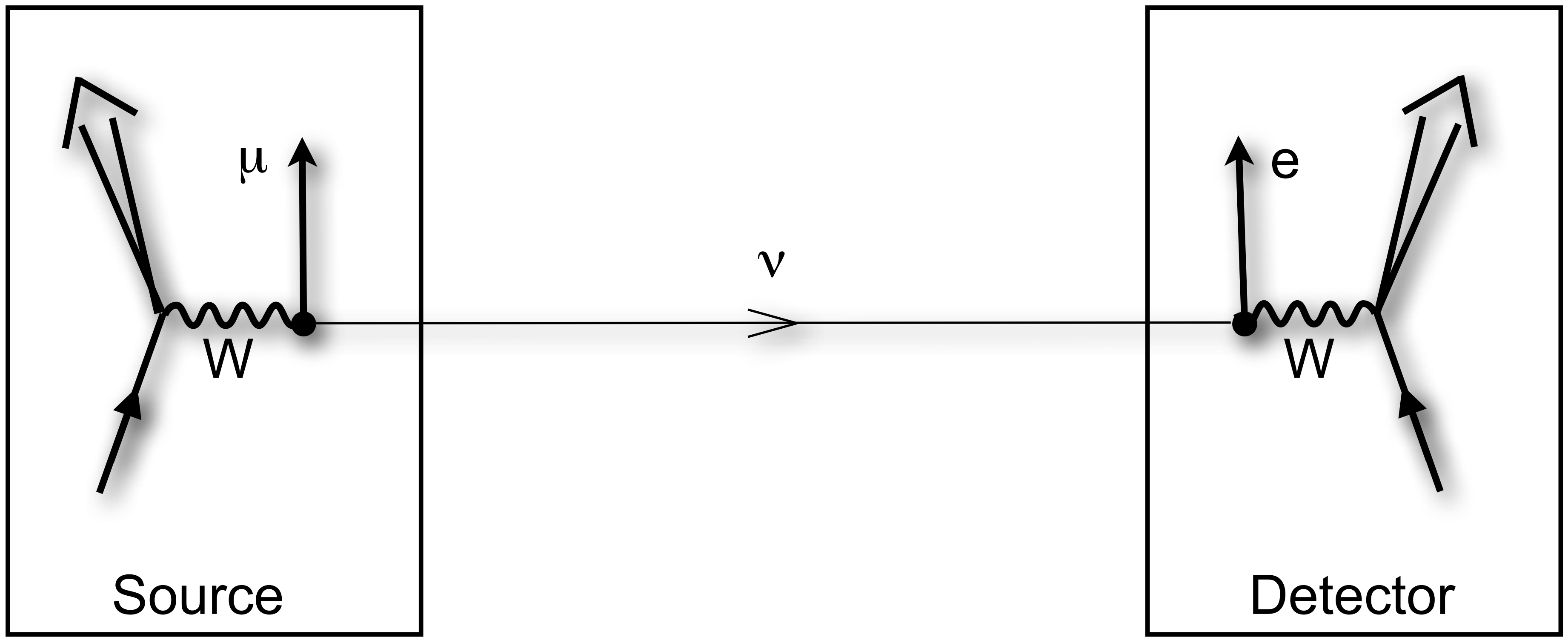
Neutrino oscillation

Pontecorvo

Sov.Phys.JETP 6:429,1957

Sov.Phys.JETP 26:984-988,1968



Maki, Nakagawa, Sakata

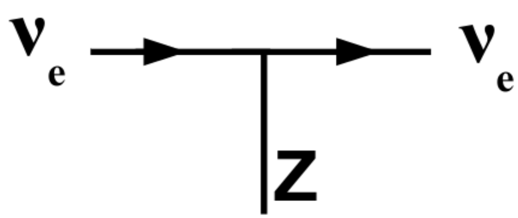
Prog.Theor.Phys. 28, 870 (1962)

- 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. $\nu_e\, n \rightarrow e^- p$)

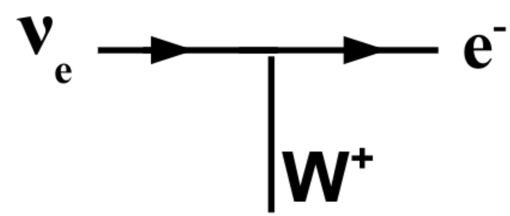
Neutrino Basics

- Weakly interacting isospin partners of charged leptons

Neutral current



Charged current



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

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

$$\left.\begin{aligned} \nu_e &= \nu_1 \cos\delta - \nu_2 \sin\delta, \\ \nu_\mu &= \nu_1 \sin\delta + \nu_2 \cos\delta. \end{aligned}\right\} \qquad (2\cdot18)$$

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 $\nu_e \rightleftarrows \nu_\mu$ 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 $T(\nu_e \rightleftarrows \nu_\mu)$ becomes $\sim 10^{-18}$ sec for fast neutrinos with a momentum of ~Bev/c. Therefore, a chain of reactions such as[10)]

$$\pi^+ \to \mu^+ + \nu_\mu, \qquad (2\cdot19\text{a})$$

$$\nu_\mu + Z(\text{nucleus}) \to Z' + (\mu^- \text{ and/or } e^-) \qquad (2\cdot19\text{b})$$

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

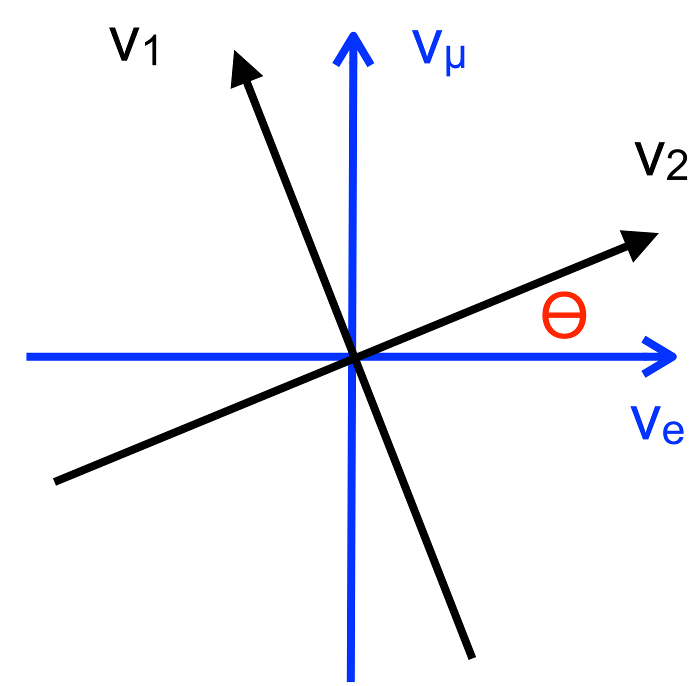
As early as fifty-two years ago, discussions of massive neutrinos and oscillations had begun!

Maki, Nakagawa, Sakata (June 1962)

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:

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

$$|\nu_\mu(t) > = -sin\theta \left(|\nu_1 > e^{-iE_1 t}\right) + cos\theta \left(|\nu_2 > e^{-iE_2 t}\right)$$

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

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

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

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

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:

$$\begin{pmatrix} \nu_1(t) \\ \nu_2(t) \end{pmatrix} = \begin{pmatrix} e^{-iE_1t} & 0 \\ 0 & e^{-iE_2t} \end{pmatrix} \begin{pmatrix} \nu_1(0) \\ \nu_2(0) \end{pmatrix} \tag{1.2}$$

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

$$\begin{pmatrix} \nu_\alpha(t) \\ \nu_\beta(t) \end{pmatrix} = U \begin{pmatrix} e^{-iE_1t} & 0 \\ 0 & e^{-iE_2t} \end{pmatrix} U^{-1} \begin{pmatrix} \nu_\alpha(0) \\ \nu_\beta(0) \end{pmatrix} \tag{1.3}$$

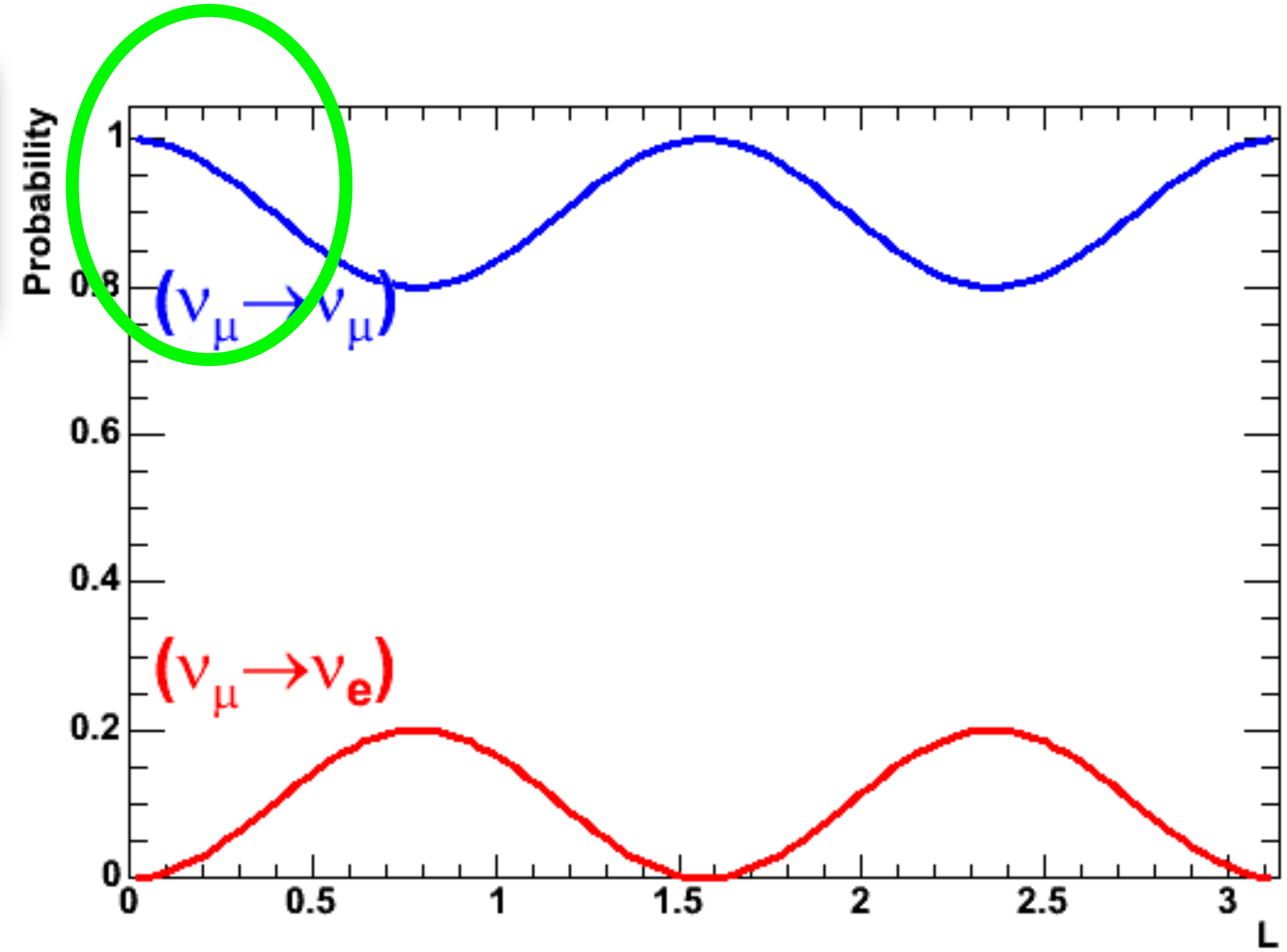
Supposing a neutrino is generated as ν_α (*i.e.* $\nu_\alpha(0) = 1$ and $\nu_\beta(0) = 0$), its surviving probability in the same flavor eigenstate after traveling a certain distance L is obtained as

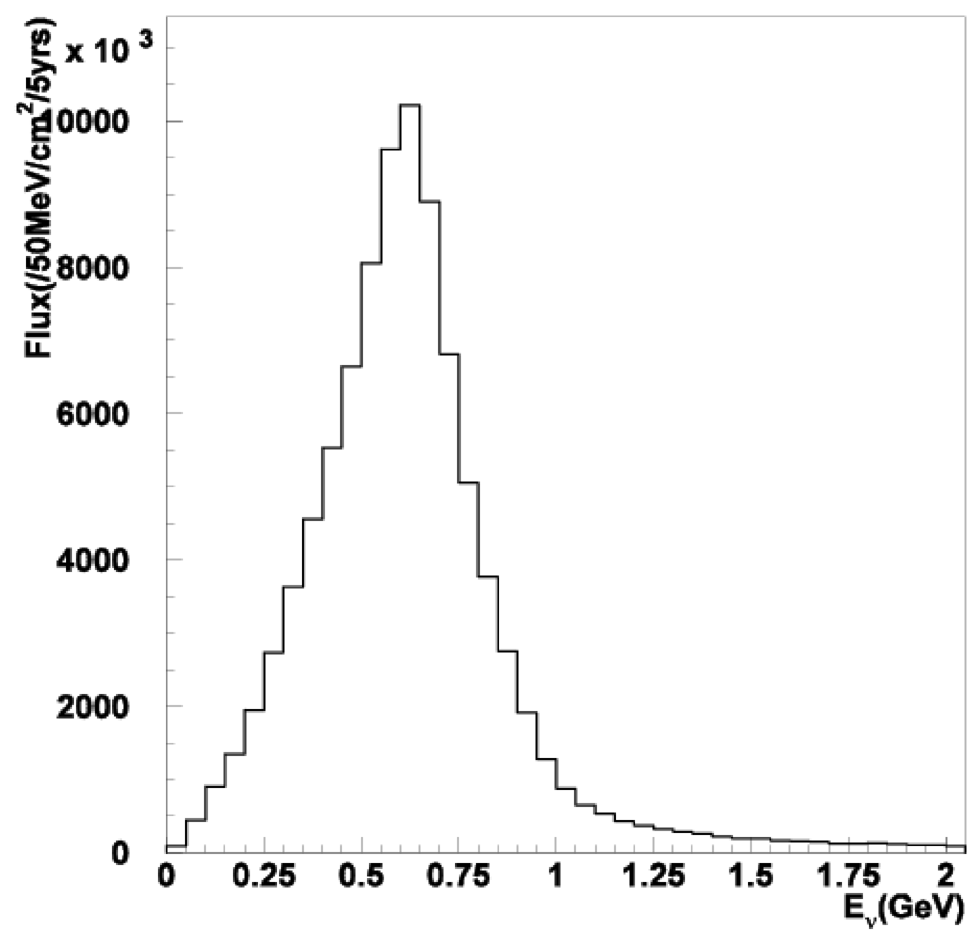
$$P(\nu_\alpha \to \nu_\alpha) = |\nu_\alpha(t)|^2 = 1 - \sin^2 2\theta \cdot \sin^2\left(1.27\Delta m^2[\mathrm{eV}^2/\mathrm{c}^4]\frac{L[\mathrm{km}]}{E[\mathrm{GeV}]}\right) \tag{1.4}$$

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.

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

- 2 fundamental parameters
  - Δm^2 ↔ period
  - θ_{12} ↔ 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





$$P(\nu_\mu \to \nu_e) = sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12}\frac{L}{E})$$

- 2 fundamental parameters
  - $\Delta m^2 \leftrightarrow$ period
  - $\theta_{12} \leftrightarrow$ magnitude
- 2 experimental parameters
  - L = distance travelled
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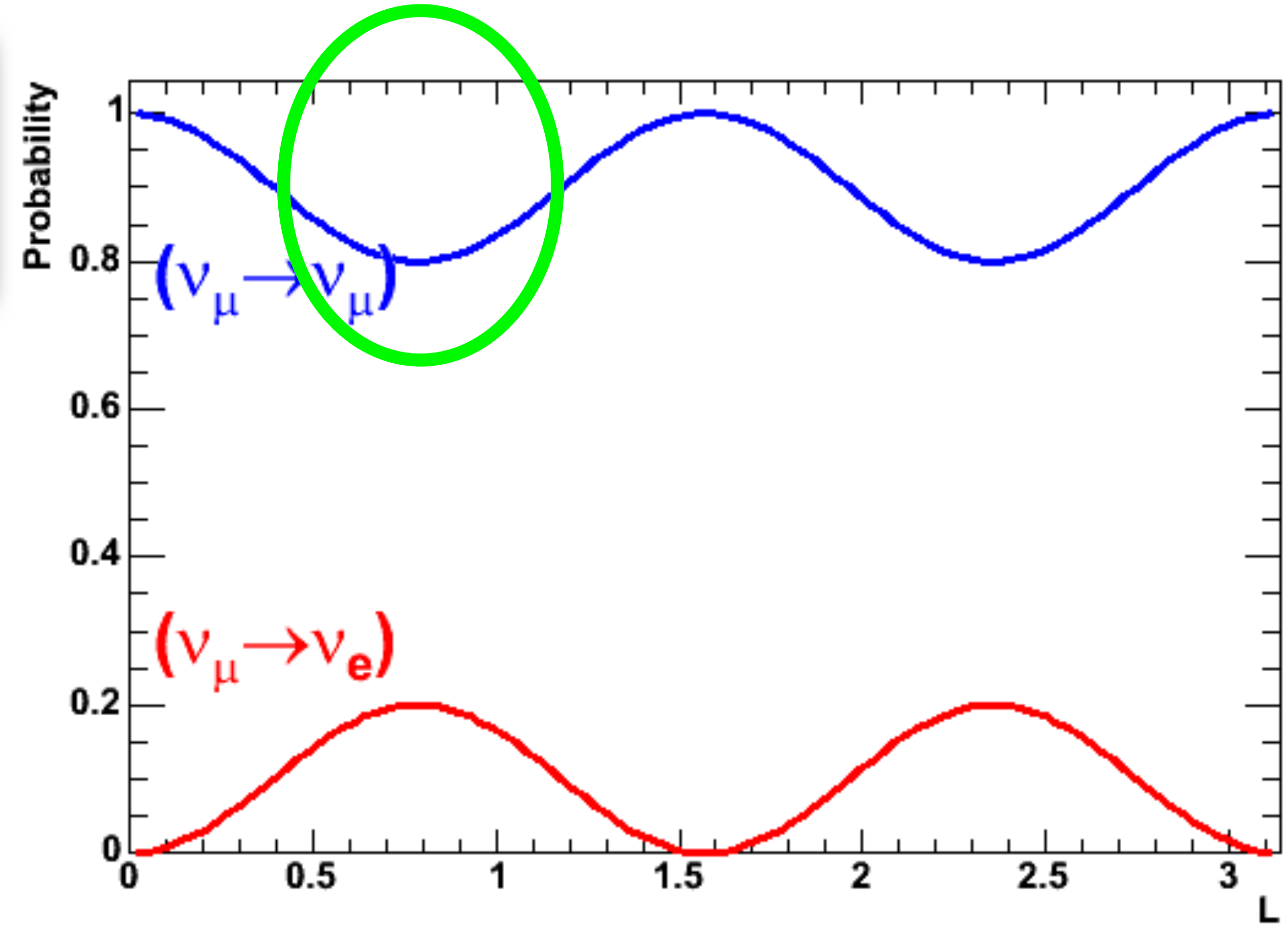

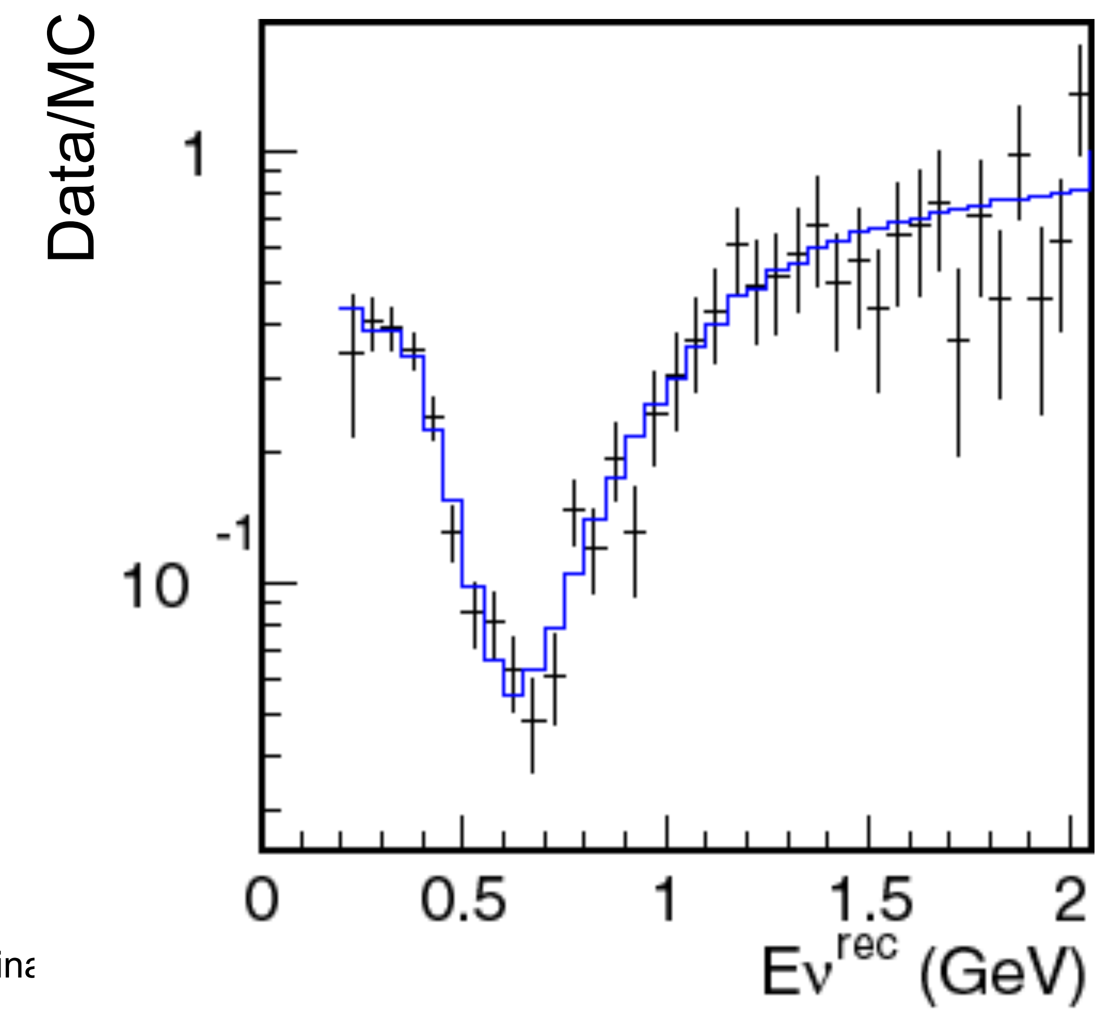

$$P(\nu_\mu \rightarrow \nu_e) = sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12} \frac{L}{E})$$

- 2 fundamental parameters
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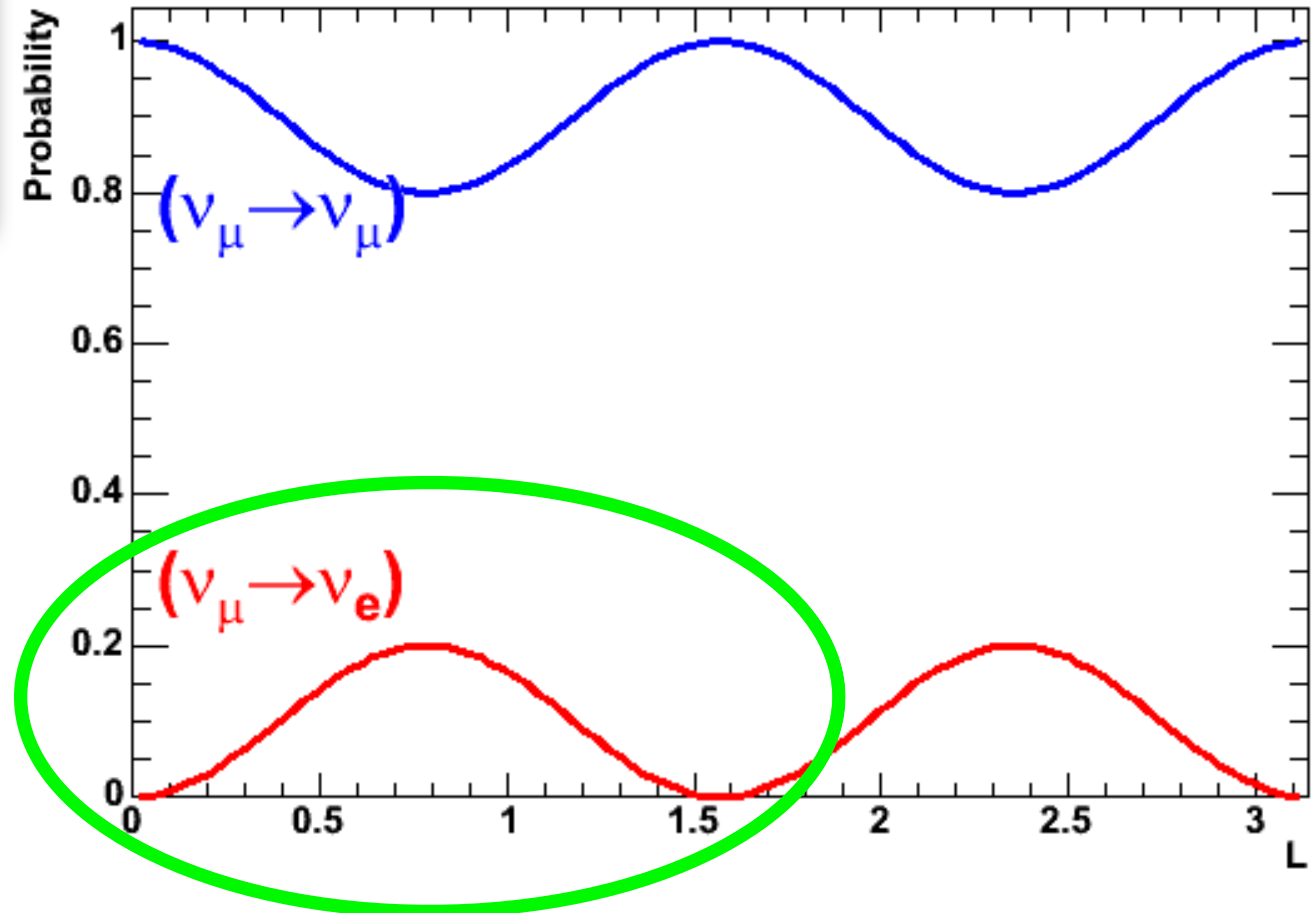
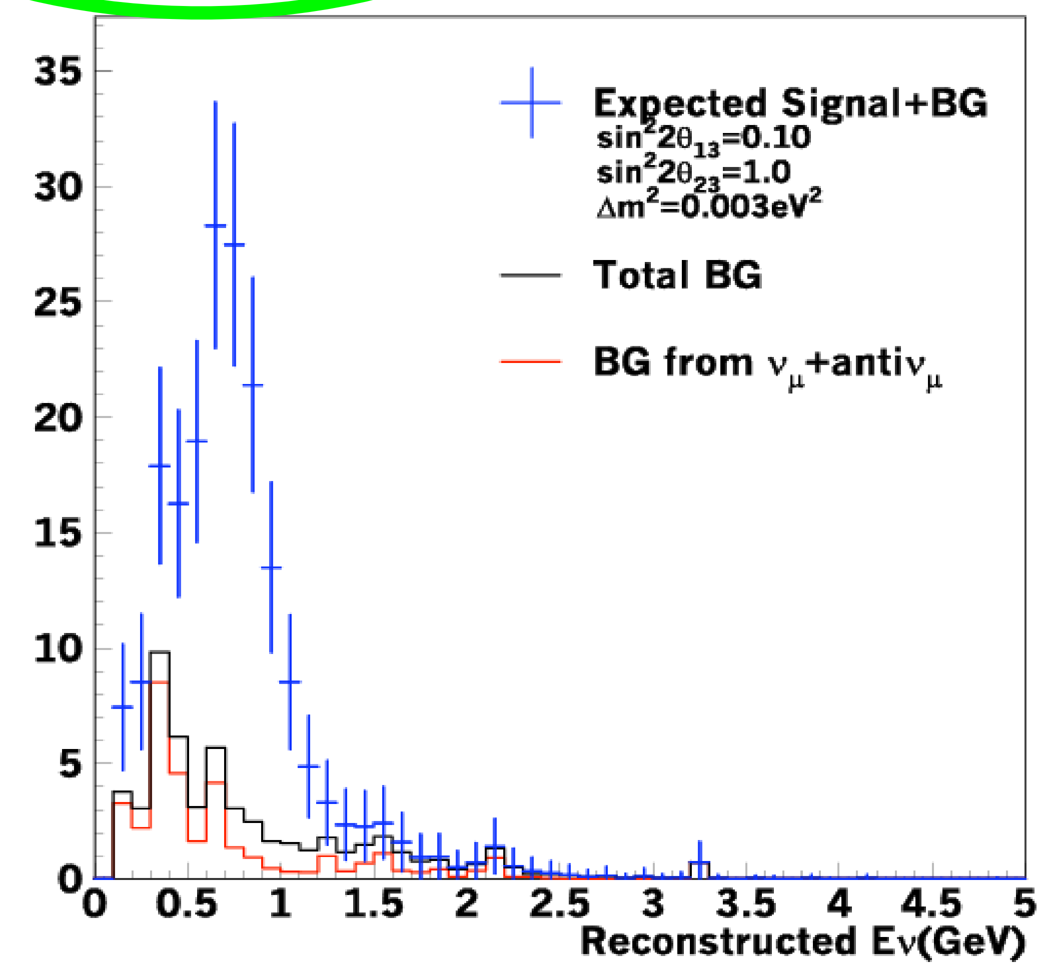
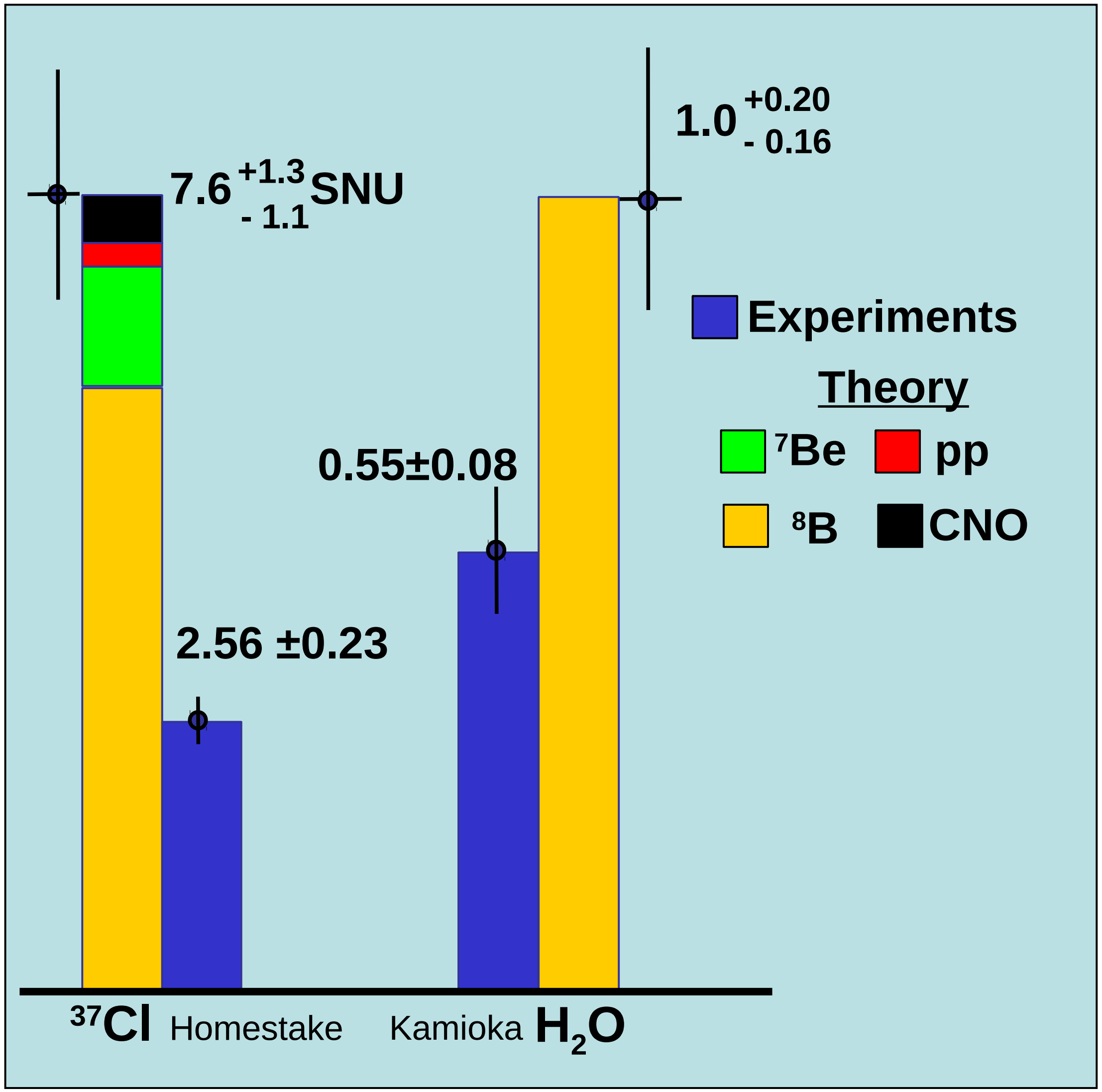


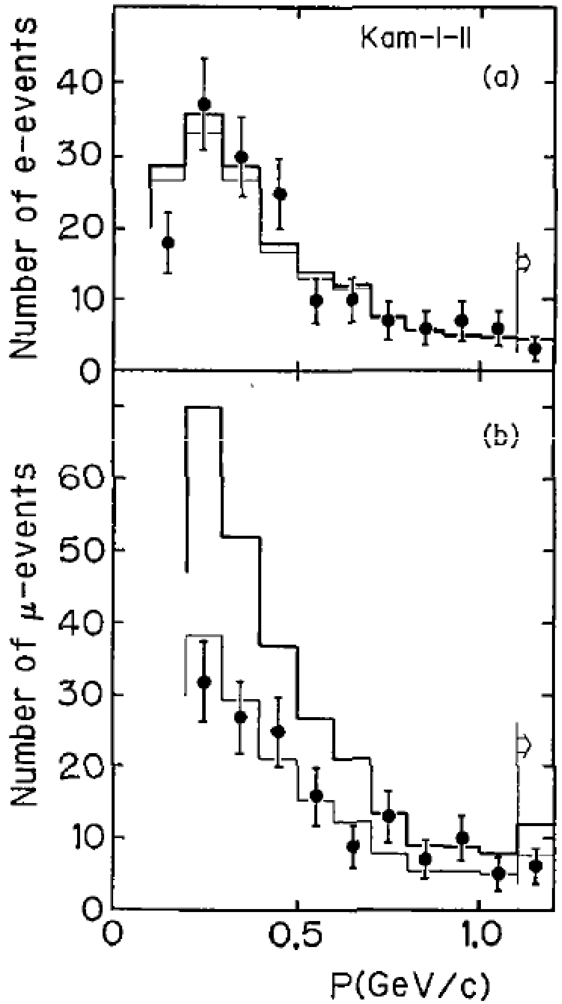


Early Hints of Oscillation

Solar Neutrinos

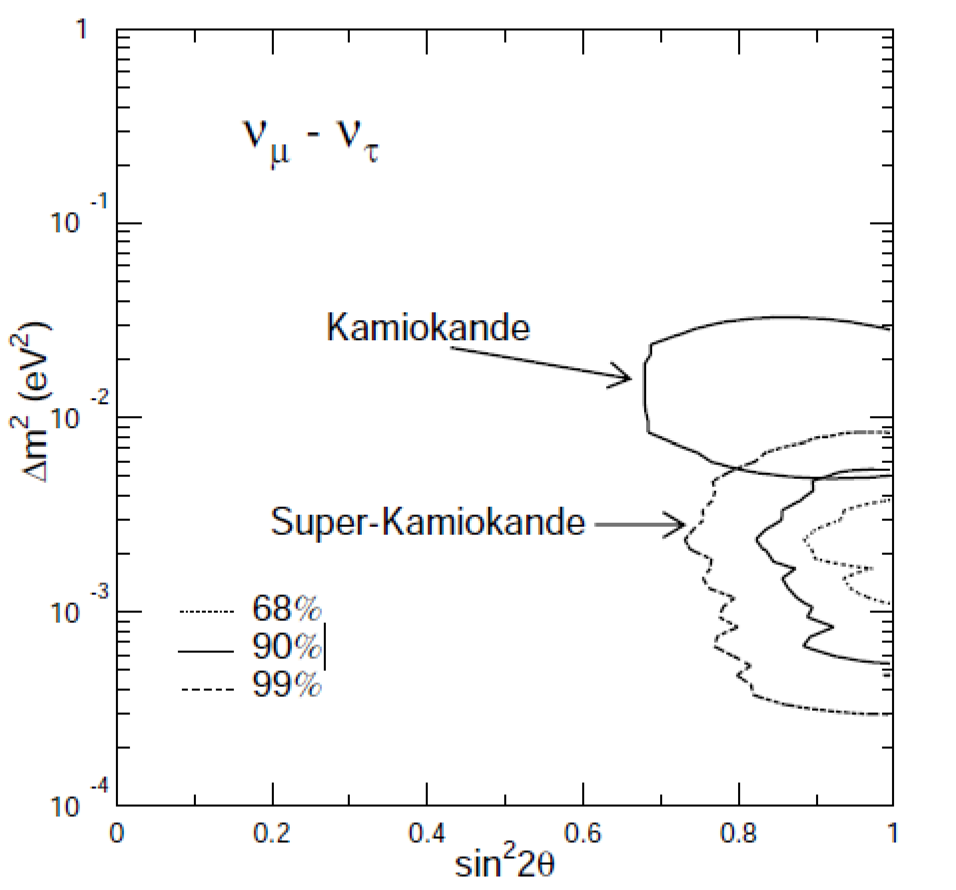


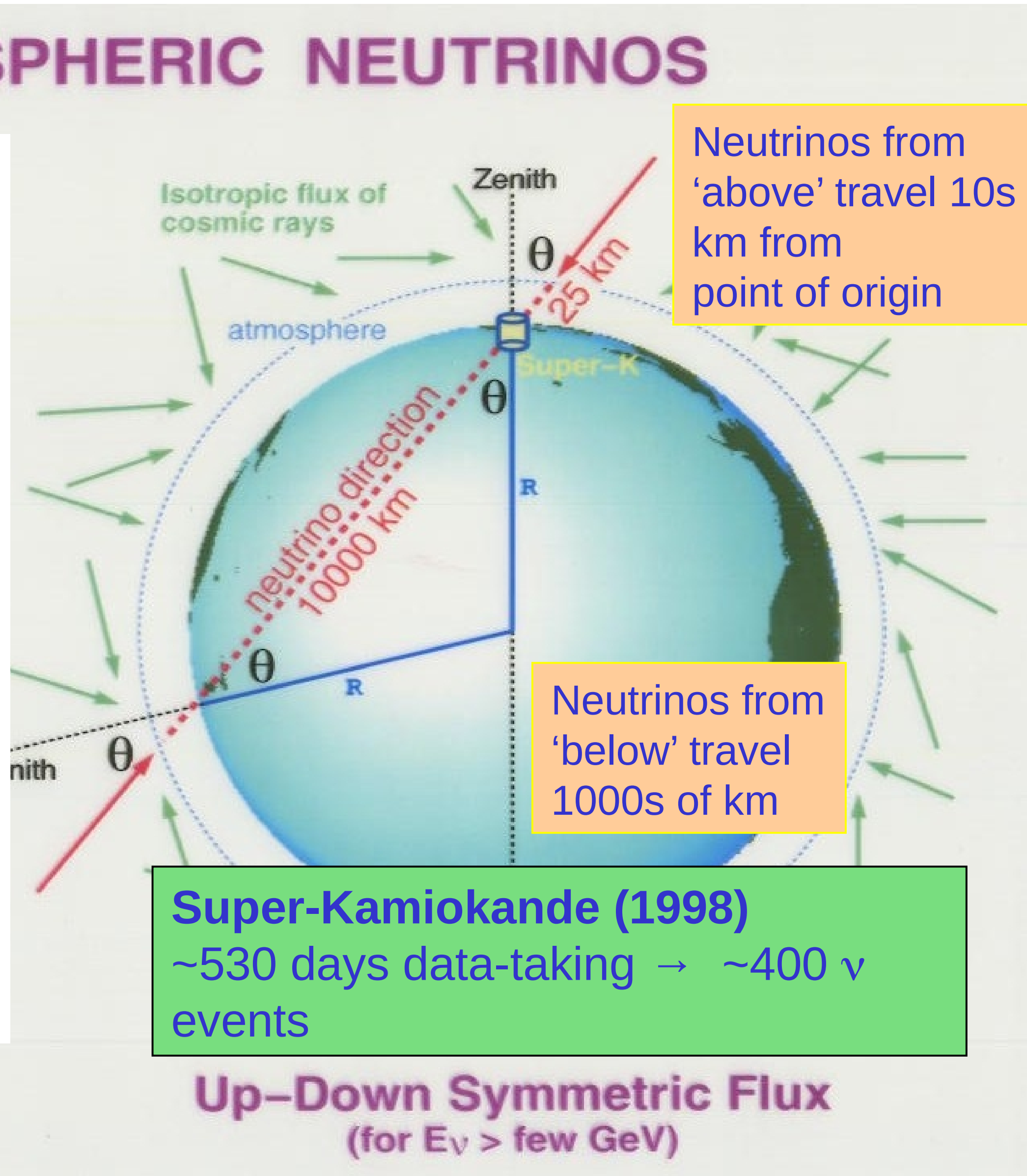
Atmospheric Neutrinos



Kamiokande (1992)

1998: Neutrino Mass!





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 → ~400 ν events

Oscillation Basics

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

where:

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

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)

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

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

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.)
$|\Delta m^2_{32}| = 2.43 \pm 0.13 \times 10^{-3}$ eV^2

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

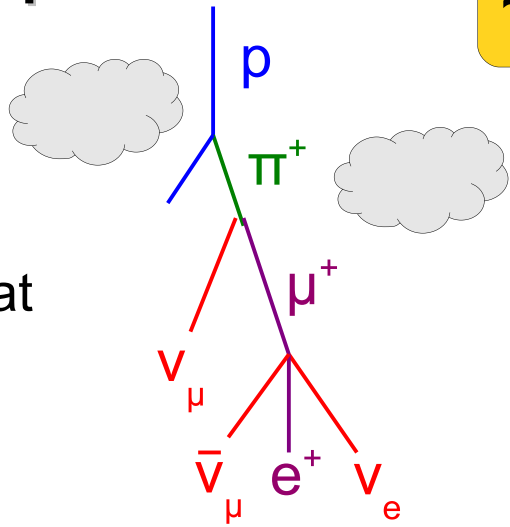
Neutrino Sources

Where do the neutrinos that experiments measure come from?

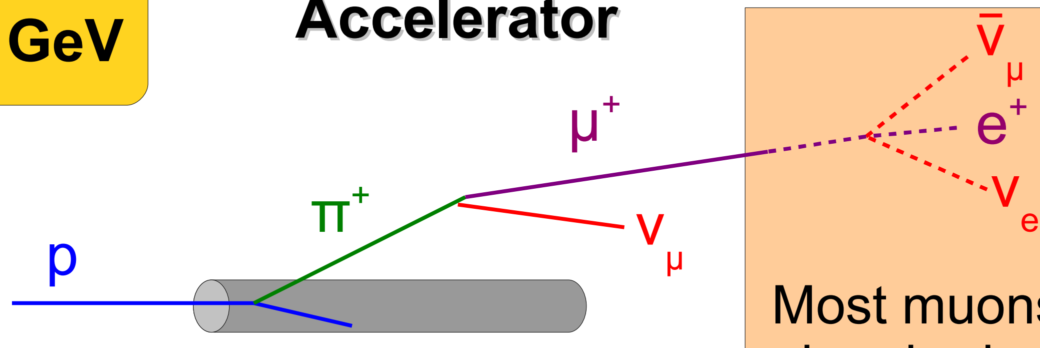
Atmospheric

~1-10 GeV

Cosmic ray showers produce pions and muons that decay to neutrinos



Accelerator

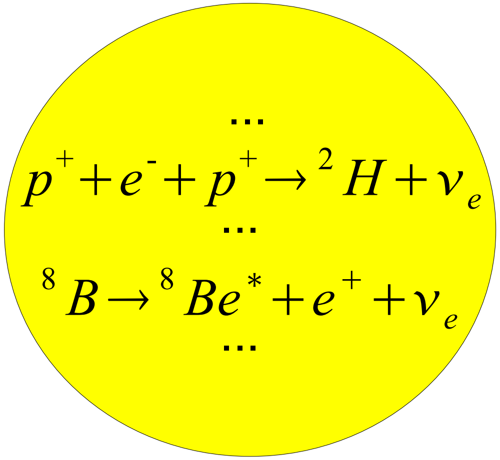


Most muons absorbed before decaying

Proton beam from accelerator collides with fixed target

Solar

~ 10 MeV



Produced in fusion reactions inside sun.

Energy thresholds matter for experiments

Reactor

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

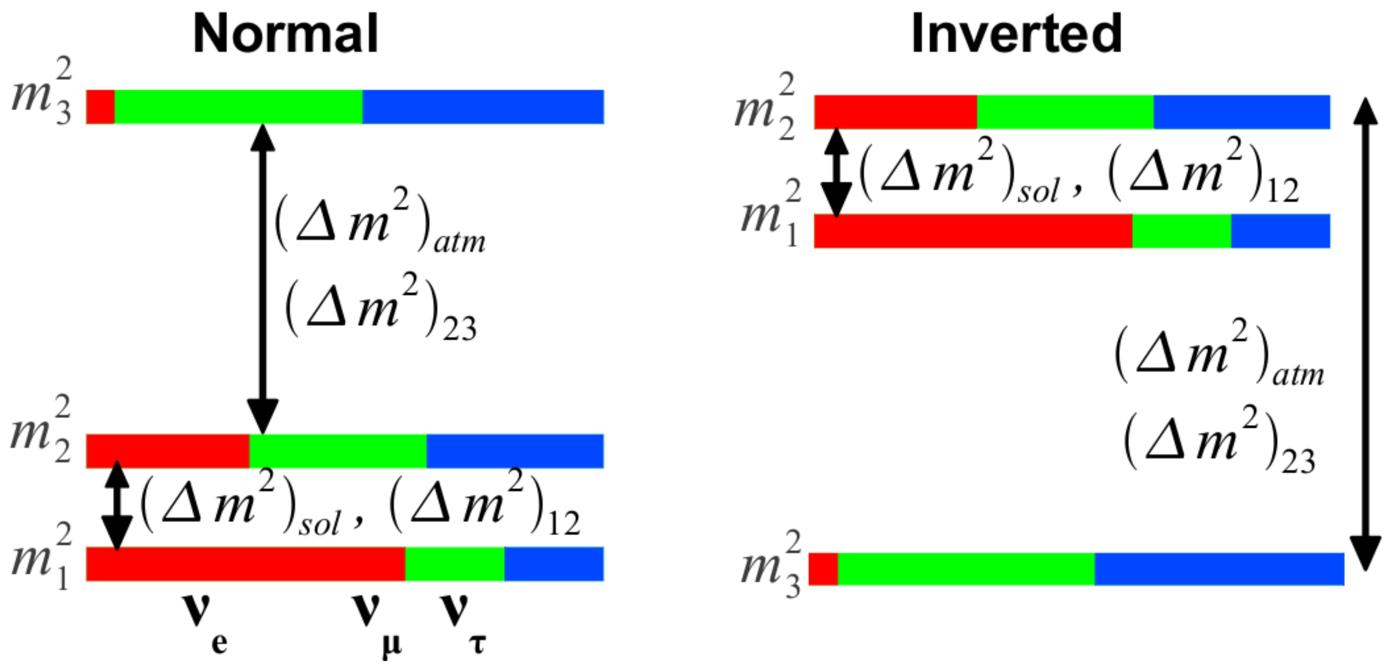
[Some] Open Questions

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 : $\overline{\nu}_e$ disappearance

$$P(\overline{\nu}_e \to \overline{\nu}_e) \approx 1 - \underline{\sin^2(2\theta_{13})} \sin^2\left(\frac{1.27\Delta m^2_{31} L(m)}{E_\nu(MeV)}\right)$$

pure θ_{13} measurement

- Accelerator neutrino experiments : ν_e appearance

$$P(\nu_\mu \to \nu_e) \approx \underline{\sin^2(2\theta_{13})} \sin^2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{31} L(km)}{E_\nu(GeV)}\right)$$

leading term

sub-leading terms

$$+ \quad 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \cdot \sin\Phi_{31} \cdot \sin\Phi_{21}$$ CPC

$$- \quad 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \cdot \sin\Phi_{31} \cdot \sin\Phi_{21}$$ CPV

$$+ \quad 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2\Phi_{21}$$ solar

$$- \quad 8C_{13}^2 S_{13}^2 S_{23}^2 (1 - 2S_{13}^2) \frac{aL}{4E_\nu} \cos\Phi_{32} \sin\Phi_{31}.$$ matter effect

$\delta \to -\delta$
$a \to -a$
for $P(\overline{\nu}_\mu \to \overline{\nu}_e)$

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

CP violating (flips sign for anti-ν)

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

Solar

Matter

where:

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

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

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

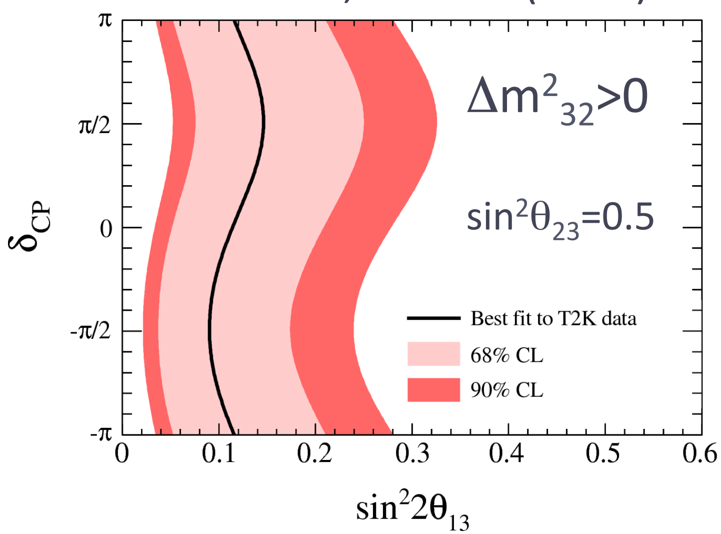
Short baseline reactor: Sensitive only to θ_{13}

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

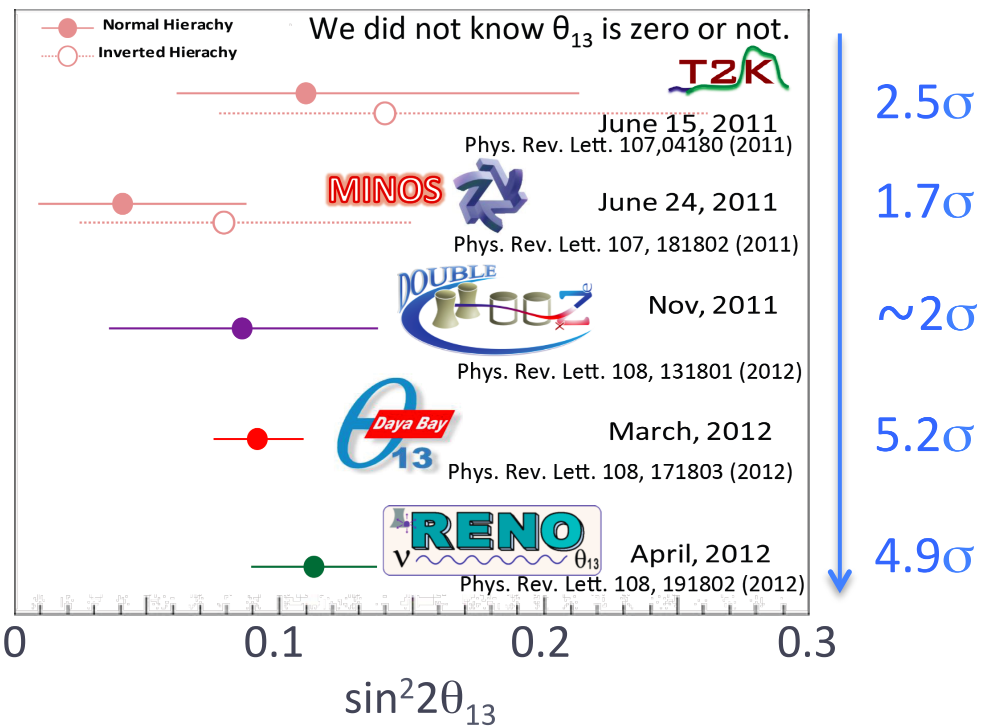
Breakthrough of non-zero θ_{13} search (2011~)

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

PRL 107, 041801 (2011)



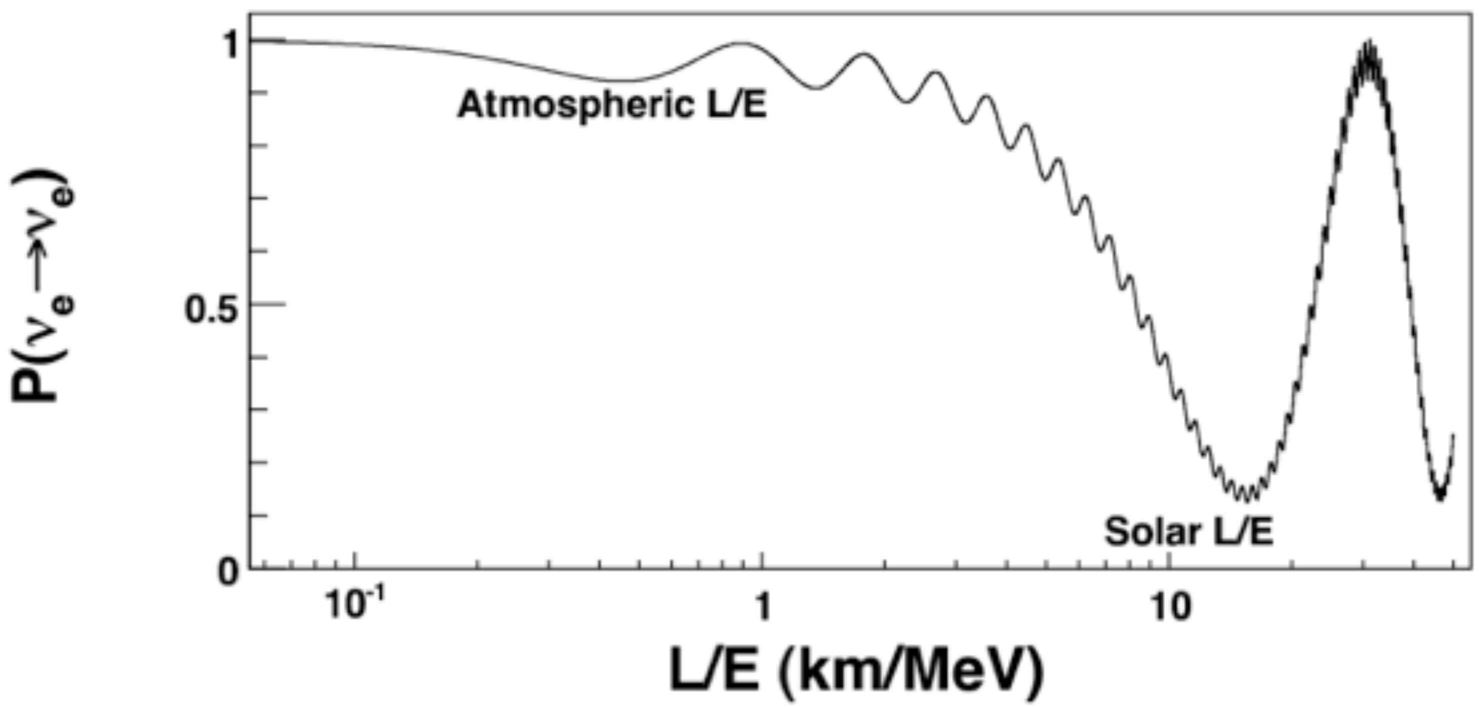
1σ confidence intervals (before Neutrino2012)



- In 2012, solid confirmation by reactor experiments.

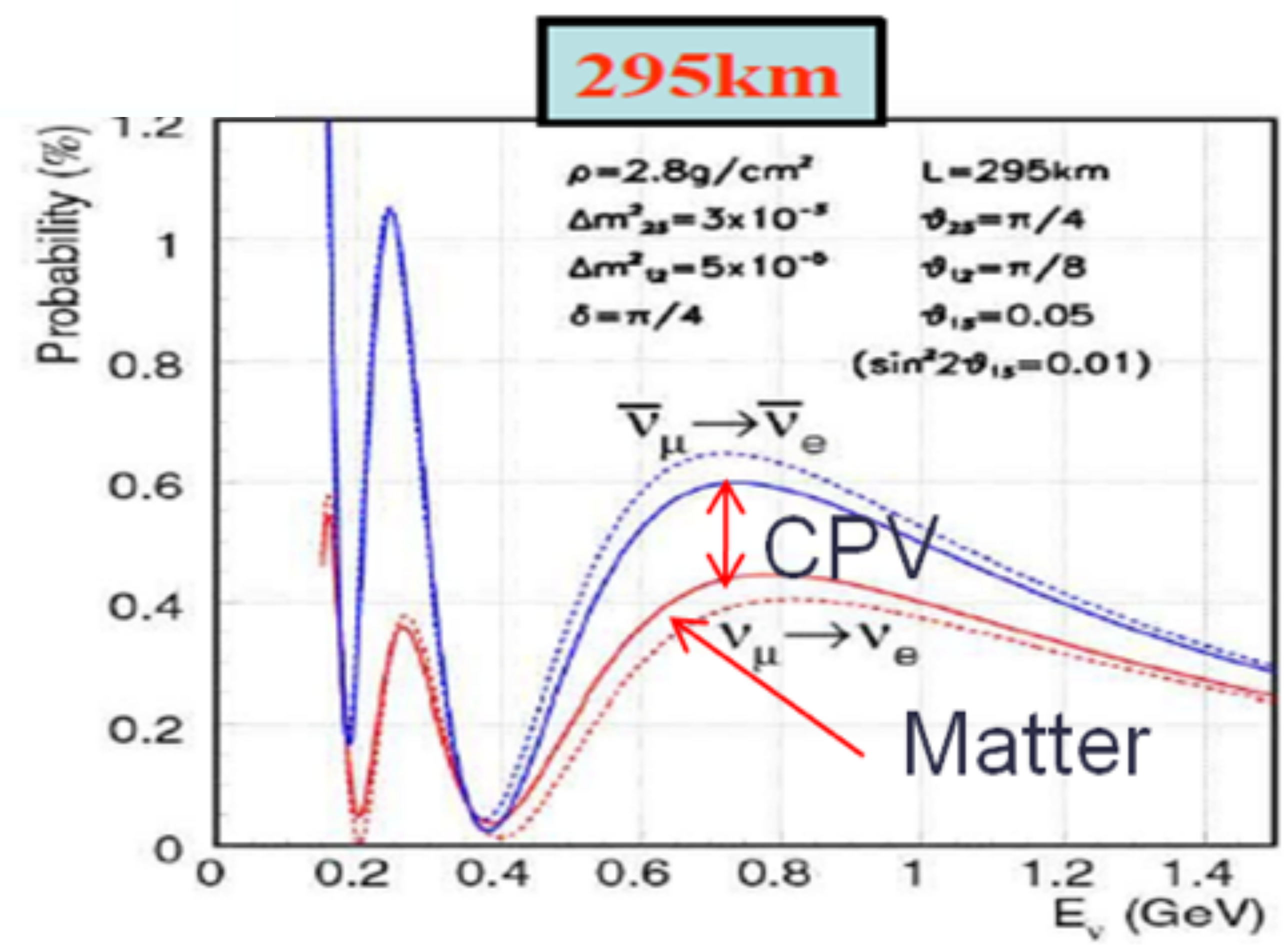
This talk : Updated ν_e appearance analysis using the full T2K data set

How to measure θ_{13}

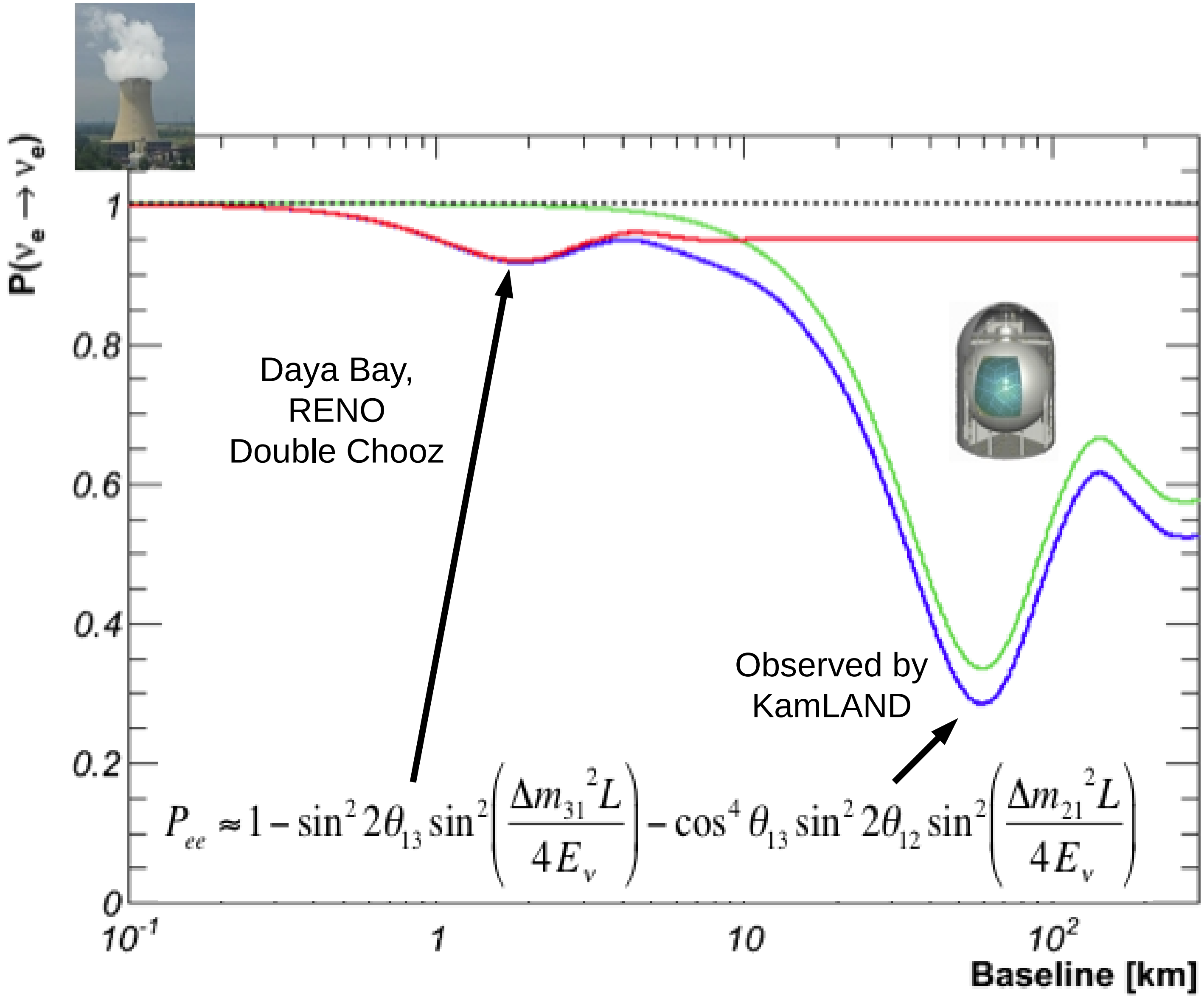


θ_{13} can cause $\bar{\nu}_e$ disappearance in reactor neutrinos

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

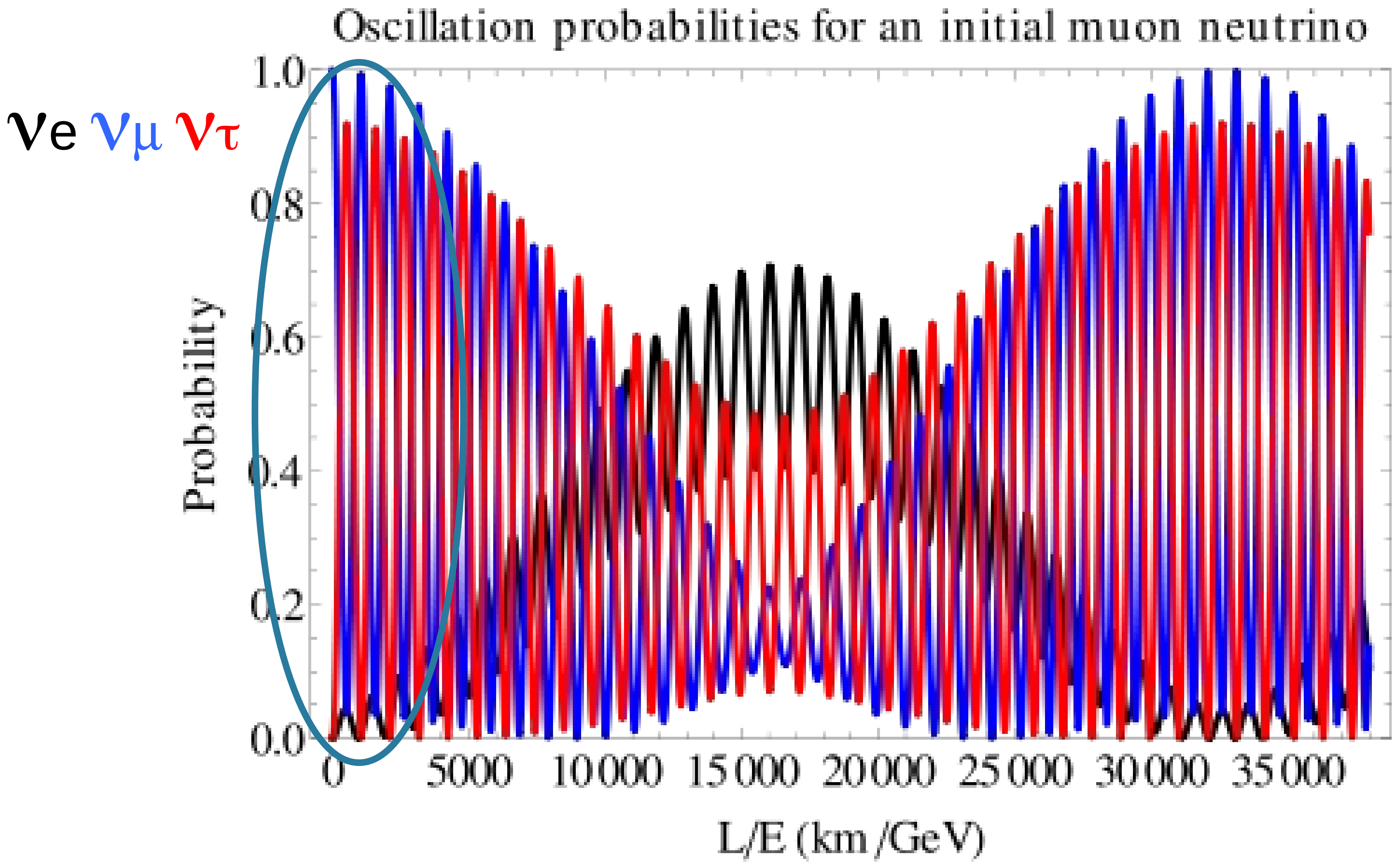


Oscillation @Reactors



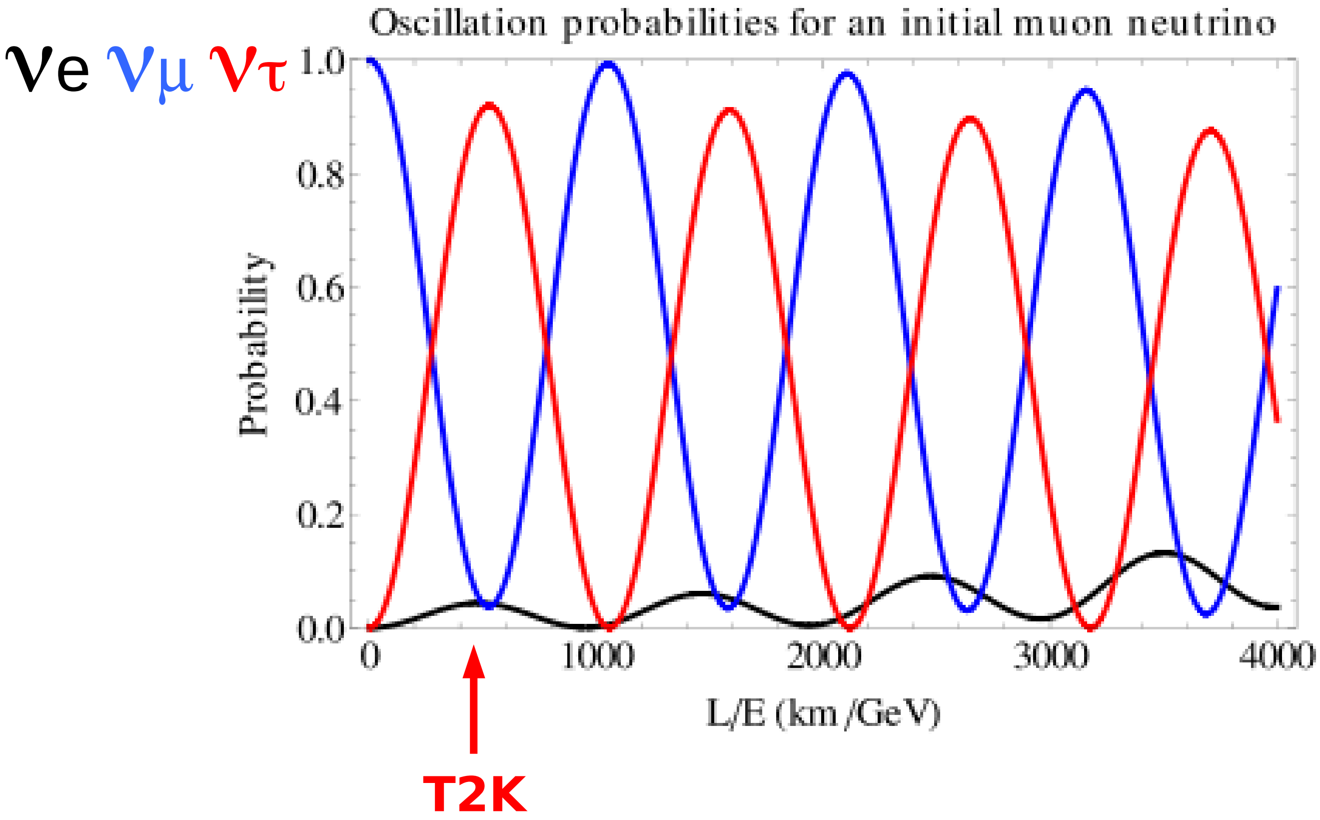
Oscillation @Accelerators

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



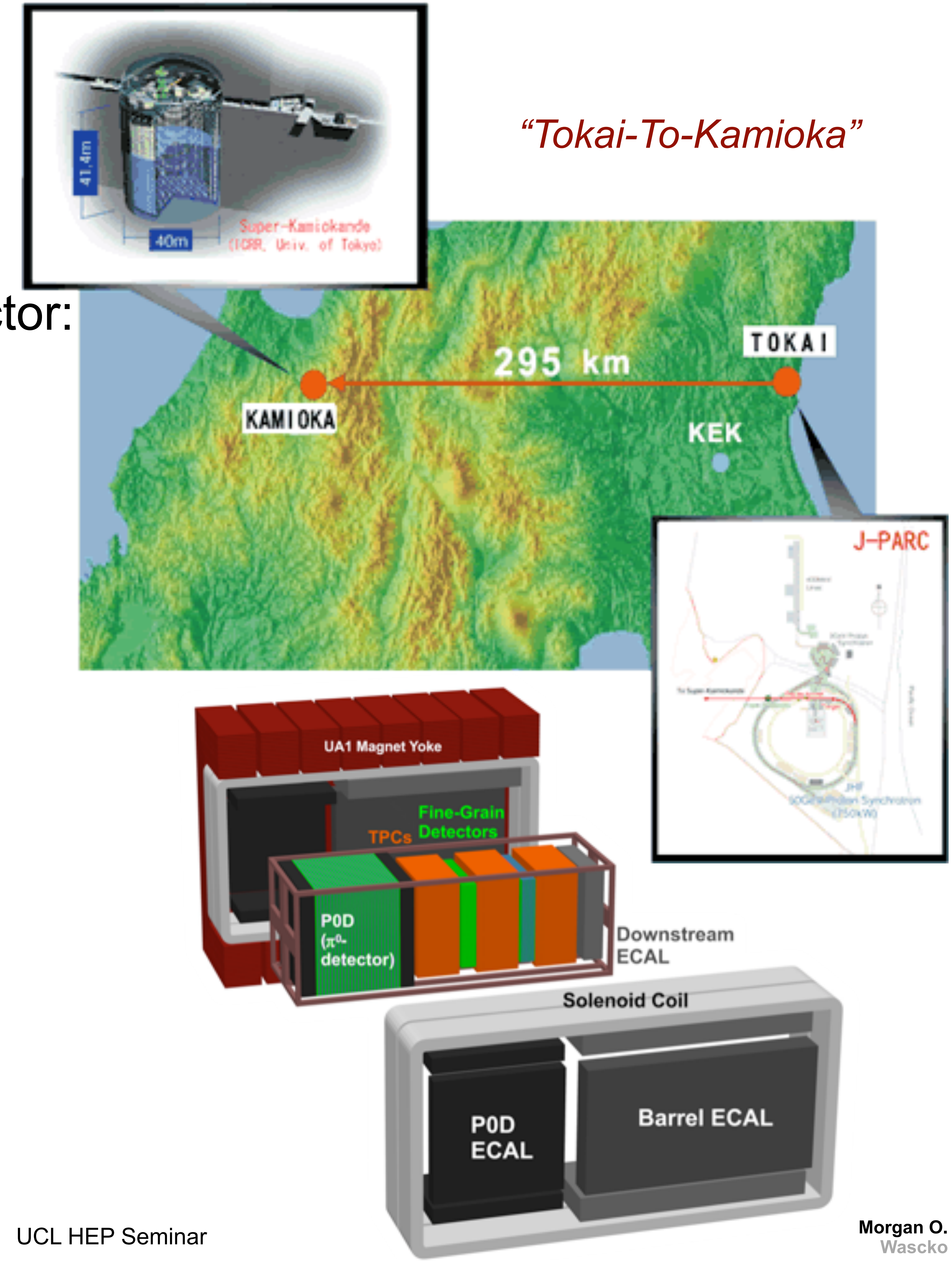
$$P_{\mu\to\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

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


T2K

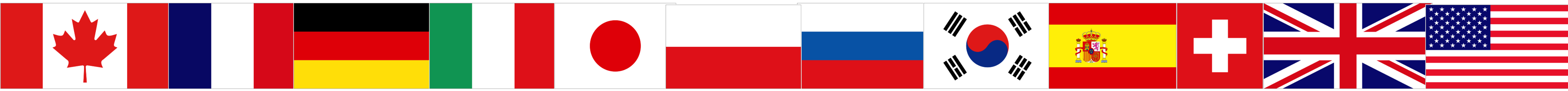
T2K

“Tokai-To-Kamioka”



- Start with world’s largest detector: Super-Kamiokande
- Build new neutrino beam
- Off-axis beam to Super-K
  - L = 295 km
  - E = 0.6 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



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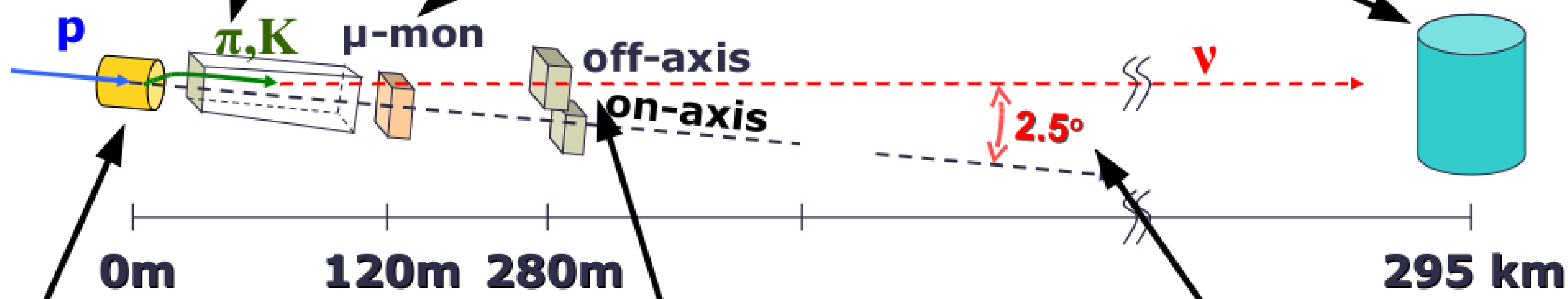
~500 members, 59 Institutes, 12 countries

30 GeV proton beam from J-PARC

Pions, kaons, muons decay in 96 m decay volume

MUMON measures muons from pion decay

Off-axis **far detector** at 295 km: Super-Kamiokande (SK) water cherenkov detector measures oscillated flux



Off-axis = narrow band beam

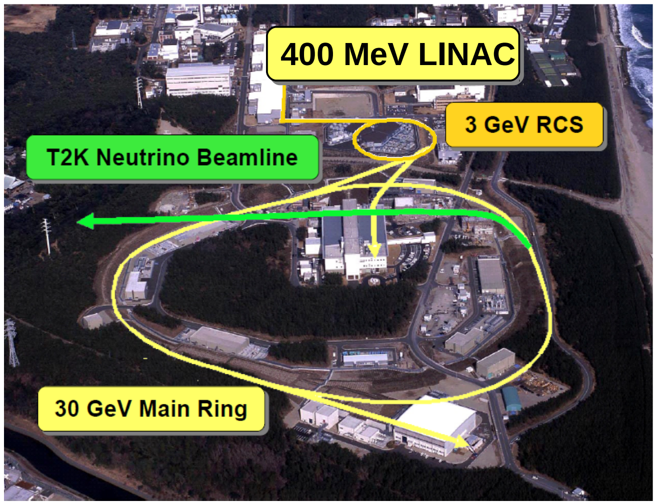
Beam on graphite target

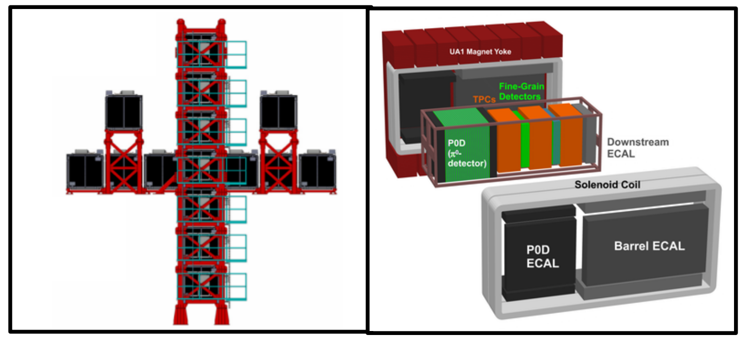
3 magnetic horns focus positively charged hadrons

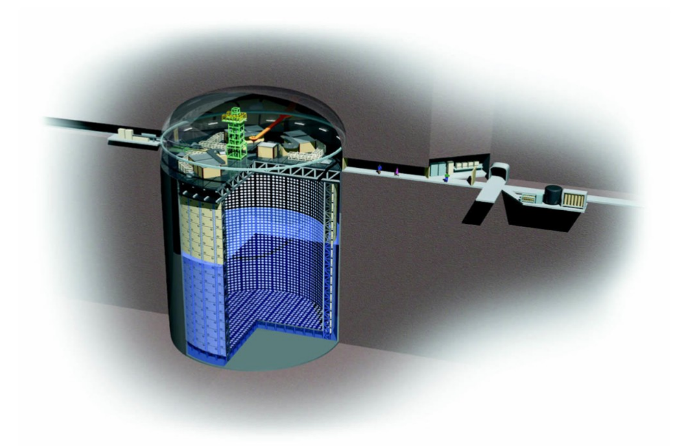
At 280 m, on-axis INGRID detector measures neutrino rate, beam profile

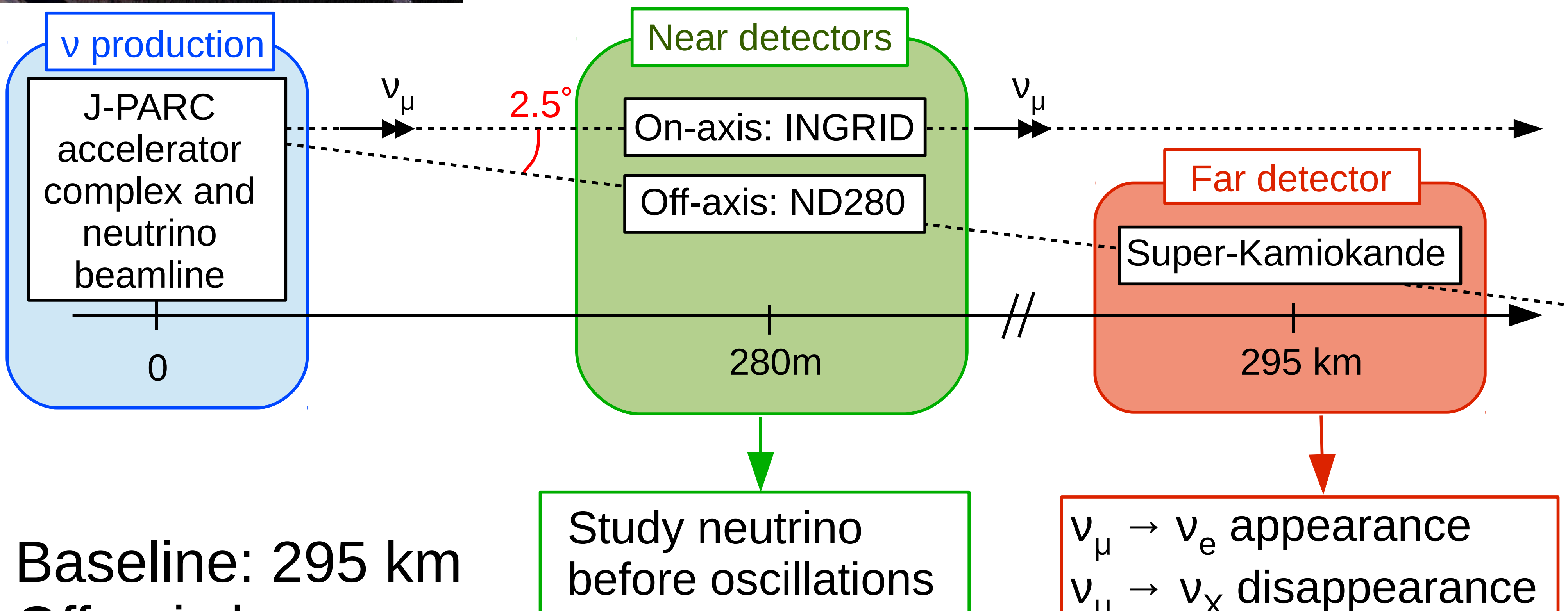
Off-axis **near detector**: ND280 detector measures spectra for various neutrino interactions

The T2K experiment Overview





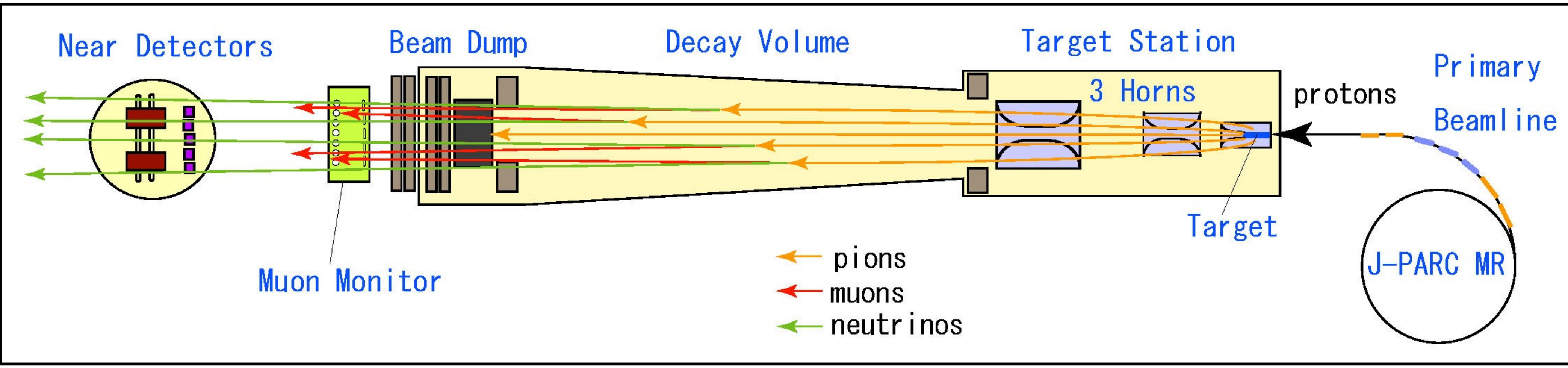




- Baseline: 295 km
- Off-axis beam

The T2K experiment
Neutrino production

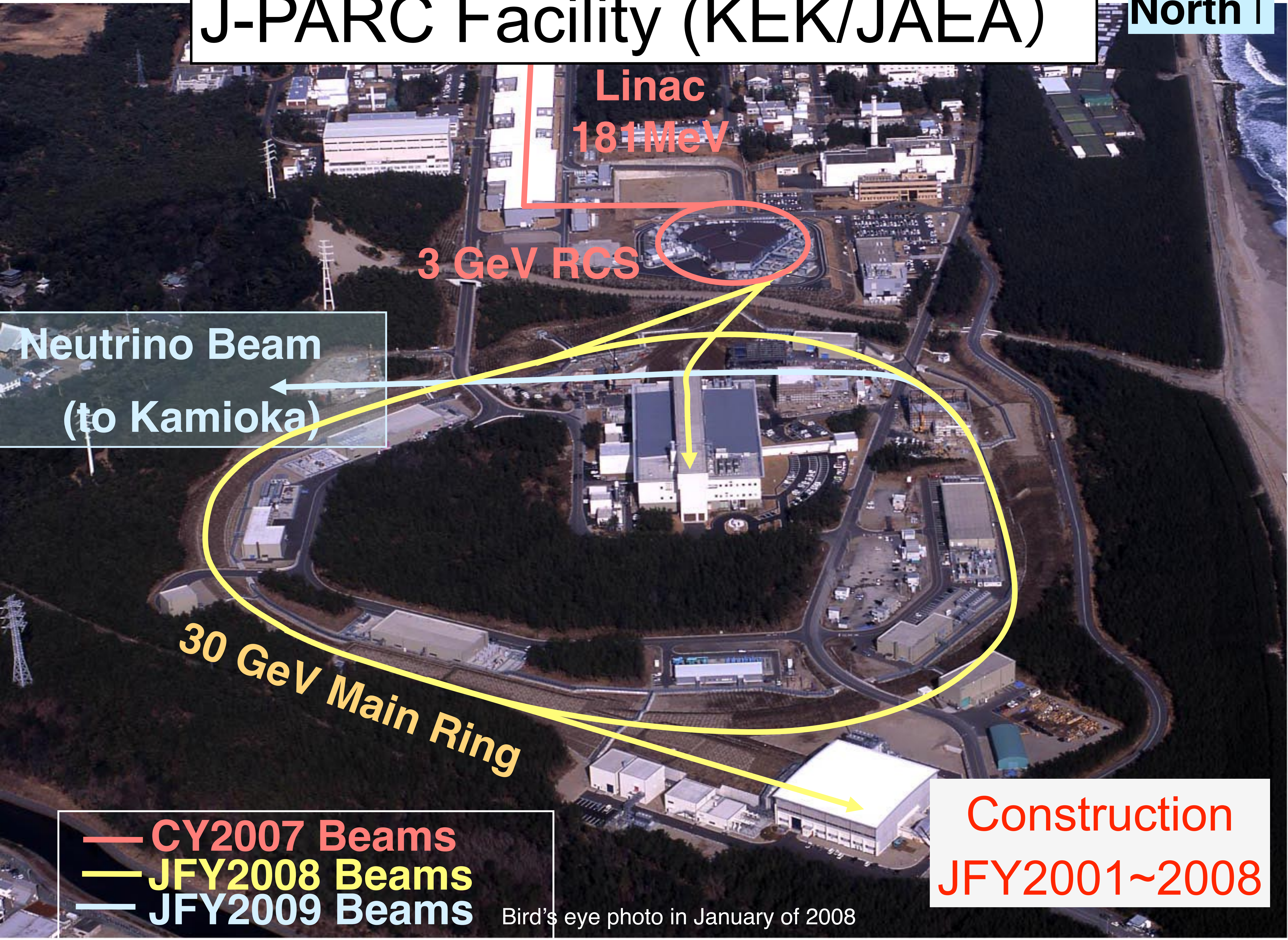
Conventional neutrino beam produced from 30 GeV protons



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

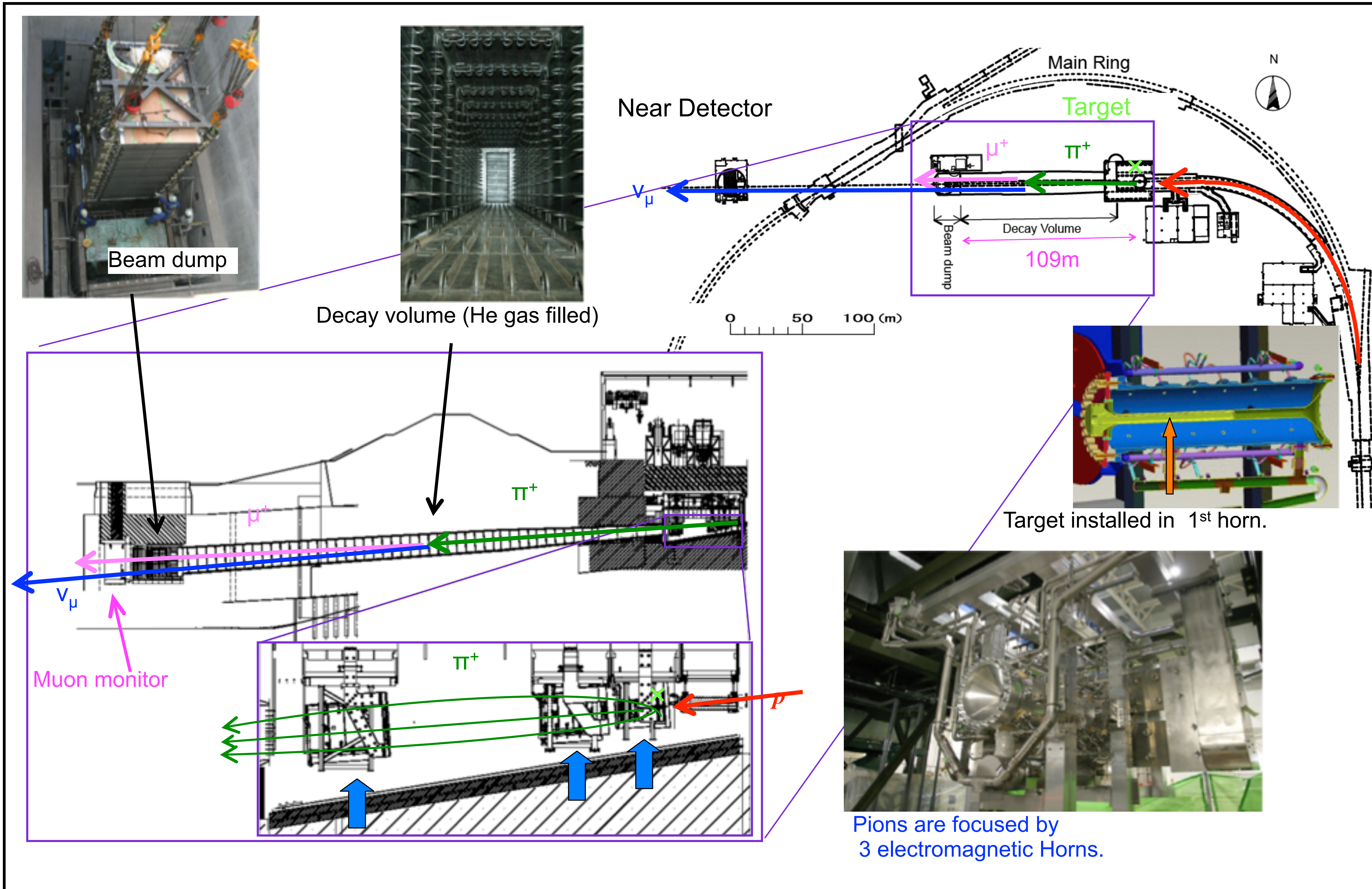
Can switch from ν_μ beam to $\bar{\nu}_\mu$ beam by inverting the horn polarities

J-PARC Facility (KEK/JAEA)



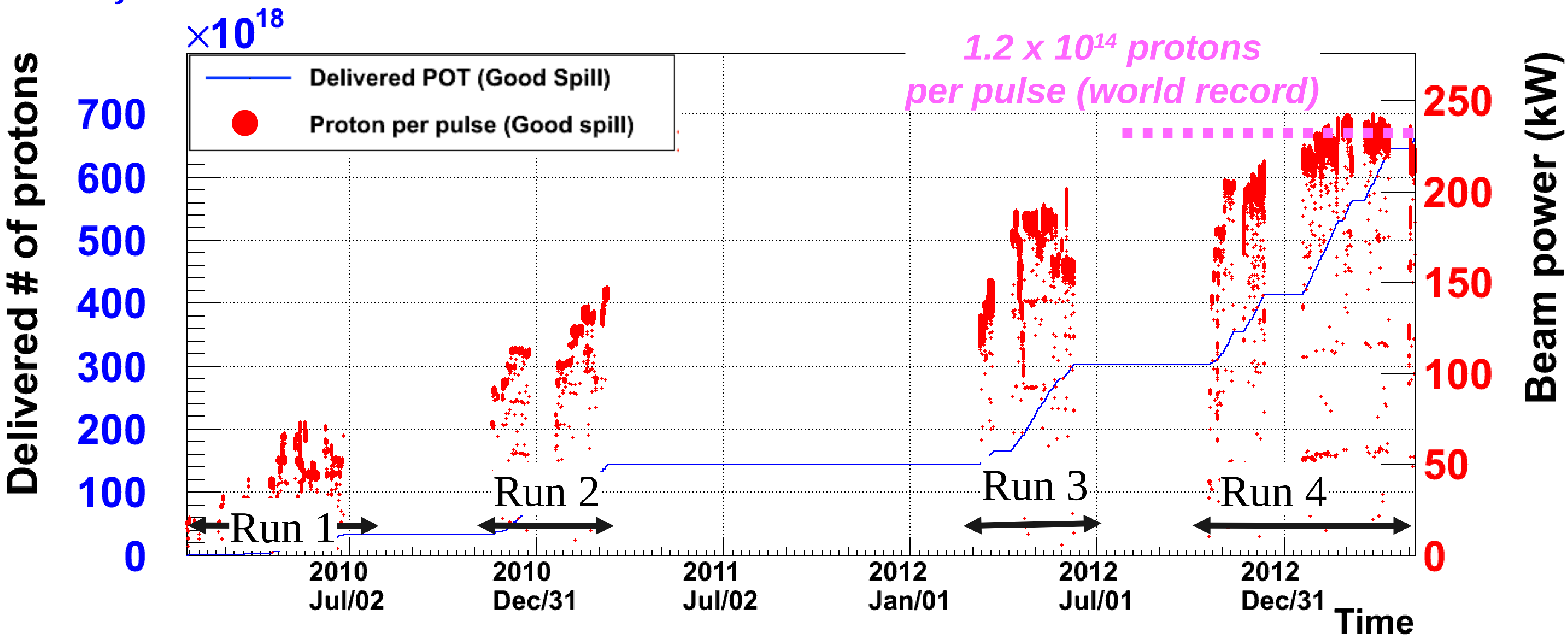
Bird’s eye photo in January of 2008

J-PARC neutrino beamline overview



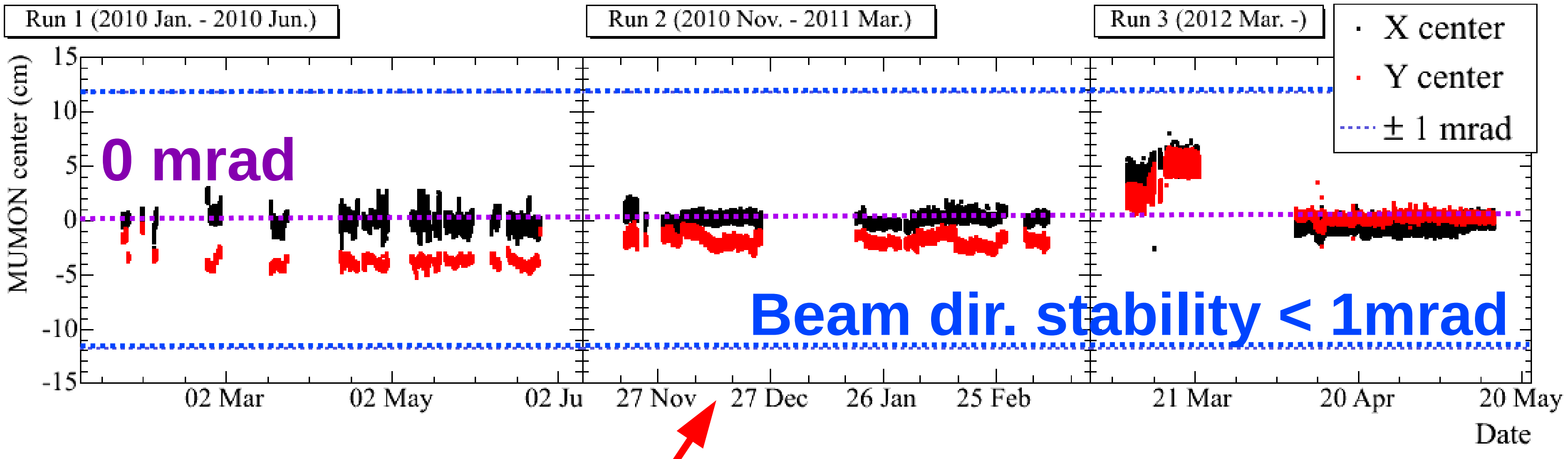
T2K Data Taking

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

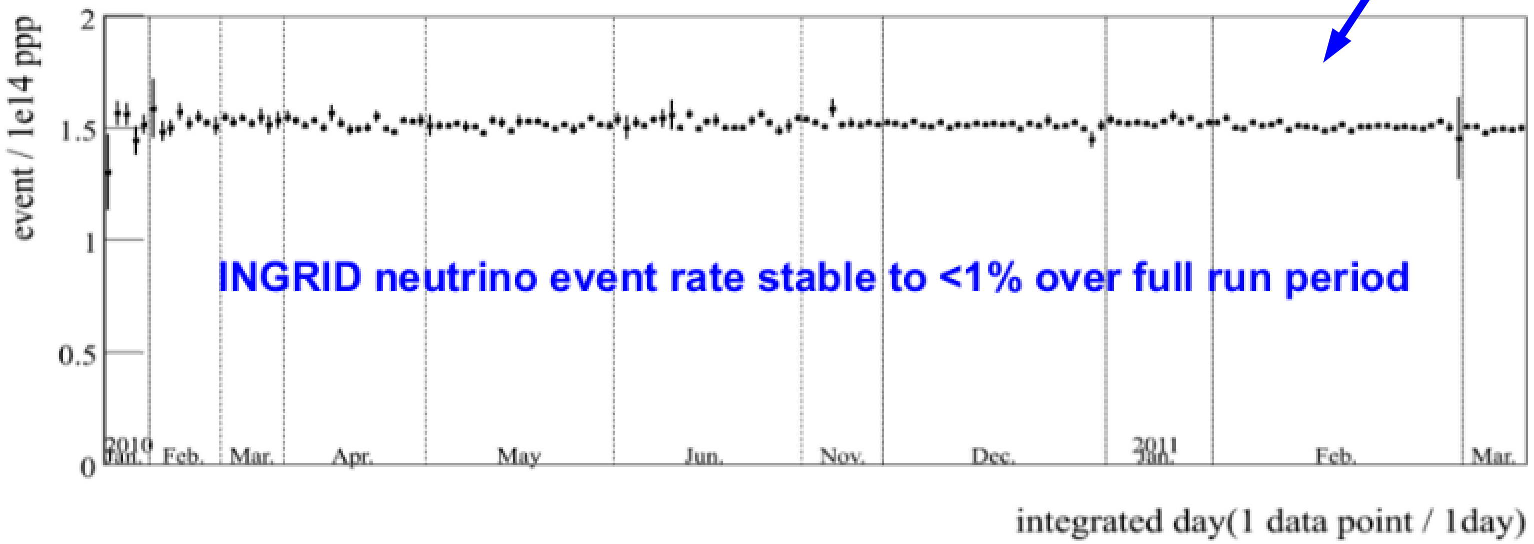


- **NEW!** Full Run 1 – 4 data sets published this week! Phys. Rev. Lett. **107:041801** (Feb 10th)
  - Featured in an APS "Viewpoint" article (http://physics.aps.org/articles/v7/15)
- Total exposure at far detector is 6.57 x 10^{20} P.O.T.
  - Previous ν_e appearance result (2012) used 3.01 x 10^{20} 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 x 10^{14} protons per pulse) → **World record!**

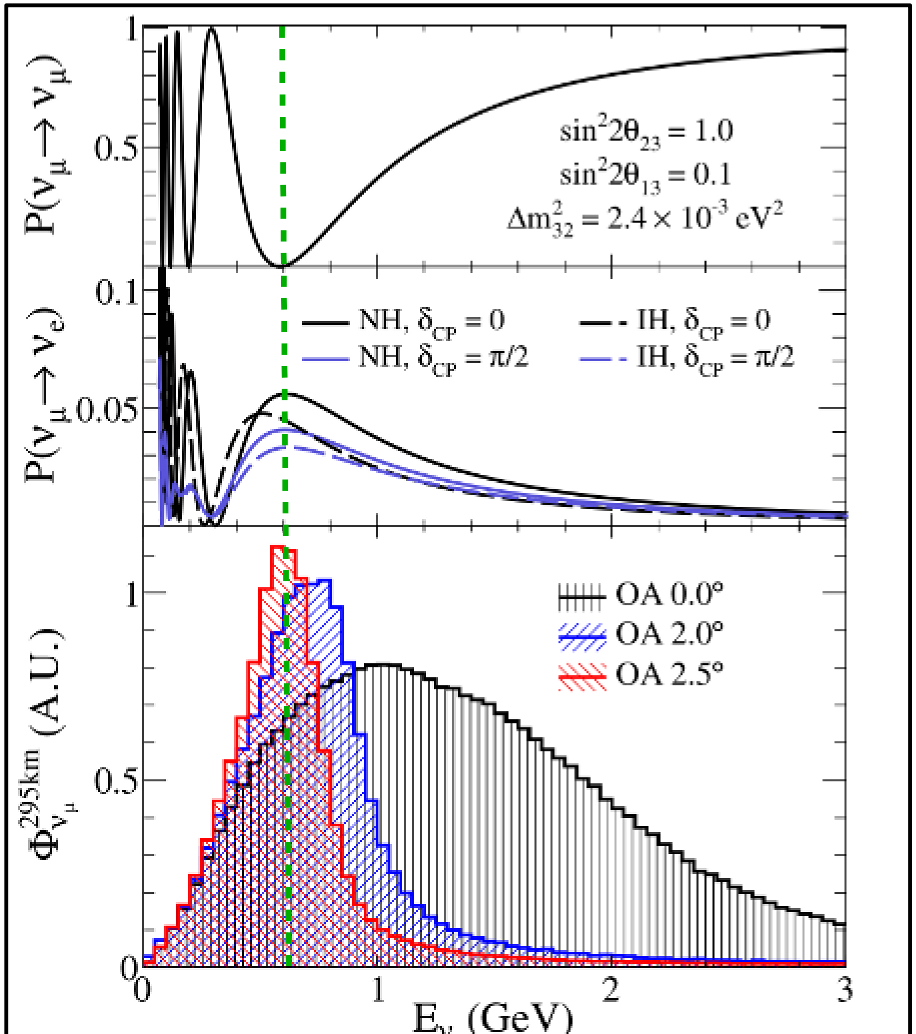
Beam Stability: Rate & Direction

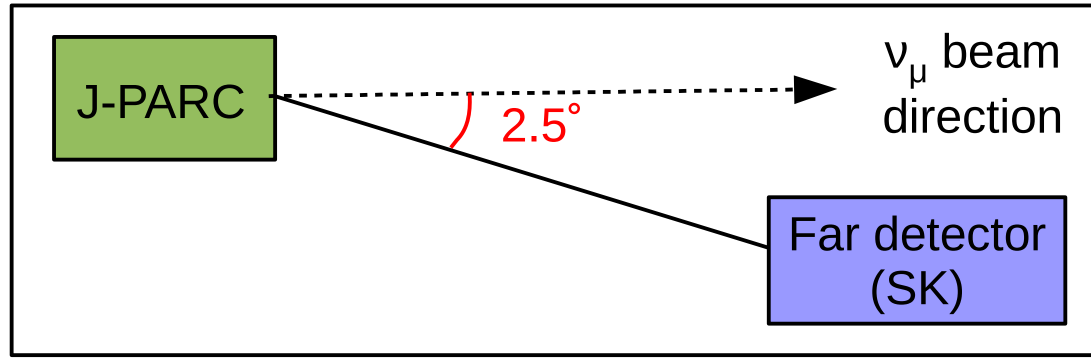


Beam is quite stable in **space** (1 mrad tolerance) and **time** (within 1%)



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 ($\pi \to \mu\nu_\mu$). The energy of the neutrino in the pion rest frame (in which quantities are labeled with the superscript $*$) is

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

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

$$\begin{pmatrix} \\ p_\mu \\ \\ \end{pmatrix} \to \begin{bmatrix} \gamma_\pi & 0 & 0 & \gamma_\pi\beta_\pi \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \gamma_\pi\beta_\pi & 0 & 0 & \gamma_\pi \end{bmatrix} \begin{pmatrix} \\ p_\mu \\ \\ \end{pmatrix} \tag{1.24}$$

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

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:

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

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

$$\tan\theta \simeq \frac{E_\nu^* \sin\theta^*}{E_\nu} \tag{1.27}$$

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

$$\tan\theta_{max} \simeq \frac{E_\nu^*}{E_\nu} \tag{1.28}$$

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

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

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

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

, 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.

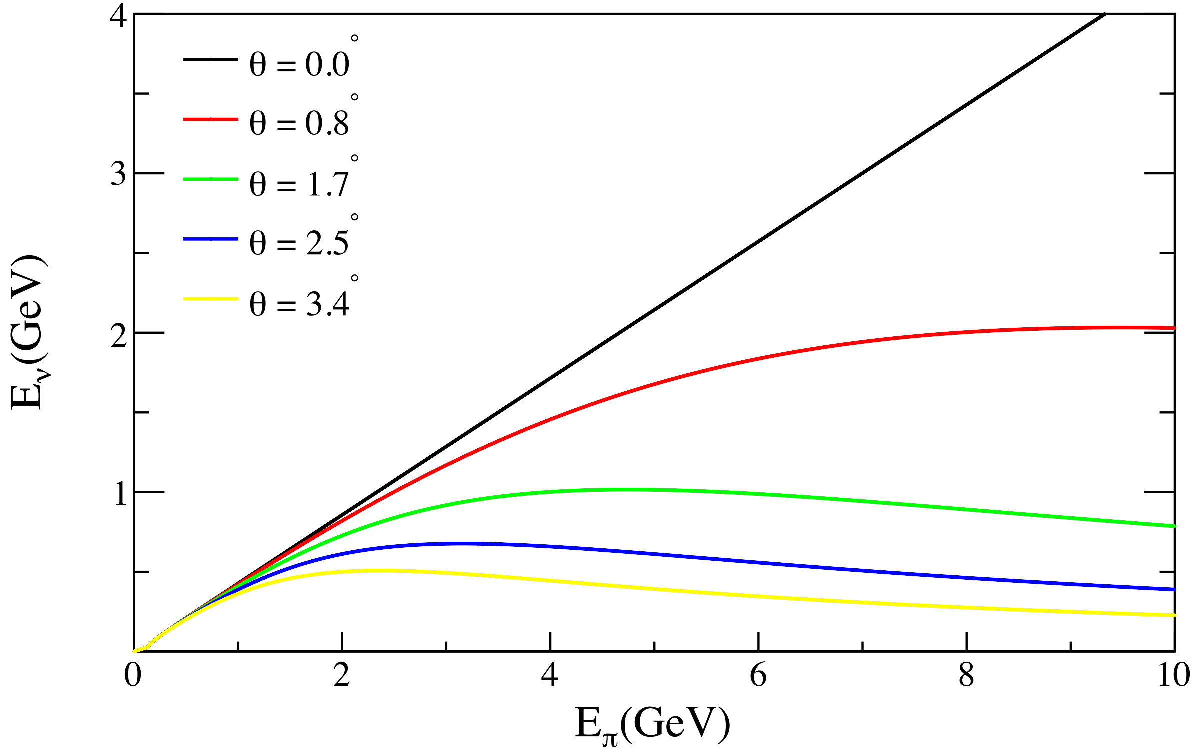


Figure 1.4: Relation between neutrino energy (E_ν) and pion energy (E_π) in the pion decay with several off-axis angles.

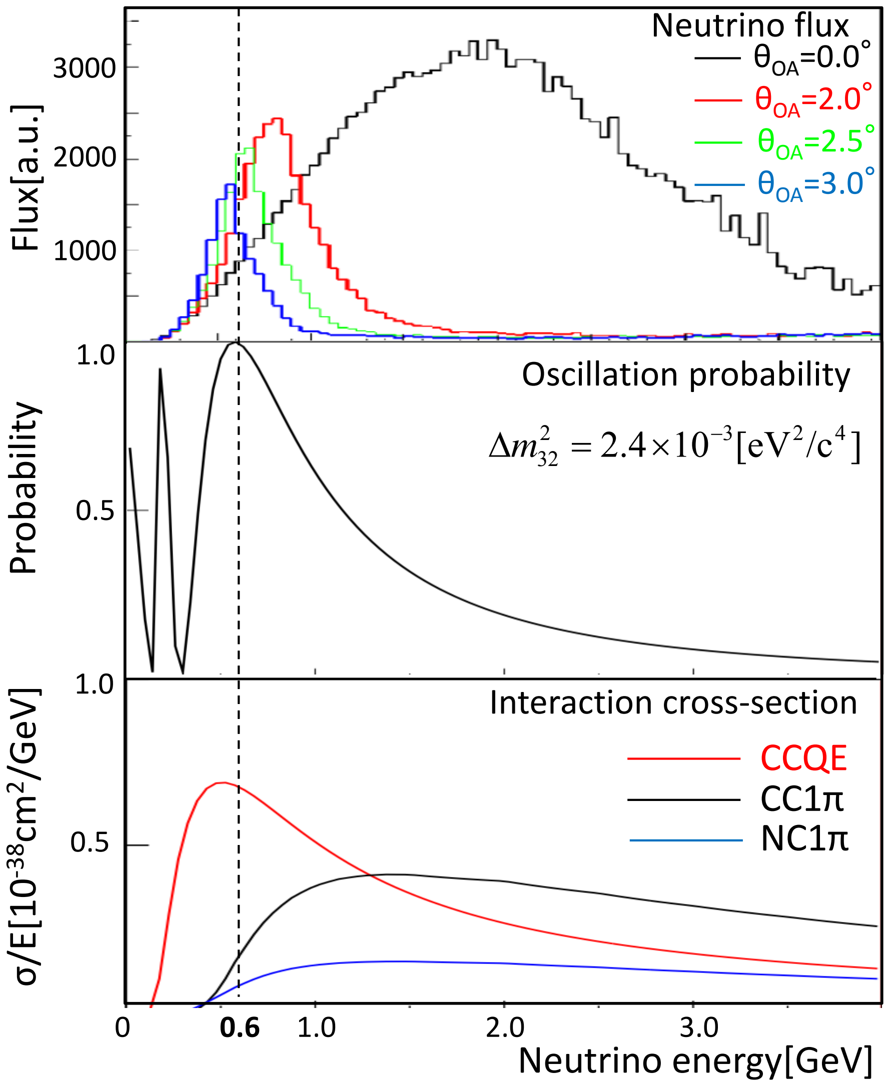


Figure 1.5: (Top) Neutrino energy spectra with several off-axis angles (θ_{OA}). (Middle) Oscillation probability as a function of the neutrino energy. (Bottom) Neutrino interaction cross-sections.

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,

$$\nu_\ell + n \to \ell^- + p \tag{1.31}$$

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):

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

  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 ($N_{\mathrm{SK}}^{\mathrm{exp.}}$) is calculated by using the number of events measured in the near detector ($N_{\mathrm{ND}}^{\mathrm{obs}}$):

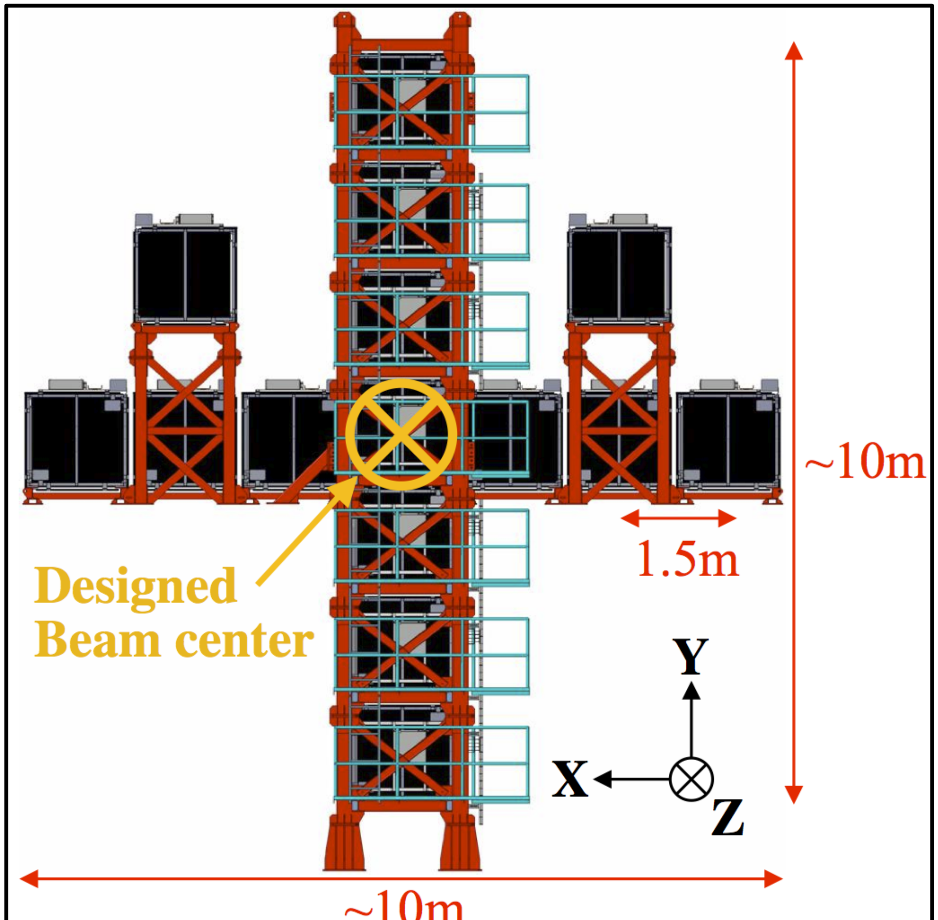
$$\begin{aligned} N_{\mathrm{SK}}^{\mathrm{exp}} &= N_{\mathrm{ND}}^{\mathrm{obs}} \cdot \frac{N_{\mathrm{SK}}^{\mathrm{MC}}}{N_{\mathrm{ND}}^{\mathrm{MC}}} \\ &= N_{\mathrm{ND}}^{\mathrm{obs}} \cdot \frac{\int dE_\nu \Phi_{SK} \cdot \sigma_{SK} \cdot \epsilon_{SK} \cdot P(E_\nu; \sin^2 2\theta_{23},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

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 $N_{\mathrm{SK}}^{\mathrm{exp.}}$ estimation.

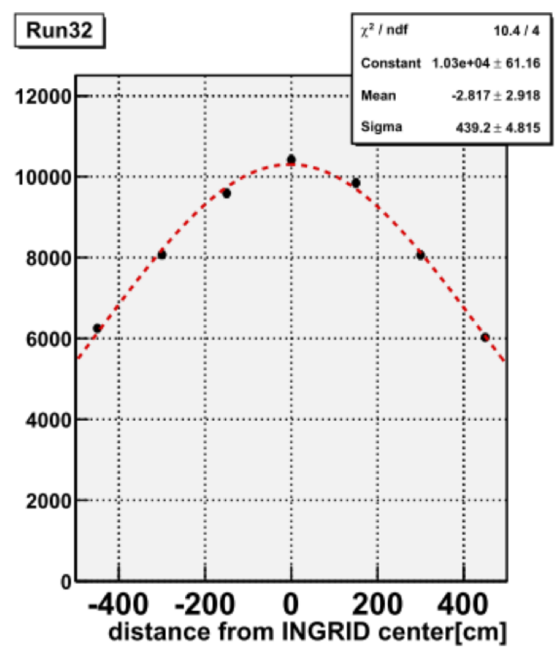
An analysis of the neutrino oscillation in ν_e appearance is performed with almost same procedure; the beam direction measurement is also important for this analysis.

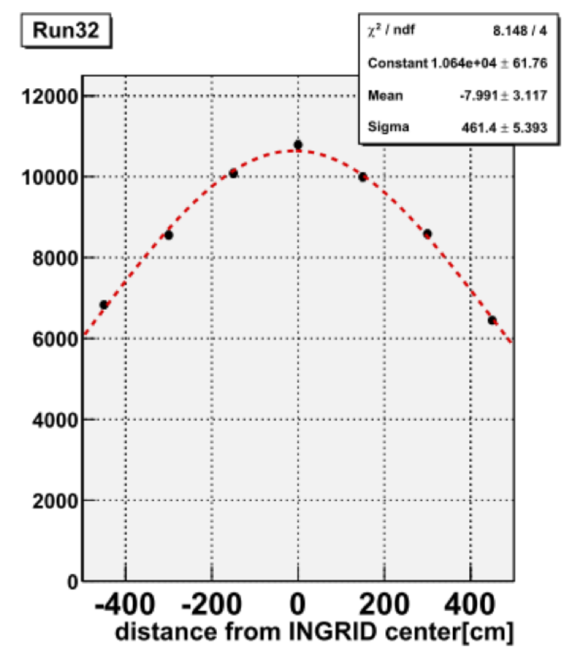
The T2K experiment
Near detectors

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



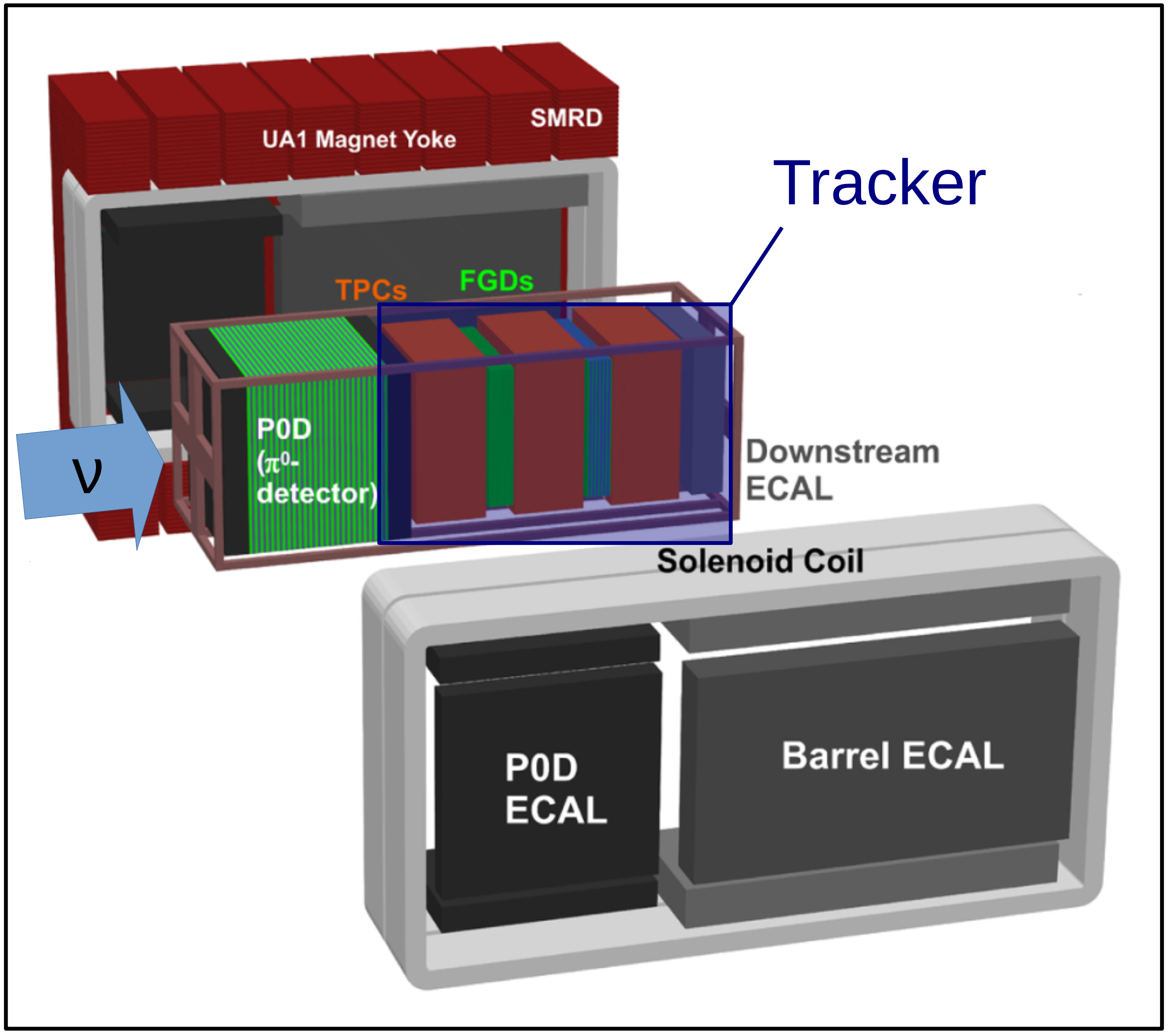
- 16 identical modules made of iron and scintillators
- 'counting neutrinos' by reconstructing muon tracks from ν_μ interactions
- Monitors neutrino beam: rate, direction and stability



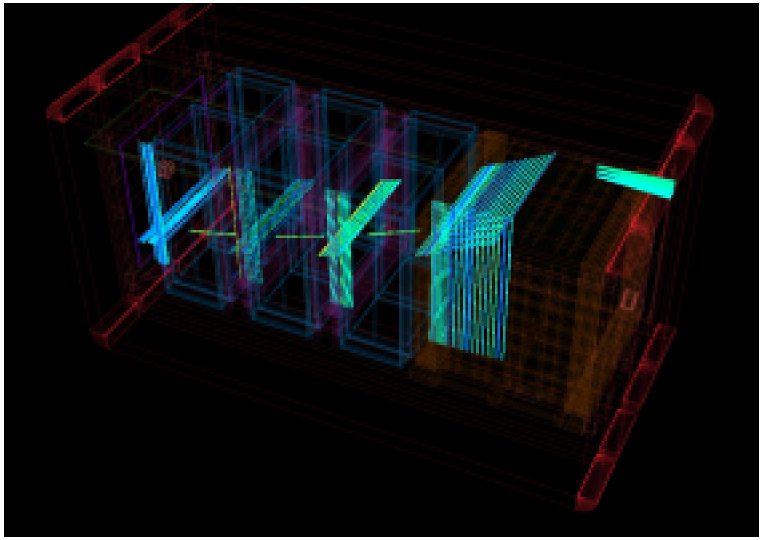


The T2K experiment
Off-axis near detectors

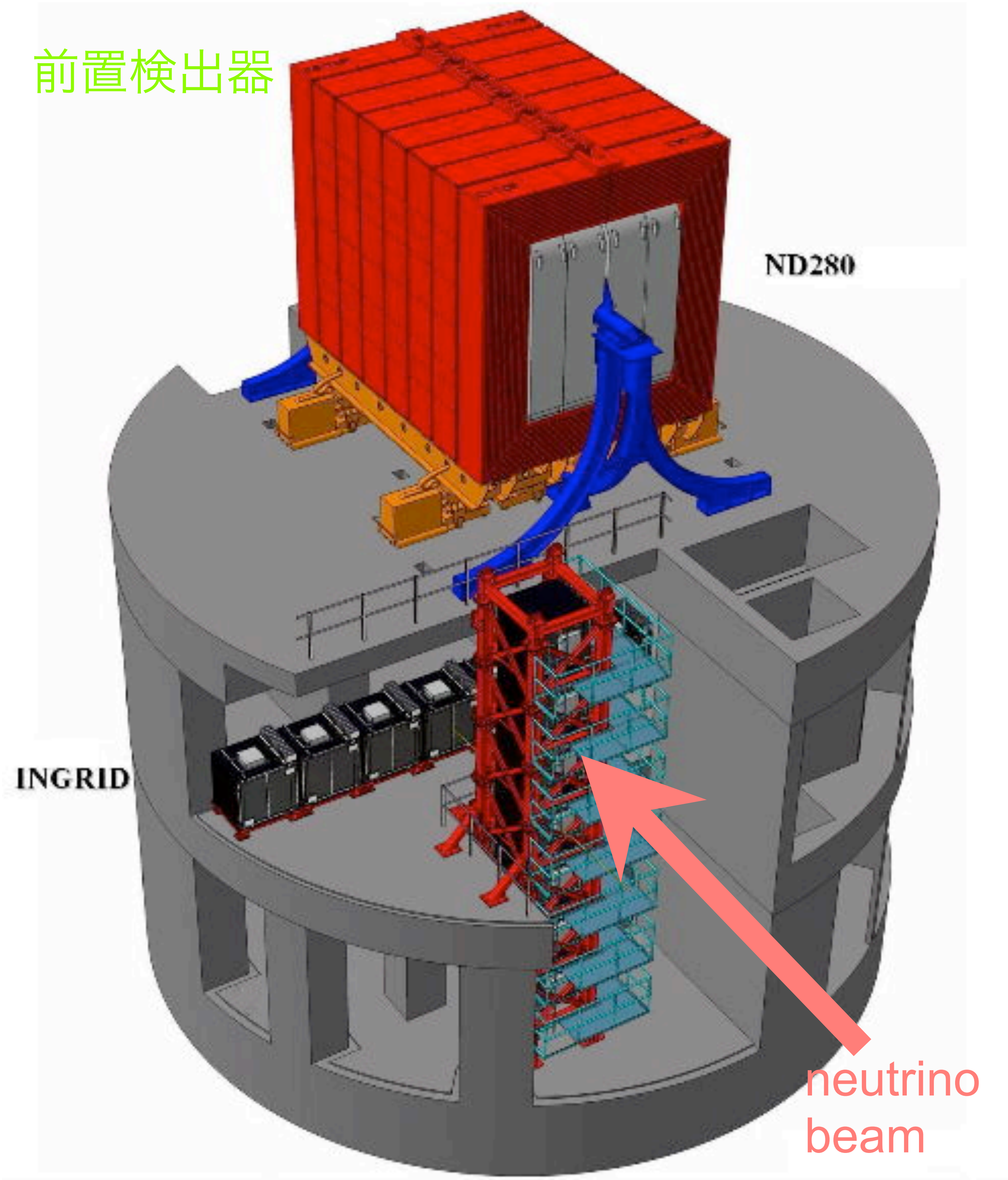
Off-axis near detector ND280
Located 280m from the target



- 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



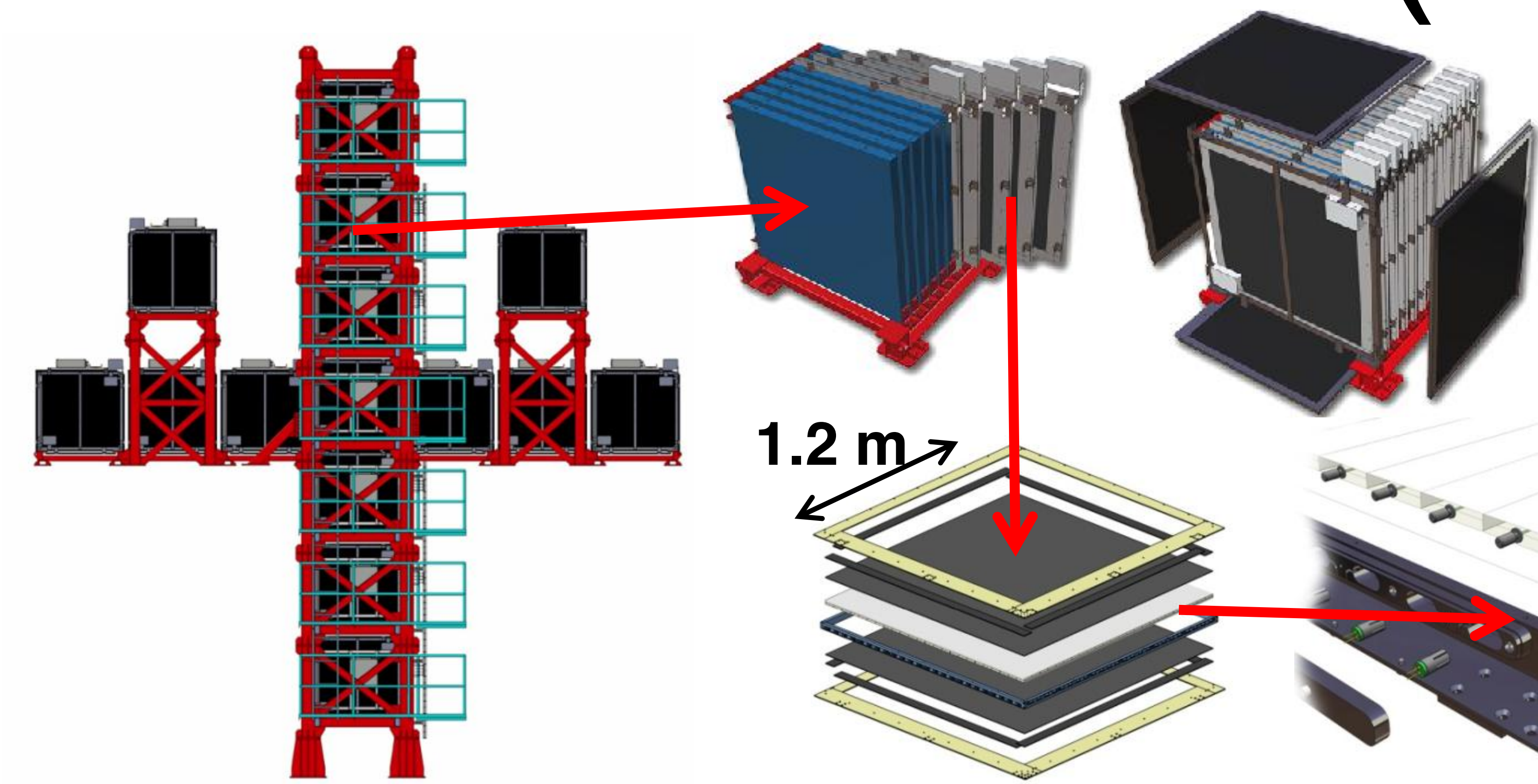
Near Detectors



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

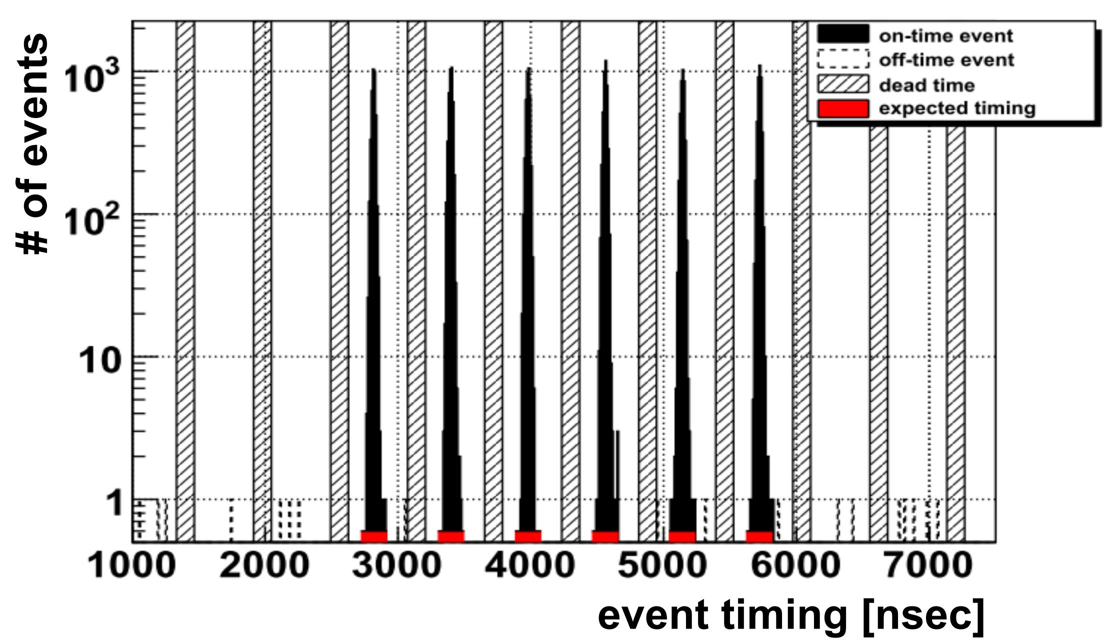
ND280 on-axis (INGRID)



First large scale application of MPPC (~56,000 MPPCs are used for ND280 /INGRID)

~10,800 ch. in INGRID

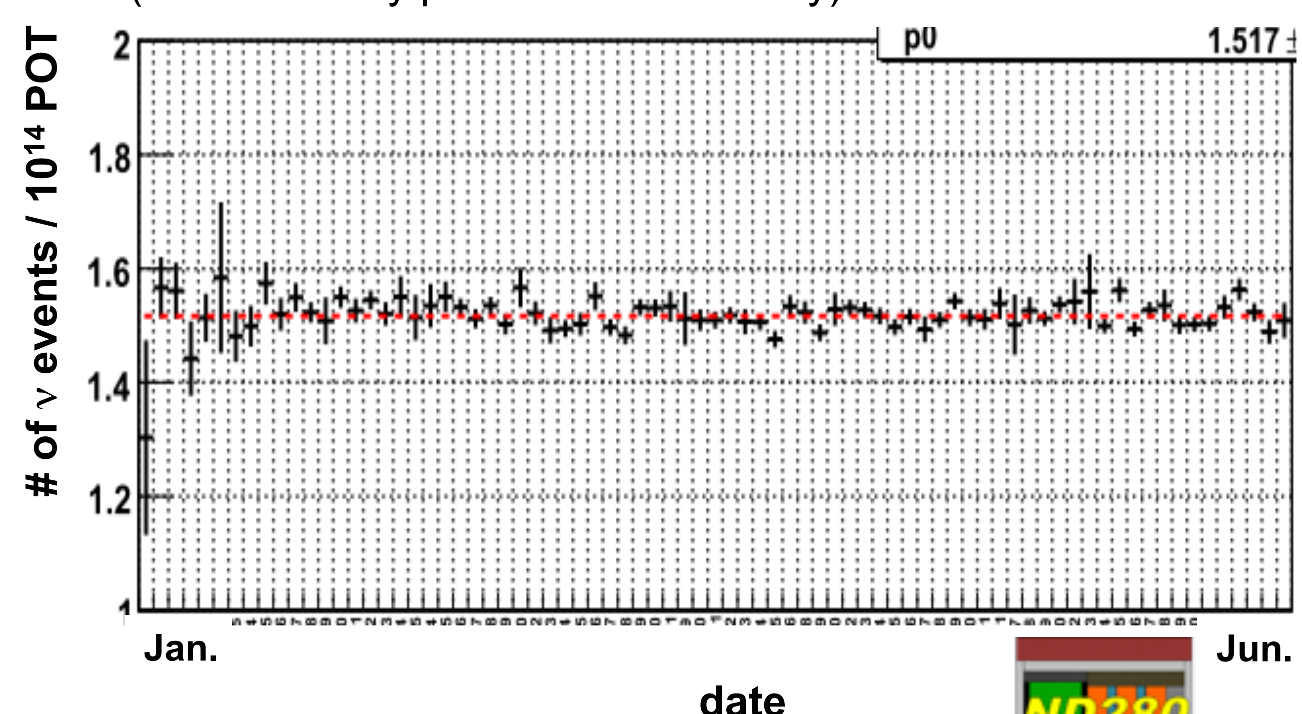
Event timing of ν events



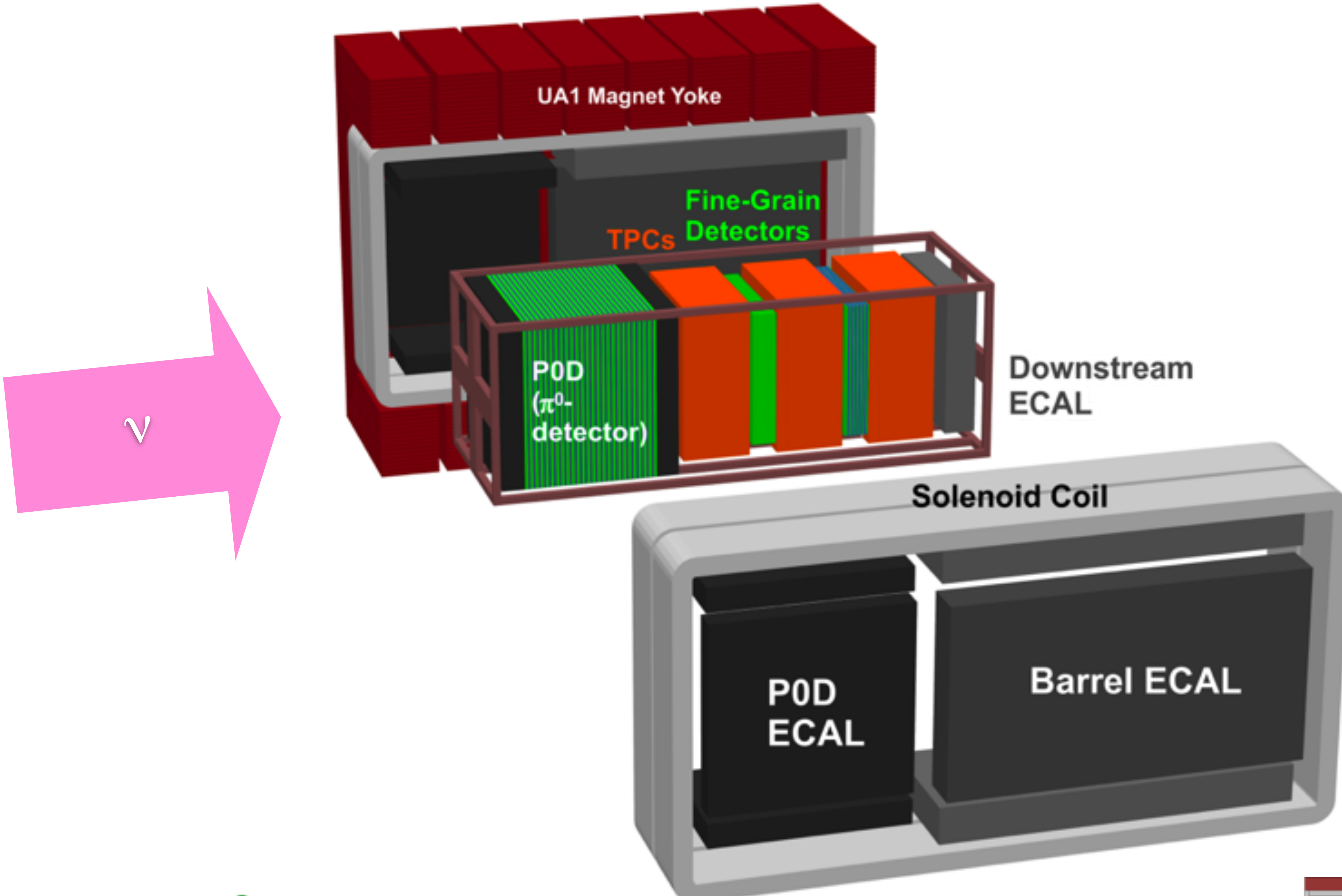
→ Clear 6 bunch structure (581 ns bunch period)

ν beam intensity

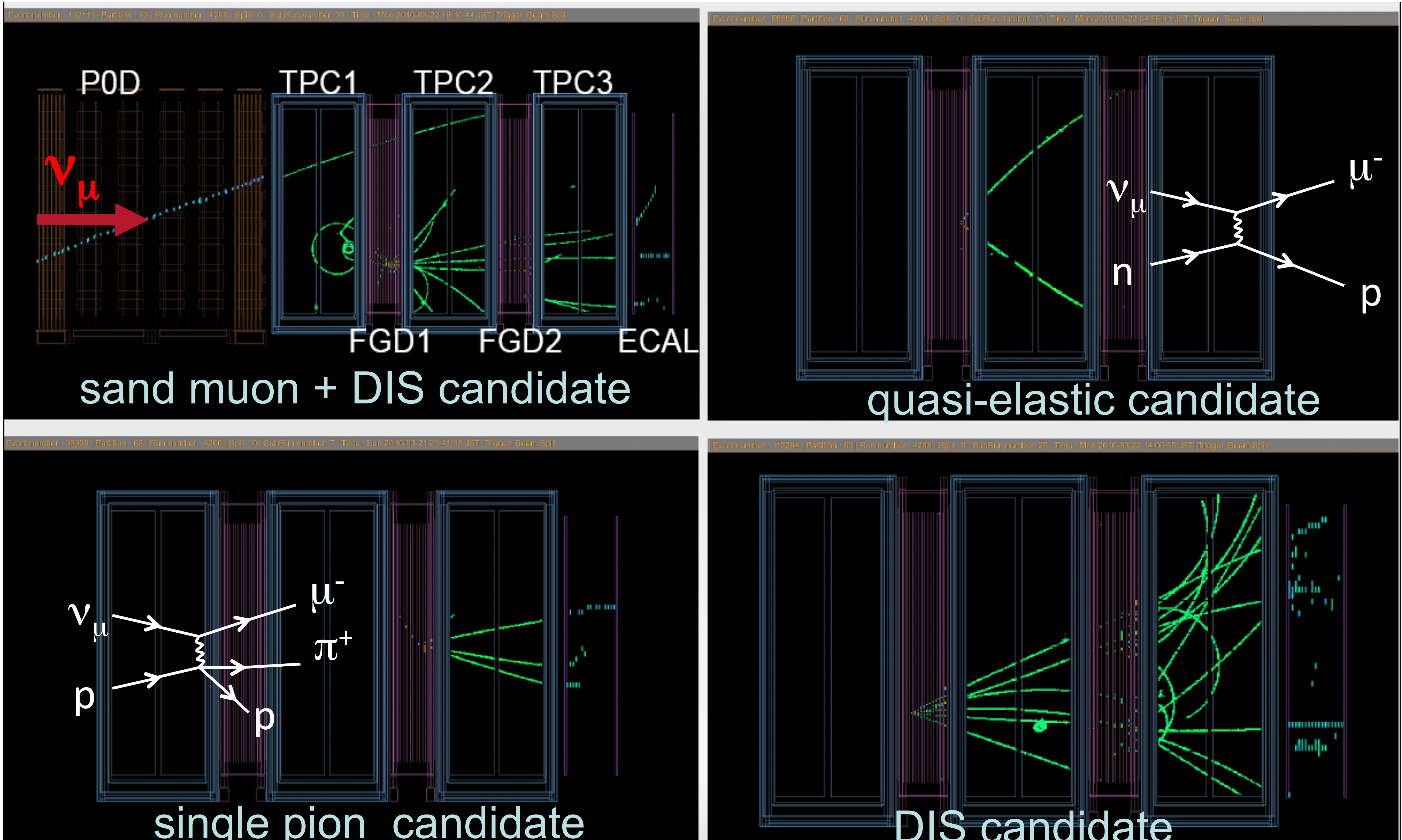
(normalized by proton beam intensity)



ND280 off-axis detector

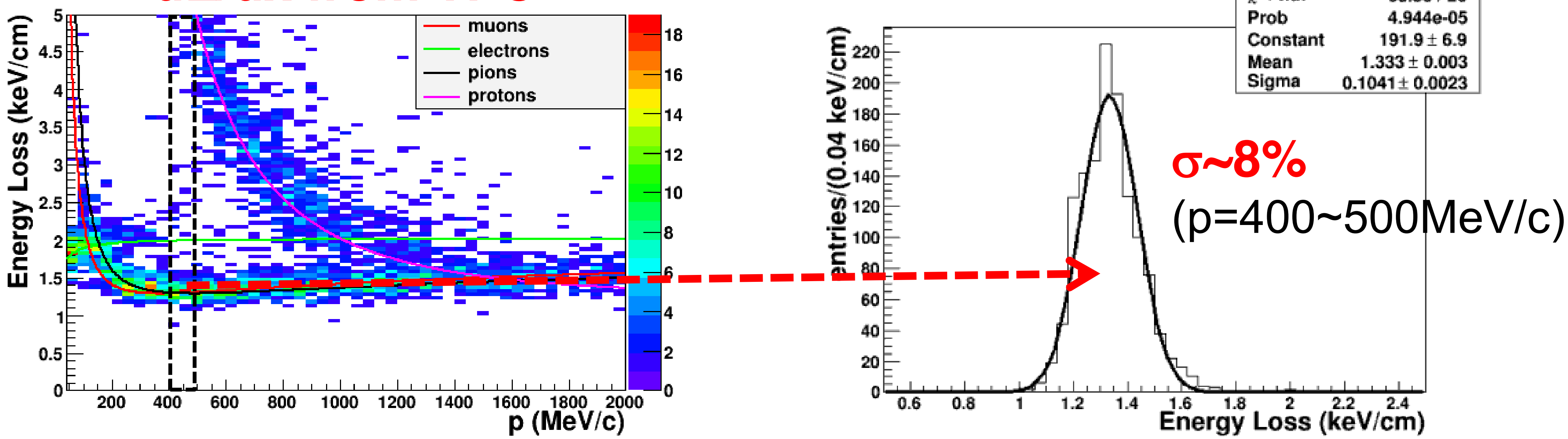


ND280 off-axis event gallery



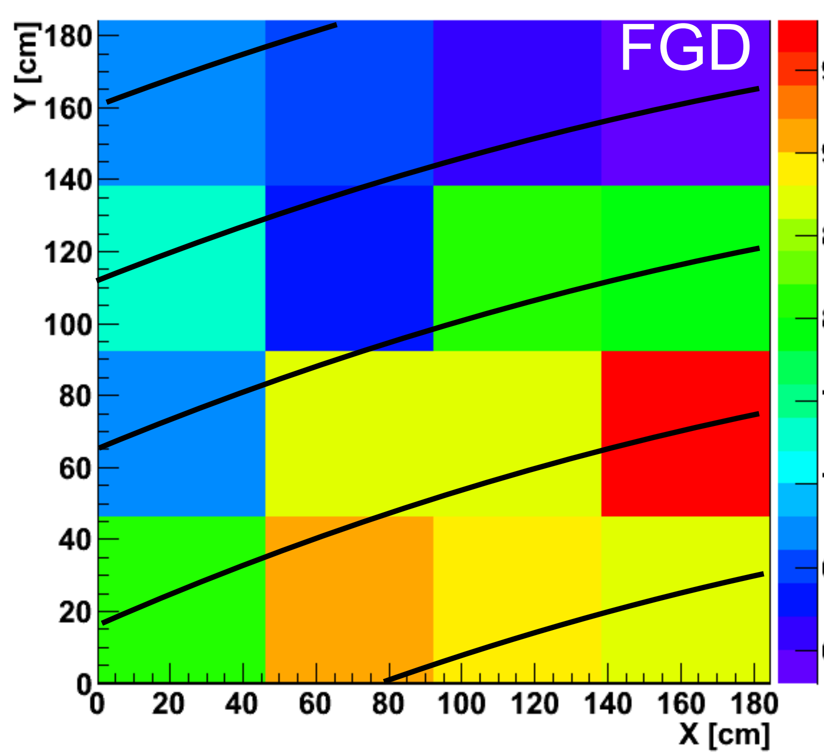
ND280 off-axis performance

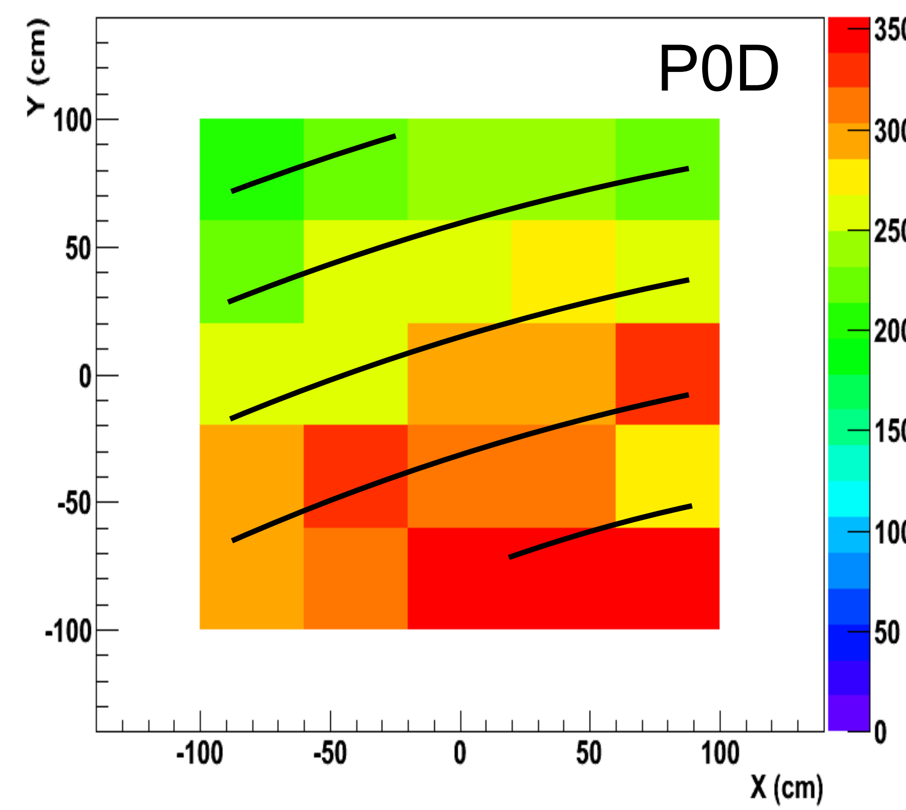
dE/dx from TPC



Vertex X-Y distribution

⊙ ν **beam direction**

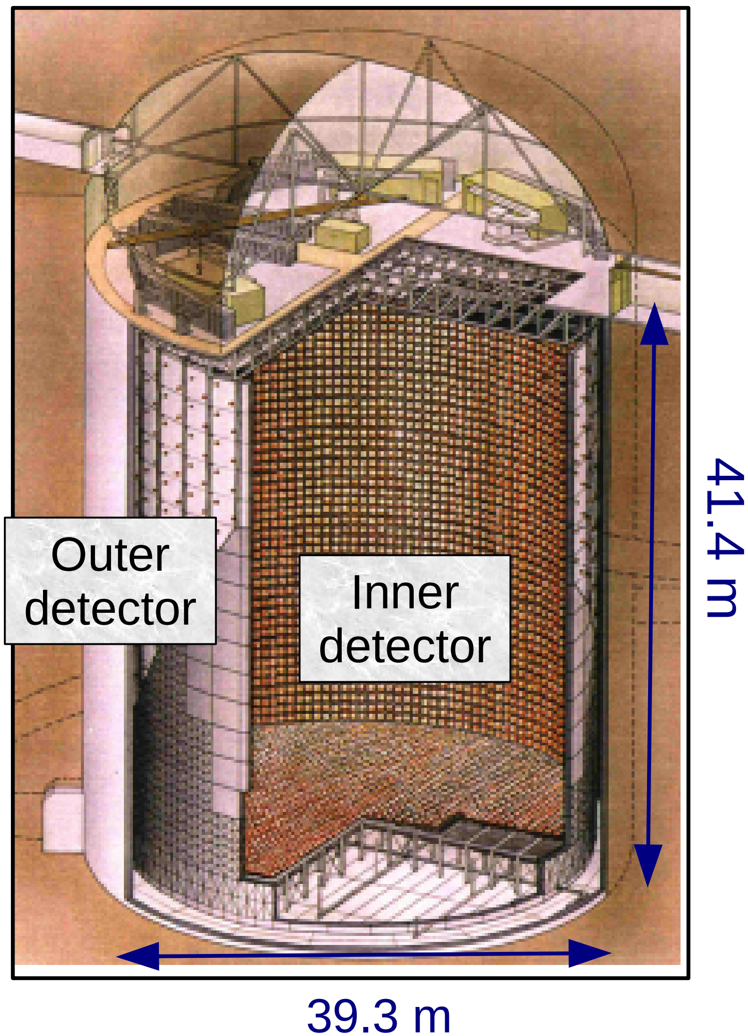




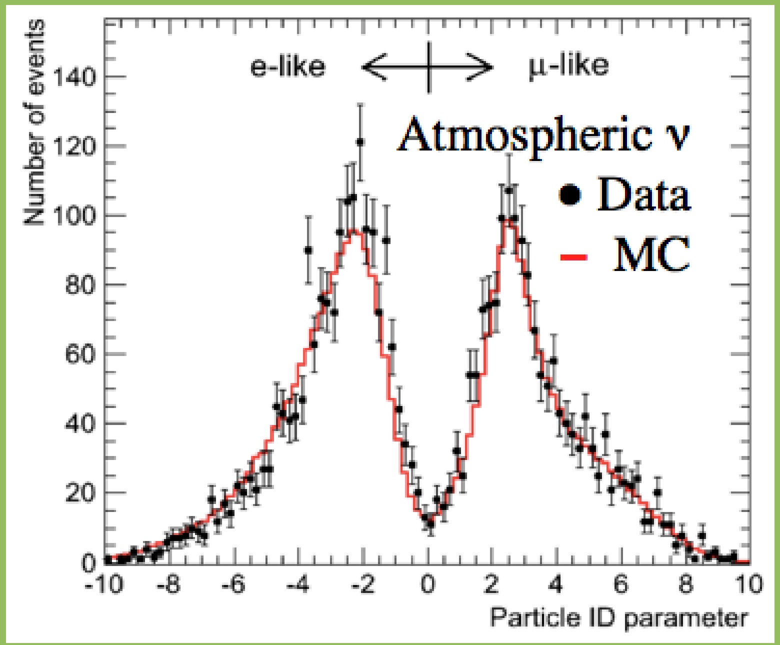
The T2K experiment
Far detector: Super-Kamiokande

Located 295 km from the target
Synchronized with beamline via GPS

- 50 kt water Cherenkov detector
- Operational since 1996

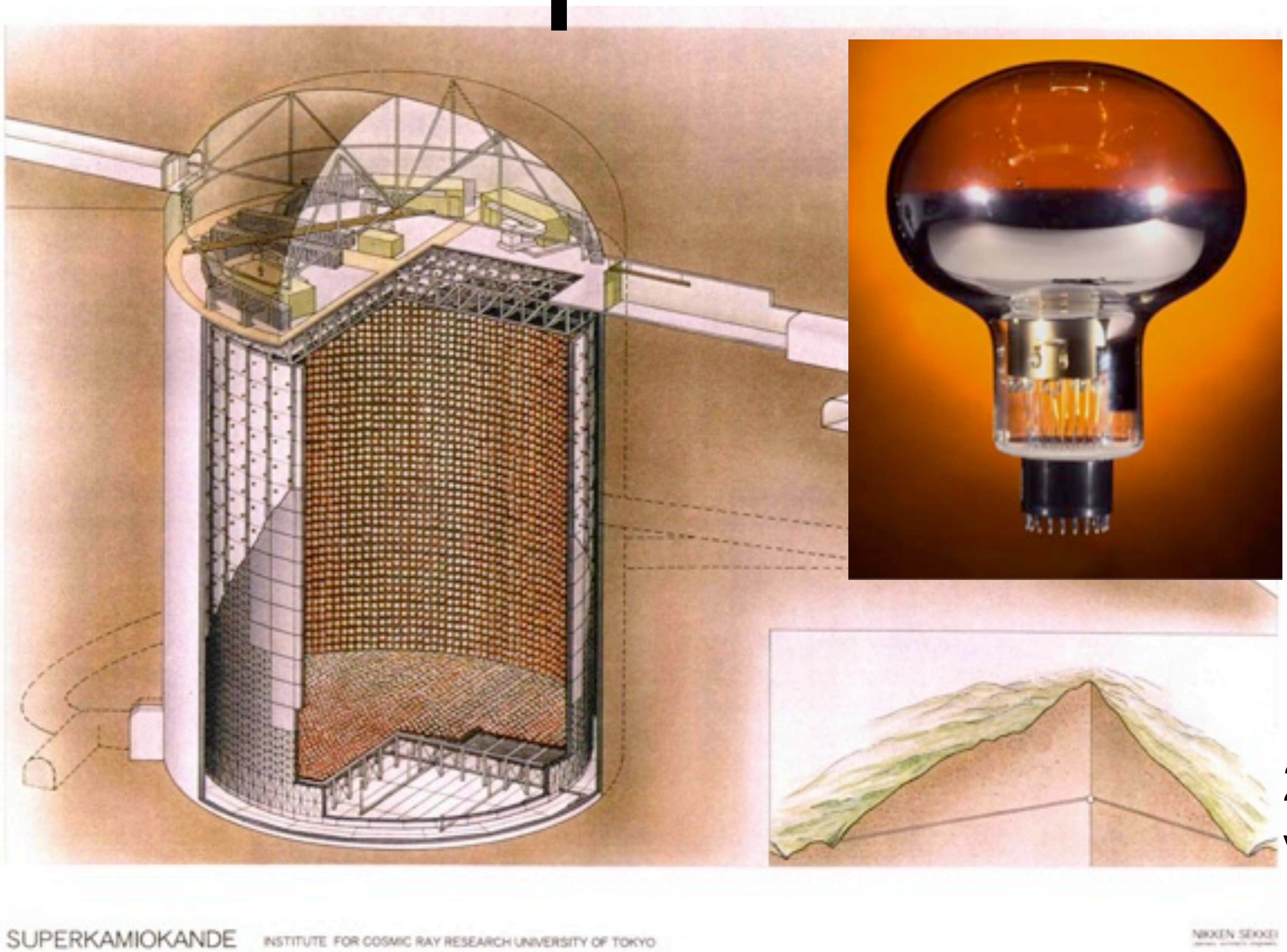


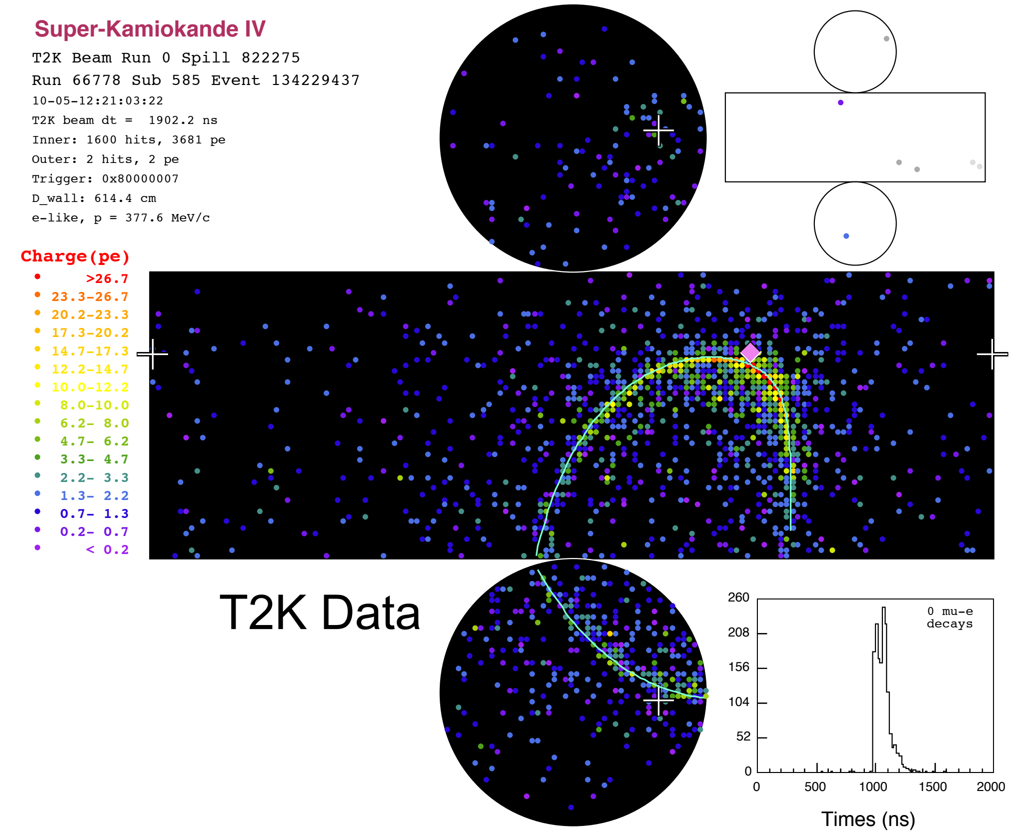
Good separation between $\mu^{\pm}$ and $e^{\pm}$ (separate ν_μ and ν_e CC interactions)



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

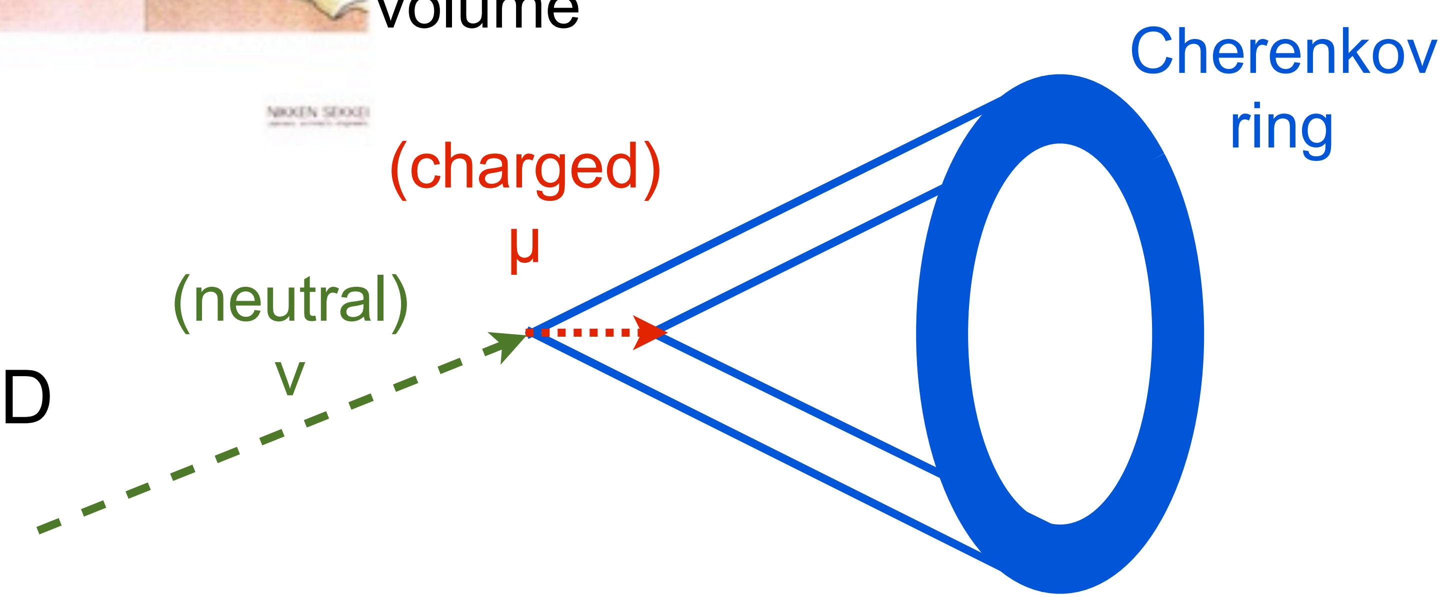
Super-Kamiokande



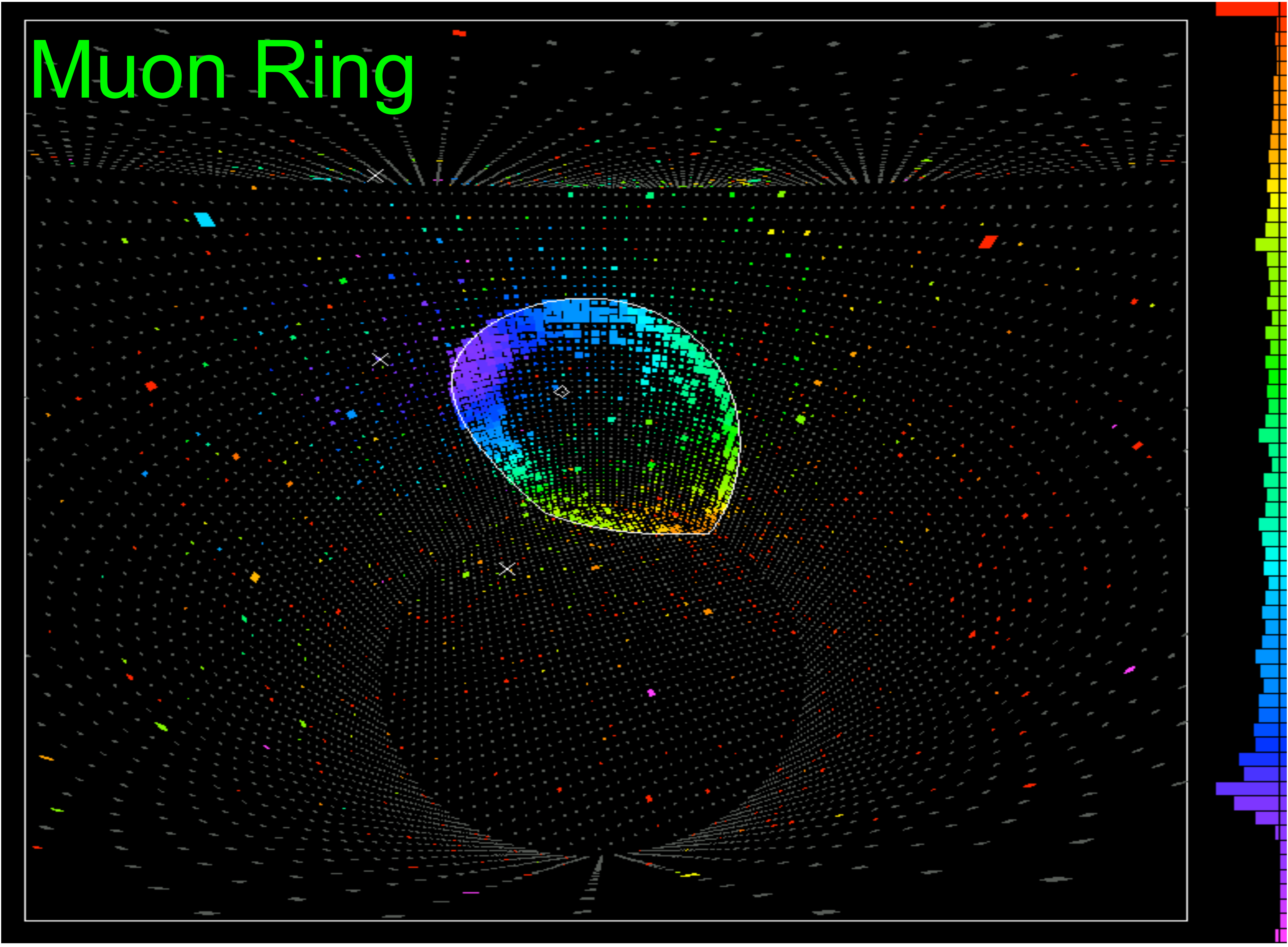


22.5 kton fiducial volume

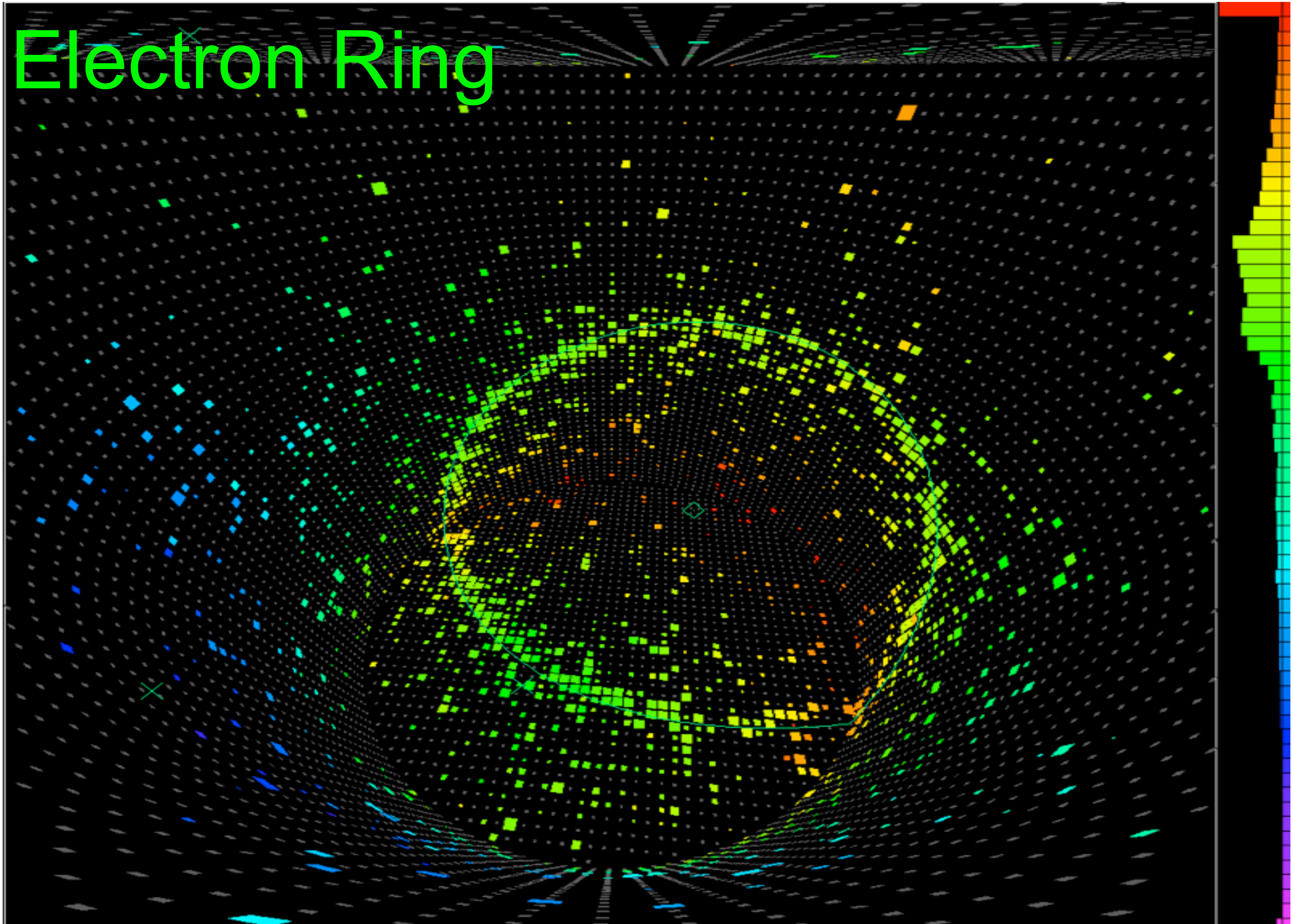
- 50,000 ton water Cherenkov detector
- 11,146 PMTs in ID, 1,885 in OD
- ~1km underneath Ikenoyama

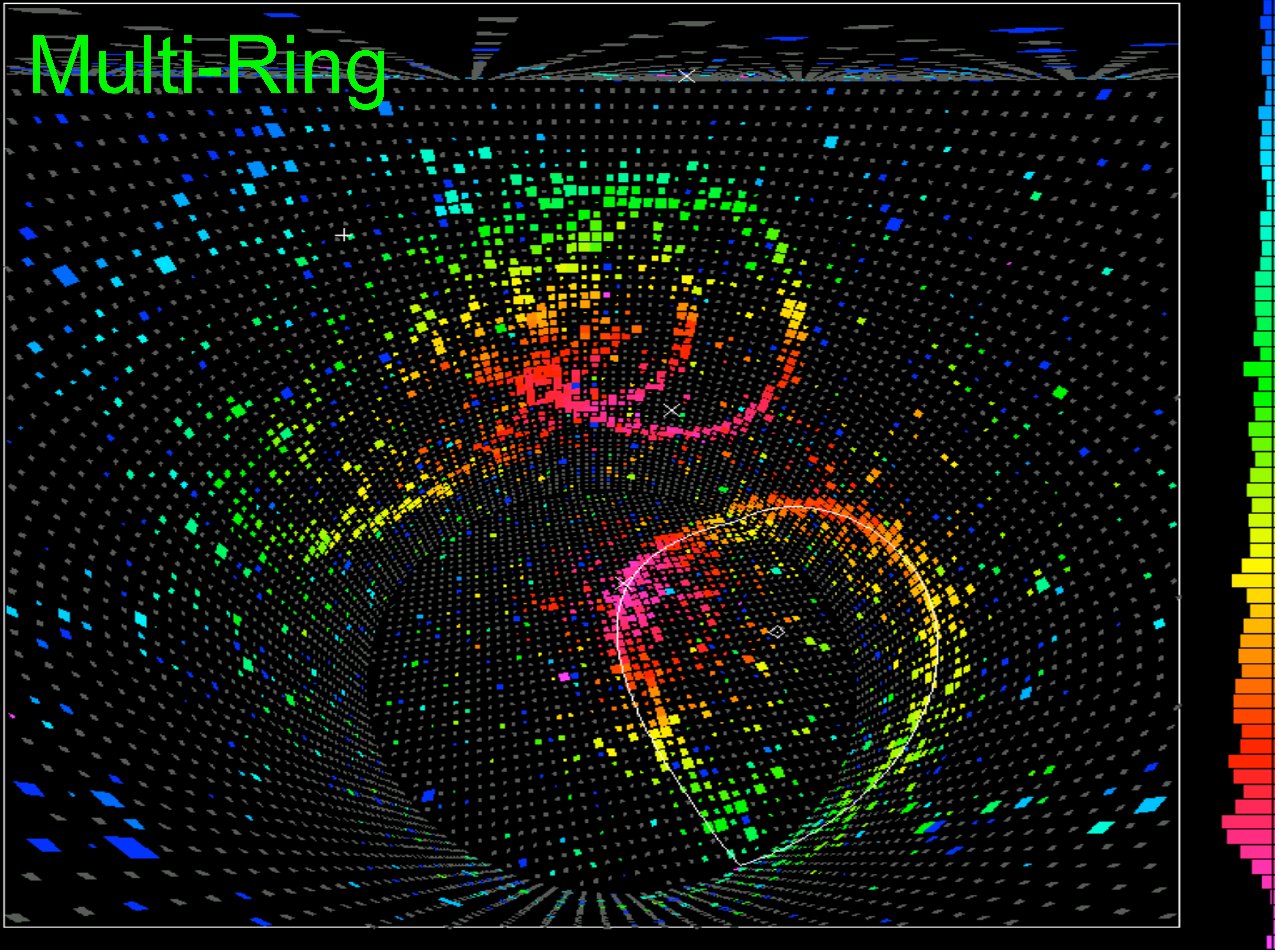


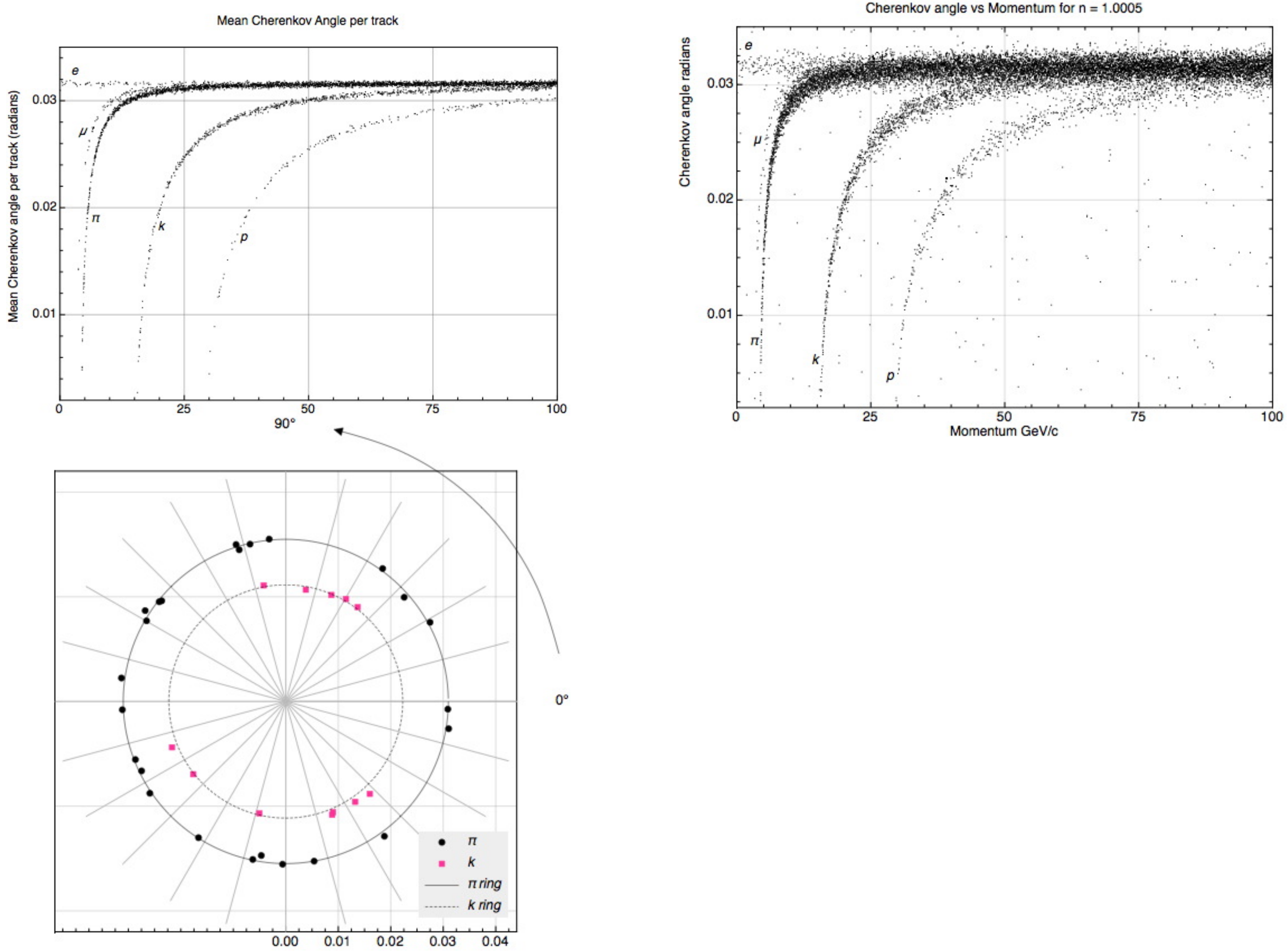
Muon Ring



Electron Ring




Multi-Ring



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

SK Particle Identification

Muons:

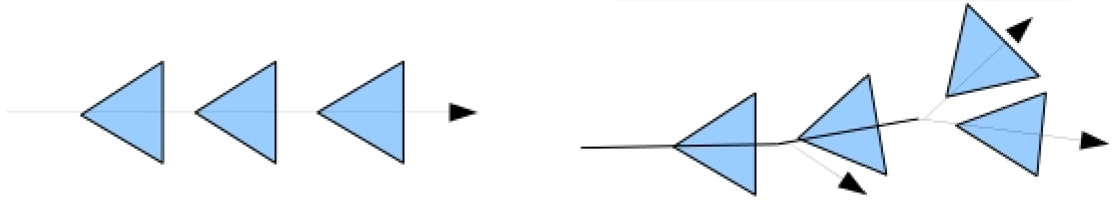
- Minimal scattering
- Ring has sharp edges

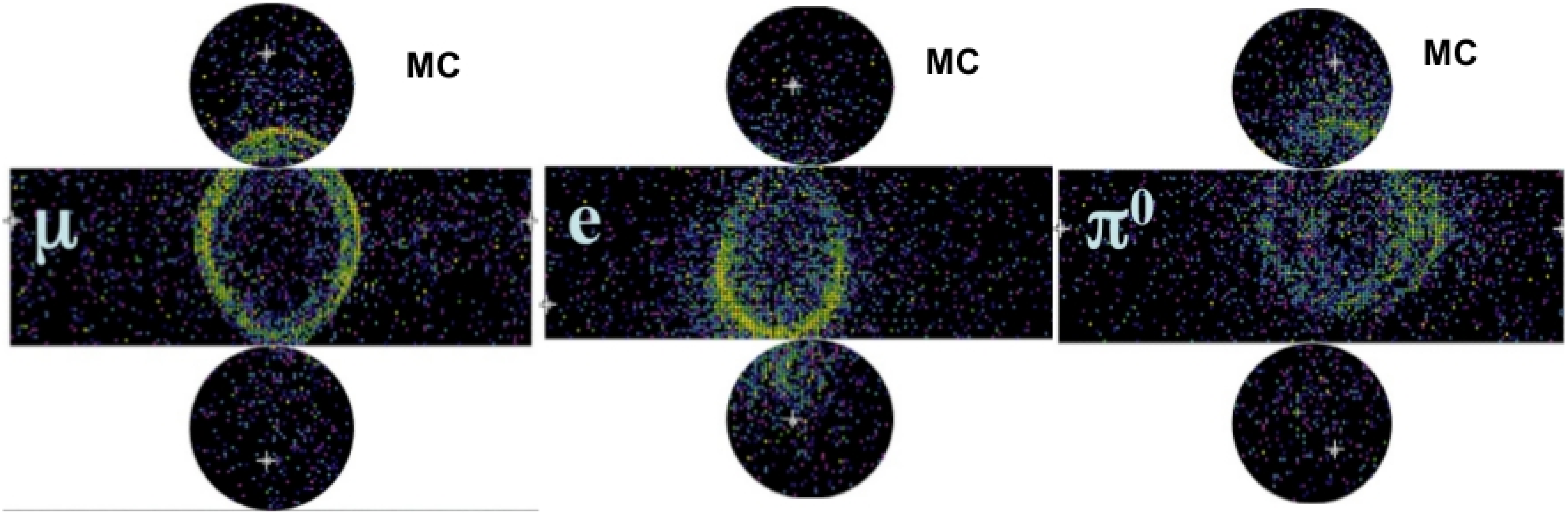
Electrons

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

Neutral Pions

- γs from π^0 decays shower and look like electrons

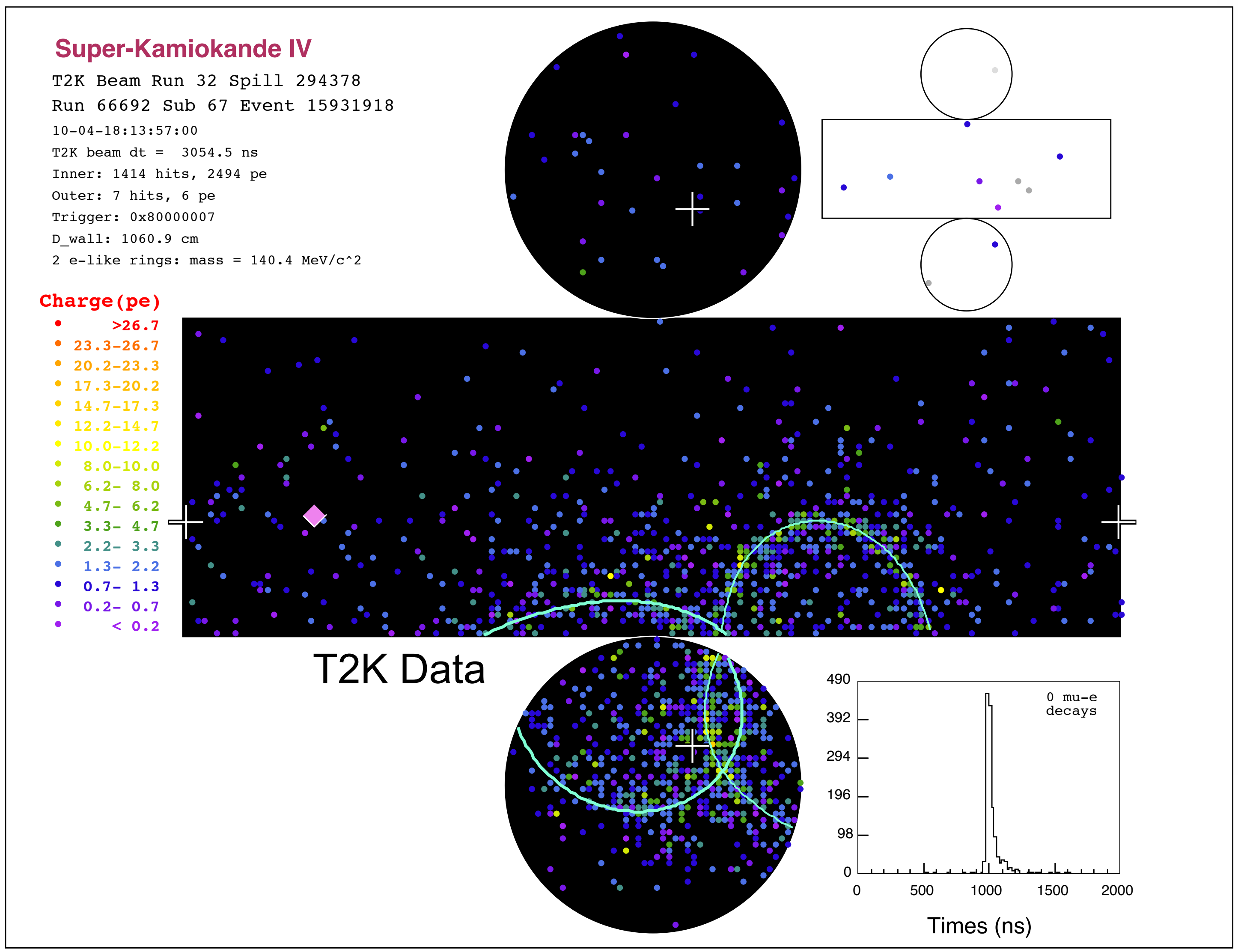


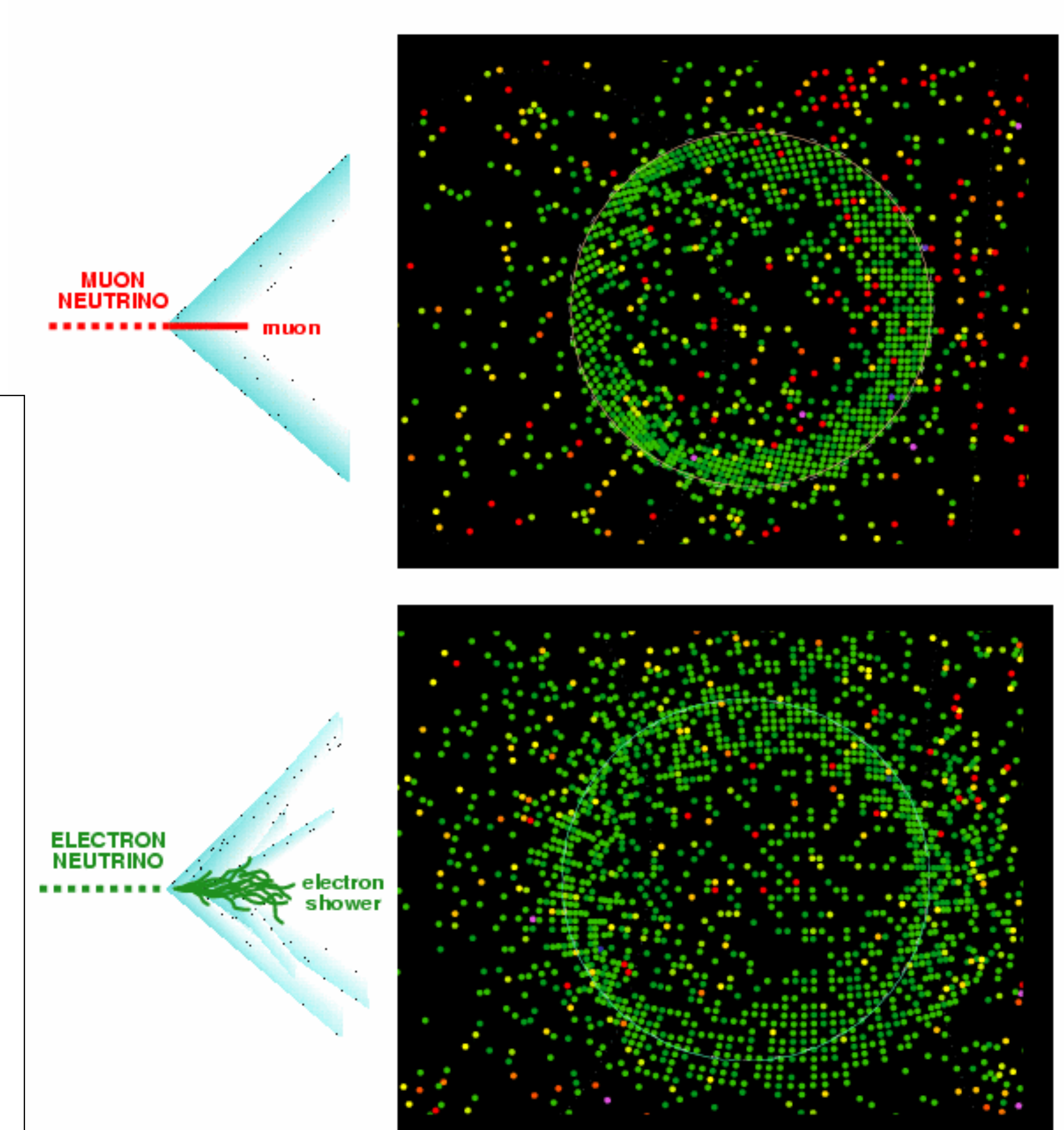


- Reliable PID particularly crucial to ν_e appearance analysis
- PID well-established at KEK beam test (1kton tank) in 1990s

SK Reconstruction

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

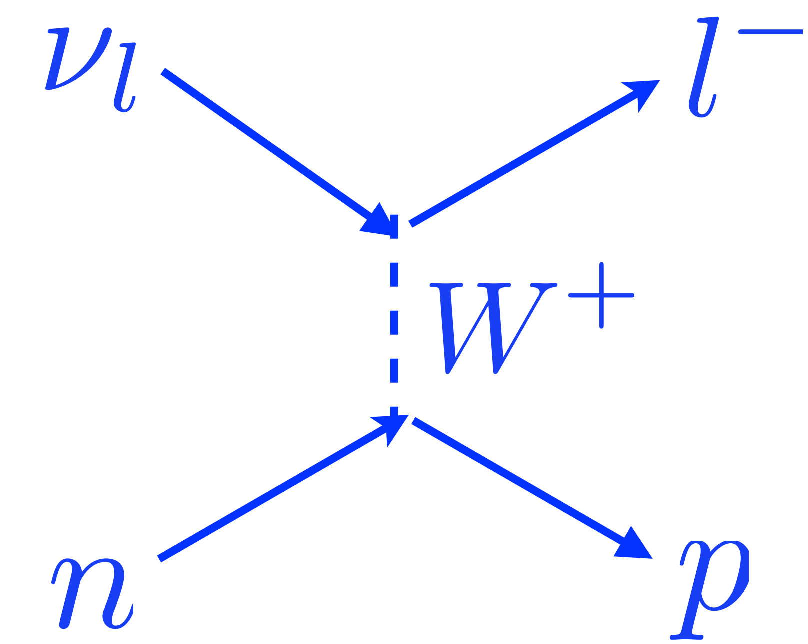




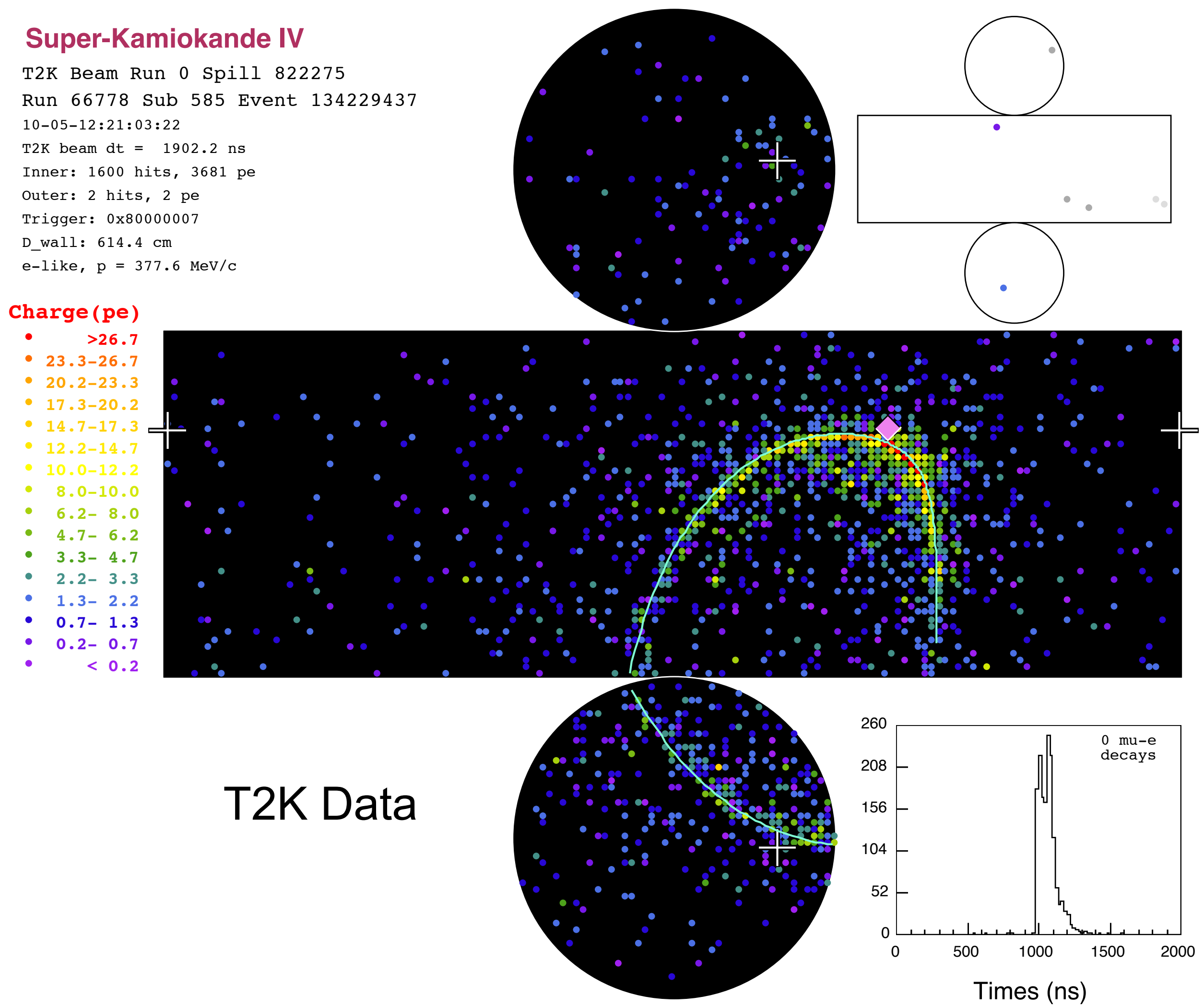
Use atmospheric data vs. MC to check reconstruction and set systematic errors

Signal at SK

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



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

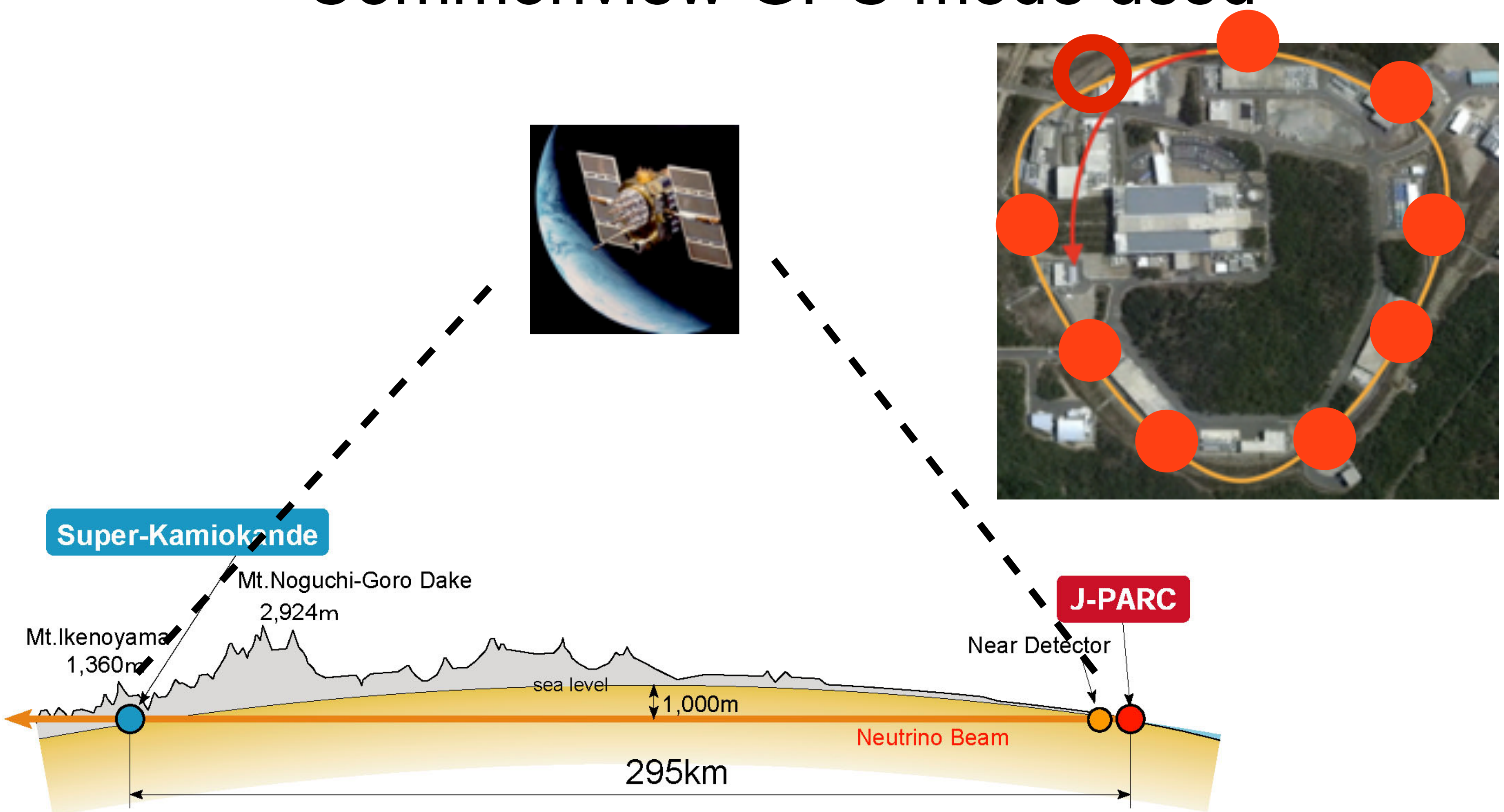


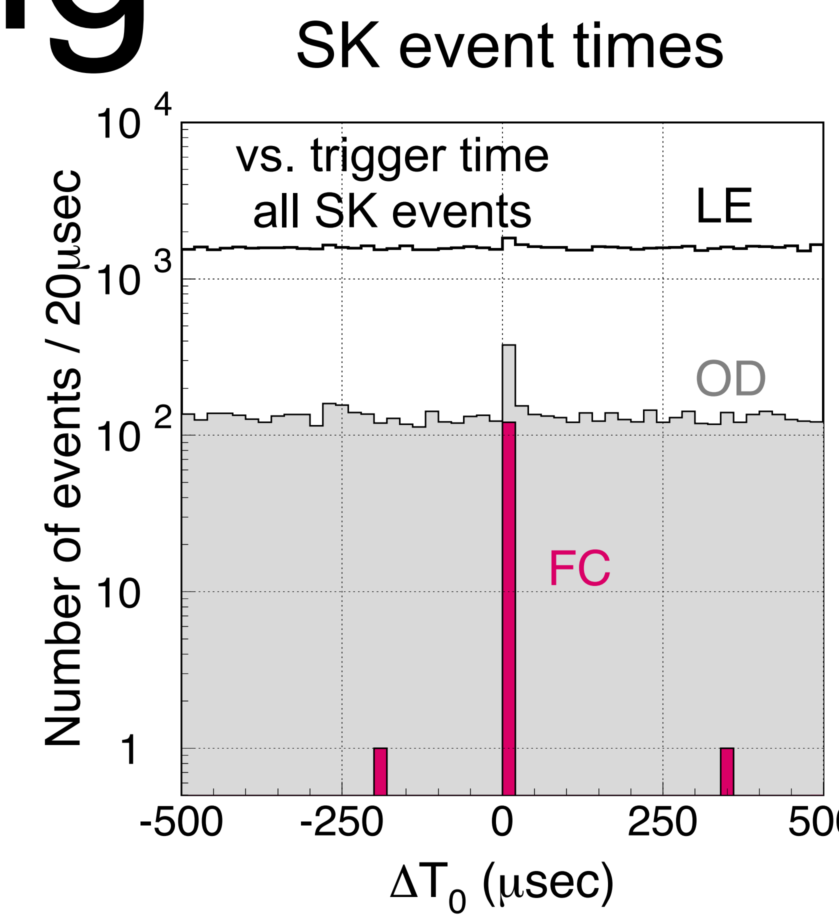
T2K Data

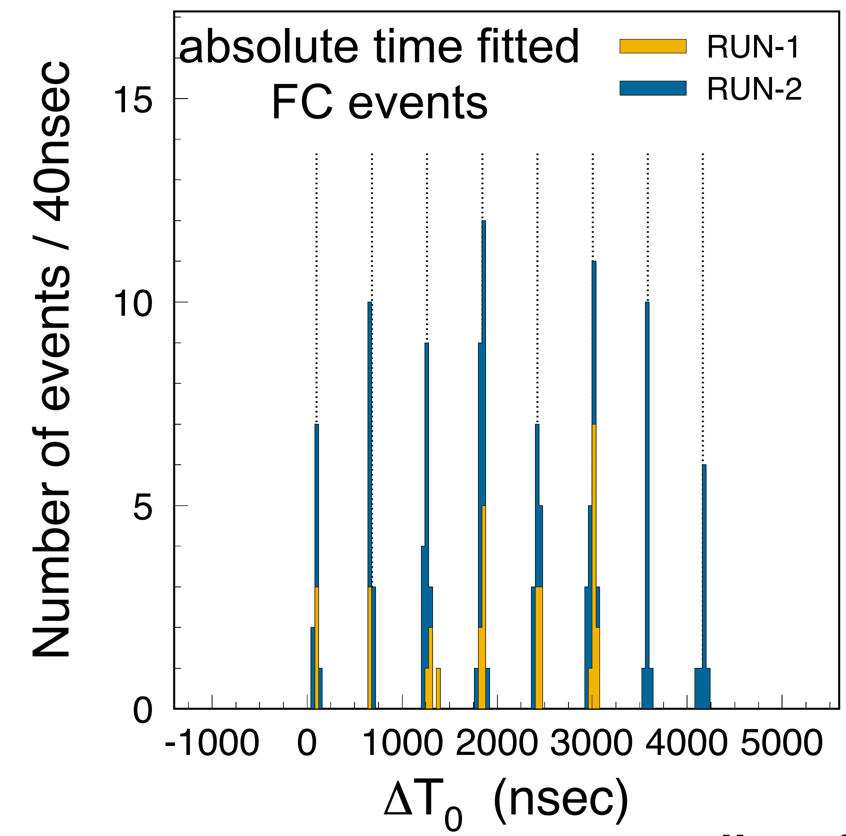
- Incident neutrino energy can be reconstructed (best for CCQE)!
- Recoil proton usually below threshold at T2K beam energy.

Beam Trigger/Timing

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







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

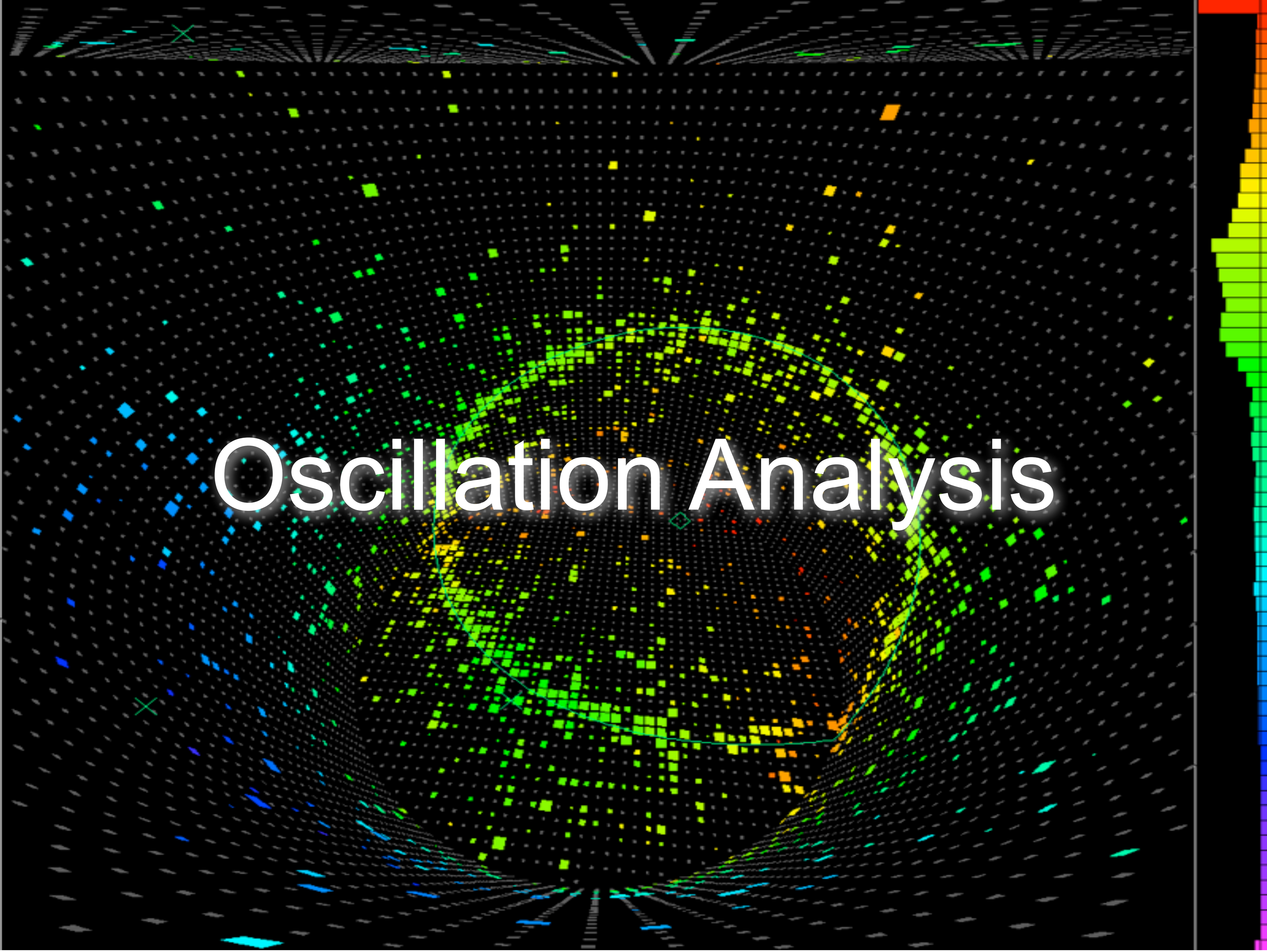
11 March, 14:46...

Much exterior damage, but inside equipment largely undamaged.

Rapidly repaired!

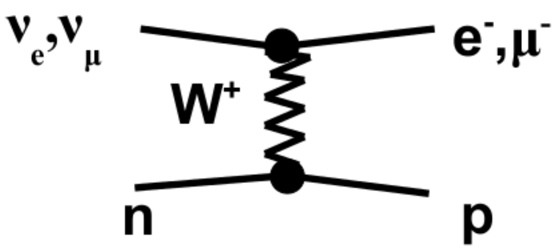
Repairs are basically complete.
Physics data taking resumed in January!

Oscillation Analysis



Neutrino Interactions

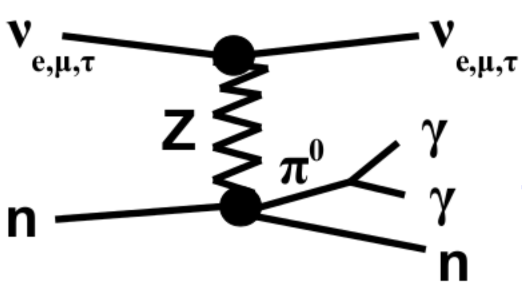
- In the region of interest for T2K, large contribution from charge current quasi-elastic scattering:



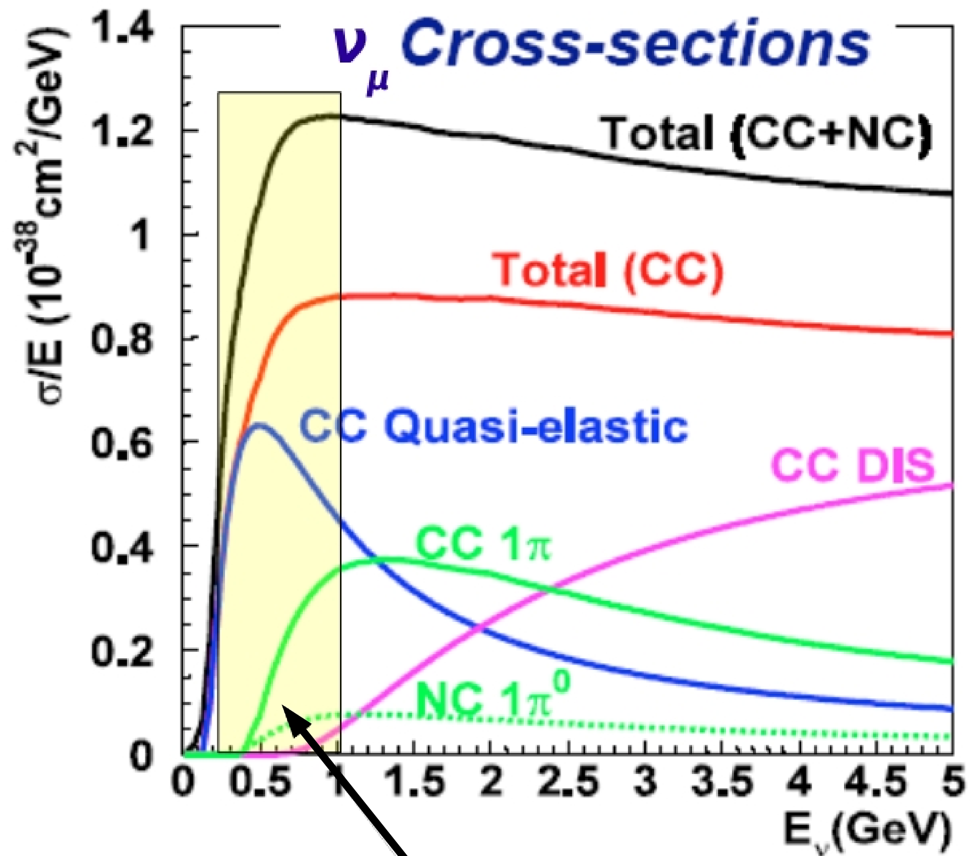
T2K signal at SK

- Also significant CC contribution with pion in final state

- $NC\pi^0$ is a major background mode from electron appearance:

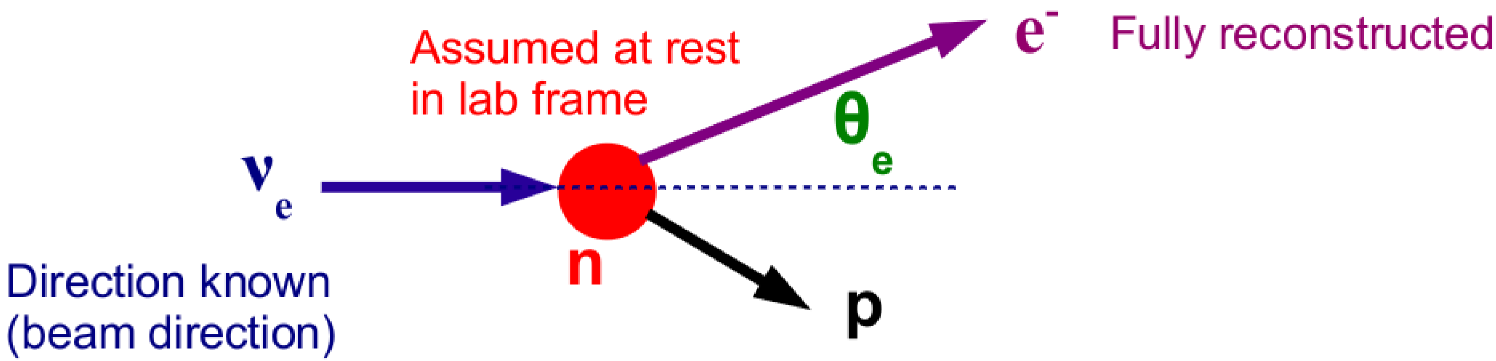


Photons from π^0 can fake electron signal



T2K beam peak energy

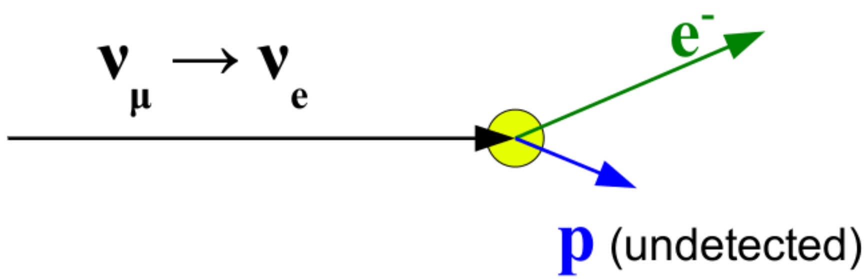
Reconstructing ν Energy

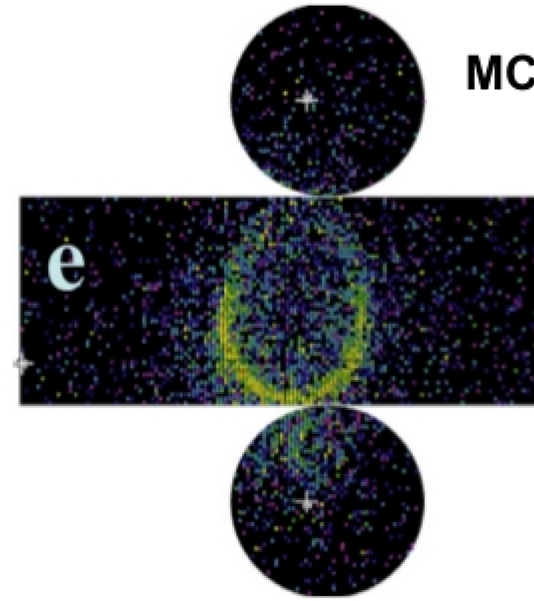


$$E_\nu^{QE} = \frac{2M_n E_e - (M_n^2 + m_e^2 - M_p^2)}{2[M_n - E_e + \sqrt{E_e^2 - m_e^2}\cos\theta_e]}$$

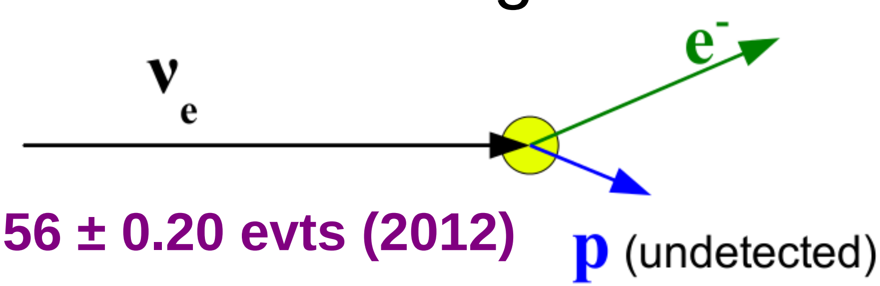
- Only final state lepton is reconstructed
- Neutrino energy can be determined with certain assumptions:
  - Neutrino direction is known (beam direction)
  - Recoil nucleon mass is known (use neutron mass)
  - Target nucleon is at rest (not quite true; introduces smearing)

- Oscillation signal:





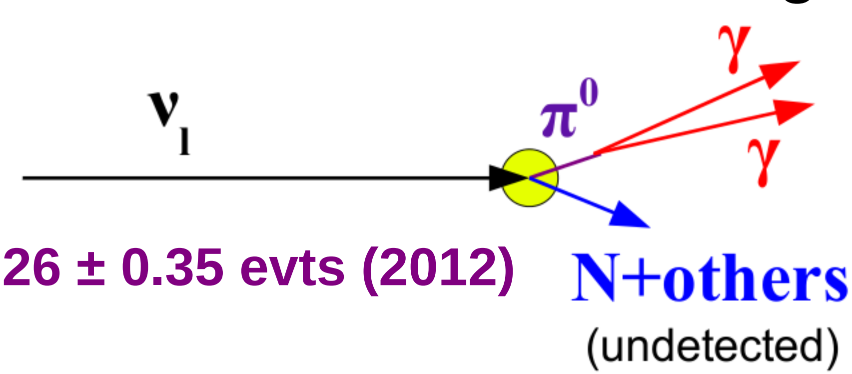
- Beam νe background:



Beam background has harder energy spectrum

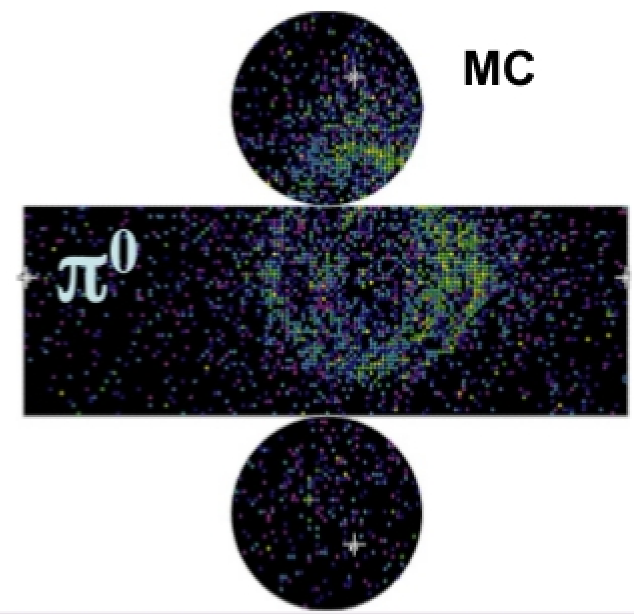
1.56 ± 0.20 evts (2012)

- Neutral current π^0 background:



Can be removed by identifying second photon ring

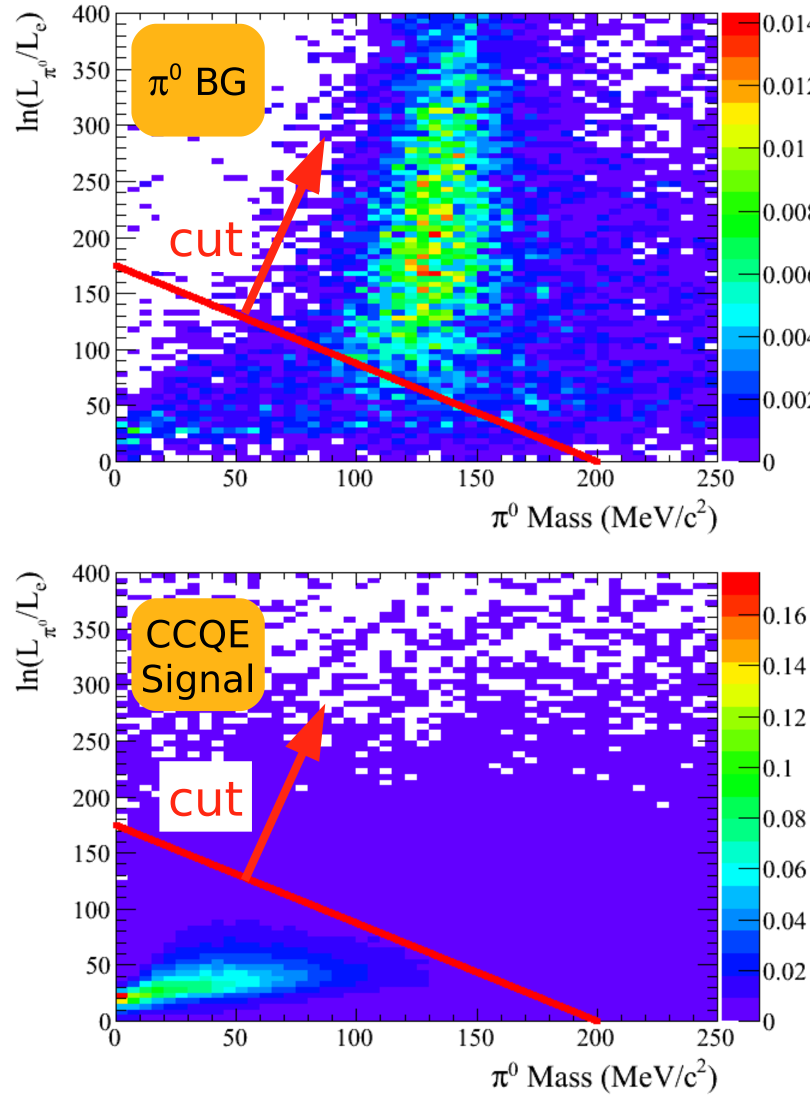
1.26 ± 0.35 evts (2012)



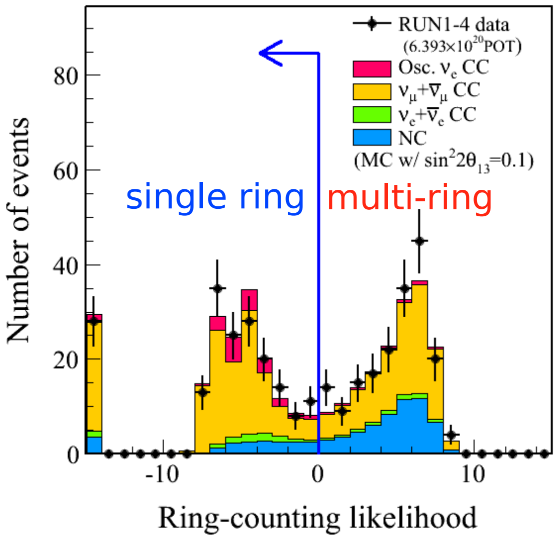
Improved π^0 Rejection

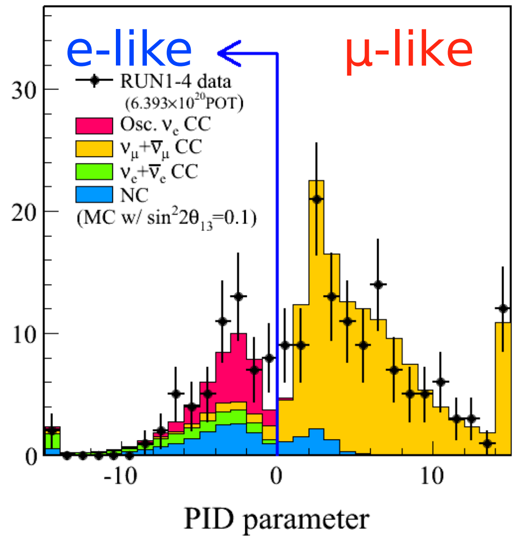
- New likelihood fitter used to distinguish electrons from π^0
- Assumes two electron-like rings produced at a common vertex
- Uses 12 parameters in fit:
  - Vertex (X, Y, Z, T)
  - Directions (θ_1, φ_1, θ_2, φ_2)
  - Momenta (p_1, p_2)
  - Conversion lengths (c_1, c_2)
- This 2D cut **removes 70% of the π^0 background remaining** after previous selection applied (for same signal efficiency)
- Total background is reduced by 27%
- 6.74 BG events → 4.92 BG events expected (in full Run 1 – 4 dataset)

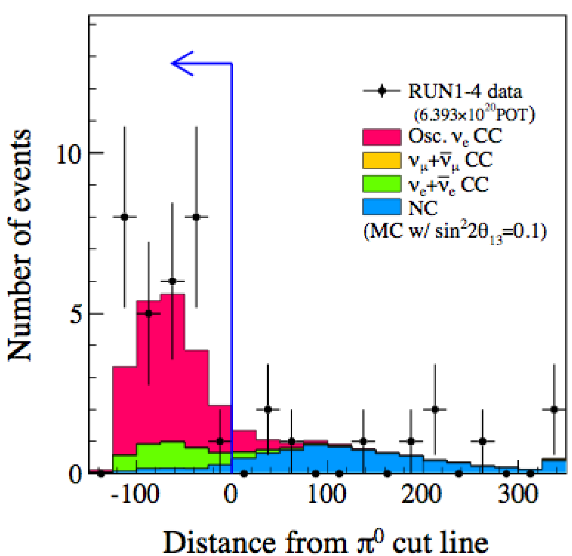
Likelihood Ratio vs π^0 Mass (T2K Monte Carlo)

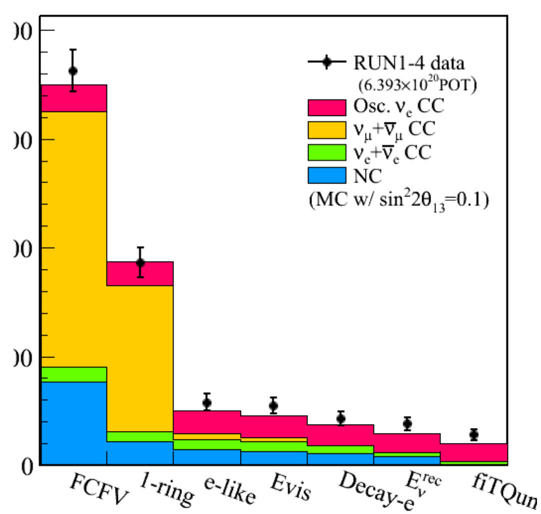


T2K-SK ν_e Event Selection





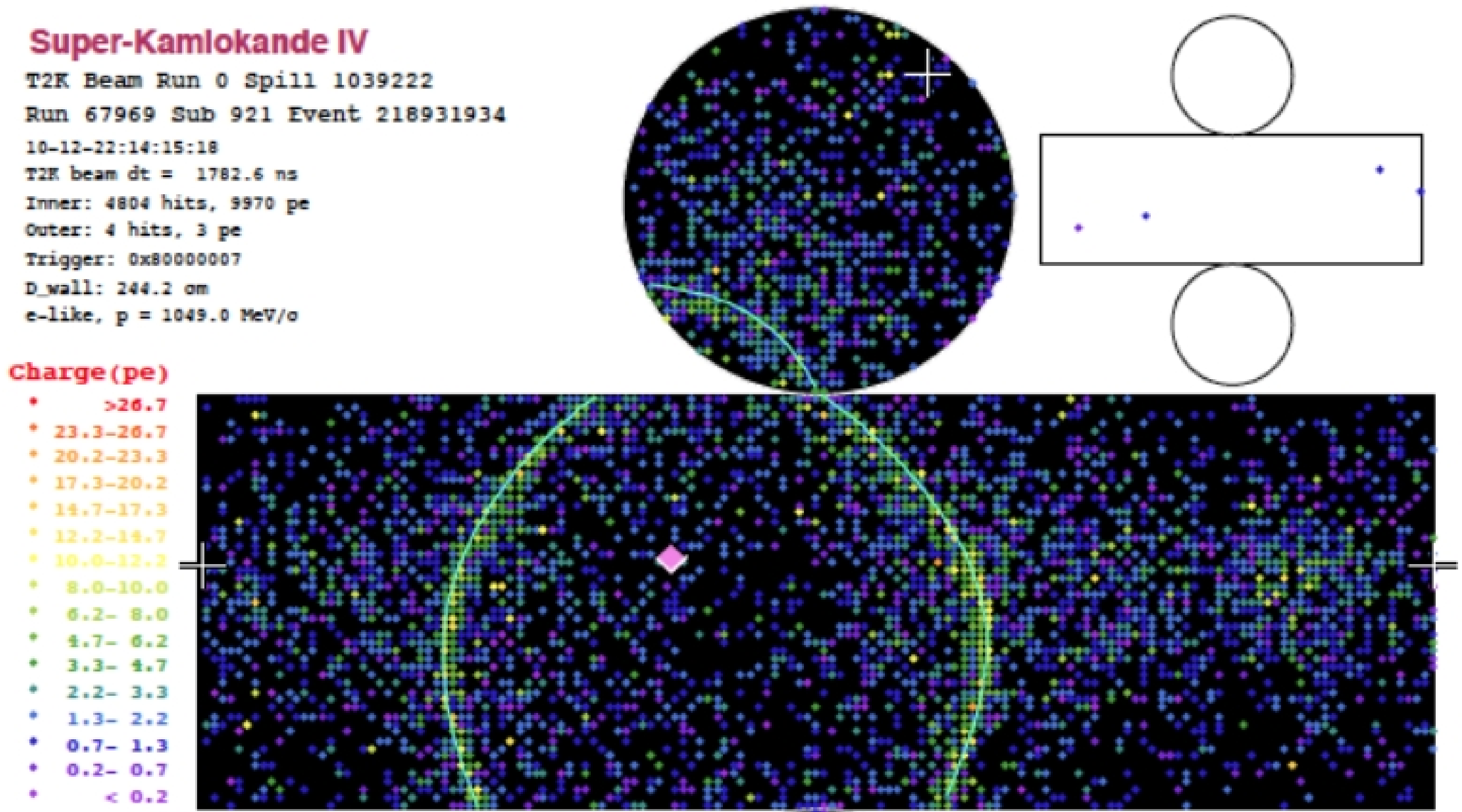




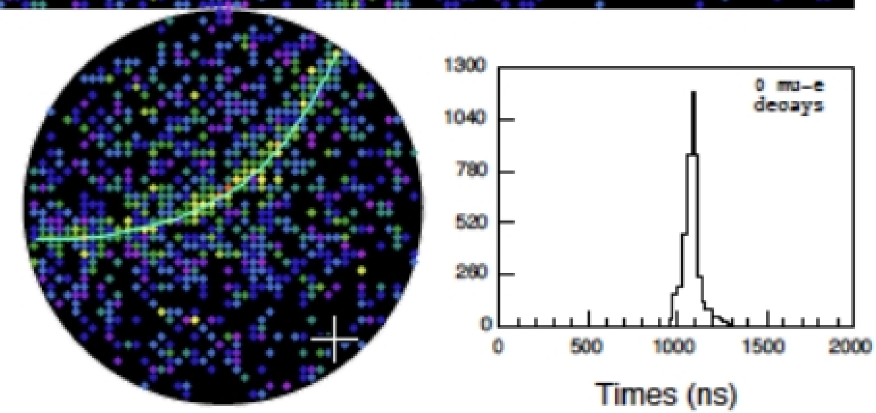
ν_e Selection Criteria

- # 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

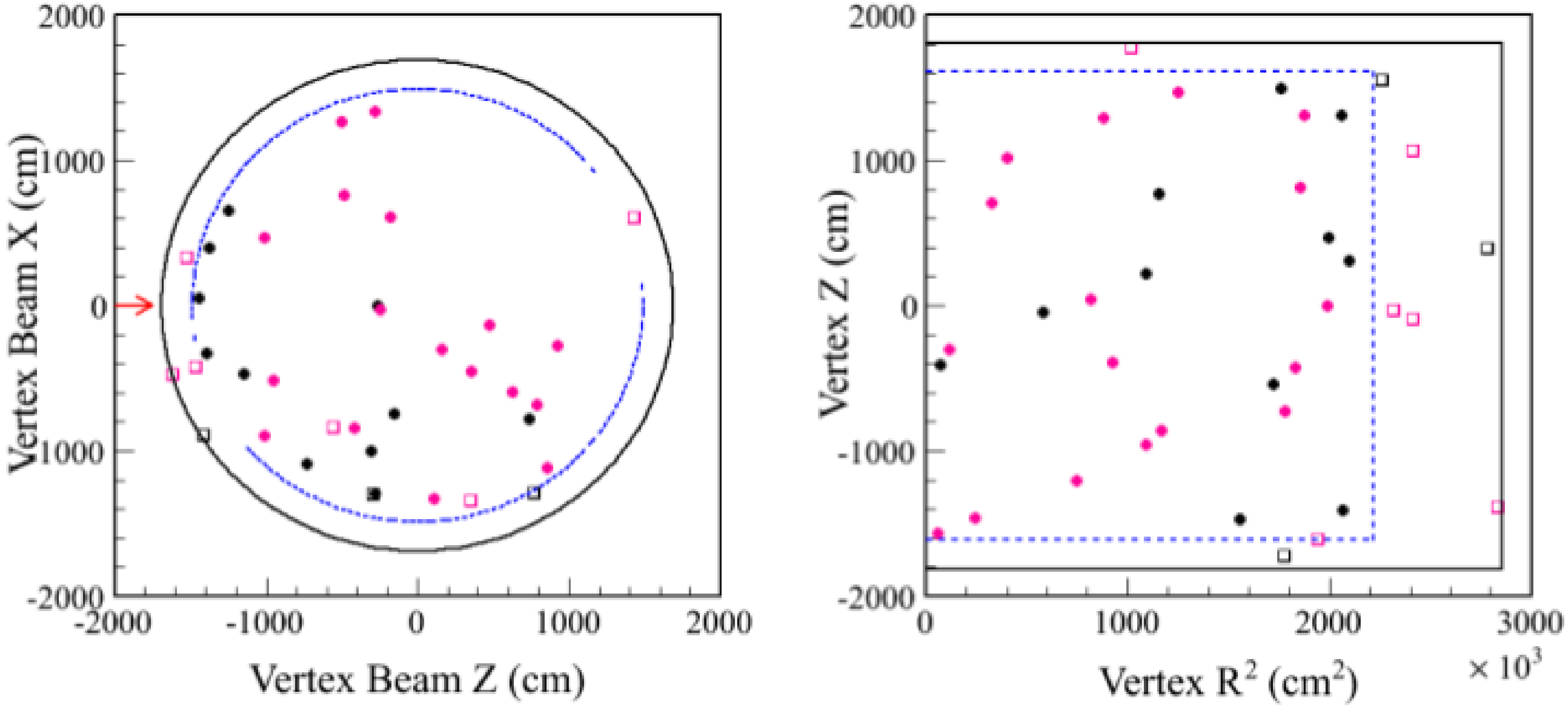


visible energy : 1049 MeV
# of decay-e : 0
2γ Inv. mass : 0.04 MeV/c²
recon. energy : 1120.9 MeV



ν_e Vertex Distributions

Vertex distributions for ν_e candidates at the far detector:



	RUN1+2+3	RUN4	RUN1+2+3+4
Dwall	34.4%	54.7%	20.9%
Fromwall beam$_{\|\|}$	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)

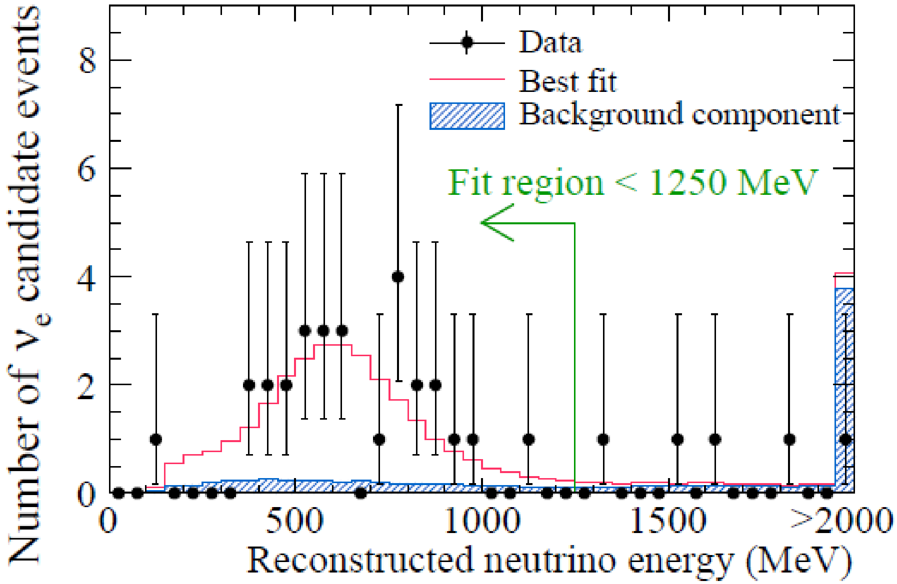
	Runs 1-3 (2012)	Runs 1-3 (2013)	Runs 1-4 (2013)
$\sin^2 2\theta_{13}=0.1$	4.7%	3.5%	3.0%
$\sin^2 2\theta_{13}=0.0$	6.1%	5.2%	4.9%

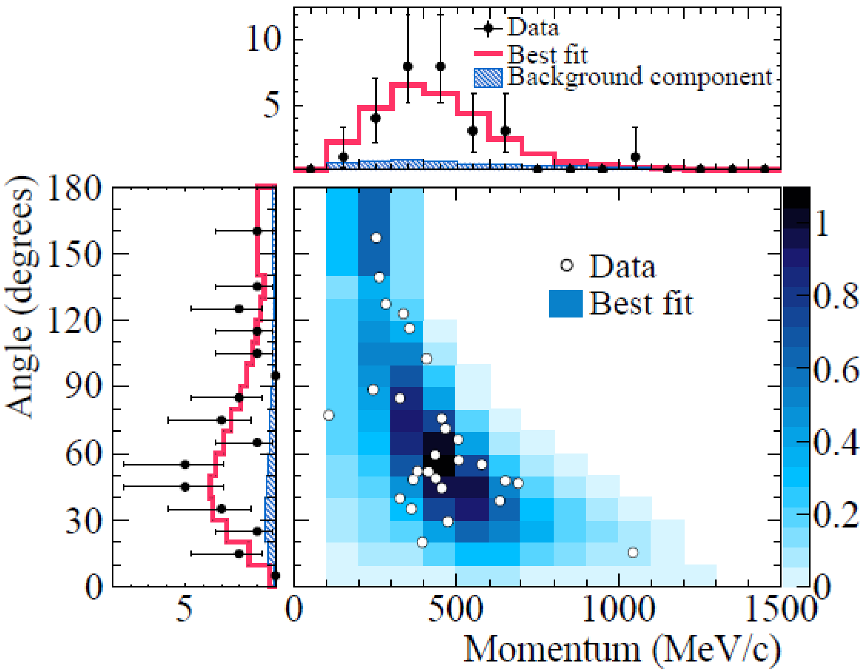
Error on Cross Section Parameters
(After Near Detector Constraint)

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



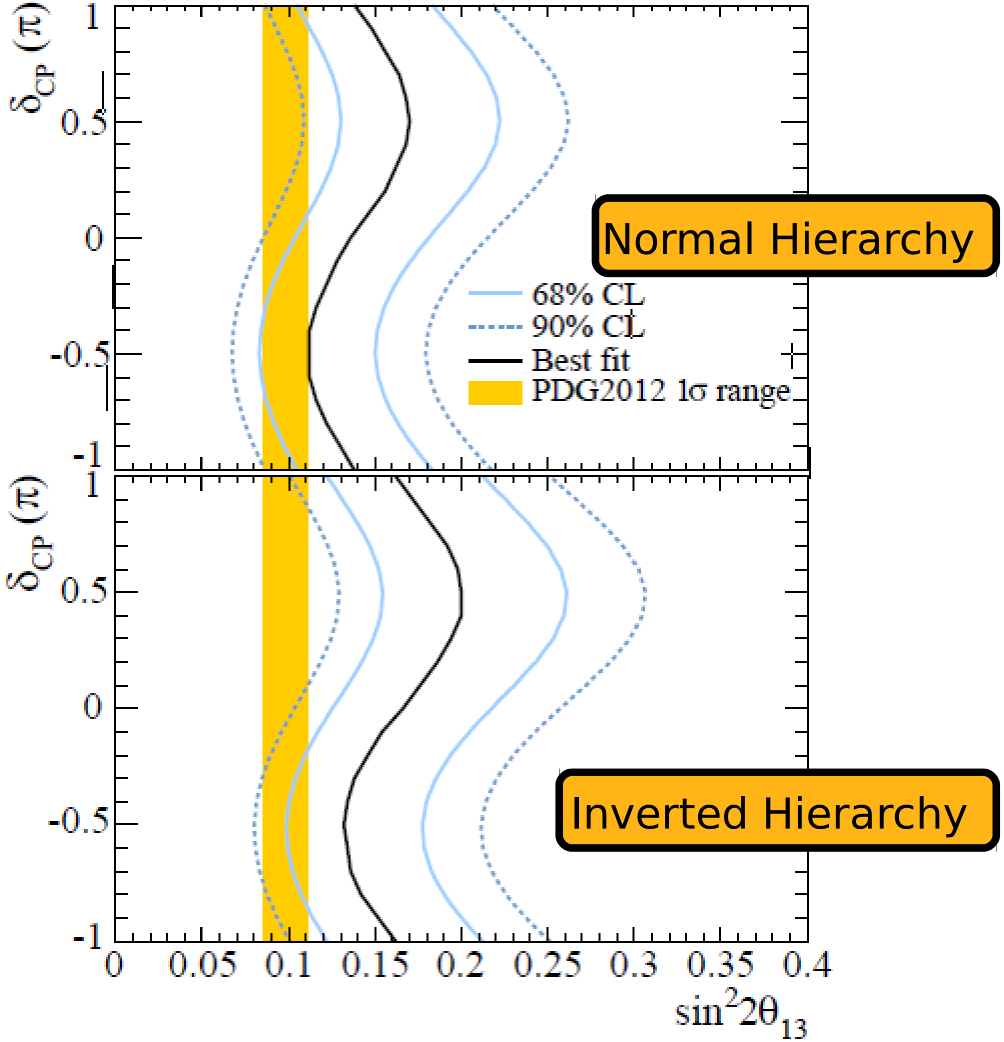


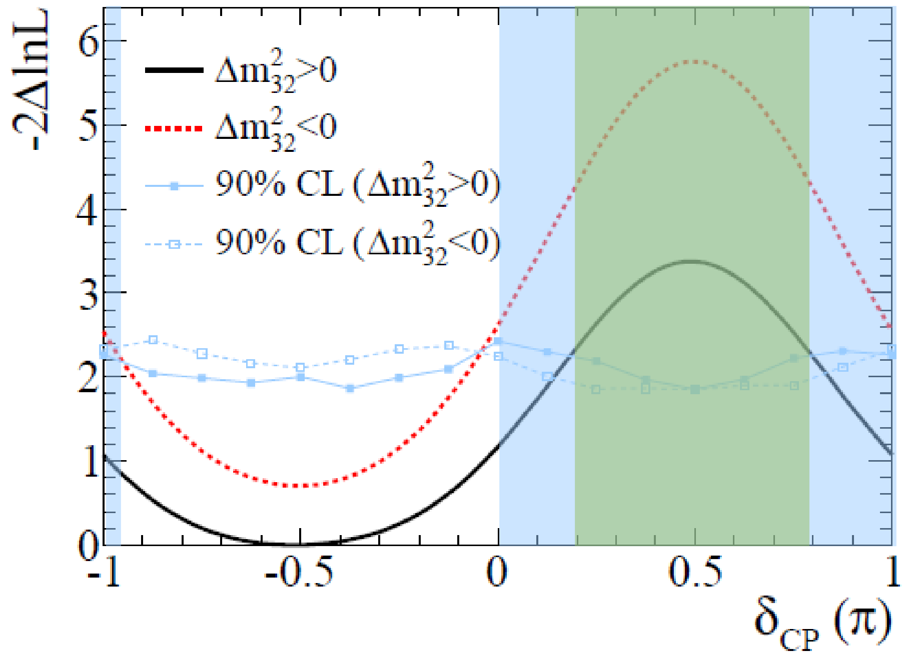
- Expected background:
  - 4.92 ± 0.55 events
- With the following assumptions:
  - $\sin^2(2\theta_{13}) = 0.1$
  - $\sin^2(2\theta_{23}) = 1$
  - $\delta_{CP} = 0$
  - normal mass hierarchy

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

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

- If I want at least O(10^3) events in one year O(10^7 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

$$N_d = 2\frac{M}{M_{D2O}} \approx \frac{2\times 10^6 Kg}{20\times m_N} = 6\times 10^{31}$$

SNO - detector

- Logic: tank of 1000 tonns 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 detuterium 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)
    - $\cos\theta_{sun}$ (depends on the correlation btw electron directions and primary neutrinos)

SNO – detector sketch

Main features:

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

Heavy water tank 1000 tonns

Light water envelope 7000 tonns

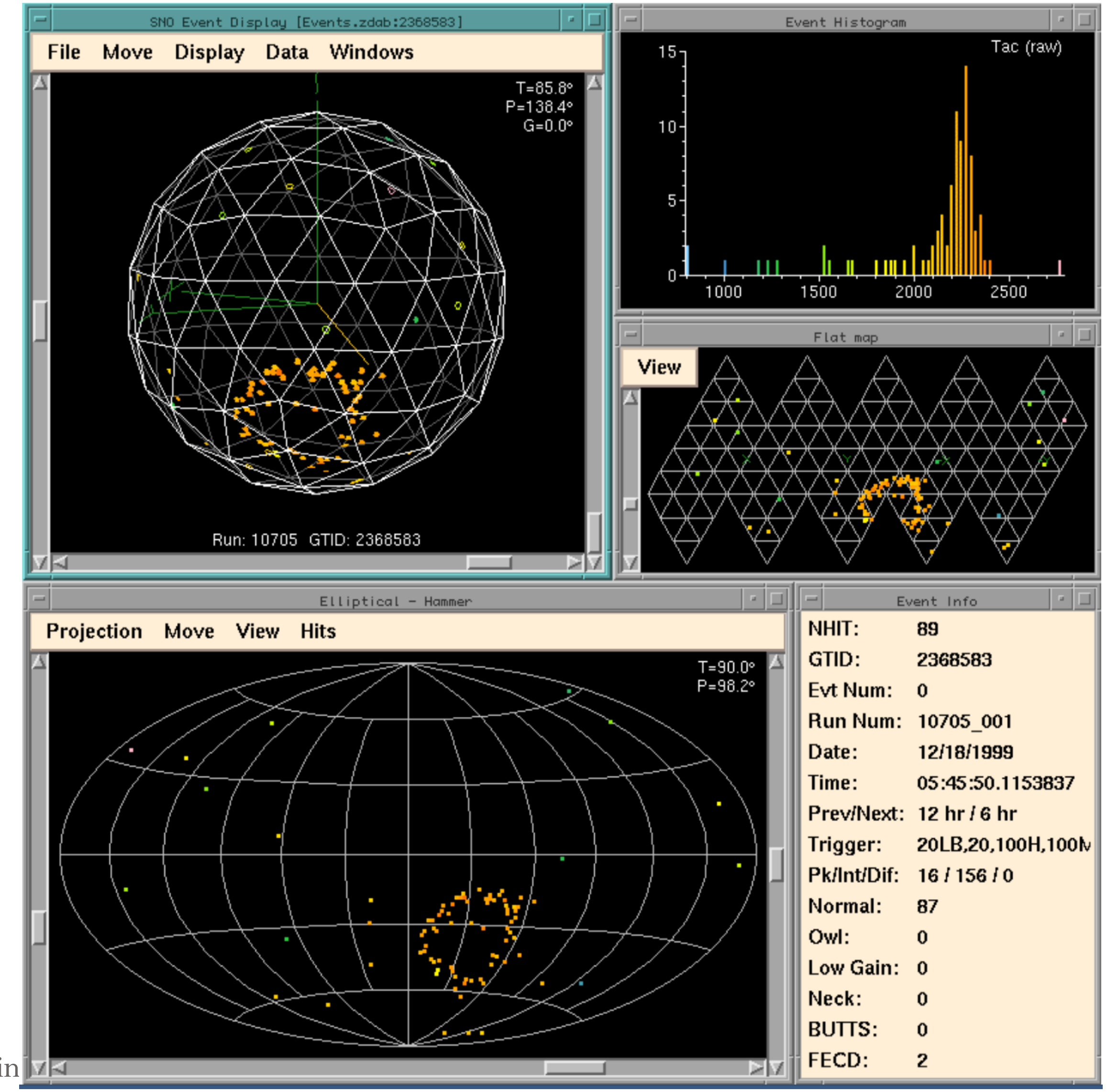
Sphere of 10000 PMTs around the envelope (inward and backward)

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 Event Display [Events.zdab:2368583]
File Move Display Data Windows
T=85.8°
P=138.4°
G=0.0°
Run: 10705 GTID: 2368583
Event Histogram
Tac (raw)
15
10
5
0
1000
1500
2000
2500
Flat map
View
Elliptical - Hammer
Projection Move View Hits
T=90.0°
P=98.2°
Event Info
NHIT: 89
GTID: 2368583
Evt Num: 0
Run Num: 10705_001
Date: 12/18/1999
Time: 05:45:50.1153837
Prev/Next: 12 hr / 6 hr
Trigger: 20LB,20,100H,100M
Pk/Int/Dif: 16 / 156 / 0
Normal: 87
Owl: 0
Low Gain: 0
Neck: 0
BUTTS: 0
FECD: 2

SNO – variables used

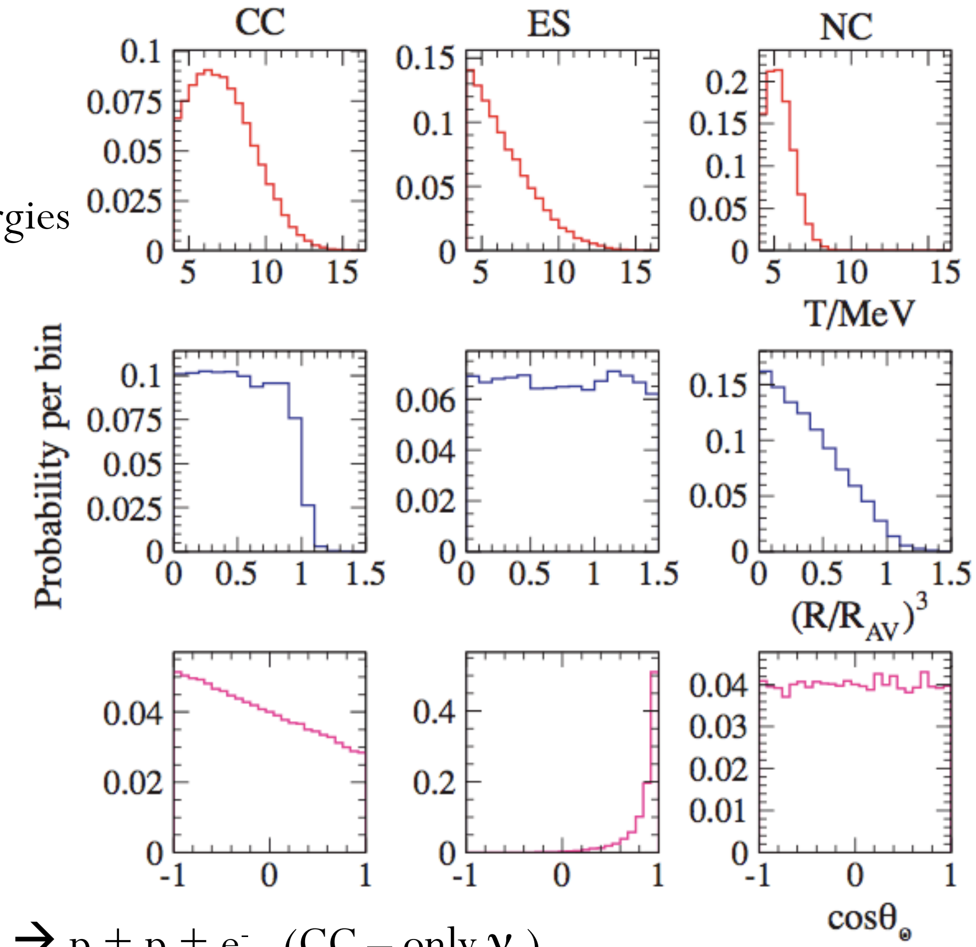
Energy

NB solar neutrinos energies

E_ν<15 MeV

Radius

Direction



$\nu + d \rightarrow p + p + e^-$ (CC – only ν_e)

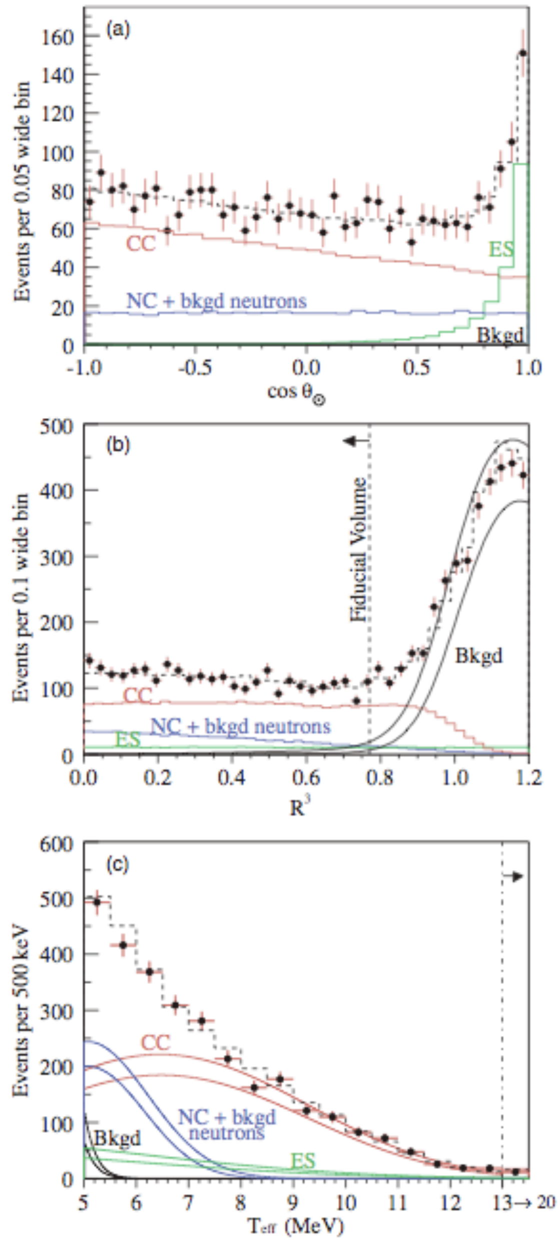
$\nu + e^- \rightarrow \nu + e^-$ (ES – all three flavours BUT different rates)

$\nu + d \rightarrow p + n + \nu$ (NC – all three flavours)

SNO - results

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

$$\phi_{\rm CC} = 1.76^{+0.06}_{-0.05}\,(\text{stat.})^{+0.09}_{-0.09}\,(\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1},$$
$$\phi_{\rm ES} = 2.39^{+0.24}_{-0.23}\,(\text{stat.})^{+0.12}_{-0.12}\,(\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1},$$
$$\phi_{\rm NC} = 5.09^{+0.44}_{-0.43}\,(\text{stat.})^{+0.46}_{-0.43}\,(\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1},$$
$$\phi(\nu_e) = 1.76^{+0.05}_{-0.05}\,(\text{stat.})^{+0.09}_{-0.09}\,(\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1},$$
$$\phi(\nu_{\mu\tau}) = 3.41^{+0.45}_{-0.45}\,(\text{stat.})^{+0.48}_{-0.45}\,(\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}.$$



SNO – result interpretation

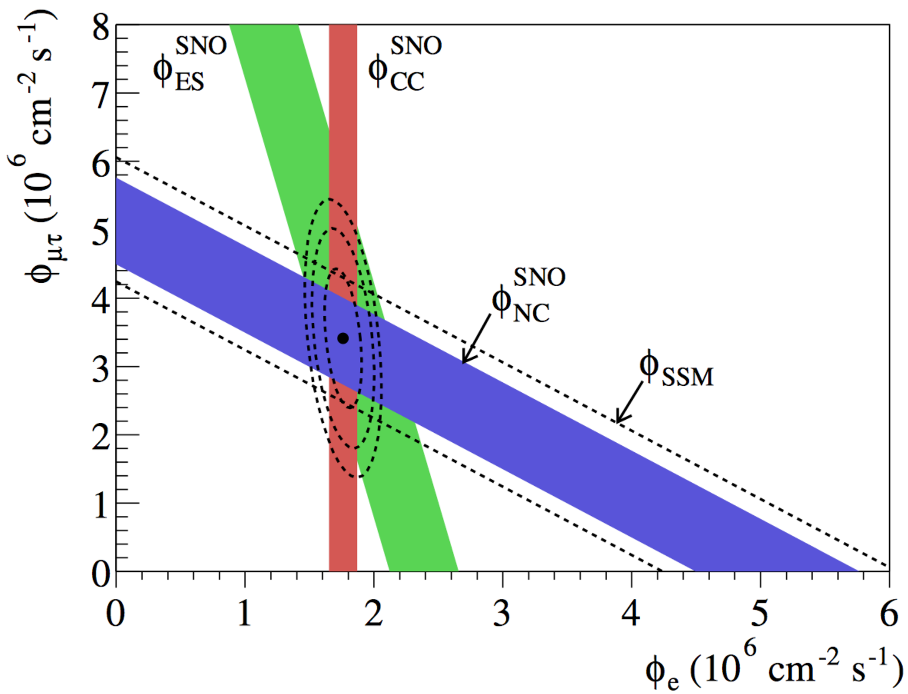


Figure 5: SNO's CC, NC and ES measurements from the D_2O phase. The x- and y-axes are the inferred fluxes of electron neutrinos and muon plus tau neutrinos. Since the NC and ES measurements are sensitive to both ν_e and ν_μ/ν_τ, the ES and NC bands have definite slopes. The CC measurement is sensitive 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}.