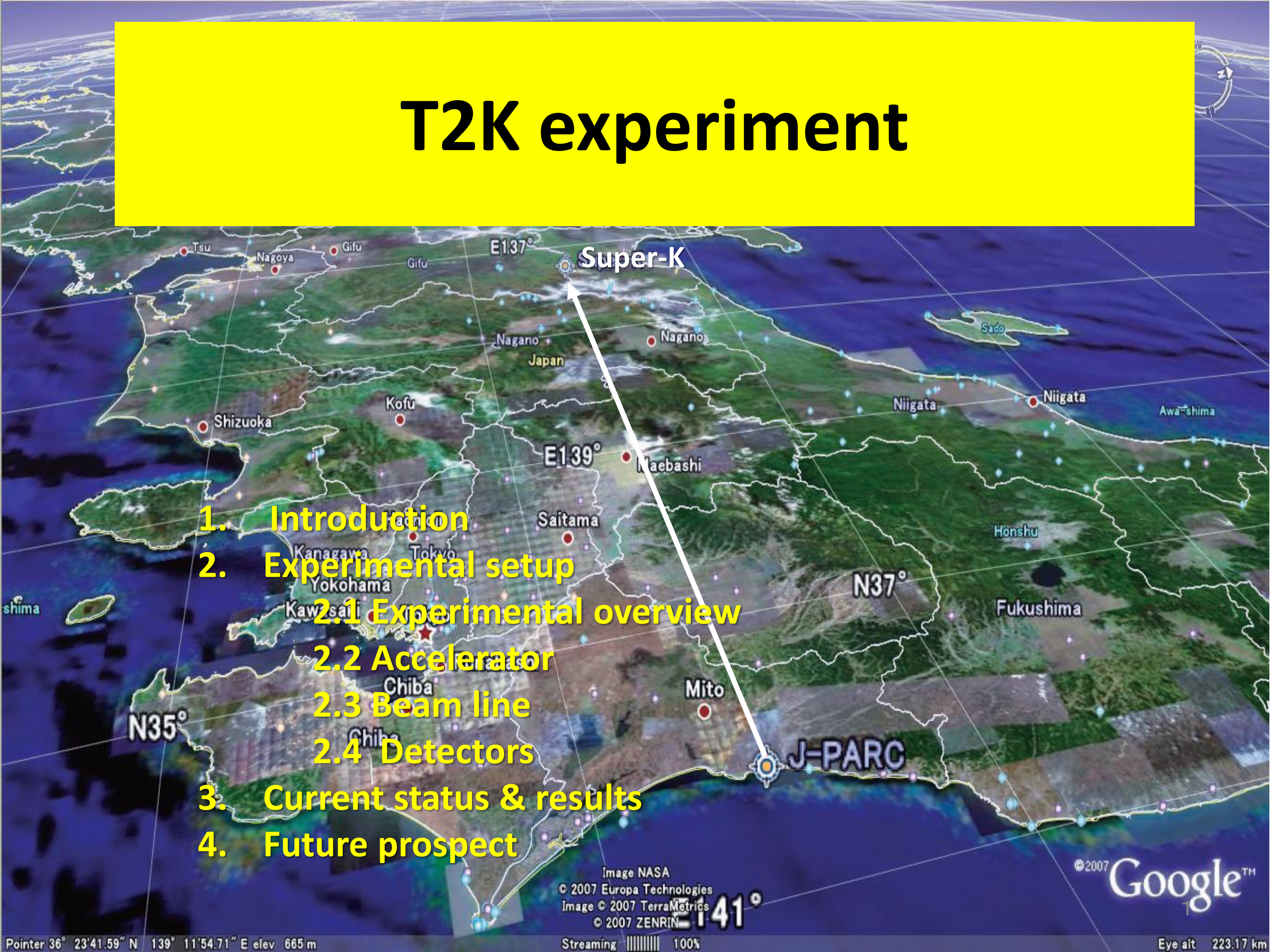
T2K experiment



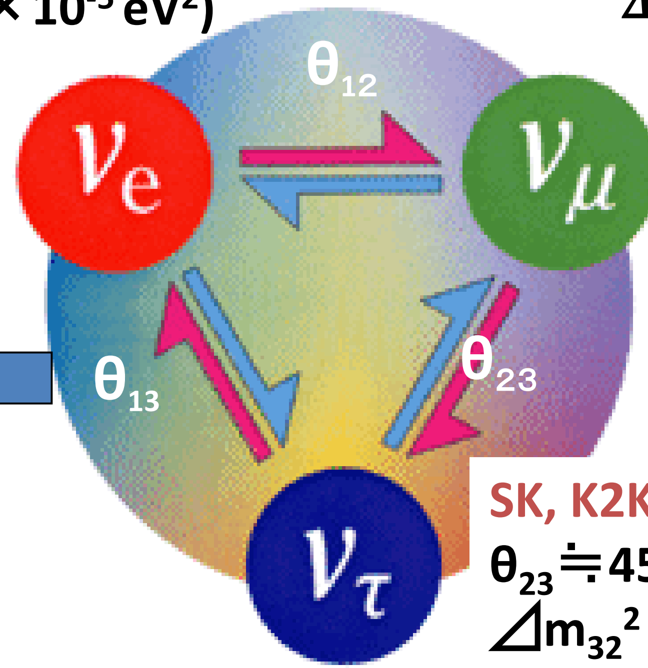
1. Introduction
2. Experimental setup
   - 2.1 Experimental overview
   - 2.2 Accelerator
   - 2.3 Beam line
   - 2.4 Detectors
3. Current status & results
4. Future prospect

1. Introduction

Neutrino oscillation measurement before T2K

SK, SNO, KamLand
(θ_{12}≒34°
$\Delta m_{21}^2 \sim 8\times10^{-5}$ eV^2)

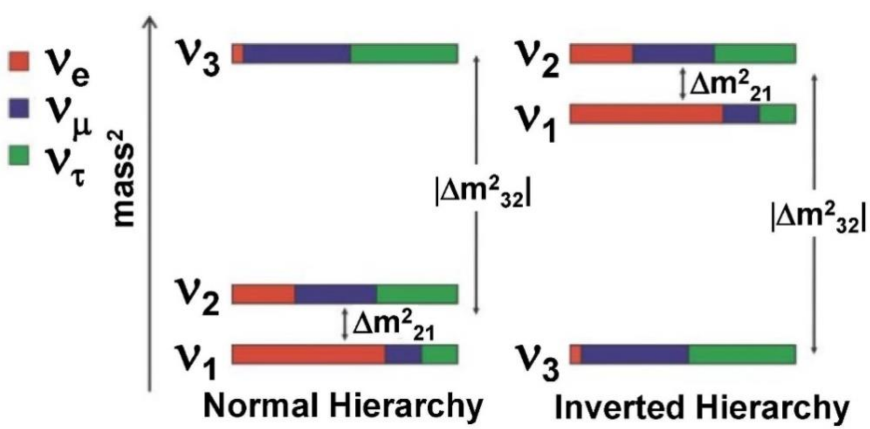
$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$



Not observed

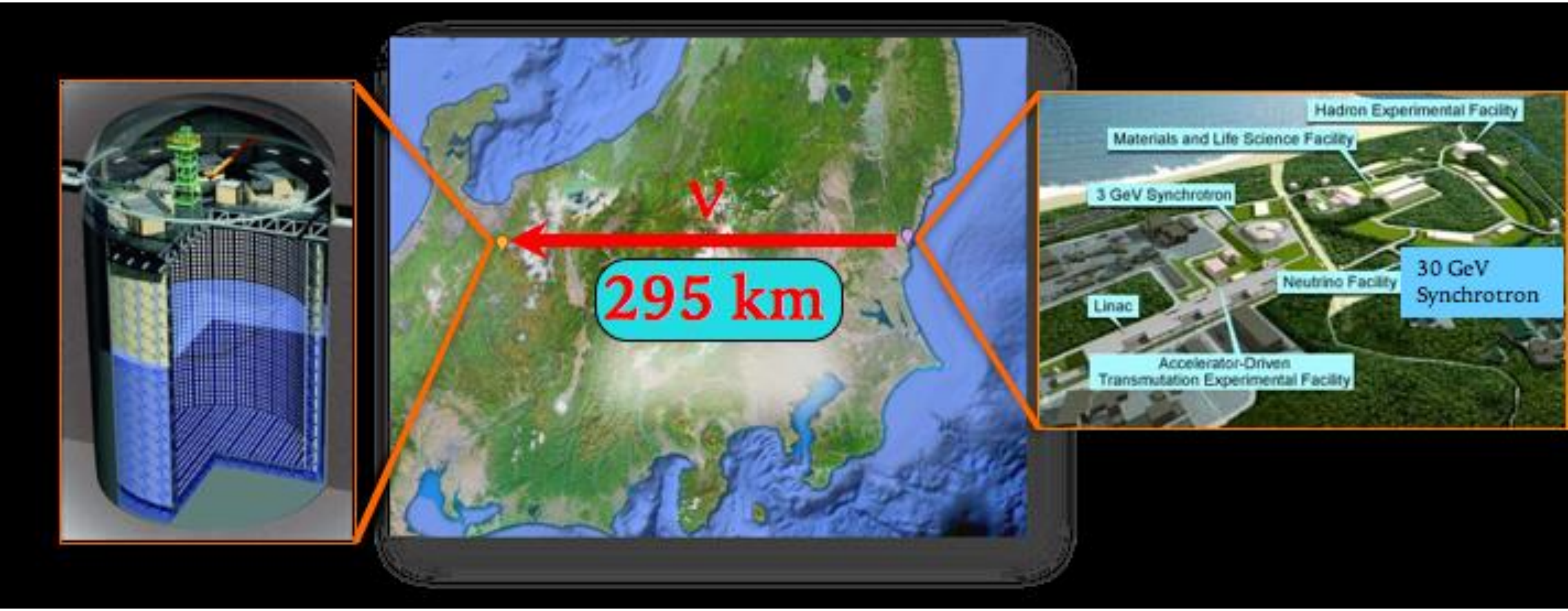
θ_{13} =?, δ_{CP} = ?

SK, K2K, MINOS
θ_{23}≒45°
$\Delta m_{32}^2 \sim 2.5\times10^{-3}$ eV^2



Which mass hierarchy ,
$m_1 < m_2 < m_3$ (Normal Hierarchy, NH) or
$m_3 < m_1 < m_2$ (Inverted Hierarchy, IH) ?

T2K experiment



- Tokai to Kamioka (T2K) long-baseline neutrino oscillation experiment
- Muon neutrinos from J-PARC ⇒ Super-Kamiokande @ 295 km
- T2K accomplishments
  - Discovery of ν_e appearance in 2013
  - World-best precision measurement of ν_μ disappearance

The main goals of T2K

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

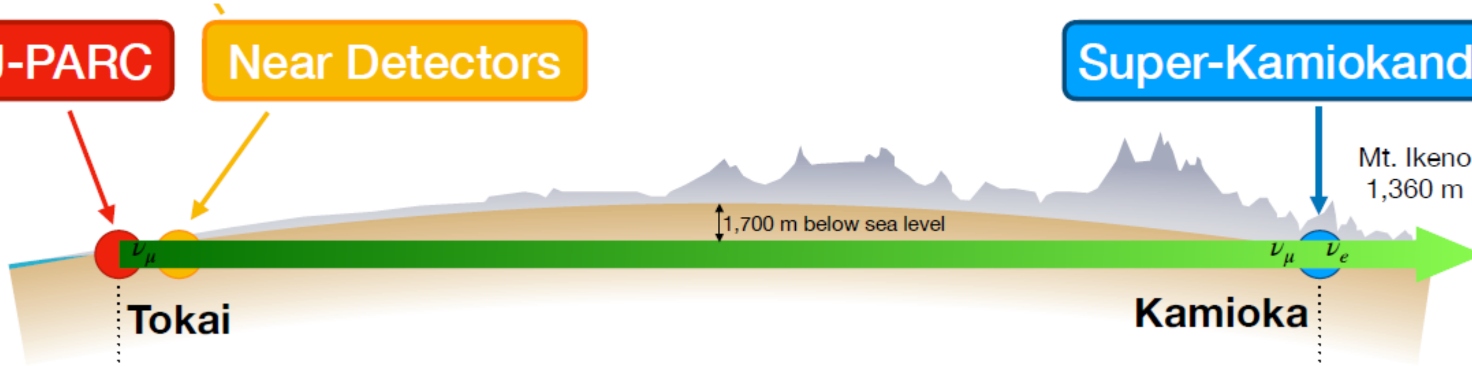
Flavor eigen states | **Atmospheric term** | **Reactor term** | **Solar term** | **Mass eigen states**

$$C_{ij} = \cos\theta_{ij}, S_{ij} = \sin\theta_{ij}$$

- **ν_μ disappearance** (We measure how much ν_μ's disappear after the flight.)
  ⇒ **θ_{23}, $\Delta m_{32}{}^2$ precision measurement** (Neutrino energy of T2K is low and τ cannot be produced.*)
- **ν_e appearance** (We measure how much ν_e's which do not exist originally appear after the flight.)
  ⇒ **θ_{13}, δ_{CP} measurement**

*Homework 1
How much energy do we need for a neutrino to produce a τ?

T2K experiment



ν mode

$\nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu$ → $\nu_\tau, \nu_\tau, \nu_\tau, \nu_e, \nu_e, \nu_\mu, \nu_\mu$

(Forward Horn Current, FHC)

$\bar{\nu}$ mode

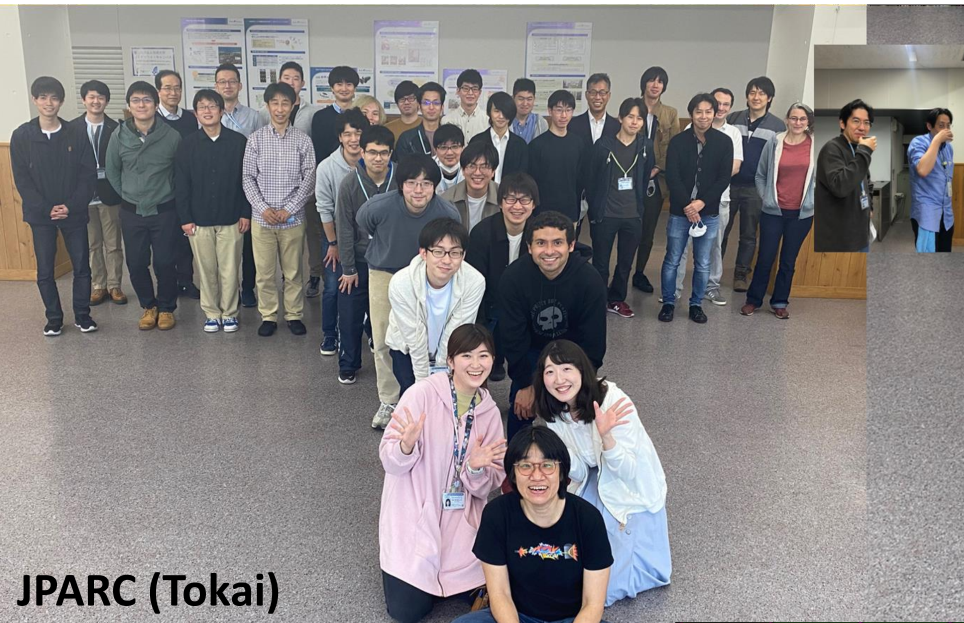
$\bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu$ → $\bar{\nu}_\tau, \bar{\nu}_\tau, \bar{\nu}_\tau, \bar{\nu}_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\mu$

(Reversed Horn Current, RHC)

For δ_{CP}, look for $\nu/\bar{\nu}$ difference of ν_e appearance

$P(\nu_\mu \to \nu_e) = P(\overline{\nu_\mu} \to \overline{\nu_e})$?

T2K Collaboration



JPARC (Tokai)

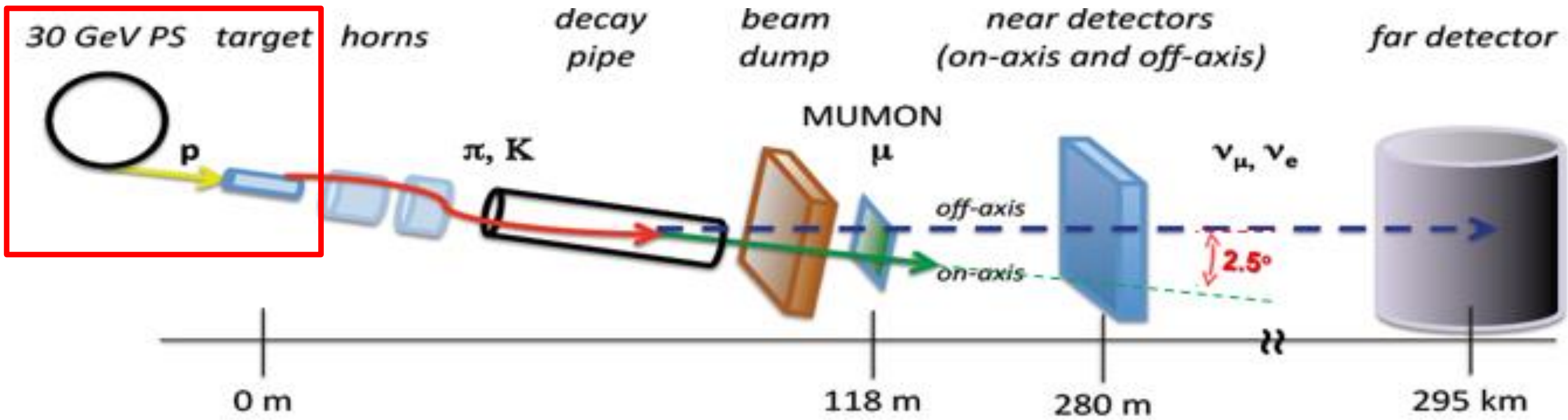
CERN

Virtual

~530 members, 76 institutes, 14 countries

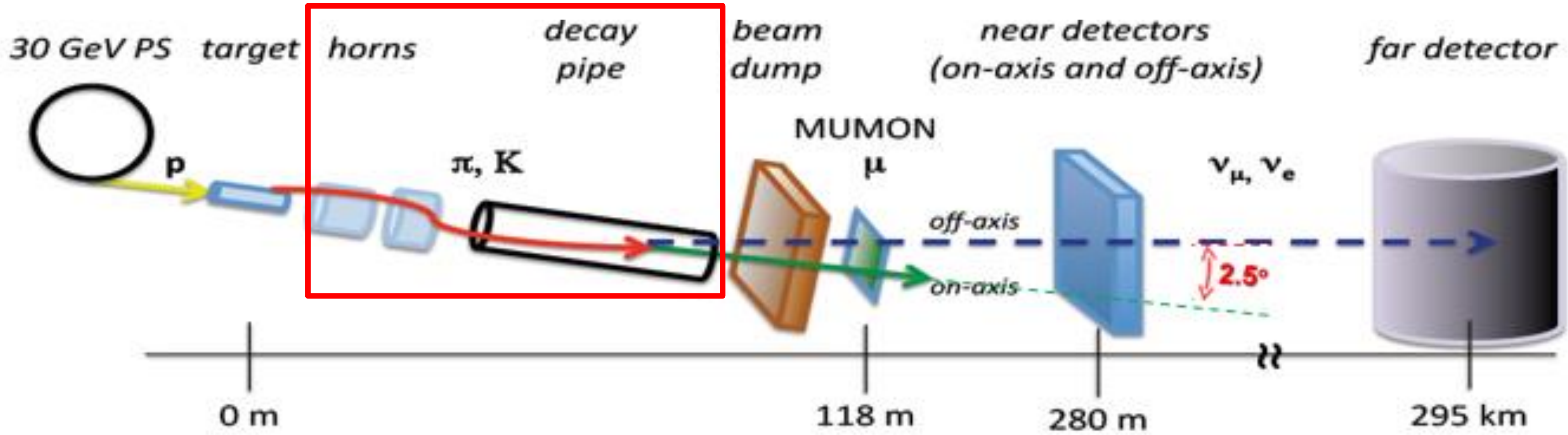
2. Experimental setup

2.1 Experimental overview



- **High intensity proton beam hits the graphite target.**
- **Secondary π/K's focused by magnetic horns and decay to neutrinos**
  - **Neutrino beam from $\pi^+ \rightarrow \mu^+ + \nu_\mu$**
  - **Antineutrino beam from $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$**
  - **Changing neutrino beam mode by flipping the horn polarity**
- **Beam dump absorbs remained hadrons & the direction & intensity of the muons from $\pi(K) \rightarrow \mu + \nu$ are measured by MUMON.**
- **Unoscillated neutrinos are measured by near detectors**
- **Neutrinos are measured by far detector 295km far away from target**

2.1 Experimental overview



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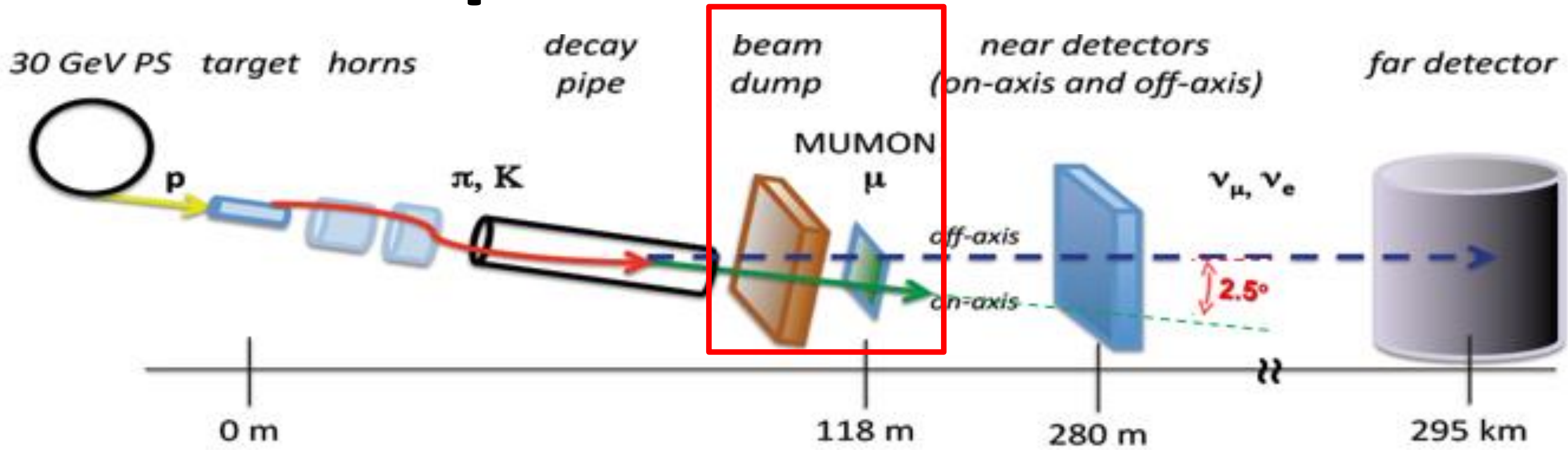

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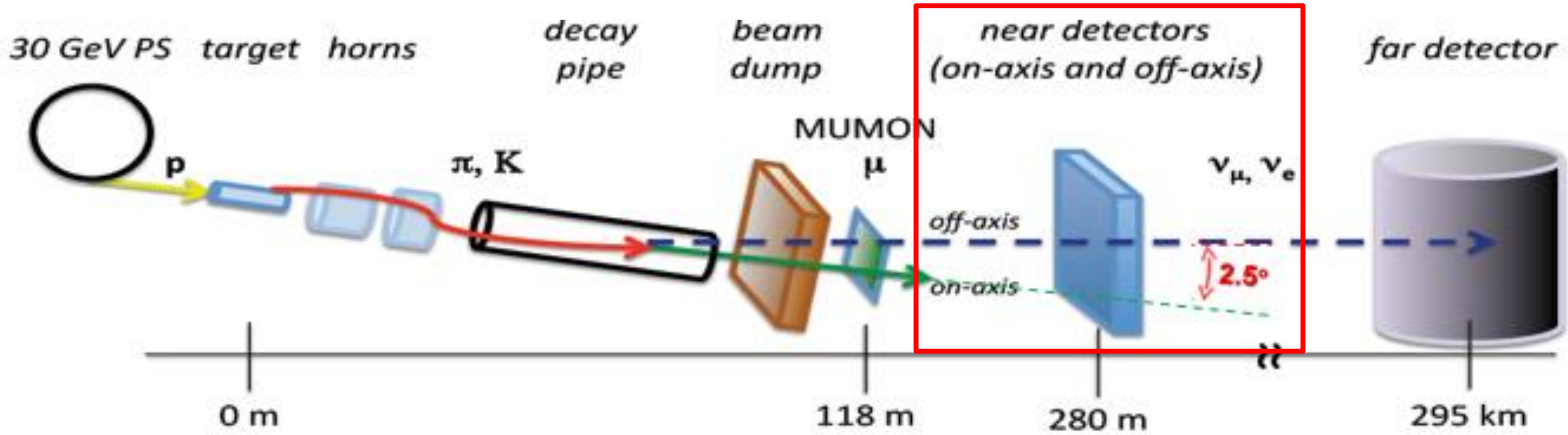

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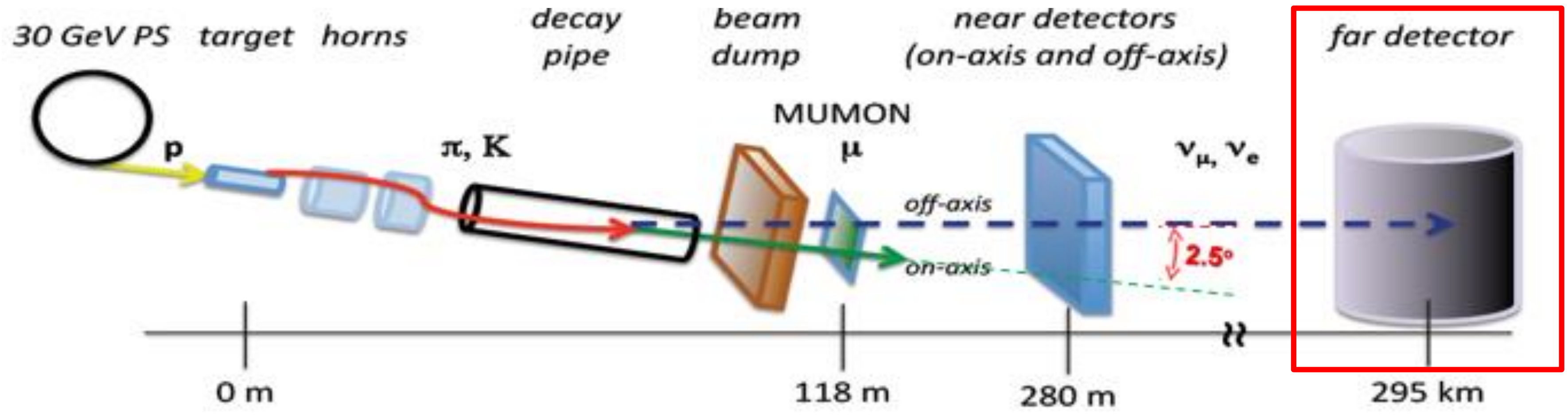

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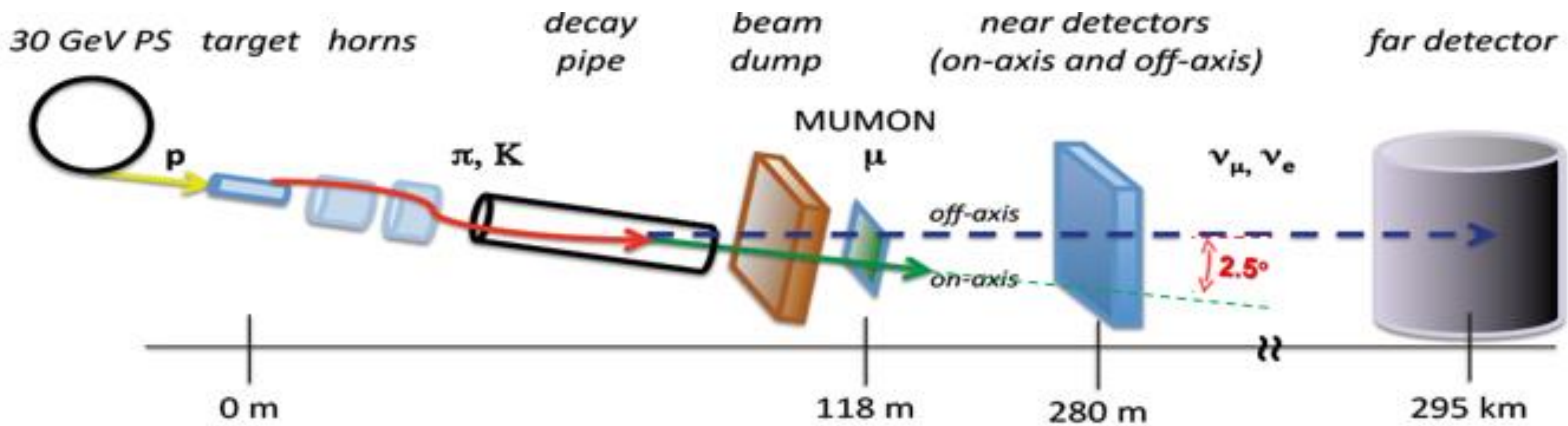
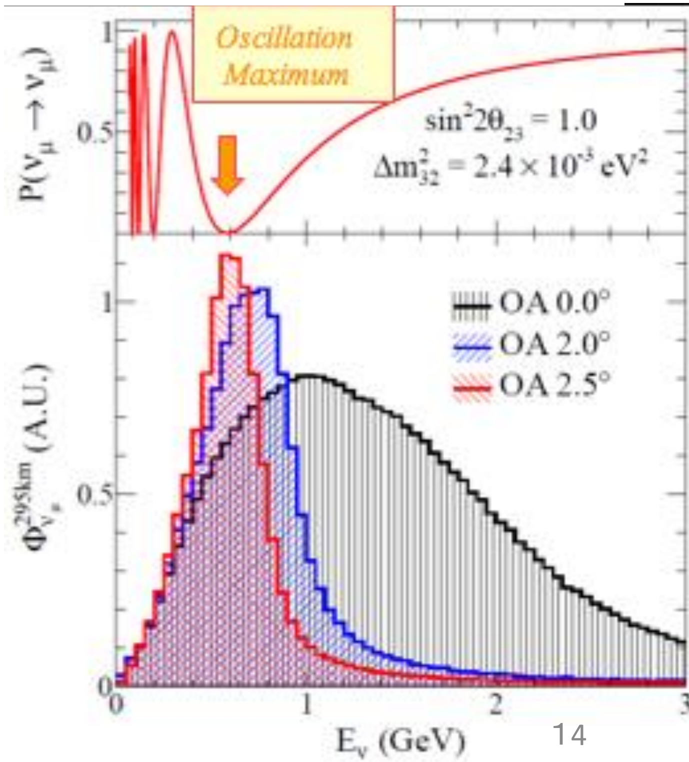
- **Unoscillated neutrinos are measured by near detectors**
- **Neutrinos are measured by far detector (SK) 295km far away from target.**

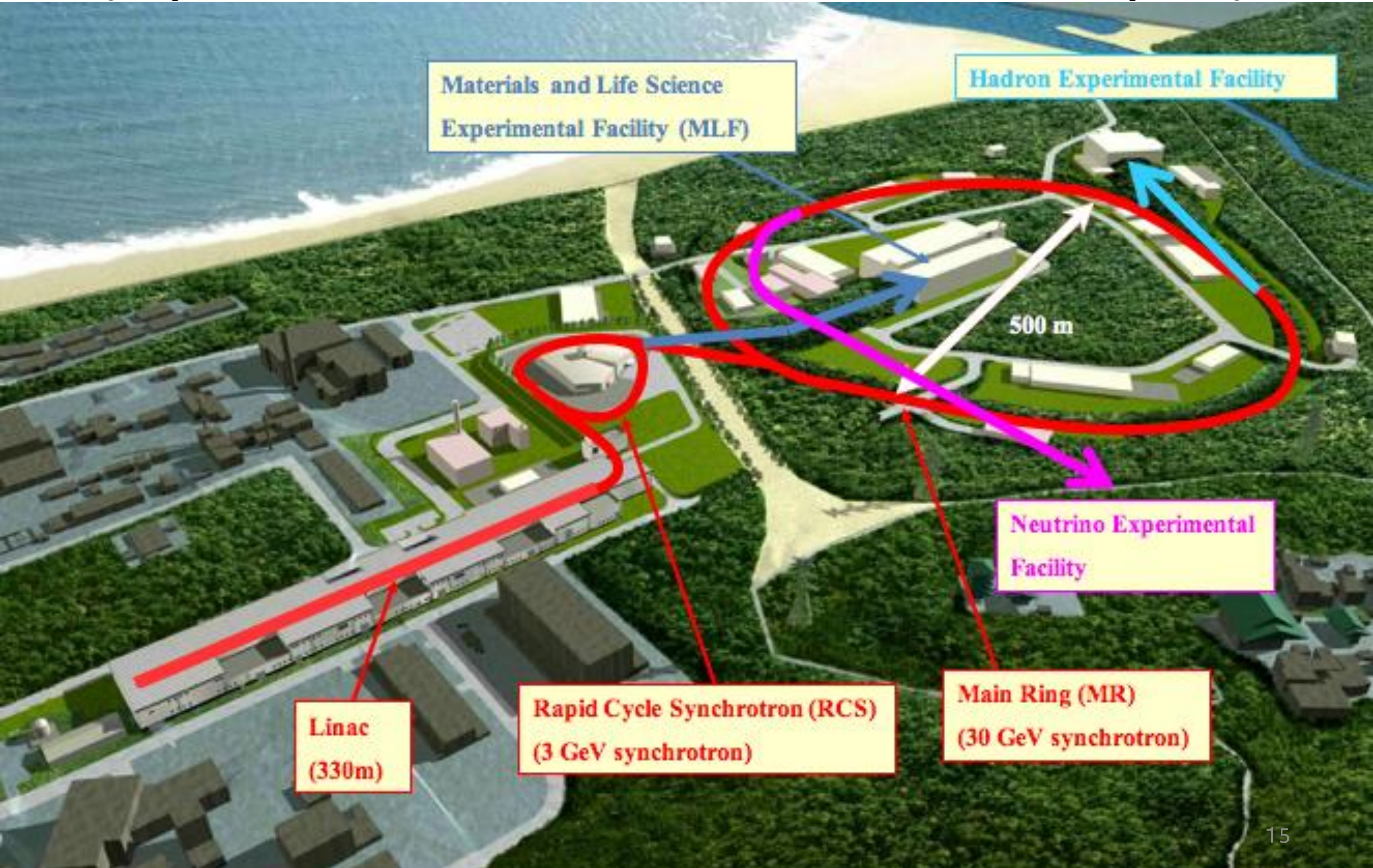
2.1 Experimental overview



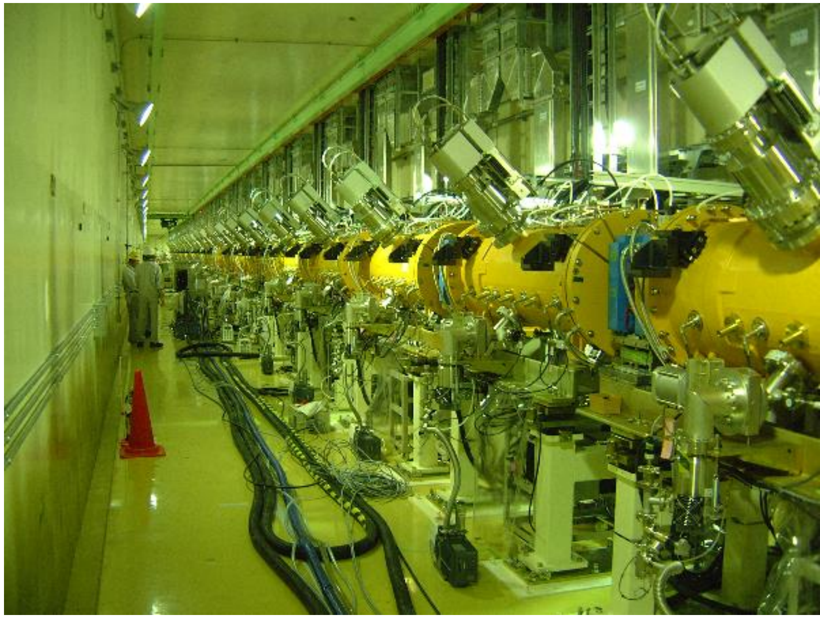
- **2.5° off-axis neutrino beam**
  - **Narrow band beam below 1 GeV**
  - **Peak at 0.6 GeV at oscillation max w/ 295km**
  - **Small high energy tail**
    - **High energy neutrino background can be suppressed**



2.2 J-PARC
(Japan Proton Accelerator Research Complex)



Linac (Linear accelerator)



- The first stage accelerator, 330 m in length.
- Protons are accelerated to 400 MeV.

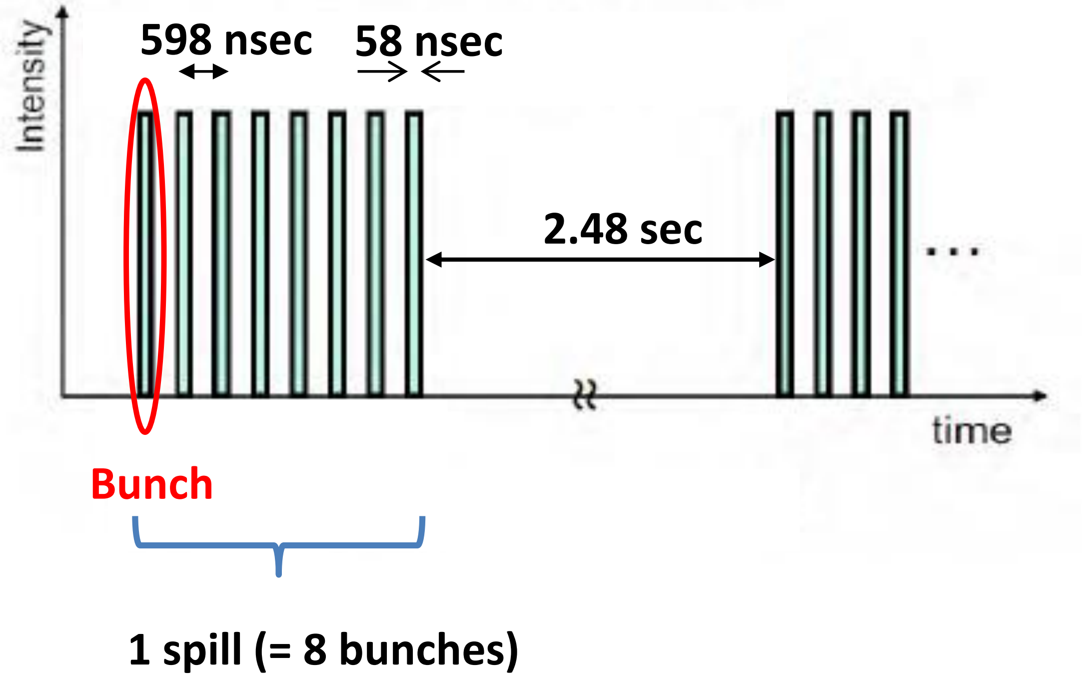
RCS
(Rapid Cycling Synchrotron)

- The second stage accelerator, Proton Synchrotron of 348 m circumference.
- Protons are accelerated up to 3 GeV.

Main Ring

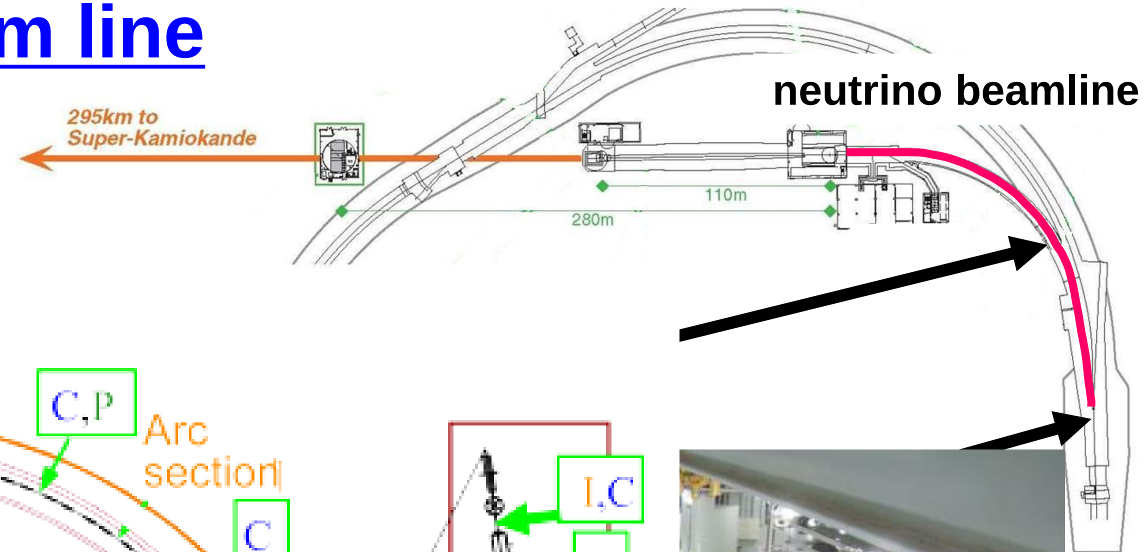
- The third (and final) stage accelerator. Proton Synchrotron
of 1568 m circumference.
- The 30 GeV proton beam is extracted to the neutrino
beamline and to hadron hall.

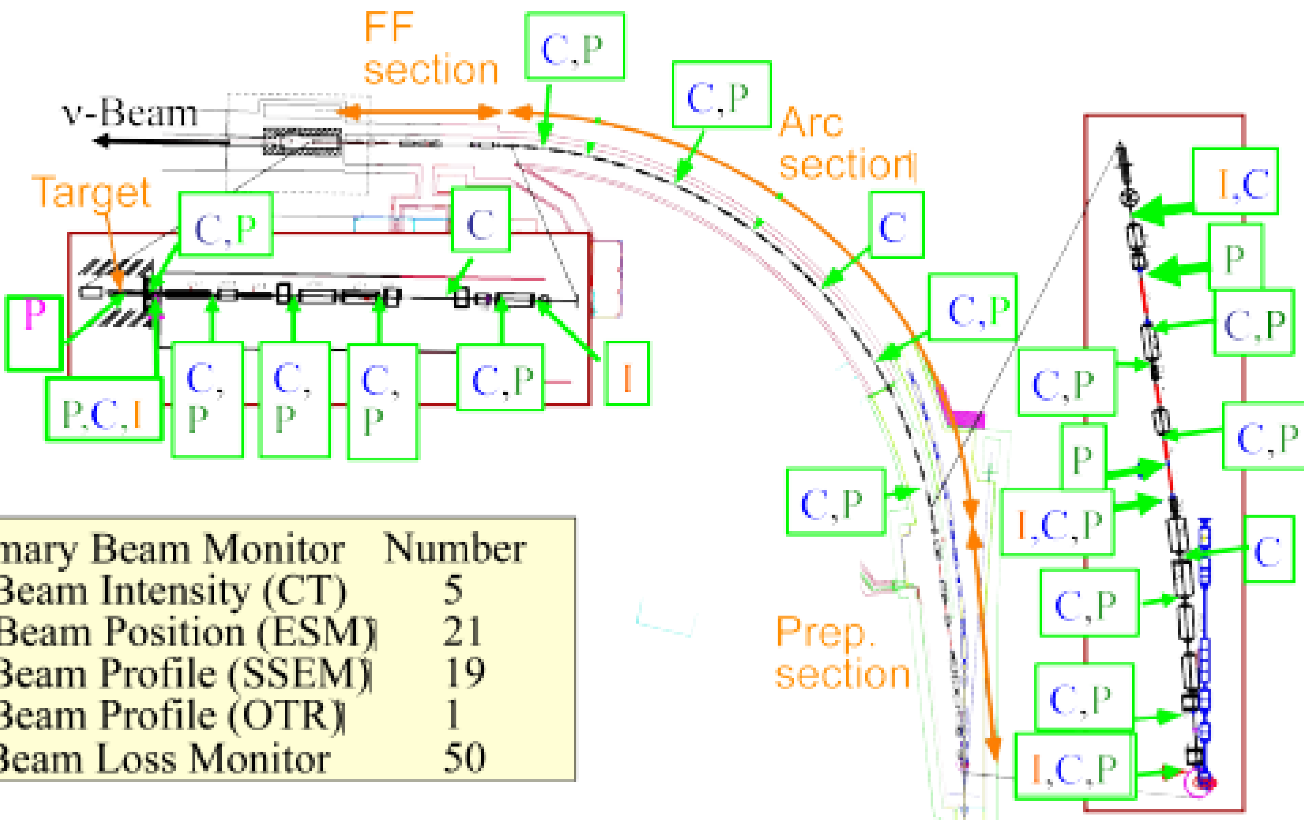
Proton beam to neutrino beam line



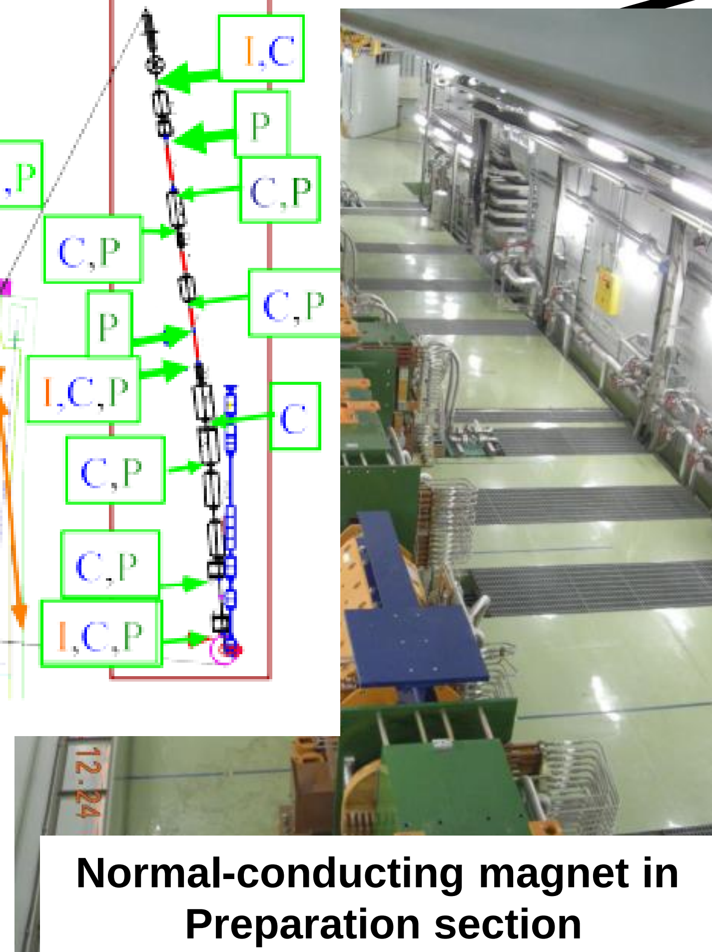
2.3 Beam line

Primary Proton beam line



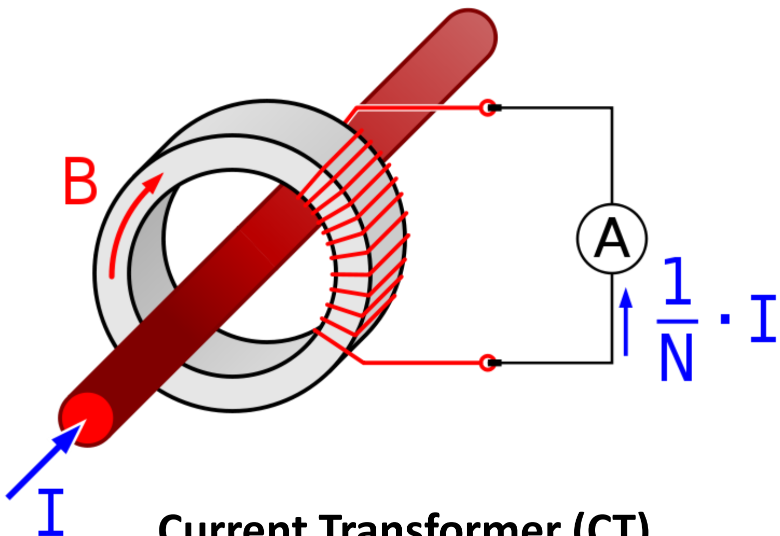


Primary Beam Monitor	Number
I : Beam Intensity (CT)	5
C: Beam Position (ESM)	21
P: Beam Profile (SSEM)	19
P: Beam Profile (OTR)	1
Beam Loss Monitor	50

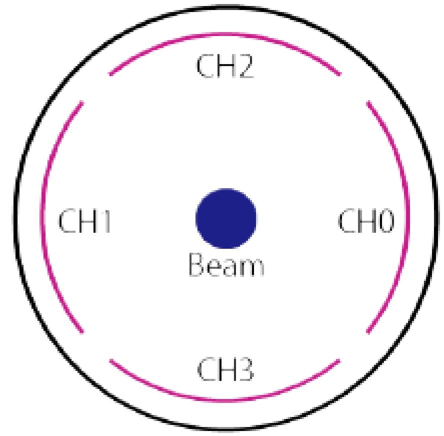


Normal-conducting magnet in Preparation section

Beam monitors



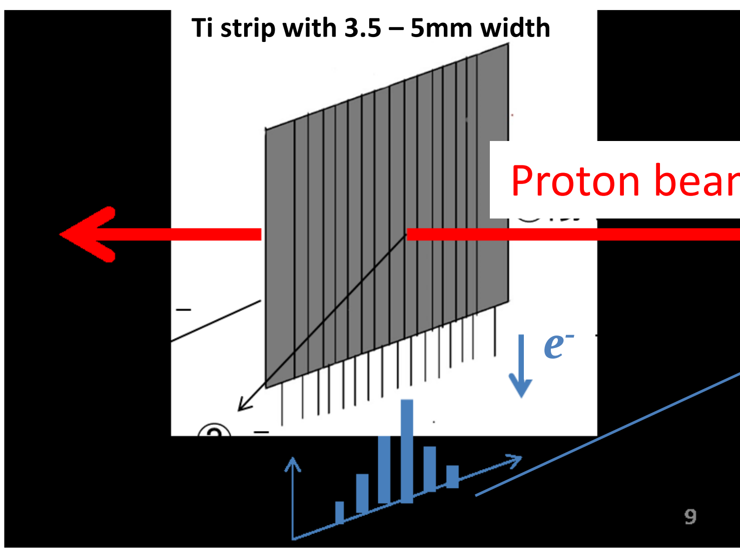
Current Transformer (CT)

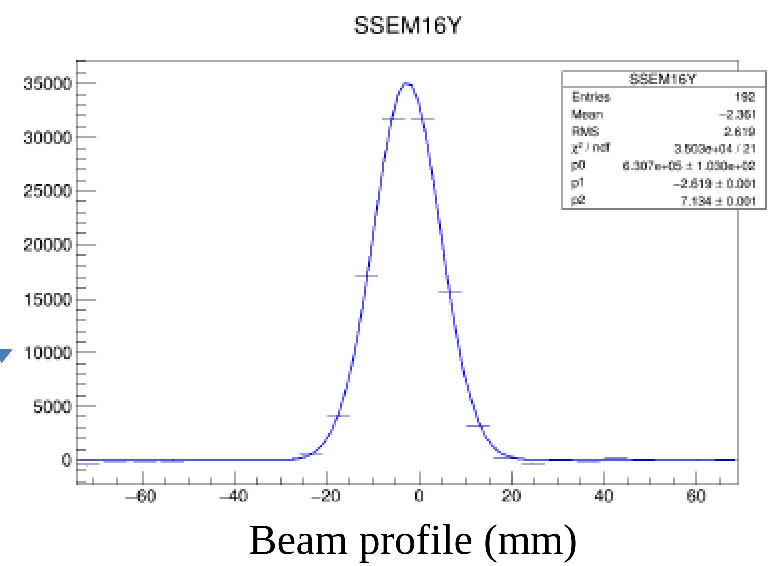


$$x \propto \frac{CH0 - CH1}{CH0 + CH1}$$

$$y \propto \frac{CH2 - CH3}{CH2 + CH3}$$

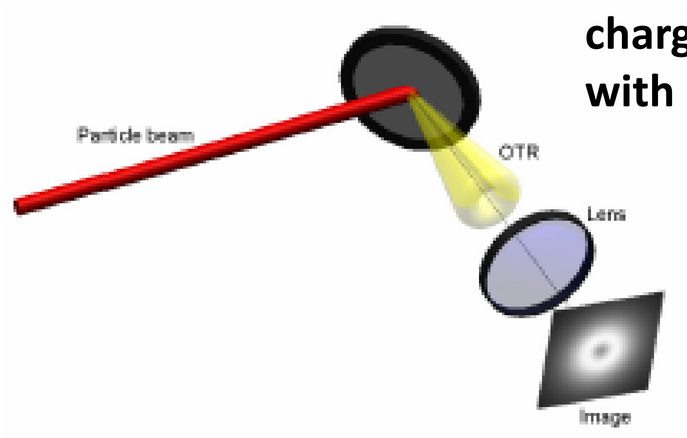
Electrostatic Monitor (ESM)





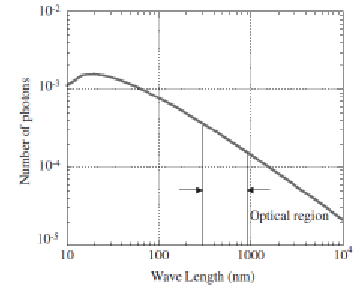
Secondary Segmented Emission Monitor (SSEM)

Optical Transition Radiation monitor (OTR)

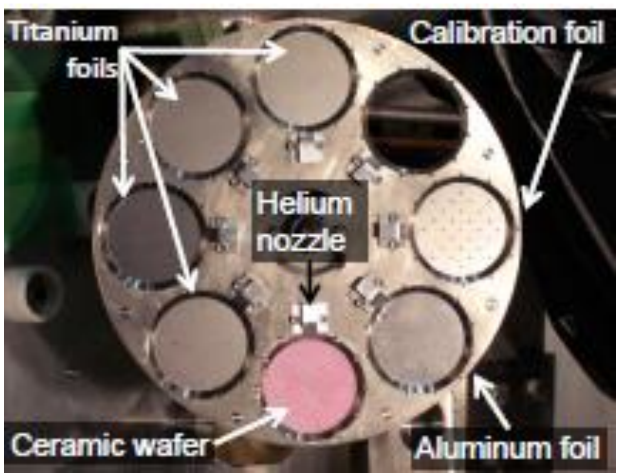


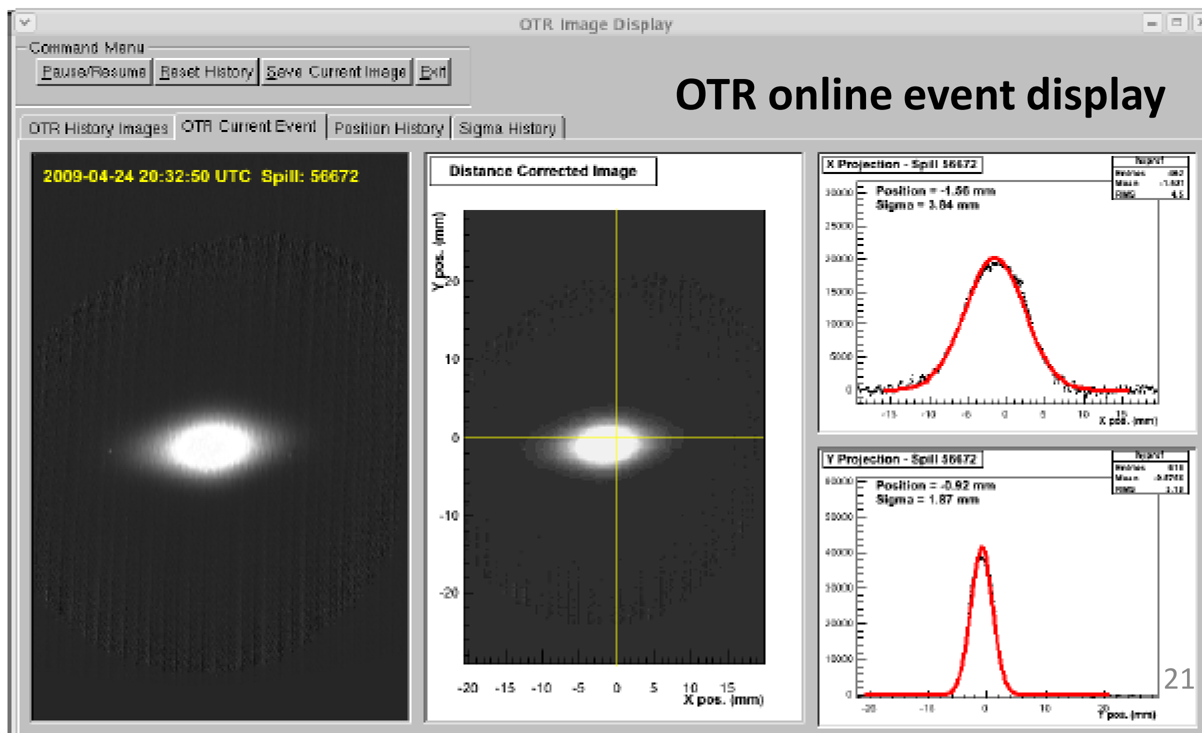
Transition radiation is a form of EM radiation emitted when a charged particle crosses the boundary between two media with different permittivities.

$$\frac{dN_{photon}}{d\lambda} = \frac{2\alpha}{\pi\lambda}\left\{\ln\left(\frac{\gamma\lambda}{\lambda_{pe}}\right) - 1\right\}$$

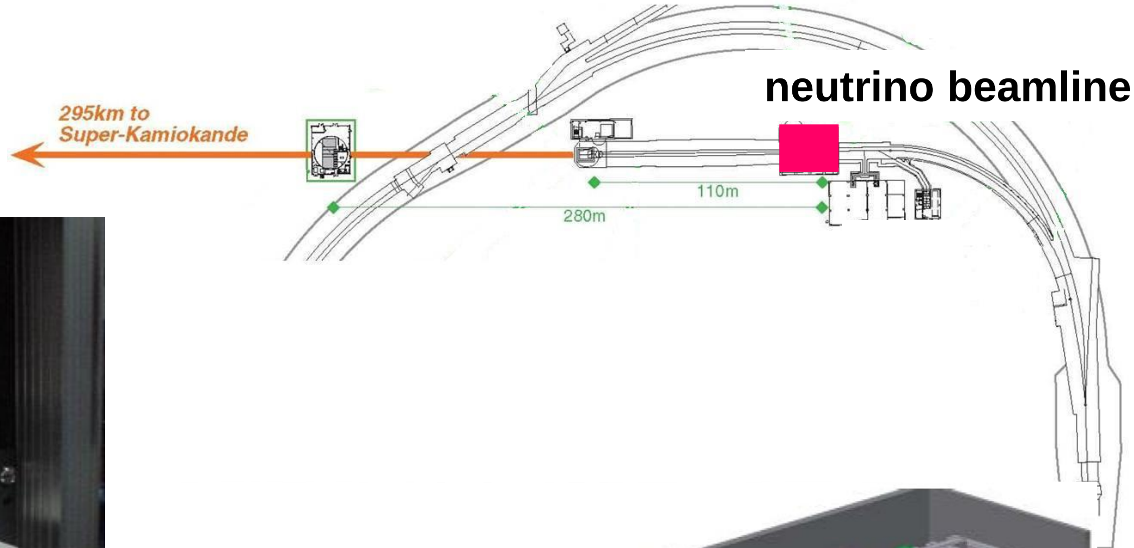


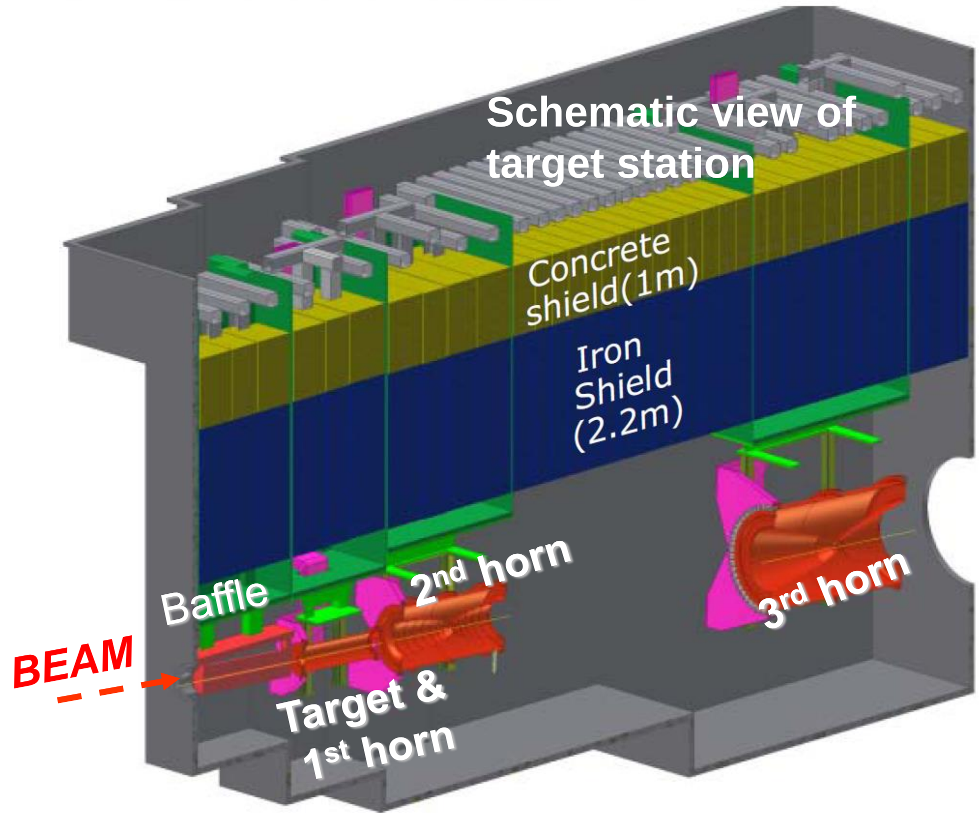
F. Sakamoto, et. al - **Emittance and energy measurements of low-energy electrons beam using optical transition radiation techniques**, JJAP vol.44, 3, 2005, 1485-1491.

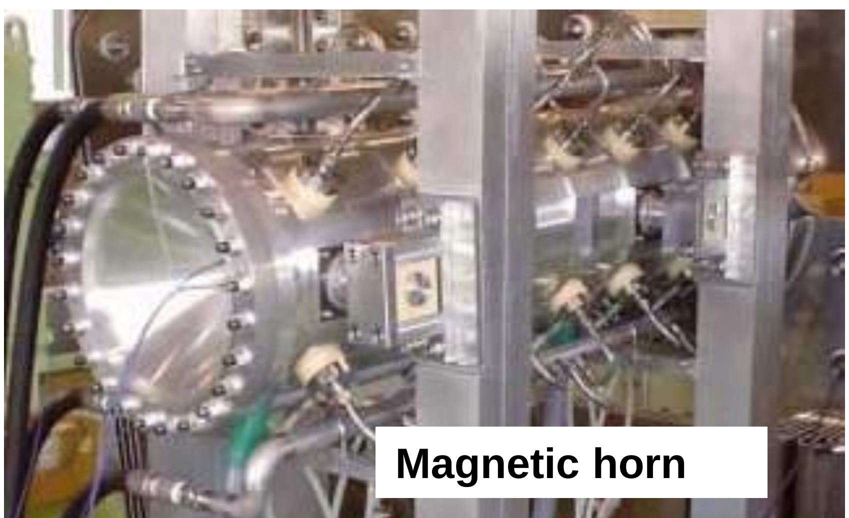




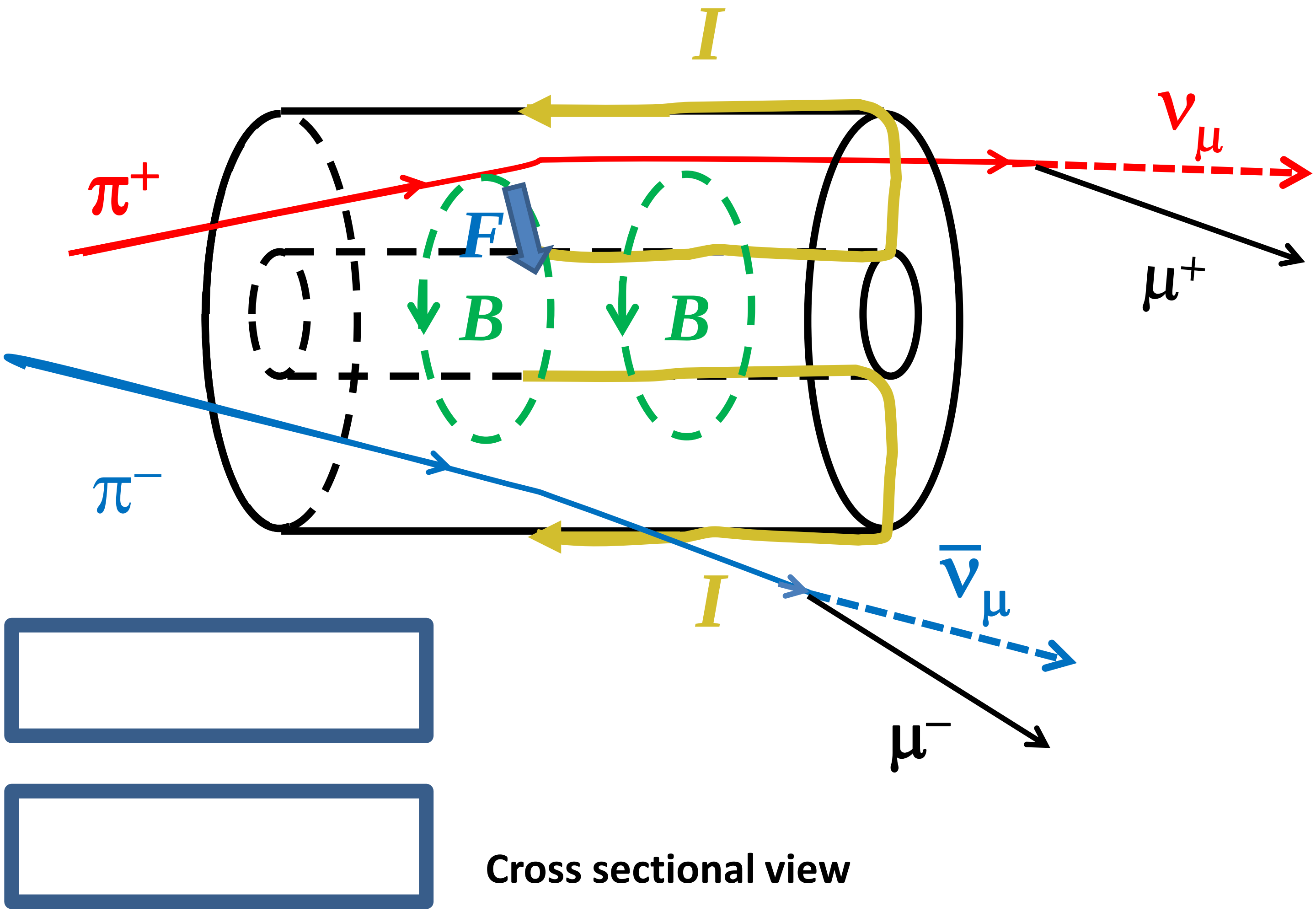
Target Station







Magnetic horn



Cross sectional view

Magnetic horn

- Magnetic horn is **focus/defocus** device installed just downstream of the target. High current (**~320kA**) generate magnetic field, and direction of π's are changed.

- In ν-mode, π^+ is focused and π^- is defocused. Accordingly, ν-rich beam is generated in the forward direction.

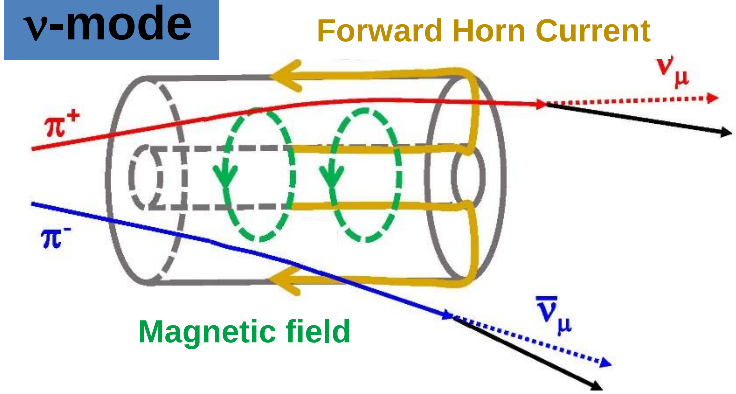
- In $\bar{\nu}$-mode, π^- is focused, and π^+ is defocused. $\bar{\nu}$-rich beam is generated in the forward direction.

- Neutrino flux at SK is enhanced by factor **~10** (total) and **~16** (at ~0.6GeV).

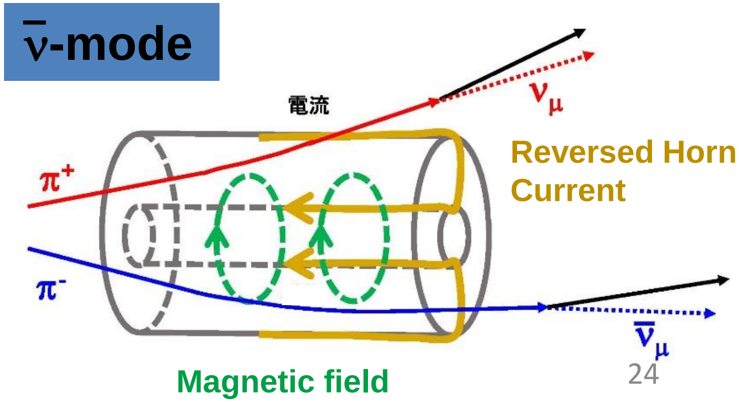
- Neutrino components in each mode:

	ν_μ	$\bar{\nu}_\mu$	$\nu_e+\bar{\nu}_e$
ν-mode	~97%	~2%	~1%
$\bar{\nu}$-mode	~2%	~97%	~1%

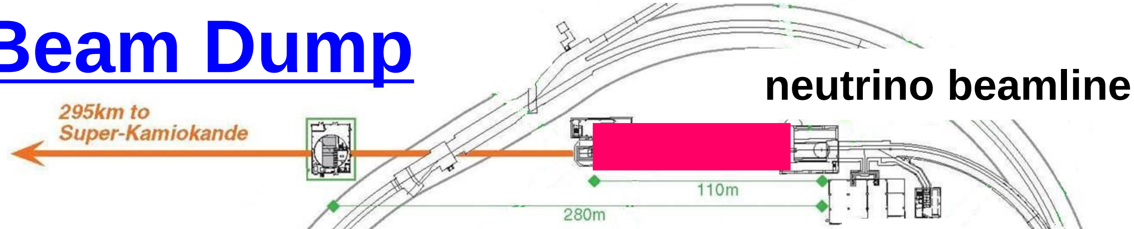
ν-mode



$\bar{\nu}$-mode

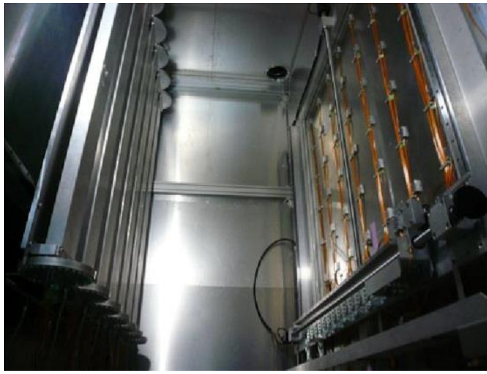


Decay Volume and Beam Dump



neutrino beamline

Muon monitors in Muon Pit



Remaining protons and undecayed π-mesons are absorbed by a **beam dump** composed of large graphite blocks.

Beam Dump (installation)

Installation of decay volume

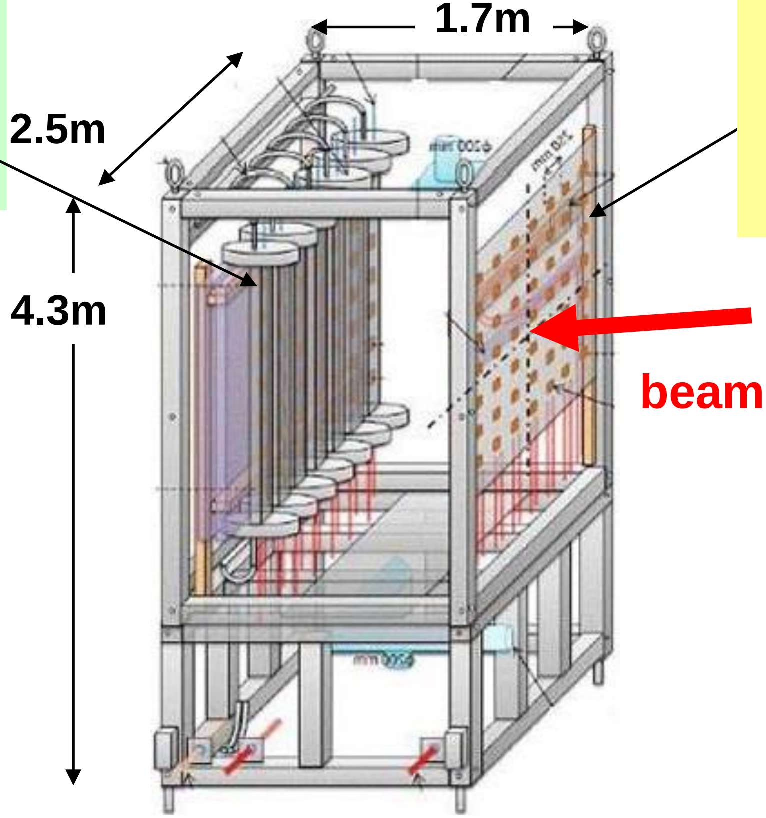
Inside of decay volume (rectangular shape)

Muon monitors

- Two types of muon monitors are installed downstream of the beam dump for redundancy.

Ionization chamber

7x7 channels
Ar+2%N_2gas (~Mar. 2015)
He+1%N_2gas (May~ 2015)



Semiconductor array

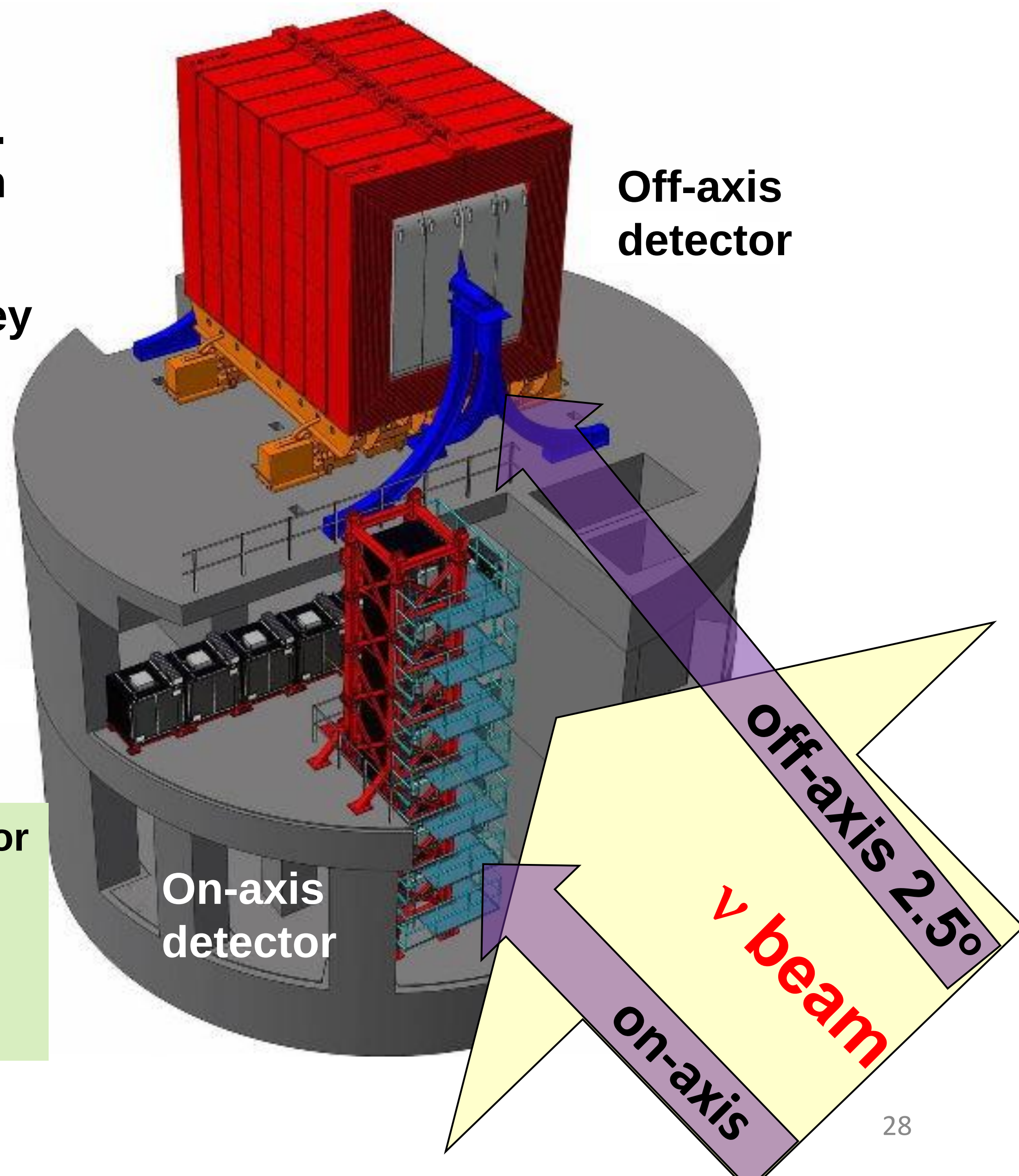
7 x 7 channels of Silicon PIN photo diode.

- Confirm the position of the beam center with < 3cm resolution on a bunch by bunch basis. This corresponds to < 0.3mrad beam direction accuracy.

2.4 Detectors

Near Detectors at 280m downstream

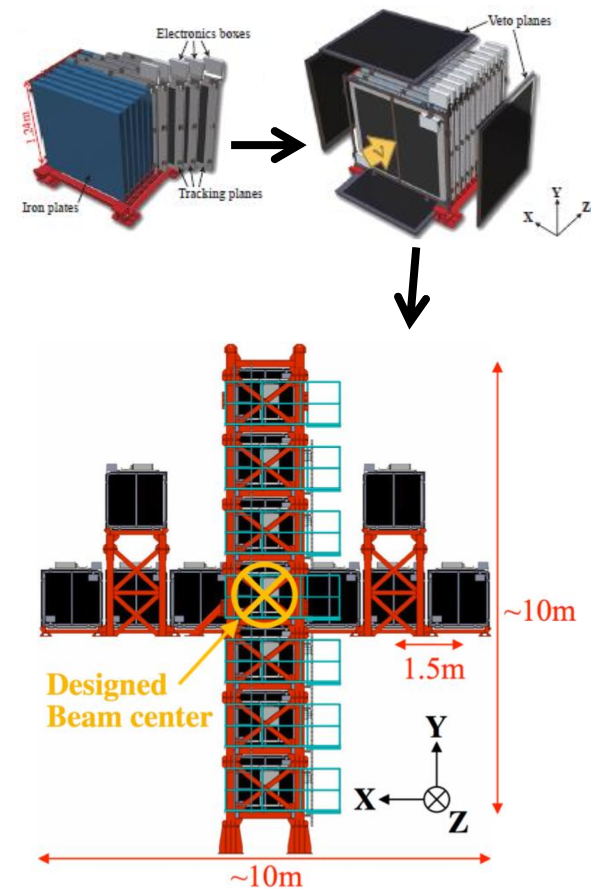
- The detectors were made in the underground experimental hall, 33.5m depth and 17.5m diameter. It is located at 280m downstream from the target.
- Two detectors were installed; they are On-axis Detector in the direction of the neutrino beam center, and Off-axis detector in the direction of Super-Kamiokande.



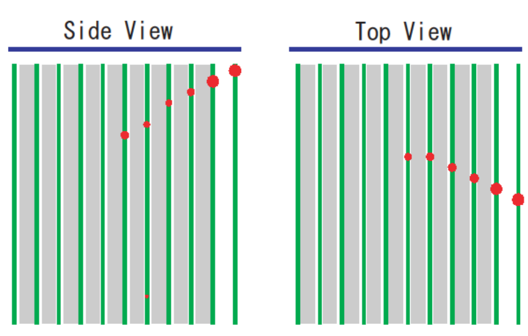
Unlike K2K, a water Cherenkov detector cannot be used in T2K near detector.
-Event rate is too high.
-Neutrino energy is high and muons escape from an 1kt tank.

On-axis detector (INGRID)

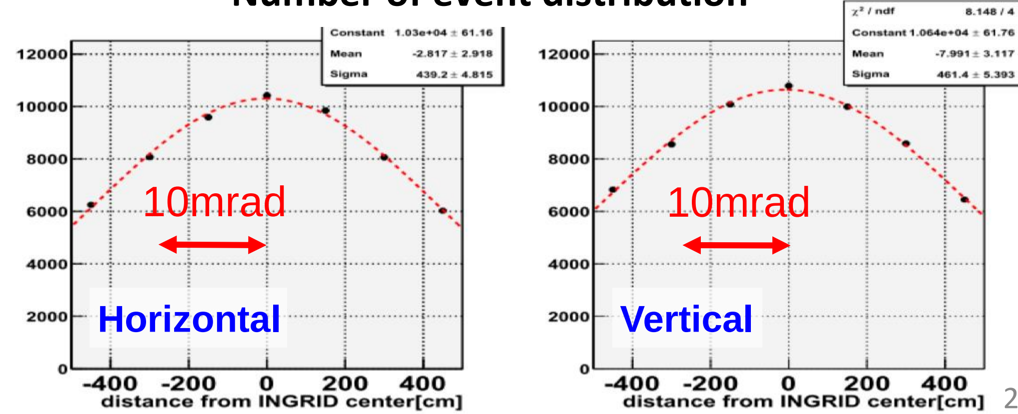
- Consists of 16 modules; 7 horizontal, 7 vertical, and 2 off-diagonal. Each module is 1m x 1m x 1m cube.
- Each module is "sandwich" of 11 plastic scintillator layers and 10 iron layers. They are surrounded by 4 veto planes.
- The neutrino beam center is obtained from horizontal/vertical distributions of the neutrino event rate. The nominal accuracy is ~0.1 mrad.



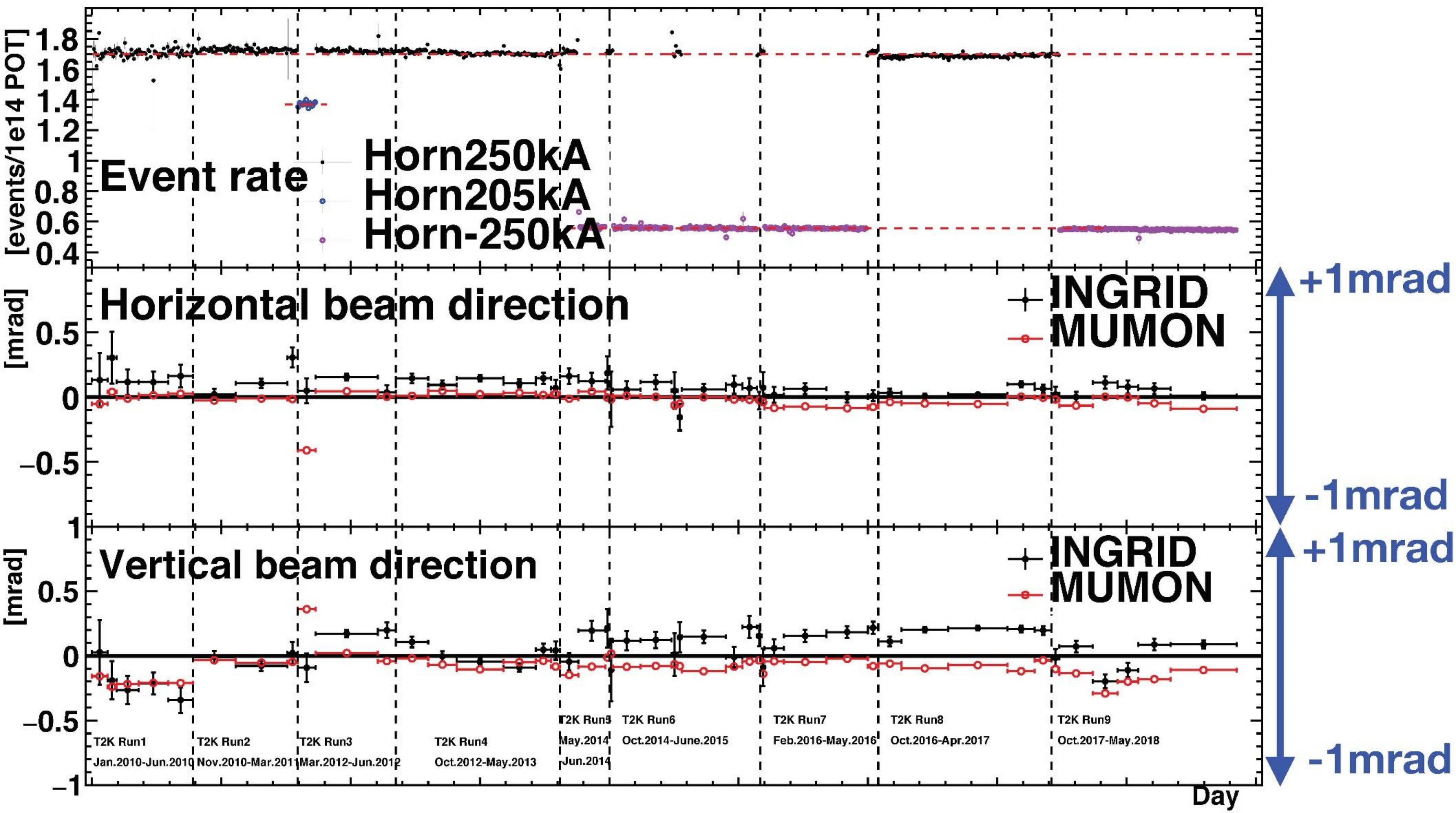
INGRID event view



Number of event distribution

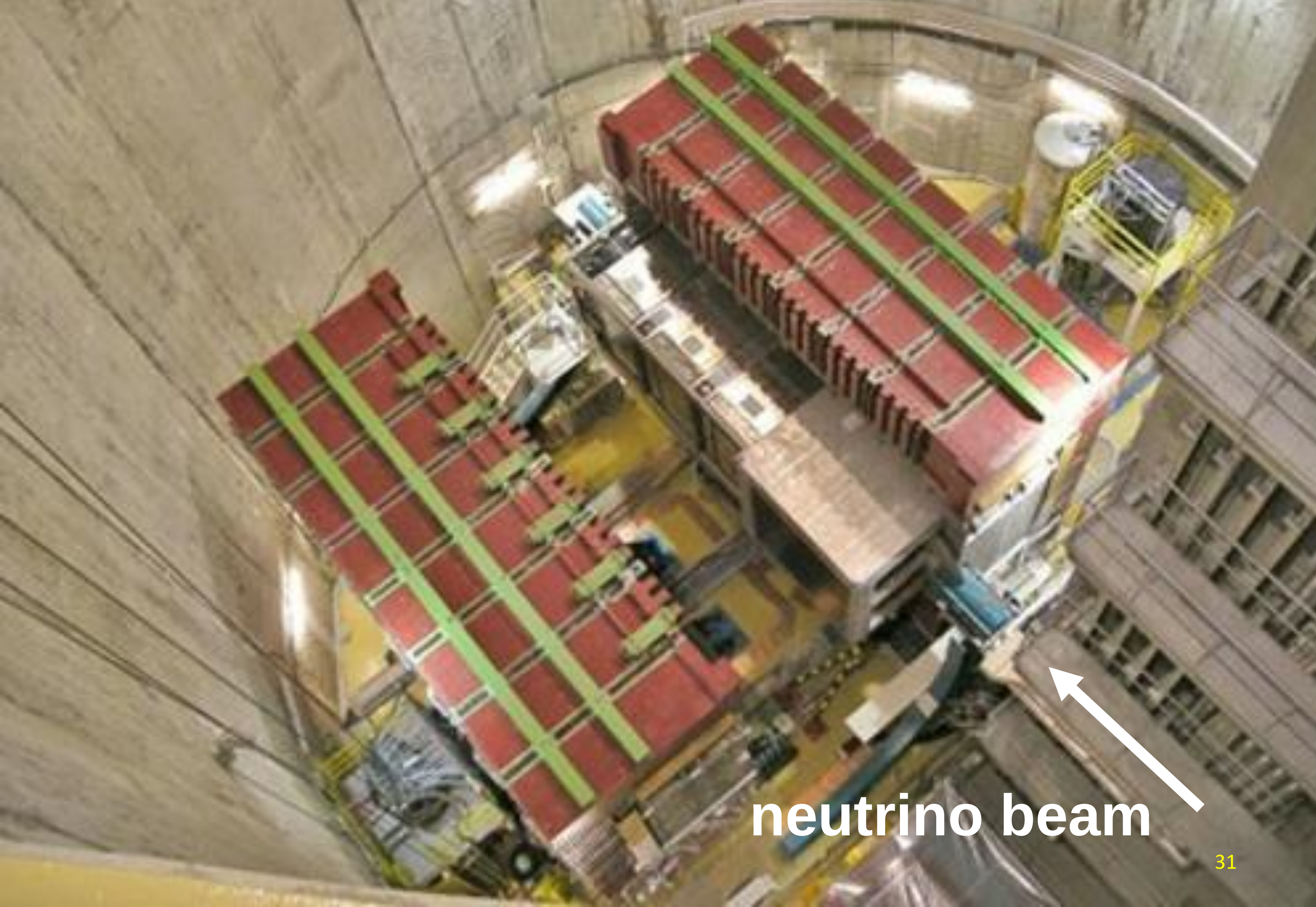


Stability of event rate and beam direction



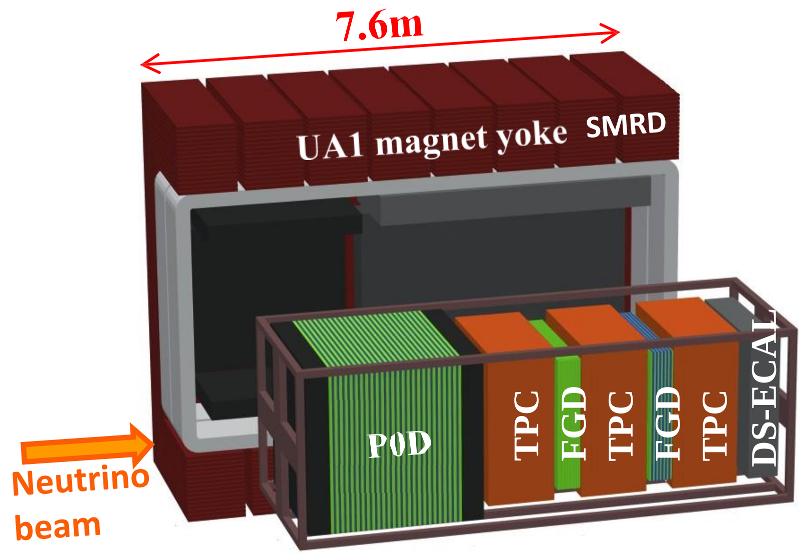
- Event rate is stable over neutrino and anti-neutrino periods.
- Beam direction is much stable than our requirement, 1 mrad.

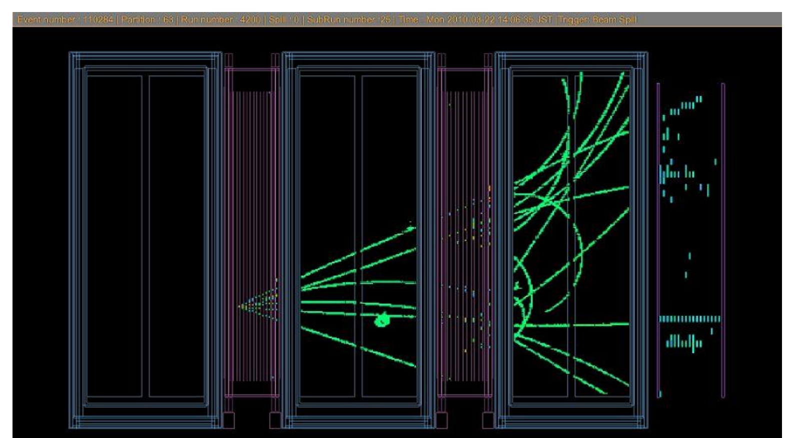
ND280 detector



Off-axis detector (ND280)

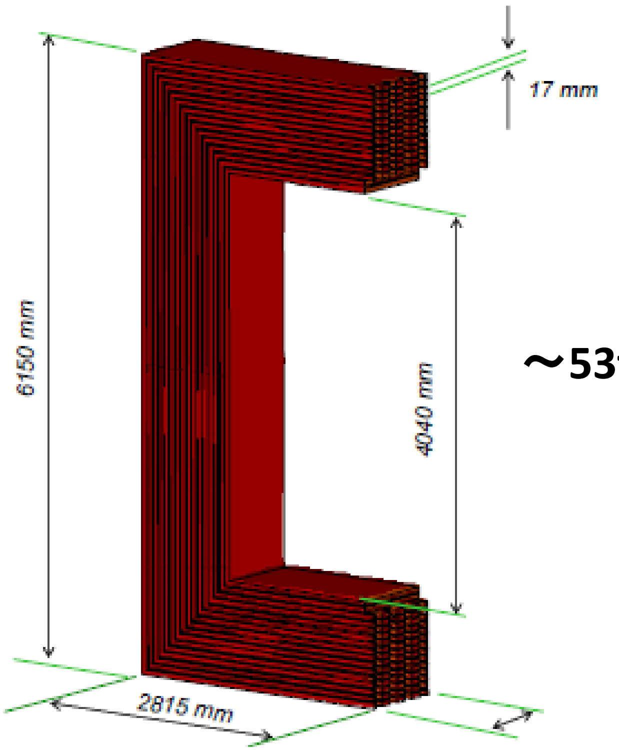
- **ND280 is made of several components.**
- **2 FGDs (Fine-Grained Detectors) consist of scintillator bars. FGD2 has water as a target material.**
- **3 gas-filled TPCs (Time Projection Chambers) track charged particles.**
- **All components are in 0.2 T of magnetic field. The magnets were previously used in UA1* and NOMAD.**
- **Charged particles are deflected by the magnetic field. The curvature of the track recorded by TPC are used to determine the momentum of the particles.**
- **Neutrino flux as well as neutrino interactions can be studied from the reconstructed track information.**
- **Other components are P0D (π^0 detector), ECAL(Electromagnetic CALorimeter) and SMRD(Side Muon Range Detector).**





* W & Z were discovered by this experiment.

Magnet yoak



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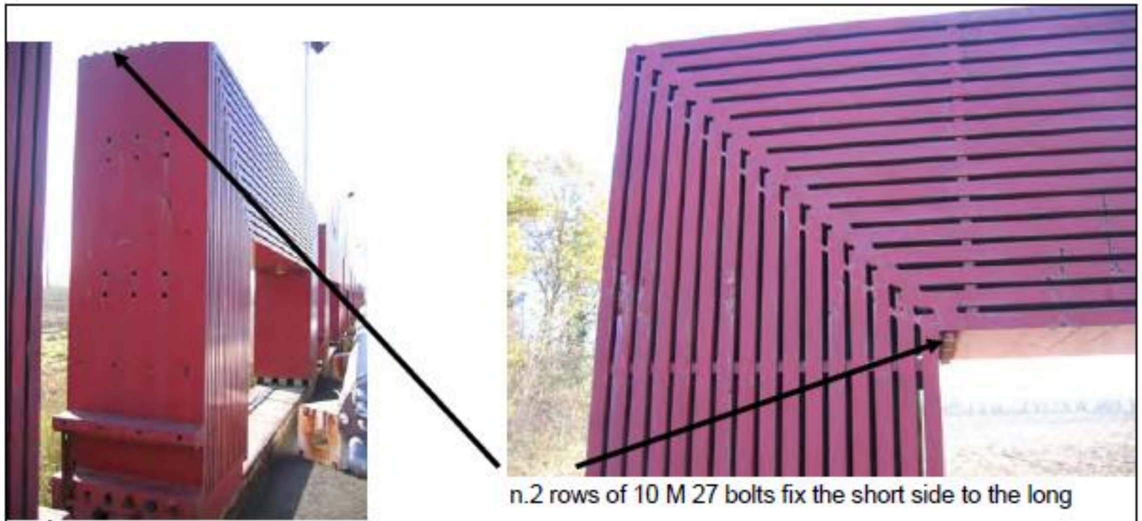
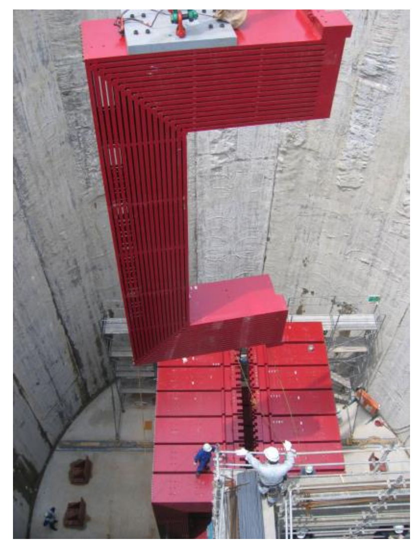


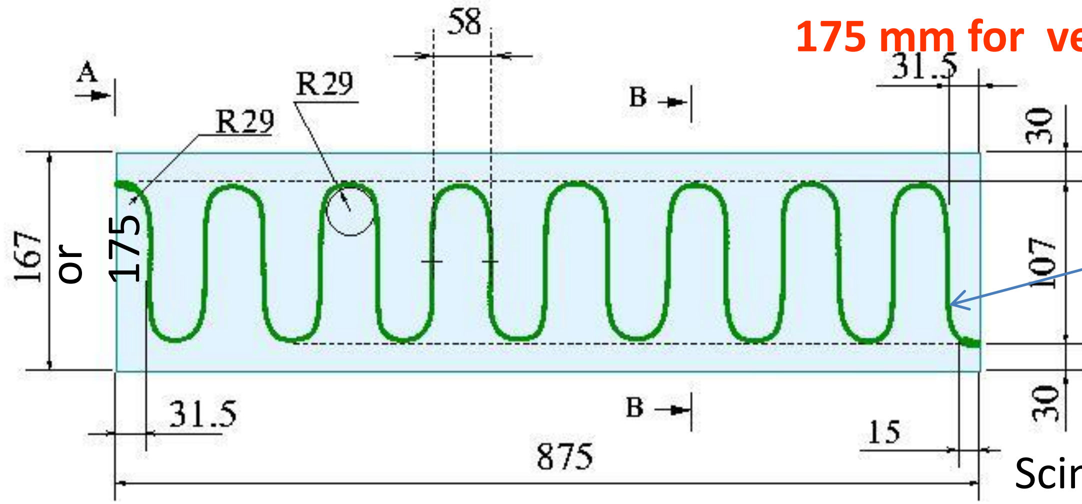
n.2 rows of 10 M 27 bolts fix the short side to the long

Magnet yoak installation



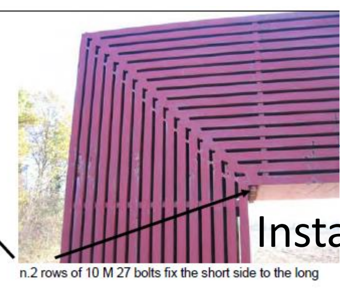
SMRD scintillator

width:
167 mm for horizontal gaps
175 mm for vertical gaps

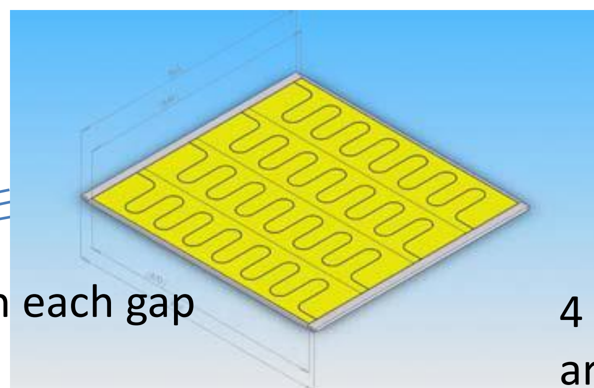


Wave length shifting fiber

Scintillator thickness: 7.1 mm
Groove depth: 2.5 mm

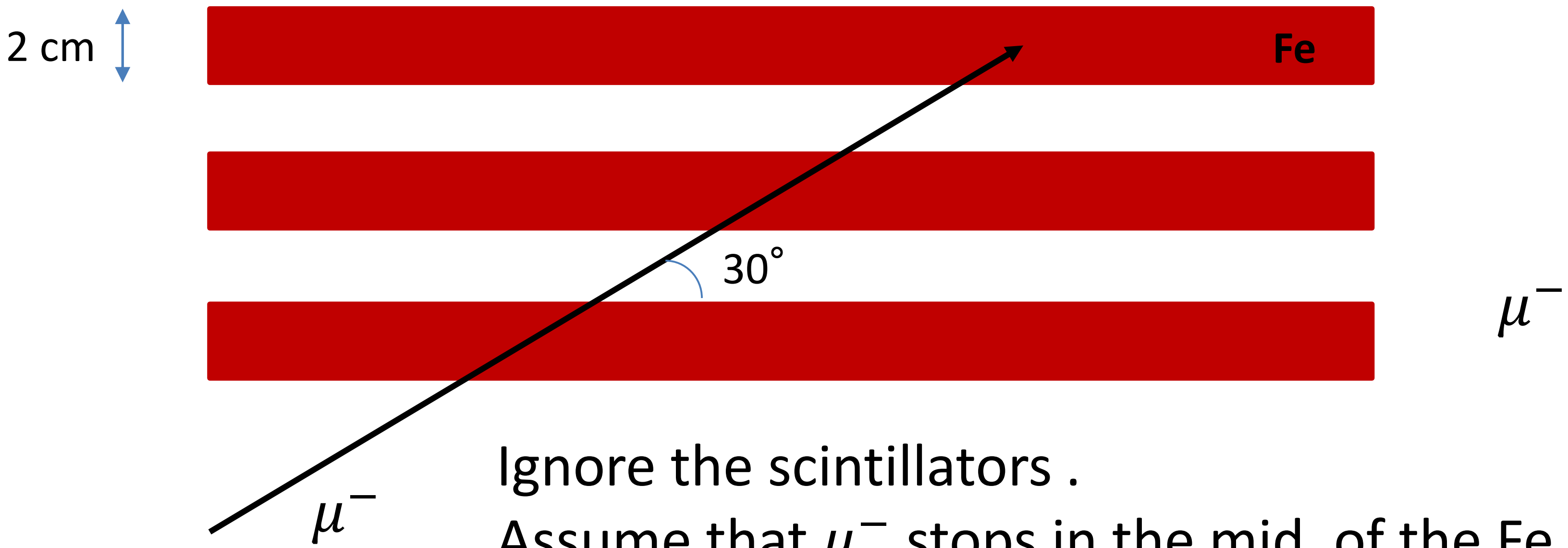


Installed in each gap



4 or 5 scintillators are combined into one module.

Easy excercize for the rage detector

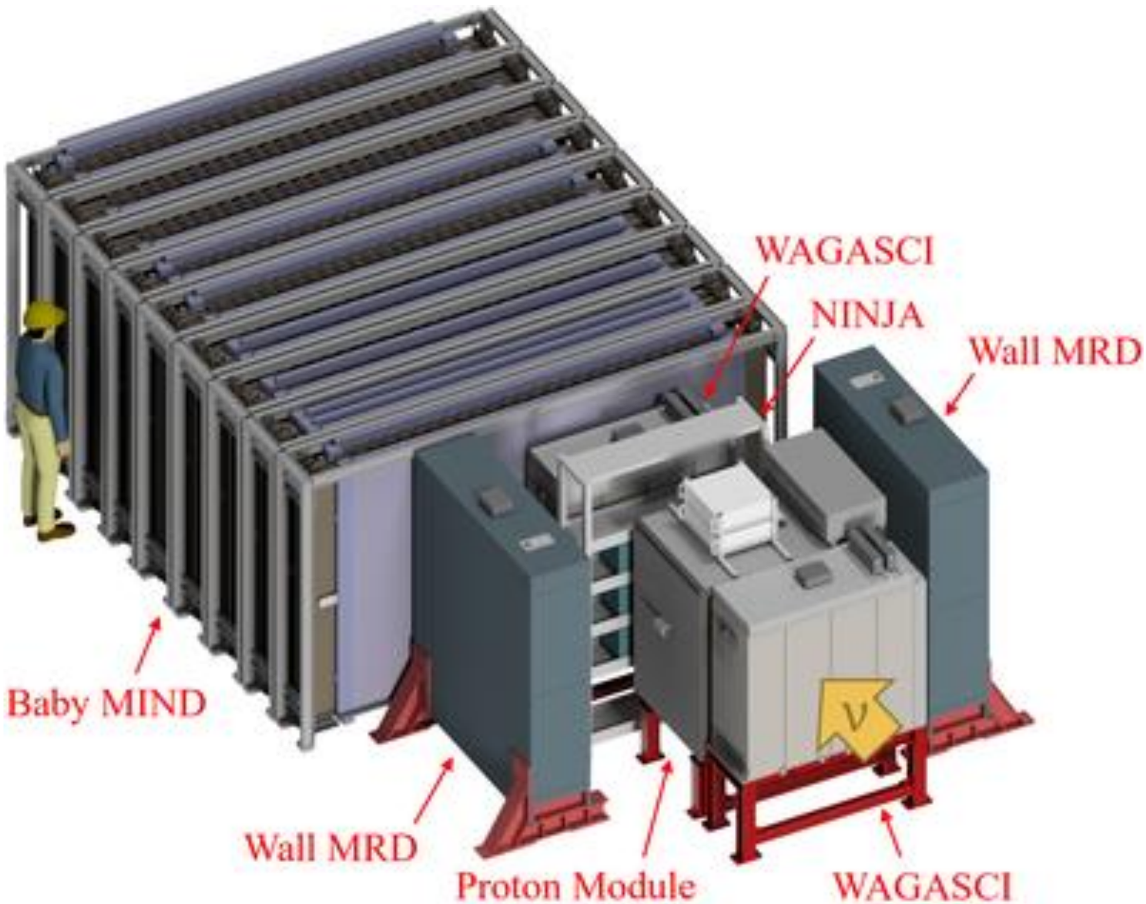


Ignore the scintillators .
Assume that μ^- stops in the mid. of the Fe layer.
Density of Fe: 8 $\mathrm{g/cm^3}$
de/dx ~ 2 MeV/(g/cm^2)

Muon deposit energy: $E_\mu^{\mathrm{deposit}} = ?$

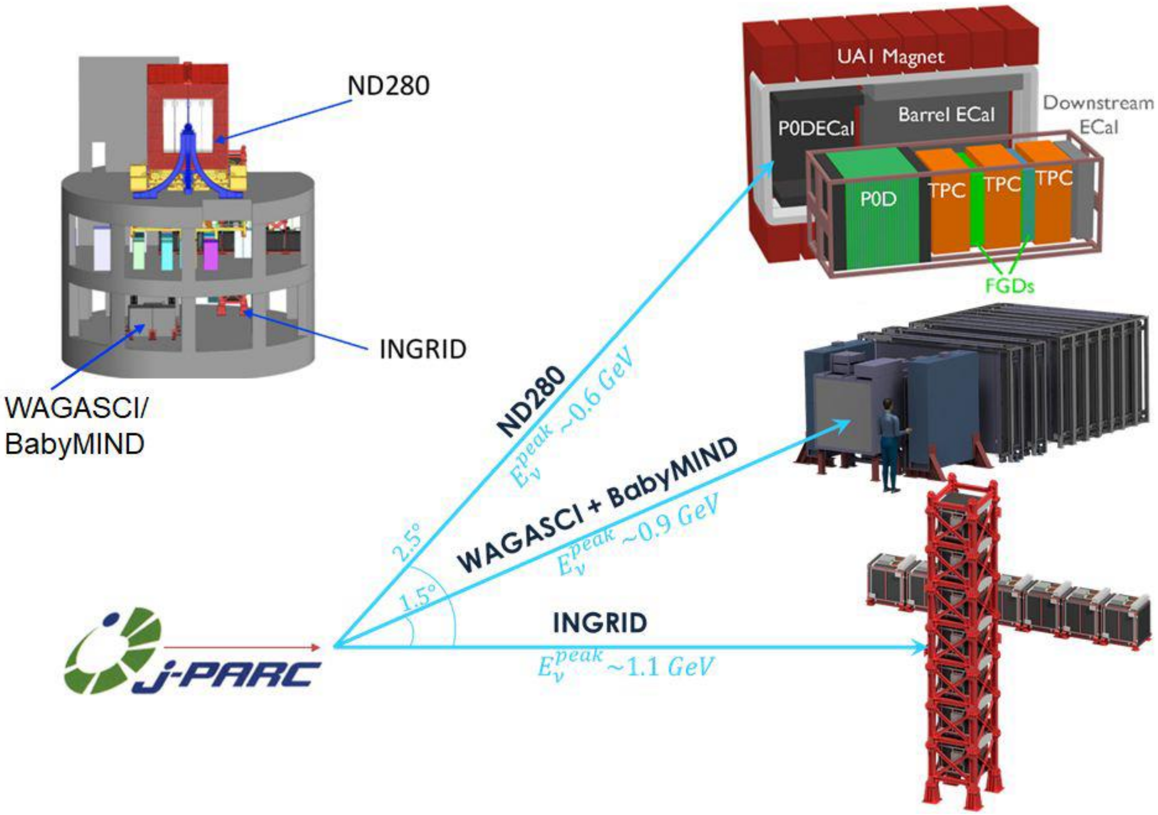
$$E_\mu^{\mathrm{deposit}} = 5\ \mathrm{cm} / \sin 30° \times 8\ \mathrm{g/cm^3} \times 2\ \mathrm{MeV/(g/cm^2)}$$
$$= 160\ \mathrm{MeV}$$

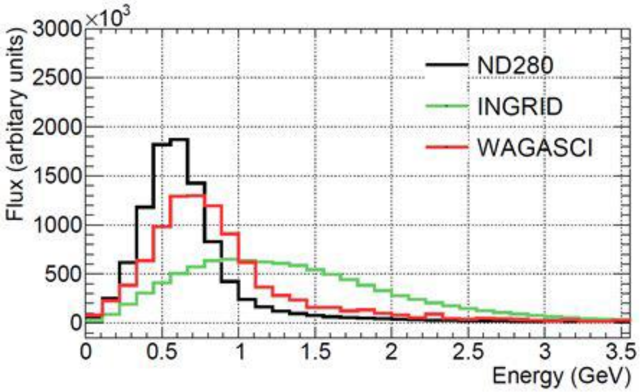
WAGASCI & BabyMIND detectors (1.5 degrees off-axis)



- Water filled plastic scintillator Lattice and magnetised tracking (BabyNIND) detectors
- We plan to use in the oscillation analysis
- First WAGASCI cross section paper: Phys. Rev. **D 97**, 012001

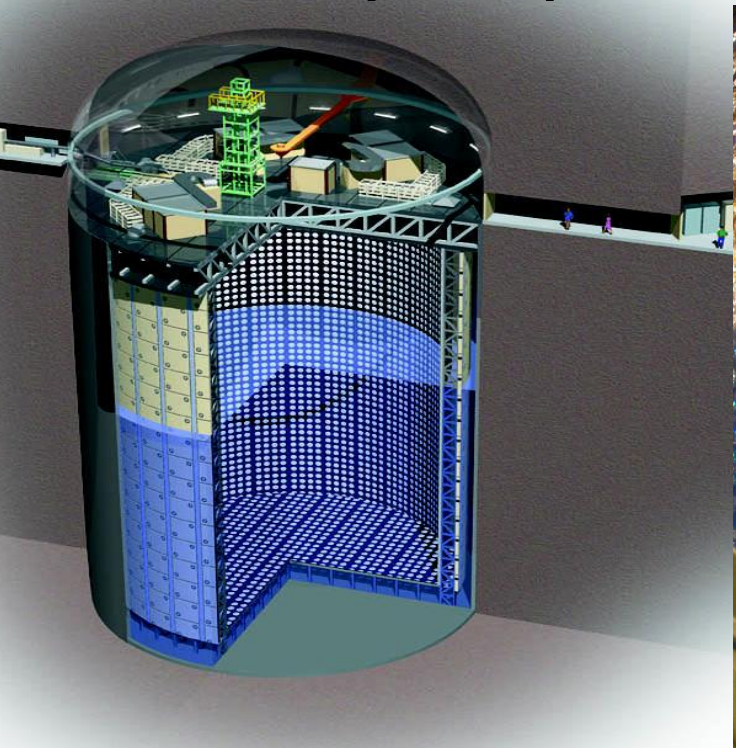
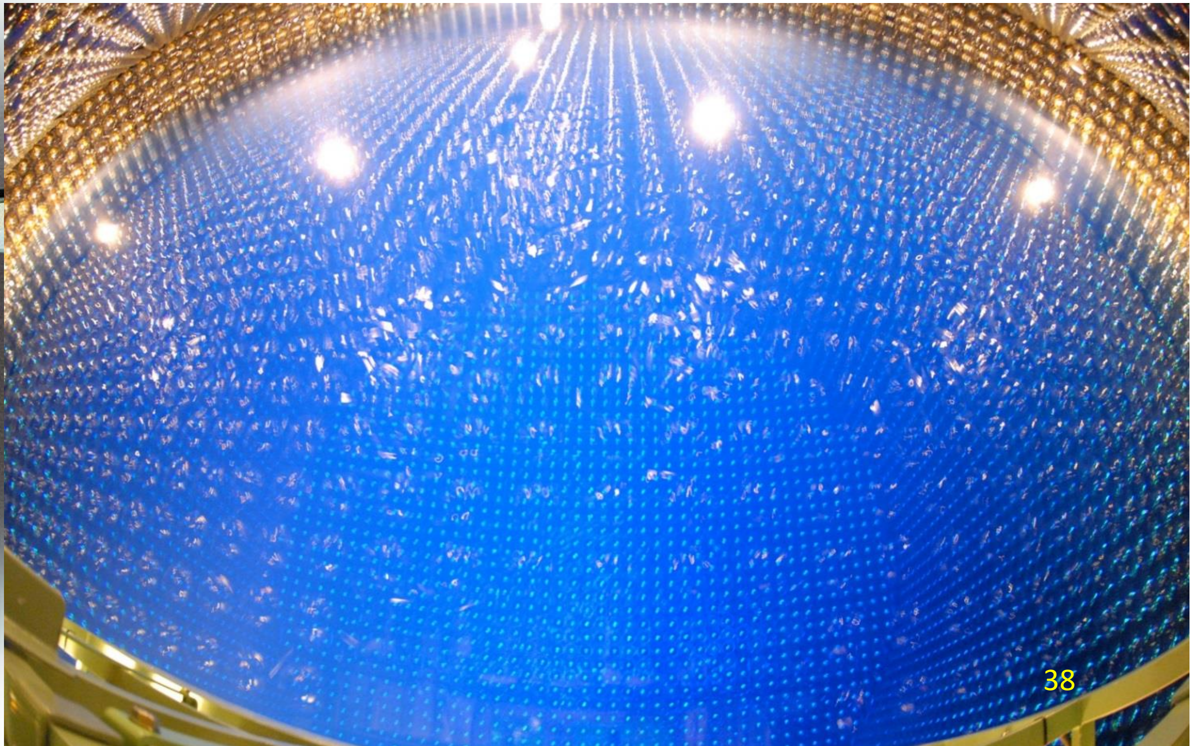
Near Detector Complex





Far detector : Super-Kamiokande (SK)

- **50kt water Cherenkov detector. The fiducial volume of the inner detector is 22.5 kton, and is viewed by 11129 20-inch diameter PMTs. Outer water layer surrounding the inner volume is viewed by 1885 8-inch diameter PMTs.**
- **Located at 1000 m underground in Kamioka mine, Japan. The distance from the J-PARC is 295 km.**
- **Now Gd was loaded for enhanced neutron detection to separate between ν_e and $\overline{\nu}_e$ interactions.**

3. Current status & results

Parameters related to beam power

- **Beam power**

Energy of one proton × **Protons per second (pps)**

Let's calculate yourself for T2K case.

・Proton energy: 30 GeV,
Protons per cycle: 2.67×10^{14},
Cycle time: 2.48 sec
(1 GeV=10^9 eV, 1eV=1.6×10^{-19} J)

・Answer in "kW".

$$30\ \mathrm{GeV} \times 2.67 \times 10^{14}/2.48\,\mathrm{sec} = 30 \times 10^9 \times 2.67 \times 10^{14}/2.48 \times 1.6 \times 10^{-19}/10^3\ \mathrm{kW}$$
$$= 517\ \mathrm{kW}$$

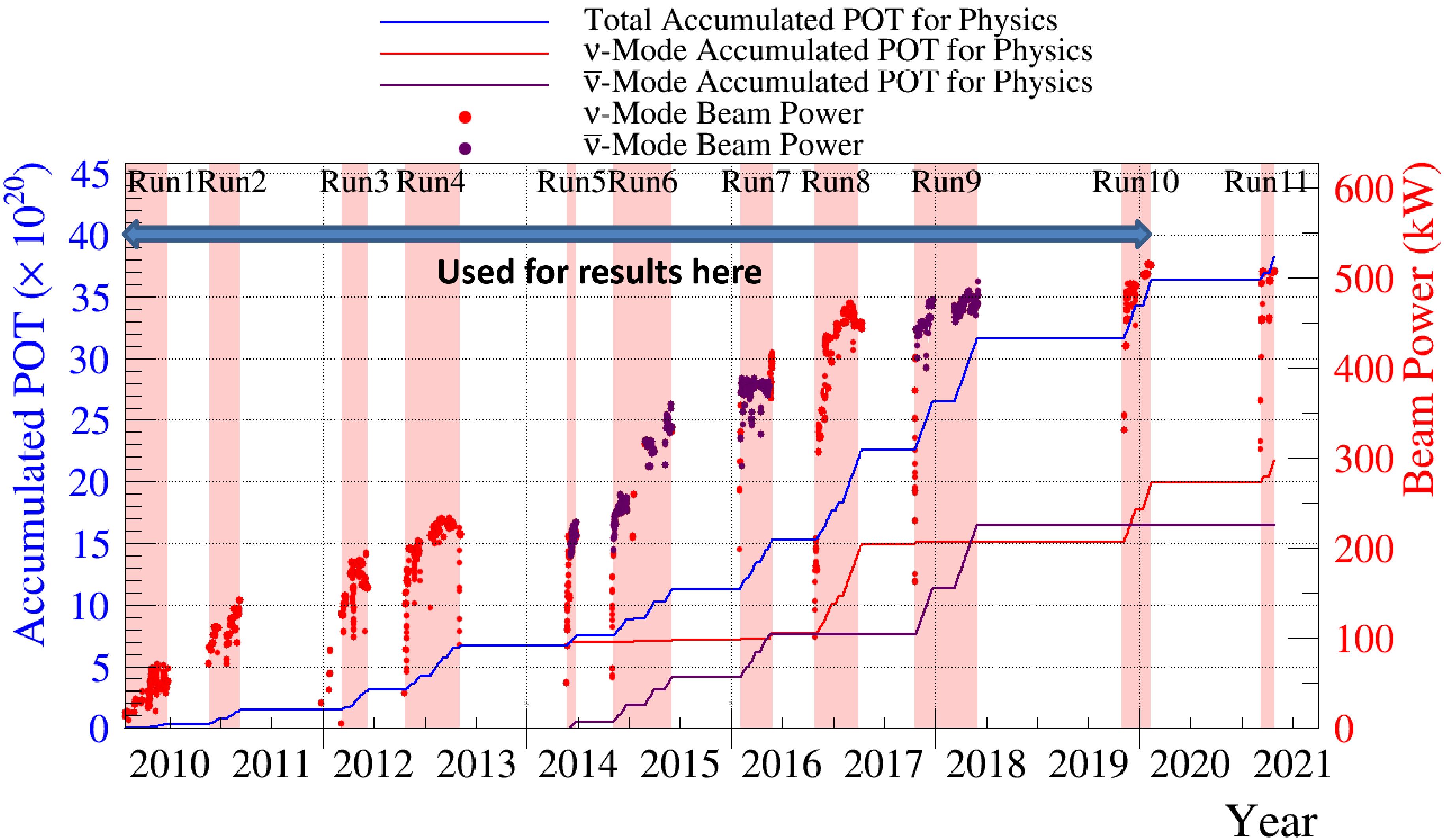
(K2K Proton energy: 12 GeV, protons per cycle: 6×10^{12}, cycle time: 2.2 sec,
beam power: 5 kW)

- **POT (protons On Target)**

pps × **Beam time**

***Homework 2**
How many years do we need to get 1×10^{22} POT if the beam power is 517 kW as described above ?

T2K Data Accumulation Summary



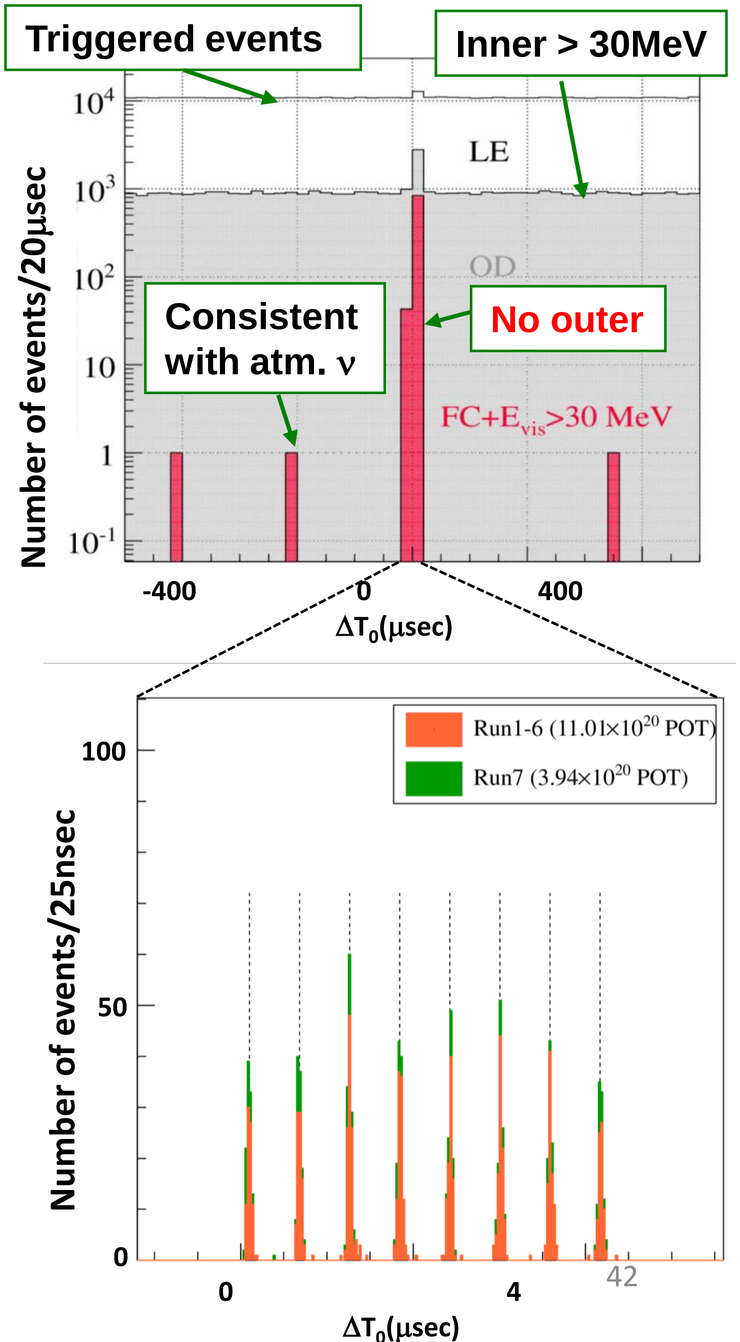
Total POT for the results hear: 3.60×10^{21} **ν mode: 1.97×10^{21} POT**
(Protons on Target) **$\bar{\nu}$ mode: 1.63×10^{21} POT**

522.6 kW beam power was achieved ! **(Run11, 1.78×10^{20} POT in ν mode, the very first T2K data with a Gd-doped Super-K)**

Event Selection at the Far Detector (SK)

Event Selection Criteria

1. **Total energy deposit in the inner detector is larger than 30 MeV equivalent.**
2. **No outer detector activity**
3. **The event time agrees with ~5 μsec beam period in 2.48 sec accelerator cycle.**
   (8 bunch structure can be found.)
4. **1 Ring events**
   → e/μ particle identification is applied

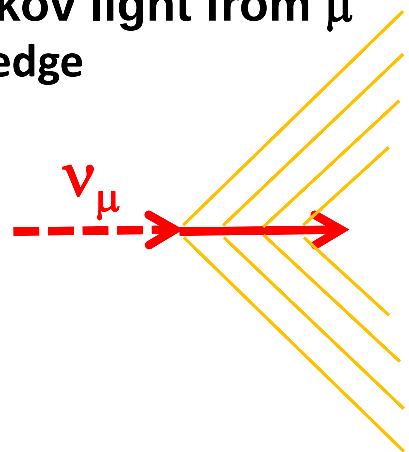


μ/e identification in Super-Kamiokande

$\nu_\mu \rightarrow \mu$

Only direct Cherenkov light from μ

Clear Cherenkov ring edge

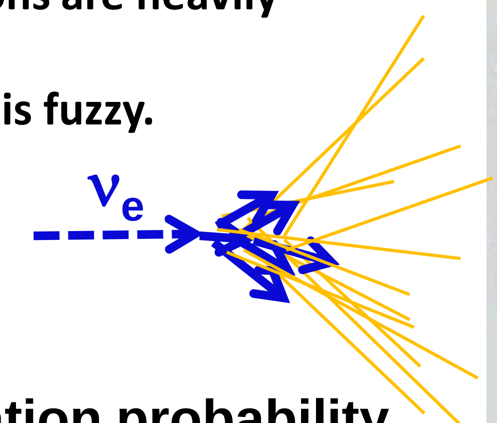


$\nu_e \rightarrow e$

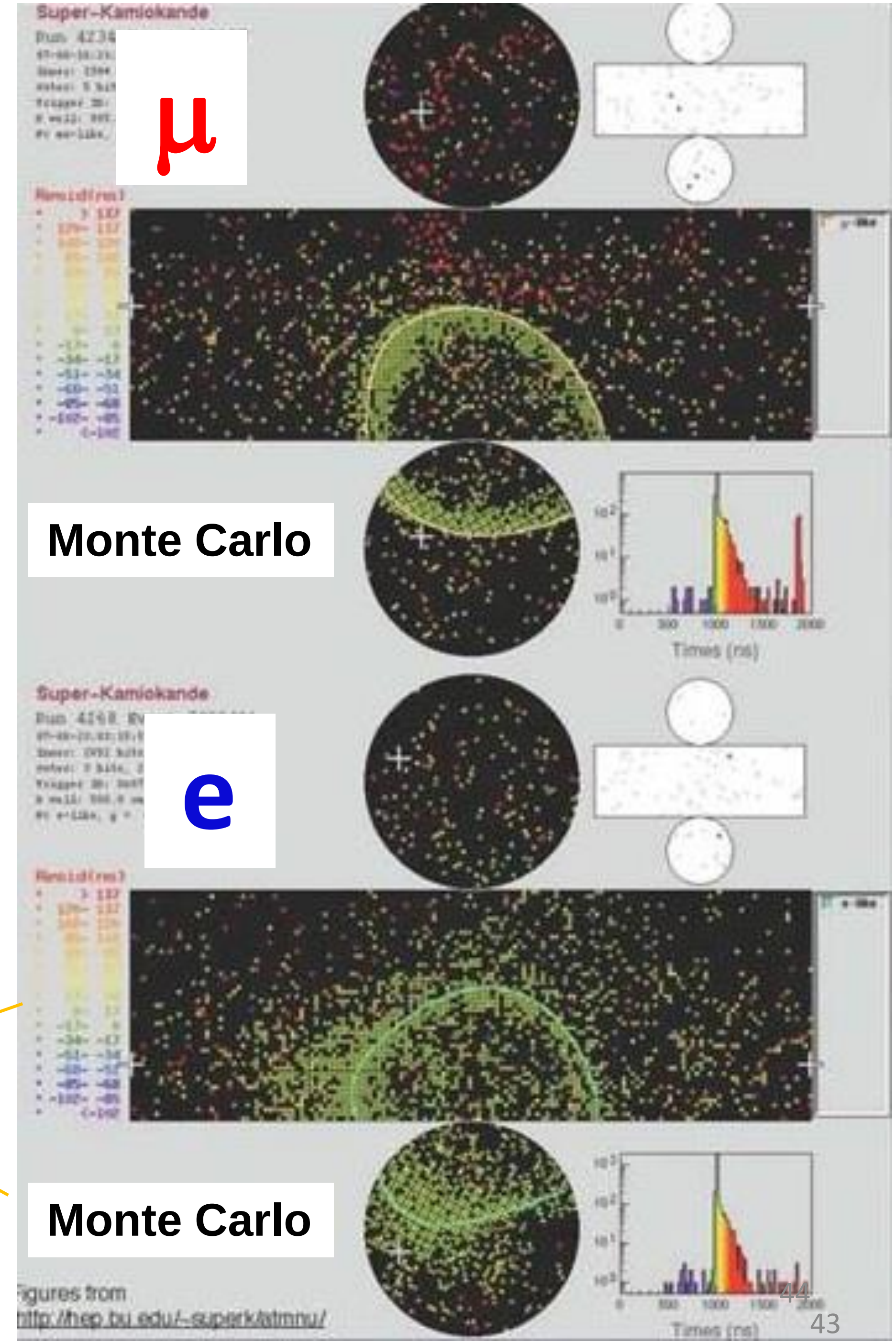
Cherenkov light from e-m shower.

Electrons and positrons are heavily scattered.

Cherenkov ring edge is fuzzy.



- **μ/e misidentification probability is less than 1 %.**

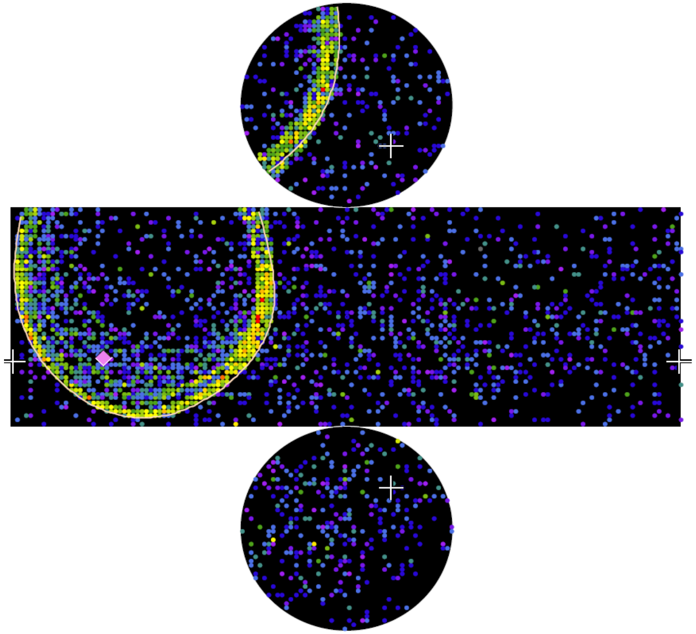


Event Selection at the Far Detector (cont'd)

Examine Particle ID of 1 ring events

ν_μ selection

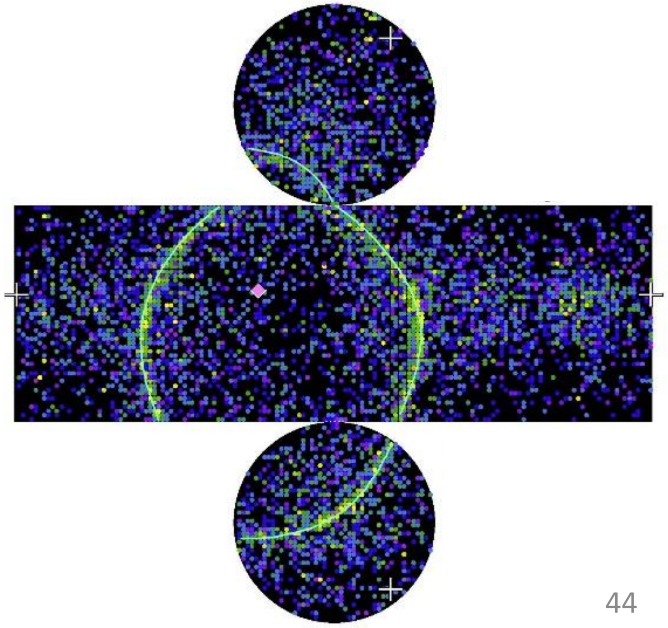
- μ-like PID
- p_μ > 200 MeV/c
- Michel electron 1 or 0



ν_e selection

- e-like PID
- p_e > 100 MeV/c
- Michel electron 0
- E_{rec} < 1250 MeV
- π^0 rejection

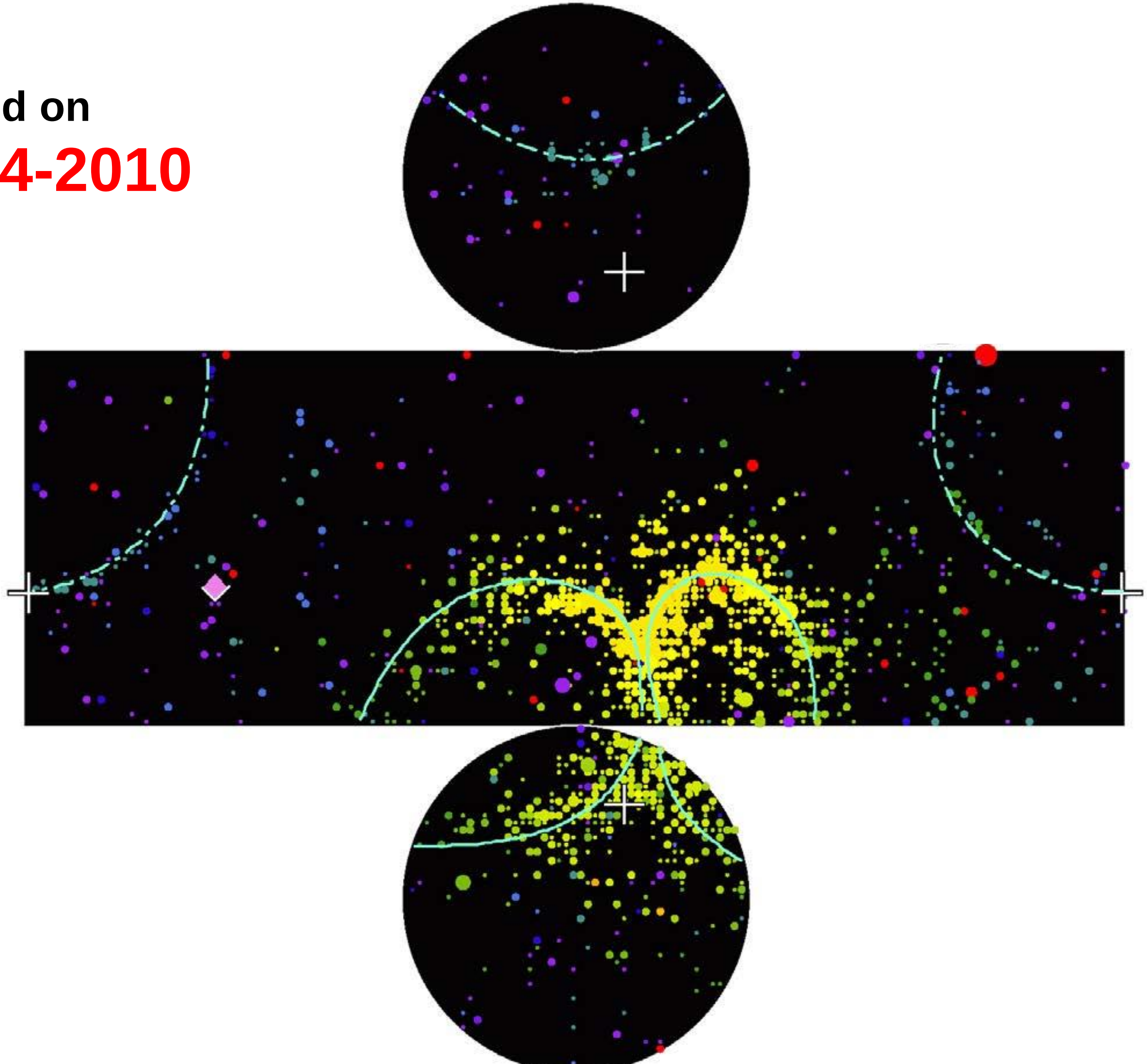
π^0 rejection : Forced 2^{nd} ring is assumed. Invariant mass and likelihood for π^0 are examined.



The first neutrino event in the T2K experiment

Recorded on

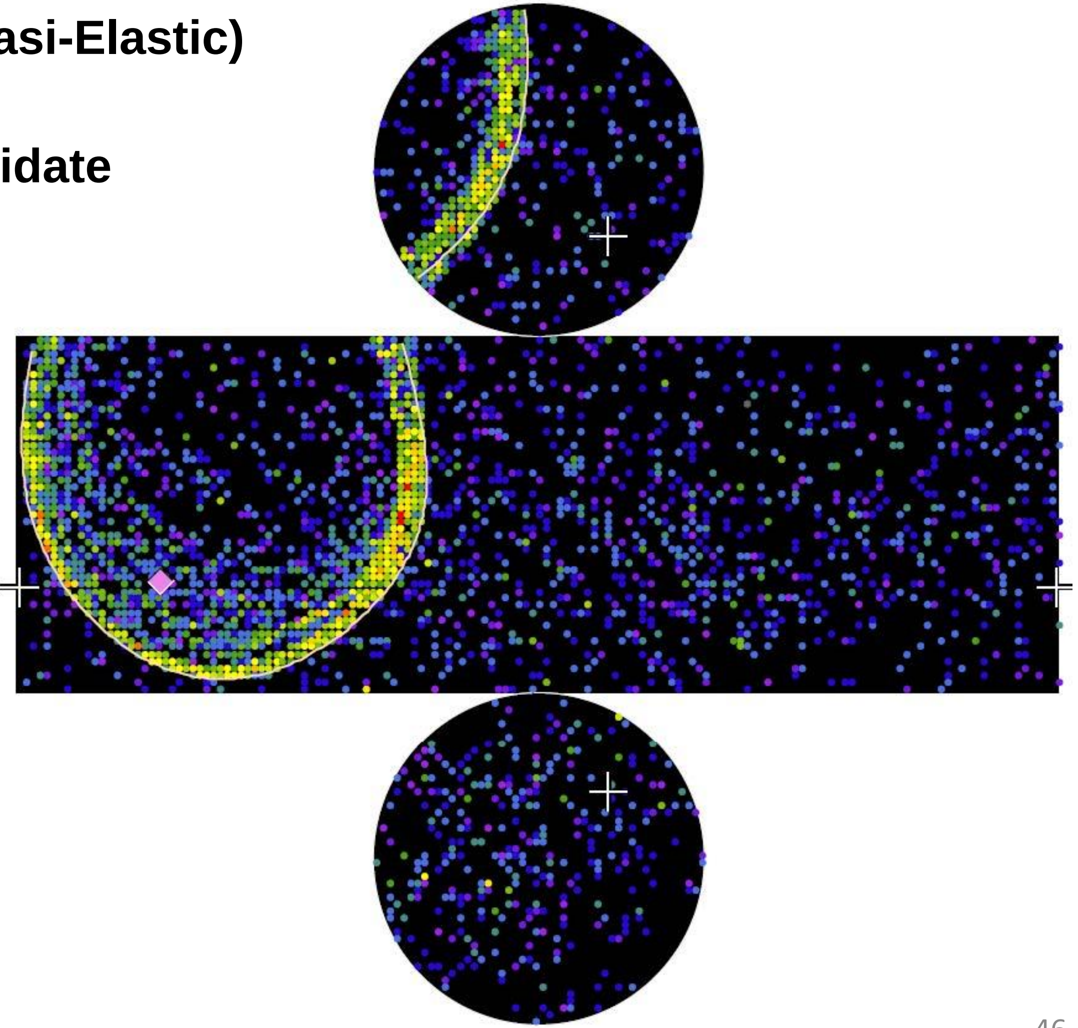
Feb-24-2010



ν_μ disappearance analysis

CCQE (Charged Current Quasi-Elastic)

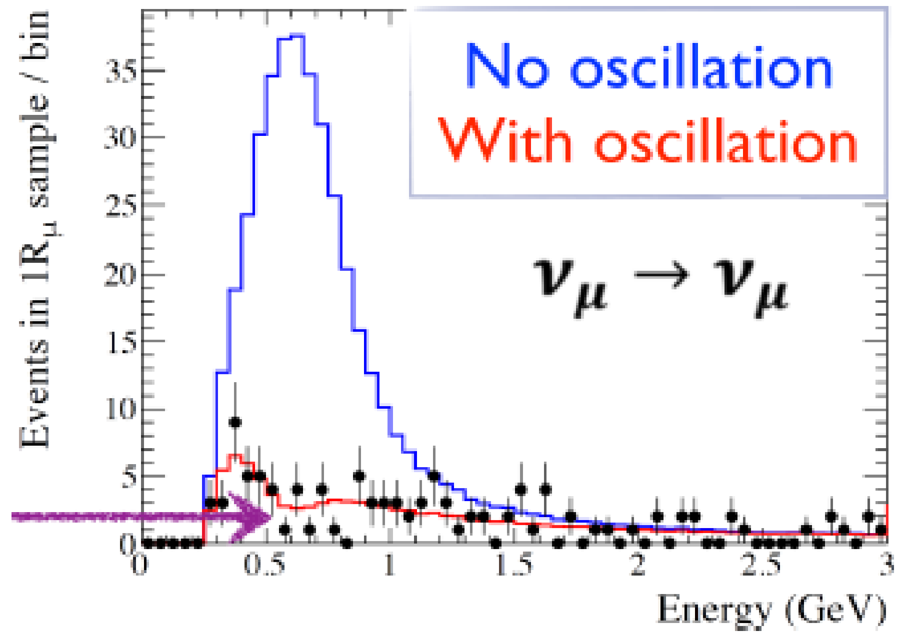
$\nu_\mu + n \rightarrow \mu^- + p$ **candidate**



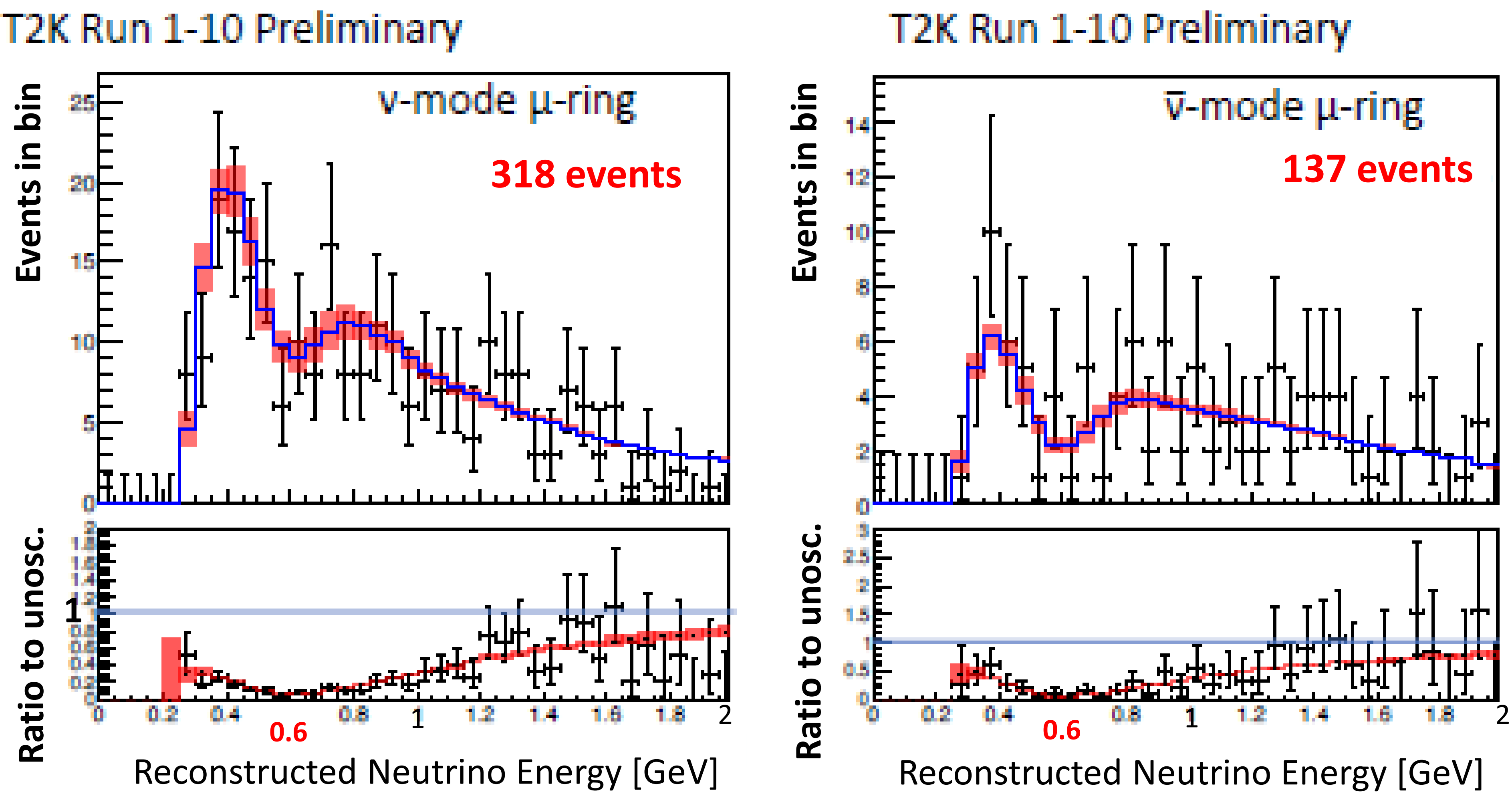
Disappearance of $\nu_\mu/\bar{\nu}_\mu$:

$$P(\overleftrightarrow{\nu_\mu} \rightarrow \overleftrightarrow{\nu_\mu}) = 1 - 4cos^2(\theta_{13})sin^2(\theta_{23}) \times \left[1 - cos^2(\theta_{13})sin^2(\theta_{23})\right] sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) + \text{(solar, matter effect terms)}$$

location of dip: Δm^2_{32}
depth of dip: $sin^2(\theta_{23})$

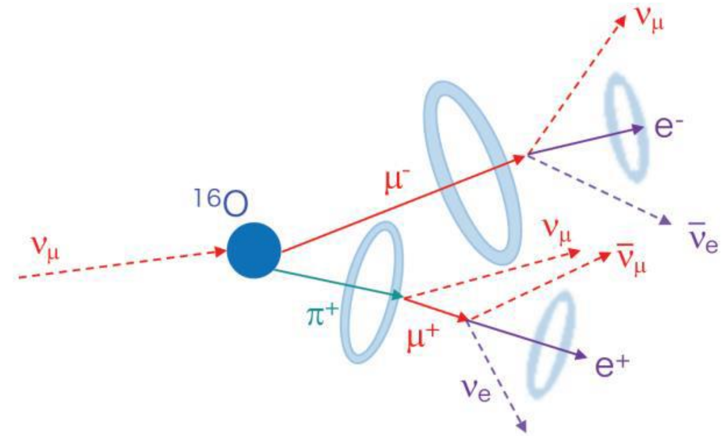


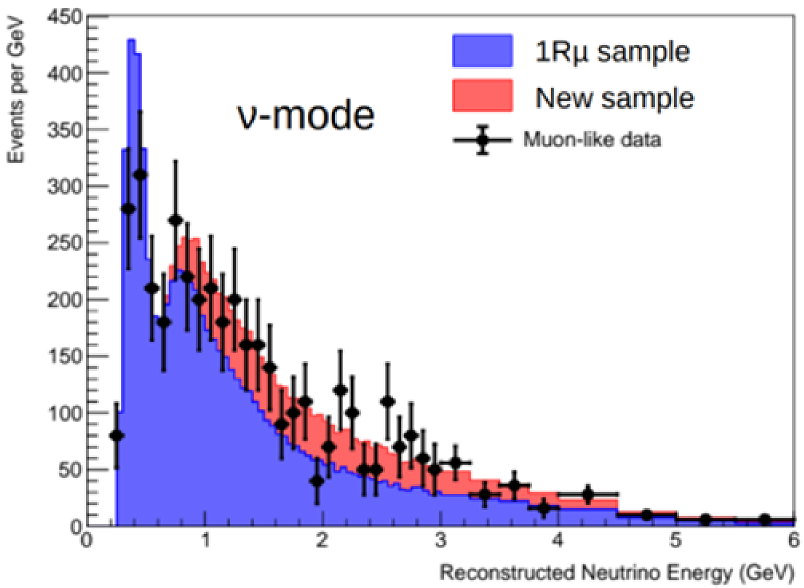
Recent result of $\nu_\mu/\overline{\nu_\mu}$ (1)

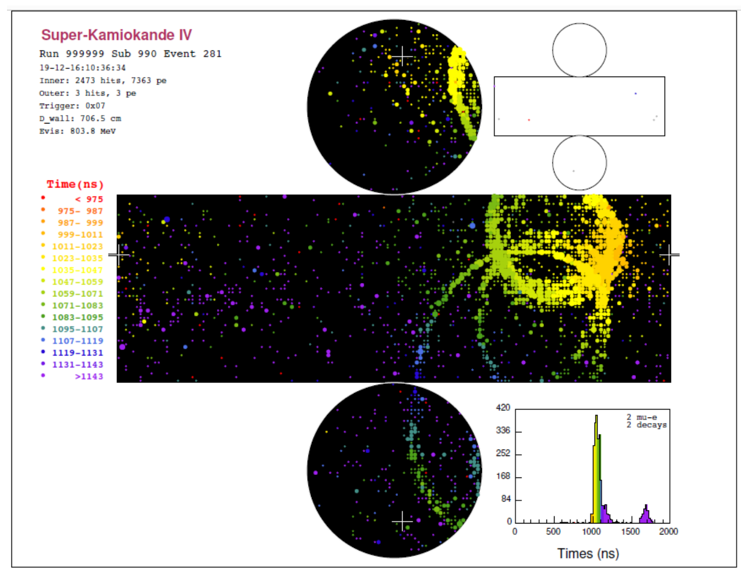


Far detector new samples

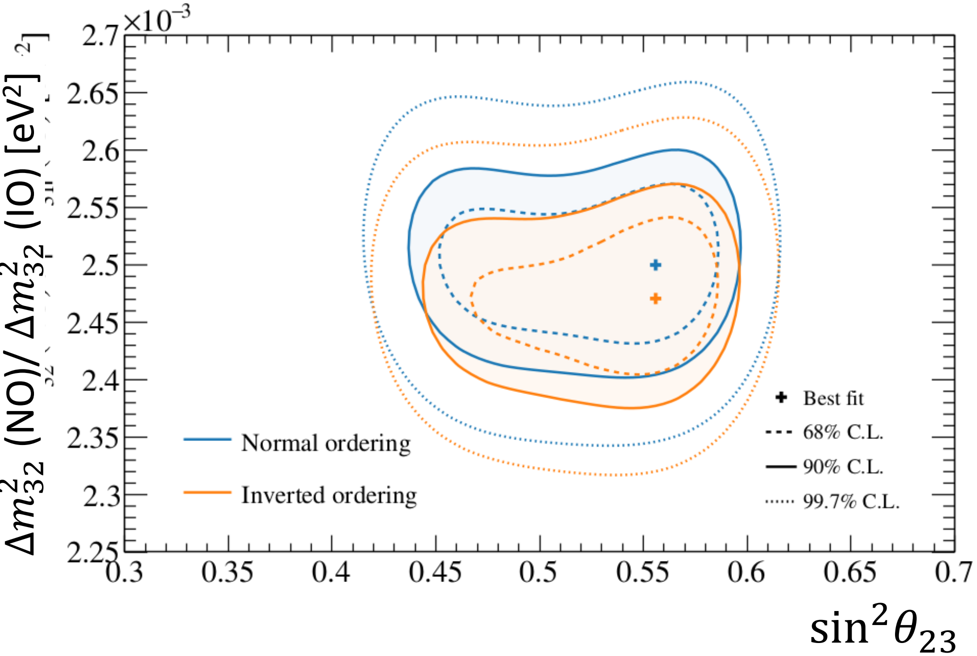
- $\nu_\mu \mathrm{CC}1\pi^+$ interactions in ν-mode were added to CCQE events.
- "Two rings ($1\mu^-$ and $1\pi^+$) and Michel electron (from $1\mu^-$)" or "one $1\mu^-$ ring and 2 Michel electrons (from$1\mu^-$ & $1\pi^+$)"
- Increase ν-mode μ-like statistics by ~30%

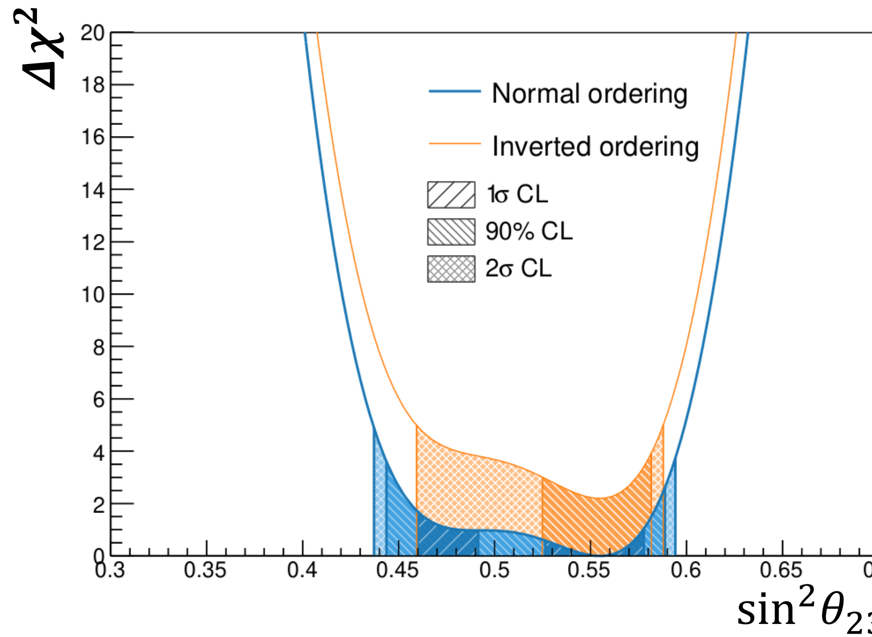






Measurements on θ_{23} and Δm^2_{32}





P values

T2K only

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.24	0.39	0.63
IH ($\Delta m^2_{32} < 0$)	0.15	0.22	0.37
Sum	0.39	0.61	1.000

T2K + Reactor θ_{13}

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.20	0.54	0.74
IH ($\Delta m^2_{32} < 0$)	0.05	0.21	0.26
Sum	0.25	0.75	1.000

Slight preference for upper octant ($\sin^2\theta_{23} > 0.5$) and normal hierarchy.

Appearance of $\nu_e/\bar{\nu}_e$:

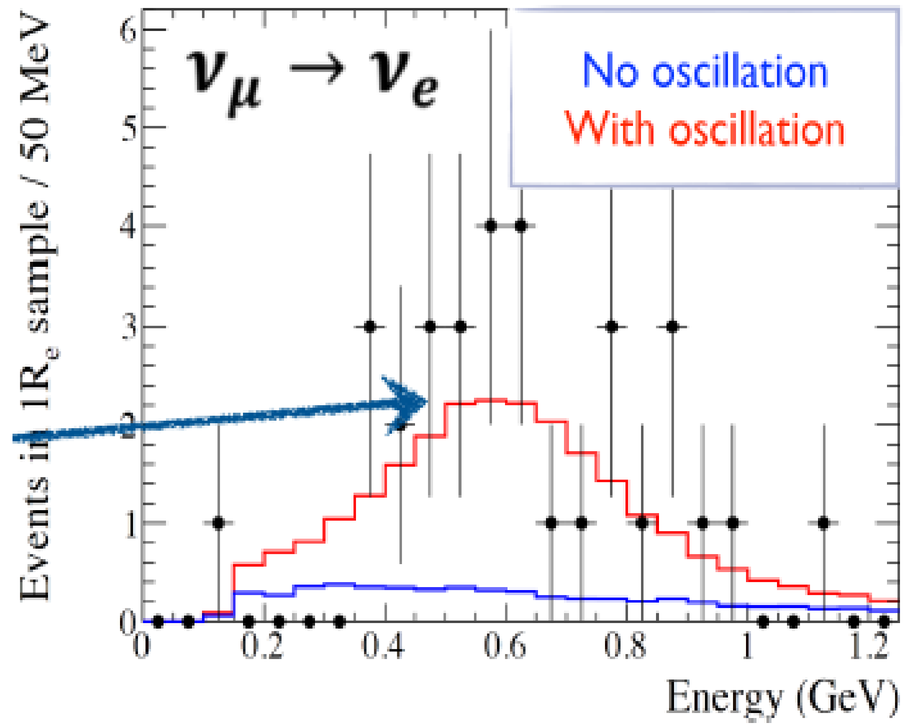
$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) =$$

$$\sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)$$

$$\overset{(+)}{-}\left[\sin(2\theta_{12})\sin^2(2\theta_{23})\sin^2(2\theta_{13})\cos(\theta_{13})\right.$$

$$\times \sin\left(\frac{\Delta m^2_{21}L}{4E}\right)\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)\sin(\delta_{CP})$$

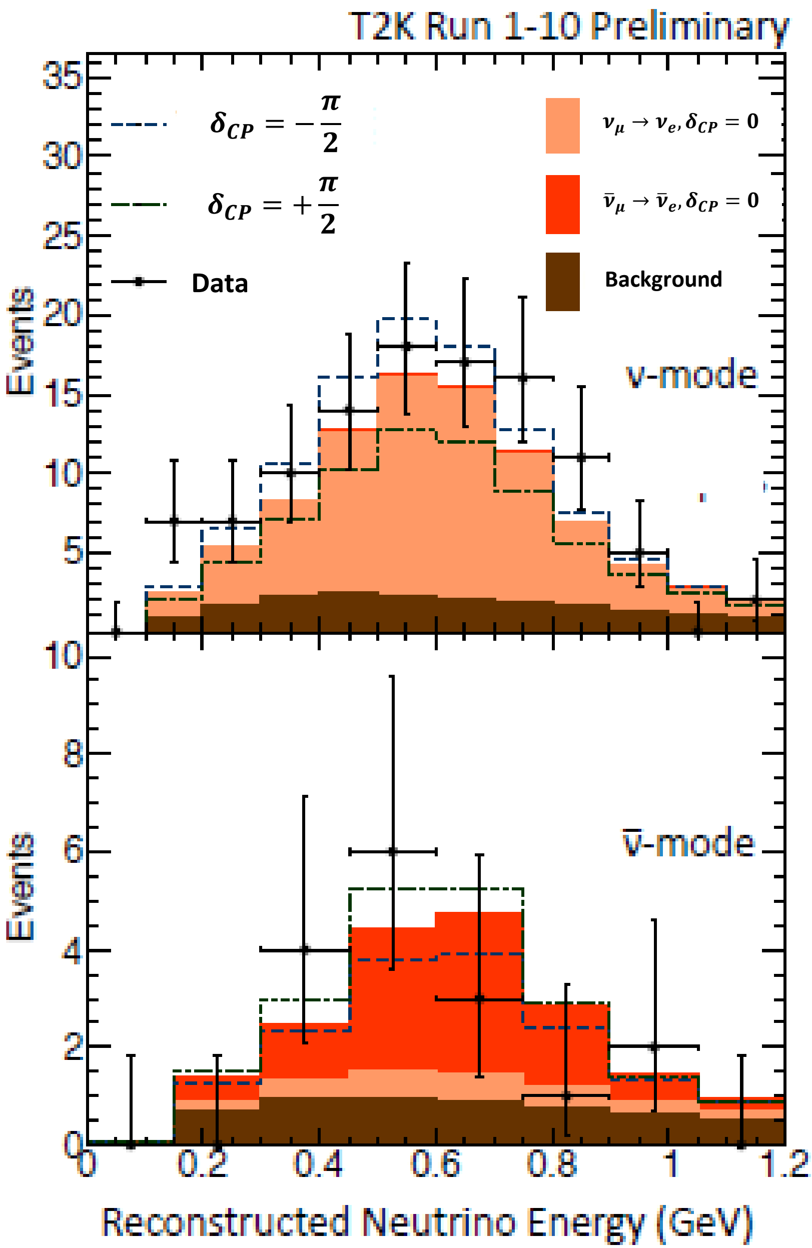
$$+ \text{(CP-even, solar, matter effect terms)}$$

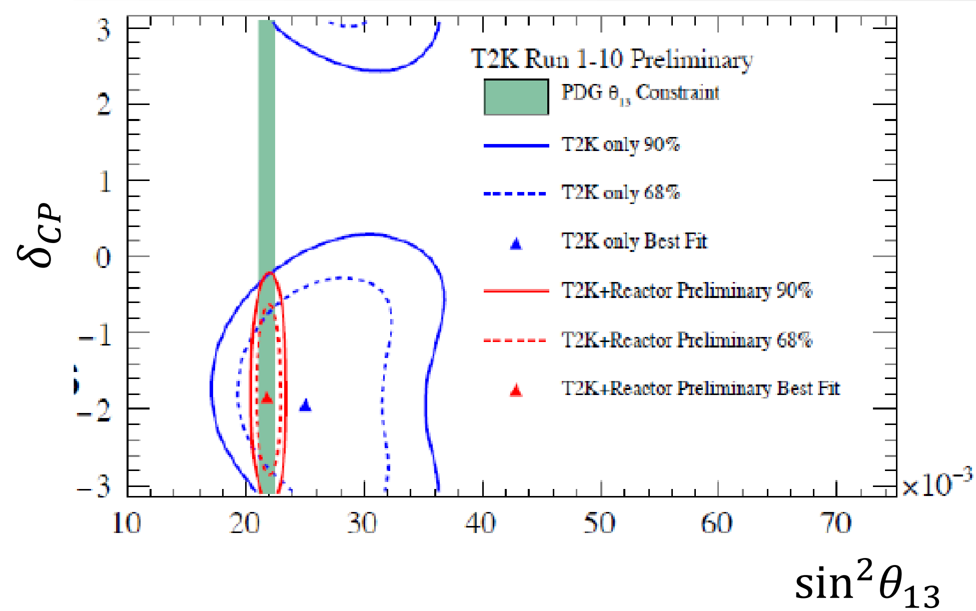


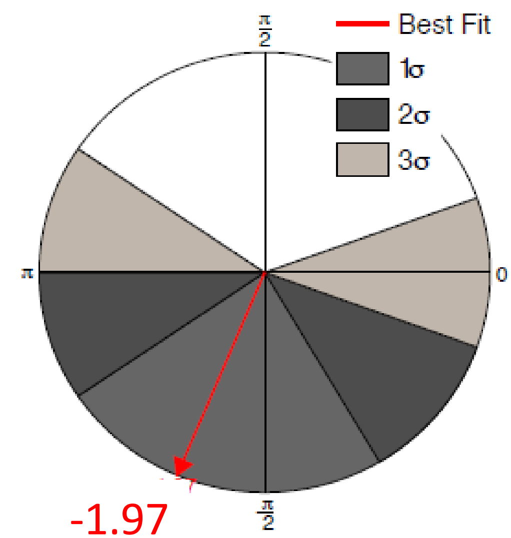
magnitude of the peak:
$\sin^2(\theta_{23})$, $\sin^2(2\theta_{13})$, δ_{CP}

$P(\nu_\mu \to \nu_e) = P(\overline{\nu_\mu} \to \overline{\nu_e})$ or not ?

Recent result of $\nu_e/\overline{\nu_e}$







NEUTRINO2020

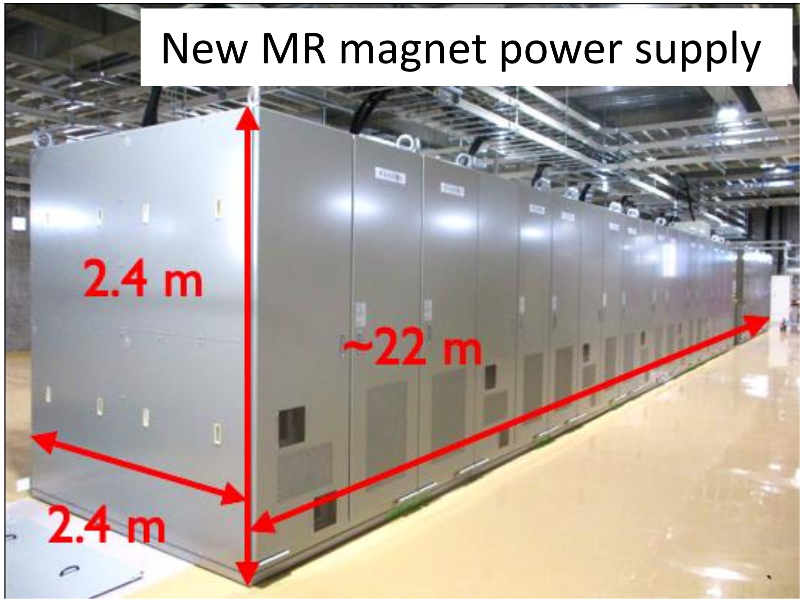
T2K Results Restrict Possible Values of Neutrino CP Phase

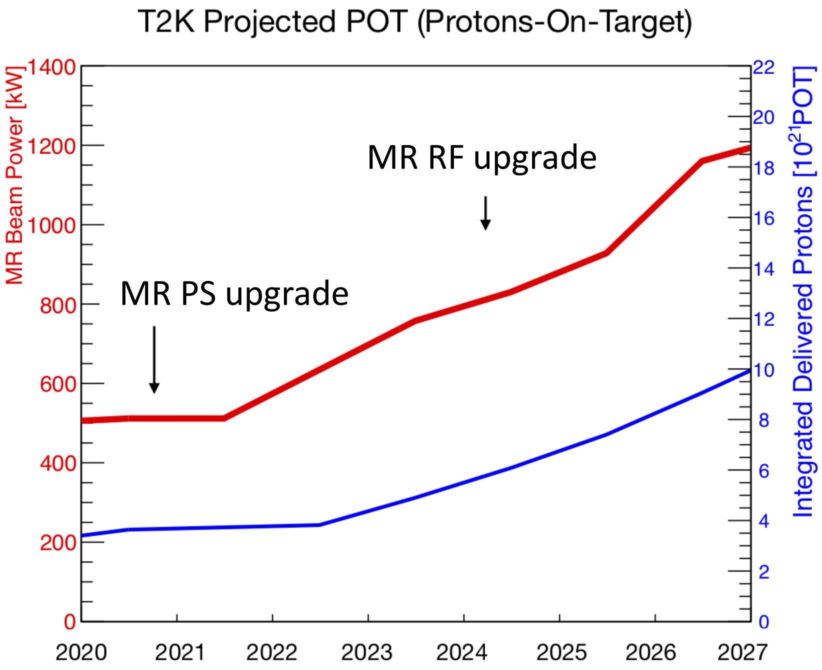
The T2K Collaboration has published new results showing the strongest constraint yet on the parameter that governs the breaking of the symmetry between matter and antimatter in neutrino oscillations. Using beams of muon neutrinos and muon antineutrinos, T2K has studied how these particles and antiparticles transition into electron neutrinos and electron antineutrinos, respectively. The parameter governing the matter/antimatter symmetry breaking in neutrino oscillation, called δ_{cp} phase, can take a value from -180º to 180º. For the first time, T2K has disfavored almost half of the possible values at the 99.7% (3σ) confidence level, and is starting to reveal a basic property of neutrinos that has not been measured until now. This is an important step on the way to knowing whether or not neutrinos and antineutrinos behave differently. These results, using data collected through 2018, have been published in the multidisciplinary scientific journal, Nature on April 16. (Nature | Vol 580 | 16 April 2020 |)

4. Future prospect

Future extension

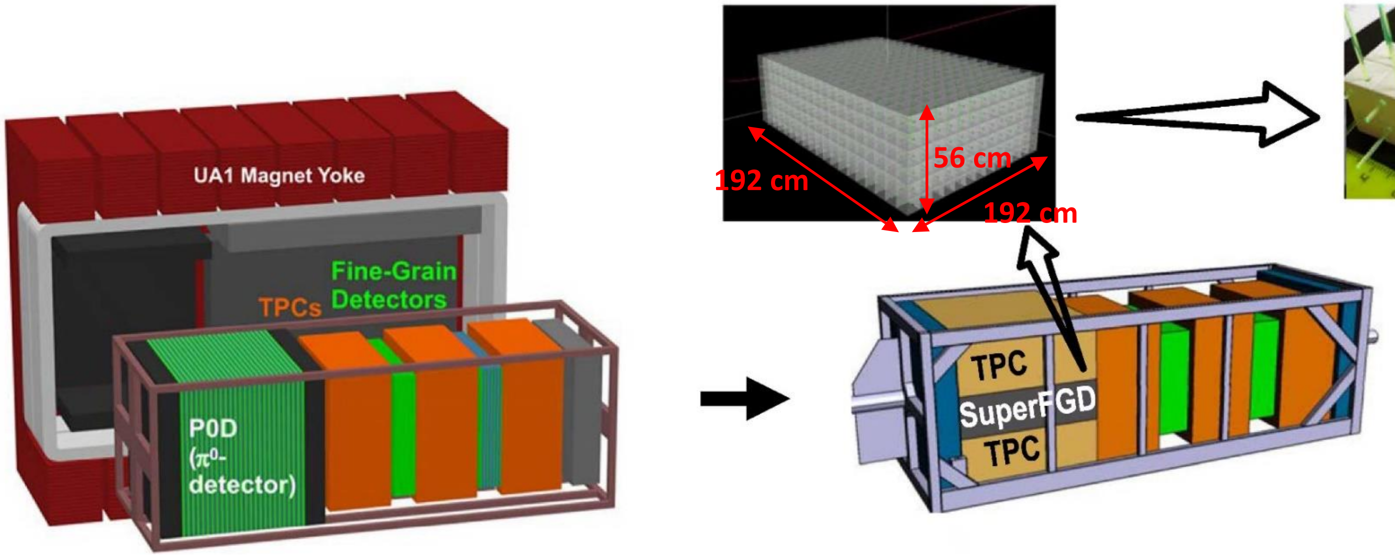
- **Upgrades**
  - **Beam :MR power supply → > 800 kW by 2023**
    MR RF upgrage → > 1 MW by 2027
  - **ND280: Super FGD, HA-TPC, & TOF (→ next page)**
- **Aiming for > 3σ sensitivity for CP violation with significantly improved statistics**





Future (ND280 upgrade)

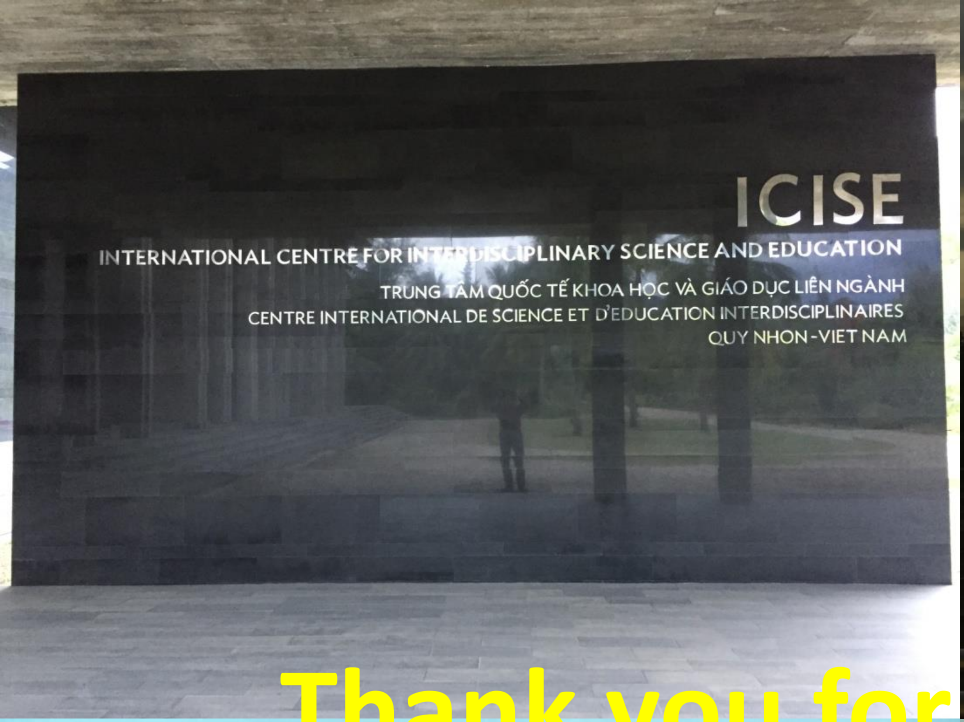
- ND280 upgrade is also planned during the long accelerator shutdown in 2021.
- The main component is Super FGD, which will be installed in the center of the ND280 detector.

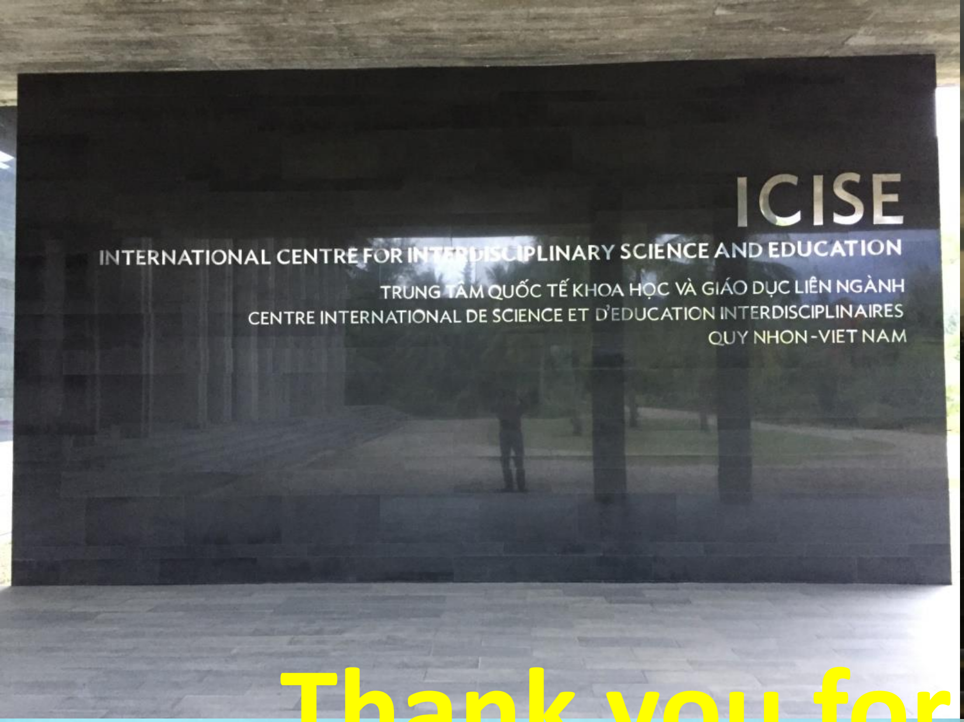


- SFGD is consist of ~2 million optically independent 1cm x 1cm x 1cm plastic scintillator cubes. The signal is read out along three orthogonal directions by wavelength shifting fibers.
- This high granularity detector will improve the understanding of the neutrino-nucleus interaction as well as the neutrino flux. And it will contribute to a reduction of the systematic errors.

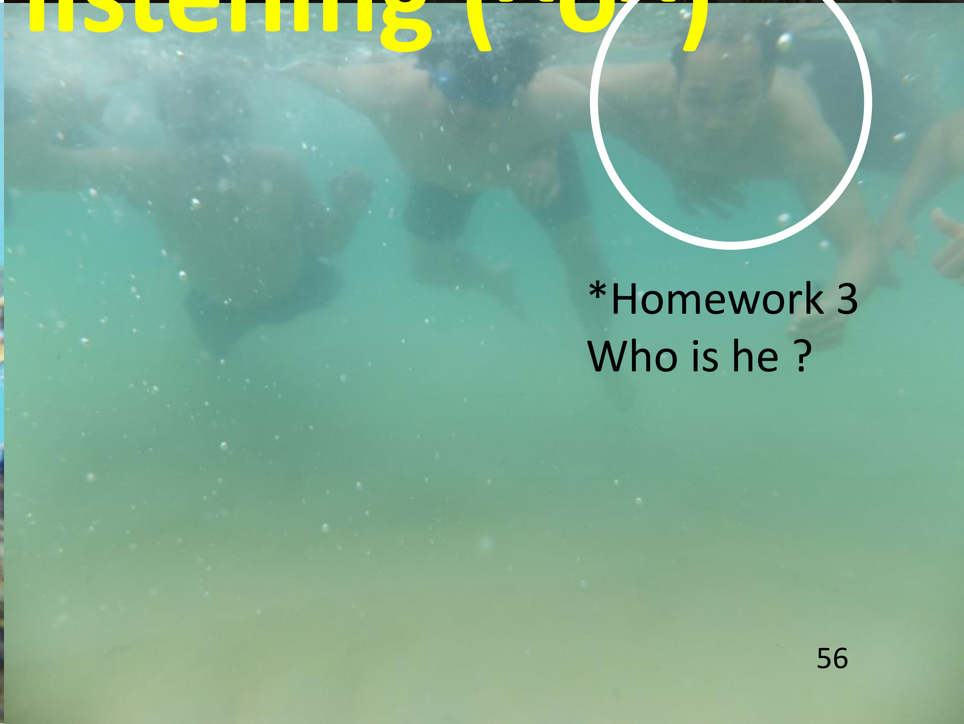
★ Installation of the upgrade is expected in the first half of 2023.

Thank you for listening (^o^)





Thank you for listening (^o^)



*Homework 3
Who is he ?

Solutions of the homeworks

***1 How much energy do we need for a neutrino to produce a τ?**

(Answer) When a τ particle is produced by CCQE interaction, i.e.

$$\nu_\tau + n \rightarrow \tau^- + p,$$

the center of mass energy squared s is

$$s = (E_\nu + m_n)^2 - p_\nu^2 = m_n^2 + 2m_n E_\nu,$$

since $E_\nu \approx p_\nu$. The threshold condition is

$$s = \left(m_\tau + m_p\right)^2 = m_n^2 + 2m_n E_\nu.$$

Hence the threshold energy is

$$E_\nu = \frac{\left(m_\tau + m_p\right)^2 - m_n^2}{2m_n} = \frac{(1.777+0.9383)^2 - 0.9396^2}{2\times 0.9396} = \underline{\mathbf{3.45\ [GeV]}}$$

***2 How many years do we need to get 1×10^{22} POT ?**

(Answer) Beam time = POT/pps = 1×10^{22} / 2.67×10^{14}/2.48 =9.29×10^8 [sec]

= <u>29.5 [yr]</u>

(This number is not realistic and we cannot operate the accelerator whole year. So we need much more beam power actually.)

***3 Who is he ?** (Answer) **Of course, Son Cao-san !!**