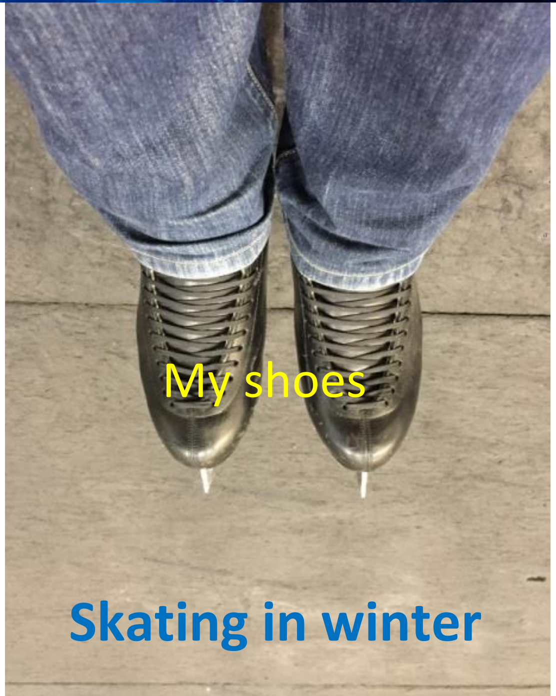
Self-introduction

My name is Atsumu Suzuki (鈴木州）
from Kobe University
Member of SK, HK, and T2K

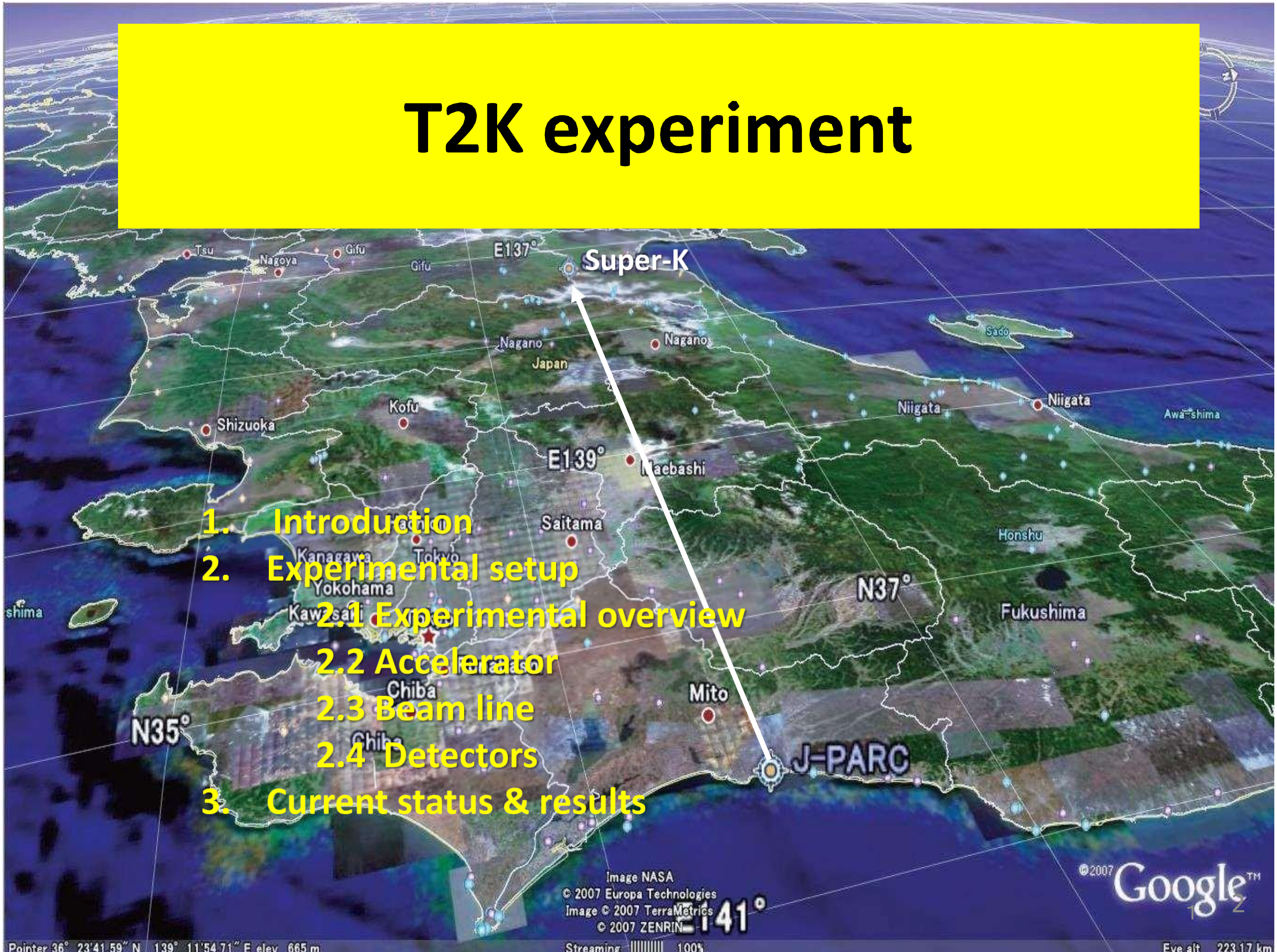
Scuba diving
(a couple of times a year)

Tennis
weekend



Skating in winter

T2K experiment



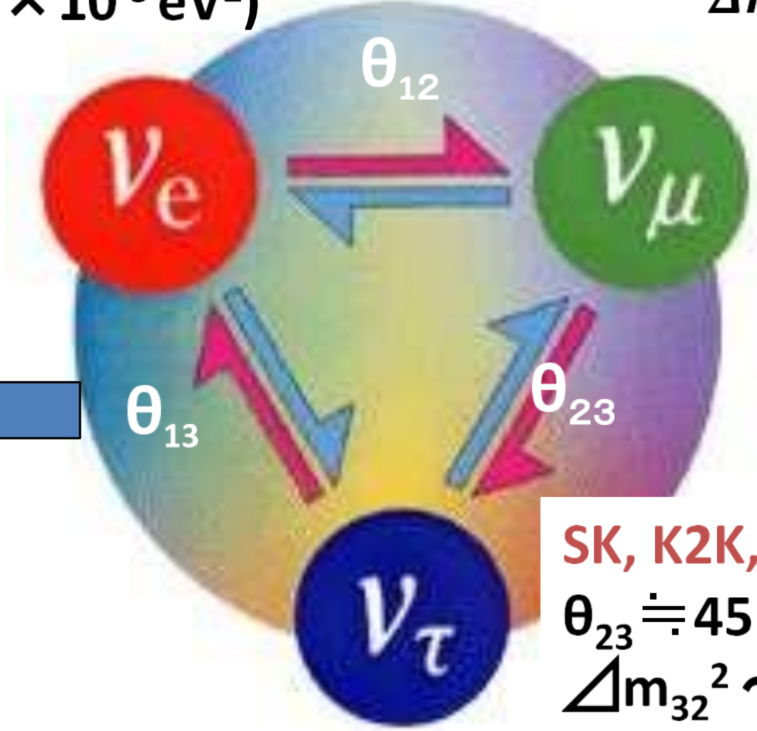
1. Introduction
2. Experimental setup
    - 2.1 Experimental overview
    - 2.2 Accelerator
    - 2.3 Beam line
    - 2.4 Detectors
3. Current status & results

1. Introduction

Neutrino oscillation measurement before T2K

SK, SNO, KamLand
($\theta_{12} \fallingdotseq 34^\circ$
$\Delta m_{21}^2 \sim 8 \times 10^{-5}\ \mathrm{eV}^2$)

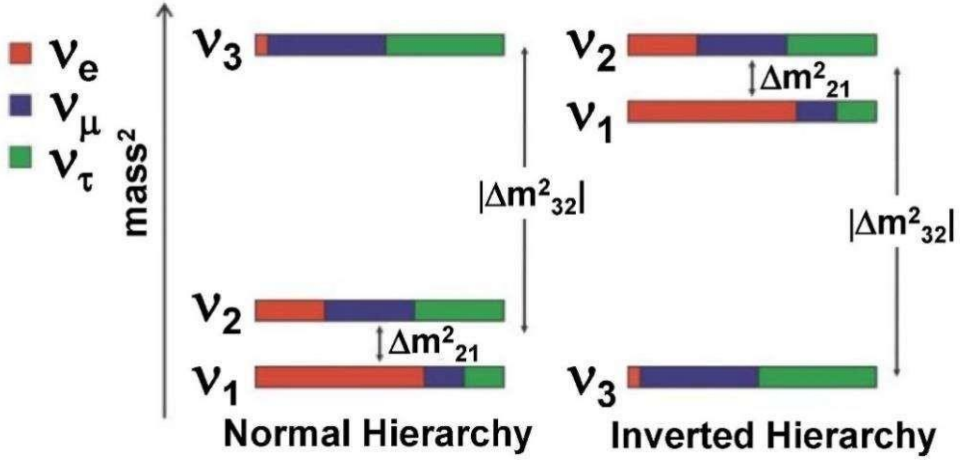
$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$



Not observed

θ_{13} =?, δ_{CP} = ?

SK, K2K, MINOS
$\theta_{23} \fallingdotseq 45^\circ$
$\Delta m_{32}^2 \sim 2.5 \times 10^{-3}\ \mathrm{eV}^2$



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

$$\underbrace{\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}}_{\text{Flavor eigen states}} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmospheric term}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13}\end{pmatrix}}_{\text{Reactor term}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar term}} \underbrace{\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}}_{\text{Mass eigen states}}$$

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

- ν_μ **disappearance** (We measure how much ν_μ's disappear after the flight.)
  ⇒ **θ_{23}, Δm_{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?
→ See Prof. Agarwalla's lecture on the 1st day)

T2K δ_{CP} measurement

ν mode

$\nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu$ → $\nu_\tau, \nu_\tau, \nu_\tau, \boxed{\nu_e,} \nu_e, \nu_\mu, \nu_\mu$

(Forward Horn Current, FHC)

$\bar{\nu}$ mode

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

(Reversed Horn Current, RHC)

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

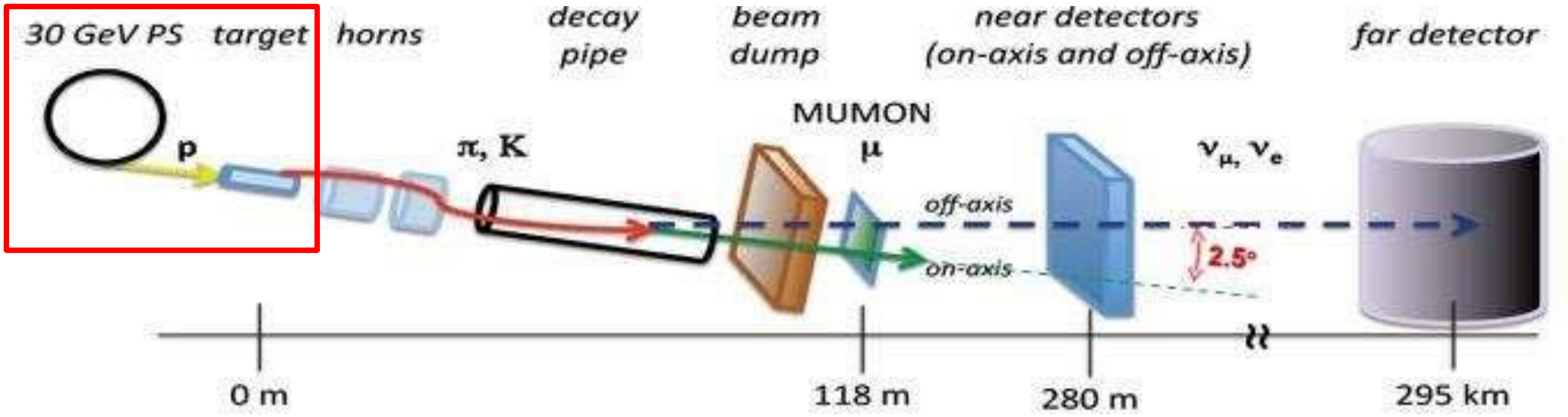
$P(\nu_\mu \rightarrow \nu_e) = P(\overline{\nu_\mu} \rightarrow \overline{\nu_e})$?

T2K Collaboration

~560 members, 74 institutes, 15 countries(incl. CERN)

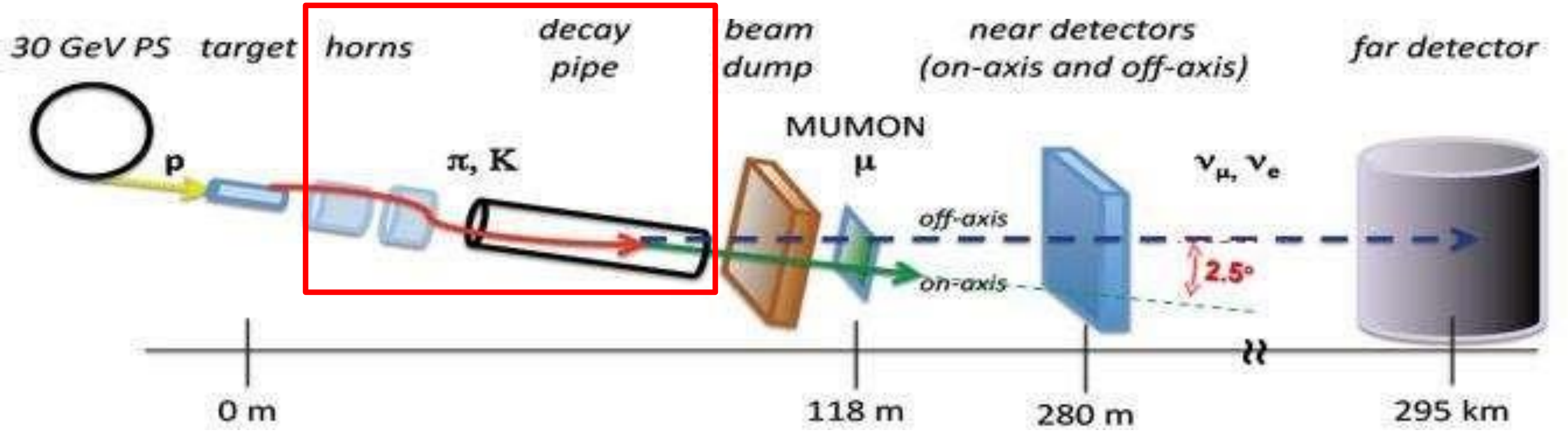
2. Experimental setup

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 $\pi^+ \to \mu^+ + \nu_\mu$
  - Antineutrino beam from $\pi^- \to \mu^- + \bar{\nu}_\mu$
  - Changing neutrino beam mode by flipping the horn polarity
- Beam dump absorbs remained hadrons & the direction & intensity of the muons from $\pi(K) \to \mu + \nu$ 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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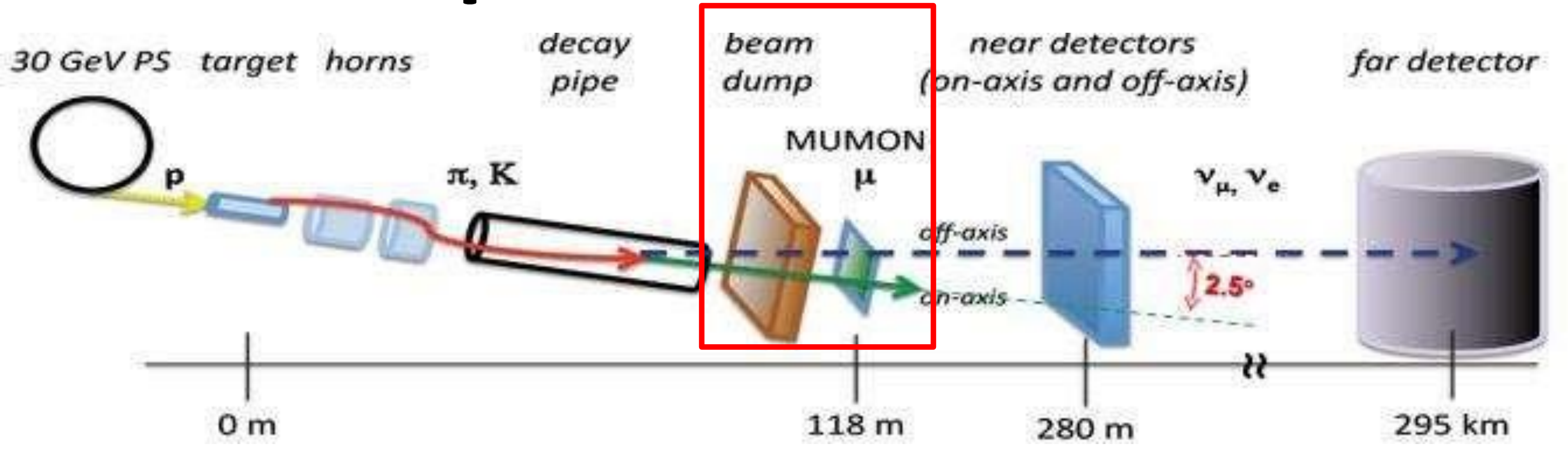

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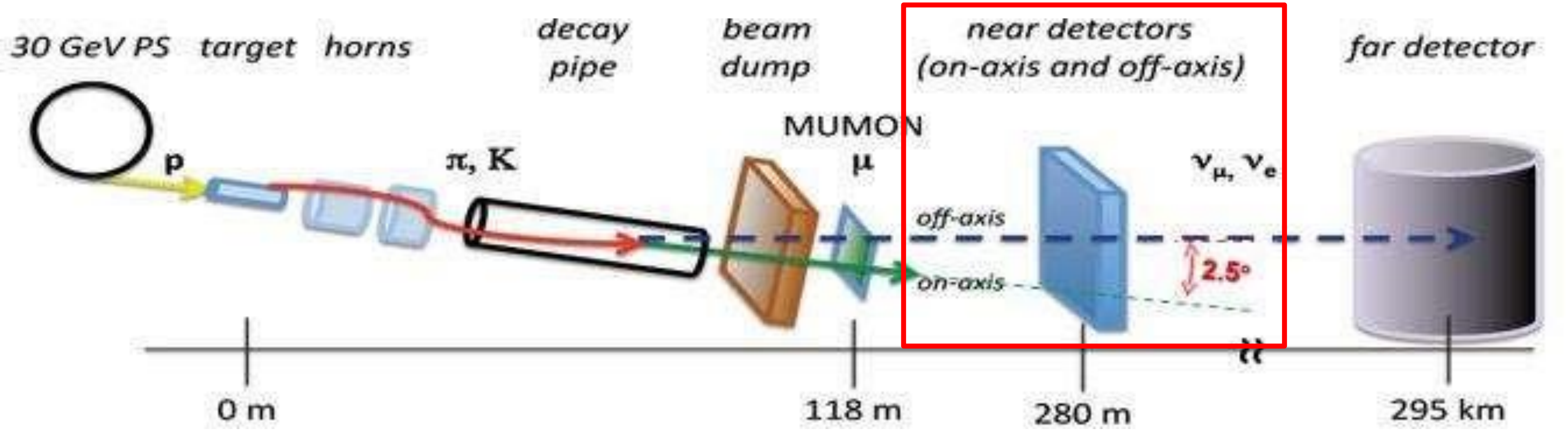

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- Neutrinos are measured by far detector 295km far away from target.

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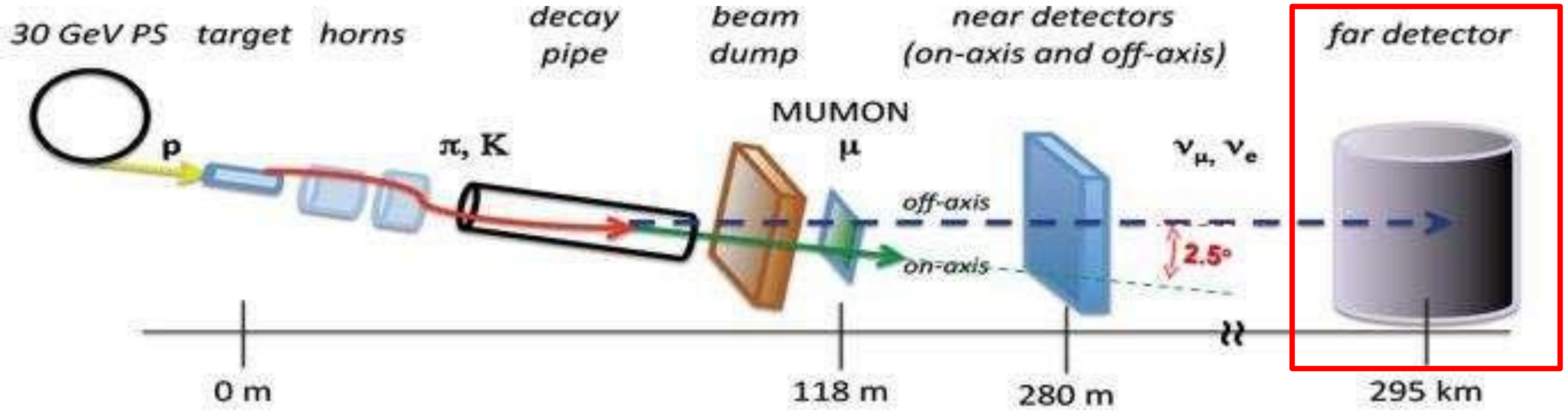

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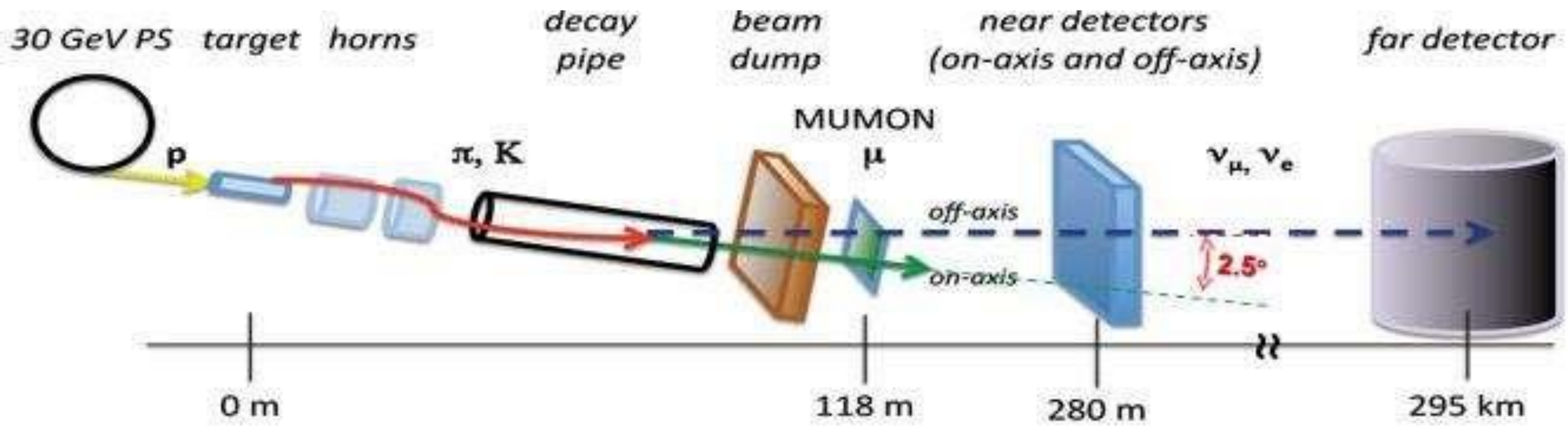
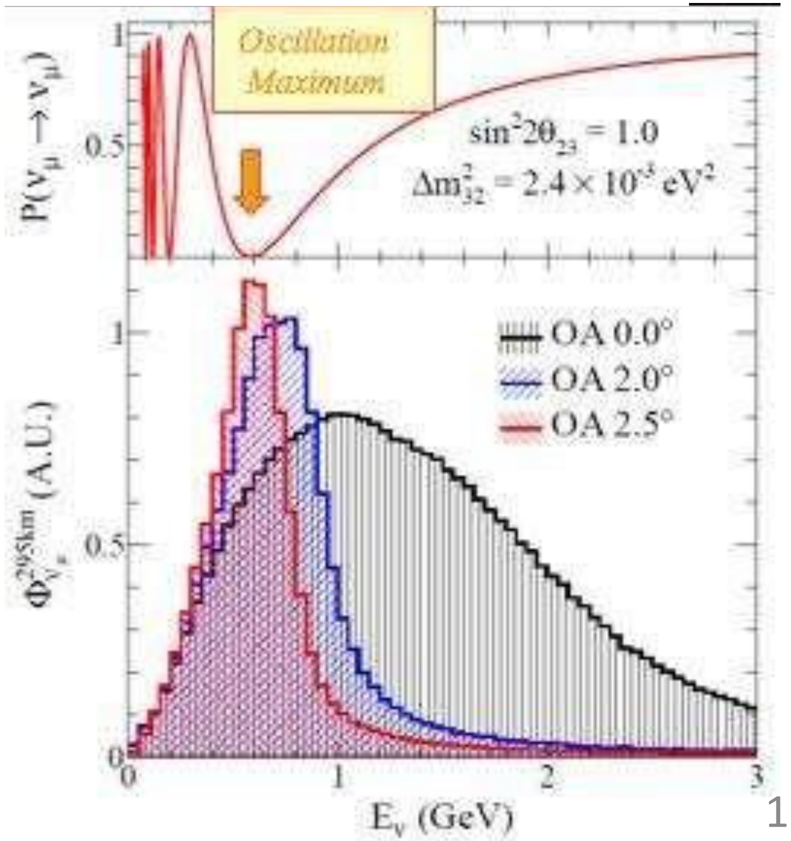
- Beam dump absorbs remained hadrons & the direction & intensity of the muons from $\pi(K) \to \mu + \nu$ are measured by MUMON.
- Unoscillated neutrinos are measured by near detectors
- Neutrinos are measured by far detector (SK) 295km far away from target.

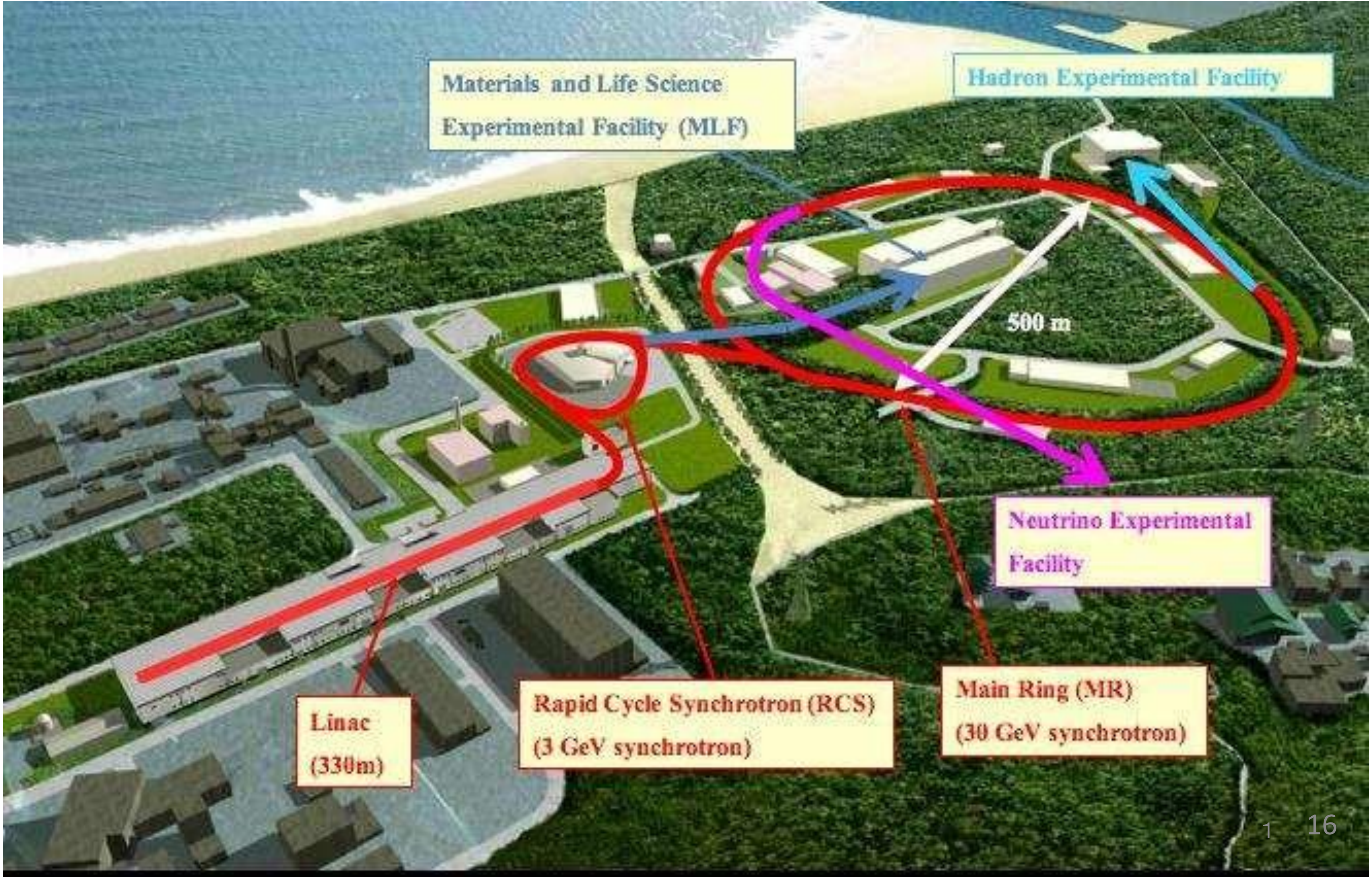
2.1 Experimental overview



- **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.

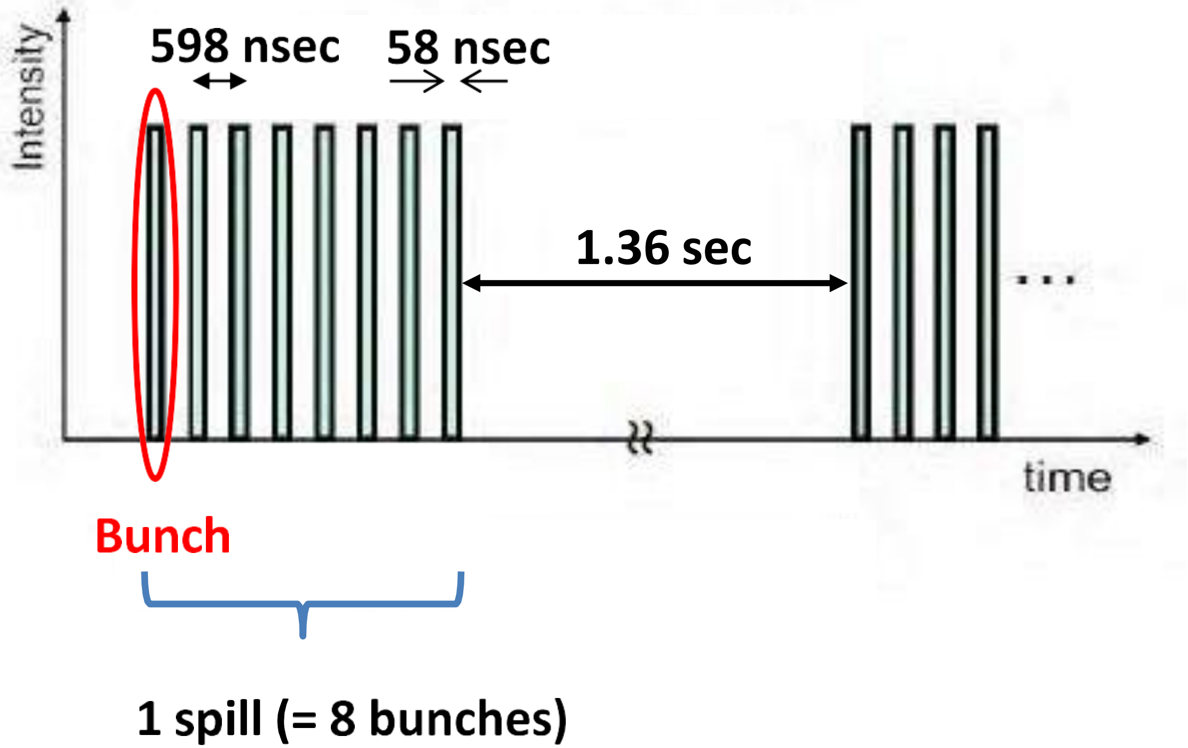
RCS
(Rapid Cycling Synchrotron)

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

Main Ring

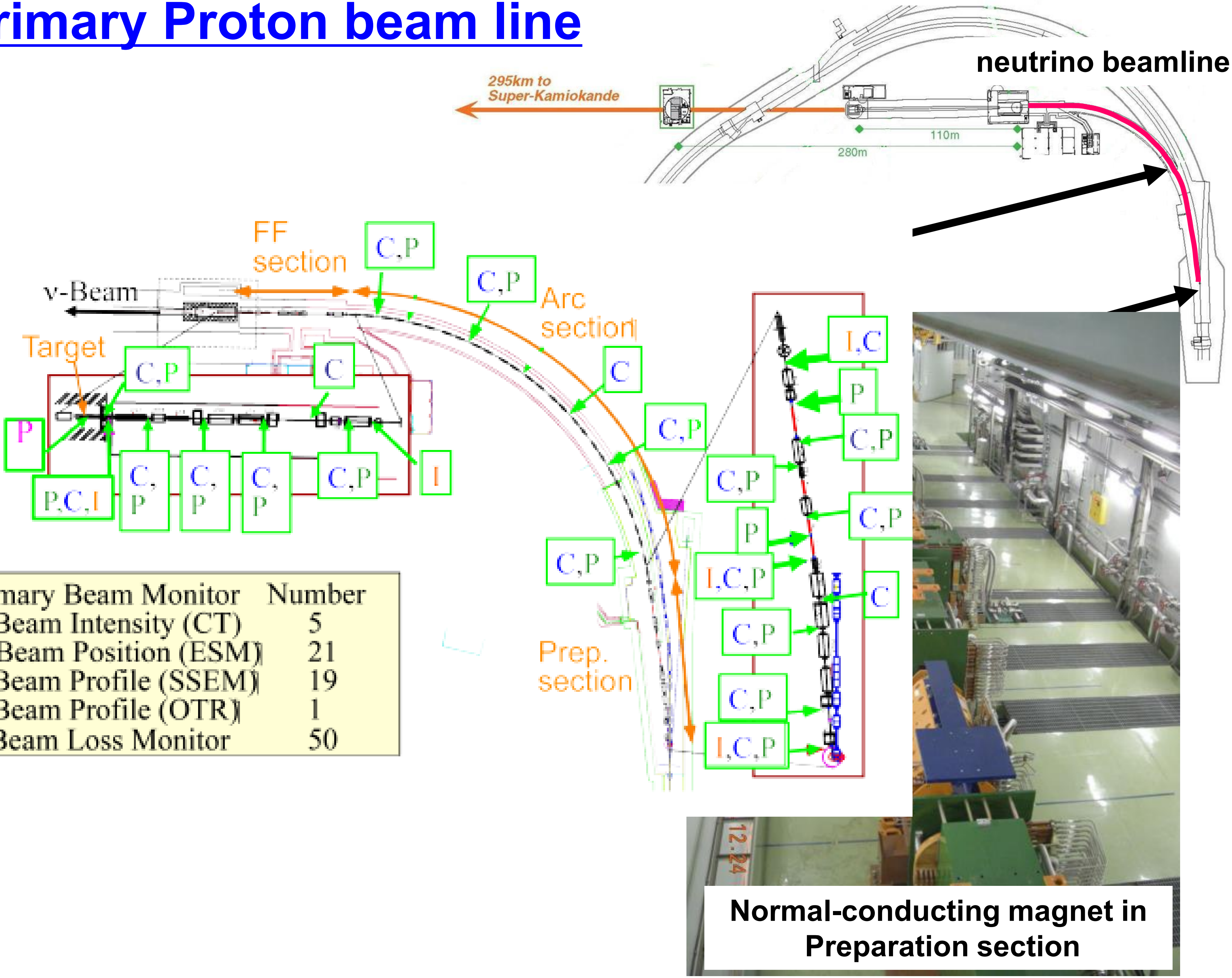
- **The third (and final) stage accelerator. Proton Synchrotron of 1568 m circumference.**
- **The 30 GeV proton beam is extracted to the neutrino beamline or to hadron hall.**

Proton beam to neutrino beam line



2.3 Beam line

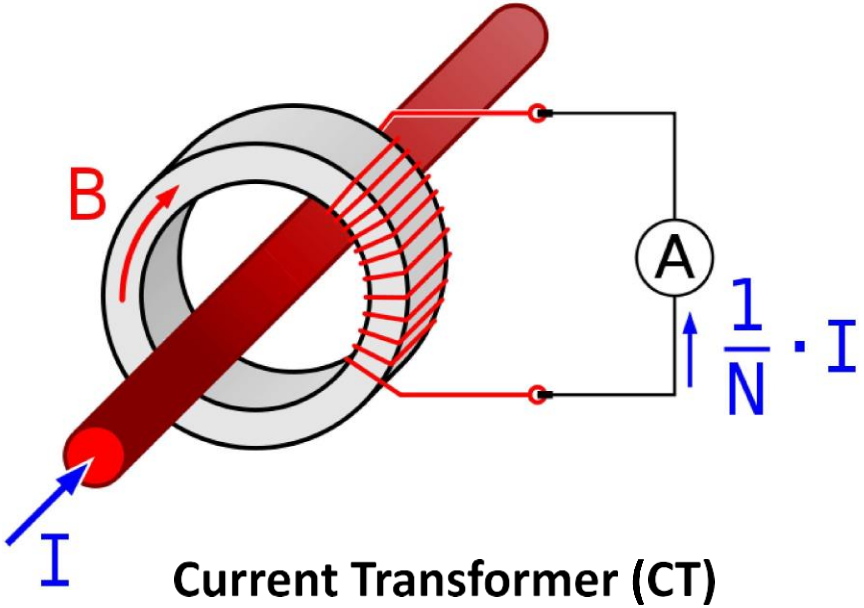
Primary Proton beam line



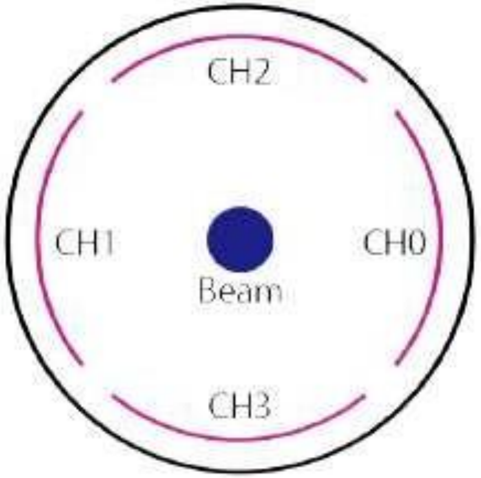
Primary Beam Monitor	Number
I : Beam Intensity (CT)	5
C: Beam Position (ESM)	21
P: Beam Profile (SSEM)	19
P: Beam Profile (OTR)	1
Beam Loss Monitor	50

Normal-conducting magnet in Preparation section

Beam monitors



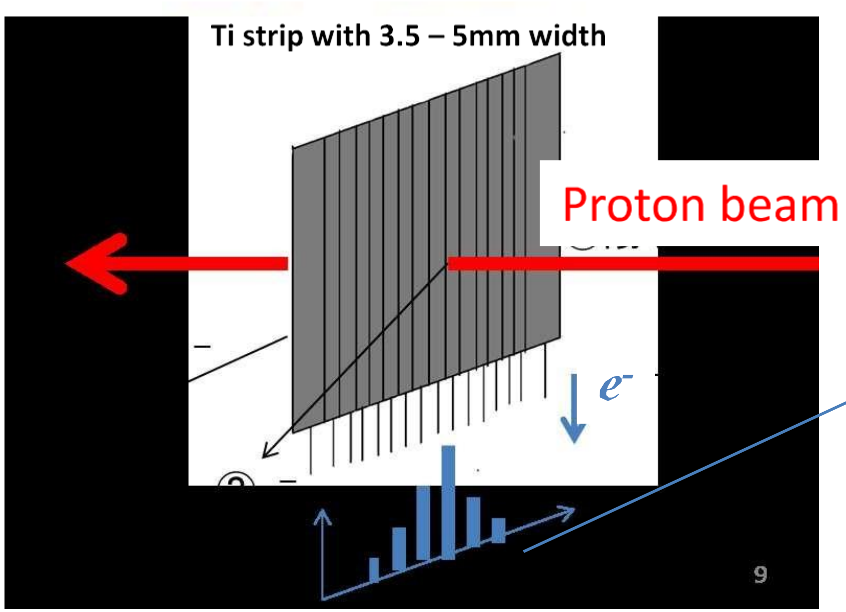
Current Transformer (CT)

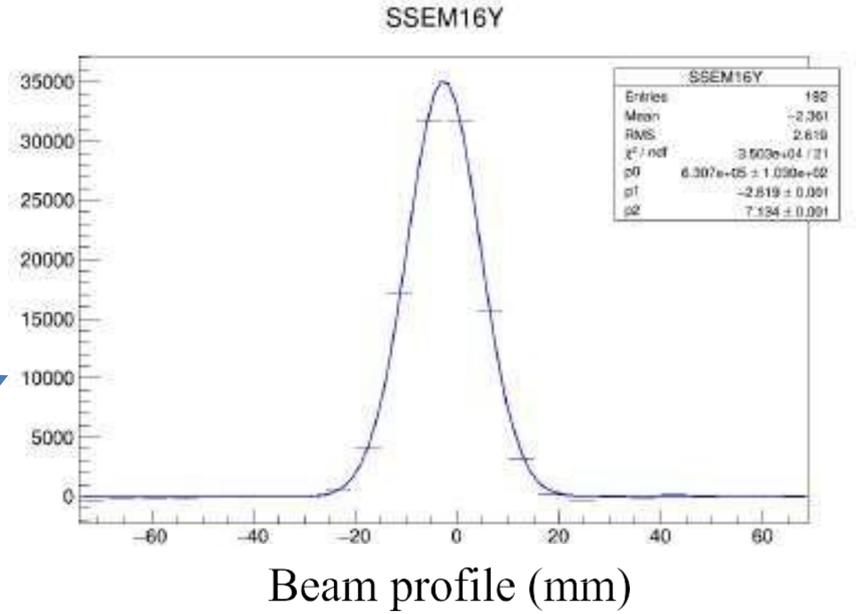


$$x \propto \frac{CH0 - CH1}{CH0 + CH1}$$

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

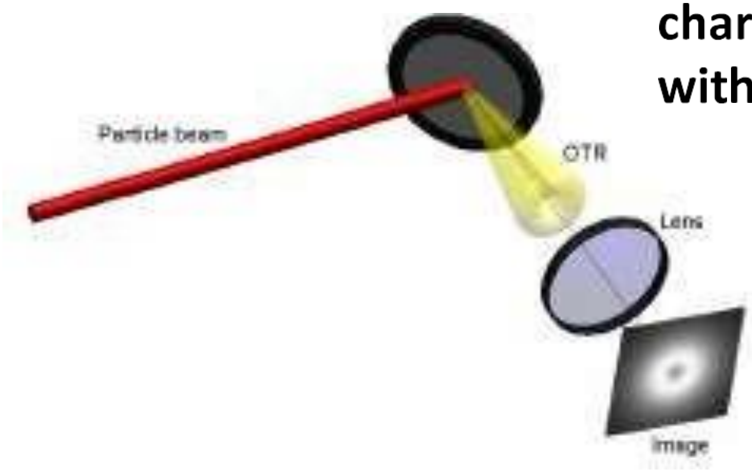
Electrostatic Monitor (ESM)





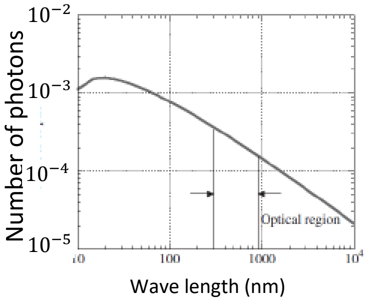
Secondary Segmented Emission Monitor (SSEM)

Optical Transition Radiation monitor (OTR)

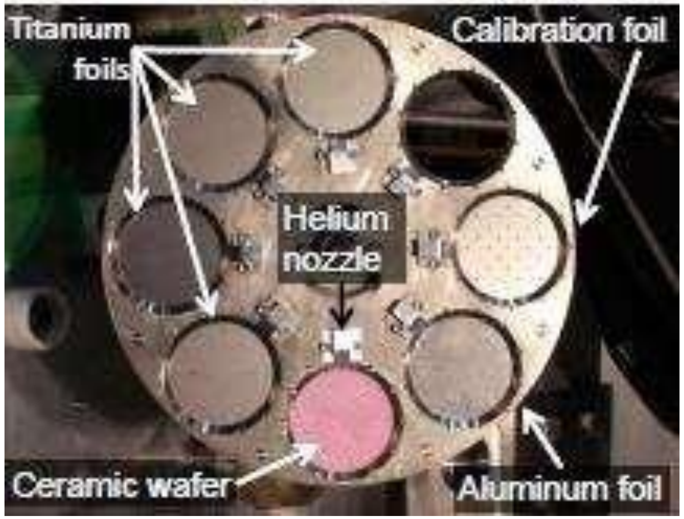


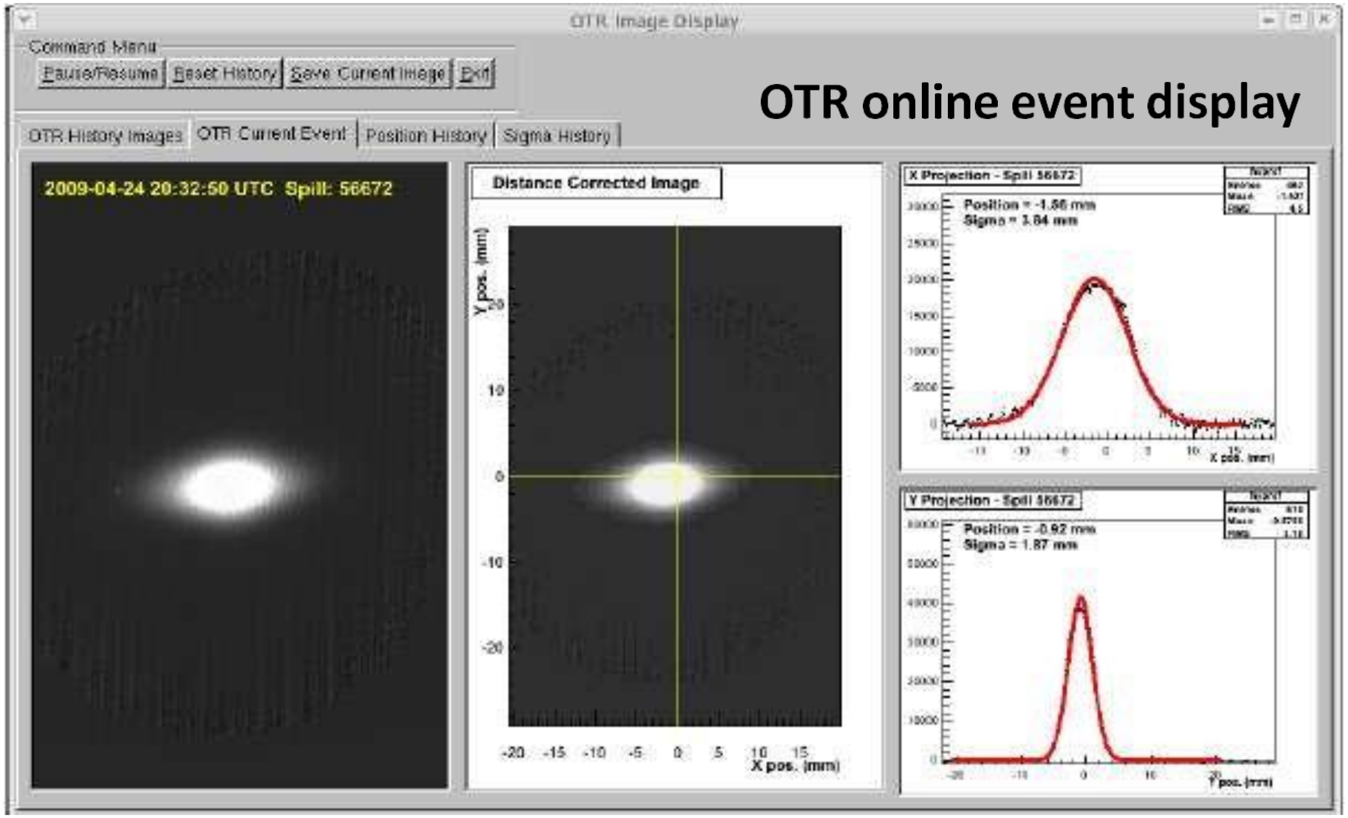
Transition radiation is a form of EM radiation emitted when a charged particle crosses the boundary between two media with different permittivities.

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



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.





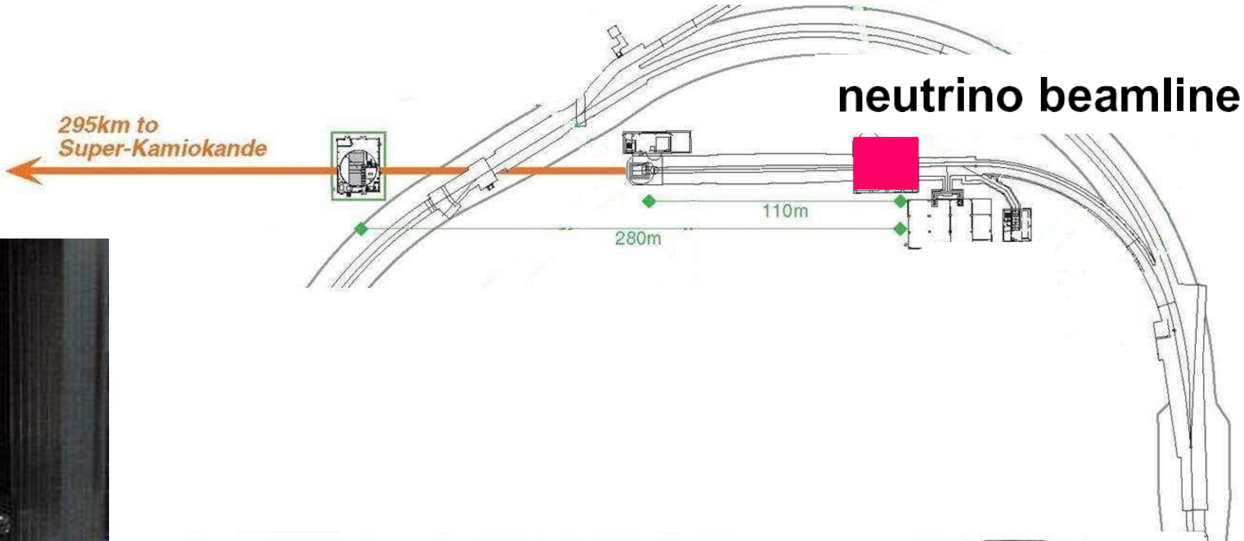
OTR online event display

2009-04-24 20:32:50 UTC Spill: 56672

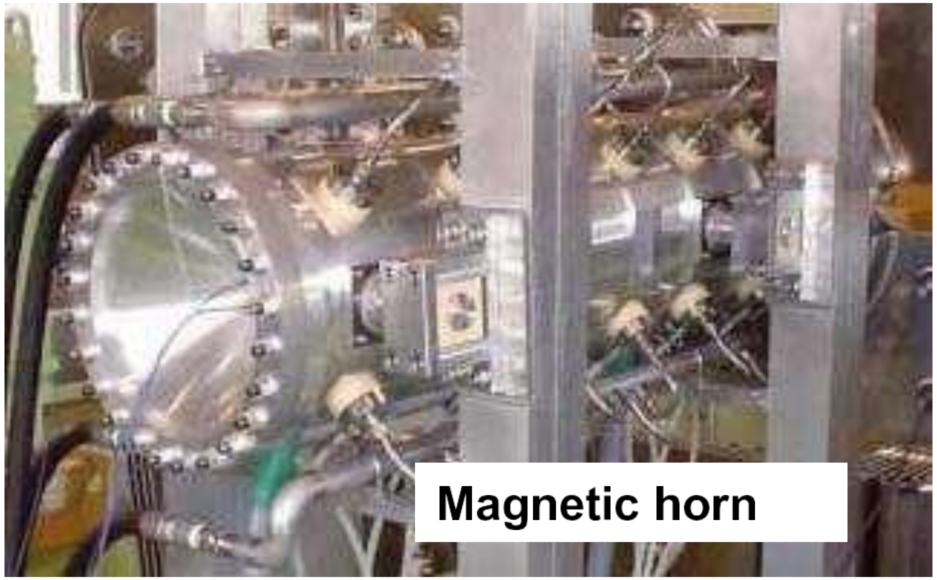
Position = -1.56 mm
Sigma = 3.84 mm

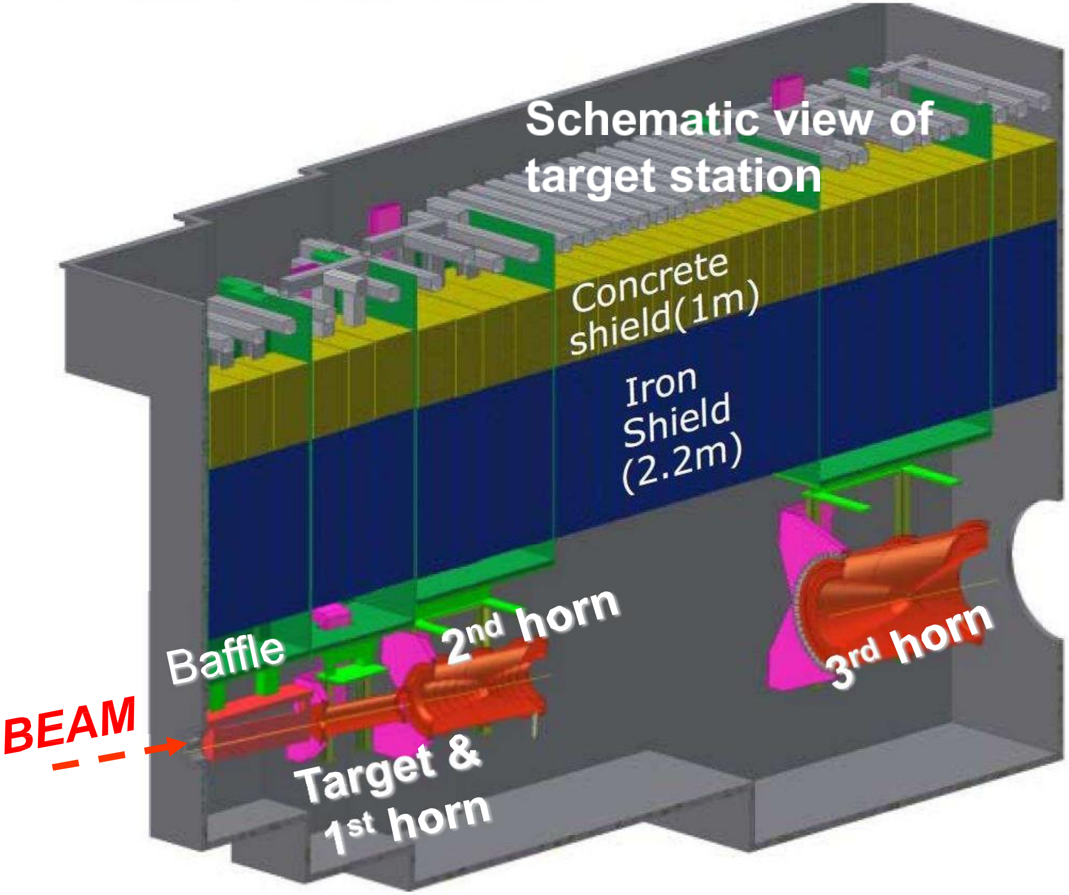
Position = -0.92 mm
Sigma = 1.87 mm

Target Station

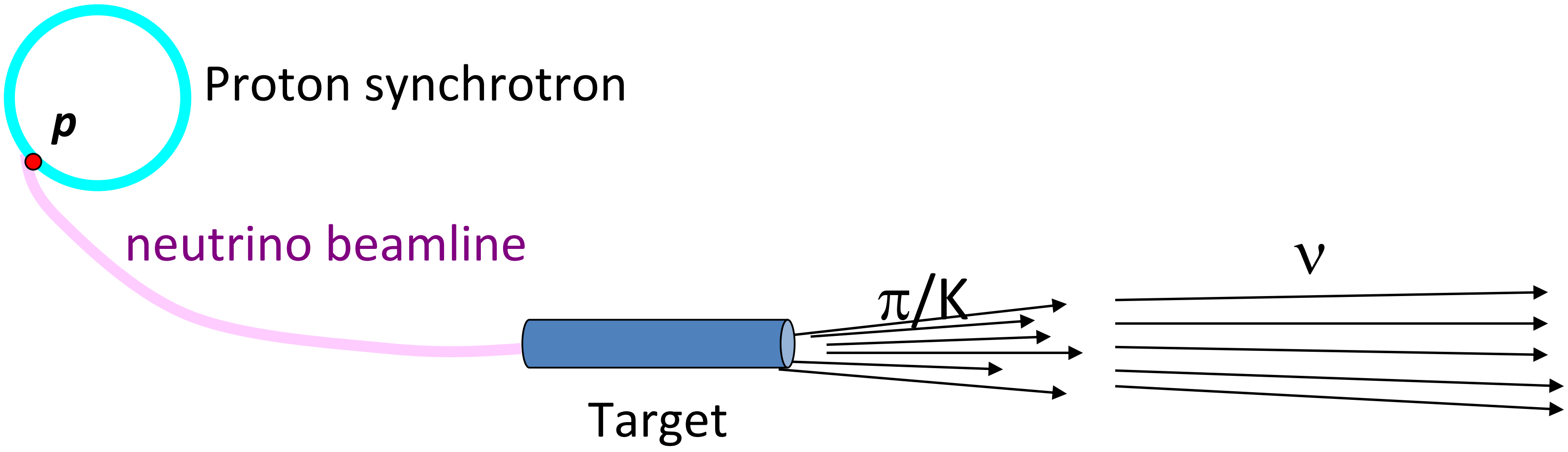



Carbon Target


Magnetic horn


Schematic view of target station

How to produce neutrino beam



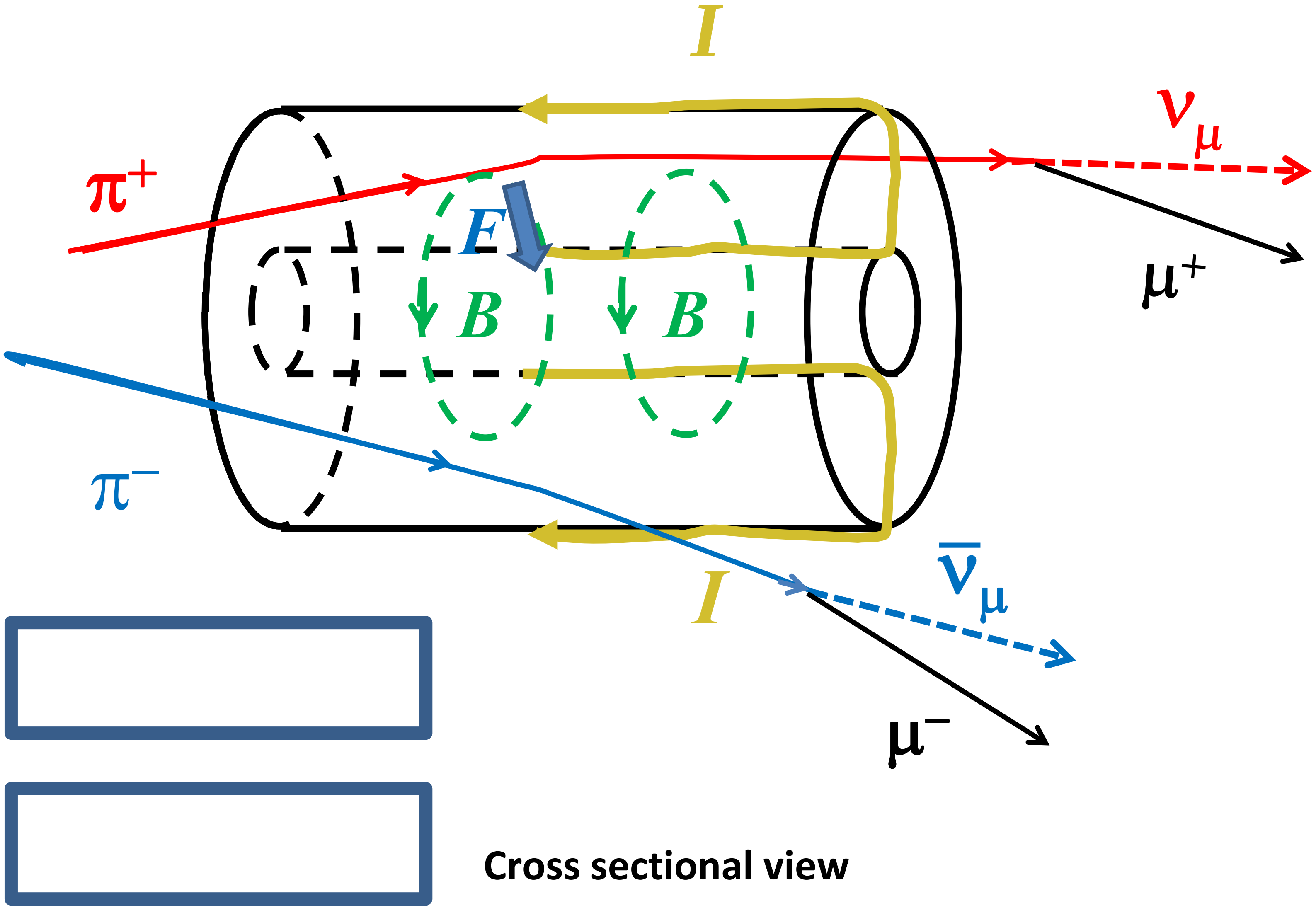
$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$K^+ \rightarrow \mu^+ + \nu_\mu$

We have to make the 2ry charged particle direction parallel and inject neutrinos to the target direction.

Magnetic horn !

Magnetic horn



Cross sectional view

Magnetic horn

- Magnetic horn is focus/defocus device installed just downstream of the target. High current (320 kA) 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.

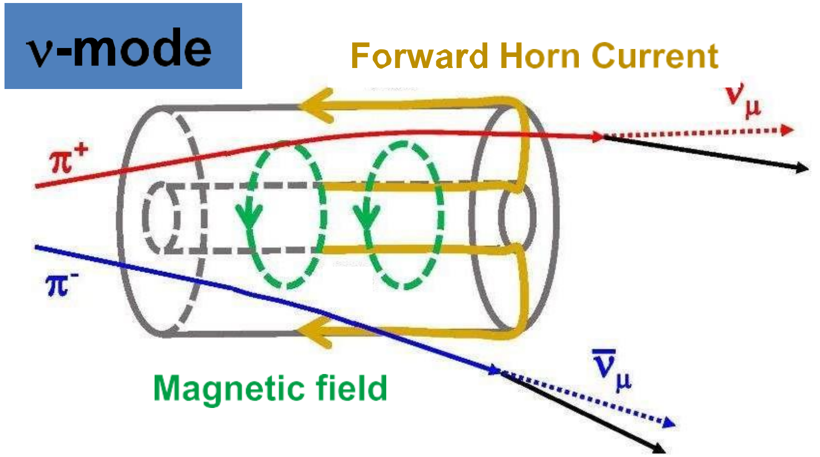
- Neutrino flux at SK is enhanced by factor ~10 (total) and ~16 (at ~0.6GeV).

- Neutrino components in each mode:

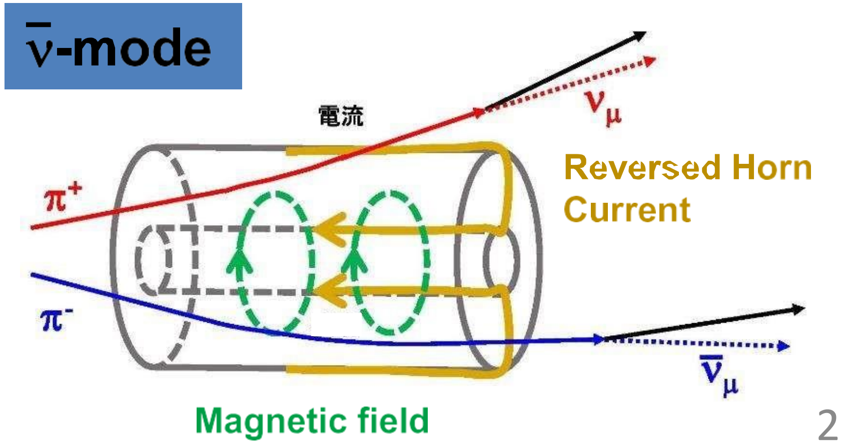
	ν_μ	$\bar{\nu}_\mu$	$\nu_e+\bar{\nu}_e$
ν-mode	~97%	~2%	~1%
$\bar{\nu}$-mode	~2%	~97%	~1%


magnetic horn

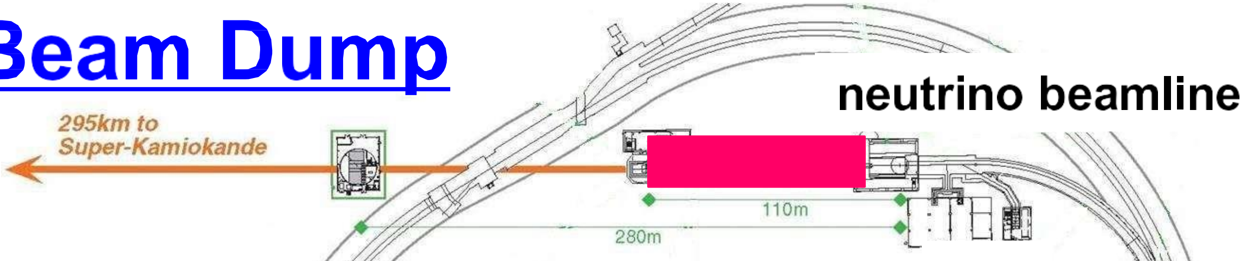
ν-mode



$\bar{\nu}$-mode

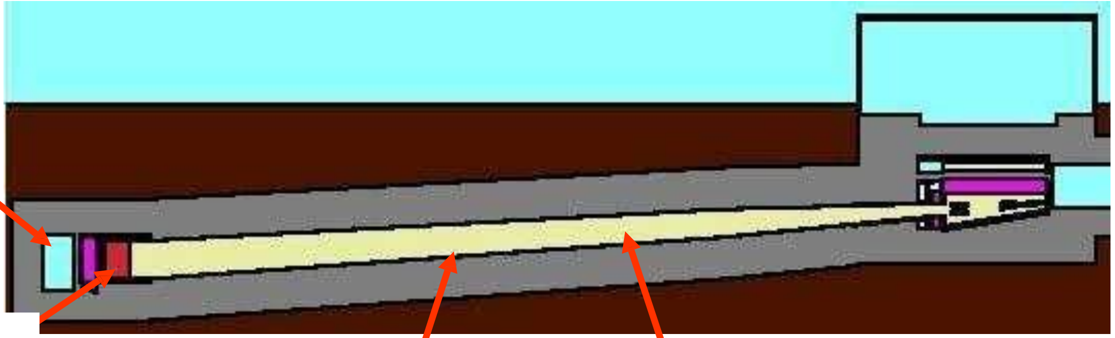


Decay Volume and Beam Dump



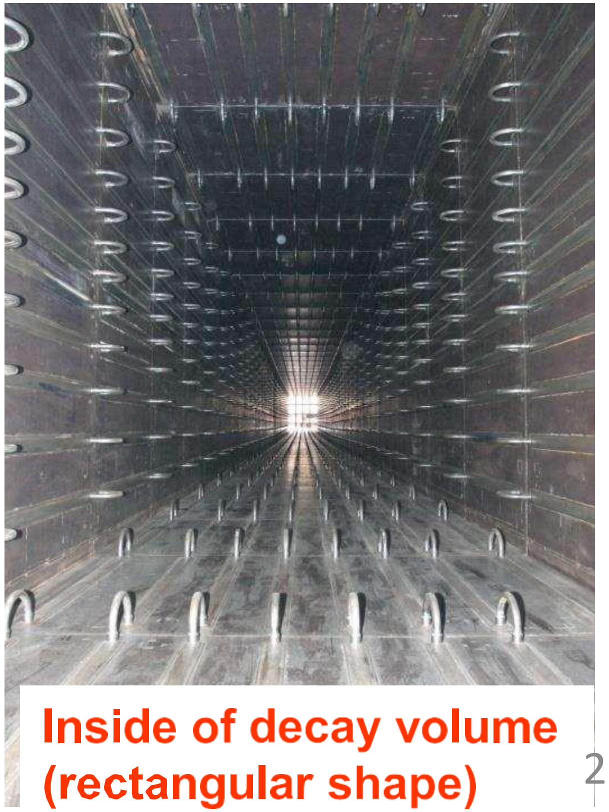
Muon monitors in Muon Pit

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



Beam Dump (installation)

Installation of decay volume



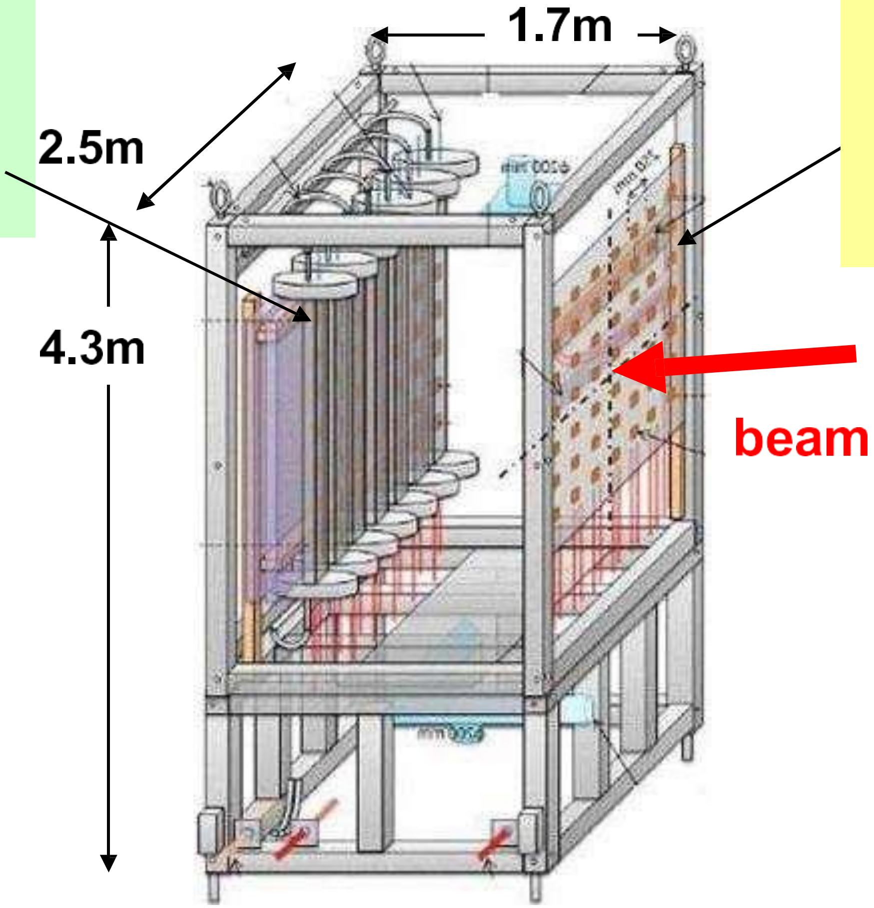
Inside of decay volume (rectangular shape)

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.

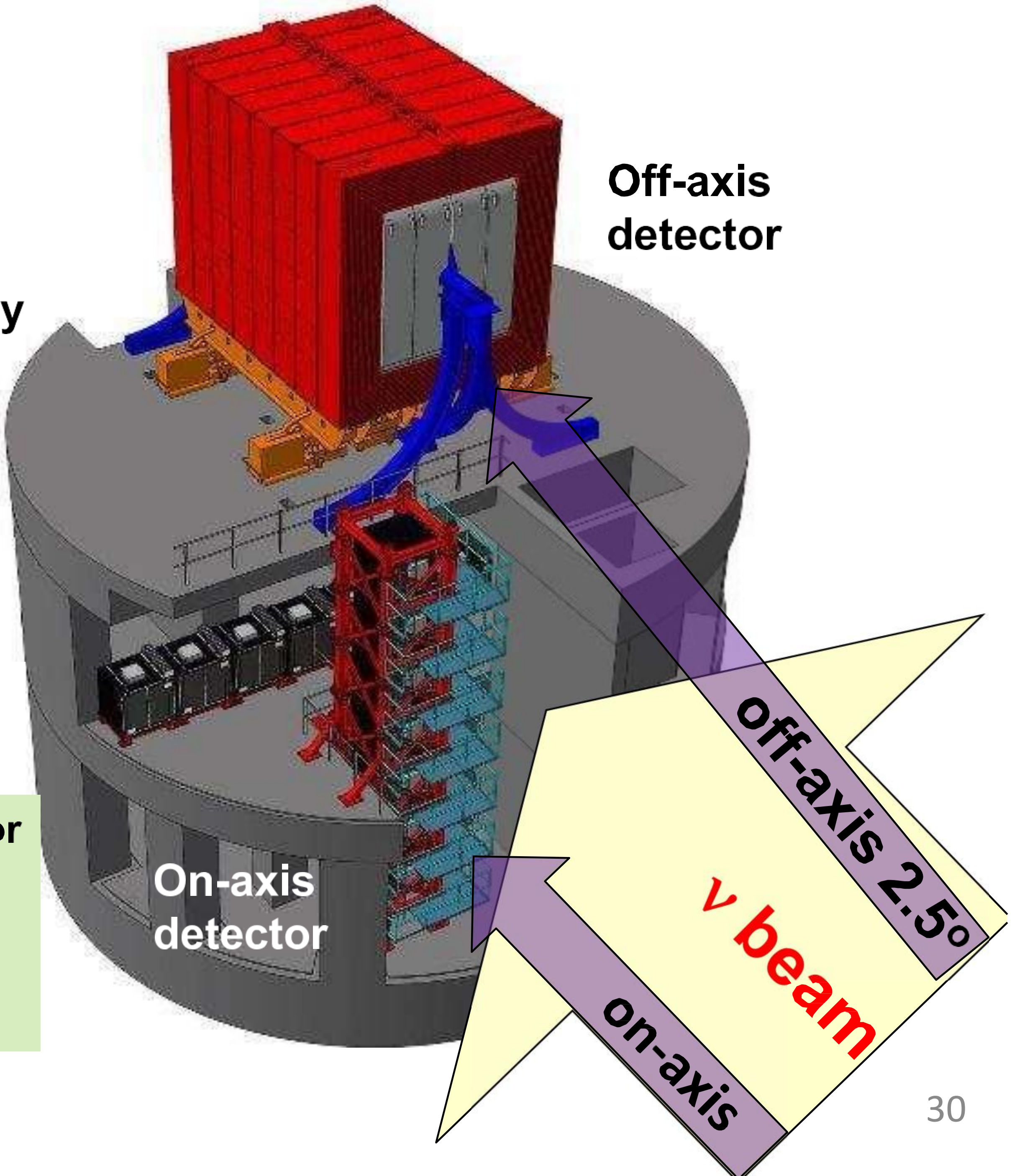
- Confirm the position of the beam center with < 3cm resolution on a bunch by bunch basis. This corresponds to < 0.3mrad beam direction accuracy.

2.4 Detectors

Near Detectors at 280m downstream

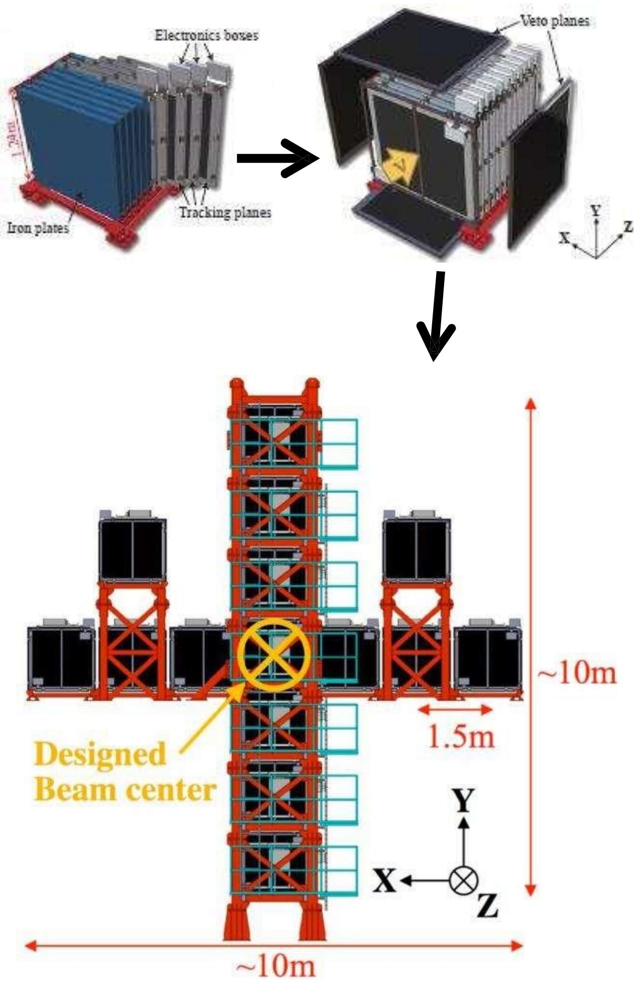
- The detectors were made in the underground experimental hall, 33.5m depth and 17.5m diameter. It is located at 280m downstream from the target.
- Two detectors were installed; they are On-axis Detector in the direction of the neutrino beam center, and Off-axis detector in the direction of Super-Kamiokande.

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.

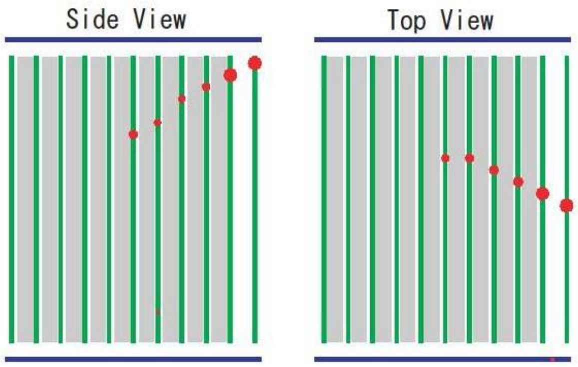


On-axis detector (INGRID)

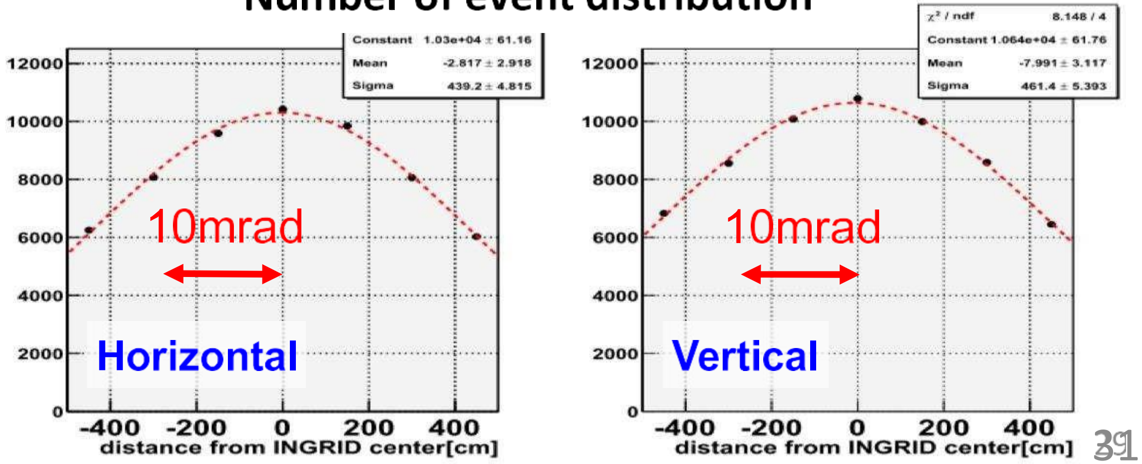
- Consists of 16 modules; 7 horizontal, 7 vertical, and 2 off-diagonal. Each module is 1m x 1m x 1m cube.
- Each module is "sandwich" of 11 plastic scintillator layers and 10 iron layers. They are surrounded by 4 veto planes.
- The neutrino beam center is obtained from horizontal/vertical distributions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



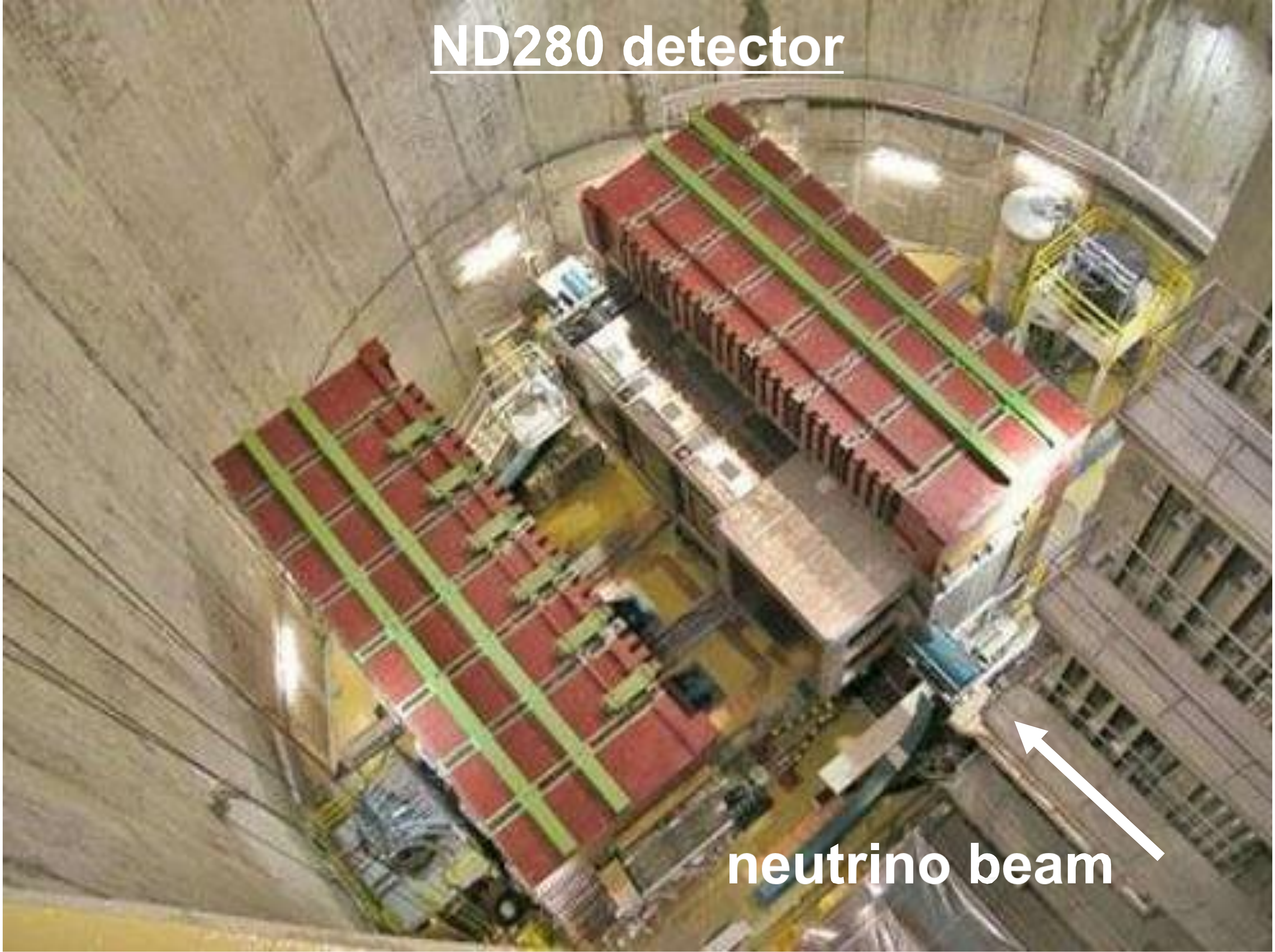
INGRID event view



Number of event distribution



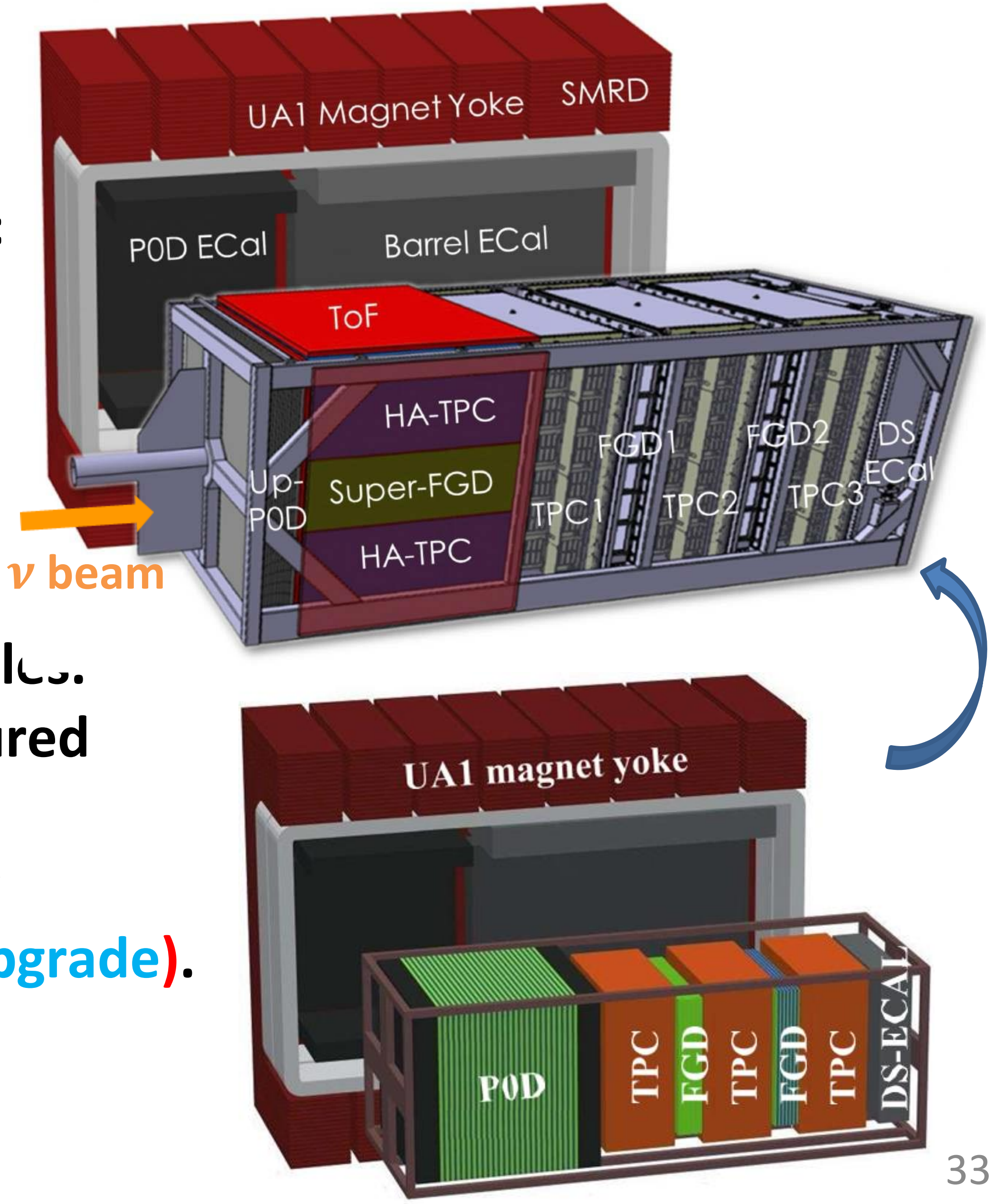
ND280 detector



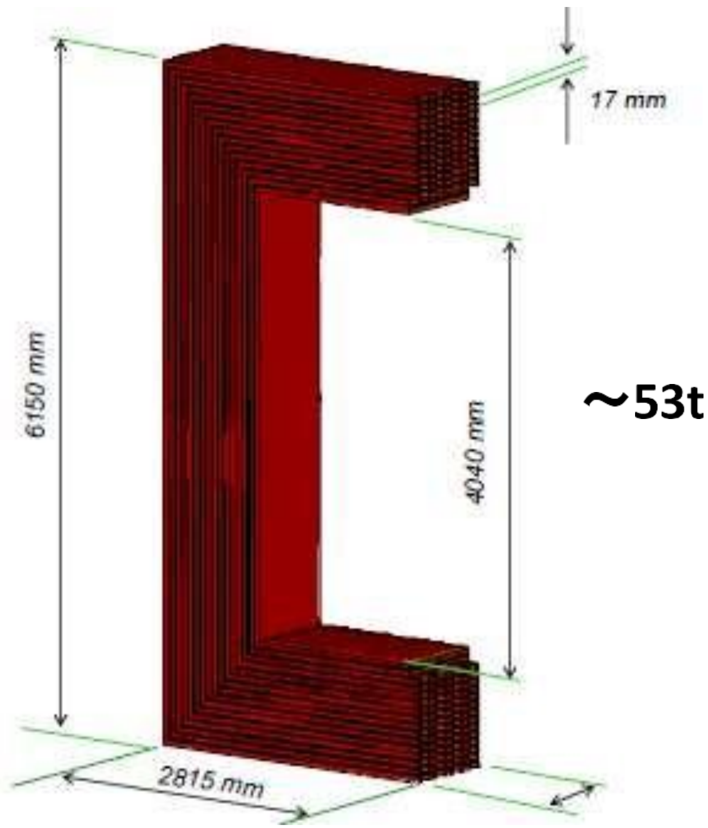
neutrino beam

Off-axis detector (ND280)

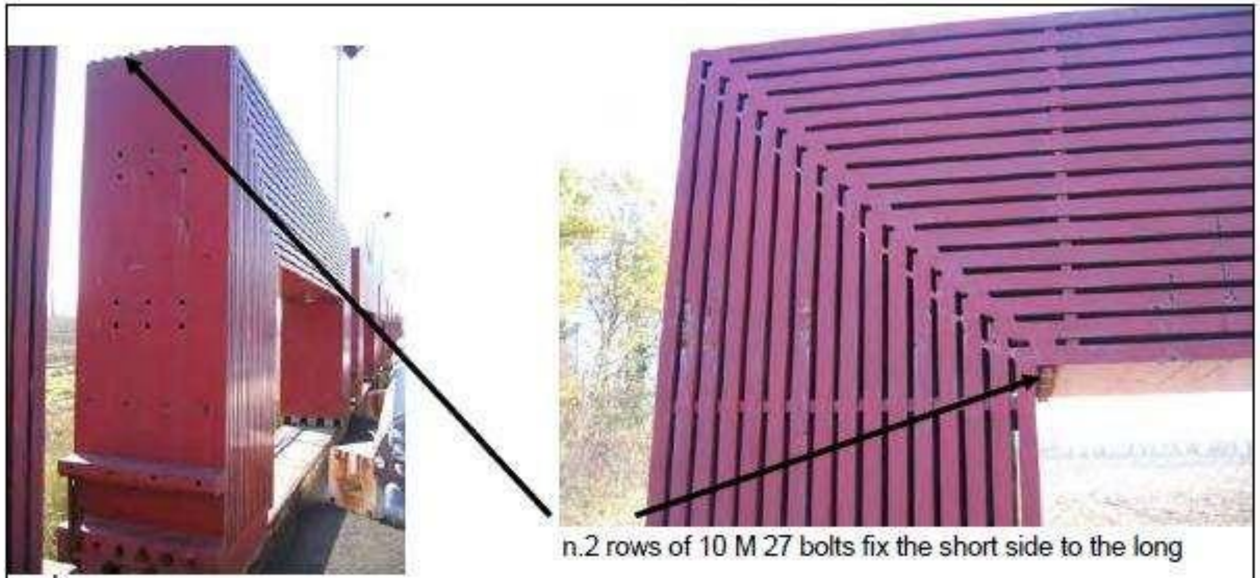
- **ND280** is made of several components.
- 2 **FGD**s (Fine-Grained Detectors) consists of scintillator bars. FGD2 has water as a target material.
- 3 gas-filled **TPC**s (Time Projection Chambers) track charged particles.
- All components are in **0.2 T** of magnetic field. The magnets were previously 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.
- Energy of wide angle muons are measured by **SMRD** (Side Muon Rage Detector)
- P0D (π^0 detector) was replaced by new detectors, **SFGD**, **HATPC**, **TOF** (**ND280 upgrade**).
- Neutrino flux as well as neutrino interactions can be studied from the reconstructed track information.



Magnet yoak

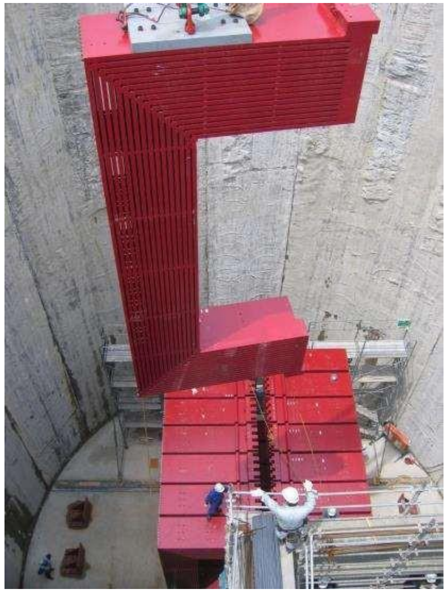


~53t



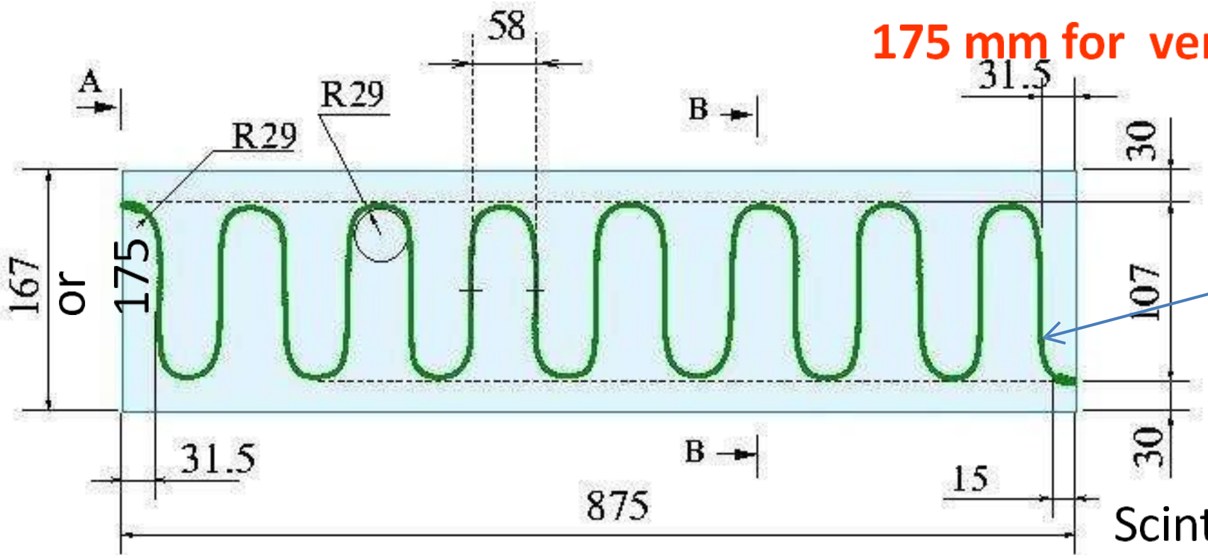
n.2 rows of 10 M 27 bolts fix the short side to the long

Magnet yoak installation



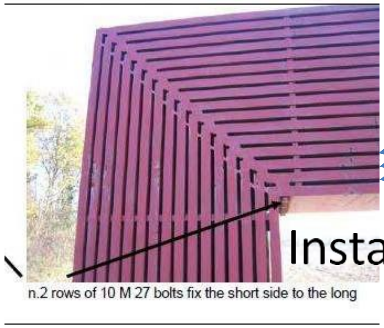
SMRD scintillator

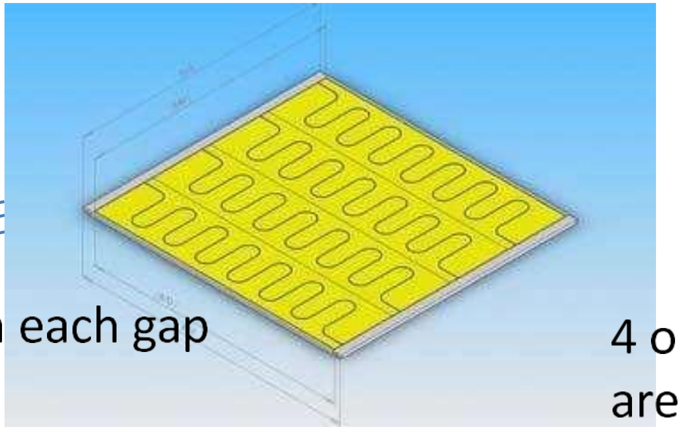
width:
167 mm for horizontal gaps
175 mm for vertical gaps



Wave length shifting fiber

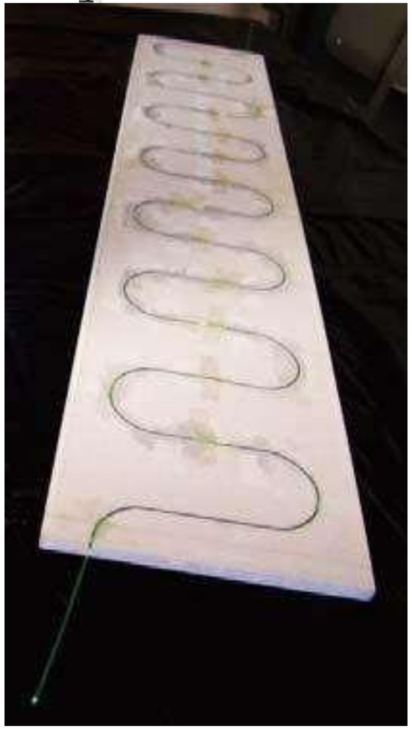
Scintillator thickness: 7.1 mm
Groove depth: 2.5 mm



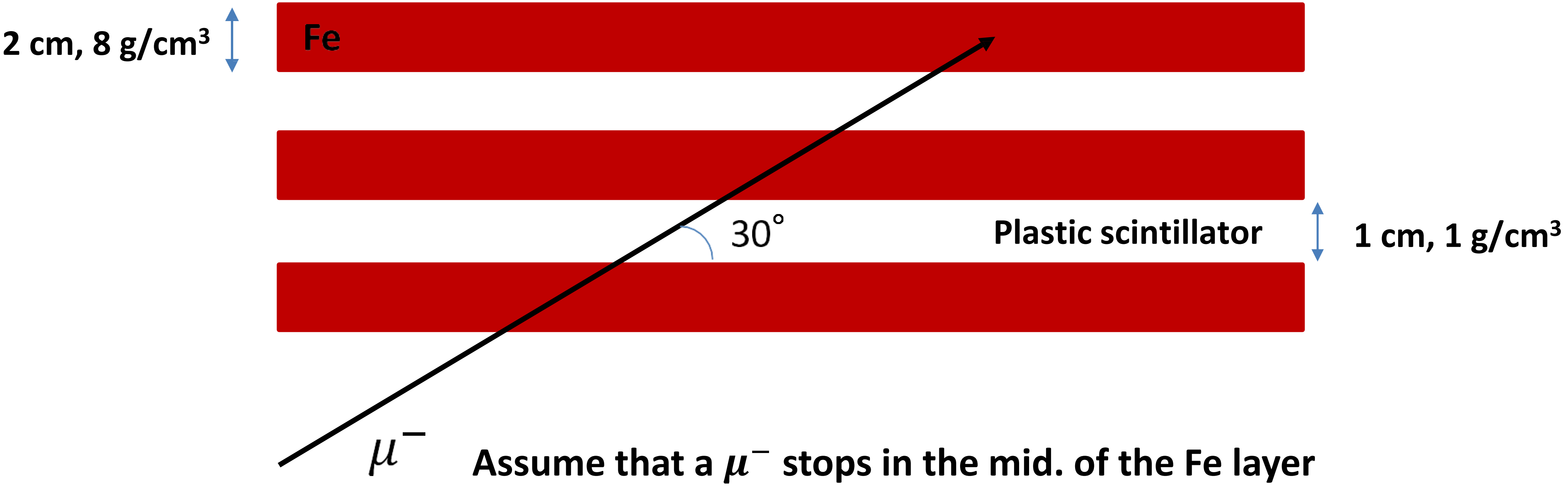


Installed in each gap

4 or 5 scintillators are combined into one module.



Easy exercise for a range detector



Assume that a μ^- stops in the mid. of the Fe layer

Densities of Fe & the scintillator : 8 g/cm³ & 1 g/cm³, respectively.

de/dx $\sim 2\ \mathrm{MeV}/\left(\mathrm{g/cm^2}\right)$

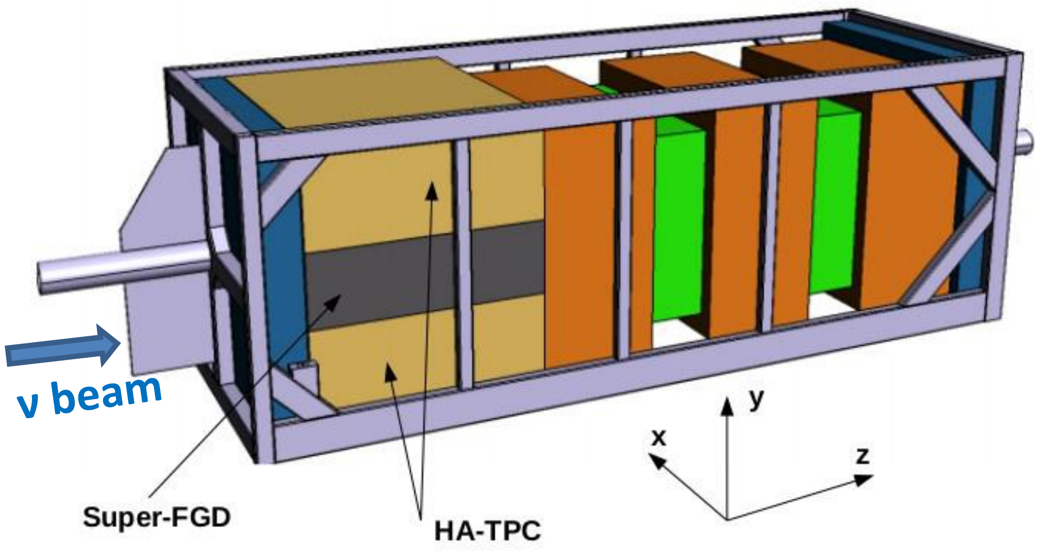
Calculate the muon deposit energy: E_μ^{deposit}

$$E_\mu^{\mathrm{deposit}} = (5\ \mathrm{cm}/\sin 30^\circ \times 8\ \ \mathrm{g/cm^3} + 2\ \mathrm{cm}/\sin 30^\circ \times 1\ \ \mathrm{g/cm^3}) \times 2\ \mathrm{MeV}/\left(\mathrm{g/cm^2}\right)$$

$= $ 168 MeV

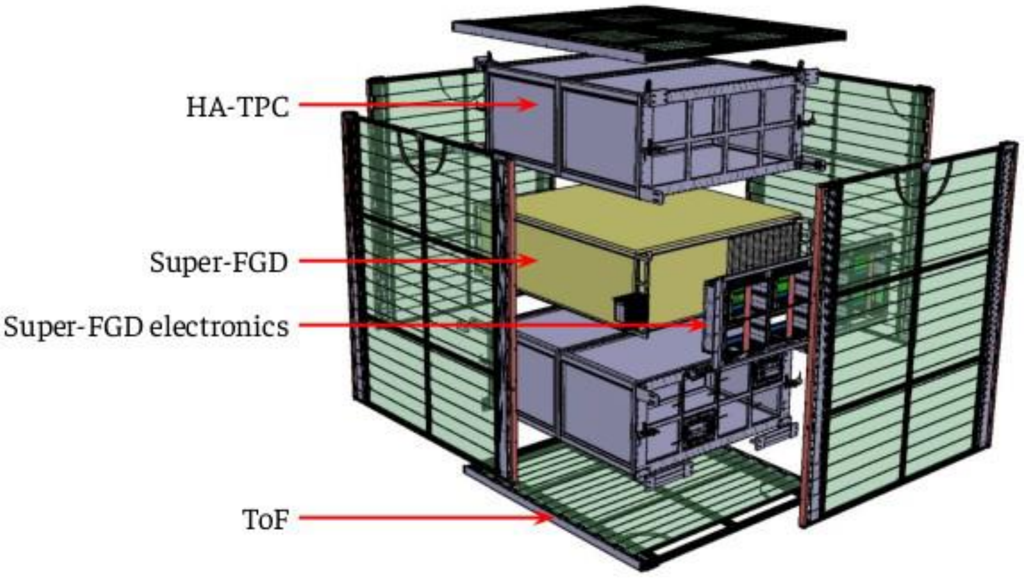
ND280 upgrade

P0D was replaced by Super-FGD, 2 High Angle TPCs, and 6 Time-of-Flight detectors.



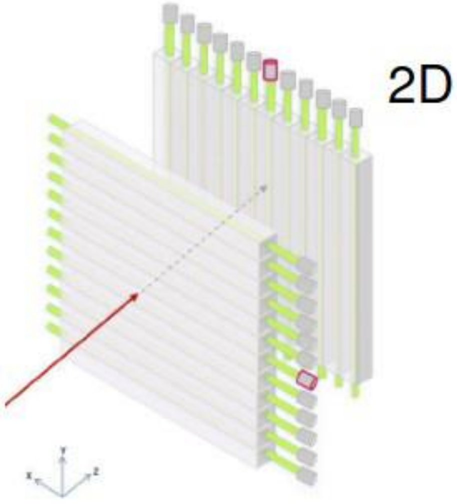
Super-FGD can fully reconstruct tracks in 3D. → Lower threshold and excellent resolution to reconstruct protons at any angle.

2 High-Angle TPCs can reconstruct muons at any angle with respect to beam.

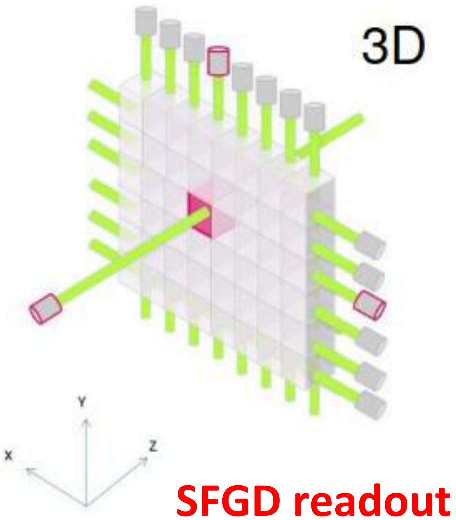


6 ToF planes can veto particles originating from outside the ND280 fiducial volume.

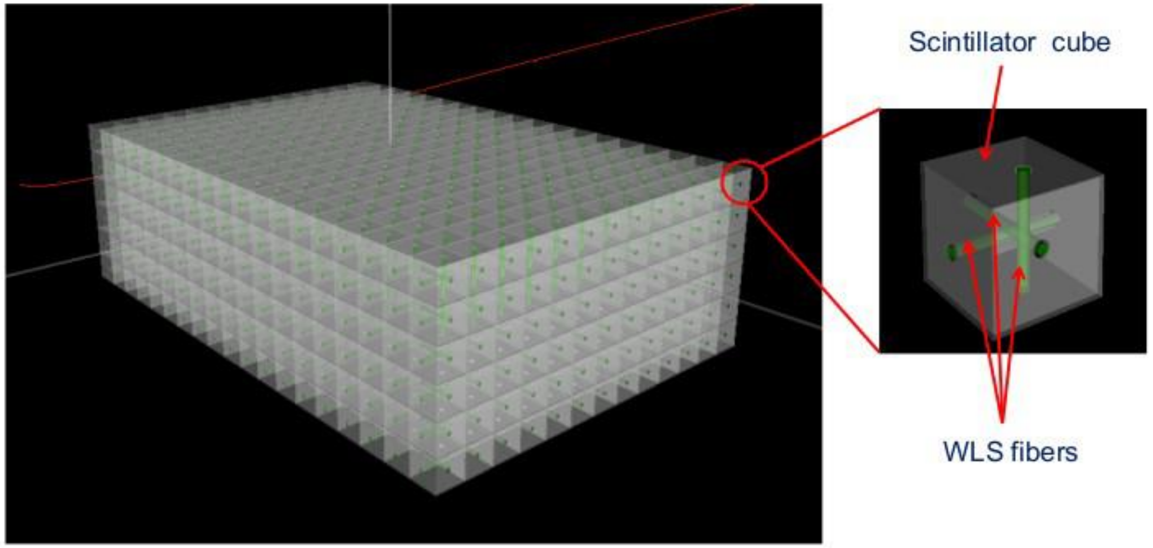
Super-Fine Grained Detector (SFGD)



FGD readout



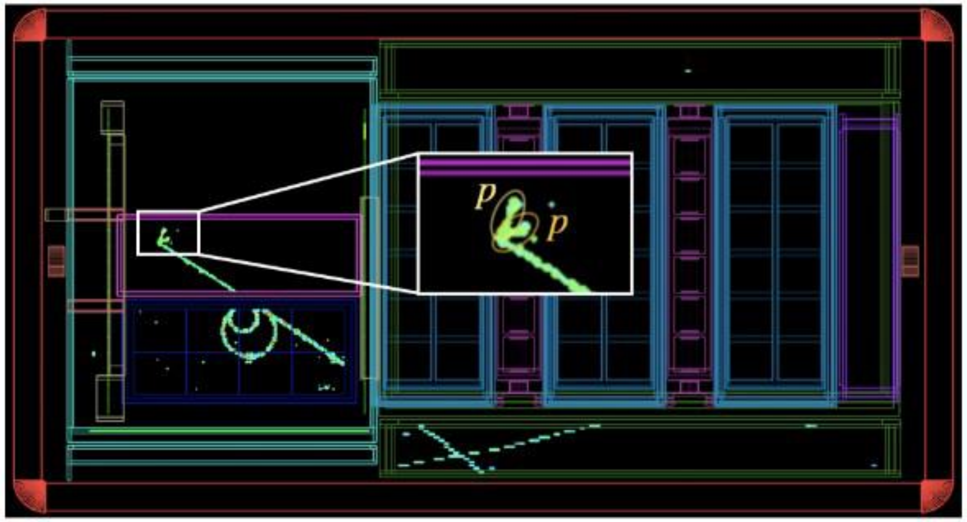
SFGD readout



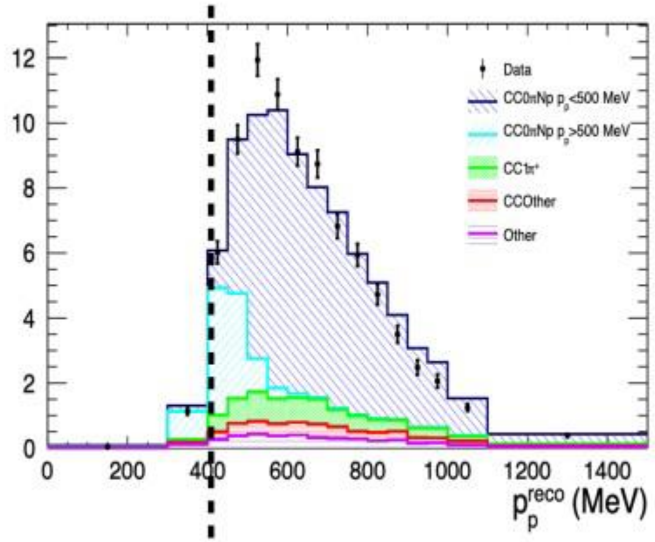
- A fully active high granularity plastic scintillator target/detector.
  - Total volume ≈ 192 × 182 × 56 cm^3
  - Fiducial mass ≈ 2 tons
- ～2 million optically isolated plastic scintillator cubes of 1 × 1 × 1 cm^3
- Readout- 55000 WLS fibers with MPPCs at one end.
- Dew to 3D tracking, 4π acceptance, and high vertex resolution, we can improve hadron reconstruction and PID.

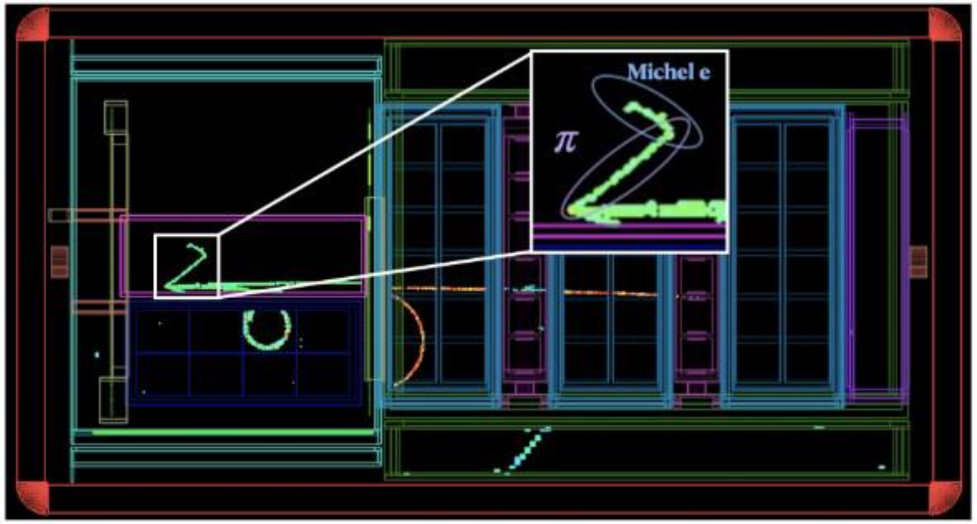
Expected performance of SFGD

First neutrino interactions recorded in SFGD !

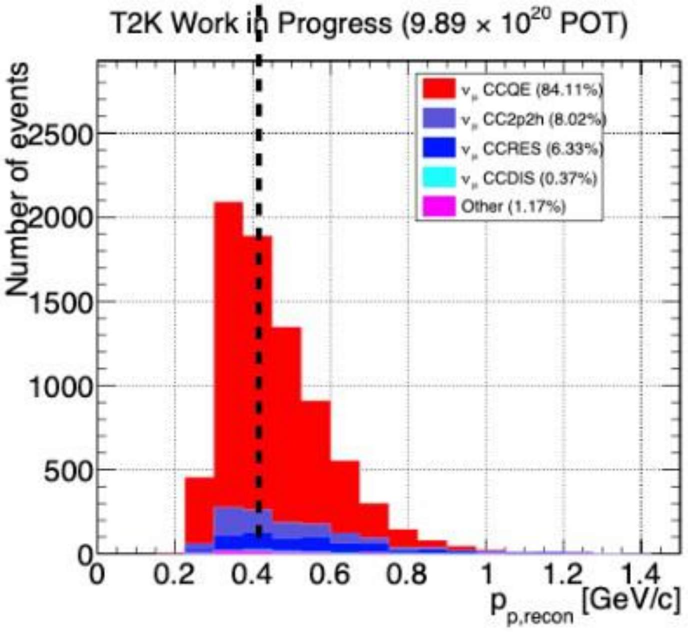


FGD data



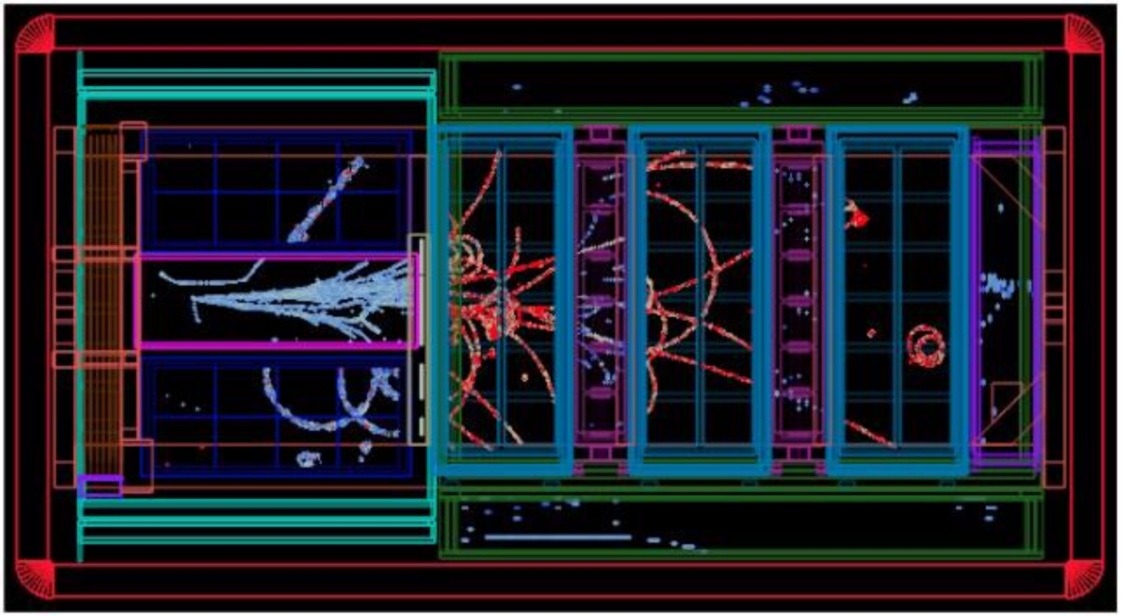


SFGD MC

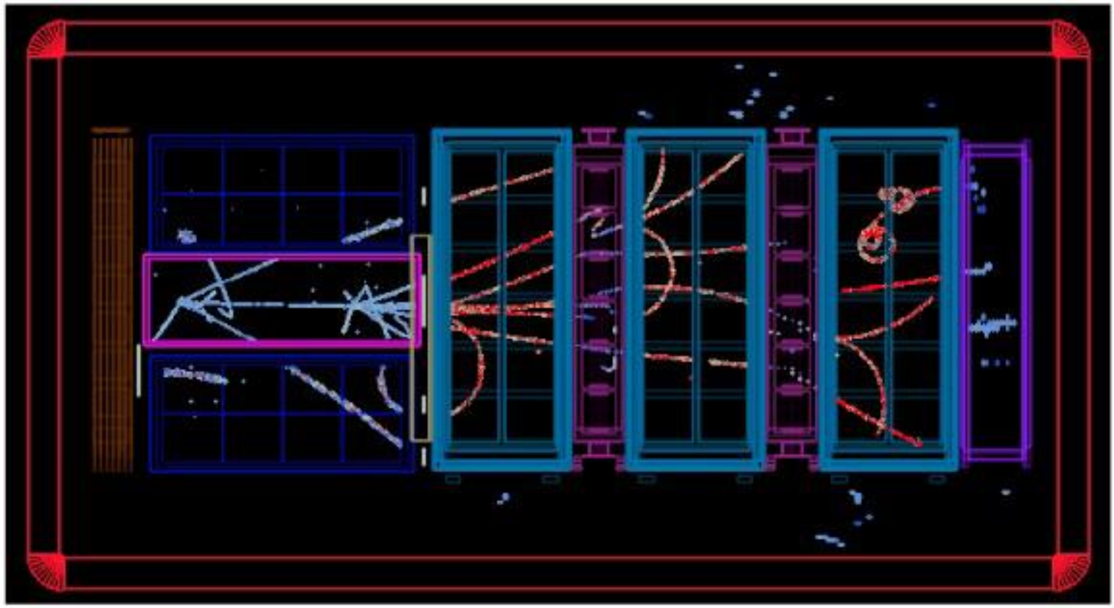


First neutrino interaction with full ND280 upgrade

June 2024



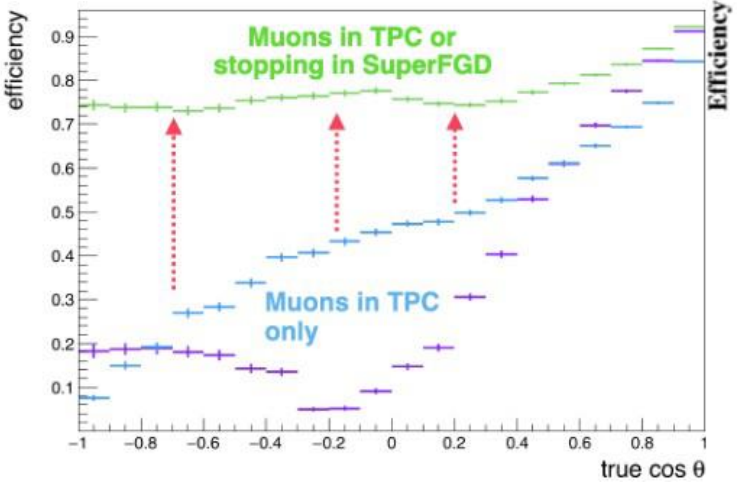
Side view



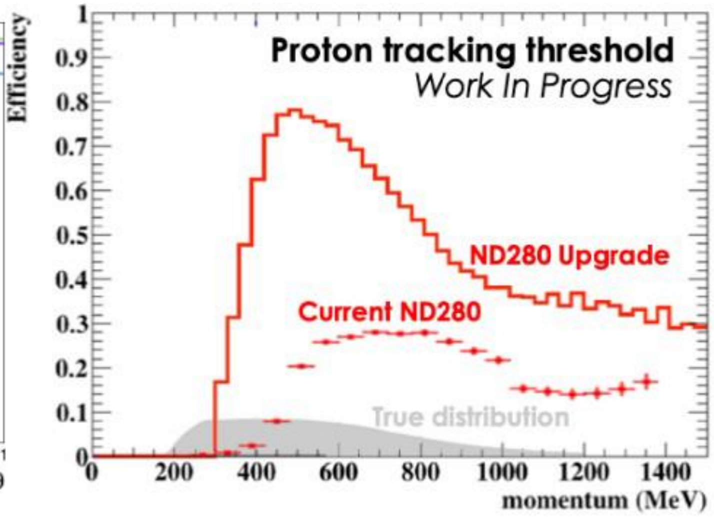
Plan view

Physics with ND280 upgrade

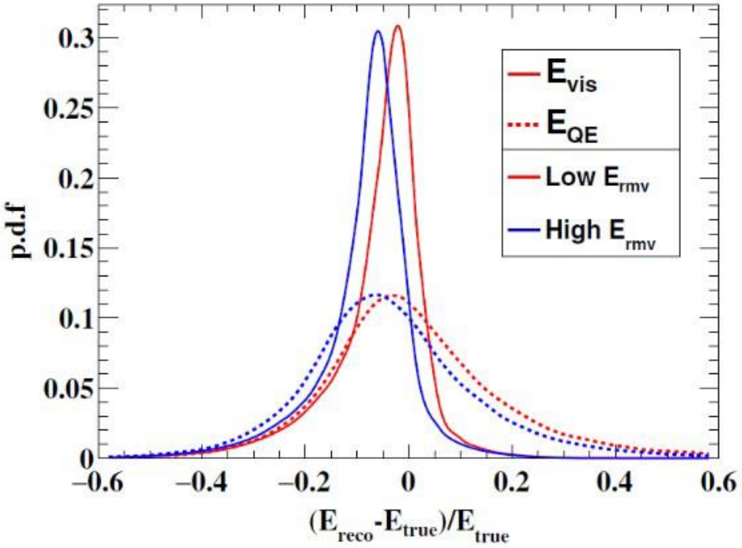
4π acceptance for outgoing muons thanks to high angle detection by HATPC.



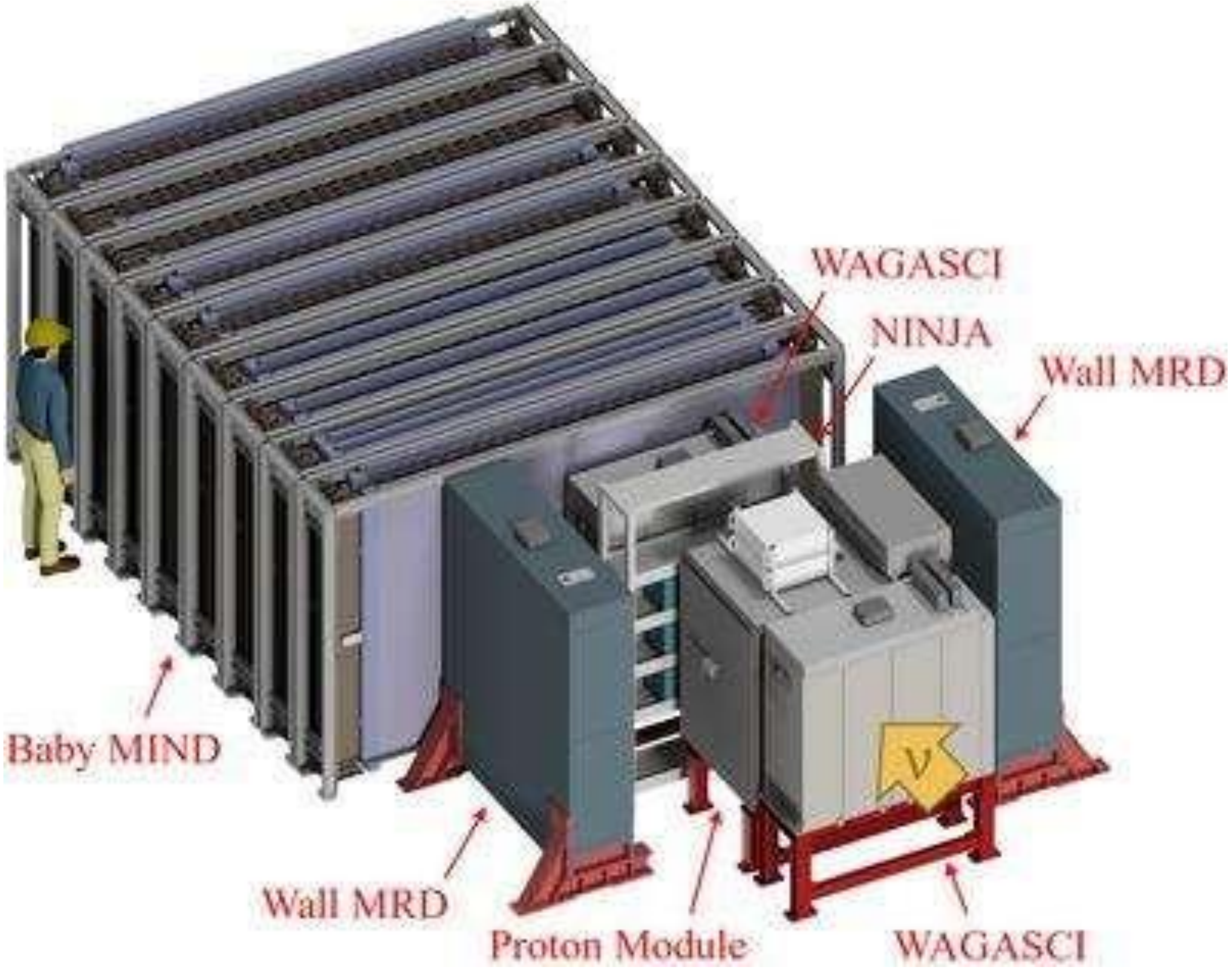
Decrease in proton detection threshold and improved efficiency over entire momentum range.



Better estimation of E_{true} using E_{vis}, which utilizes lepton and hadron kinematics.

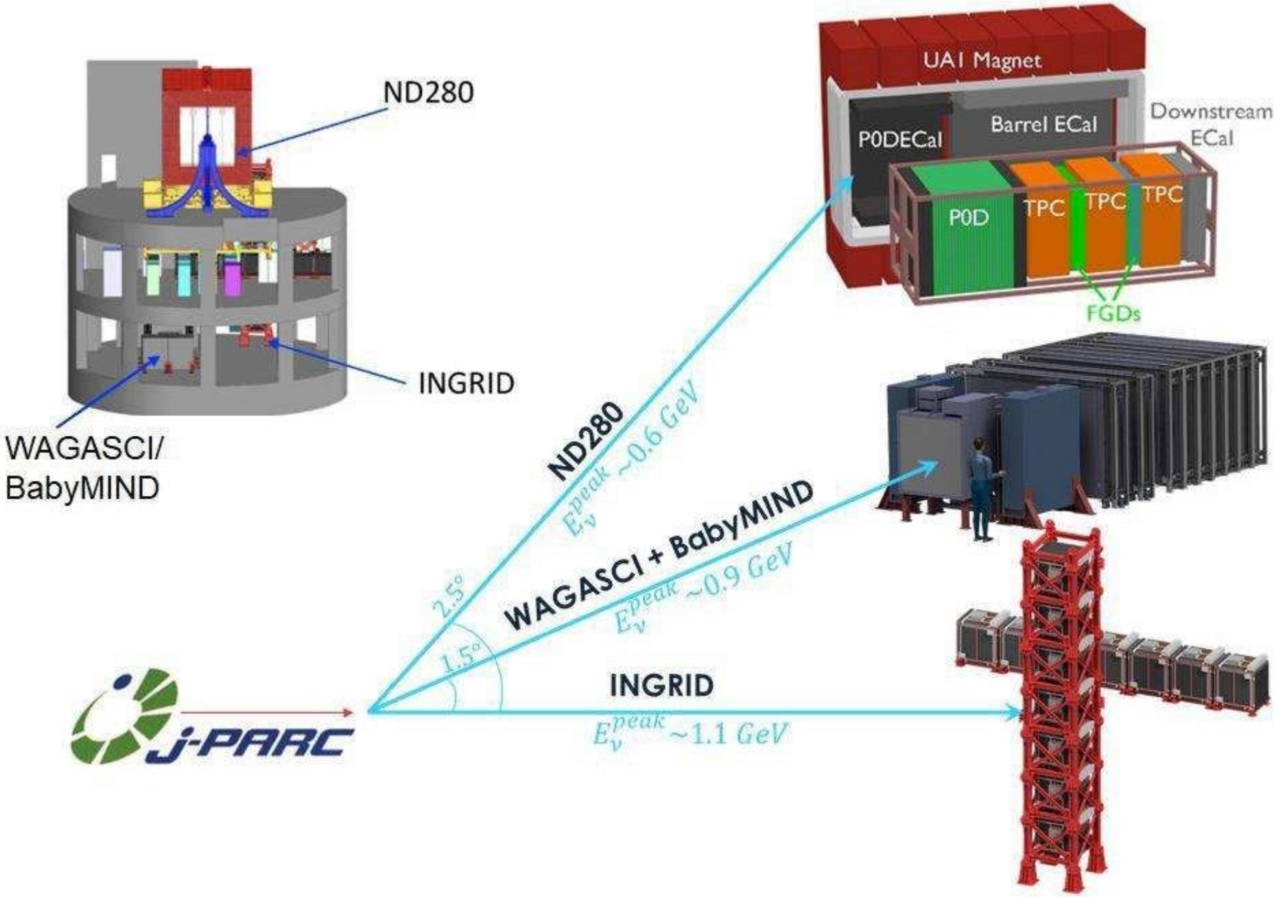


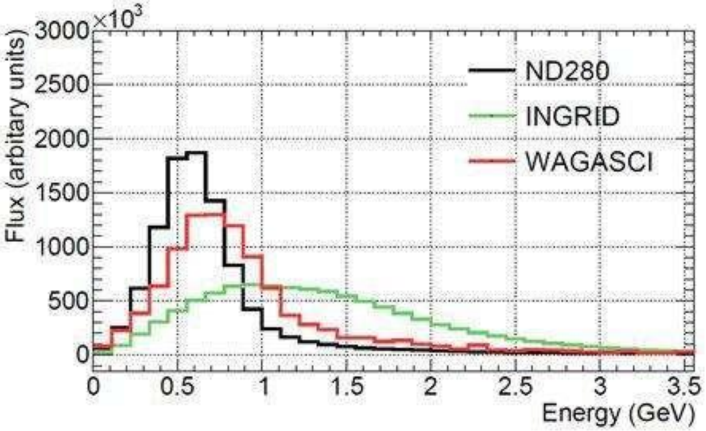
WAGASCI & BabyMIND detectors (1.5 degrees off-axis)



- 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

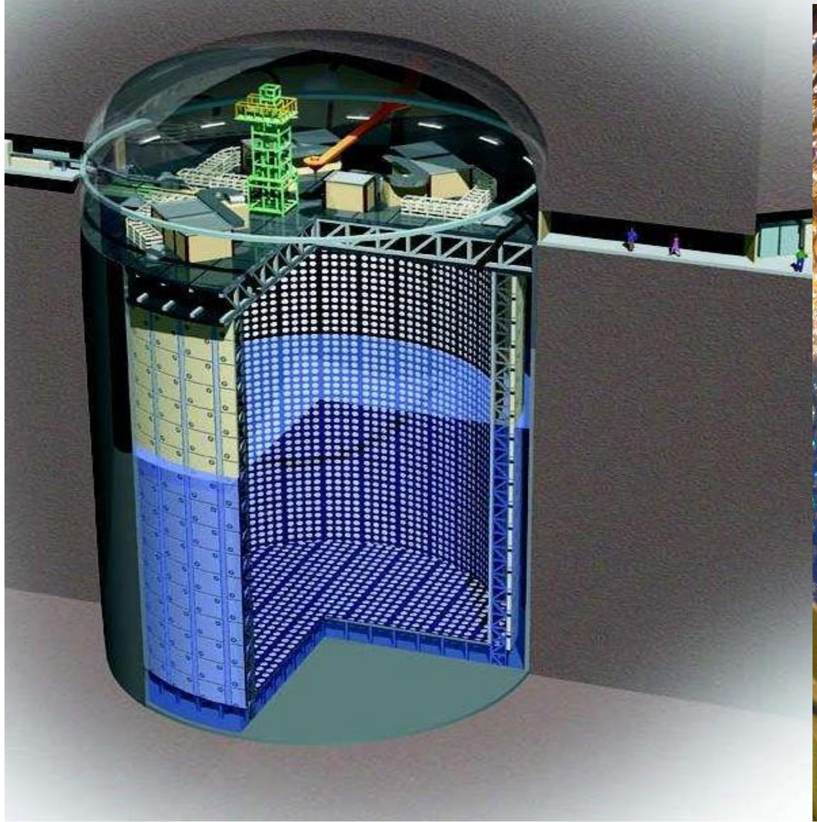
Near Detector Complex

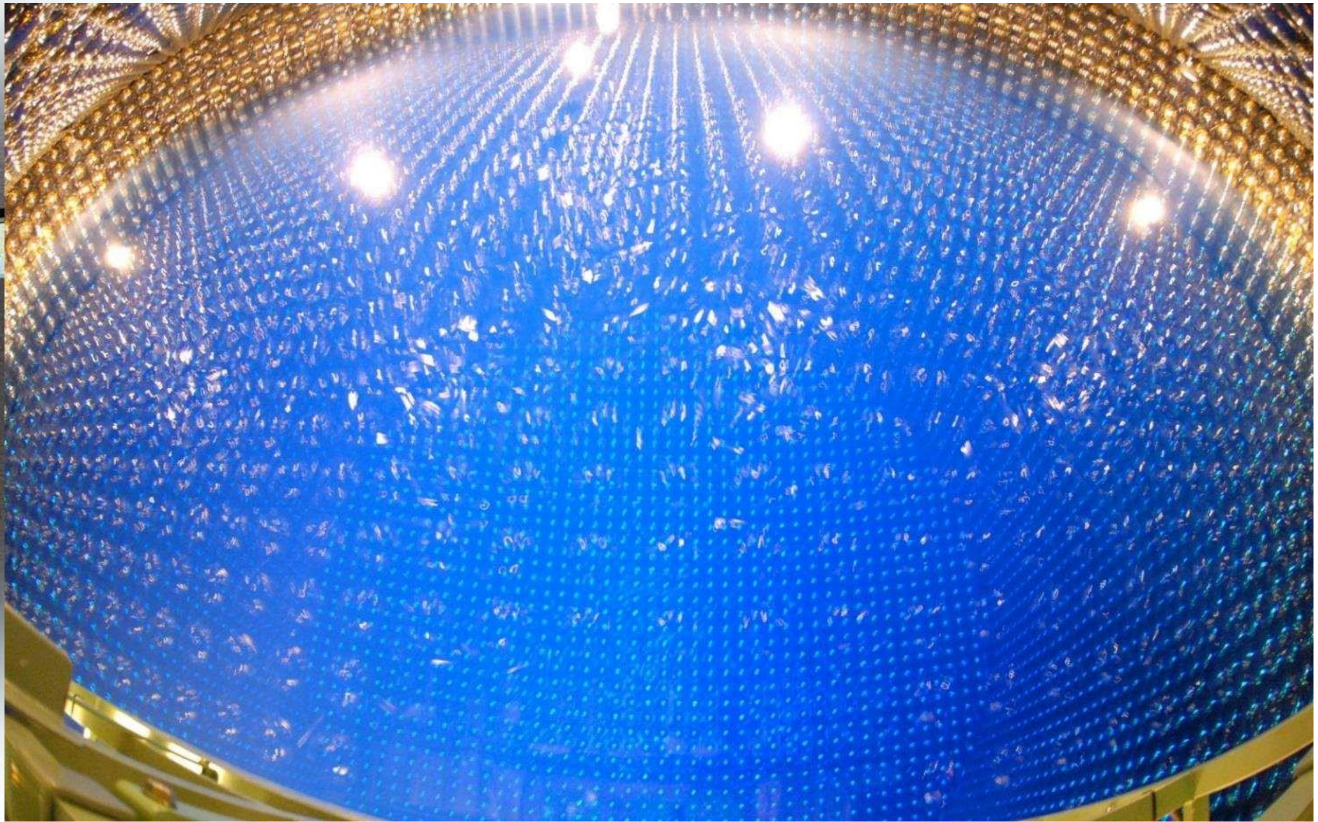




Far detector : Super-Kamiokande (SK)

- **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: 2.27×10^{14},
Cycle time: 1.36 sec
(1 GeV=10^{9} eV, 1eV=1.6×10^{-19} J)

・Answer in “kW”.

$$\mathbf{30\ GeV \times 2.27 \times 10^{14} / 1.36 \times 1.6 \times 10^{-19} \times 10^{-3}\ kW = 801\ kW}$$

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

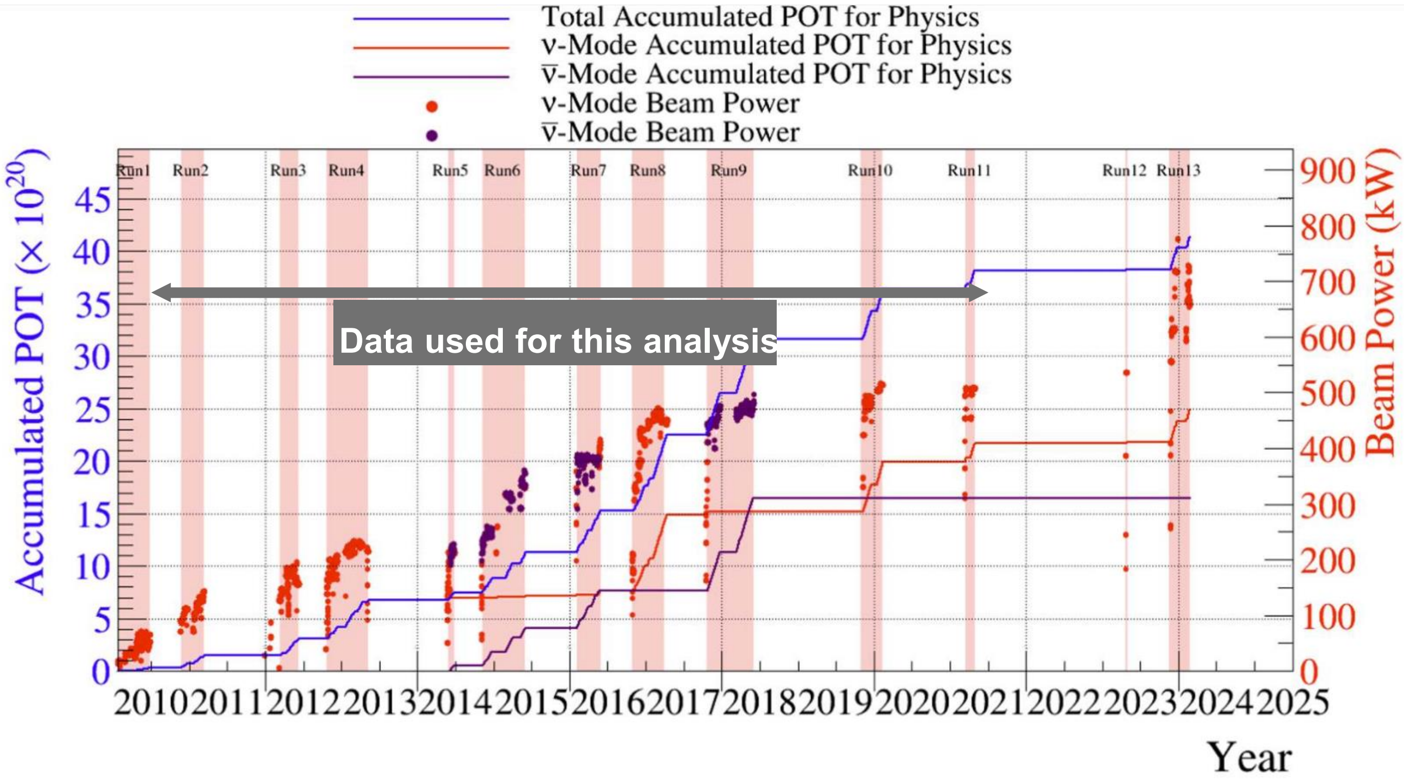
- **POT (protons On Target)**

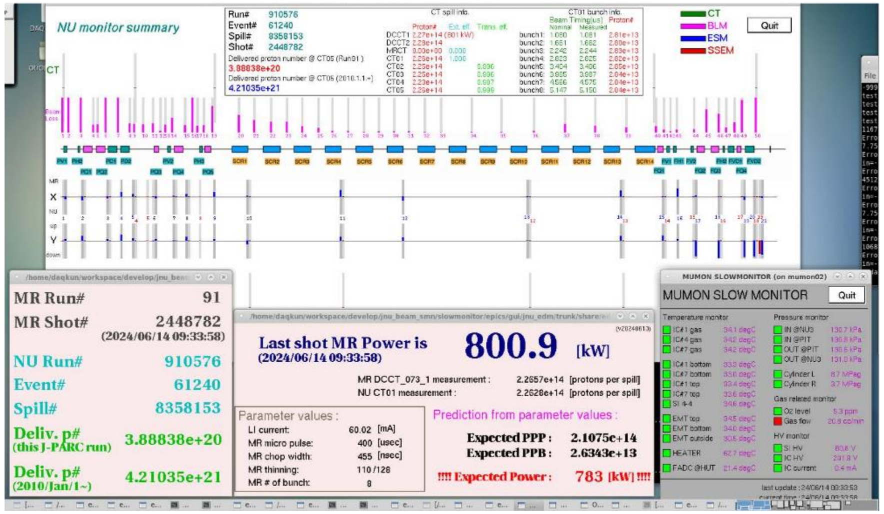
pps × Beam time

*Homework 2
How many years do we need to get 1×10^{22} POT if the beam power is 800 kW as described above ?

Data accumulation summary

- ☐ $> 4.3 \times 10^{21}$ POT
- ☐ Total POT for the result hear :
- ☐ 3.77×10^{21}
- $\boldsymbol{\nu}$ **mode** $\mathbf{2.14 \times 10^{21}}$
- $\bar{\boldsymbol{\nu}}$ **mode** $\mathbf{1.63 \times 10^{21}}$





Run# 910576
Event# 61240
Spill# 8358153
Shot# 2448782
Delivered proton number @ CT05 (Run91)
3.88838e+20
Delivered proton number @ CT05 (2010.1.1.~)
4.21035e+21

CT spill info.

	Proton#	Ext. eff.	Trans. eff.
DCCT1	2.27e+14 (801 kW)		
DCCT2	2.28e+14		
MRCT	0.00e+00	0.000	
CT01	2.26e+14	1.000	
CT02	2.25e+14		0.996
CT03	2.25e+14		0.996
CT04	2.23e+14		0.987
CT05	2.26e+14		0.999

CT01 bunch info.

	Beam Timing[us] Nominal	Beam Timing[us] Measured	Proton#
bunch1:	1.080	1.081	2.81e+13
bunch2:	1.661	1.662	2.80e+13
bunch3:	2.242	2.244	2.83e+13
bunch4:	2.823	2.825	2.82e+13
bunch5:	3.404	3.406	2.85e+13
bunch6:	3.985	3.987	2.04e+13
bunch7:	4.566	4.575	2.04e+13
bunch8:	5.147	5.150	2.04e+13

MR Run#	91
MR Shot#	2448782 (2024/06/14 09:33:58)
NU Run#	910576
Event#	61240
Spill#	8358153
Deliv. p# (this J-PARC run)	3.88838e+20
Deliv. p# (2010/Jan/1~)	4.21035e+21

/home/daqkun/workspace/develop/jnu_beam_smn/slowmonitor/epics/gui/jnu_edm/trunk/share

(v20240613)

Last shot MR Power is **800.9** [kW]
(2024/06/14 09:33:58)

MR DCCT_073_1 measurement : 2.2657e+14 [protons per spill]
NU CT01 measurement : 2.2628e+14 [protons per spill]

Parameter values :
LI current: 60.02 [mA]
MR micro pulse: 400 [usec]
MR chop width: 455 [nsec]
MR thinning: 110 /128
MR # of bunch: 8

Prediction from parameter values :
Expected PPP : 2.1075e+14
Expected PPB : 2.6343e+13
!!!! Expected Power : 783 [kW] !!!!

MUMON SLOWMONITOR (on mumon02)

MUMON SLOW MONITOR

Temperature monitor
IC#1 gas
IC#4 gas
IC#7 gas
IC#1 bottom
IC#7 bottom
IC#1 top
IC#7 top
Si 4-4
EMT top
EMT bottom
EMT outside
HEATER
FADC @HUT

Pressure monitor
IN @NU3
IN @PIT
OUT @PIT
OUT @NU3
Cylinder L
Cylinder R

Gas releted monitor
O2 level
Gas flow

HV monitor
Si HV
IC HV
IC current

last update : 24/06/14 09:33:53

◆ **Current power : 700 - 800kW (was 500 kW before upgrading)**

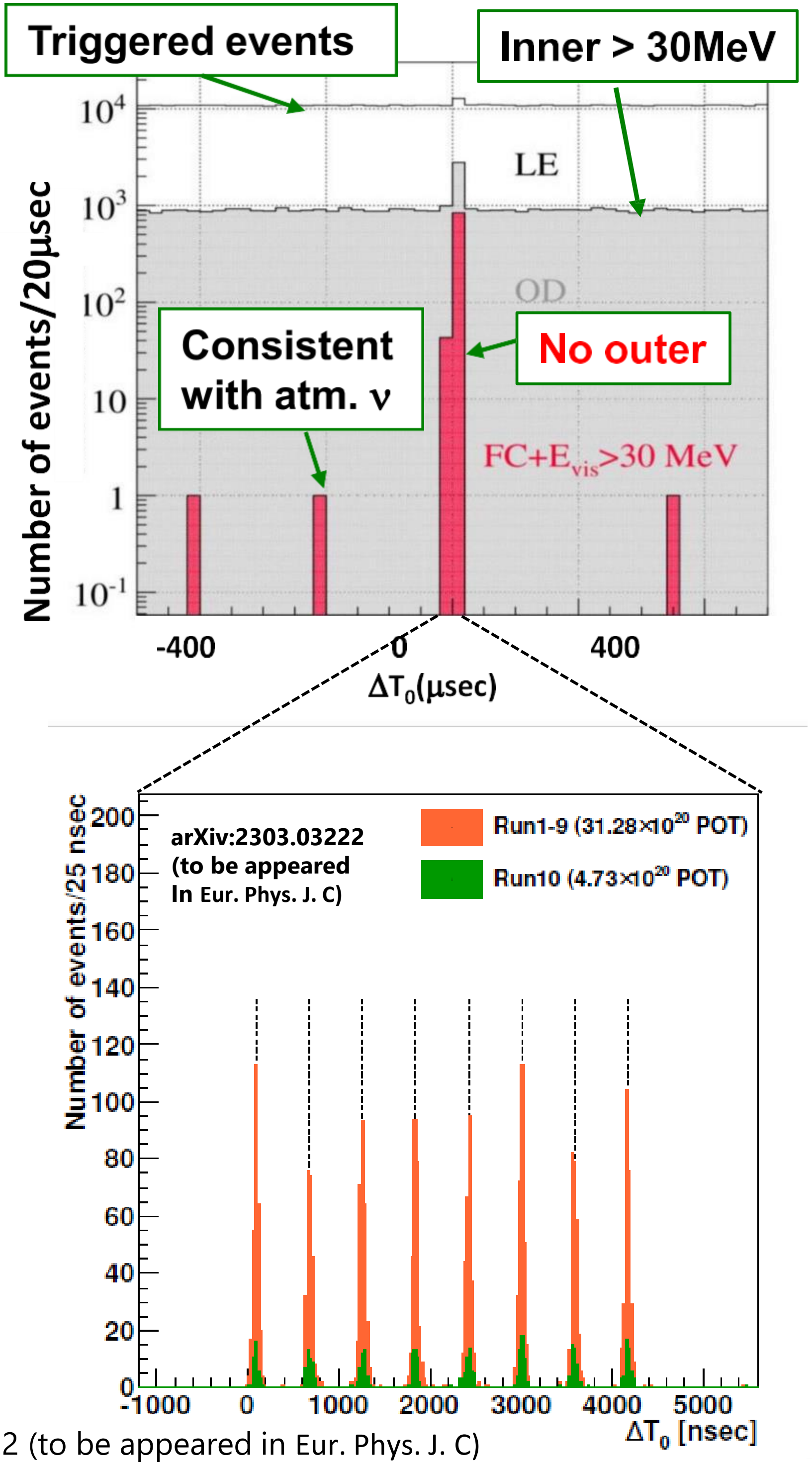
◆ **Intensified horn current from 250 kA to 320 kA**

→ ~10 % more neutrino flux

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 1.36 sec accelerator cycle.
   (8 bunch structure can be found.)



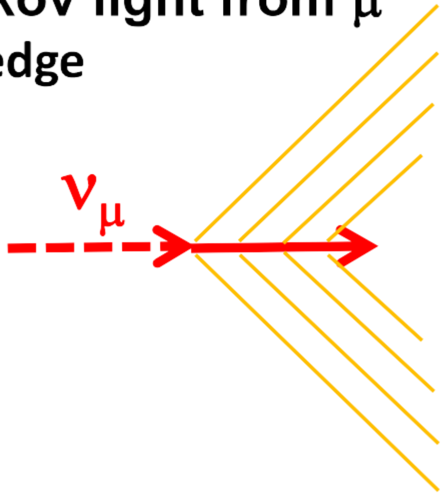
arXiv:2303.03222 (to be appeared in Eur. Phys. J. C)

μ/e identification in Super-Kamiokande

$\nu_\mu \rightarrow \mu$

Only direct Cherenkov light from μ

Clear Cherenkov ring edge

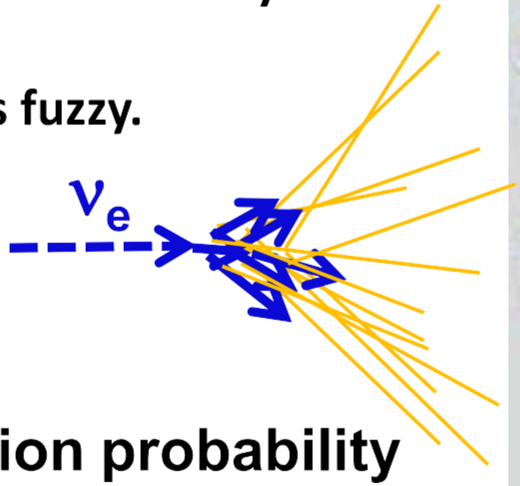


$\nu_e \rightarrow e$

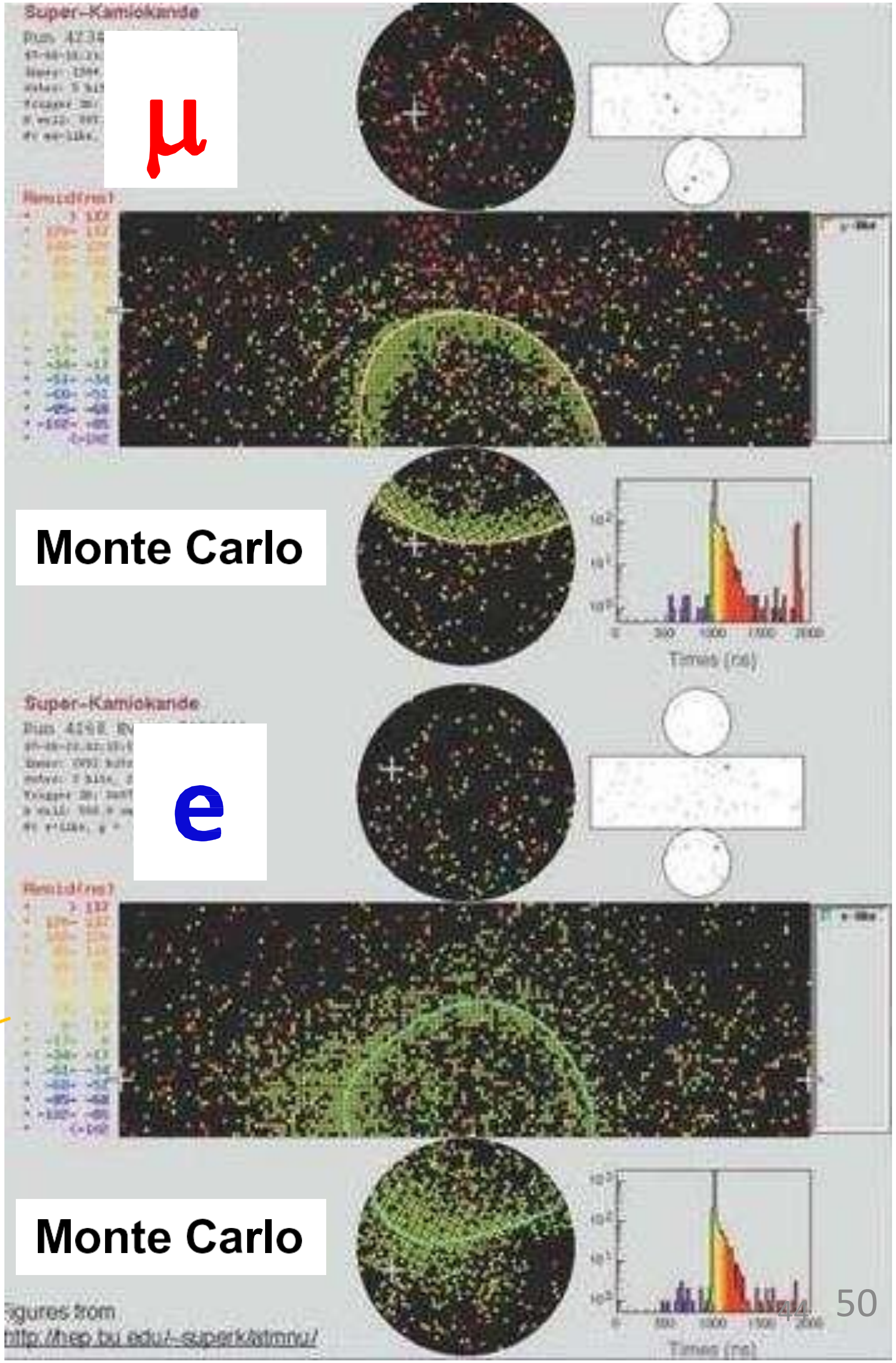
Cherenkov light from e-m shower.

Electrons and positrons are heavily scattered.

Cherenkov ring edge is fuzzy.



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



Figures from http://hep.bu.edu/~superk/atmnu/

Event Selection at the Far Detector (cont'd)

Examine Particle ID of 1 ring events

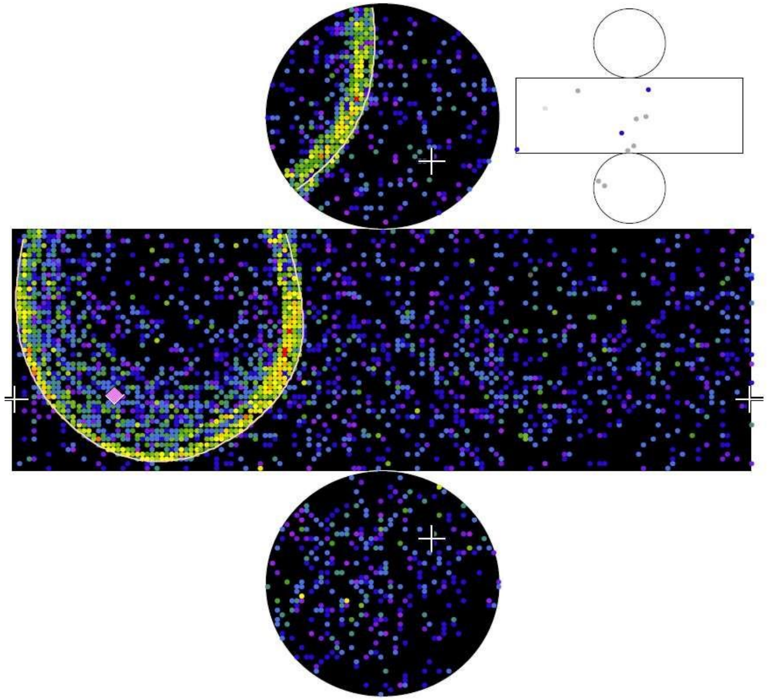
ν_μ selection

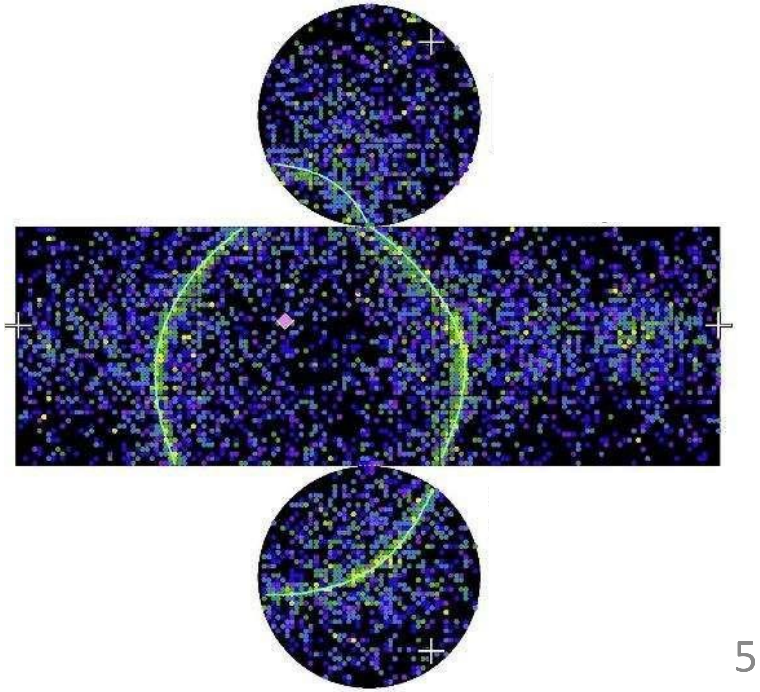
- μ-like PID
- $p_\mu > 200$ MeV/c
- Michel electron 1 or 0

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 2nd ring is assumed. Invariant mass and likelihood for π^0 are examined.

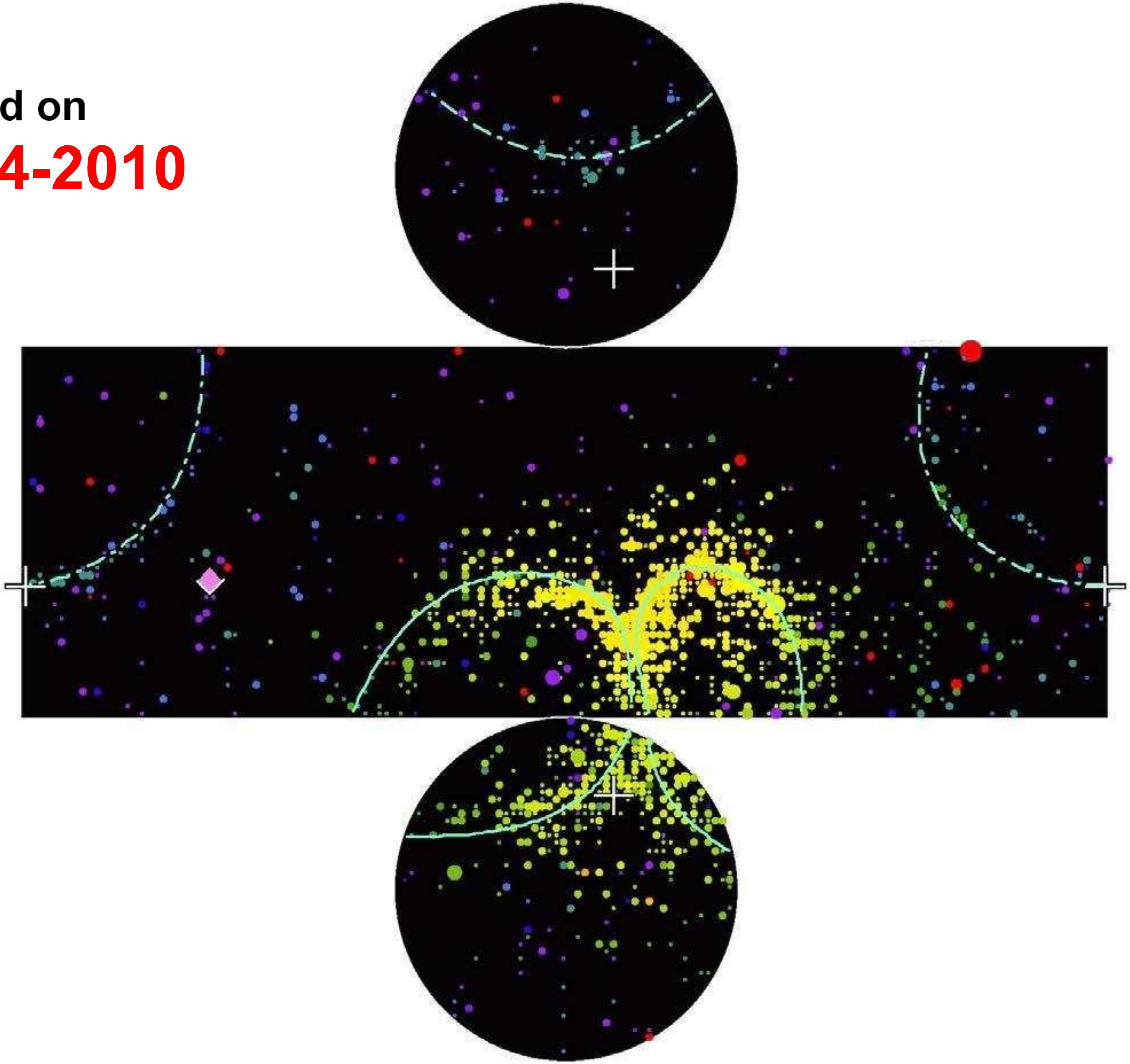




The first neutrino event in the T2K experiment

Recorded on

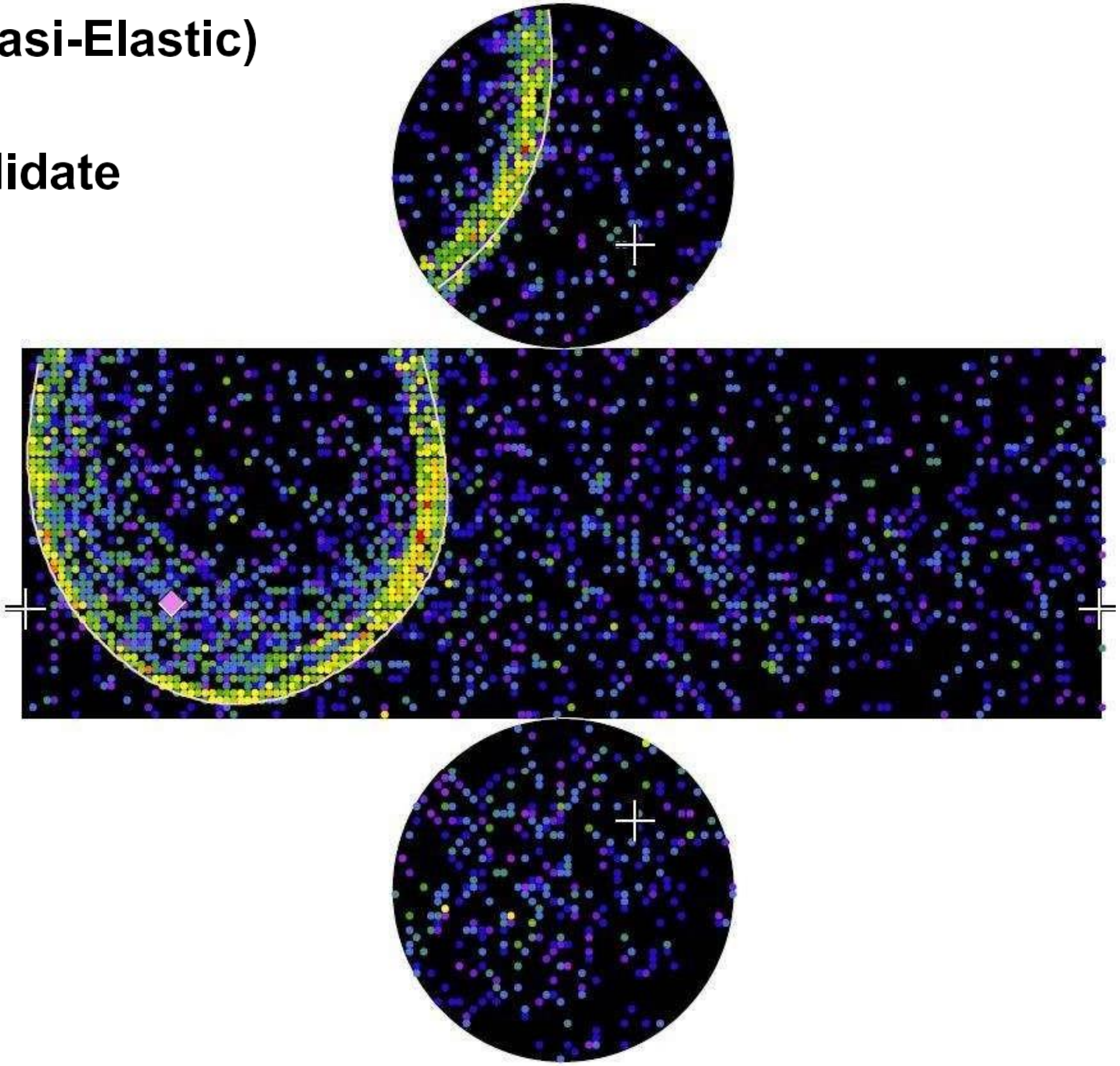
Feb-24-2010



ν_μ disappearance analysis

CCQE (Charged Current Quasi-Elastic)

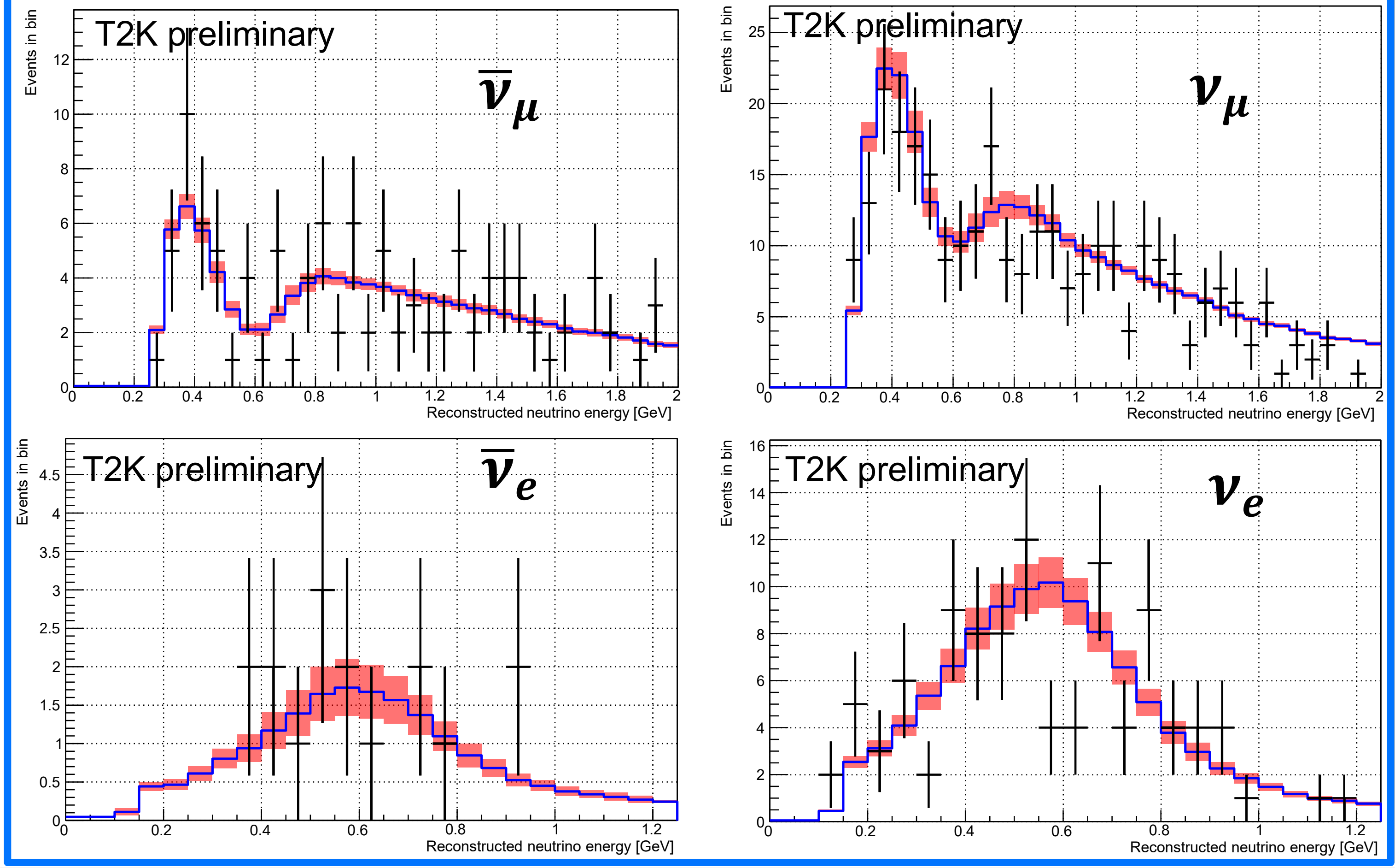
$\nu_\mu + n \rightarrow \mu^- + p$ candidate



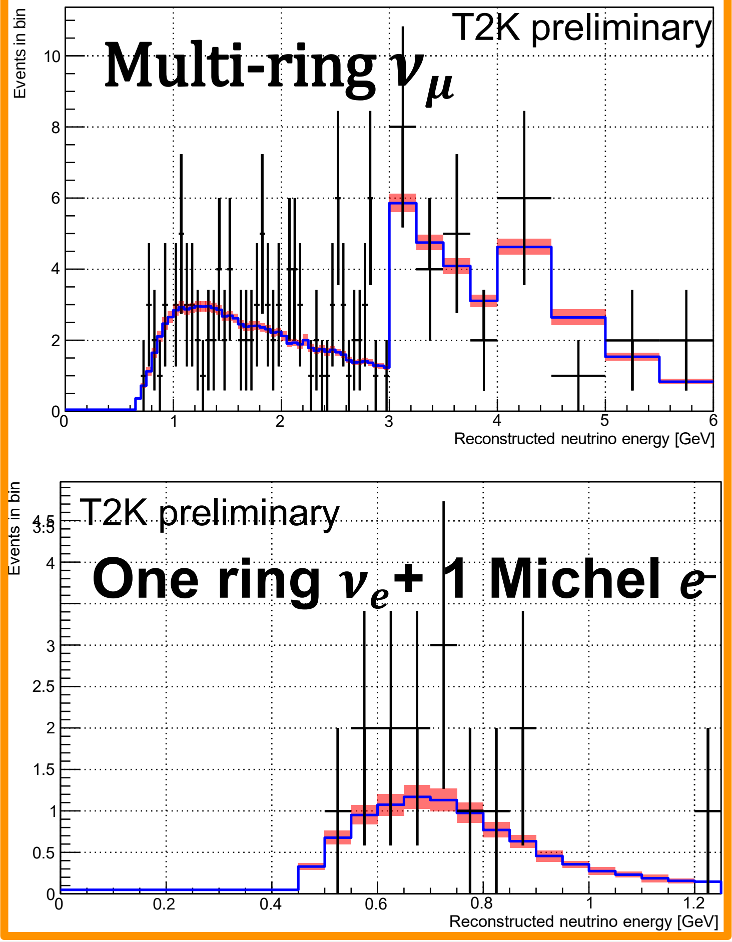
Super-K selections

Oscillated neutrino events spectra

CCQE enhanced samples (1 ring events):



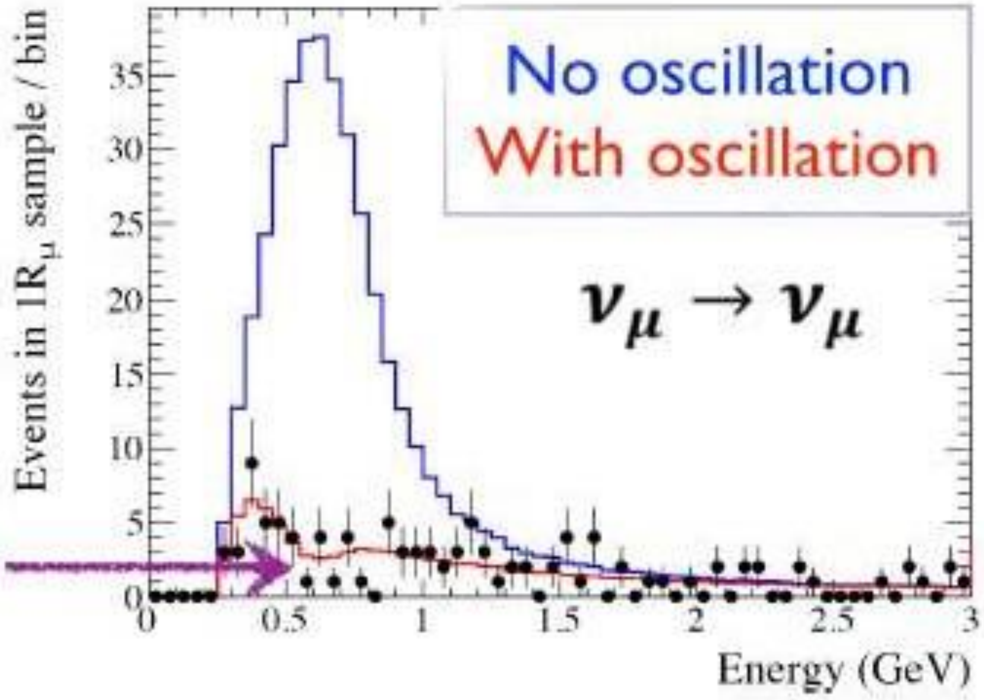
CC1π^+ enhanced samples



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

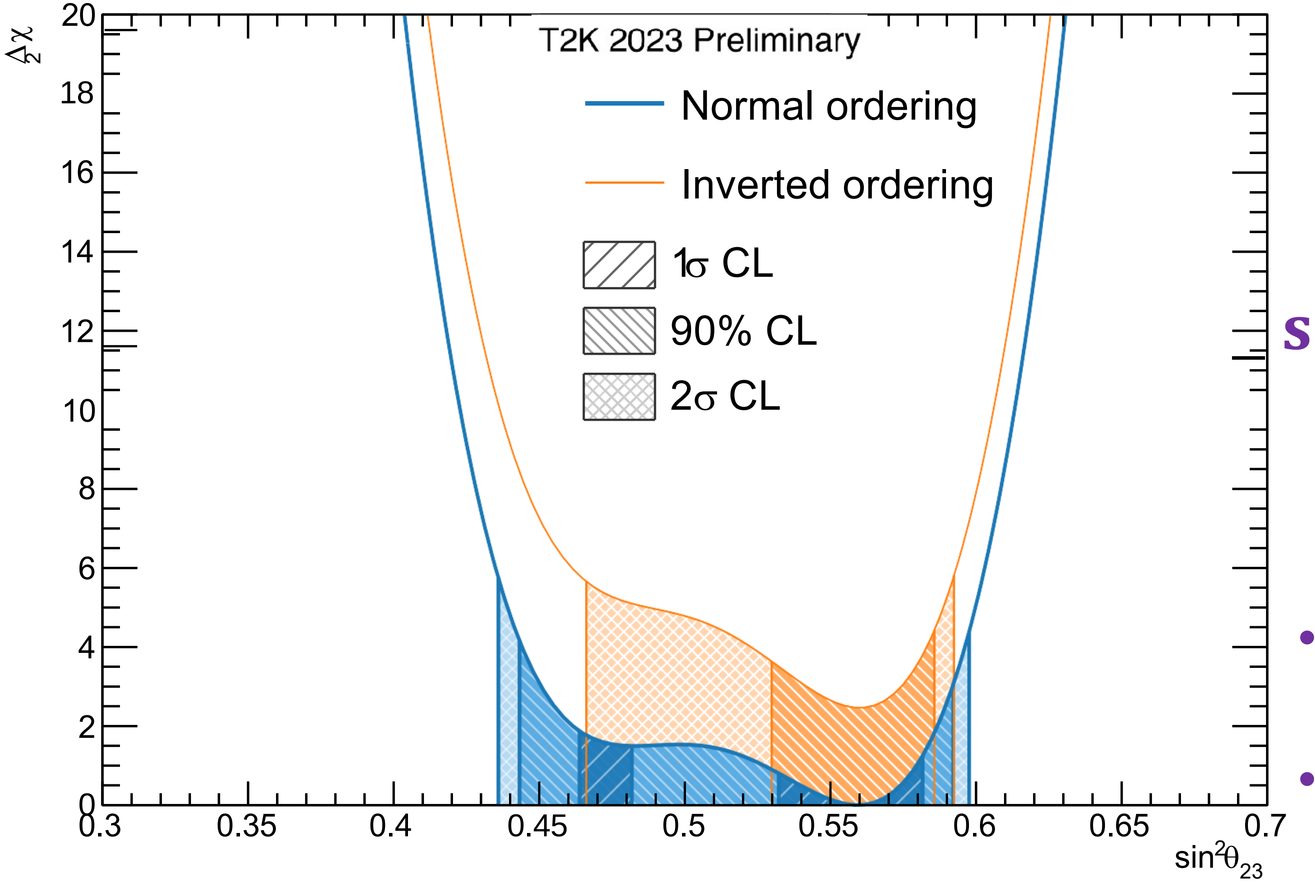
$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) = 1 - 4cos^2(\theta_{13})sin^2(\theta_{23})$$
$$\times \left[1 - cos^2(\theta_{13})sin^2(\theta_{23})\right] sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$
$$+ \text{(solar, matter effect terms)}$$

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



The latest results - θ_{23} -

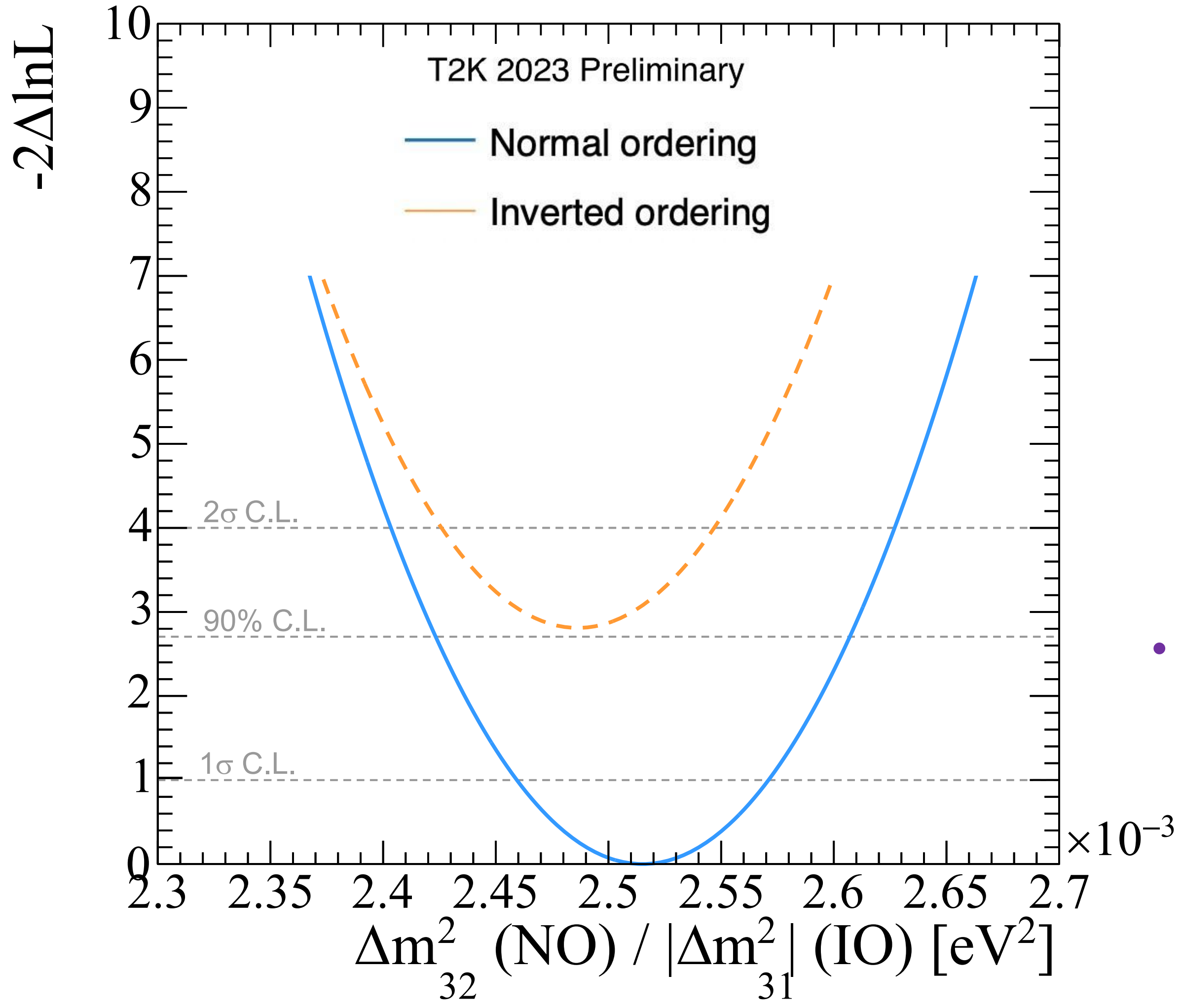
θ_{23}



$$\sin^2\theta_{23} = \begin{cases} 0.568^{+0.01}_{-0.036} - \text{Upper Octant} \\ 0.475^{+0.007}_{-0.011} - \text{Lower Octant} \end{cases}$$

- **Weak preference of upper octant**
- **Compatible with maximal mixing**

The latest results - Δm^2_{32} -



Δm^2_{32}

$$|\Delta m^2_{32}| = 2.521^{+0.037}_{-0.050} \times 10^{-3}\ eV^2/c^4$$

- **Weak preference of normal mass ordering**

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

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

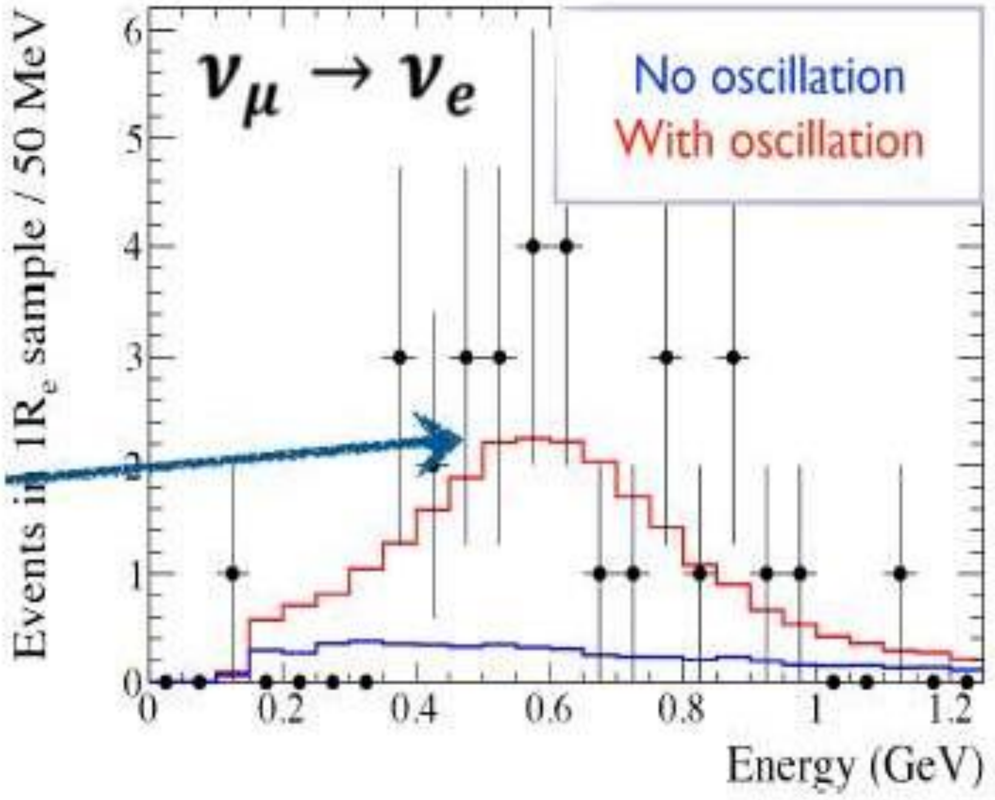
$$\sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)$$

$$\overset{(+)}{-}\,\Big[\sin(2\theta_{12})\sin^2(2\theta_{23})\sin^2(2\theta_{13})\cos(\theta_{13})$$

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

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

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

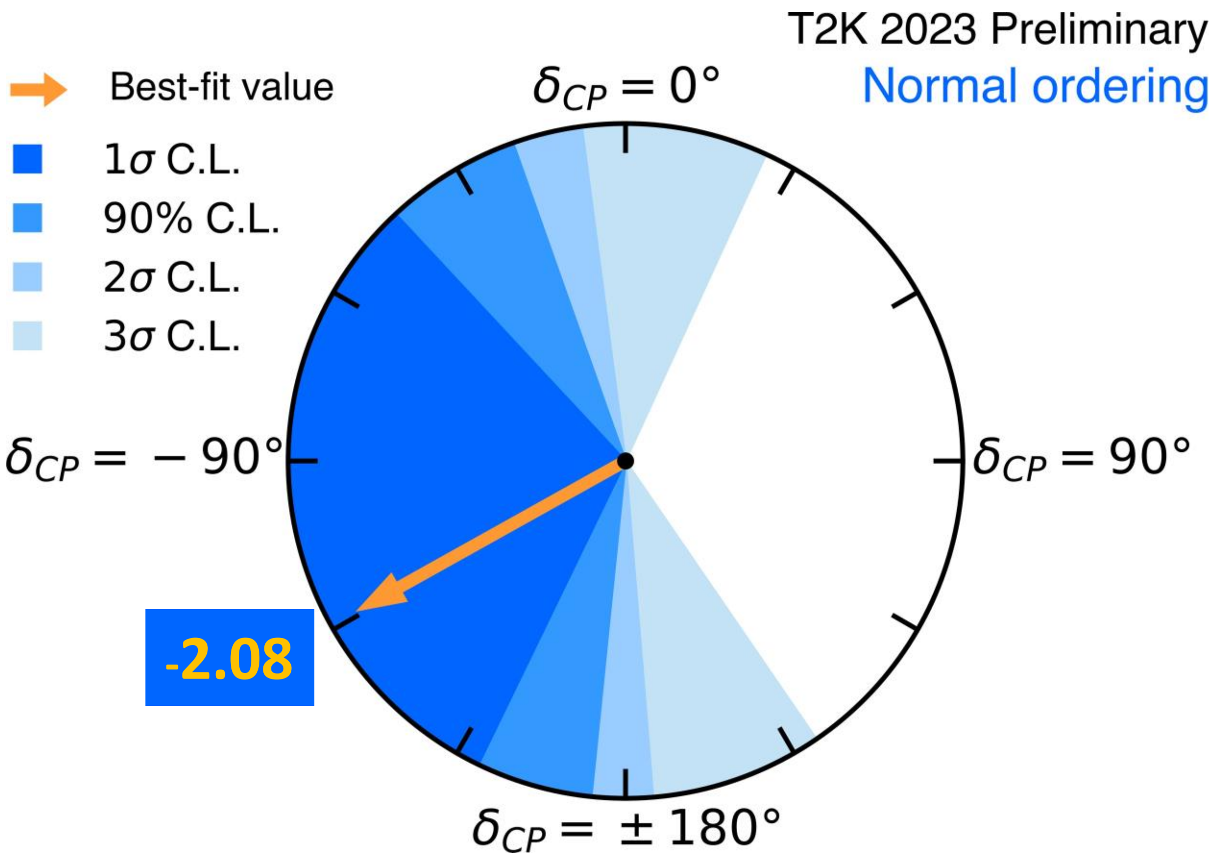


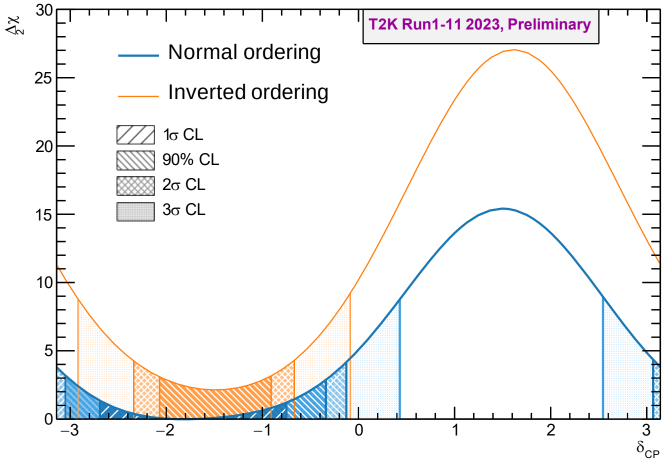
$P(\nu_\mu \to \nu_e) = P(\overline{\nu_\mu} \to \overline{\nu_e})$ or not ?

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 |)

Th latest results - CPV -





δ_{CP}

$$\delta_{CP} = -2.08^{+1.33}_{-0.61}$$

CP-conservation excluded with 90% C.L.

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

$$E_\nu = \frac{\left(m_\tau+m_p\right)^2 - m_n^2}{2m_n} = \frac{(1.777+0.9383)^2-0.9396^2}{2\times0.9396} = \underline{3.45\ [\mathrm{GeV}]}$$

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

(Answer) Beam time $= \mathrm{POT/pps} = 1 \times 10^{22}/(2.27 \times 10^{14}/1.36)$ = 5.99×10^8 [sec]

= 6,933 [days] $\approx$<u>70 [yr]</u> **(Assume that we can operate an accelerator for 100 days per year.)**

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