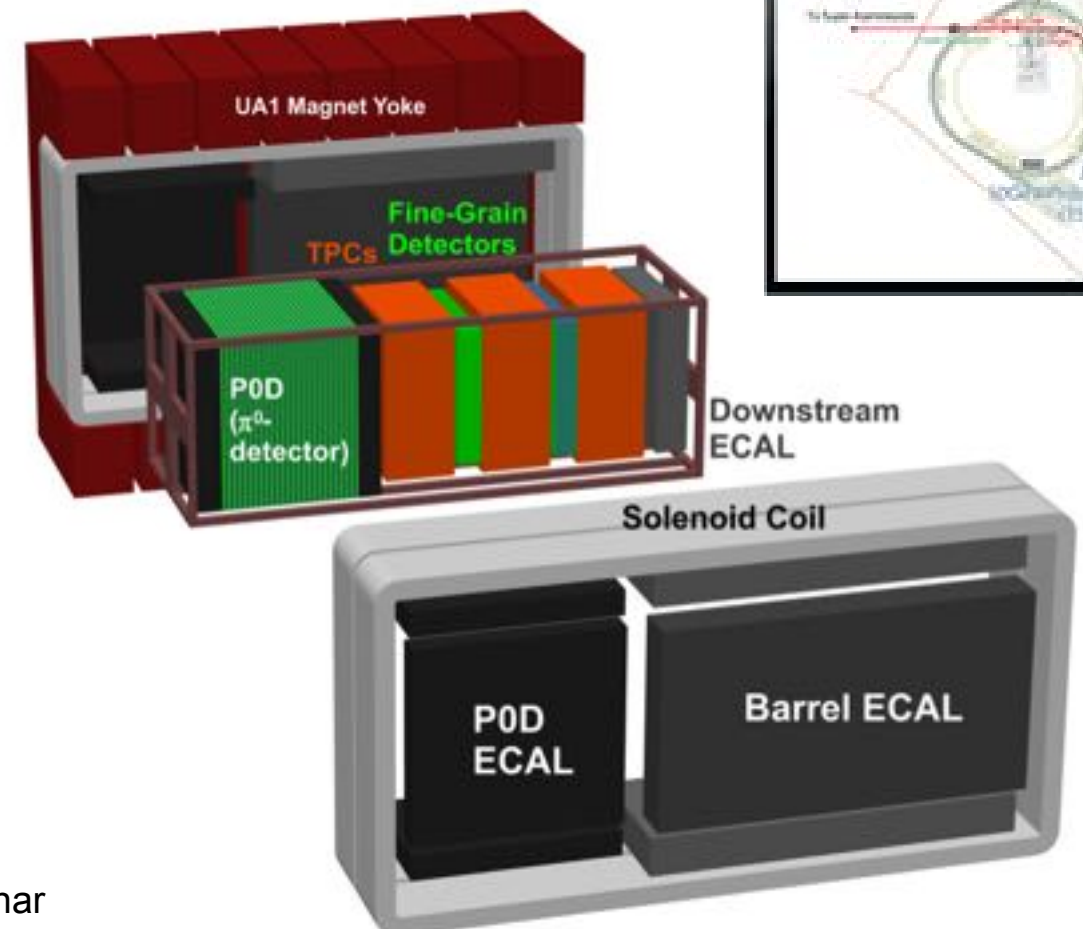
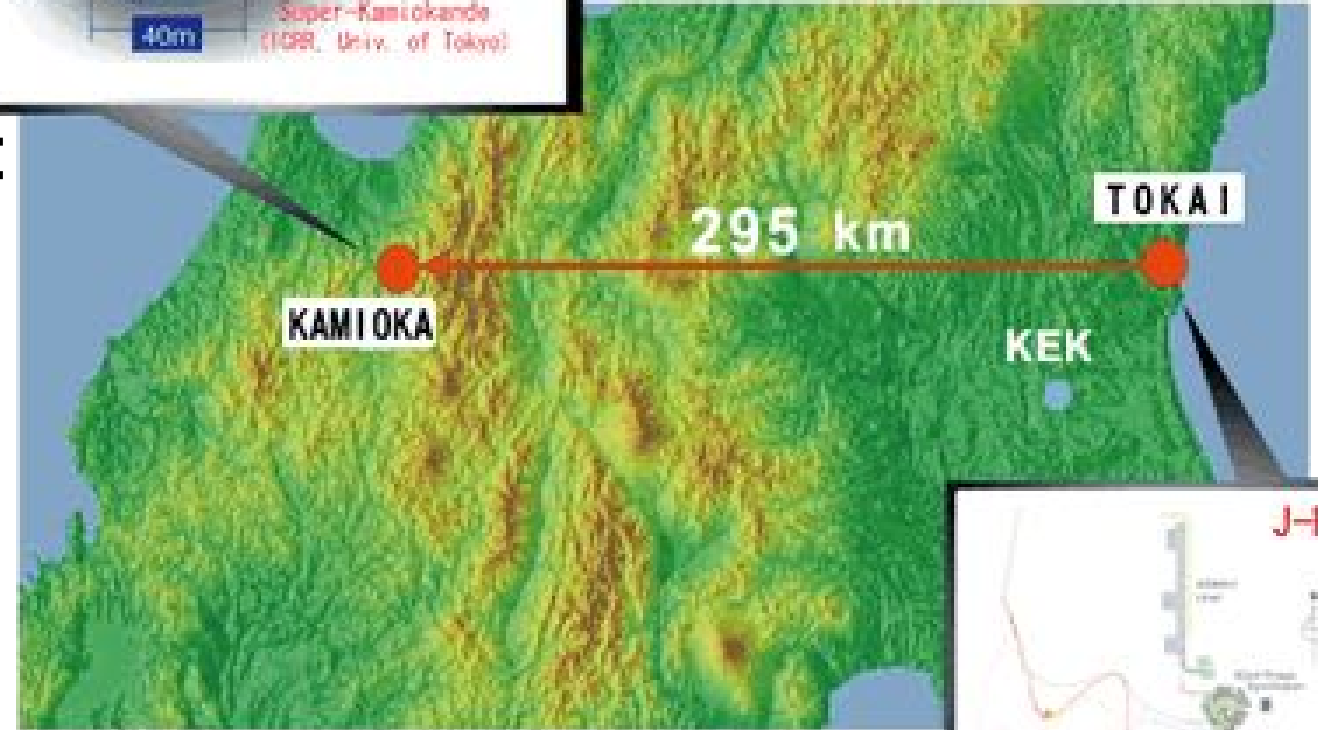
T2K

T2K



“Tokai-To-Kamioka”

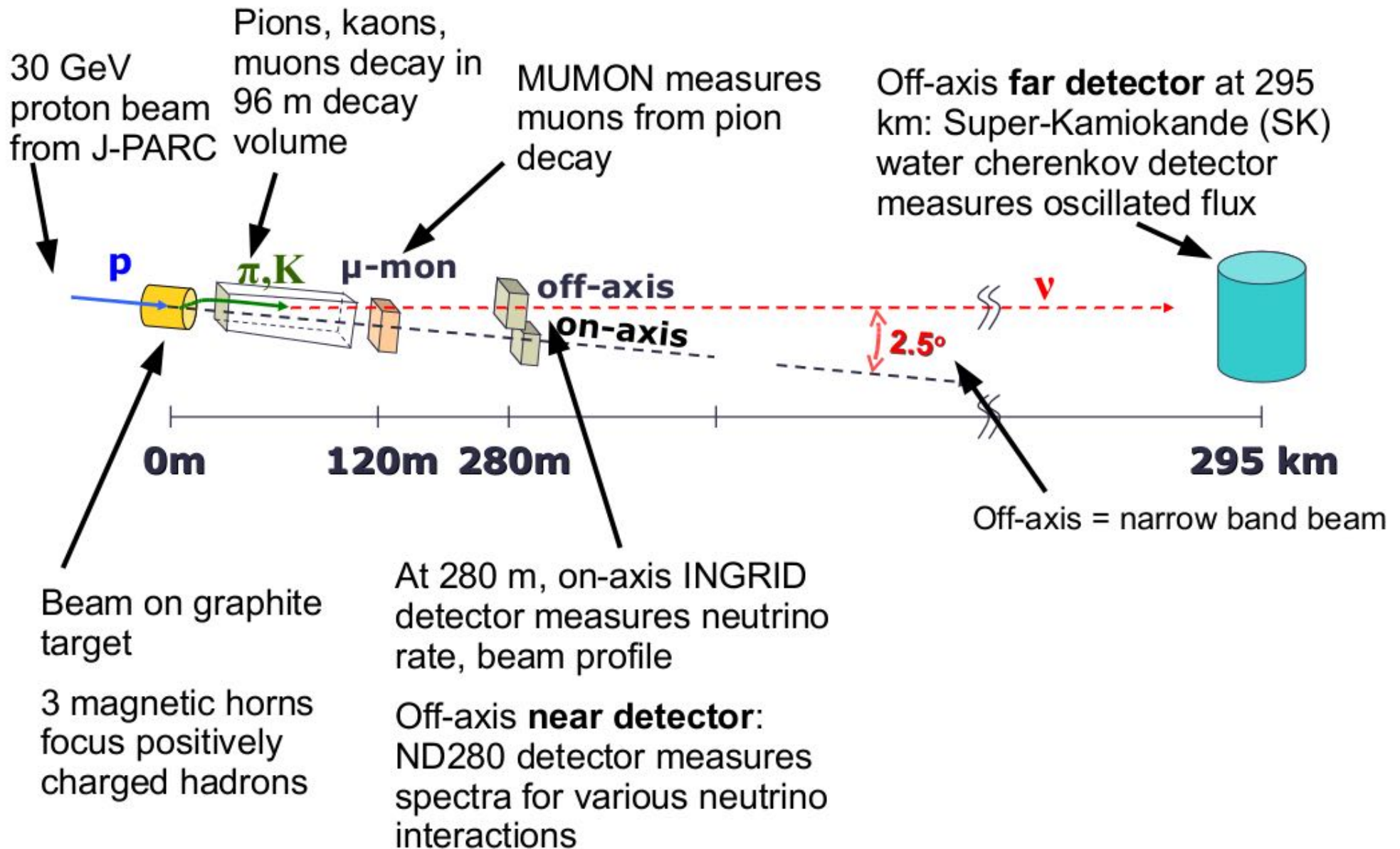
- Start with world’s largest detector: Super-Kamiokande
- Build new neutrino beam
- Off-axis beam to Super-K
 - $L = 295 \text{ km}$
 - $E = 0.6 \text{ GeV}$
- Near detectors at 280m to constrain beam flux
- Physics Goals:
 - precise $\Delta m^2_{32}, \theta_{23}$ measurements
 - search for θ_{13}



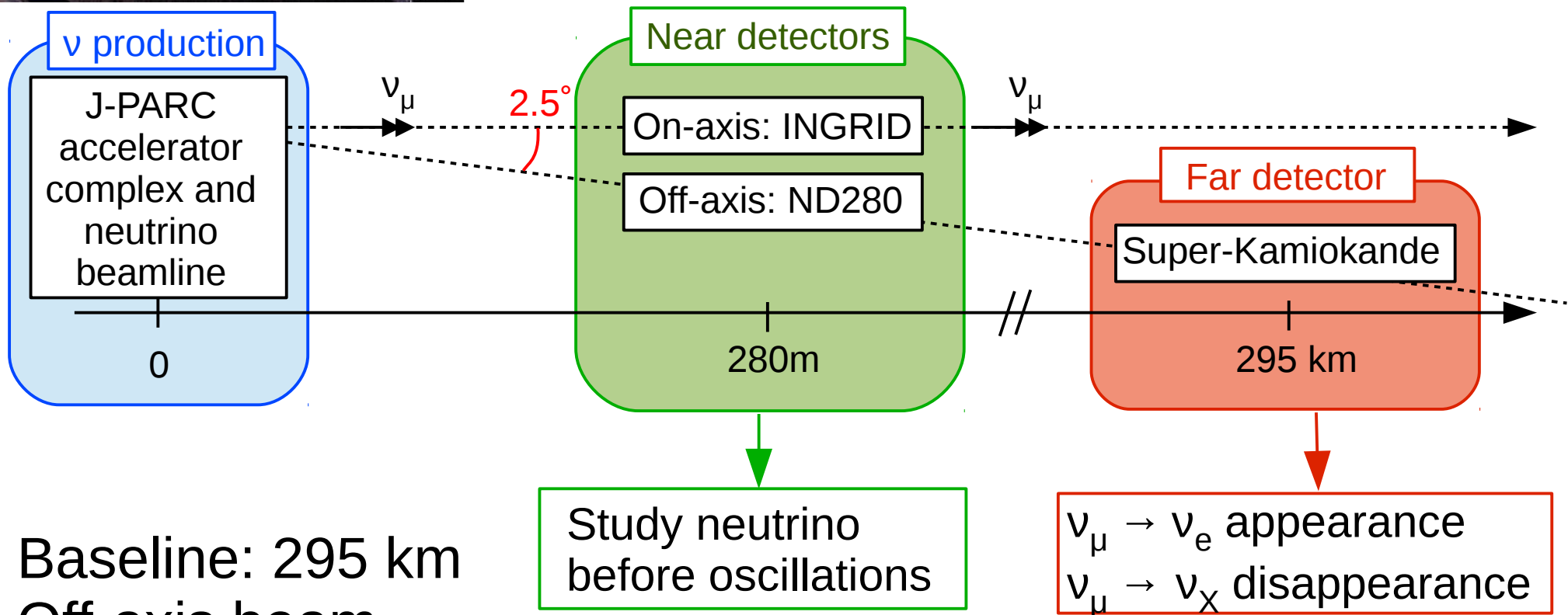
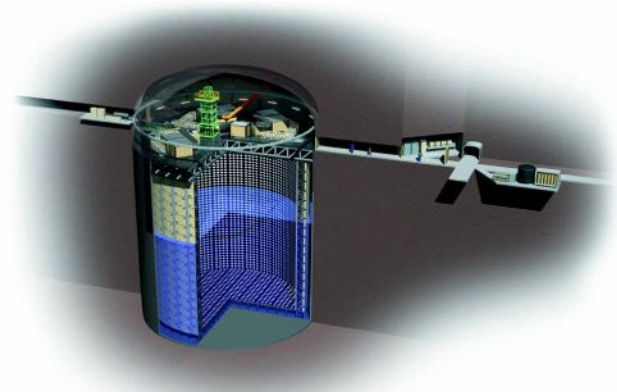
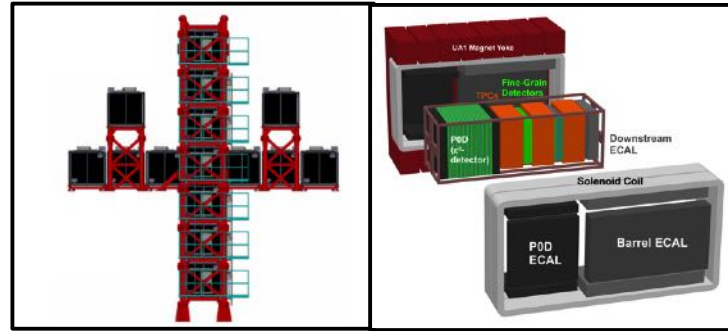
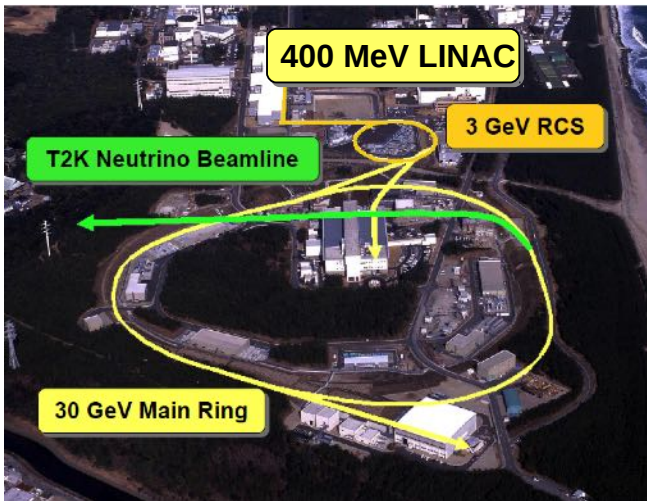
The T2K Collaboration



Experimental Overview



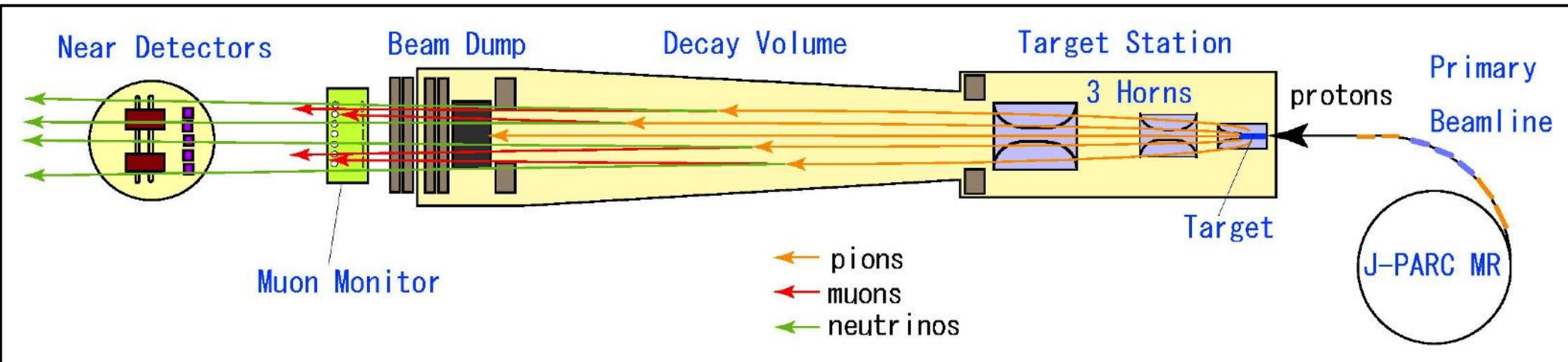
The T2K experiment Overview



- Baseline: 295 km
- Off-axis beam

The T2K experiment Neutrino production

Conventional neutrino beam produced from 30 GeV protons

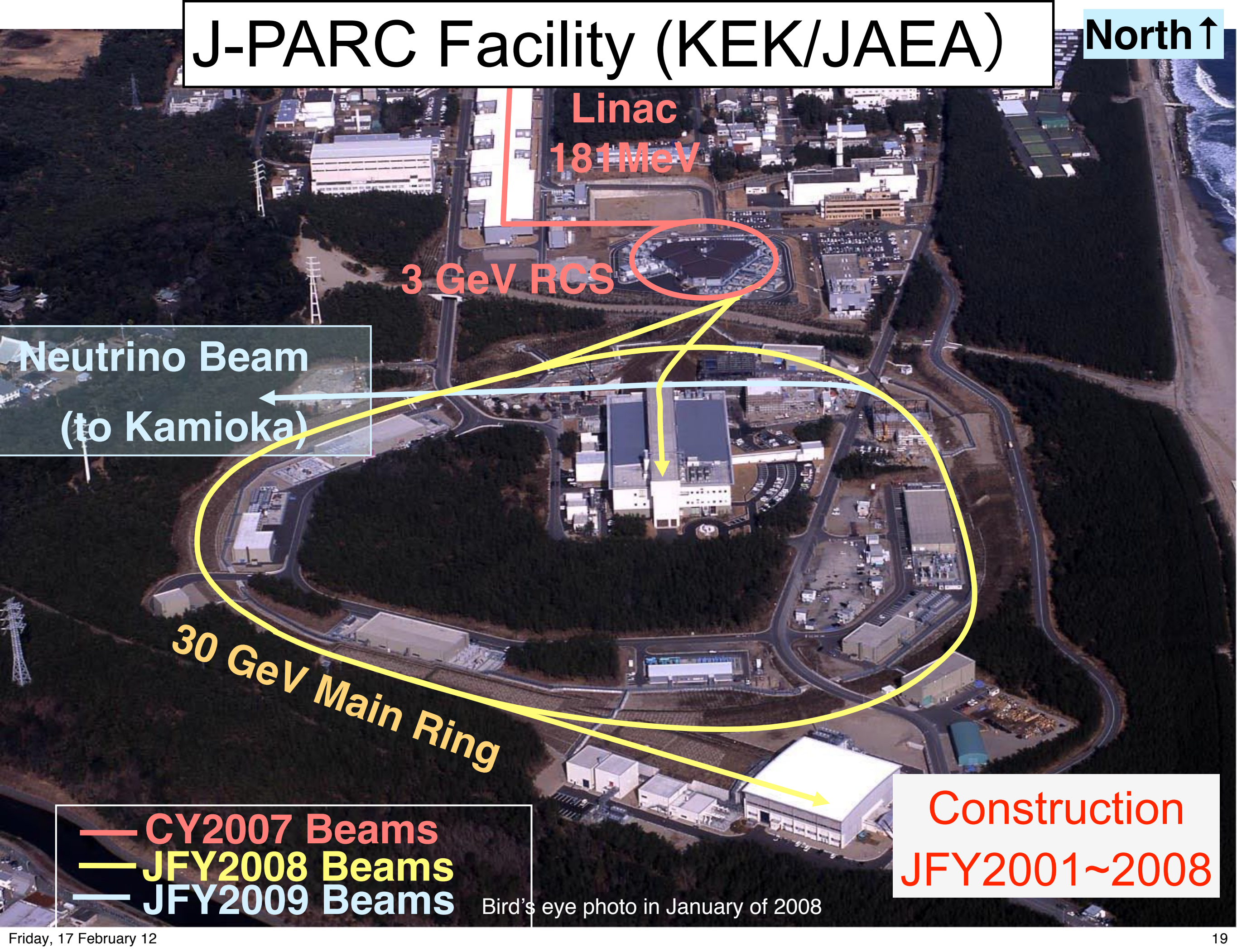


Almost pure $\nu_\mu/\bar{\nu}_\mu$ beam,
with an intrinsic $\nu_e/\bar{\nu}_e$
component (<1% at peak)

Can switch from ν_μ beam to
 $\bar{\nu}_\mu$ beam by inverting the horn
polarities

J-PARC Facility (KEK/JAEA)

North ↑



Linac
181 MeV

3 GeV RCS

Neutrino Beam
(to Kamioka)

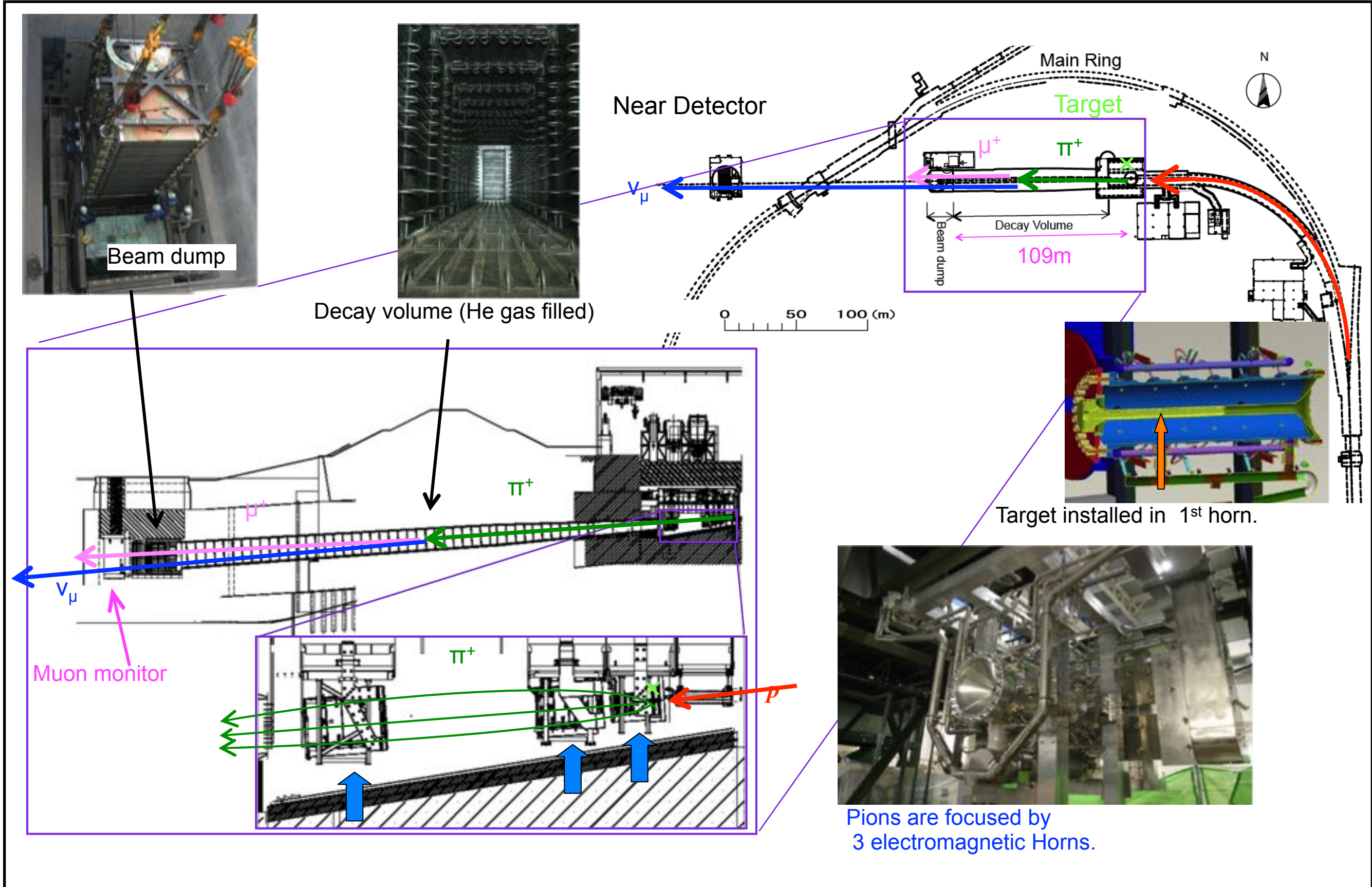
30 GeV Main Ring

Construction
JFY2001~2008

- CY2007 Beams
- JFY2008 Beams
- JFY2009 Beams

Bird's eye photo in January of 2008

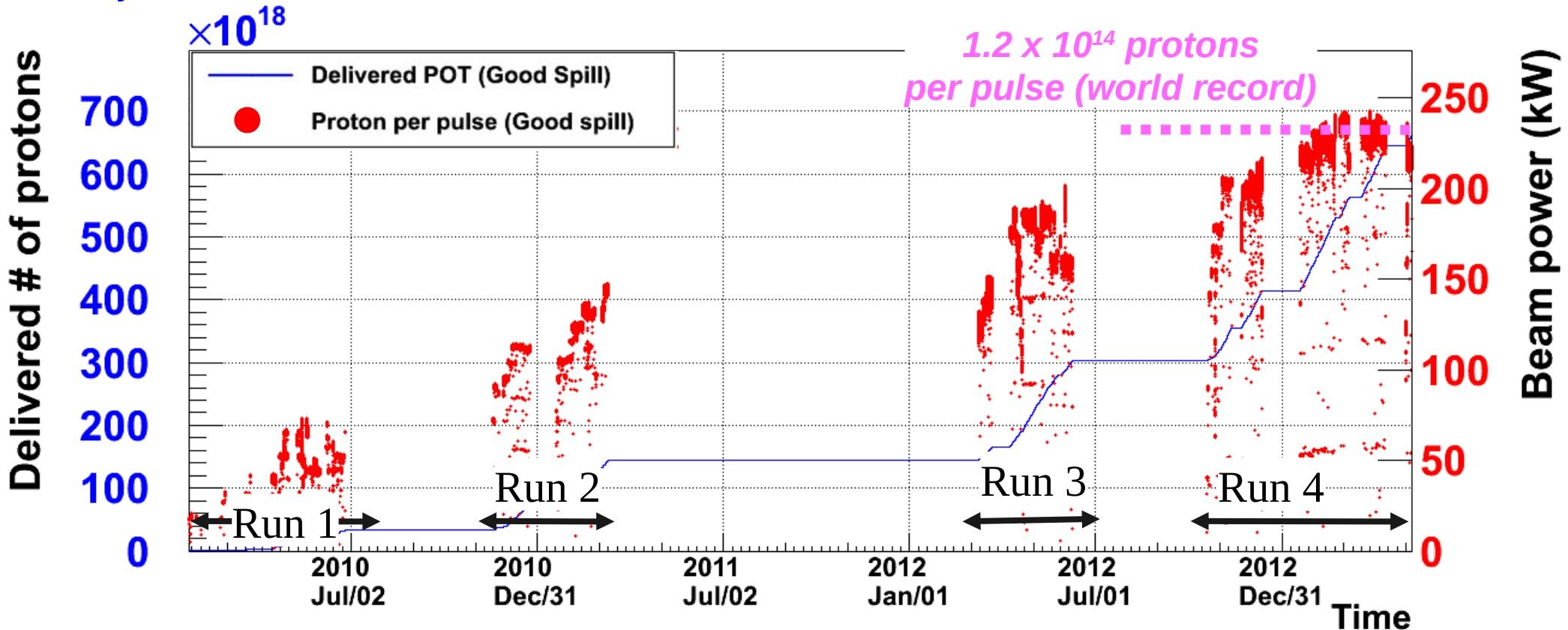
J-PARC neutrino beamline overview



T2K Data Taking

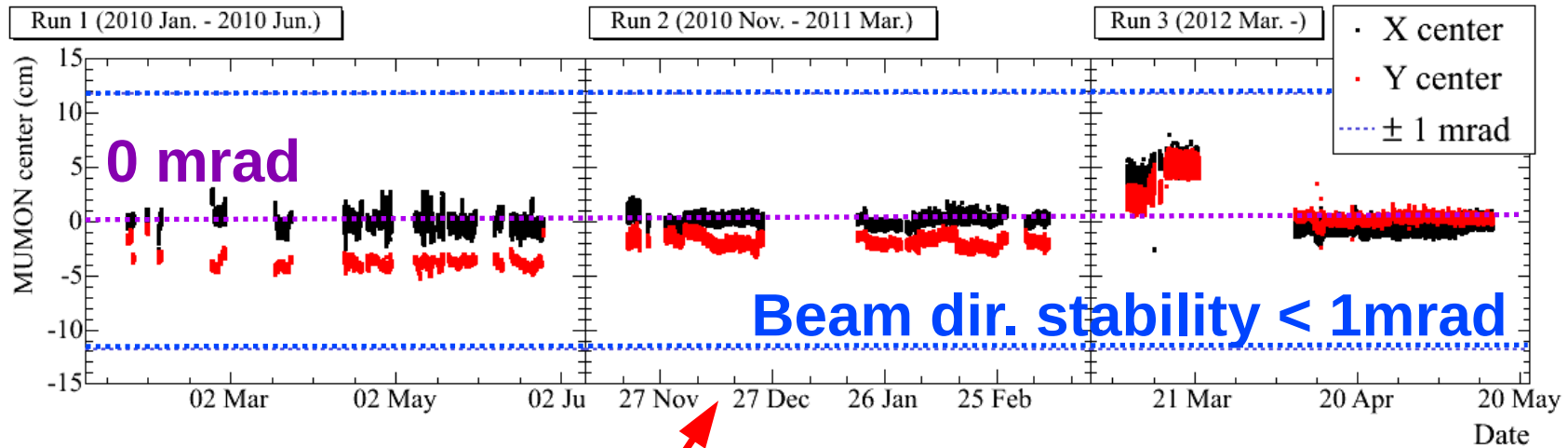


Many thanks to the J-PARC accelerator division for their efforts and much hard work!

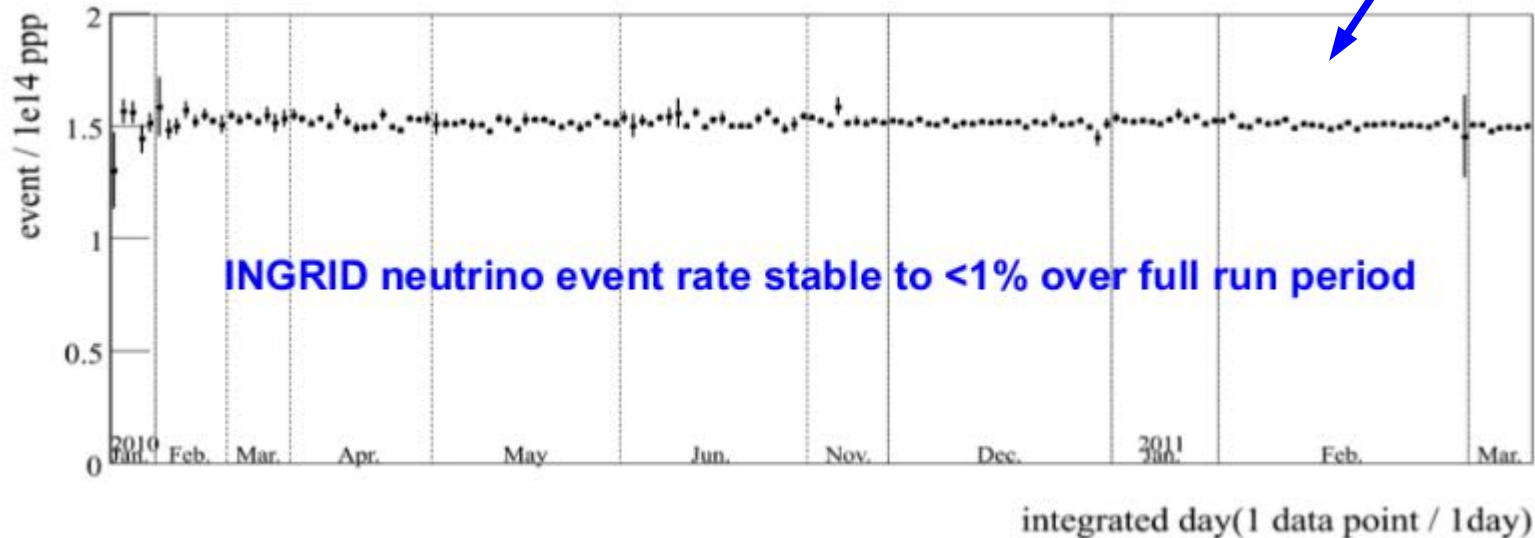


- **NEW!** Full Run 1 – 4 data sets published this week! Phys. Rev. Lett. **107:041801** (Feb 10th)
 - Featured in an APS “Viewpoint” article (<http://physics.aps.org/articles/v7/15>)
- Total exposure at far detector is 6.57×10^{20} P.O.T.
 - Previous ν_e appearance result (2012) used 3.01×10^{20} P.O.T. → **Statistics increased by factor >2!**
- Thus far, ~8% of the total data has been collected (assuming design goal)
- Instantaneous luminosity of 220 kW (1.2×10^{14} protons per pulse) → **World record!**

Beam Stability: Rate & Direction

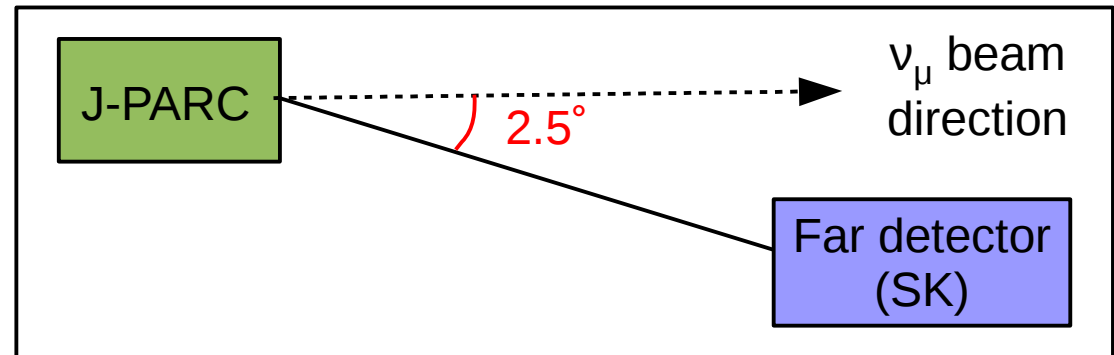
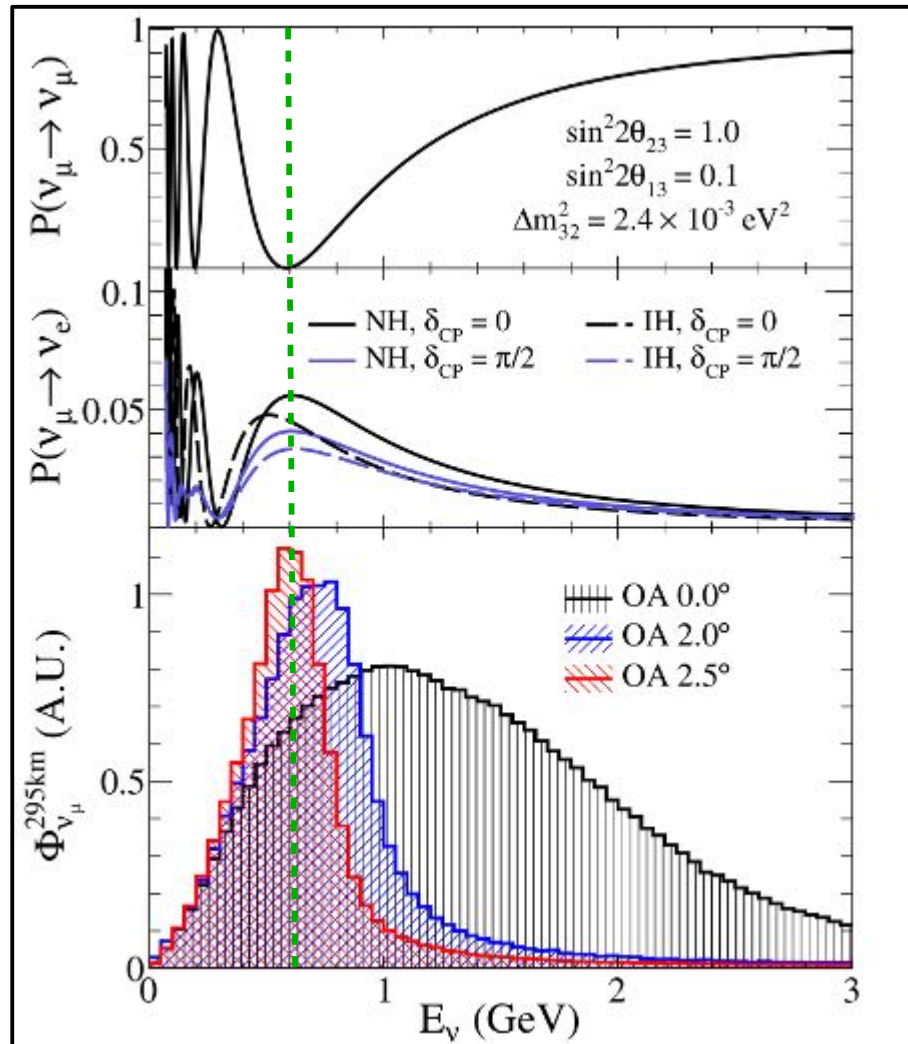


Beam is quite stable in **space** (1 mrad tolerance) and **time** (within 1%)



The T2K experiment

Off-axis beam



- Narrow band neutrino beam, peaked at oscillation maximum (0.6 GeV)
- Reduces high energy tail
- Reduces intrinsic ν_e contamination of the beam at peak energy
- Interactions dominated by CCQE mode

Here we give an explanation of the off-axis method [20]. The ν_μ beam is produced from the charged pion decay ($\pi \rightarrow \mu\nu_\mu$). The energy of the neutrino in the pion rest frame (in which quantities are labeled with the superscript $*$) is

$$E_\nu^* = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} = 29.8 \text{ MeV} \quad (1.23)$$

The laboratory frame 4-momentum can be calculated by Lorentz transformation:

$$\begin{pmatrix} p_\mu \end{pmatrix} \rightarrow \begin{bmatrix} \gamma_\pi & 0 & 0 & \gamma_\pi\beta_\pi \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \gamma_\pi\beta_\pi & 0 & 0 & \gamma_\pi \end{bmatrix} \begin{pmatrix} p_\mu \end{pmatrix} \quad (1.24)$$

$$\begin{aligned} & (E_\nu, E_\nu \sin \theta, 0, E_\nu \cos \theta) \\ \rightarrow & (E_\nu^* \gamma_\pi (1 + \beta_\pi \cos \theta^*), E_\nu^* \sin \theta^*, 0, E_\nu^* \gamma_\pi (\beta_\pi + \cos \theta^*)) \end{aligned} \quad (1.25)$$

where θ is angle between the pion momentum and the neutrino momentum. The relation between the angle in the pion rest (θ^*) and that in the lab. frame (θ) is obtained from the 1st and 3rd components of Eq. 1.25:

$$\tan \theta = \frac{E_\nu^* \sin \theta^*}{E_\nu^* \gamma_\pi (\beta_\pi + \cos \theta^*)} \quad (1.26)$$

If $E_\nu, E_\pi \gg m_\pi$ and then $\beta_\pi \simeq 1$, we can re-write Eq. 1.26 to

$$\tan \theta \simeq \frac{E_\nu^* \sin \theta^*}{E_\nu} \quad (1.27)$$

using the 0th component of Eq. 1.25. This equation indicates that a maximum lab angle θ_{max} is obtained at $\theta^* = 90^\circ$:

$$\tan \theta_{max} \simeq \frac{E_\nu^*}{E_\nu} \quad (1.28)$$

In other words, there is a maximum neutrino energy ($E_\nu^{max.}$) with fixed angle θ :

$$E_\nu^{max.} \simeq \frac{E_\nu^*}{\tan \theta} = \frac{29.8 \text{MeV}}{\tan \theta} \quad (1.29)$$

The relation between E_ν , E_π and θ is obtained from the 0th component of Eq. 1.25:

$$E_\nu = \frac{\gamma_\pi + \gamma_\pi \beta_\pi \sqrt{1 - \tan^2 \theta}}{1 + \gamma_\pi^2 \beta_\pi^2} E_\nu^* \quad (1.30)$$

, and is shown in Fig. 1.4. As expected from Eq. 1.29, there is a maximum neutrino energy $E_\nu^{max.}$ with non-zero θ , and as the neutrino energy approaches this value, pions in large range of energies contribute to neutrinos in a small range of energy. Thus semi-monochromatic energy neutrino beam with the peak around $E_\nu^{max.}$ is achieved with the fixed angle θ which is called as the off-axis angle.

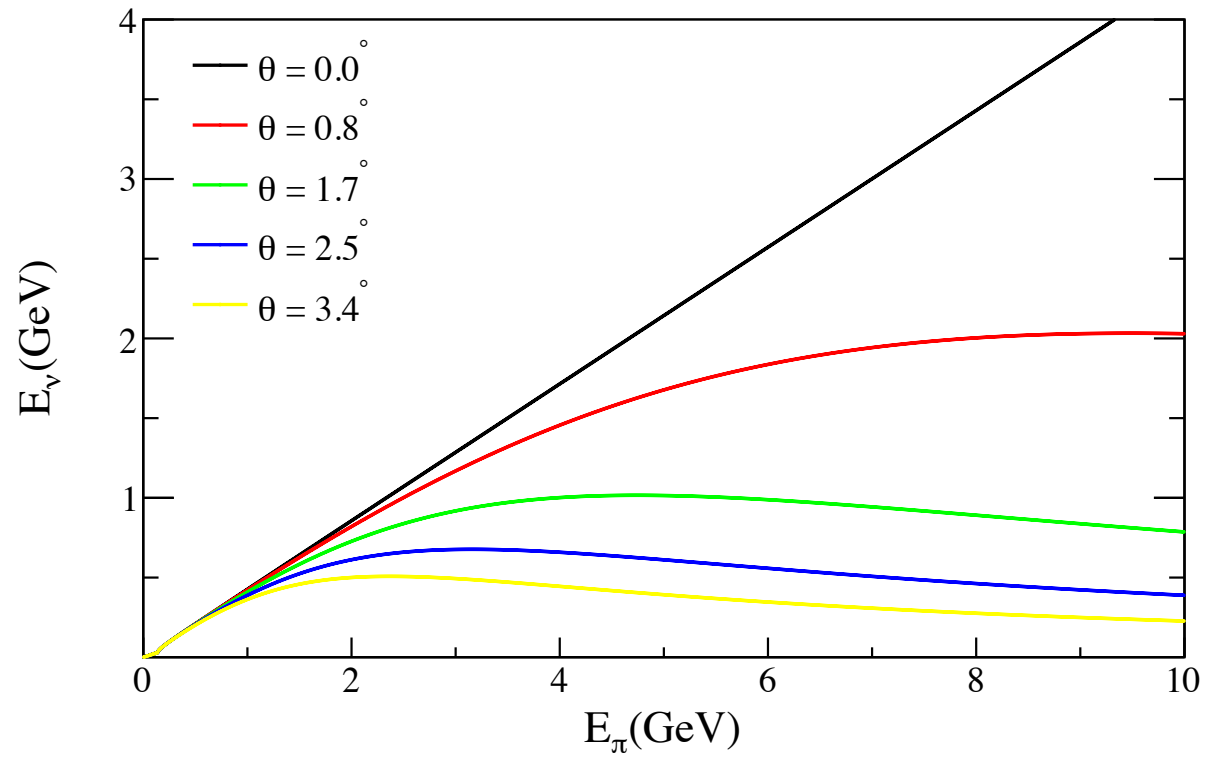


Figure 1.4: Relation between neutrino energy (E_ν) and pion energy (E_π) in the pion decay with several off-axis angles.

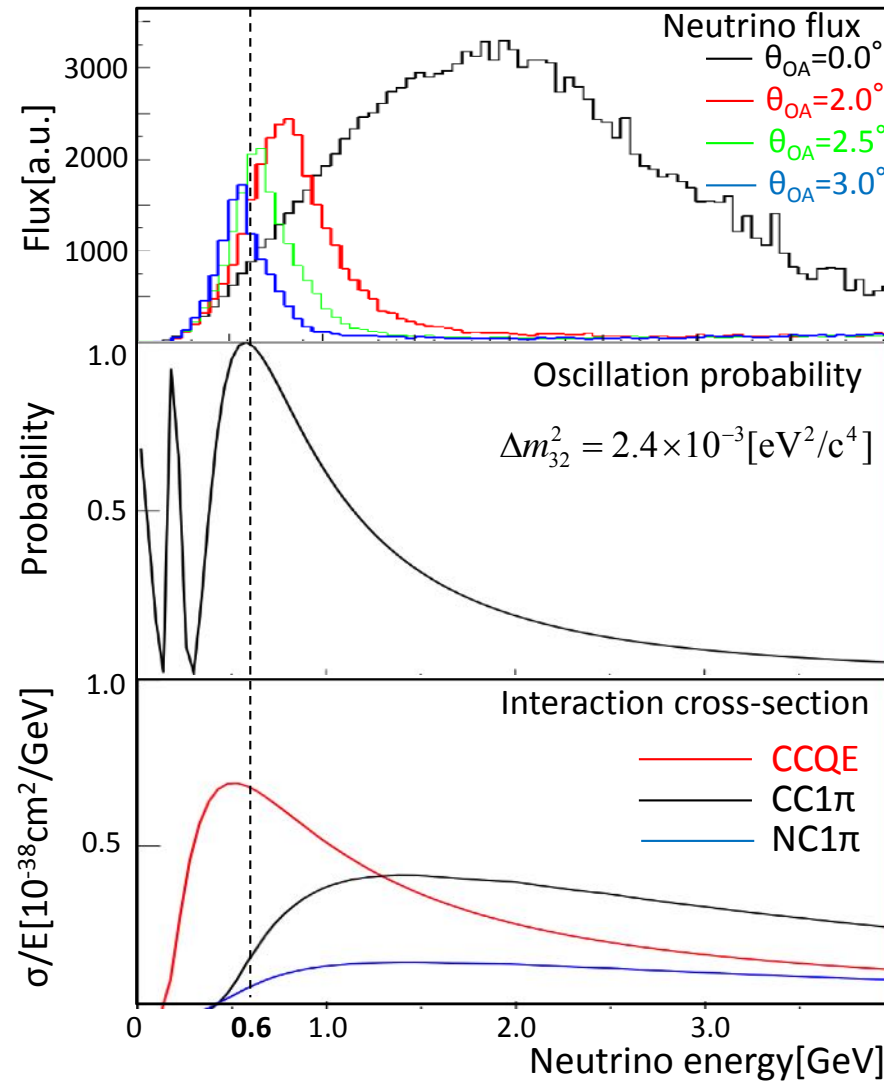


Figure 1.5: (Top) Neutrino energy spectra with several off-axis angles (θ_{OA}). (Middle) Oscillation probability as a function of the neutrino energy. (Bottom) Neutrino interaction cross-sections.

1.2.5 Analysis strategy

To catch the oscillation signals, we detect the beam neutrinos in SK which is 295 km away from J-PARC. Especially the neutrino charged current quasi-elastic (CCQE) interaction event,

$$\nu_\ell + n \rightarrow \ell^- + p \quad (1.31)$$

is selected because of following reasons.

- The CCQE interaction is a dominant interaction mode in the T2K neutrino energy region. About 40% interactions are expected to be the CCQE interactions in SK in case without neutrino oscillation.
- The neutrino energy can be reconstructed (E_ν^{rec}) by measuring the lepton momentum (p_ℓ) and the angle with respect to the neutrino (θ_ℓ):

$$E_\nu^{\text{rec}} = \frac{(m_n - V)E_\ell + (m_p^2 - m_\ell^2)/2 - (m_n - V)^2/2}{(m_n - V) - E_\ell + p_\ell \cos \theta_\ell} \quad (1.32)$$

where m_n , m_p and m_ℓ are the mass of the neutron, proton and lepton, respectively. E_ℓ is the lepton energy and V is the nuclear potential of nucleus (it is 27 MeV for oxygen).

- Flavor of the neutrino can be determined by identifying the flavor of the lepton

In order to select the CCQE interaction event, we require only one Cherenkov ring in SK because the associated proton often does not emit Cherenkov light due to its high Cherenkov threshold in water (~ 1.1 GeV/c). The momentum of the muon or the electron can be reconstructed by observed number of Cherenkov photons. The direction of the muon or the electron is determined by the Cherenkov ring direction. The muon and electron can be distinguished because a muon makes a sharp edge ring and an electron makes a fuzzy one due to electromagnetic showers.

For an analysis of the neutrino oscillation in ν_μ disappearance, both the energy spectrum and the number of the muon neutrino events in SK are compared between expectation and observation. The energy spectrum at SK, $\Phi_{SK}(E_\nu)$, strongly depends on the off-axis angle as described in Section 1.2.4. Hence precise measurement of the beam direction is important for the $\Phi_{SK}(E_\nu)$ estimation. In this thesis, the expected number of events at SK ($N_{SK}^{\text{exp.}}$) is calculated by using the number of events measured in the near detector (N_{ND}^{obs}):

$$\begin{aligned} N_{SK}^{\text{exp}} &= N_{ND}^{\text{obs}} \cdot \frac{N_{SK}^{\text{MC}}}{N_{ND}^{\text{MC}}} \\ &= N_{ND}^{\text{obs}} \cdot \frac{\int dE_\nu \Phi_{SK} \cdot \sigma_{SK} \cdot \epsilon_{SK} \cdot P(E_\nu; \sin^2 2\theta_{23}, \Delta m_{32}^2)}{\int dE_\nu \Phi_{ND} \cdot \sigma_{ND} \cdot \epsilon_{ND}} \end{aligned} \quad (1.33)$$

where σ_{SK} (σ_{ND}) is the neutrino cross-section of the target material of SK (ND), ϵ_{SK} (ϵ_{ND}) is the detection efficiency of SK (ND), and P is the oscillation probability as described in Eq. 1.9. One of the characteristic of Eq. 1.33 is the error cancellation between ND and SK. For example, Φ_{ND} and Φ_{SK} have a common uncertainty of the production rate of the parent pions. Because the uncertainty is included in both the numerator and the denominator, the uncertainty in Φ_{SK}/Φ_{ND} is canceled even if Φ_{SK} or Φ_{ND} itself has ambiguities. Thus the event rate measurement at the near detectors is important for the $N_{SK}^{\text{exp.}}$ estimation.

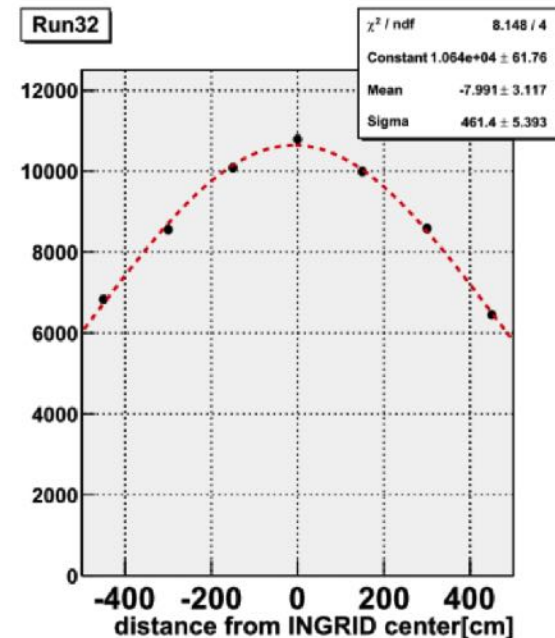
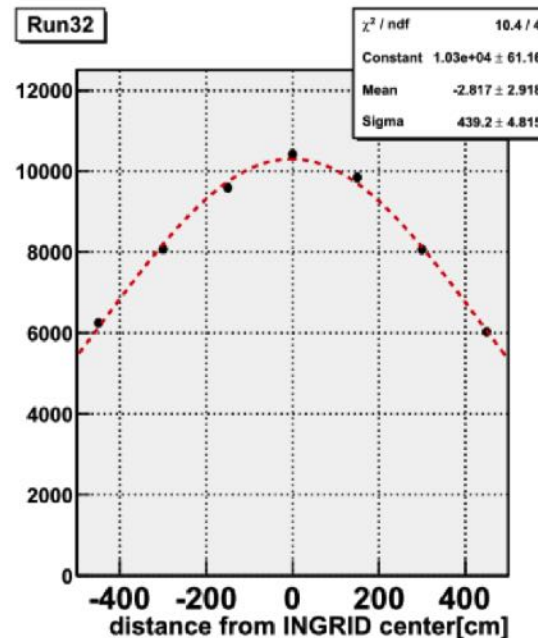
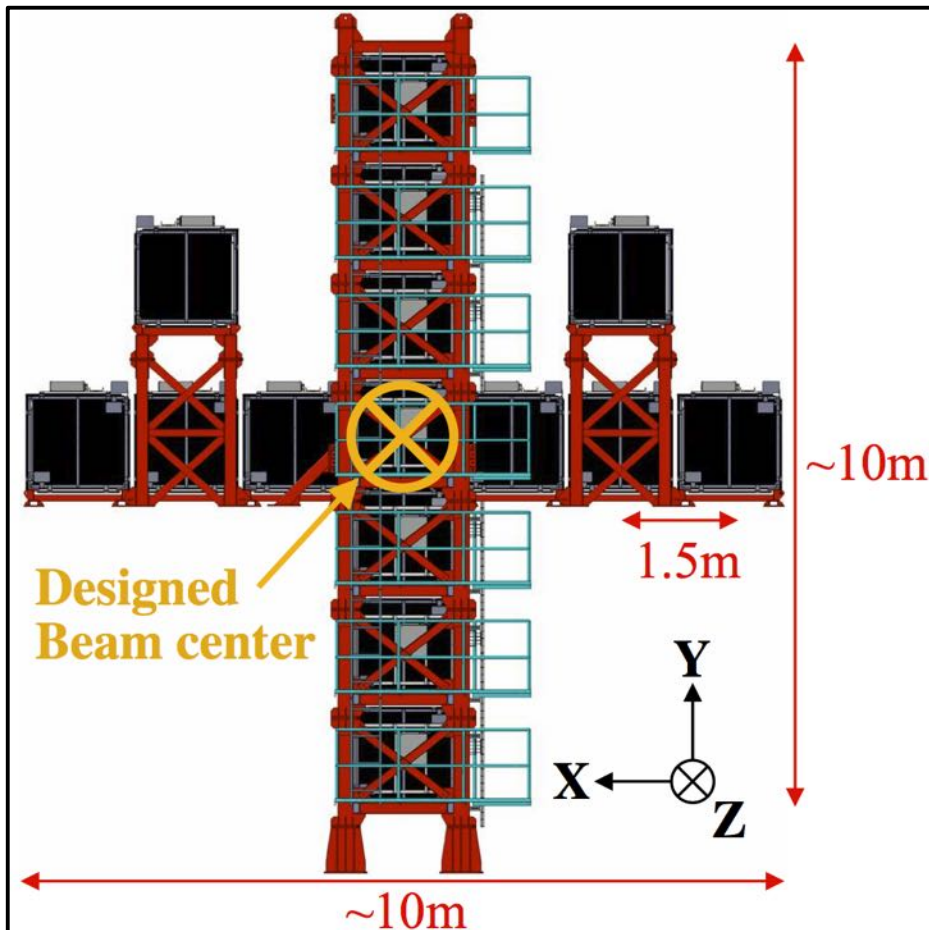
An analysis of the neutrino oscillation in ν_e appearance is performed with almost same procedure; the beam direction measurement is also important for this analysis.

The T2K experiment

Near detectors

On-axis detector INGRID (Interactive Neutrino GRID)
Located 280m from the target

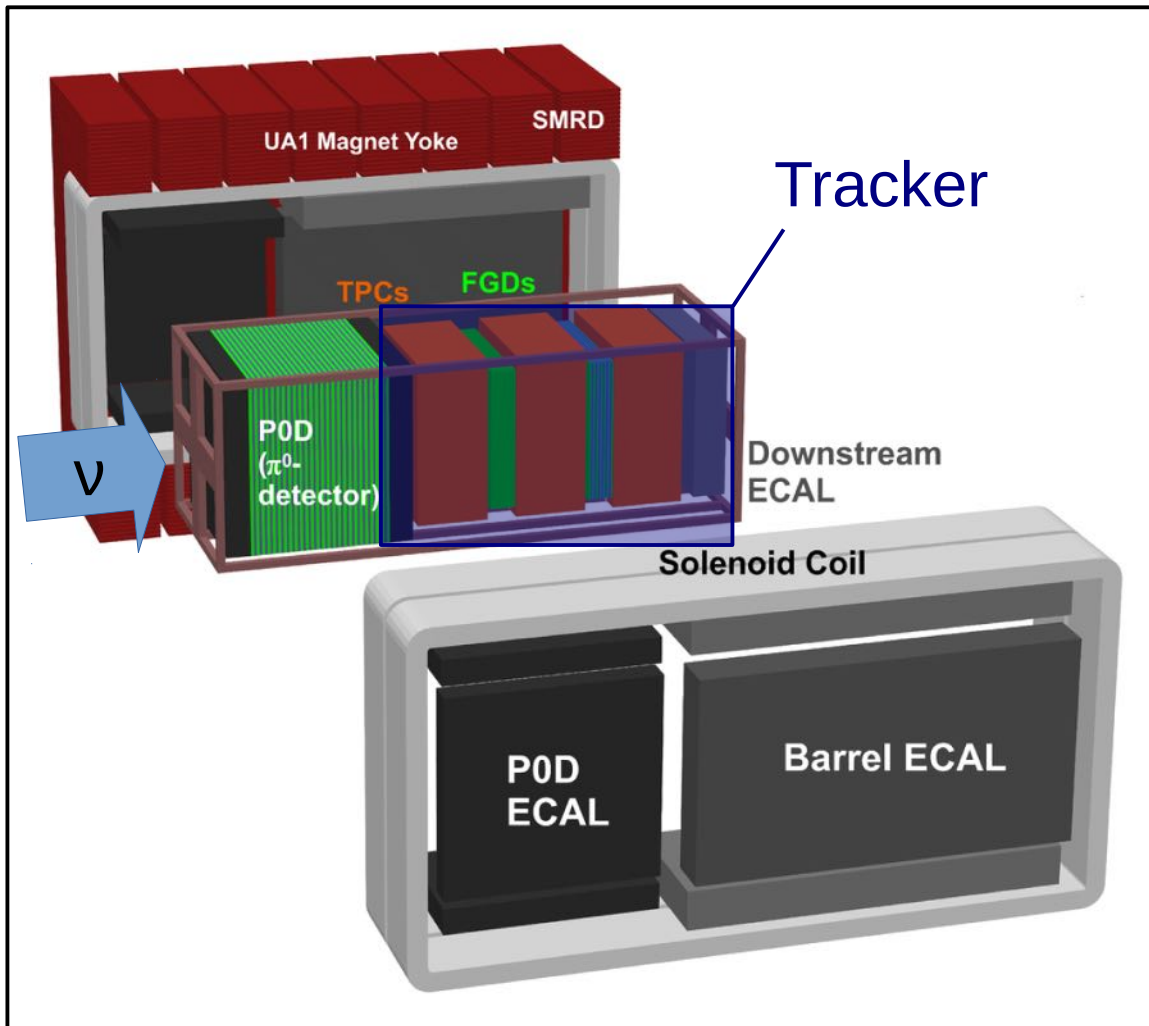
- 16 identical modules made of iron and scintillators
- 'counting neutrinos' by reconstructing muon tracks from ν_μ interactions
- Monitors neutrino beam: rate, direction and stability



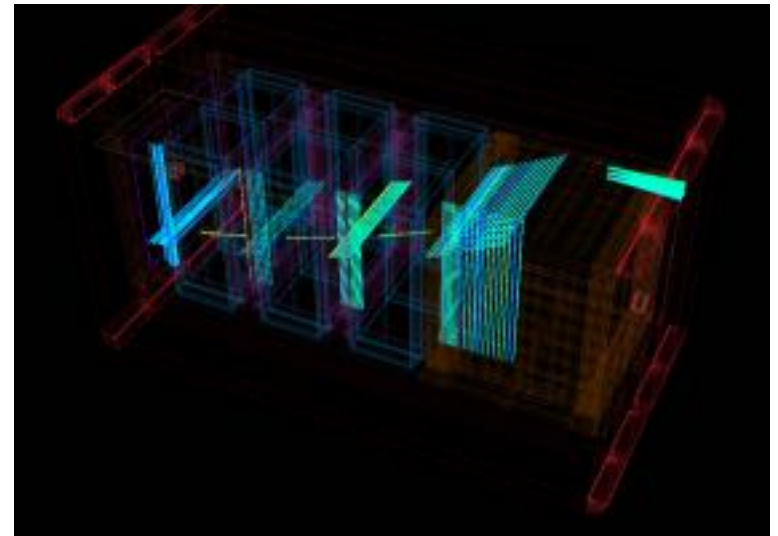
The T2K experiment

Off-axis near detectors

Off-axis near detector ND280
Located 280m from the target

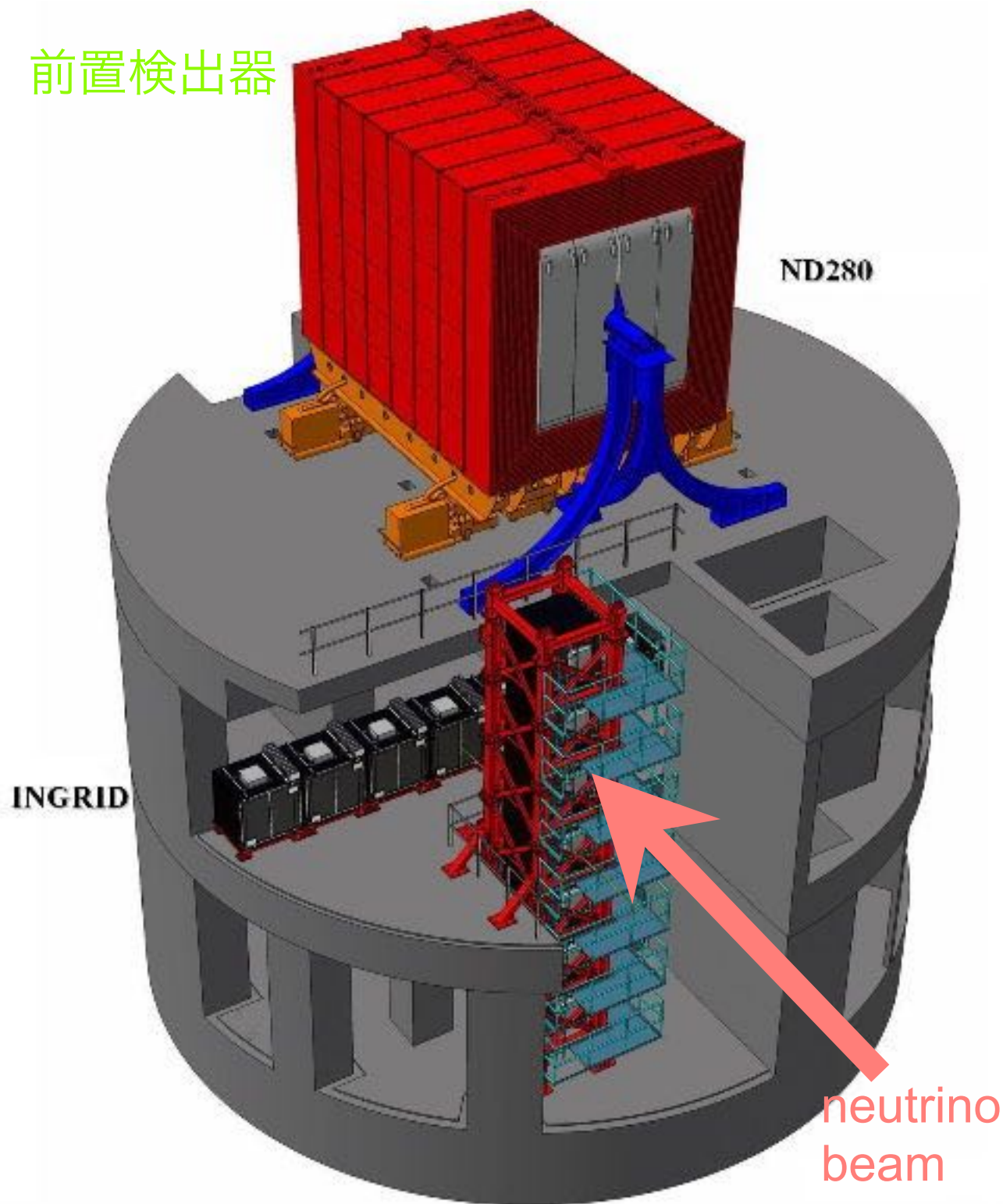


- Several detectors inside a 0.2 T magnetic field
- Good tracking capabilities
- 'Tracker' used to constrain flux and interaction uncertainties for oscillation analysis
- Rich cross-section measurement program



Near Detectors

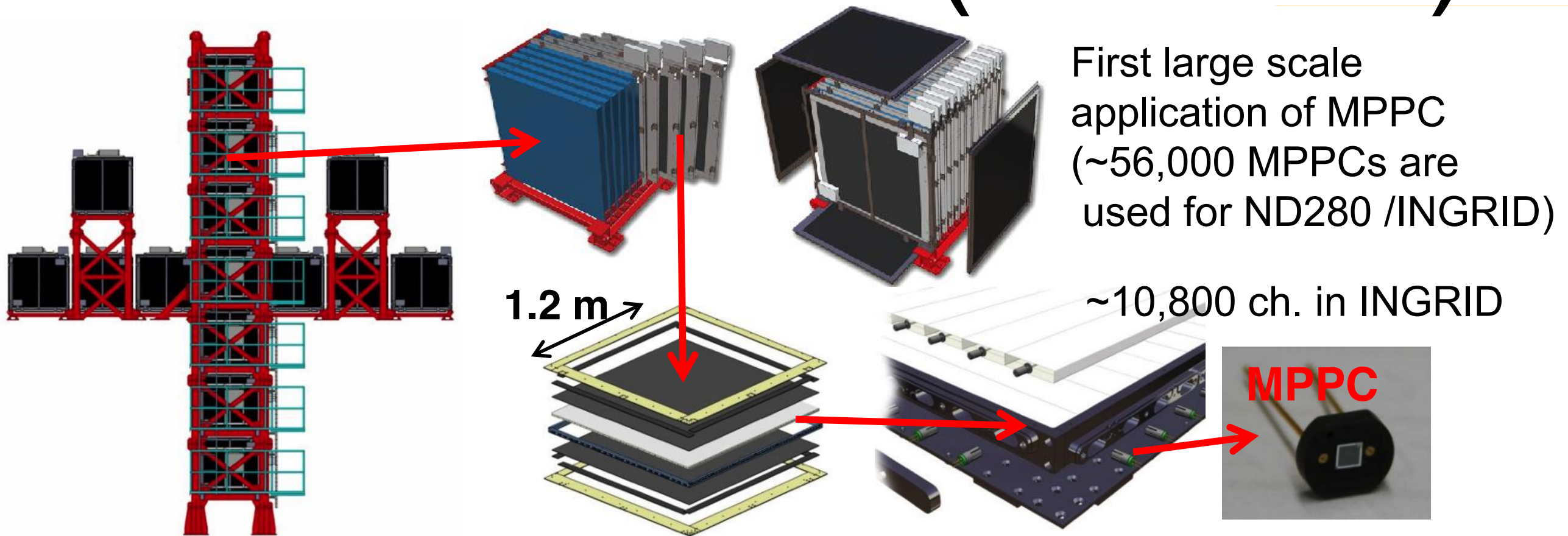
前置検出器



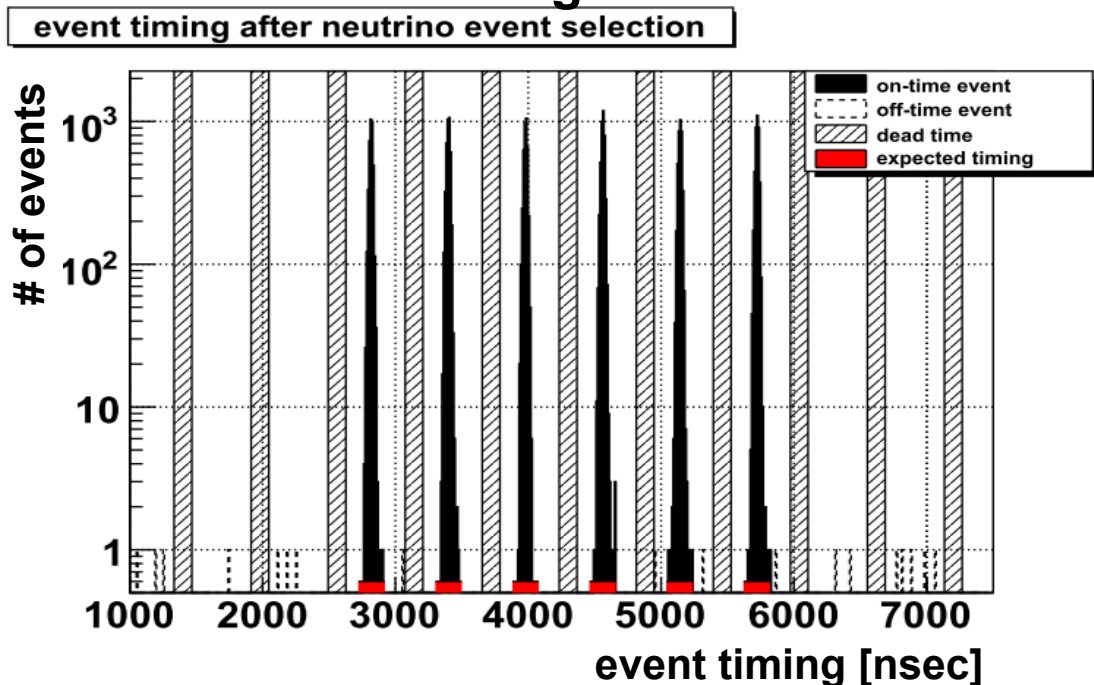
Performance Goals

- INGRID must measure
 - Beam profile and direction
 - High accuracy, short time
- ND280 designed to measure:
 - ν_μ flux: $<5\%$
 - μ energy scale: $<2\%$
 - intrinsic ν_e content: $<10\%$
 - ν_μ CC BGs $<10\%$
- Magnetic field, fine segmentation, excellent tracking

ND280 on-axis (INGRID)



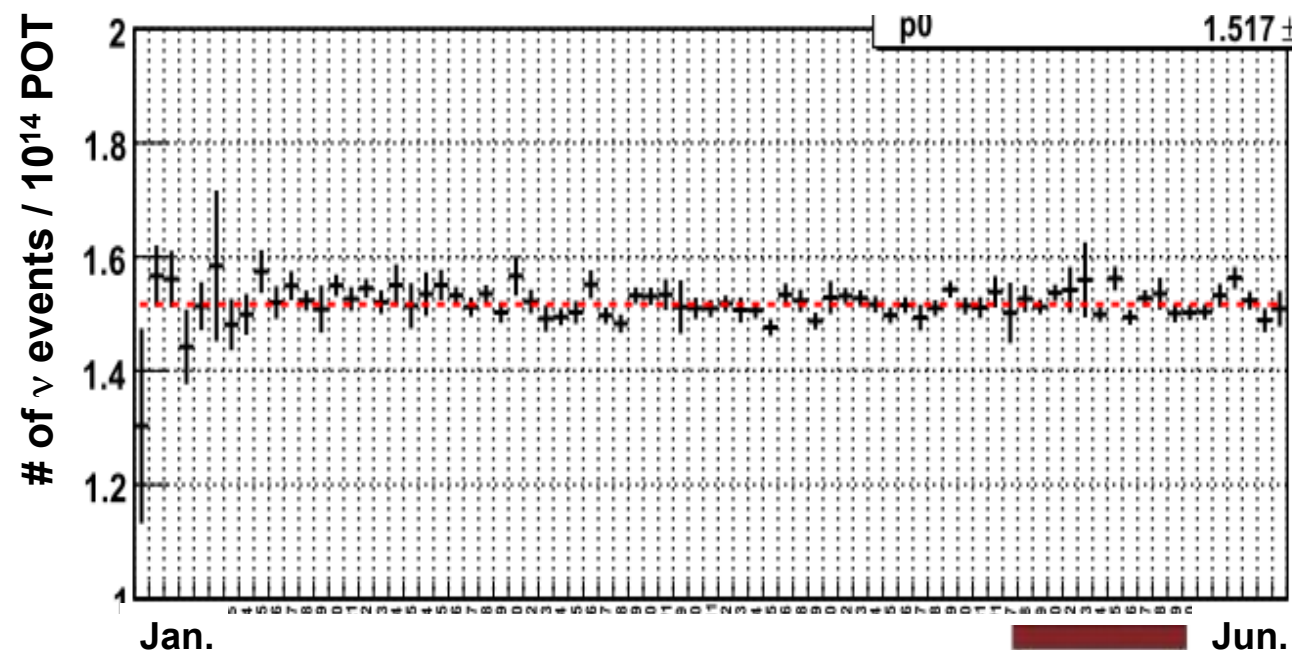
Event timing of ν events



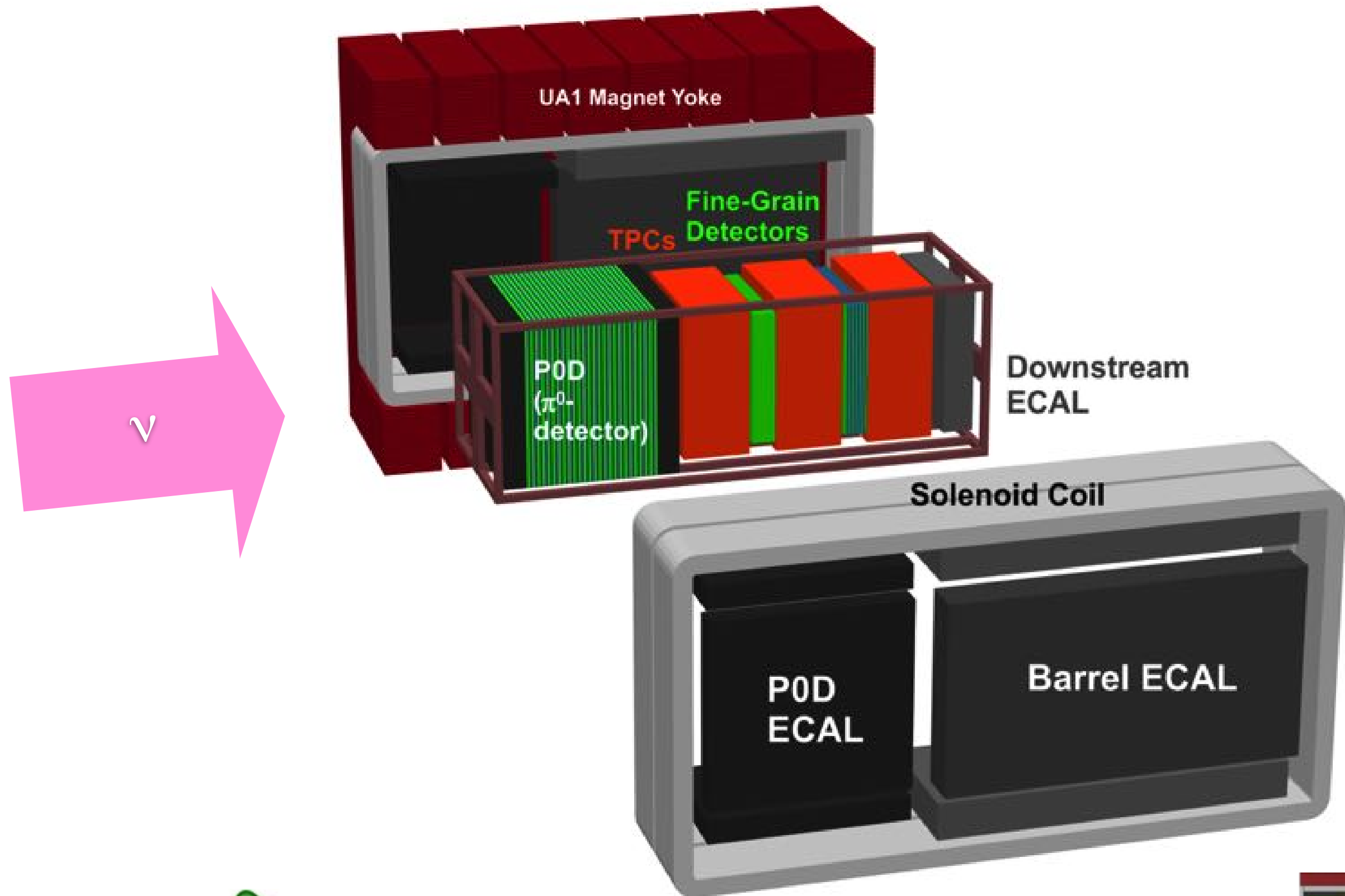
→ Clear 6 bunch structure (581 ns bunch period)

ν beam intensity

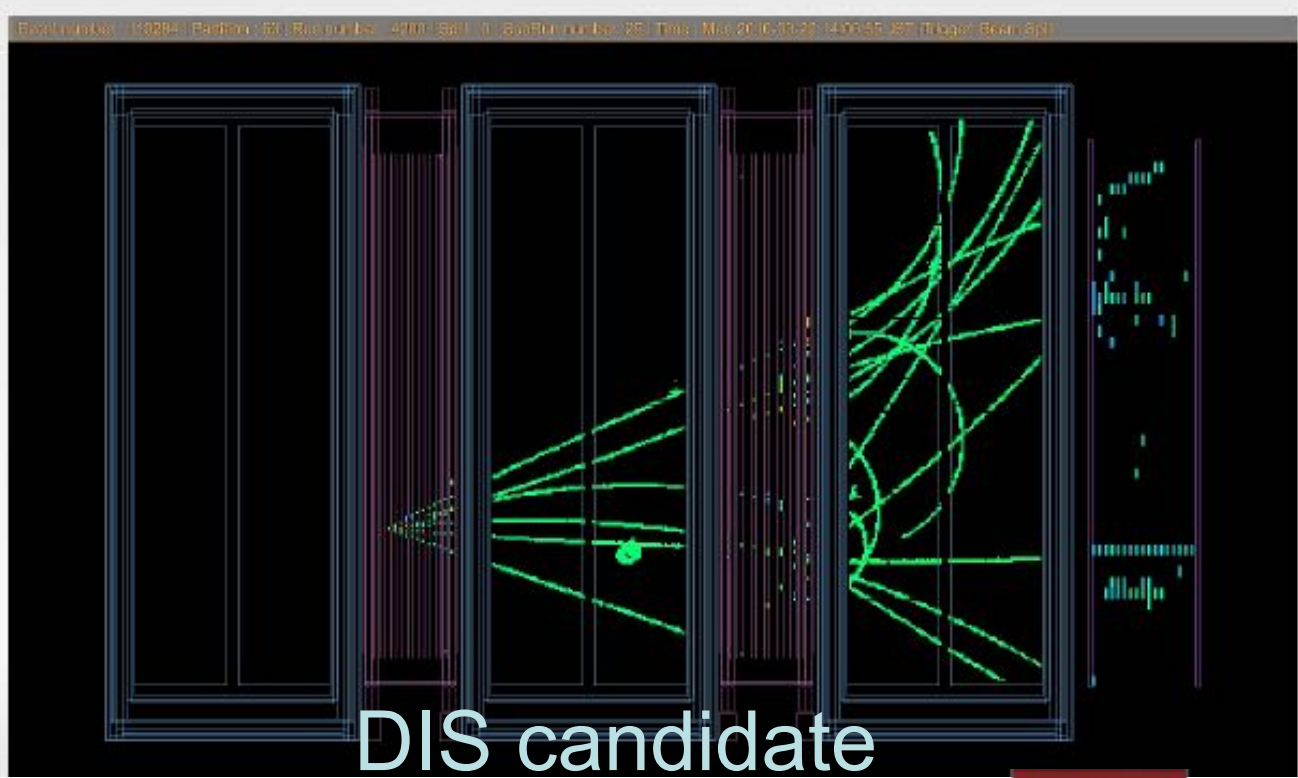
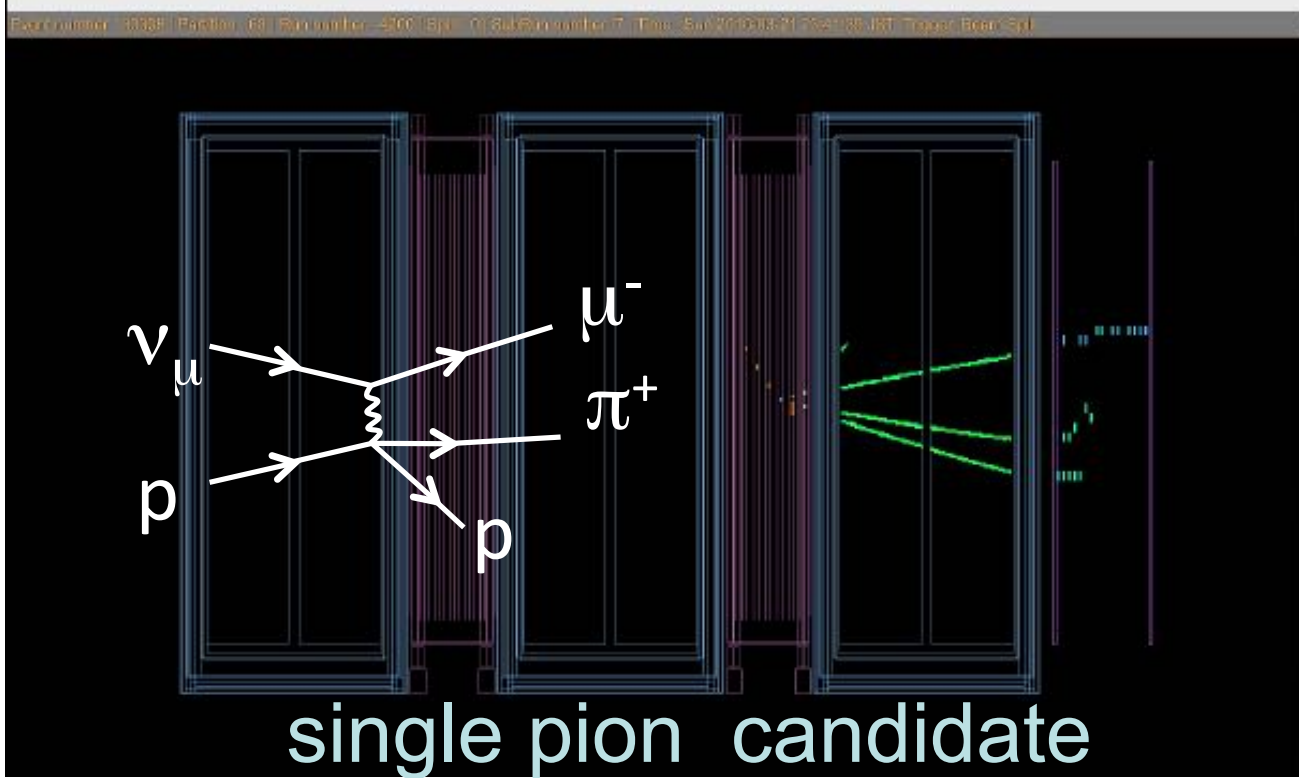
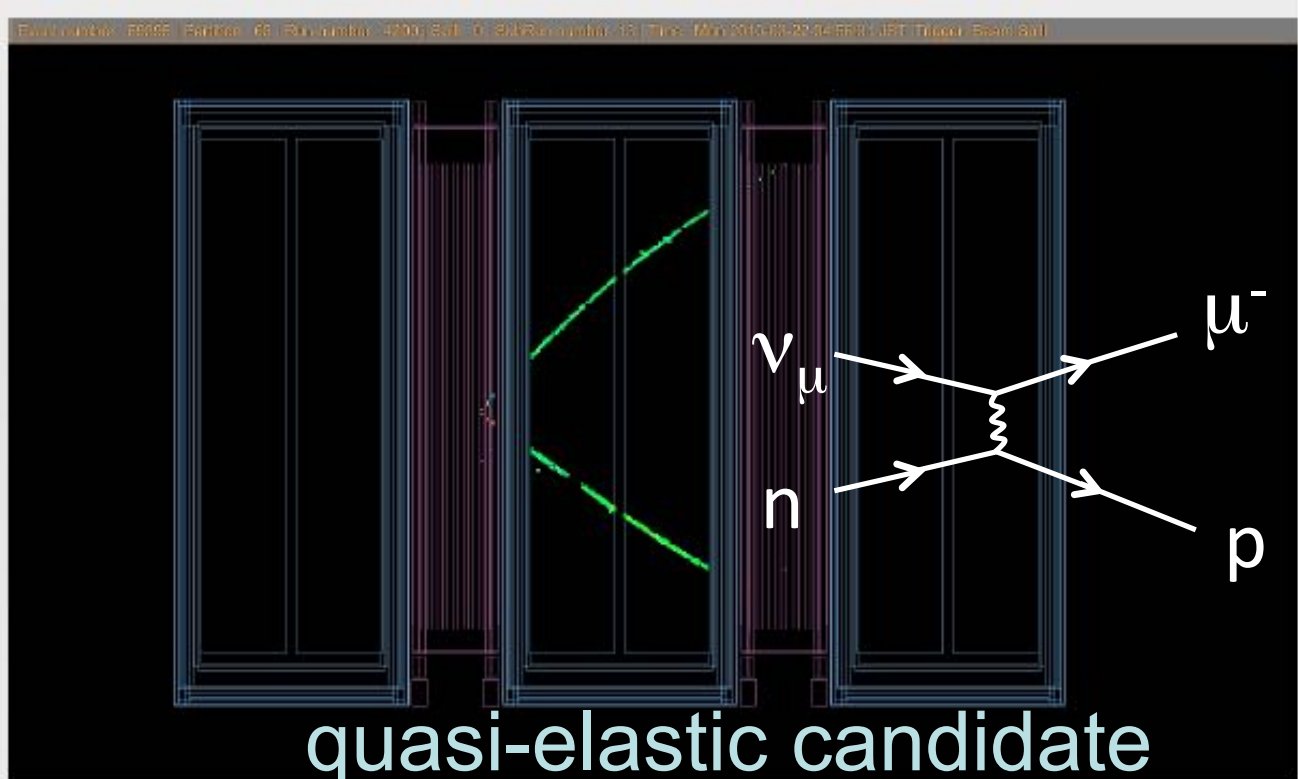
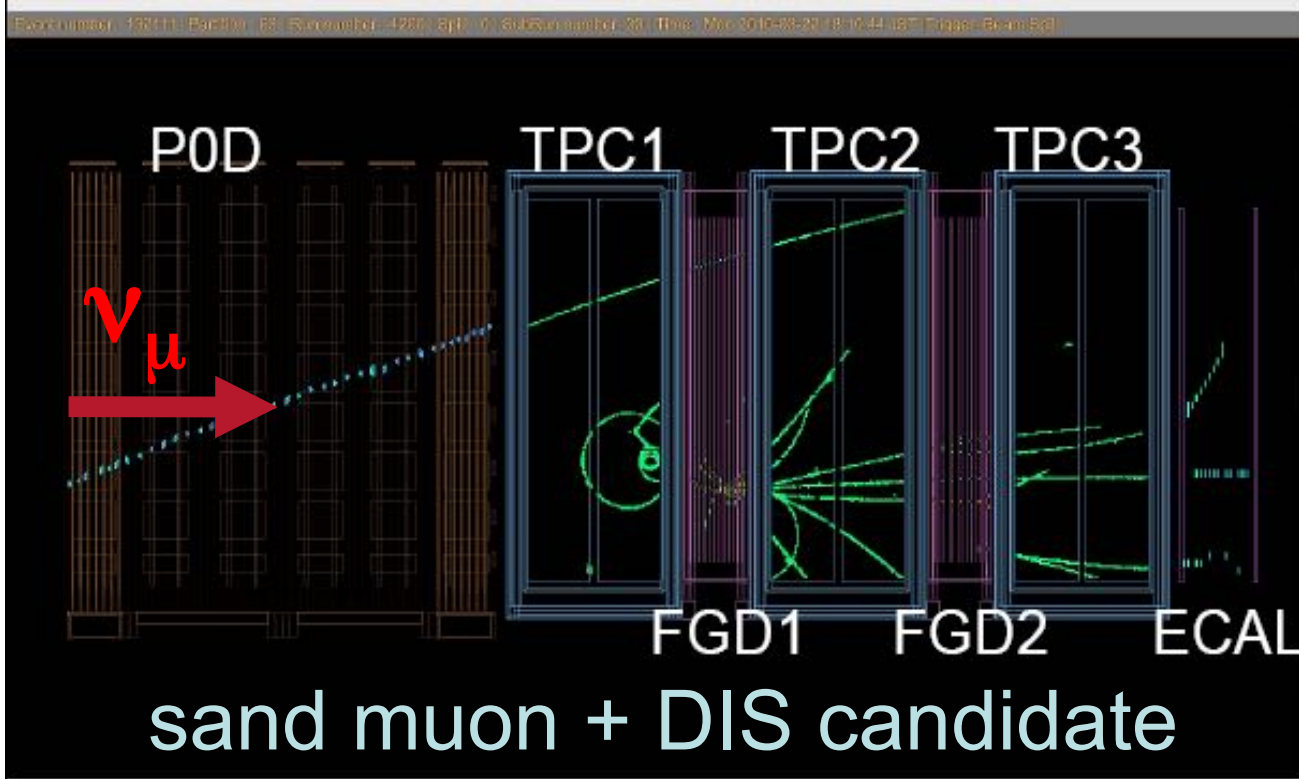
(normalized by proton beam intensity)



ND280 off-axis detector

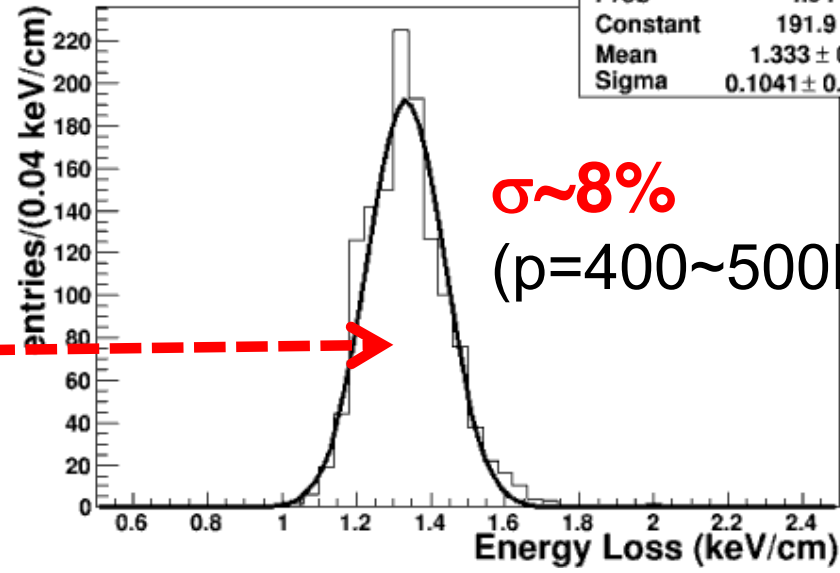
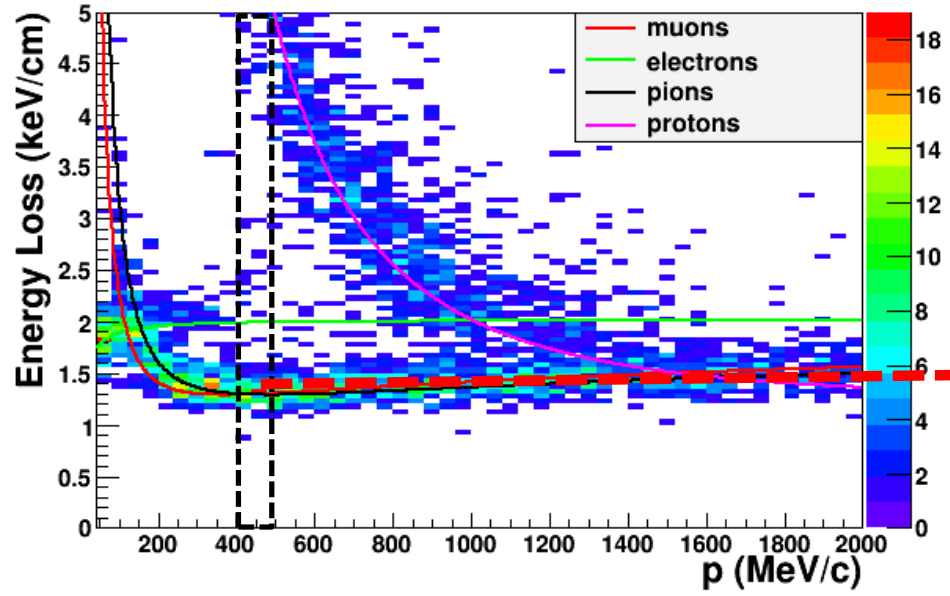


ND280 off-axis event gallery



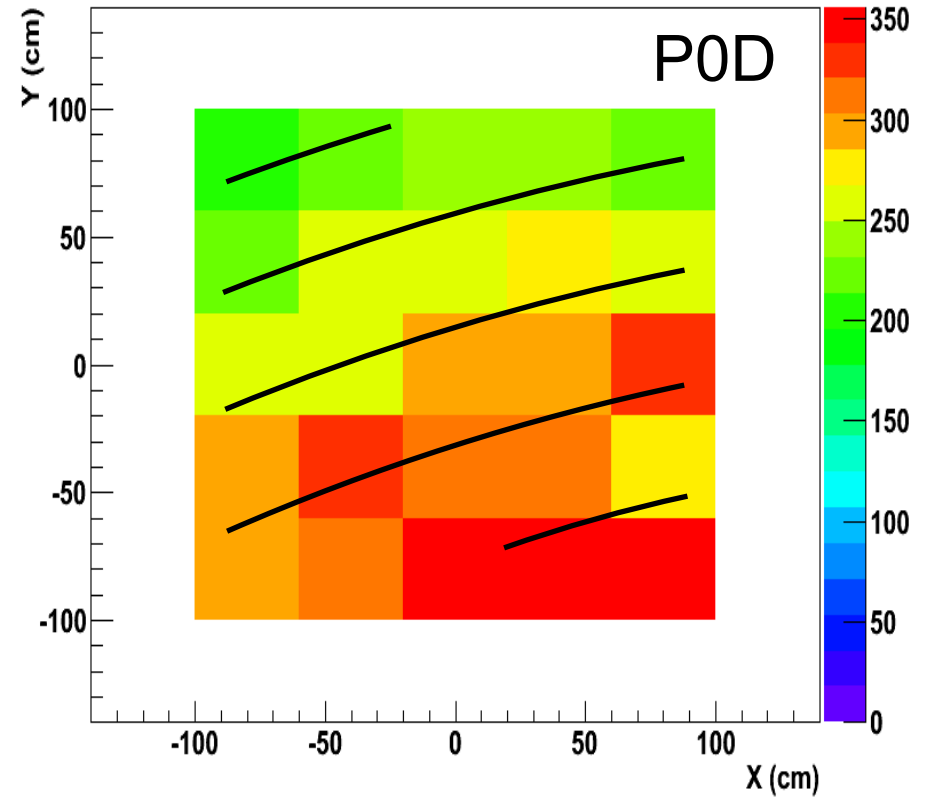
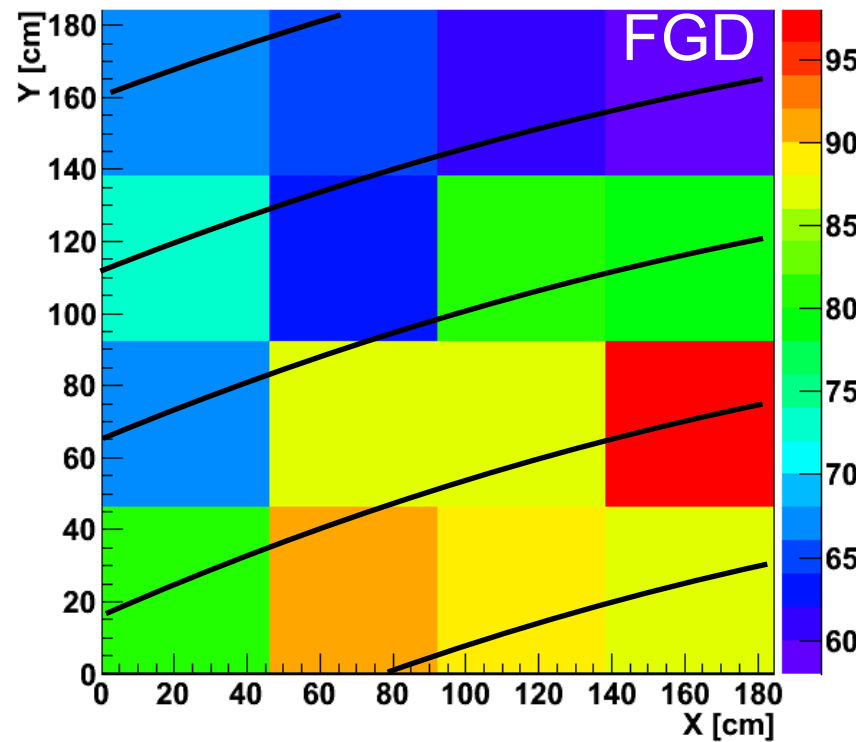
ND280 off-axis performance

dE/dx from TPC



Vertex X-Y distribution

● ν beam direction

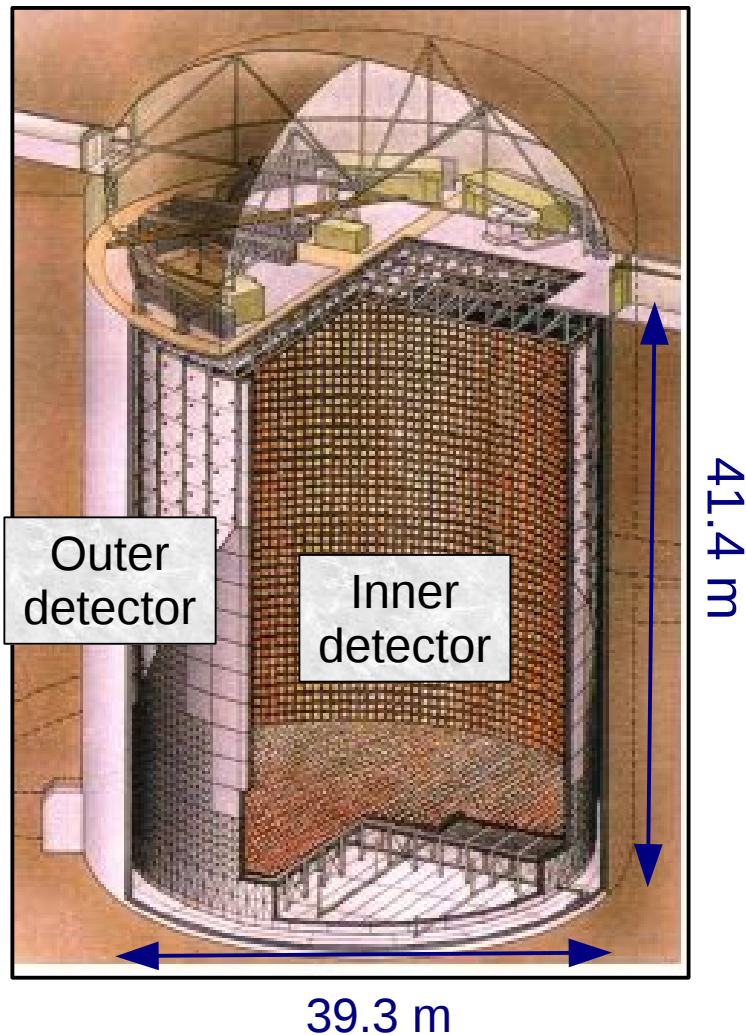


The T2K experiment

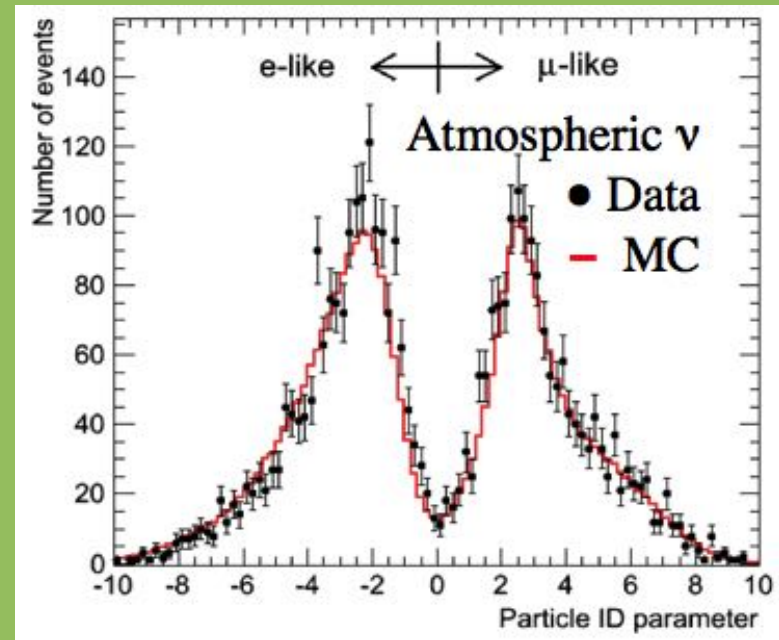
Far detector: Super-Kamiokande

Located 295 km from the target
Synchronized with beamline via GPS

- 50 kt water Cherenkov detector
- Operational since 1996

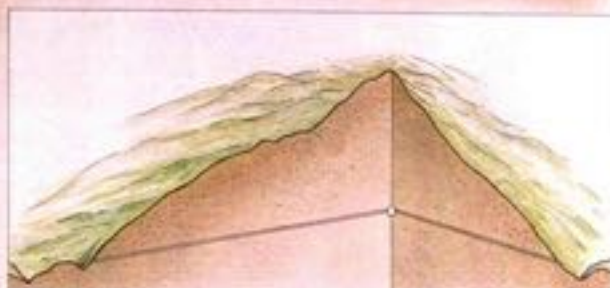
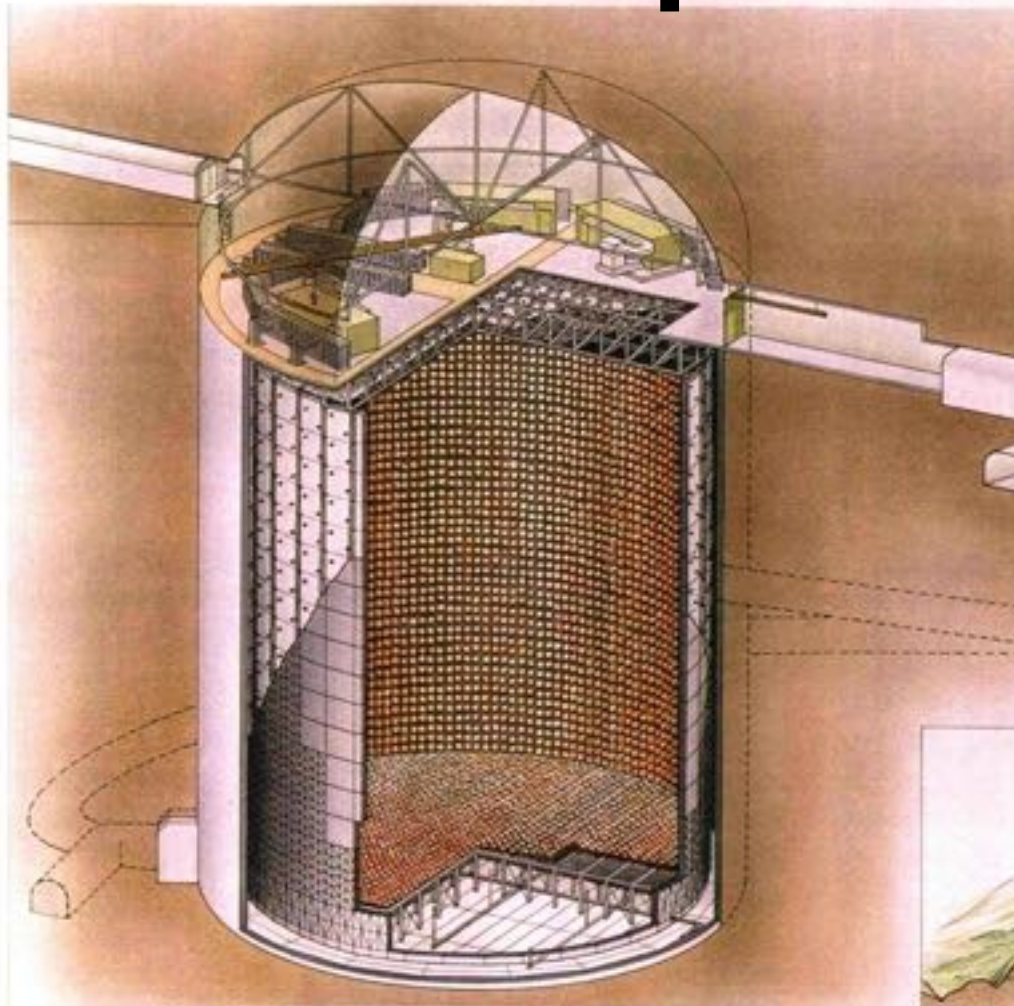


Good separation between μ^\pm and e^\pm
(separate ν_μ and ν_e CC interactions)



No magnetic field: cannot separate ν and $\bar{\nu}$ on an event by event basis

Super-Kamiokande



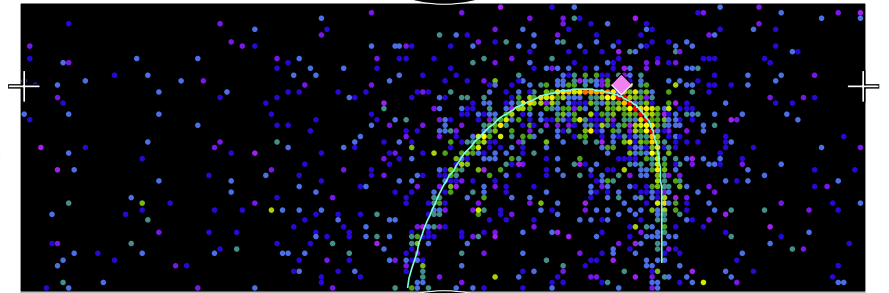
22.5 kton fiducial volume

Super-Kamiokande IV

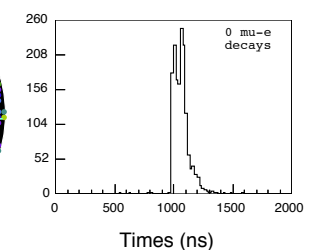
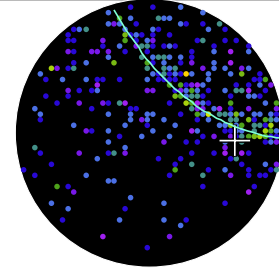
T2K Beam Run 0 Spill 822275
 Run 66778 Sub 585 Event 134229437
 10-05-12:21:03:22
 T2K beam dt = 1902.2 ns
 Inner: 1600 hits, 3681 pe
 Outer: 2 hits, 2 pe
 Trigger: 0x80000007
 D_wall: 614.4 cm
 e-like, p = 377.6 MeV/c

Charge (pe)

- >26.7
- 23.3-26.7
- 20.2-23.3
- 17.3-20.2
- 14.7-17.3
- 12.2-14.7
- 10.0-12.2
- 8.0-10.0
- 6.2- 8.0
- 4.7- 6.2
- 3.3- 4.7
- 2.2- 3.3
- 1.3- 2.2
- 0.7- 1.3
- 0.2- 0.7
- < 0.2

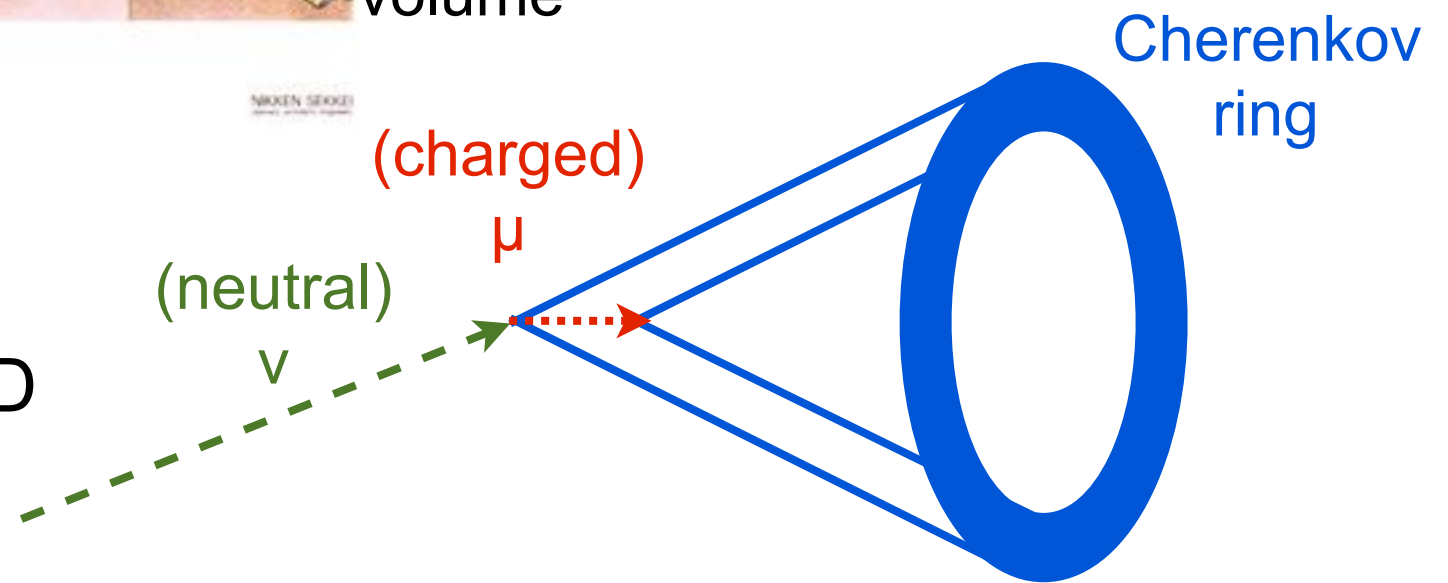


T2K Data

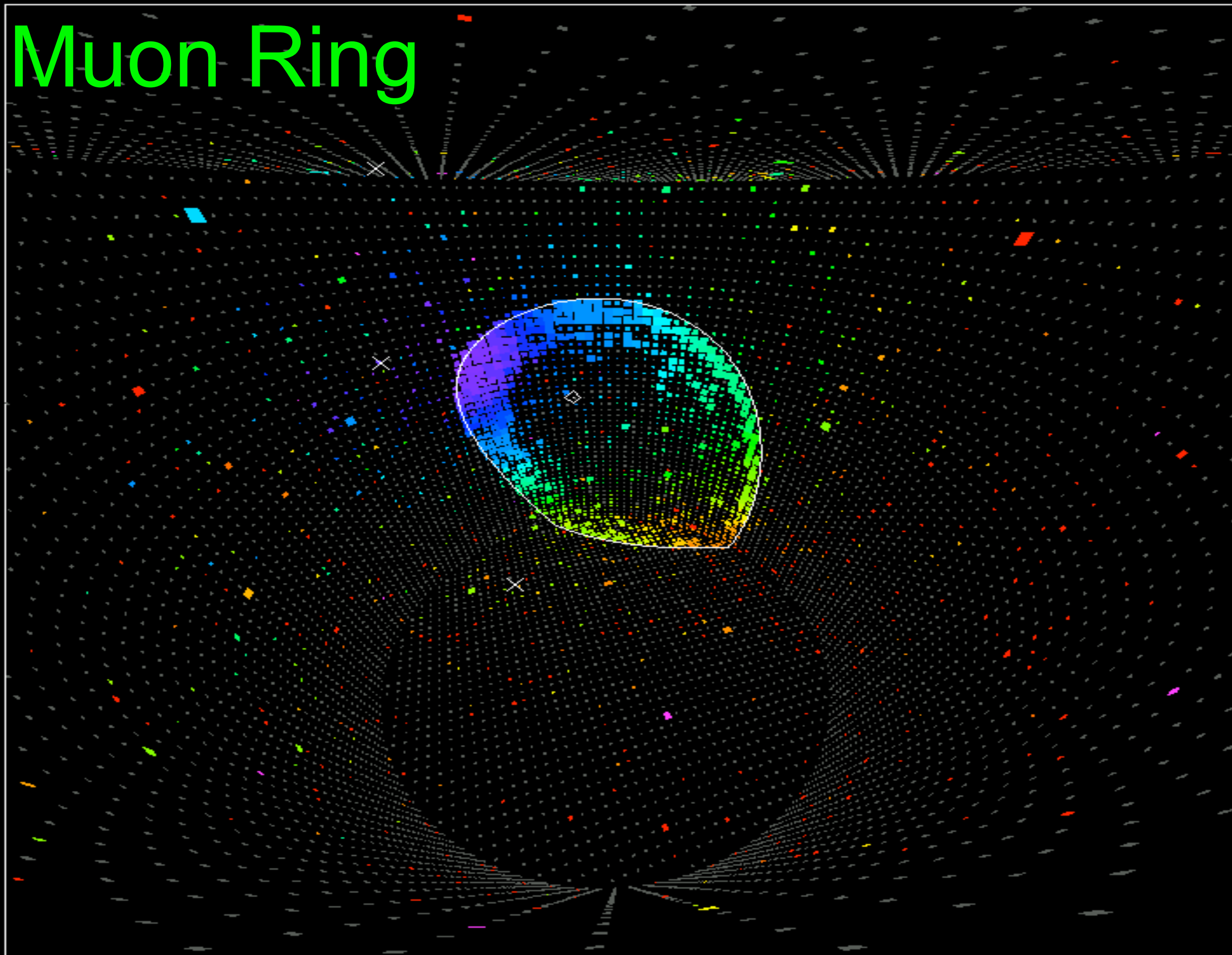


SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

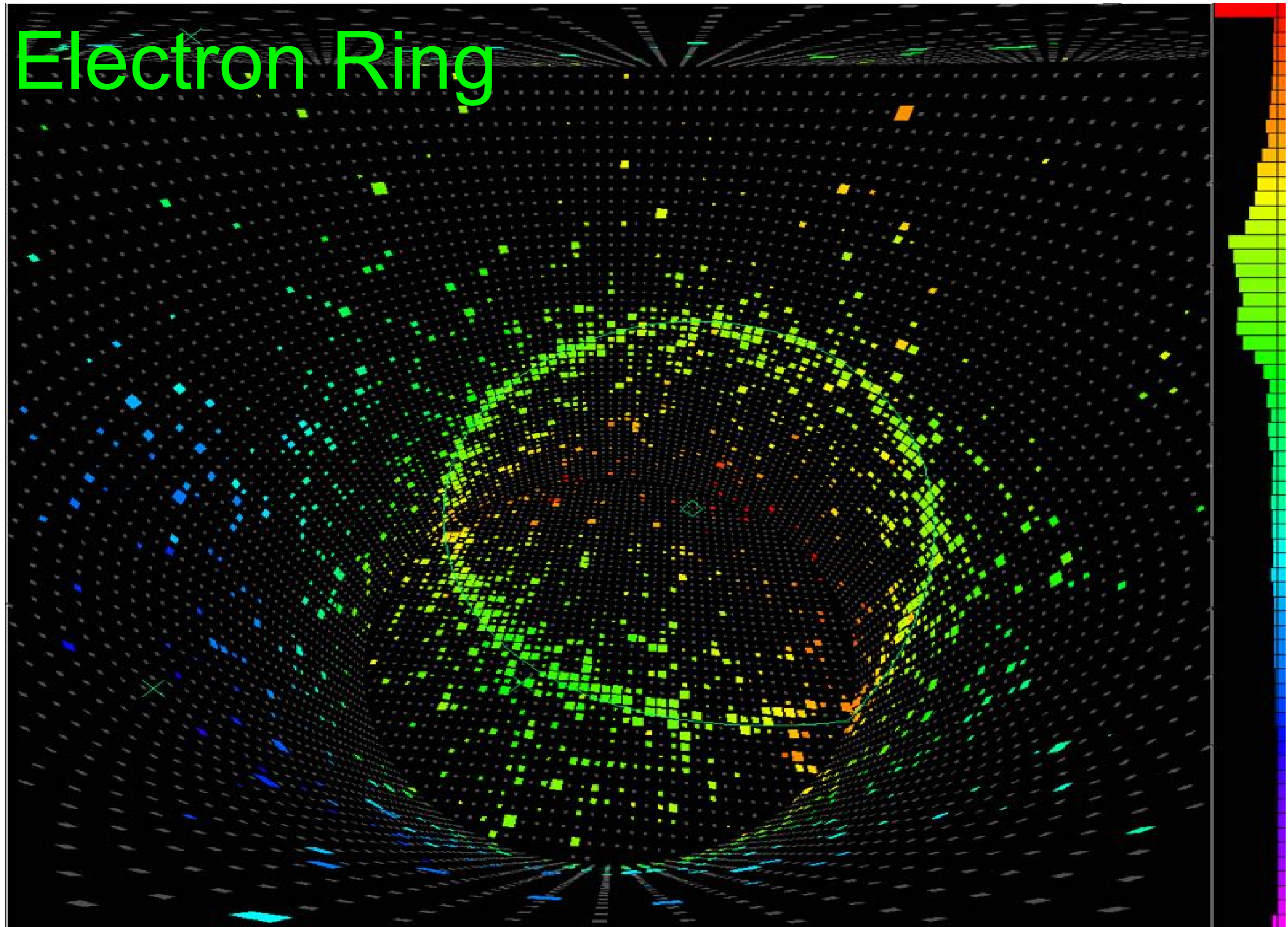
- 50,000 ton water Cherenkov detector
- 11,146 PMTs in ID, 1,885 in OD
- ~1km underneath Ikenoyama



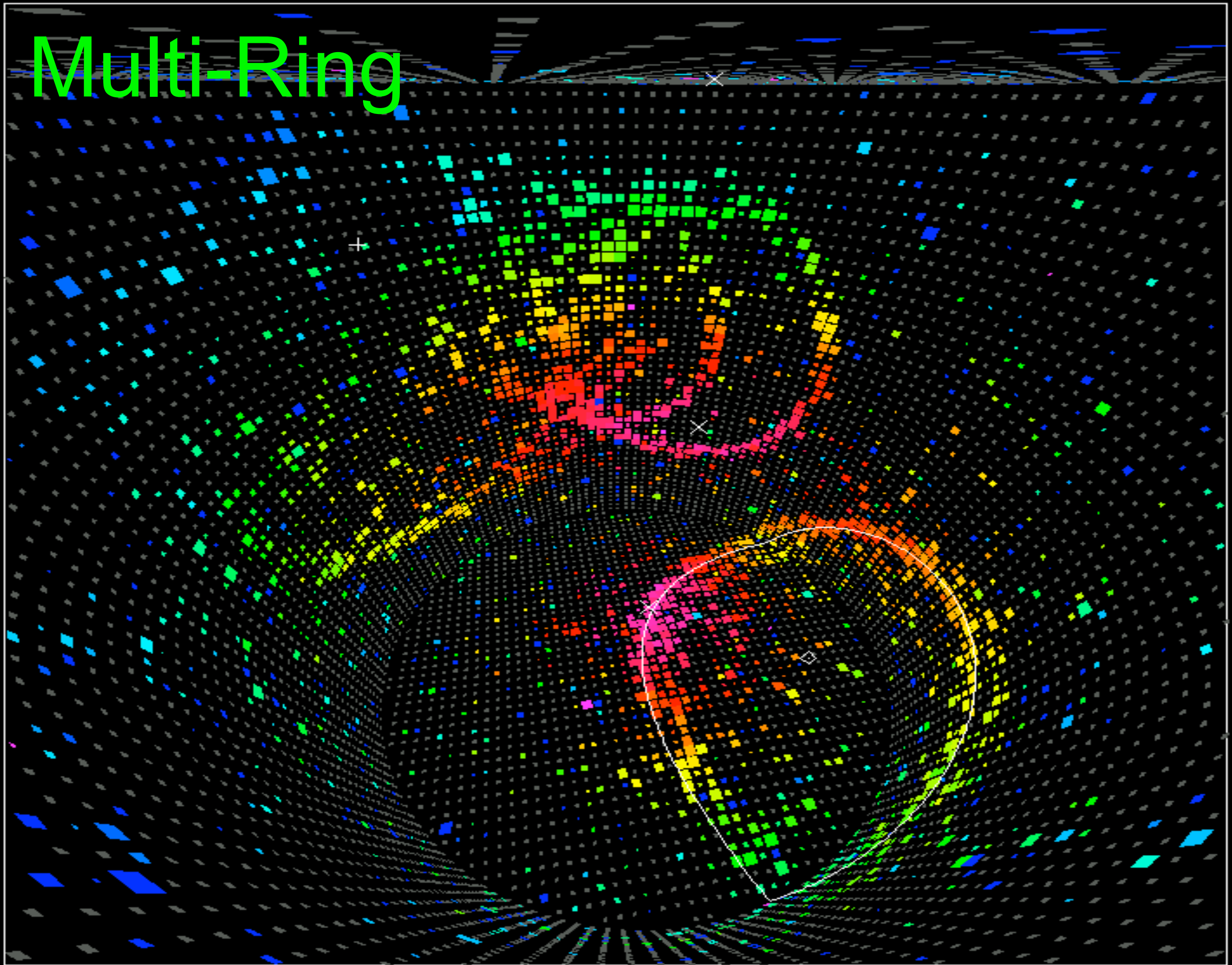
Muon Ring

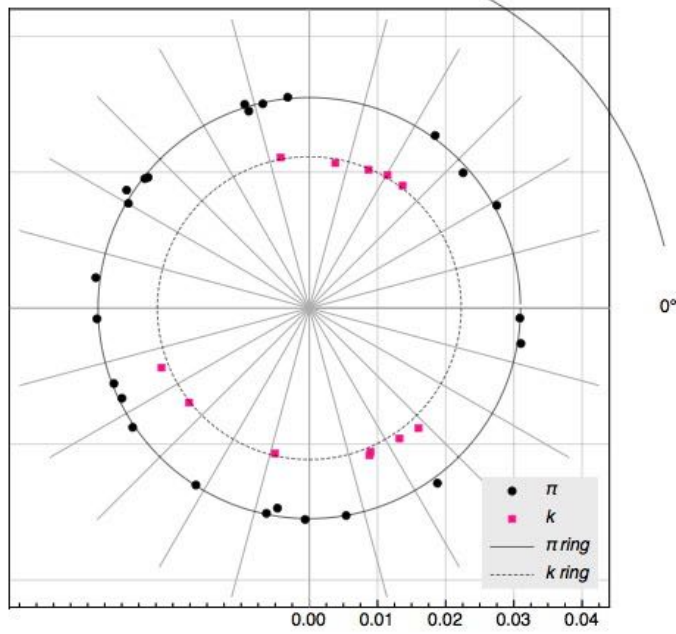
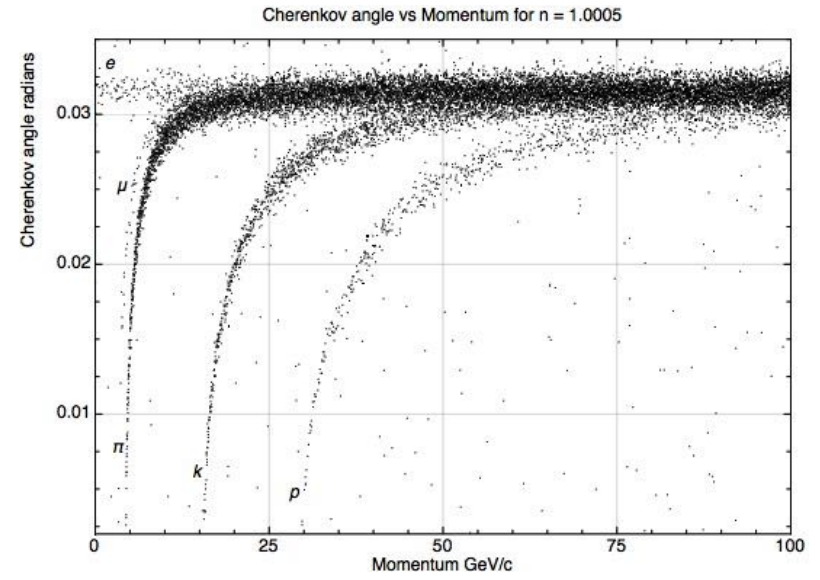
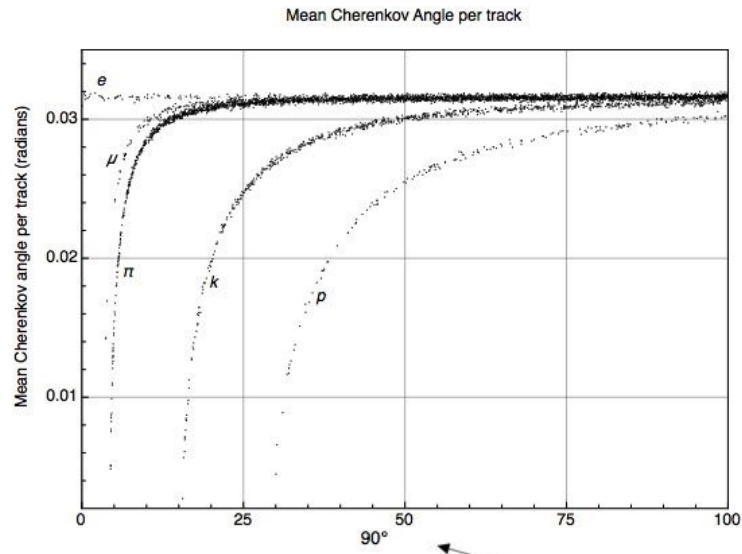


Electron Ring



Multi-Ring





Cherenkov photons emitted by a 22 GeV/c pion or kaon

SK Particle Identification

Muons:

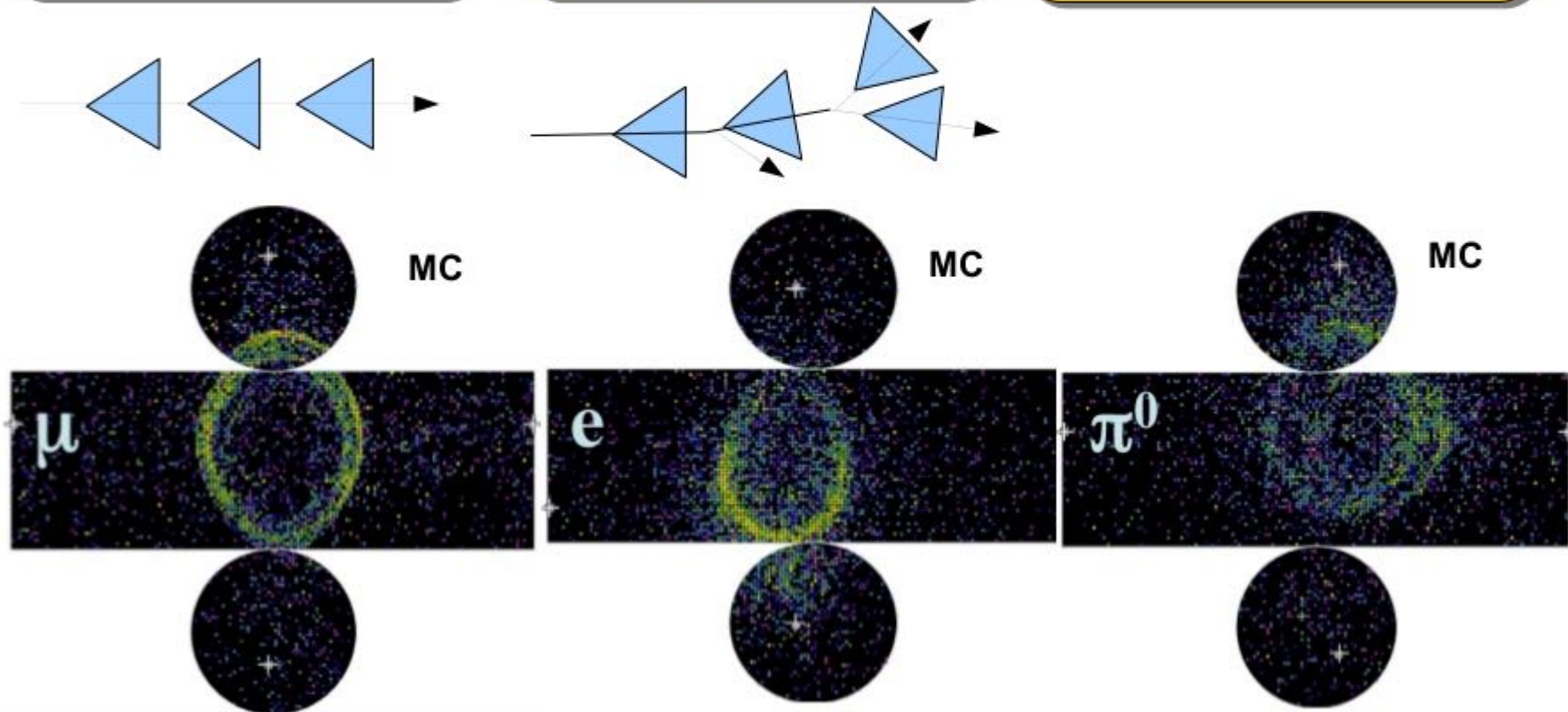
- Minimal scattering
- Ring has sharp edges

Electrons

- Electromagnetic shower
- EM scattering makes a "fuzzy" ring

Neutral Pions

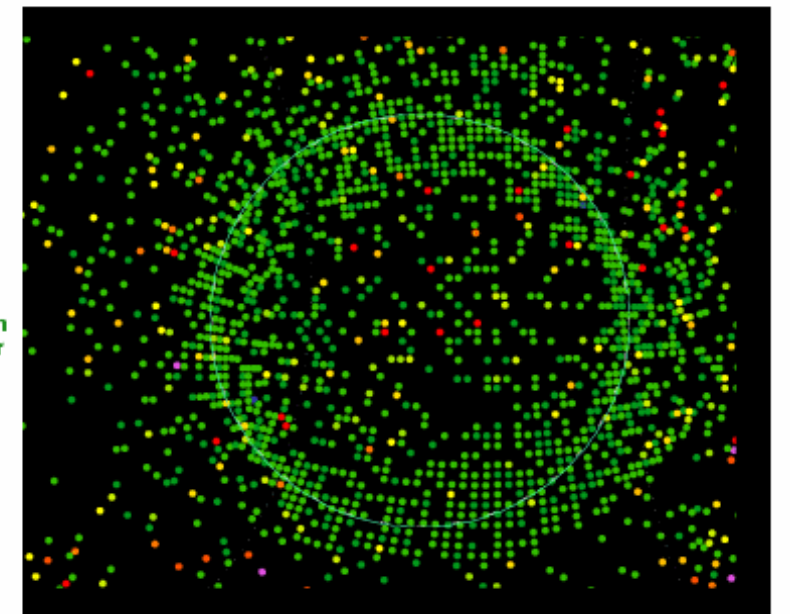
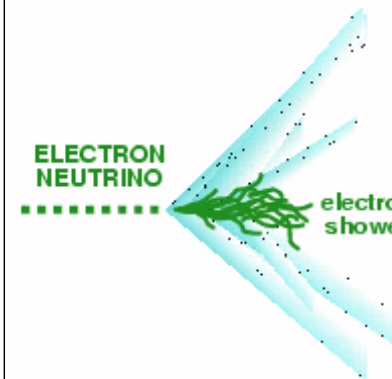
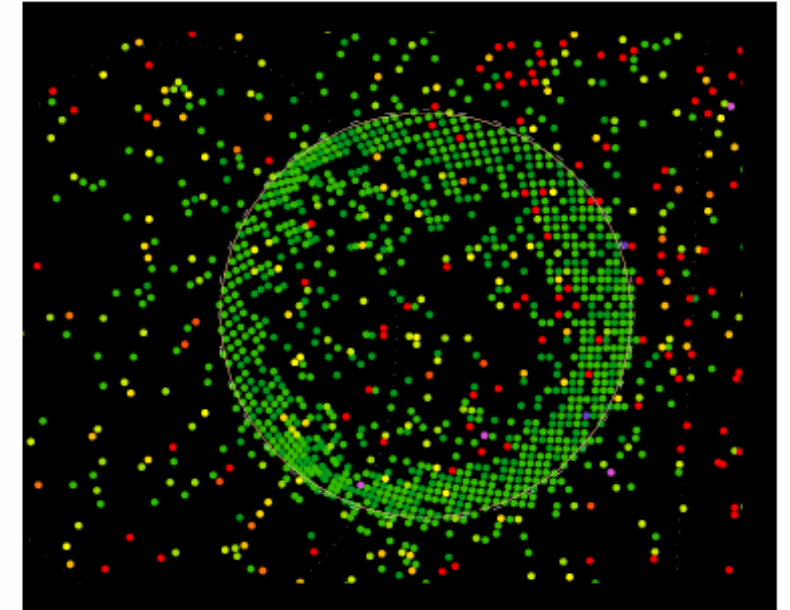
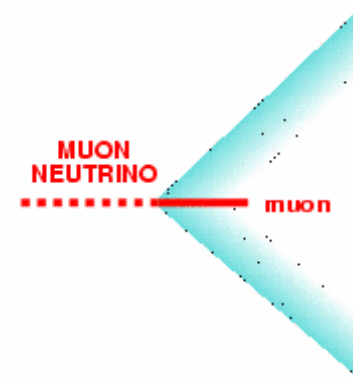
- γ s from π^0 decays shower and look like electrons



- Reliable PID particularly crucial to ν_e appearance analysis
- PID well-established at KEK beam test (1kton tank) in 1990s

SK Reconstruction

- Find vertex (mostly timing)
- Count rings
- Find momenta
- PID from ring topology (“fuzziness”)

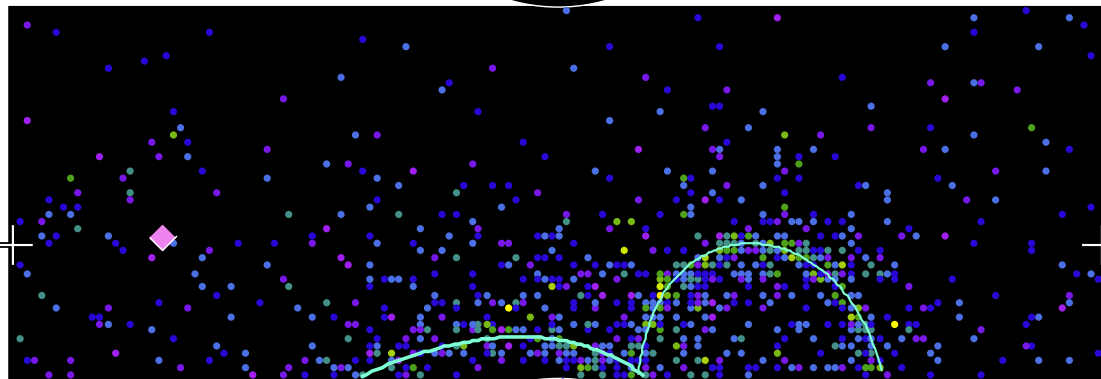


Use atmospheric data vs. MC to check reconstruction and set systematic errors

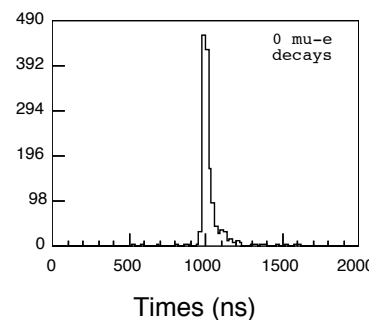
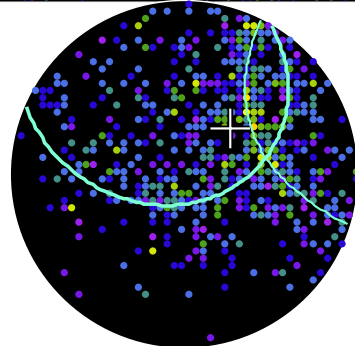
Super-Kamiokande IV
 T2K Beam Run 32 Spill 294378
 Run 66692 Sub 67 Event 15931918
 10-04-18:13:57:00
 T2K beam dt = 3054.5 ns
 Inner: 1414 hits, 2494 pe
 Outer: 7 hits, 6 pe
 Trigger: 0x80000007
 D_wall: 1060.9 cm
 2 e-like rings: mass = 140.4 MeV/c²

Charge (pe)

- >26.7
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- 17.3-20.2
- 14.7-17.3
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- 10.0-12.2
- 8.0-10.0
- 6.2- 8.0
- 4.7- 6.2
- 3.3- 4.7
- 2.2- 3.3
- 1.3- 2.2
- 0.7- 1.3
- 0.2- 0.7
- < 0.2

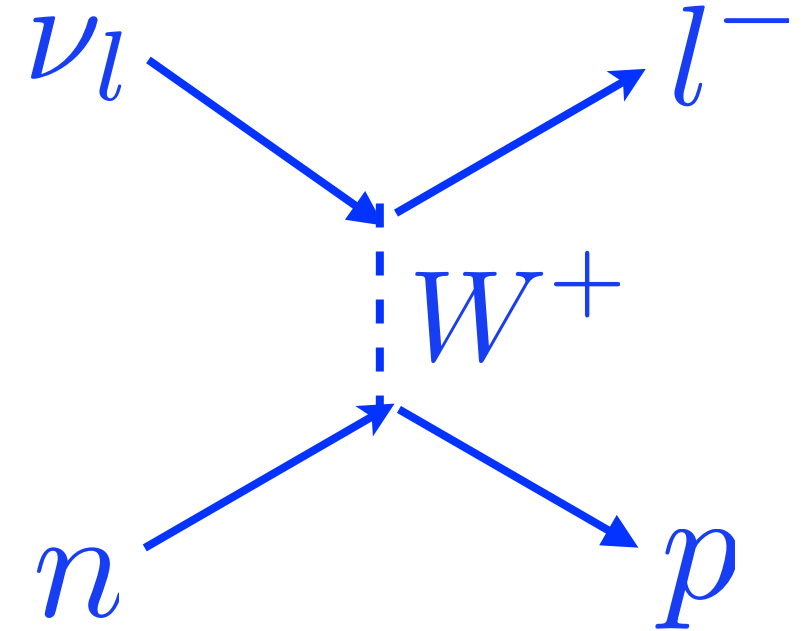


T2K Data



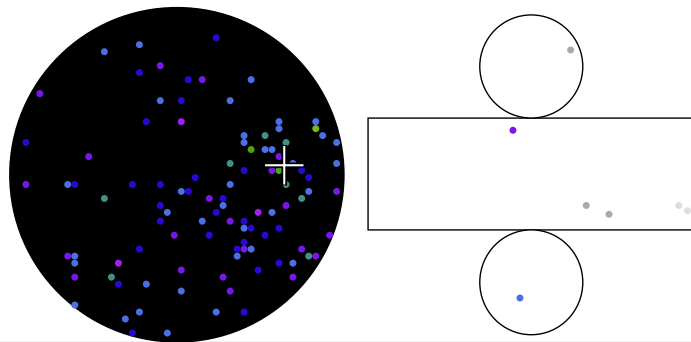
Signal at SK

- Charged Current Quasi-Elastic Events
- Only single lepton ring visible at SK
- Ring topology indicates ν_e vs. ν_μ



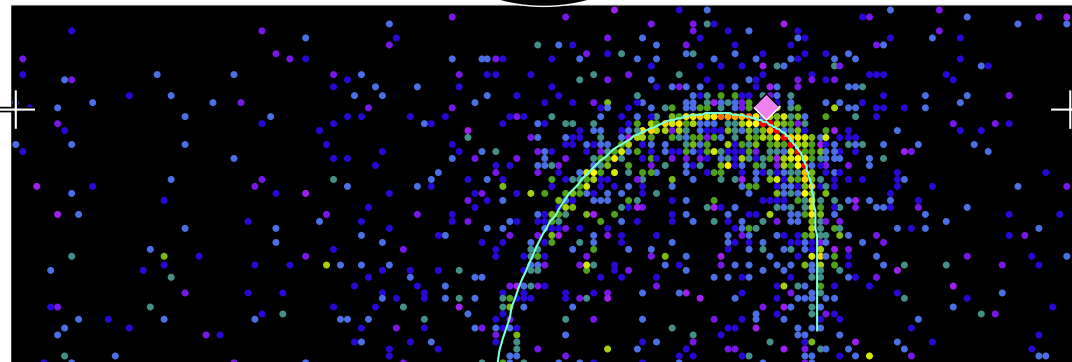
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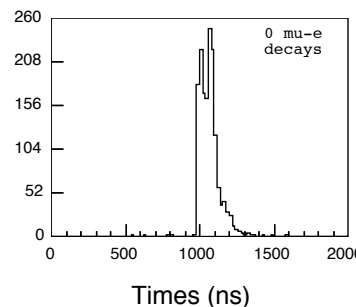
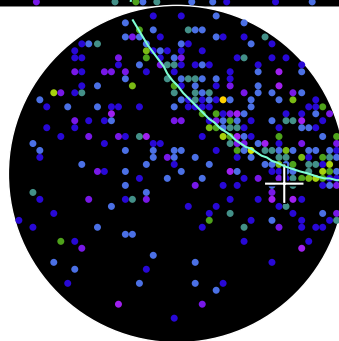


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- 3.3- 4.7
- 2.2- 3.3
- 1.3- 2.2
- 0.7- 1.3
- 0.2- 0.7
- < 0.2



T2K Data

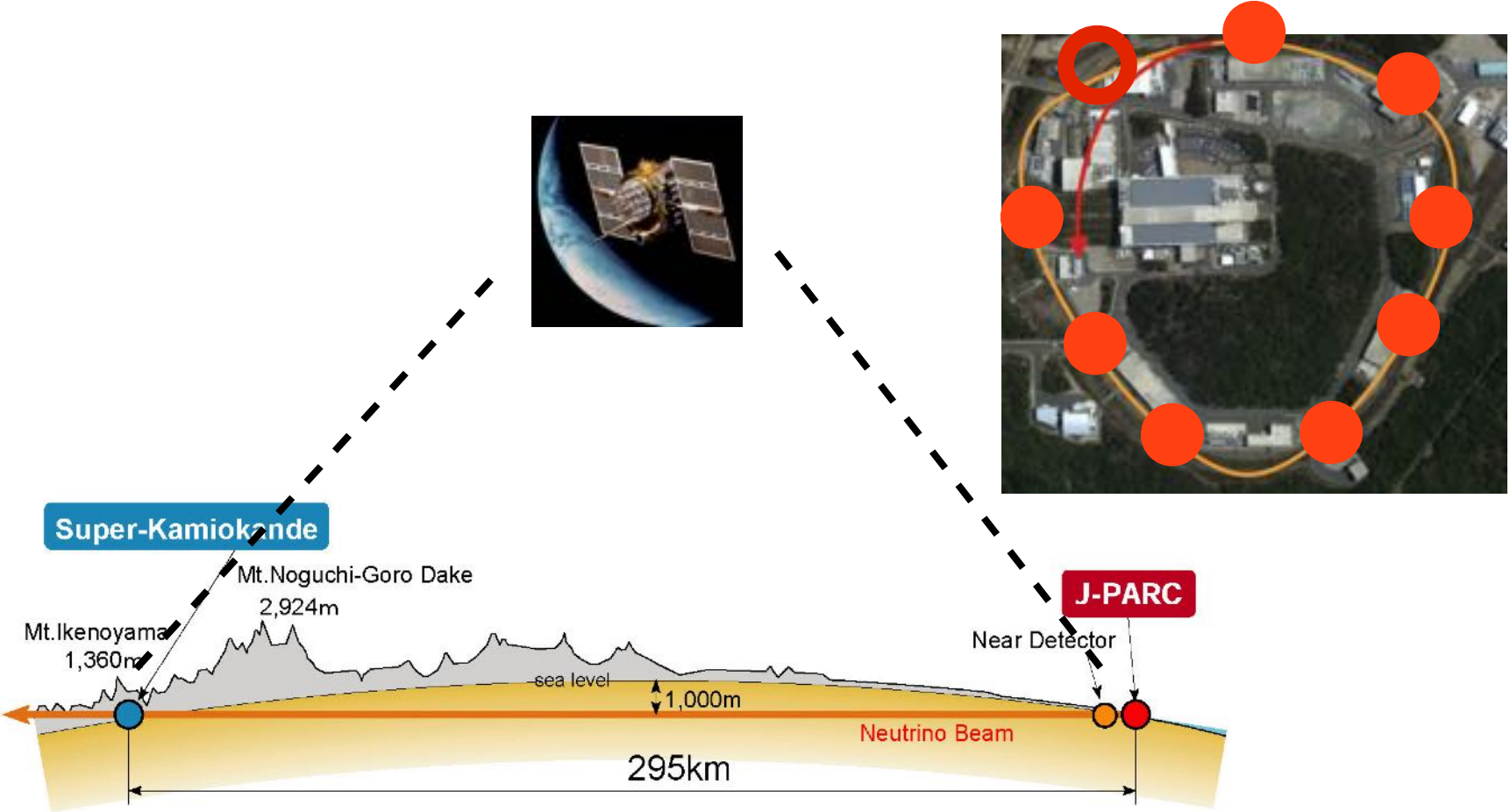


$$E_\nu = \frac{m_N E_l - m_l^2 / 2}{m_N - E_l + p_l \cos \theta_l}$$

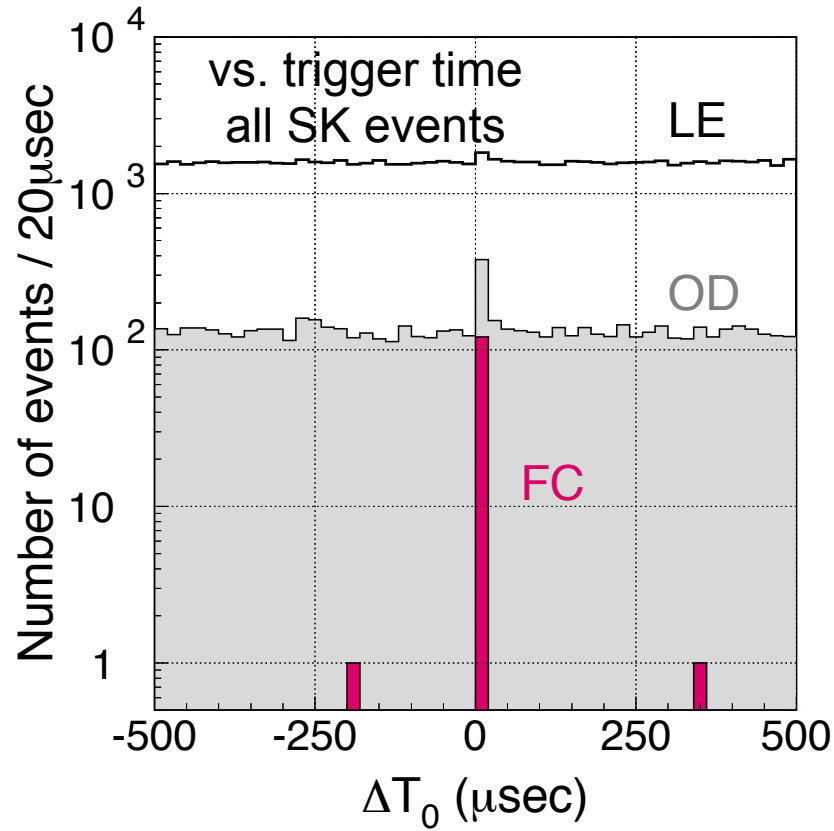
- Incident neutrino energy can be reconstructed (best for CCQE)!
- Recoil proton usually below threshold at T2K beam energy.

Beam Trigger/Timing

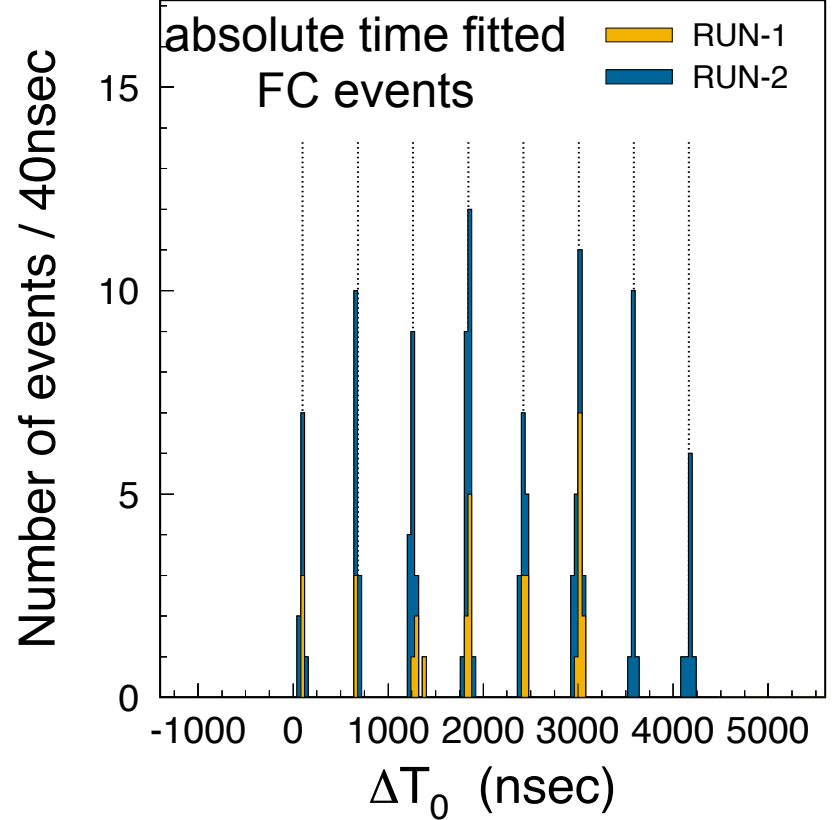
- T2K beam trigger from beam extraction
- Commonview GPS mode used



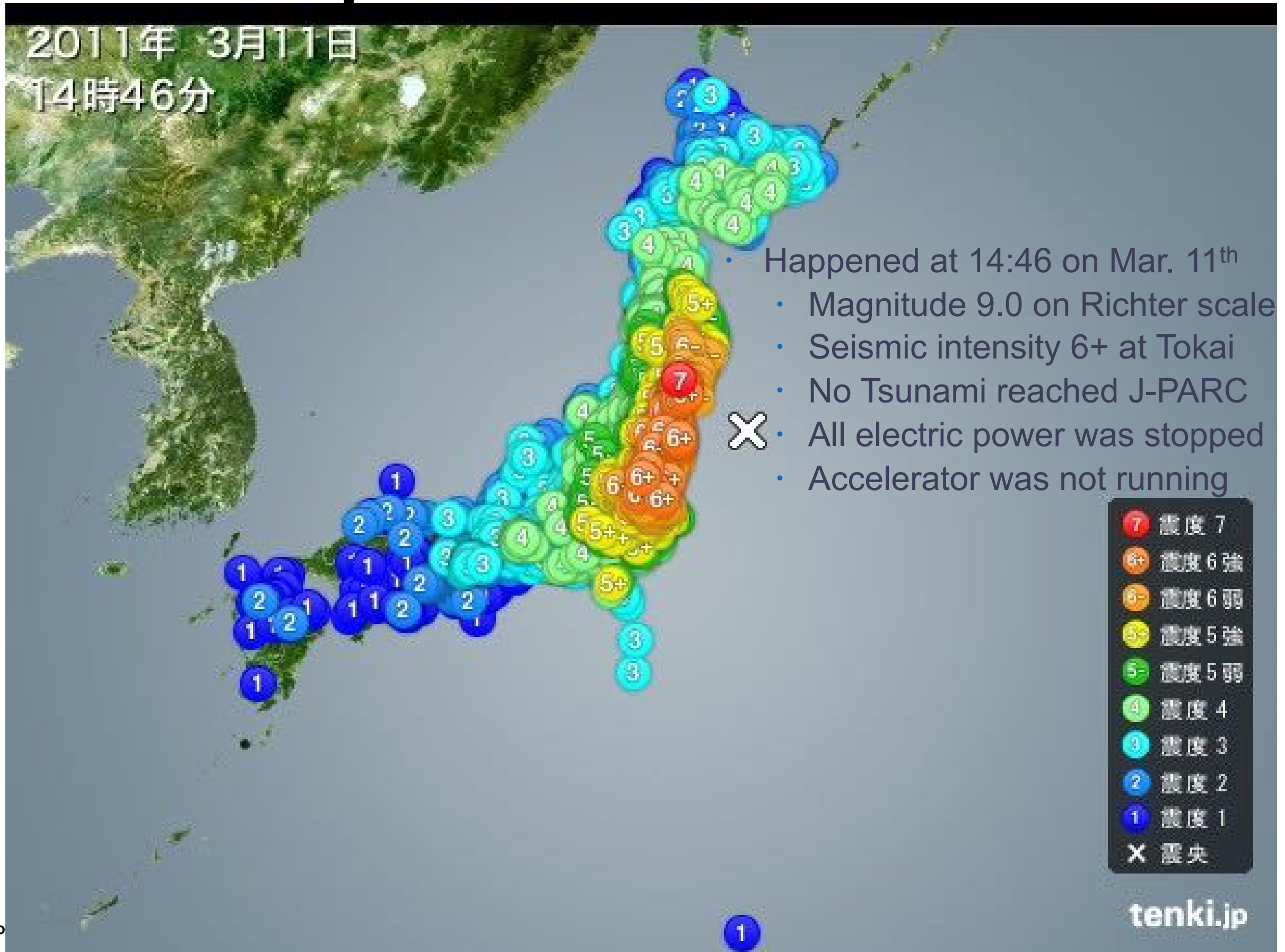
SK event times



- At SK, 2 GPS units and a Rubidium clock are used to measure and confirm the time stability.



Earthquake on Mar. 11th





11 March, 14:46...



Much exterior damage, but inside equipment largely undamaged.



Rapidly repaired!

RCS



RCS



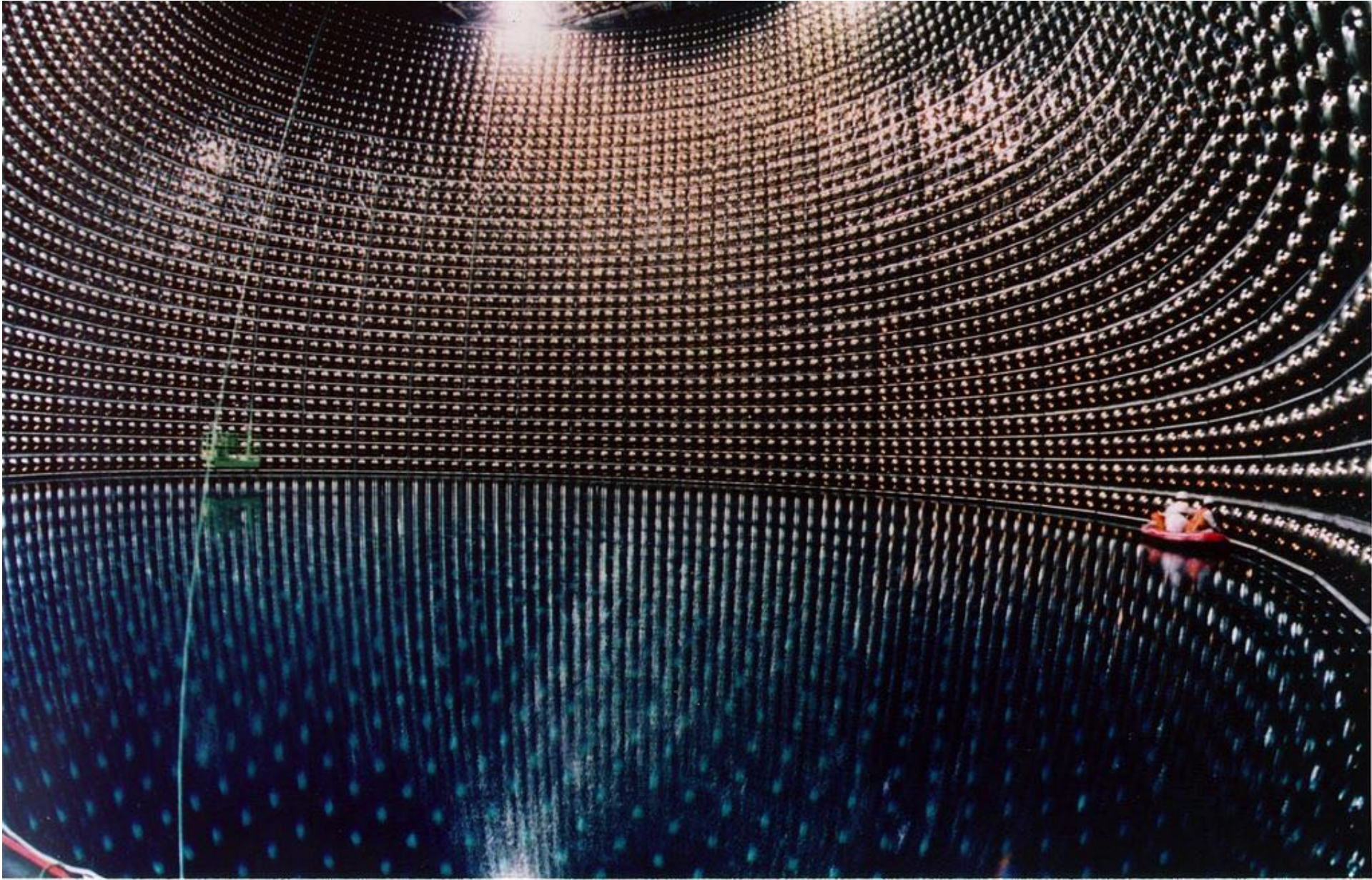
Repairs are basically complete.
Physics data taking resumed in January!

Neutrino (dump)



Neutrino (dump)







Imploding detectors shatter plans for Japan's neutrino experiments

David Cyranoski

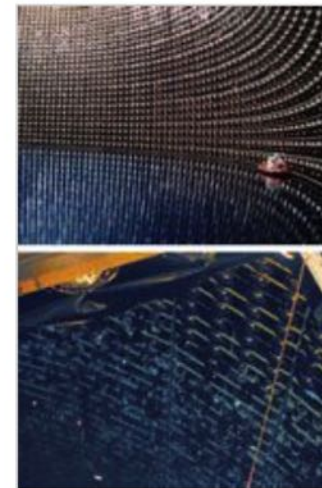
Nature **414**, 381–382 (2001) | [Download Citation](#) ↓

Tokyo

Neutrino physicists around the world have been stunned by an accident at Japan's Super-Kamiokande experiment. The damage will put 'Super-K' out of action for at least a year, delaying several research projects.

Super-K consists of a tank filled with 50,000 tonnes of water, buried deep under Mount Ikeno, some 240 kilometres northwest of Tokyo.

Neutrinos from the Sun and from supernovae, and those formed when cosmic rays strike the atmosphere, barely interact with matter. But on



Gone in a flash: Super-K (top) before the accident that left many photomultiplier tubes in pieces (bottom).

Accident Cripples Super-Kamiokande Neutrino Observatory

While the tank was being refilled with 50 000 tons of water, a photomultiplier tube imploded and the shock wave set off a chain reaction that left more than 7000 PMTs shattered. That, at least, is what scientists surmise happened on the morning of 12 November in Super-Kamiokande, the world's largest neutrino detector.

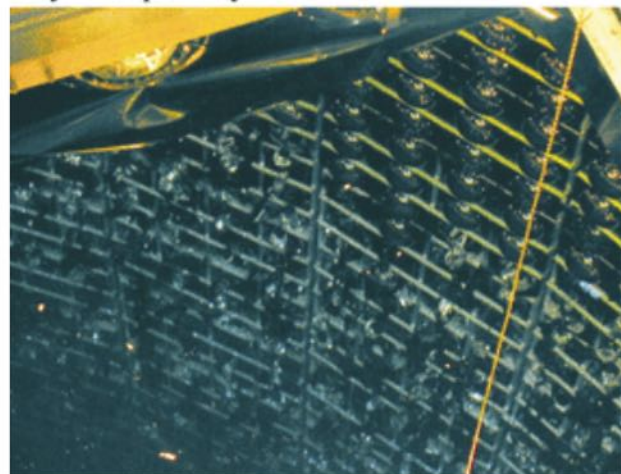
Super-K, which is buried 1000 meters deep in a defunct zinc mine in the mountains west of Tokyo, made headlines worldwide in 1998 with strong evidence that atmospheric neutrinos oscillate—or morph from one of three possible flavors into another—and therefore have mass.

The accident crippled Super-K and stunned particle physicists everywhere. “The accident was severe, but we will rebuild,” says Super-K director Yoji Totsuka. The aim, he says, is to start up with about half the original density of PMTs within a year, and fully fix Super-K by 2007.

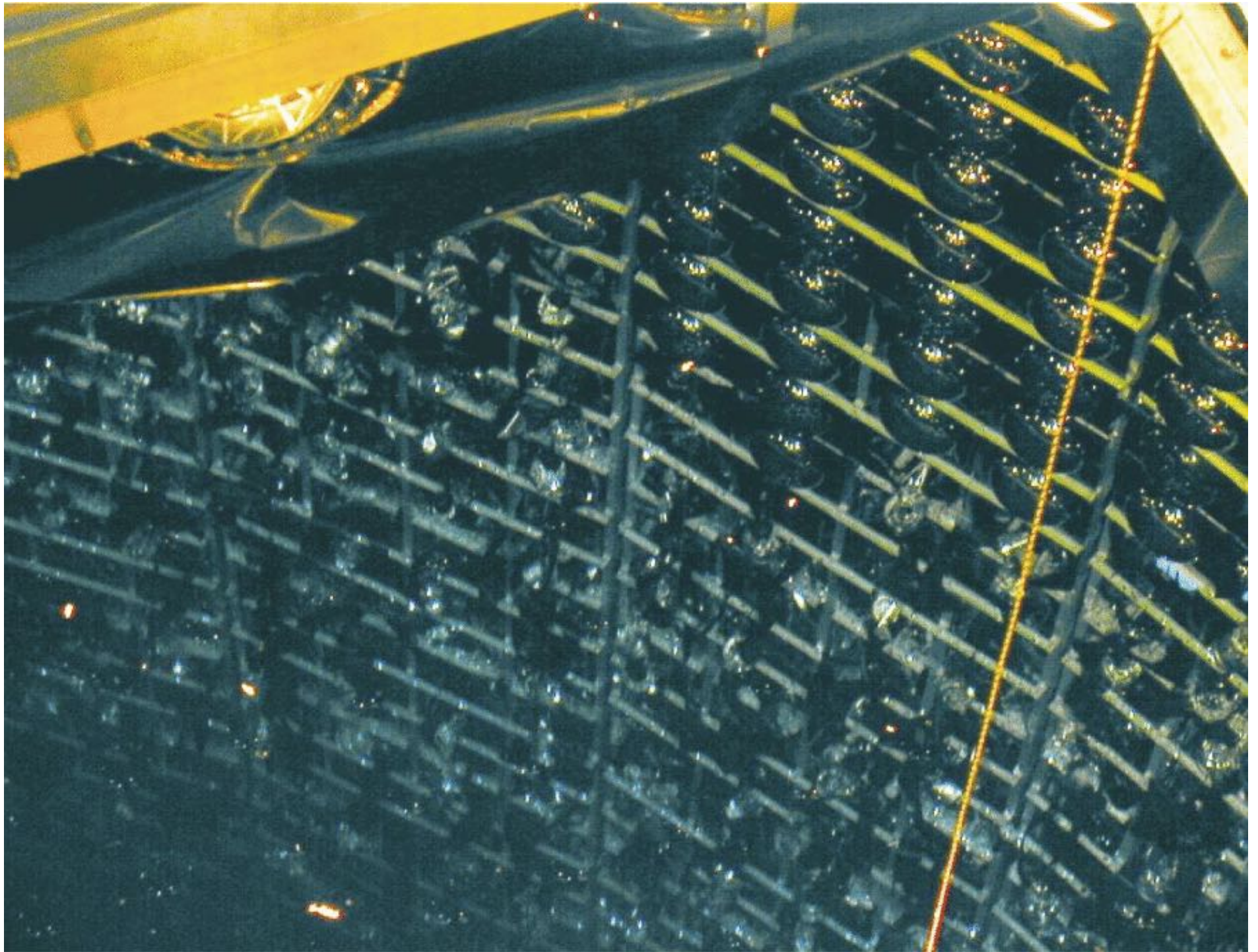
Super-K's water tank, some 41 meters high and 39 meters in diameter, is lined with more than 11 000 PMTs; they see the occasional flashes of bluish Čerenkov light emitted from interactions of incident neutrinos with the water. At the time of the accident, the Super-K team was refilling the tank after replacing burned-out PMTs and making other upgrades. Nearly all of the PMTs below the water line popped. The tank also sprang a minor leak.

For the first resuscitation phase, the surviving PMTs, plus some spares, will be spread evenly around Super-K. At half the usual density, the lowest-energy signals will be lost, so some solar neutrinos won't be detectable, and proton decay, if it actually happens, will be harder to observe, but atmospheric and other studies could resume. “This is good enough for the time being,” says Totsuka.

Scientists are especially eager to restart the K2K experiment. In K2K, which is intended to verify Super-K's spec-



SHARDS: Most of the photomultiplier tubes that were below water popped in a chain reaction that has incapacitated the Super-Kamiokande neutrino observatory in Japan. (Courtesy of the Institute for Cosmic Ray Research, The University of Tokyo.)



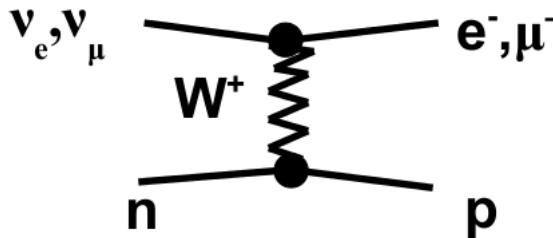


Oscillation Analysis

Neutrino Interactions

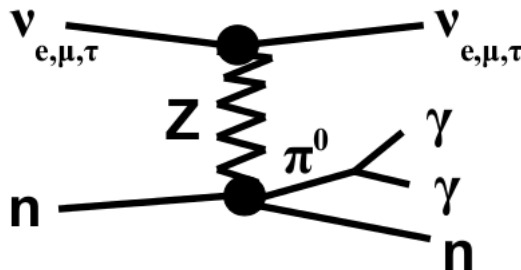


- In the region of interest for T2K, large contribution from charge current quasi-elastic scattering:

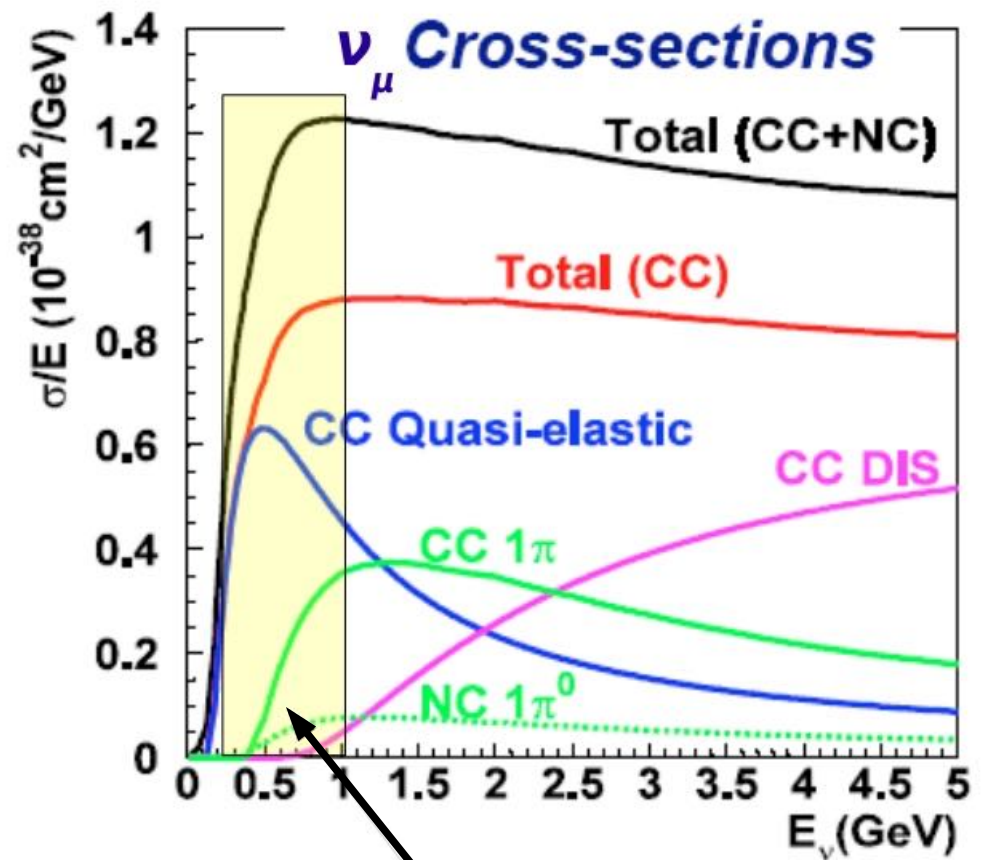


T2K signal at SK

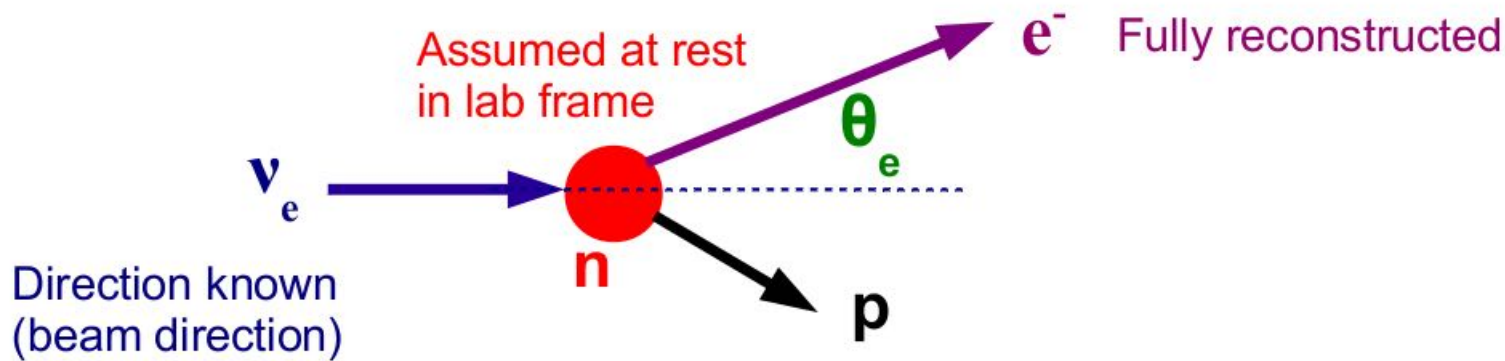
- Also significant CC contribution with pion in final state
- NC π^0 is a major background mode from electron appearance:



Photons from π^0 can fake electron signal



T2K beam peak energy



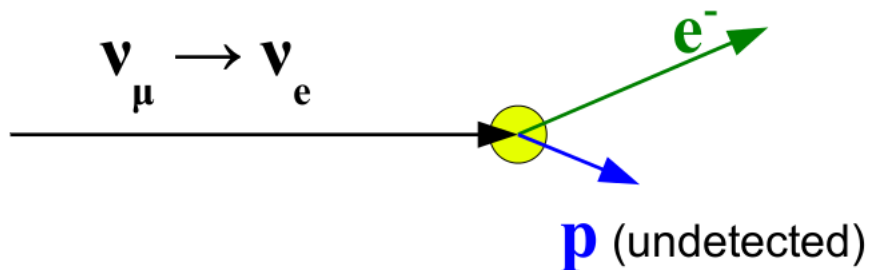
$$E_{\nu}^{QE} = \frac{2 M_n E_e - (M_n^2 + m_e^2 - M_p^2)}{2 [M_n - E_e + \sqrt{E_e^2 - m_e^2} \cos \theta_e]}$$

- Only final state lepton is reconstructed
- Neutrino energy can be determined with certain assumptions:
 - Neutrino direction is known (beam direction)
 - Recoil nucleon mass is known (use neutron mass)
 - Target nucleon is at rest (not quite true; introduces smearing)

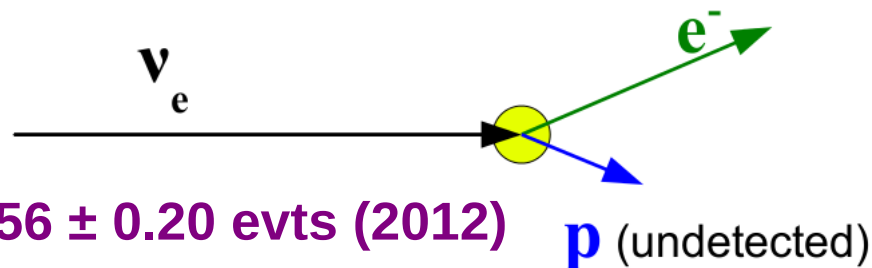
ν_e Signal & BG (at SK)



- Oscillation signal:

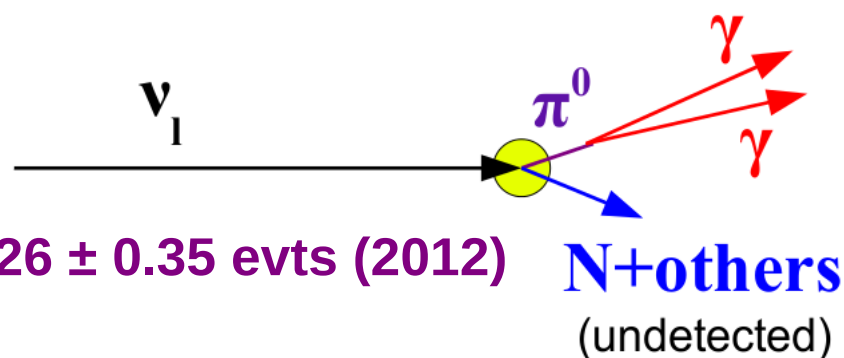


- Beam ν_e background:

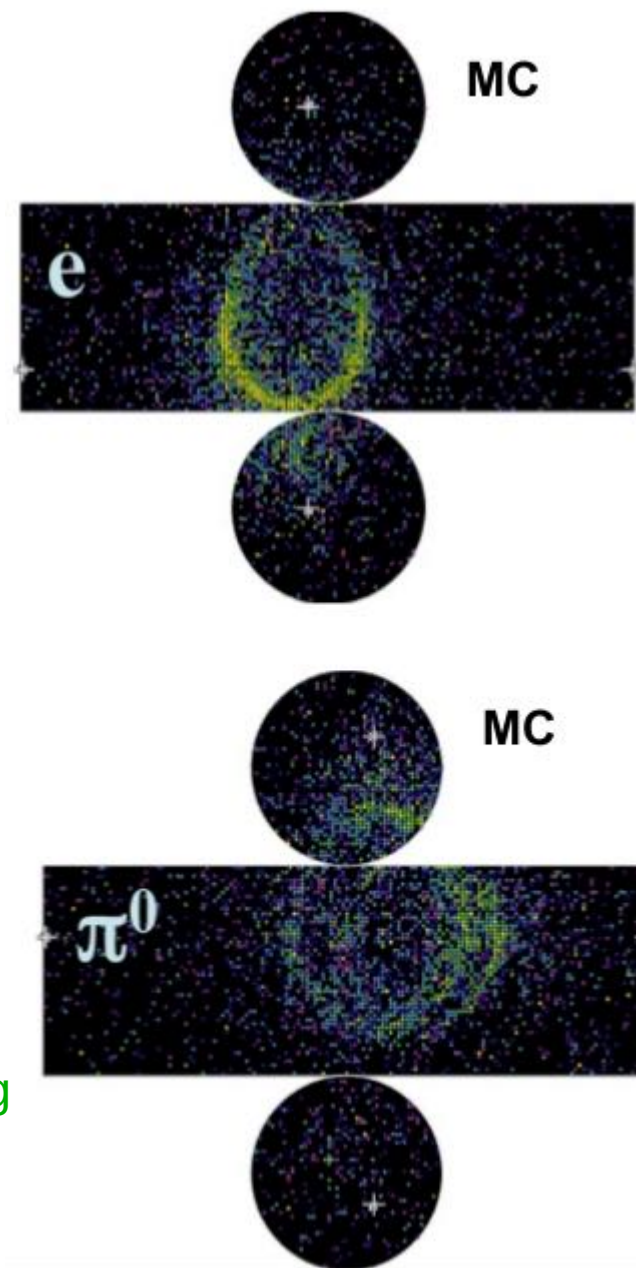


Beam background has harder energy spectrum

- Neutral current π^0 background:



Can be removed by identifying second photon ring

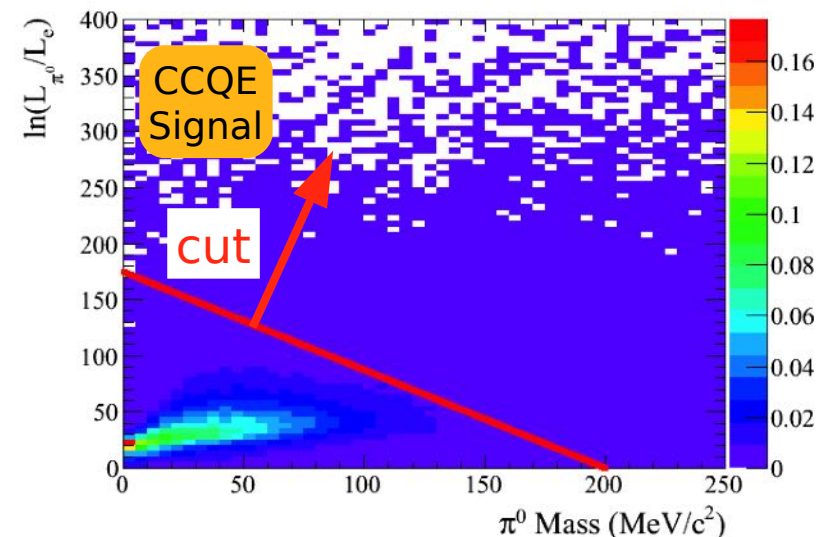
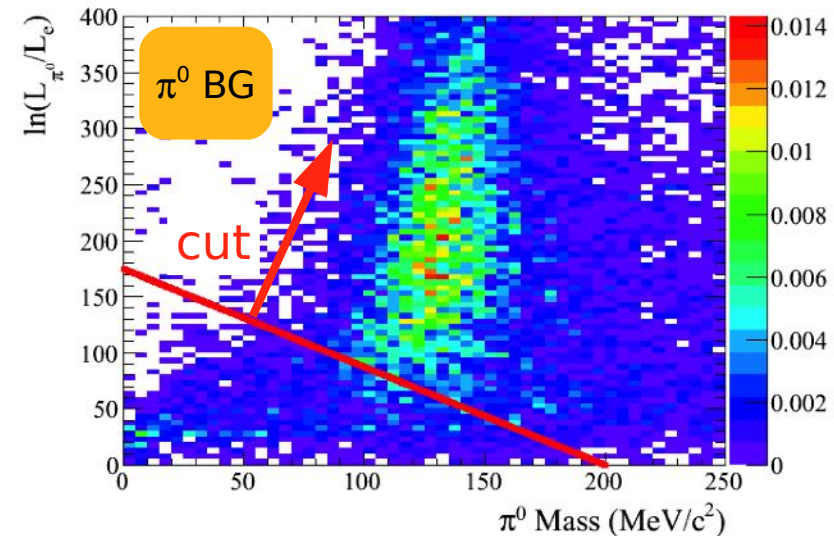


Improved π^0 Rejection

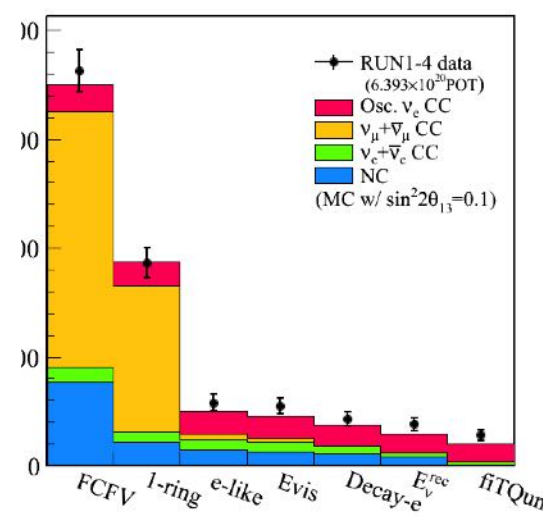
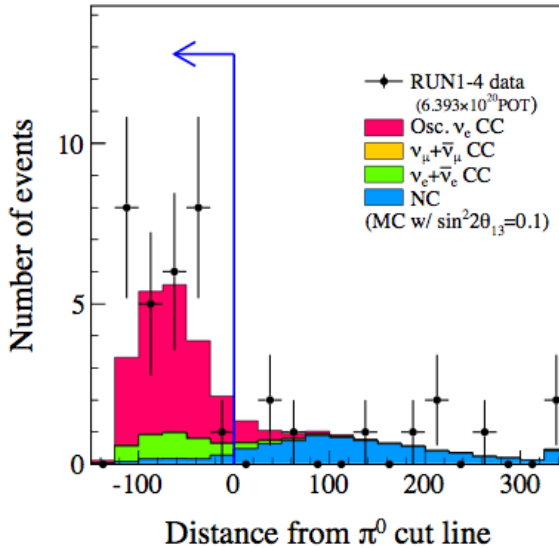
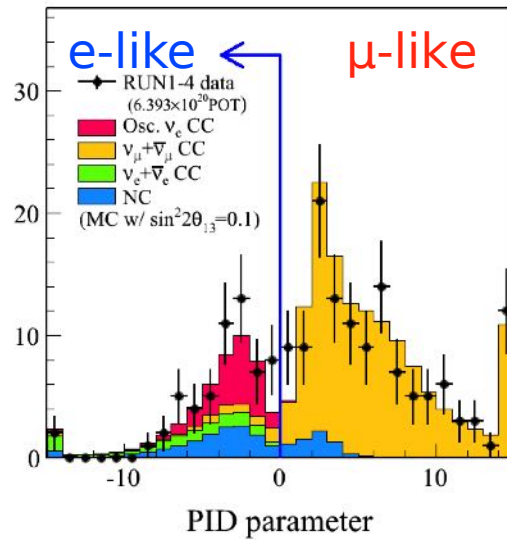
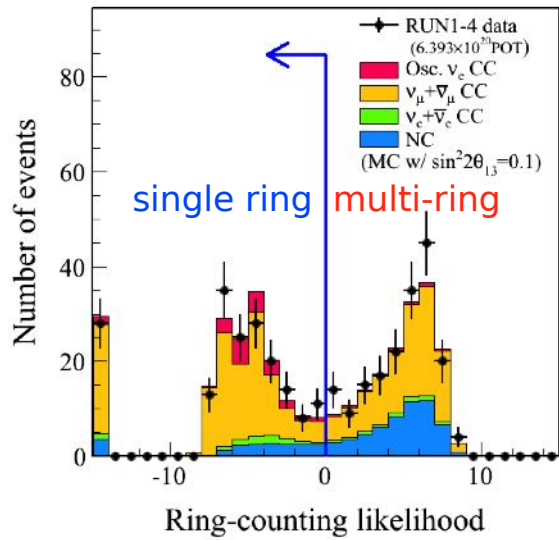


- New likelihood fitter used to distinguish electrons from π^0
- Assumes two electron-like rings produced at a common vertex
- Uses 12 parameters in fit:
 - Vertex (X, Y, Z, T)
 - Directions ($\theta_1, \varphi_1, \theta_2, \varphi_2$)
 - Momenta (p_1, p_2)
 - Conversion lengths (c_1, c_2)
- This 2D cut **removes 70% of the π^0 background remaining** after previous selection applied (for same signal efficiency)
- Total background is reduced by 27%
- 6.74 BG events \rightarrow 4.92 BG events expected (in full Run 1 – 4 dataset)

Likelihood Ratio vs π^0 Mass
(T2K Monte Carlo)



T2K-SK ν_e Event Selection



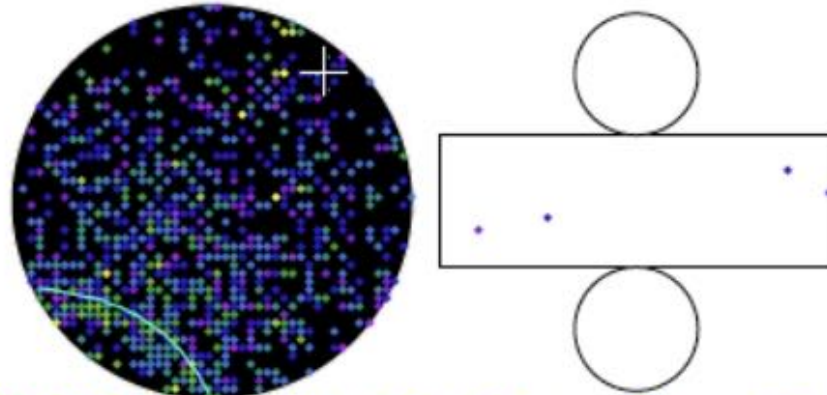
- ## ν_e Selection Criteria
- # clustered veto hits < 16
 - Distance to wall > 200 cm
 - # of rings = 1
 - PID of ring is e-like
 - Visible energy > 100 MeV
 - no Michel electrons
 - New π^0 cut
 - $0 < E_\nu < 1250$ MeV

A Typical ν_e Candidate



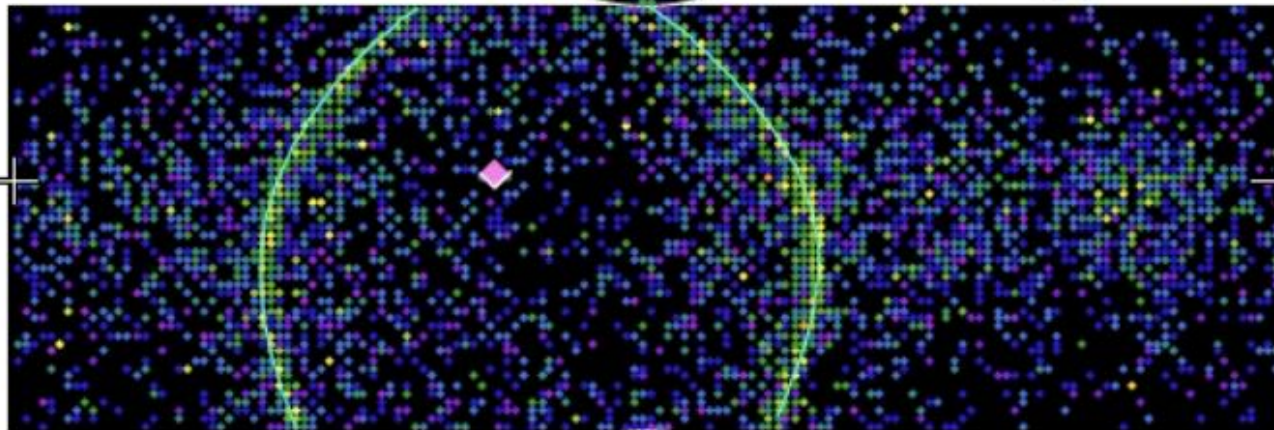
Super-Kamioke IV

T2K Beam Run 0 Spill 1039222
Run 67969 Sub 921 Event 218931934
10-12-22:14:15:18
T2K beam dt = 1782.6 ns
Inner: 4804 hits, 9970 pe
Outer: 4 hits, 3 pe
Trigger: 0x80000007
D_wall: 244.2 cm
e-like, p = 1049.0 MeV/o

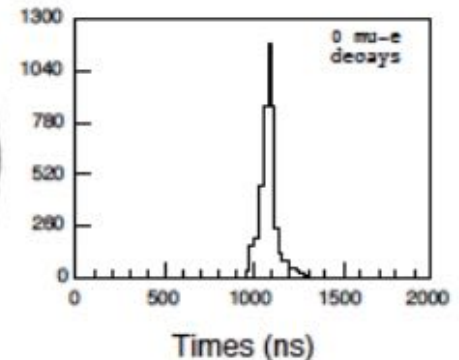
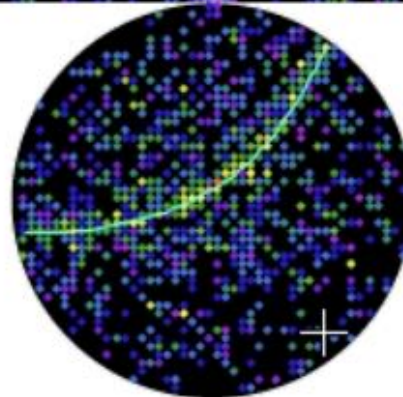


Charge (pe)

- * >26.7
- * 23.3-26.7
- * 20.2-23.3
- * 17.3-20.2
- * 14.7-17.3
- * 12.2-14.7
- * 10.0-12.2
- * 8.0-10.0
- * 6.2- 8.0
- * 4.7- 6.2
- * 3.3- 4.7
- * 2.2- 3.3
- * 1.3- 2.2
- * 0.7- 1.3
- * 0.2- 0.7
- * < 0.2

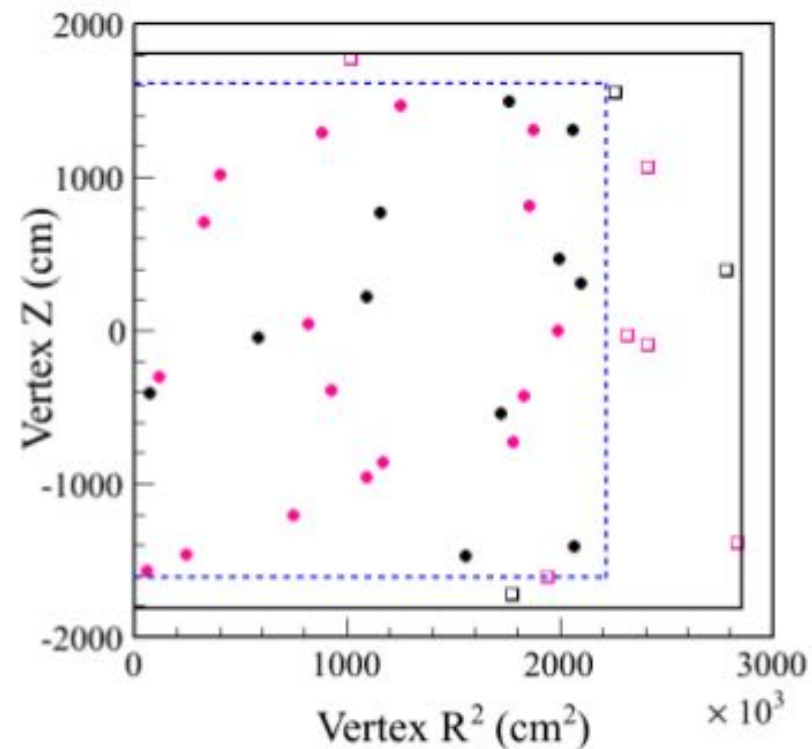
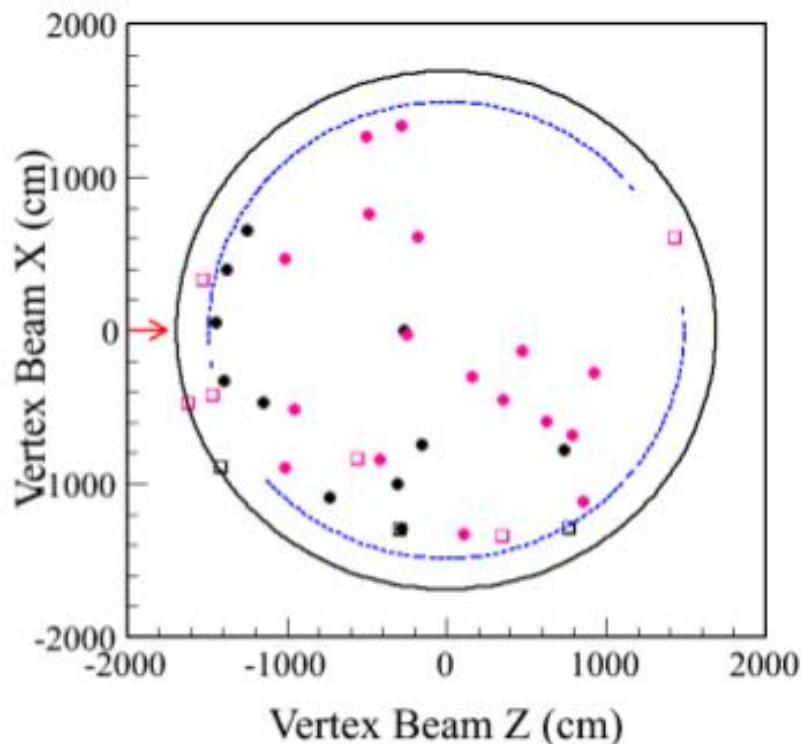


visible energy : 1049 MeV
of decay-e : 0
2 γ Inv. mass : 0.04 MeV/c²
recon. energy : 1120.9 MeV



ν_e Vertex Distributions

Vertex distributions for ν_e candidates at the far detector:



| | RUN1+2+3 | RUN4 | RUN1+2+3+4 |
|-----------------------------------|----------|-------|------------|
| <i>Dwall</i> | 34.4% | 54.7% | 20.9% |
| <i>Fromwall beam</i> | 6.04% | 85.6% | 8.93% |
| $R^2 + Z$ | 32.4% | 98.1% | 64.5% |

Near Detector Constraint



GOAL: Constrain neutrino flux & cross section parameters used for oscillation prediction (via MC) at T2K far detector

Error on Far Detector ν_e Prediction
(After Near Detector Constraint)

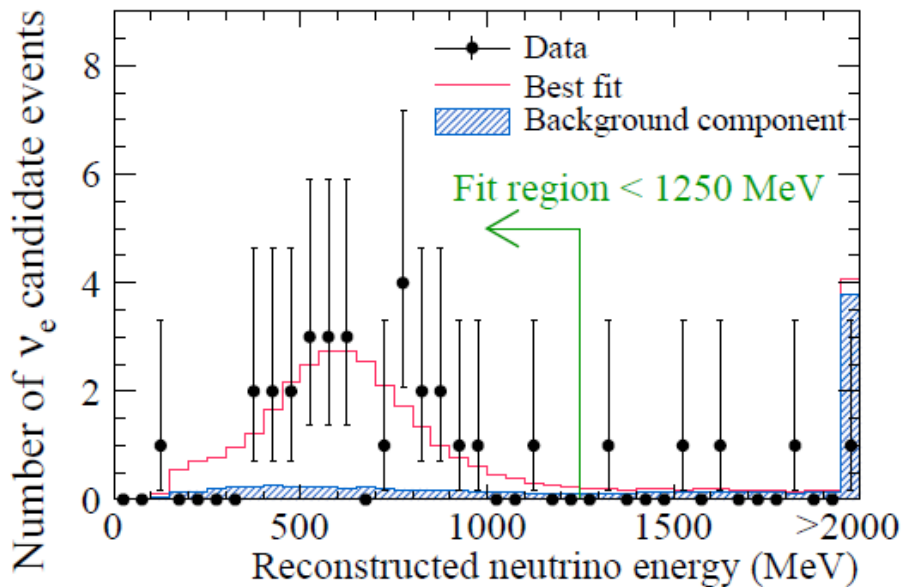
| | Runs 1-3 (2012) | Runs 1-3 (2013) | Runs 1-4 (2013) |
|---------------------------|--------------------|--------------------|--------------------|
| $\sin^2 2\theta_{13}=0.1$ | 4.7% | 3.5% | 3.0% |
| $\sin^2 2\theta_{13}=0.0$ | 6.1% | 5.2% | 4.9% |

Error on Cross Section Parameters
(After Near Detector Constraint)

| Parameter | Runs 1-3 (2012) | Runs 1-4 (2013) |
|-----------------------------------|-----------------|-----------------|
| M_A^{QE} (GeV/c ²) | 1.27 ± 0.19 | 1.22 ± 0.07 |
| M_A^{RES} (GeV/c ²) | 1.22 ± 0.13 | 0.96 ± 0.06 |
| CCQE Norm. | 0.95 ± 0.09 | 0.96 ± 0.08 |
| CC1π Norm. | 1.37 ± 0.20 | 1.22 ± 0.16 |

- Significant reduction for event rate errors at the far detector
- Uncertainties on the *cross section & flux* parameters have been reduced

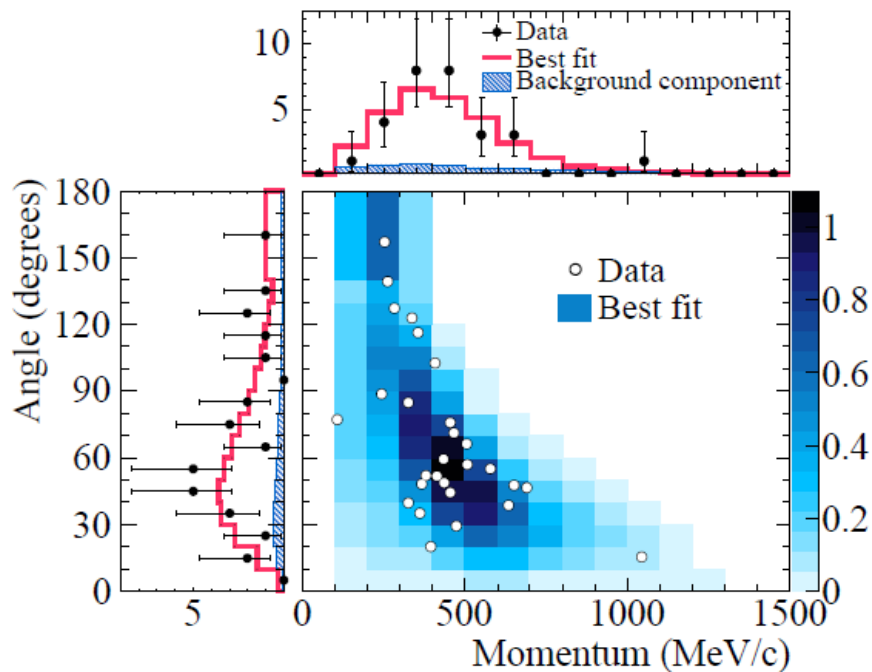
ν_e Appearance Analysis



- Expected background:
 - 4.92 ± 0.55 events
- With the following assumptions:
 - $\sin^2(2\theta_{13}) = 0.1$
 - $\sin^2(2\theta_{23}) = 1$
 - $\delta_{CP} = 0$
 - normal mass hierarchy

the expected signal is:

- 21.6 ± 1.8 events
- **5.5σ sensitivity to exclude $\theta_{13} = 0$**

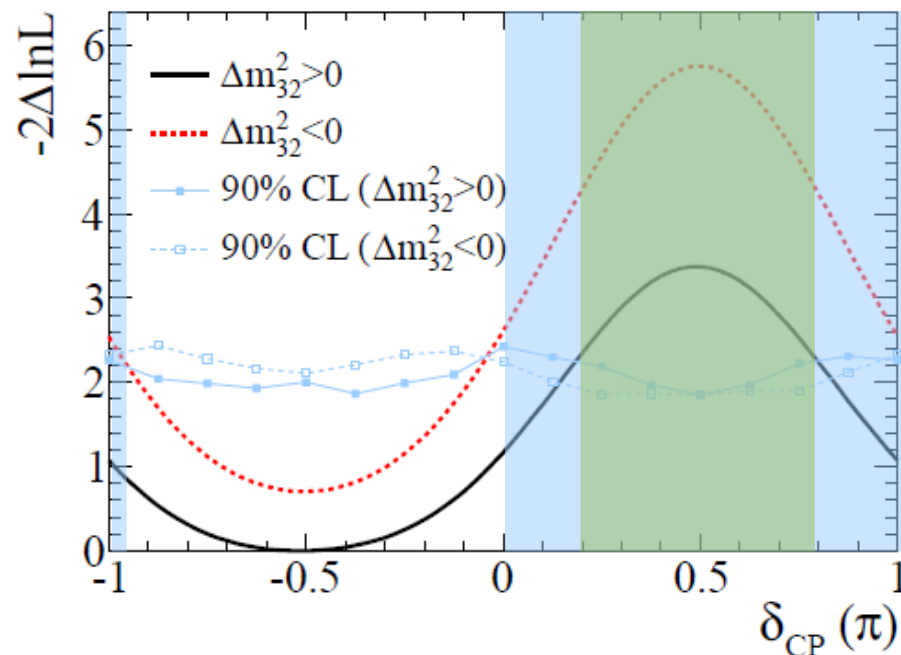
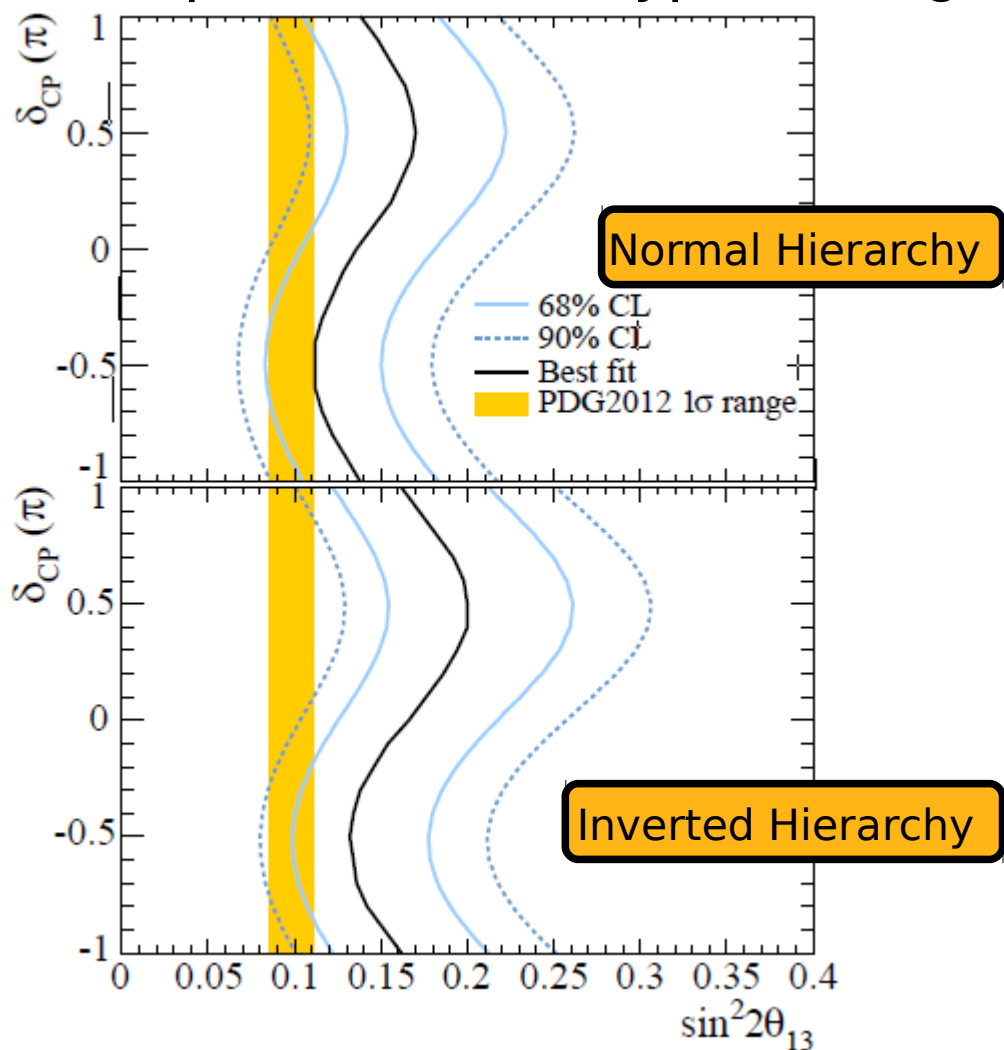


- Oscillation parameters were extracted with two parallel analyses:
 - Using the 1D E_ν distribution (top)
 - Using the 2D p - θ distribution (bottom)

ν_e Appearance Results



- **28 ν_e events observed** (recall 21.6 ± 1.8 expected for $\sin^2(2\theta_{13}) = 0.1$)
- Comparison to null hypothesis gives **7.3σ significance for $\theta_{13} \neq 0$**



- Tension with θ_{13} measurement at reactors gives some sensitivity to δ
- Some regions excluded at 90% CL
 - $\delta = -\pi/2$ preferred for both hierarchies

SNO – A “smart” solar neutrino experiment.

- Solar neutrino problem: the electron neutrino flux coming from the sun is “lower” than the flux expected from the solar model
 - the solar model is wrong;
 - the neutrinos oscillate during the travel.
- The idea of SNO is: we built a detector able to measure neutrinos from the sun, BUT not only electron neutrinos, also muon and tau neutrinos. This can be done detecting 3 different reactions:
 - $\nu + d \rightarrow p + p + e^-$ (CC – only ν_e)
 - $\nu + d \rightarrow p + n + \nu$ (NC – all three flavours)
 - $\nu + e^- \rightarrow \nu + e^-$ (ES – all three flavours BUT different rates)
- A deuterium target (Heavy water tank) helps if I can detect electrons or neutrons from the very rare reactions
- Going deeply underground helps to reduce the background

SNO – few numbers

- Neutrinos from the sun are few MeV neutrinos, cross-sections are $\approx 10^{-42} \text{ cm}^2$ (very small)
- Neutrinos from the sun fluxes are of the order of $\approx 10^6 \text{ cm}^{-2}\text{s}^{-1}$.
- How many neutrino interactions can I get, given an amount of deuterium nuclei ?

$$\dot{N} = \sigma_{\nu} \varphi N_d \approx 10^{-36} N_d (\text{s}^{-1})$$

- If I want at least $O(10^3)$ events in one year $O(10^7 \text{ s})$ we need:

$$N_d \approx 10^{32}$$

- How can I get a sample of 10^{32} deuterium nuclei ? A tank of 1000 tonns of heavy water contains

$$N_d = 2 \frac{M}{M_{D_2O}} \approx \frac{2 \times 10^6 \text{ Kg}}{20 \times m_N} = 6 \times 10^{31}$$

SNO - detector

- Logic: tank of 1000 tonnes of heavy water and PMT to see Cerenkov light
 - from electrons in case of ES and CC reactions
 - from 6.25 MeV γ from capture of neutrons from deuterium in case of NC reactions (after thermalization of the neutron)
 - The three reactions can be disentangled in terms of three measurements:
 - Energy (of electrons and of gamma through Compton or pair production)
 - Radius (in terms of $(R/R_{AV})^3$, uniformity of the scattering position)
 - $\cos\theta_{\text{sun}}$ (depends on the correlation btw electron directions and primary neutrinos)

SNO – detector sketch

Main features:

2070m below ground in INCO's Creighton mine
Deep Sudbury mine (Ontario, Canada)

Heavy water tank 1000 tonns

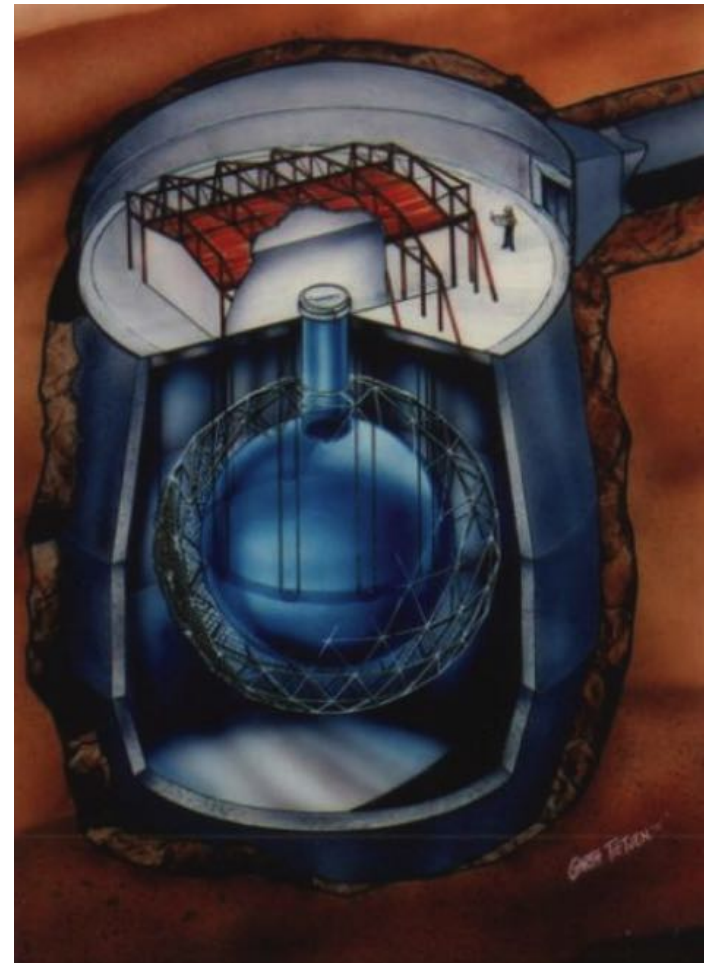
Light water envelope 7000 tonns

Sphere of 10000 PMTs around the envelope (inward and backward)

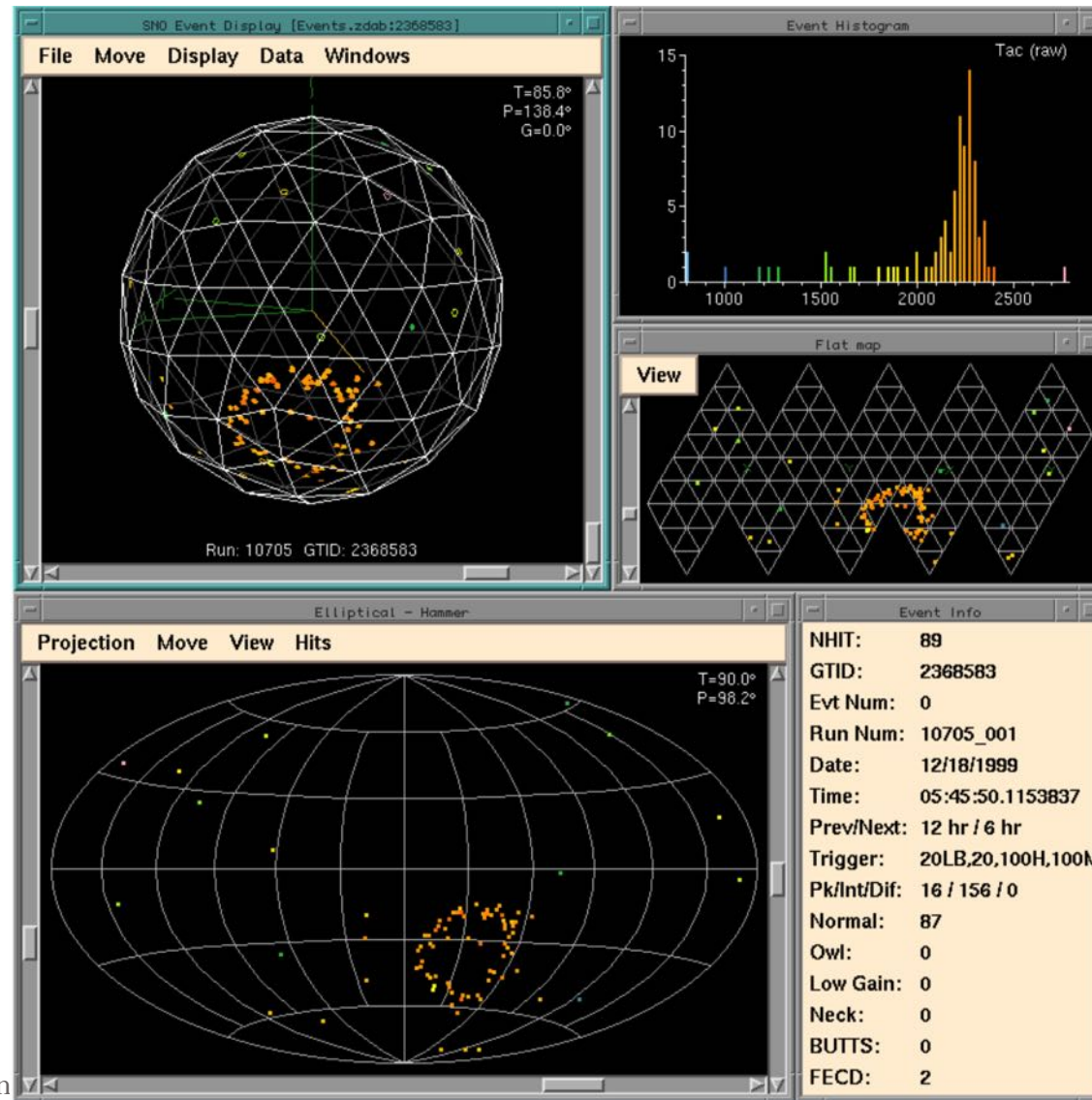
High water purity with controlled quantity of NaCl in Heavy Water tank (to enhance NC detection)

Each PMT measures charge and Time

→ Cerenkov ring → direction and energy

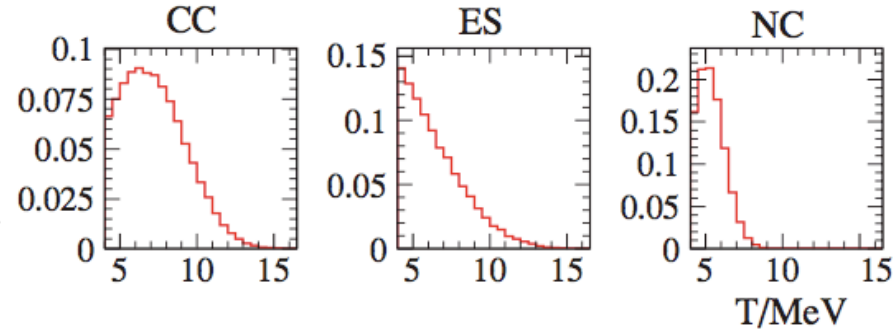


SNO event

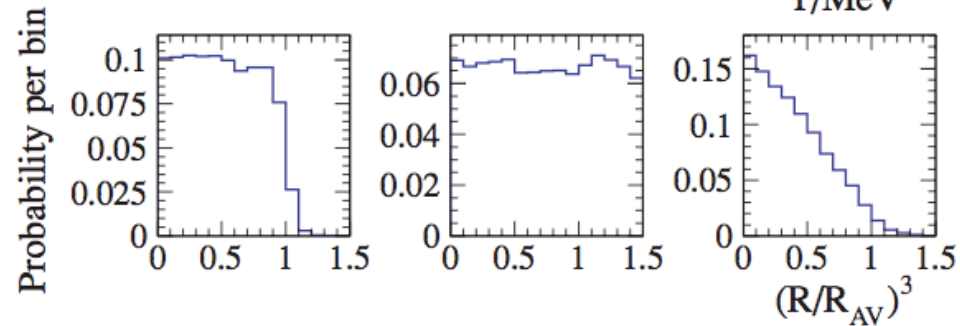


SNO – variables used

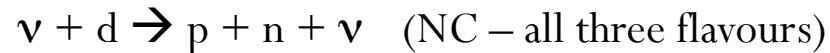
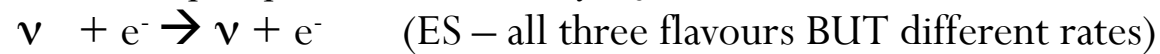
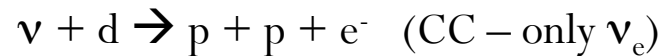
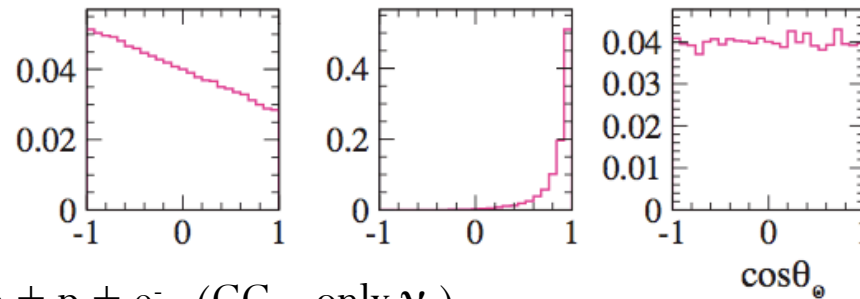
Energy
NB solar neutrinos energies
 $E_\nu < 15$ MeV



Radius



Direction



SNO - results

$$\phi_{CC} = \phi(\nu_e),$$

$$\phi_{ES} = \phi(\nu_e) + 0.1559\phi(\nu_{\mu\tau}),$$

$$\phi_{NC} = \phi(\nu_e) + \phi(\nu_{\mu\tau}),$$

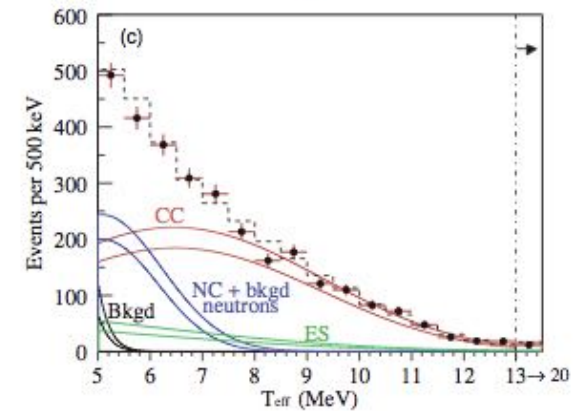
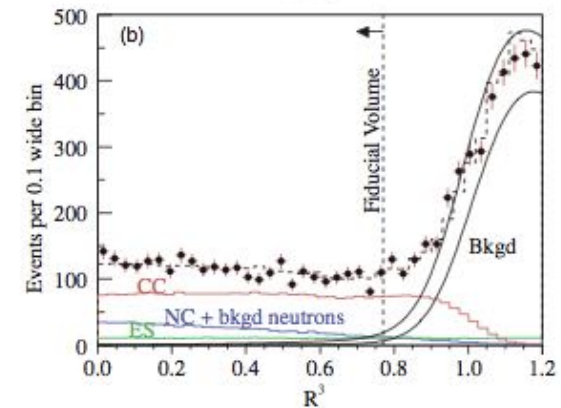
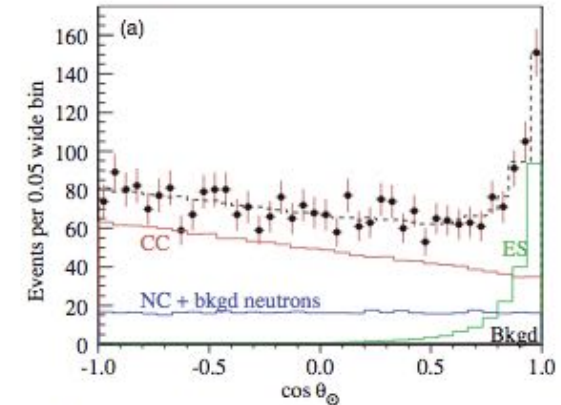
$$\phi_{CC} = 1.76_{-0.05}^{+0.06} (\text{stat.})_{-0.09}^{+0.09} (\text{syst.}) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1},$$

$$\phi_{ES} = 2.39_{-0.23}^{+0.24} (\text{stat.})_{-0.12}^{+0.12} (\text{syst.}) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1},$$

$$\phi_{NC} = 5.09_{-0.43}^{+0.44} (\text{stat.})_{-0.43}^{+0.46} (\text{syst.}) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1},$$

$$\phi(\nu_e) = 1.76_{-0.05}^{+0.05} (\text{stat.})_{-0.09}^{+0.09} (\text{syst.}) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1},$$

$$\phi(\nu_{\mu\tau}) = 3.41_{-0.45}^{+0.45} (\text{stat.})_{-0.45}^{+0.48} (\text{syst.}) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}.$$



SNO – result interpretation

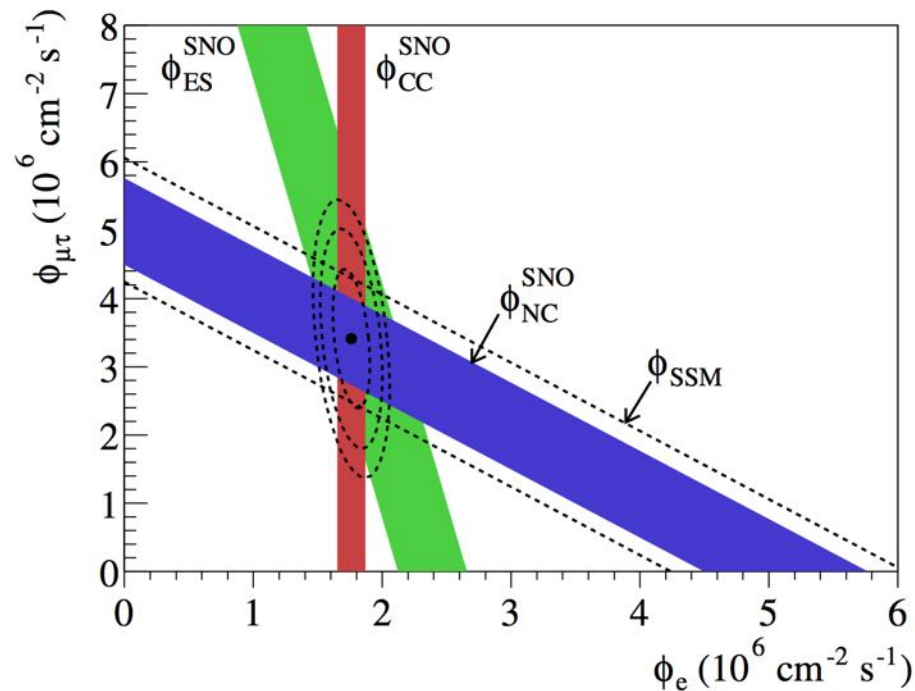


Figure 5: SNO's CC, NC and ES measurements from the D₂O phase. The x- and y-axes are the inferred fluxes of electron neutrinos and muon plus tau neutrinos. Since the NC and ES measurements are sensitive to both ν_e and ν_μ/ν_τ , the ES and NC bands have definite slopes. The CC measurement is sensitive to ν_e only, so has an infinite slope. The widths of the bands represent the uncertainties of the measurements. The intersection of the three bands gives the best estimate of $\phi_{\mu\tau}$ and ϕ_e . The dashed ellipses around the best fit point give the 68%, 95%, and 99% confidence level contours for $\phi_{\mu\tau}$ and ϕ_e . The flux of neutrinos predicted by the SSM is indicated by ϕ_{SSM} .