The T2K EXPERIMENT

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Outline

- Introduction
  - Neutrino oscillation thus far
- Overview of the T2K experiment
  - Physics goals and experimental apparatus
- Primary and secondary beam
-
- ND280 measurements
  - Primary Canadian contribution

Present State of Knowledge

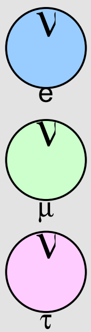
- Neutrino -- an elementary particle in SM
  - (Almost) massless neutral lepton with spin ½
  - Only (or mostly) left-handed neutrinos
  - Three flavours (active neutrinos) below *Z* mass, i.e. ν_e, ν_μ and ν_τ
- In late 1990's and early-mid. 2000's:
  - Evidence for neutrino oscillations!
    - Atmospheric ν from Super-K (1998), confirmed by accelerator neutrino experiments, K2K (2004) and MINOS (2006).
    - Solar ν from Super-K + SNO (2001), confirmed by a reactor neutrino experiment, KamLAND (2002,2004)
  - Thus neutrinos have finite mass and flavour mixing!
  - New era of "neutrino flavour physics"!

Neutrino flavour mixing

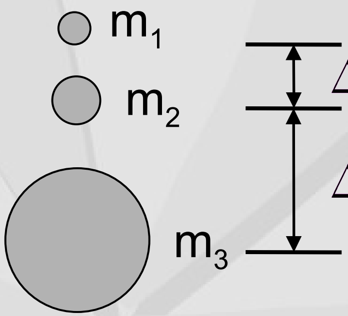
- If neutrinos have mass, flavour (or weak) eigenstates are not necessarily equal to mass eigenstates.

Flavour (weak) eigenstate

Mass eigenstate



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\rm PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



$$\Delta m^2_{12} = m^2_1 - m^2_2$$

$$\Delta m^2_{23} = m^2_2 - m^2_3$$

Atmospheric ν + acc. ν (K2K, MINOS)

Solar ν (SK, SNO) + reactor ν (KamLAND)

$$U_{\rm MNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij}, \; c_{ij} = \cos\theta_{ij}$$

Parameters for flavour mixing:

3 Mixing angles = θ_{12}, θ_{23}, θ_{13}

CP phase = δ

Mass differences = Δm^2_{12}, Δm^2_{23}, Δm^2_{13}

Neutrino oscillation

- A neutrino of one flavour can change into one of other flavour once they are mixed--this is called "neutrino oscillation"
  - E.g. in two flavour case for simplicity:

    What happens at time *t* (or travel distance *L*) to a neutrino of flavour "α" at *t* = 0?

    - Probability that ν_α changes to ν_β at distance *L*:

$$P(\nu_\alpha \to \nu_\beta; L) = |\langle \nu_\beta | \nu_\alpha(L) \rangle|^2 = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$

Oscillation parameters

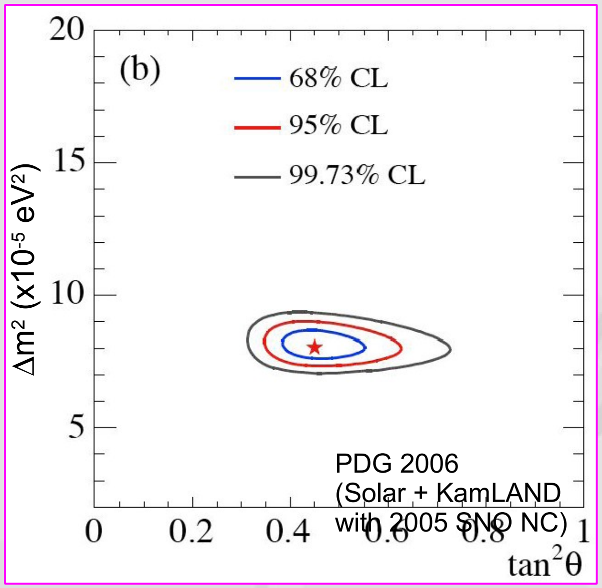
  - ν_α (and ν_β) flux varies
    - As a function of neutrino energy
    - As a function of the distance from neutrino source

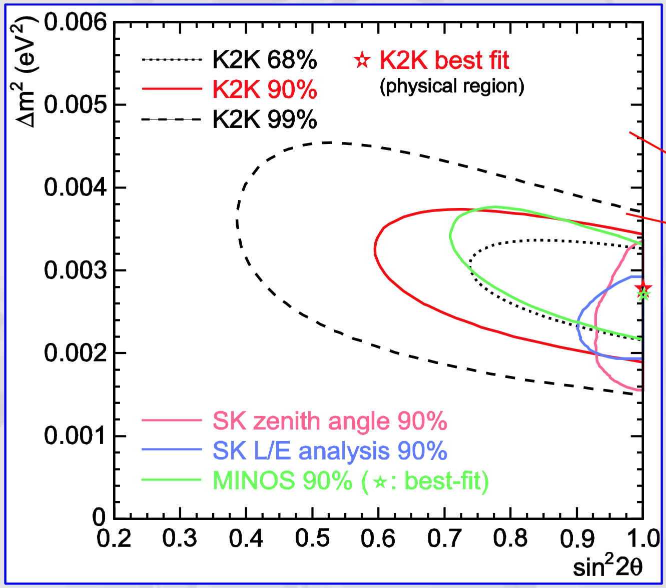
Current status of oscillation parameters

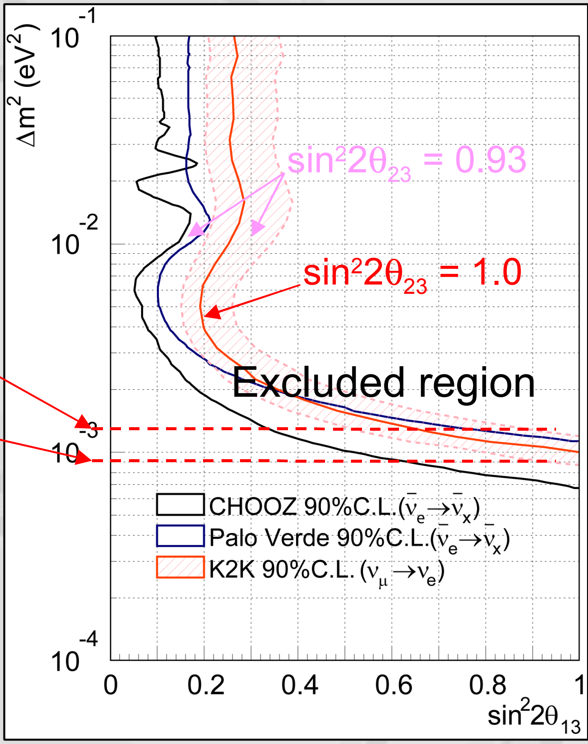
Solar ν region: Δm^2_{12}, θ_{12}

Atmospheric ν region: Δm^2_{23}, θ_{23}

Δm^2_{13}, θ_{13}







SK: PRD 71, 112005 (2005)
K2K: PRD 74, 072003 (2006)
MINOS: PRL, 191801 (2006)

CHOOZ: Eur. Phys. J. C 27, 331 (2003)
Palo Verde: PRD 64, 112001 (2001)
K2K: PRL, 181801 (2006)

$\Delta m^2_{12} = (8.0^{+0.6}_{-0.4}) \times 10^{-5}\ \mathrm{eV}^2$
$\theta_{12} = (33.9^{+2.4}_{-2.2})^\circ$

$\Delta m^2_{23} \sim (2.2 - 3.0) \times 10^{-3}\ \mathrm{eV}^2$
$\theta_{23} \sim 45^\circ\ (\sin^2 2\theta_{23} > 0.93)$

Δm^2_{13} is unknown,
(expected to be $\sim \Delta m^2_{23}$)
$\theta_{13} \lesssim 10^\circ$
@ $\Delta m^2_{13} = 2.5 \times 10^{-3}\ \mathrm{eV}^2$

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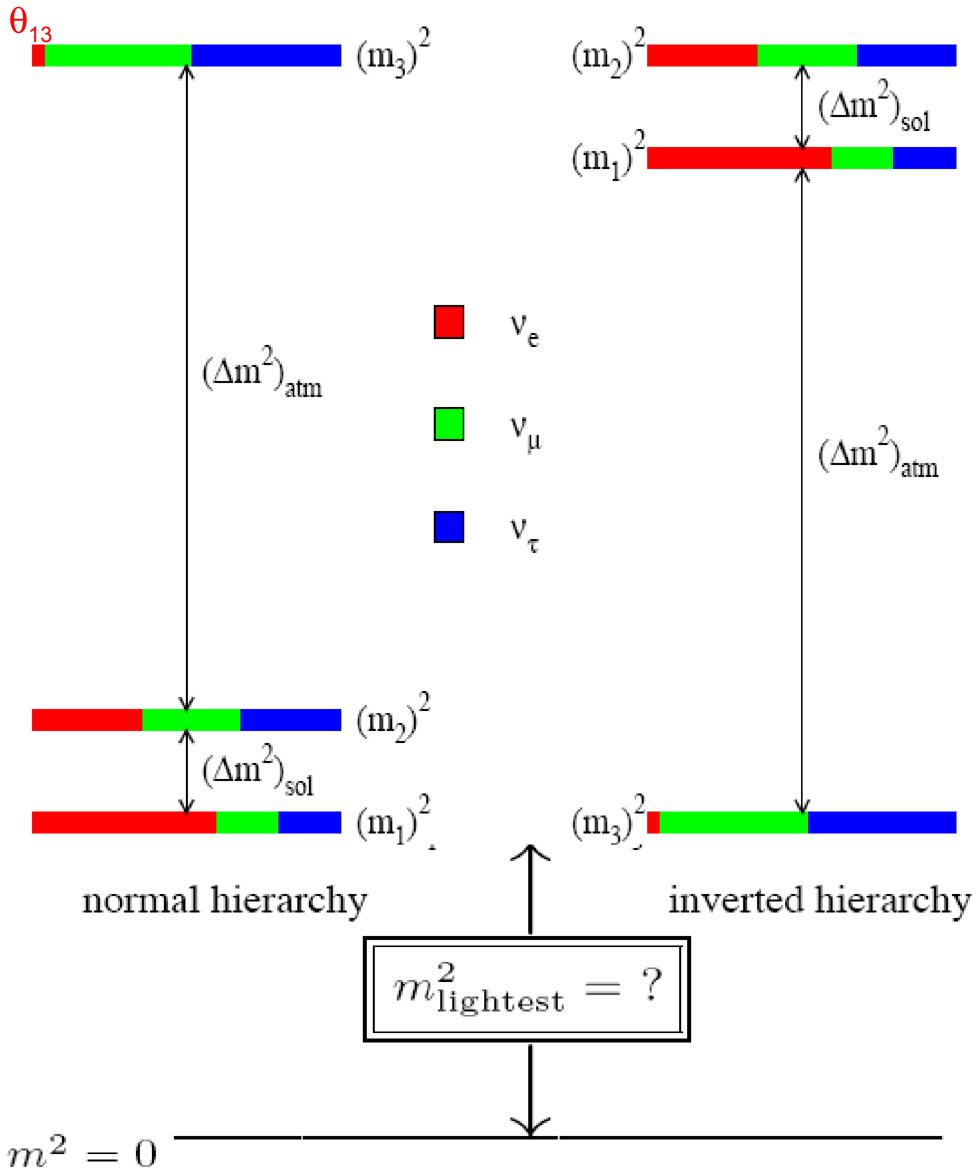
4 - What We Know We Don't Know, Oscillation Edition



- What is the ν_e component of ν_3? ($\theta_{13} \neq 0$?)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?)
- Is ν_3 mostly ν_μ or ν_τ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$?)
- What is the neutrino mass hierarchy? ($\Delta m^2_{13} > 0$?)

$\Rightarrow$ All of these can be addressed in neutrino oscillation experiments **if** we get lucky, that is if θ_{13} is large enough.

Key issue: What is θ_{13} ? Is it finite ?

- Search for $\nu_\mu \rightarrow \nu_e$ oscillation

$$U_{e3} = \sin\theta_{13} \cdot e^{-i\delta} = 0??$$

$$U_{\rm PMNS} \sim \begin{pmatrix} 0.8 & 0.5 & ??? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$\theta_{12} \sim 34^o$, $\theta_{23} \sim 45^o$
$\theta_{13} < 10^o$
CP phase δ is unknown

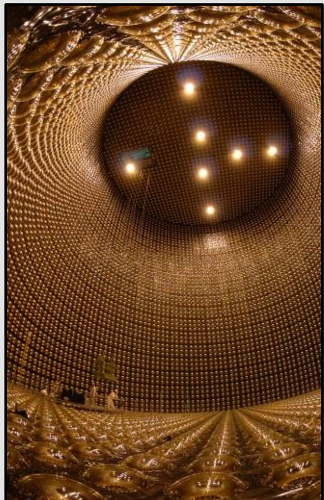
$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(\Delta m^2_{13} L/4E)$$

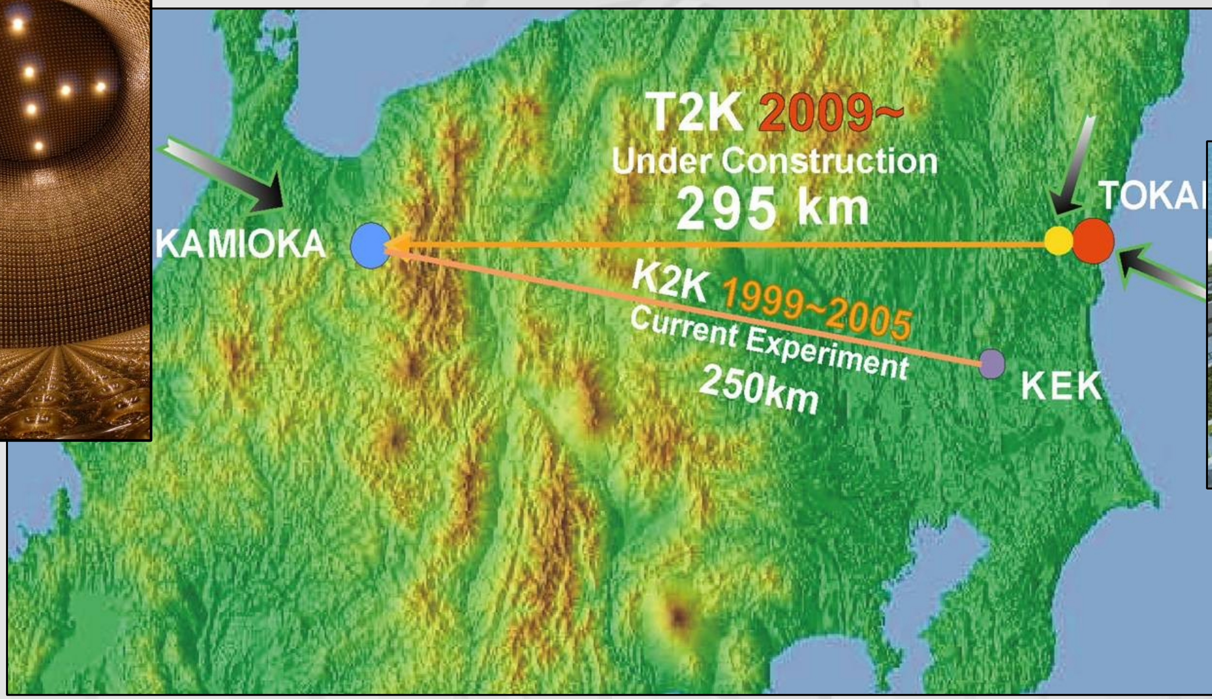
- Precise measurements for θ_{23}, Δm^2_{23}, …

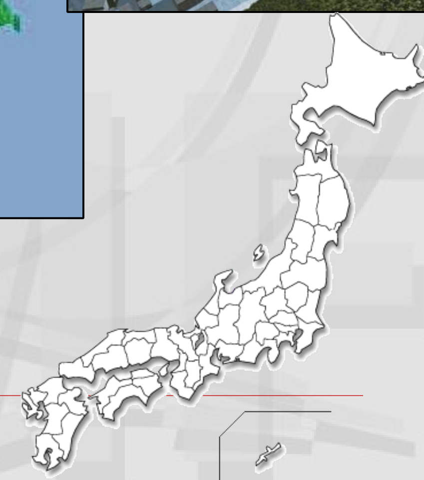
– If we find non-zero θ_{13}, then we can go further…
  - Is the CP violated in lepton sector? $A_{\rm CP} \propto P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)$
  - What is the neutrino mass hierarchy? Is $\Delta m^2_{13} < 0$ or > 0?

T2K is the next generation long baseline neutrino experimen

Neutrino beam using
a new accelerator at J-PARC







Far detector:
Super-Kamiokande

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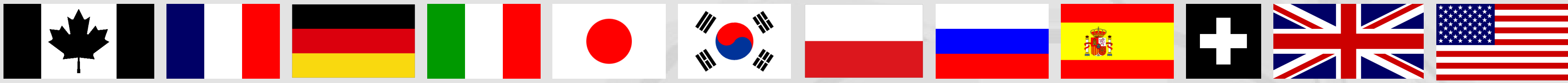
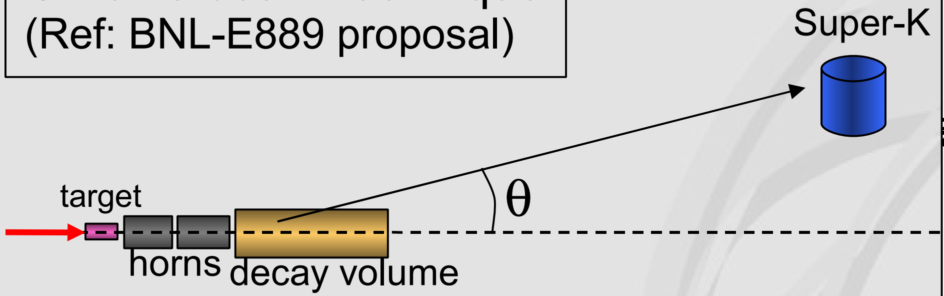
T2K collaboration

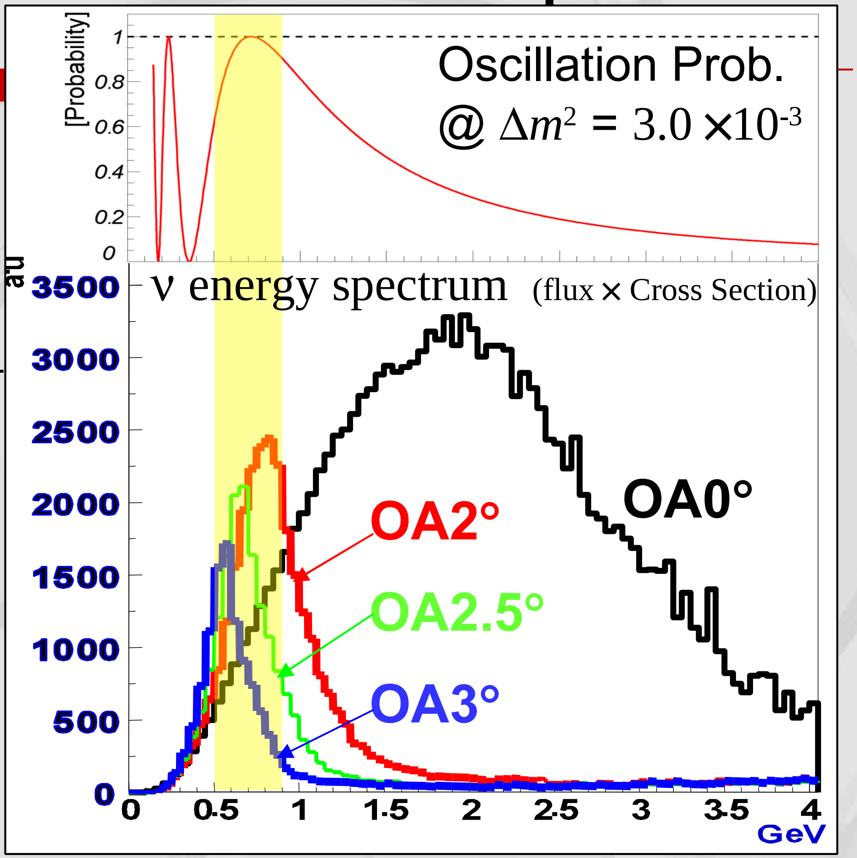


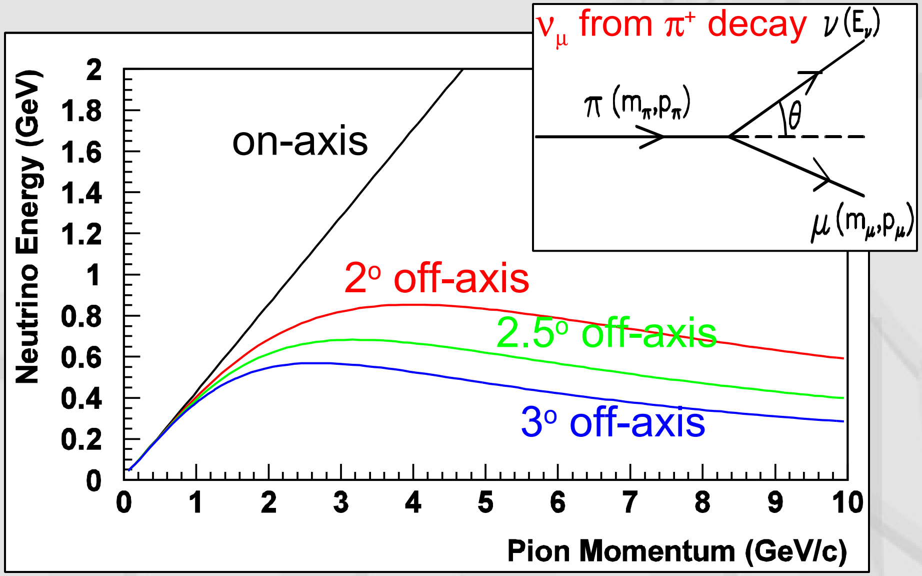
- ~350 members from 12 countries:
  - Japan(66), US(58), Canada(50), France(38), UK(37) Switzerland(31), Poland(22), Korea(13), Russia(12), Spain(11), Itary(9), Germany(2)

T2K neutrino beam: intense narrow band beam using "off-axis beam" technique

Off-axis beam technique
(Ref: BNL-E889 proposal)







- Quasi-monochromatic energy
- 2–3 times more intense than conventional narrow band beam
- Tuned at oscillation maximum
- Almost pure (> 99%) ν_μ beam

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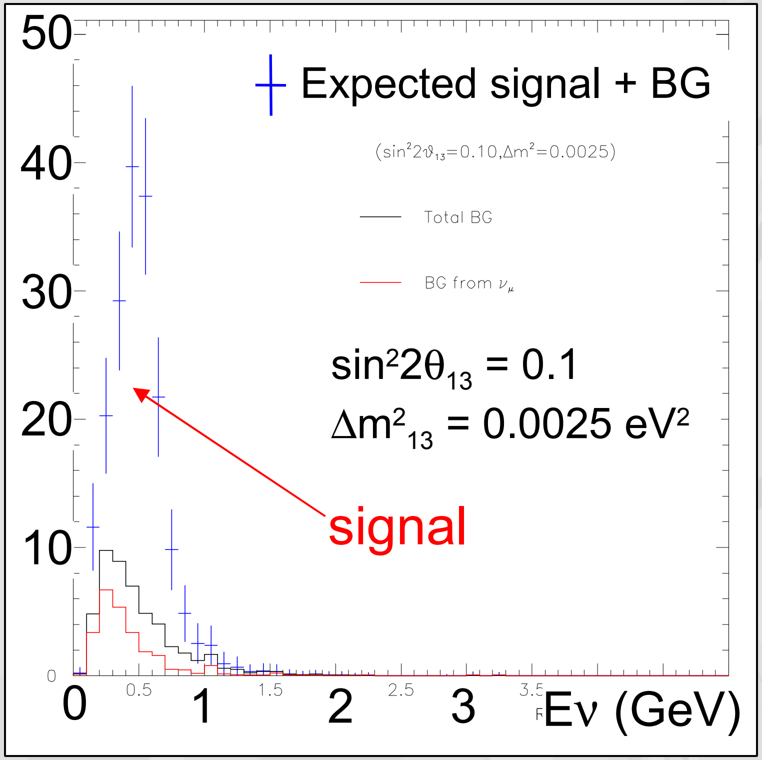
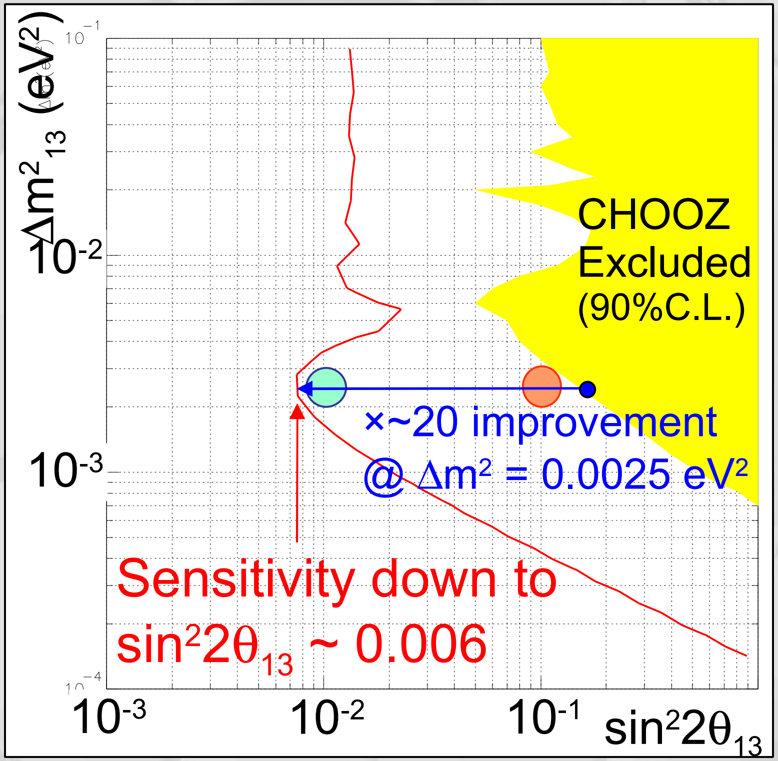
The goals of T2K – ν_e appearance

- Finding evidence for $\nu_\mu \rightarrow \nu_e$ oscillation and non-zero θ_{13}
  - Search for 'oscillated' electron neutrino events





$\sin^2 2\theta_{13}$	Backgrounds			Signal	Signal + BG
	ν_μ induced	Beam ν_e	total		
0.1	10	13	23	103	126
0.01				10	33

(5 years)

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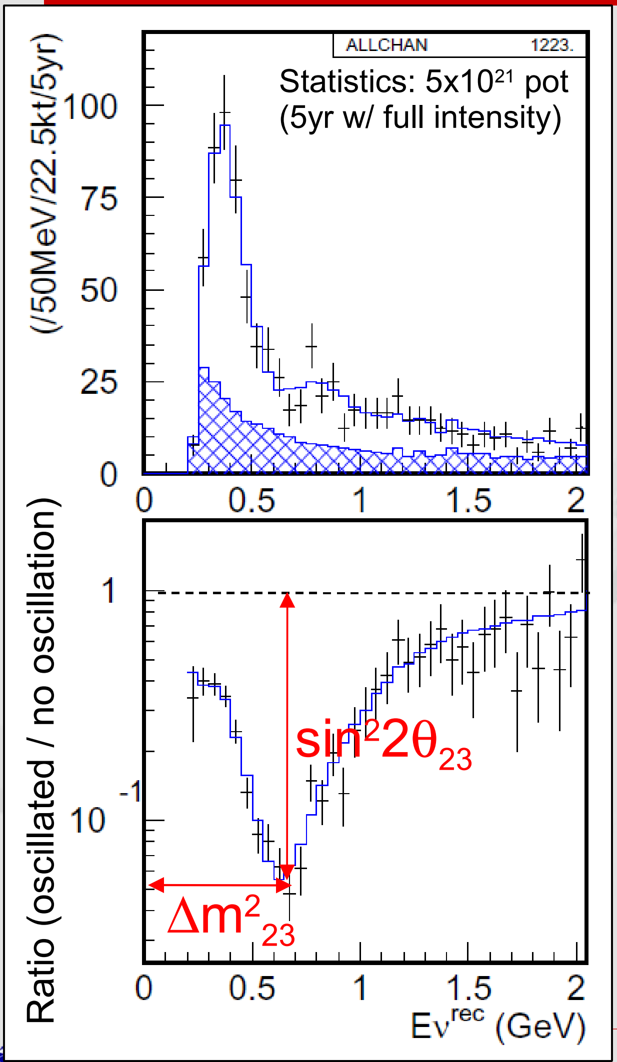
Goals of T2K – ν_μ disappearance

- Precise measurements of ν_μ disappearance



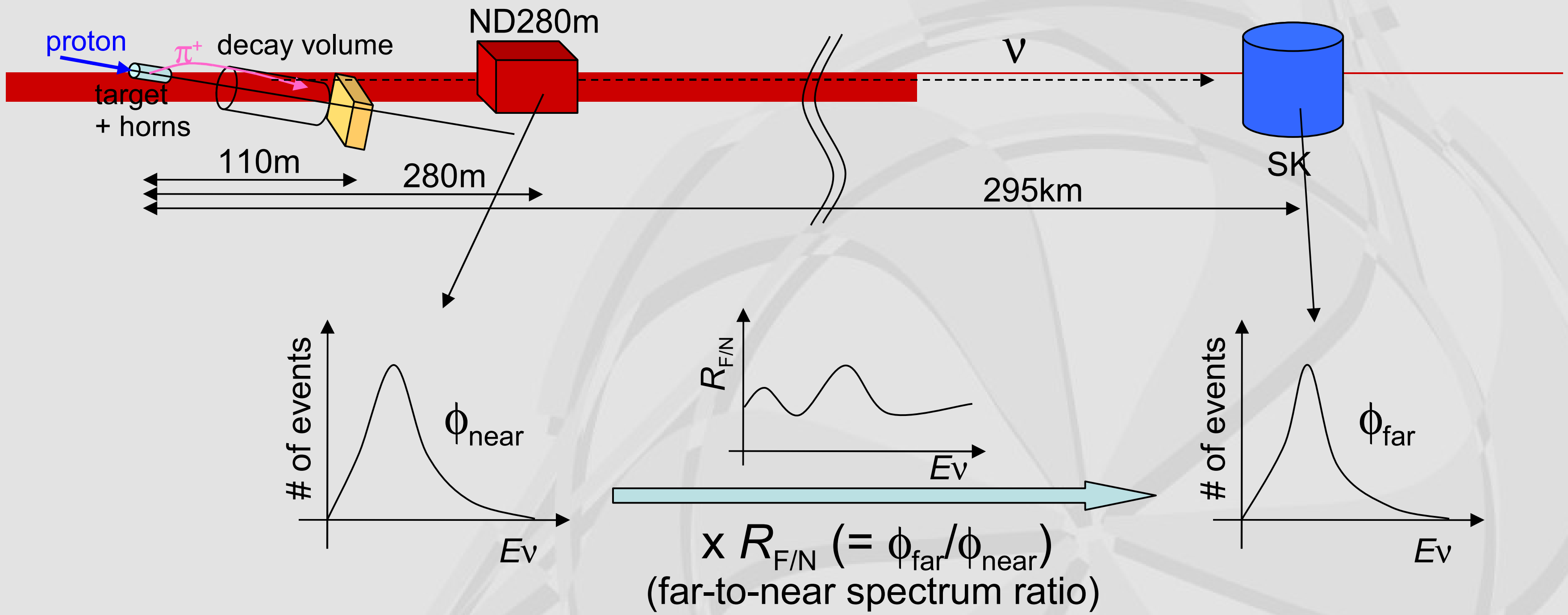
To be measured:

- Oscillation pattern in the energy spectrum
- In particular, re-appearance in low energy region

Goal of precision

- $\delta(\sin^2 2\theta_{23}) \sim 0.01$,
- $\delta(\Delta m^2_{23}) < 10^{-4}\ eV^2$

A possible strategy of oscillation studies



[spectrum measured at ND] x [far/near ratio]$_{MC}$ → [spectrum expected at SK]

compare

[spectrum observed at SK]

- Reliable spectrum measurements
- Reliable near-to-far extrapolation

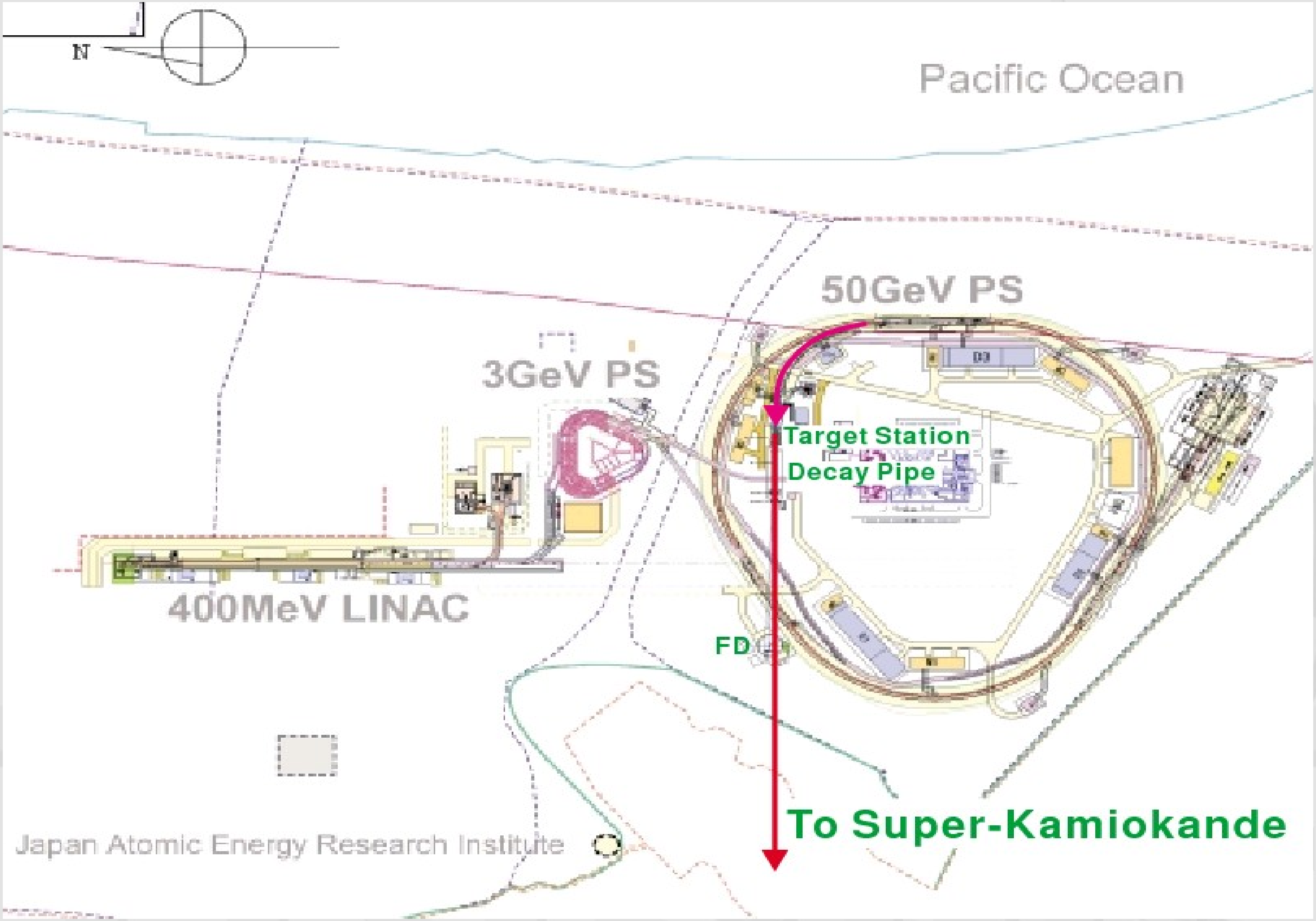
} Key issues!!

What we need to do to achieve the T2K goals...

- Understanding the primary proton beam
  - Stable beam steering required
  - Impact on secondary hadrons, and hence neutrino beam

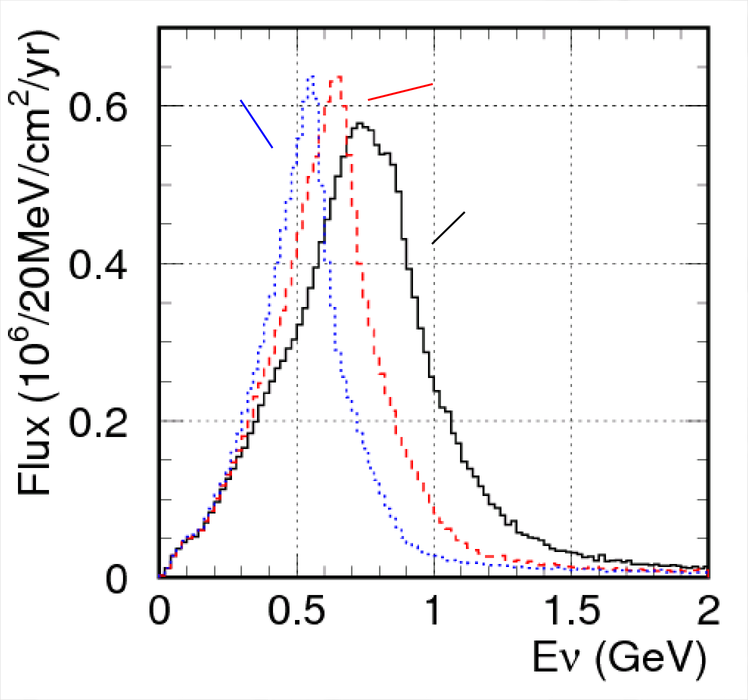
    → impact on near-to-far extrapolation

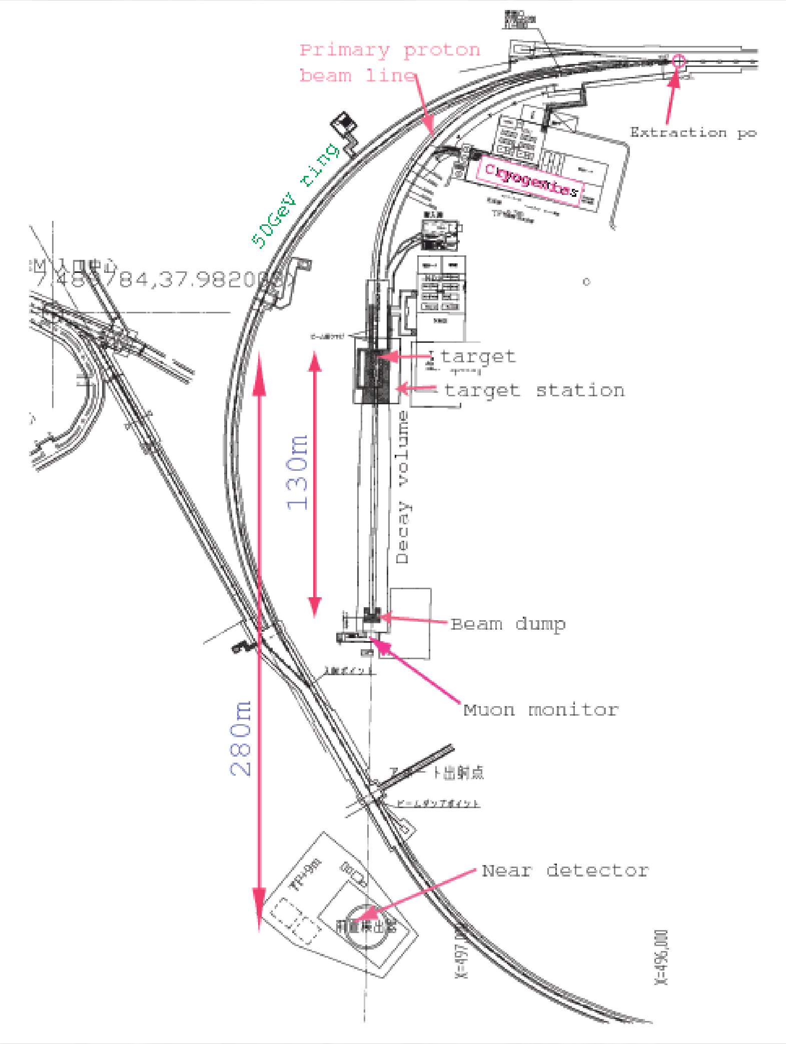
- Understanding the neutrino beam properties
  - Neutrino flux and spectrum
  - Beam ν_e contamination
  - Neutrino cross section, especially for backgrounds
    - Non-QE events for neutrino energy reconstruction
    - NC-1π^0 events for ν_e appearance search


N
Pacific Ocean
50GeV PS
3GeV PS
Target Station
Decay Pipe
400MeV LINAC
FD
To Super-Kamiokande
Japan Atomic Energy Research Institute

T2K neutrino beamline

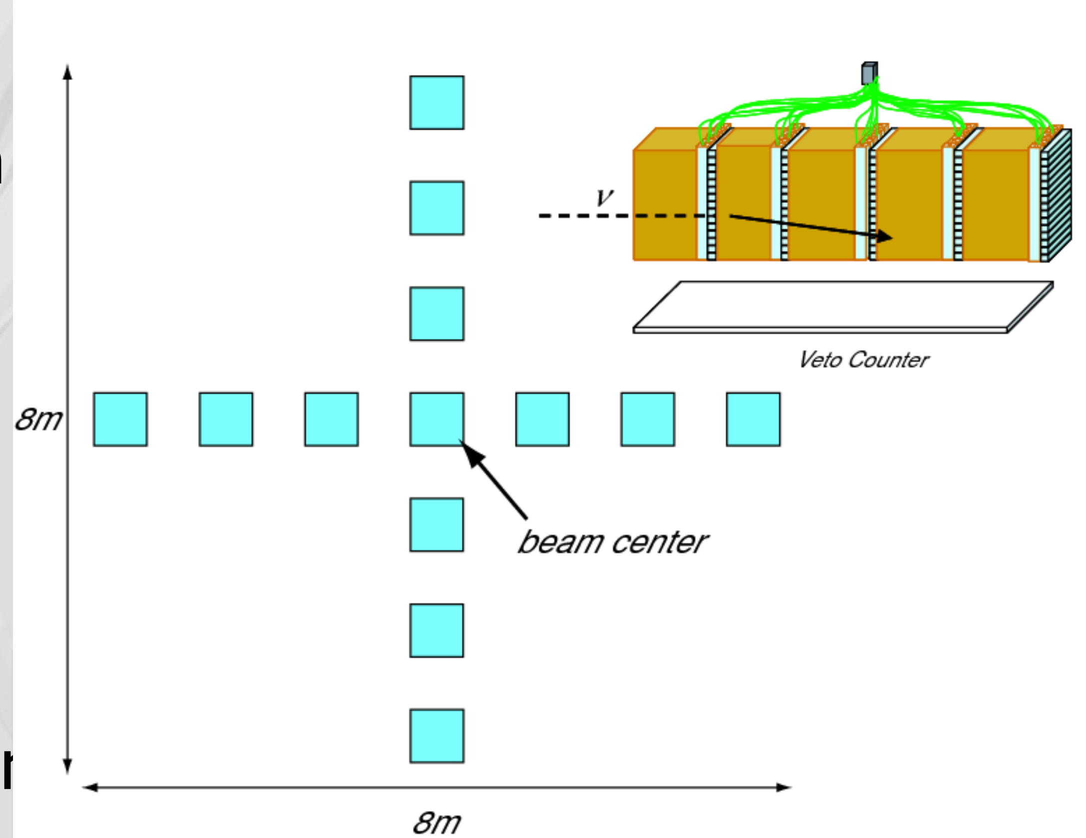
- Use off-axis principle
  - select angle correspondir
    to oscillation maximum



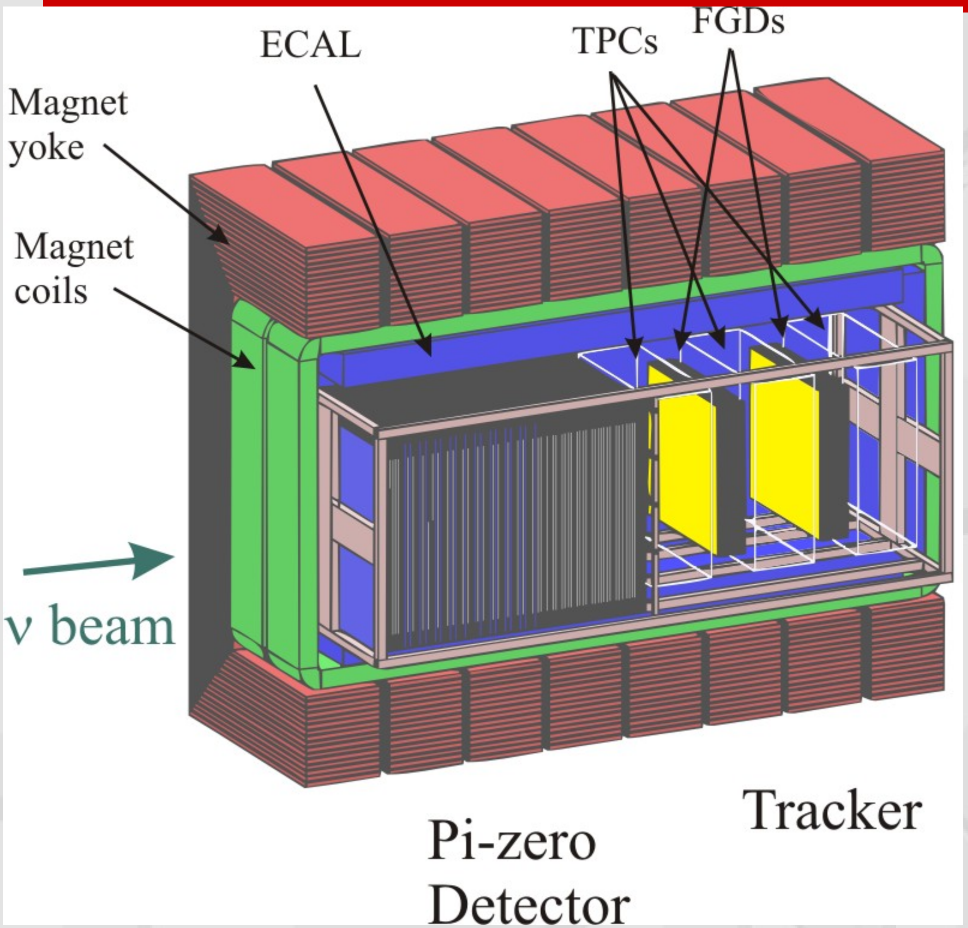


T2K near detectors: on axis ν monitor

- Located 280 m downstream of the proton target
  - monitor ν beam properties on a day-by-day basis
    - centre
    - profile
  - iron-scintillator stacks



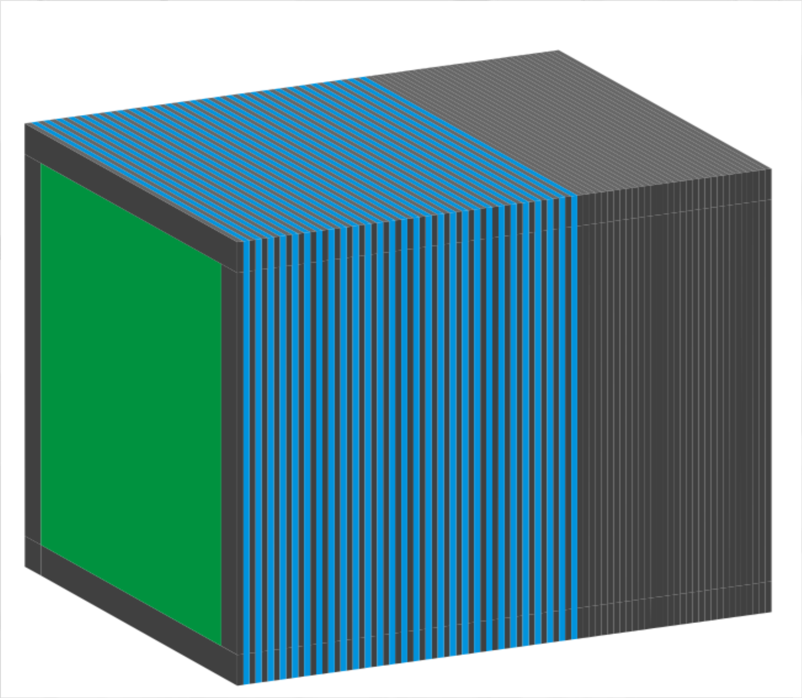
OFF-AXIS NEAR DETECTOR - ND280



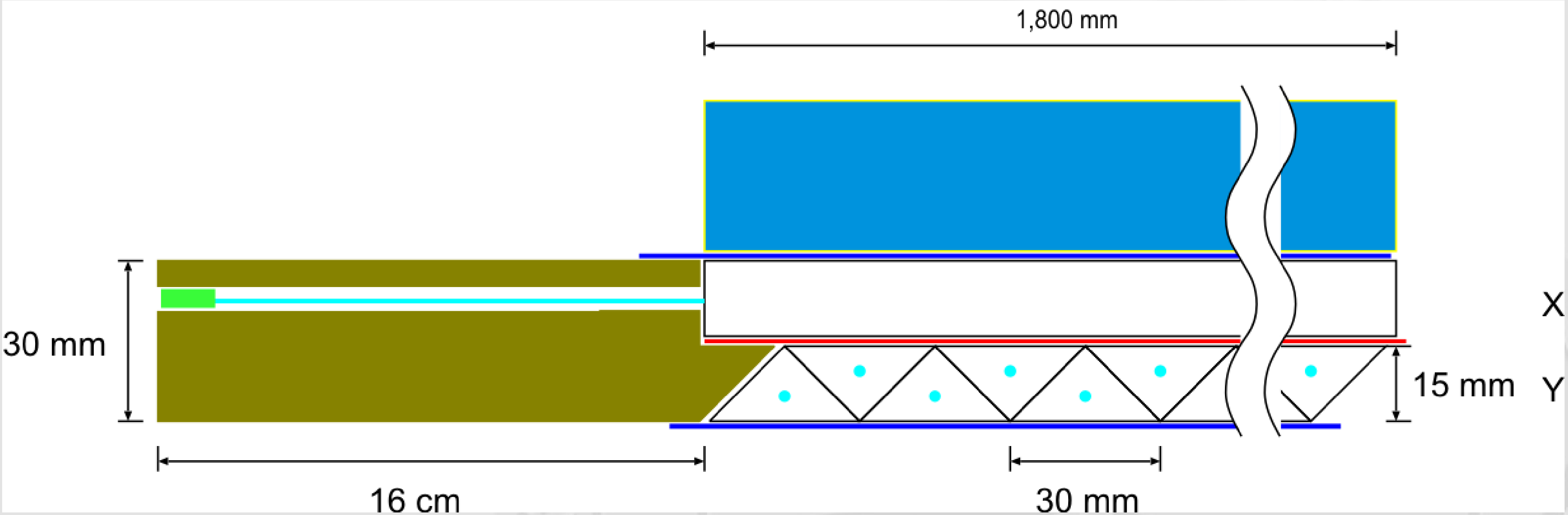
- Pi-zero detector (P0D)
  - To study NCπ^0 production with high statistics
- Tracker
  - To study CC interactions
  - Measure the ν spectrum
- ECAL
  - Detect the EM components from tracker and P0D
  - For π^0 and ν_e studies
- SMRD
  - To measure the energy of μ going sideway
- Housed in UA1 magnet
  - *B* field = 0.2 T

Pi-zero detector

- designed to make high statistics measurements of ν interactions with electromagnetically showering particles
  - scintillating bar tracking planes
  - front section interleaved with passive water layers (blue)
    - statistical subtraction of events in rear from front used to determine oxygen cross sections



Pi-zero detector

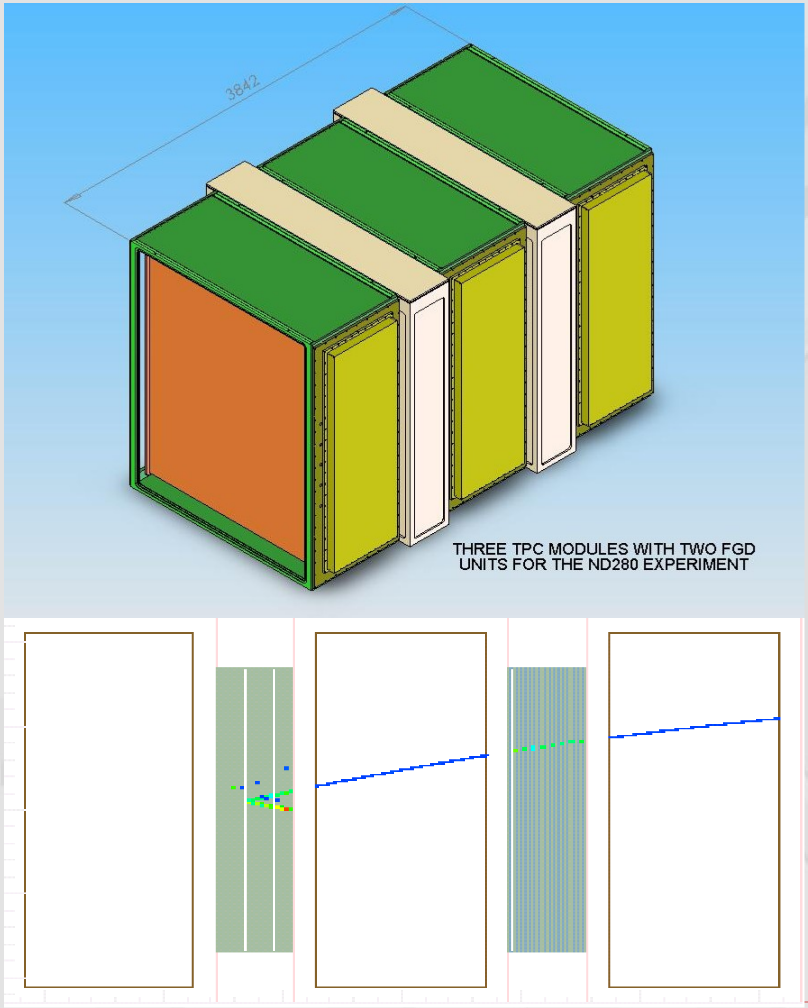


- co-extruded triangular polystyrene bars with TiO_2 reflective layer and central hole with WLS fiber
- thin (0.6 mm) lead sheets (red) to promote photon conversion

Tracker

- The tracker is optimized to study neutrino interactions that produce charged particles:
  - ν_μ CC quasi-elastic (CCQE) interactions to measure the ν_μ flux and spectrum prior to oscillation
  - ν_μ CC in-elastic interactions that can be misinterpreted by SK to be CCQE, and thus assigning an incorrect ν_μ energy
  - ν_μ NC in-elastic interactions that produce π^+ and π^- that can be misinterpreted by SK to be CCQE
  - ν_e CCQE interactions, to determine the ν_e flux and spectrum, an important background to ν_e appearance at SK

The tracker: FGDs + TPCs



– **Fine Grained Detector (FGD):**

Alternating X and Y layers of square scintillator bars, provides:

- neutrino interaction target mass
- tracks around interaction vertex
- particle ID by dE/dx and Michel electron

– **Time Projection Chambers (TPC):**

surrounding FGD, provides

- Measure momenta of particles emerges from FGD with ~10% resolution at 1 GeV/c
- Particle ID by dE/dx

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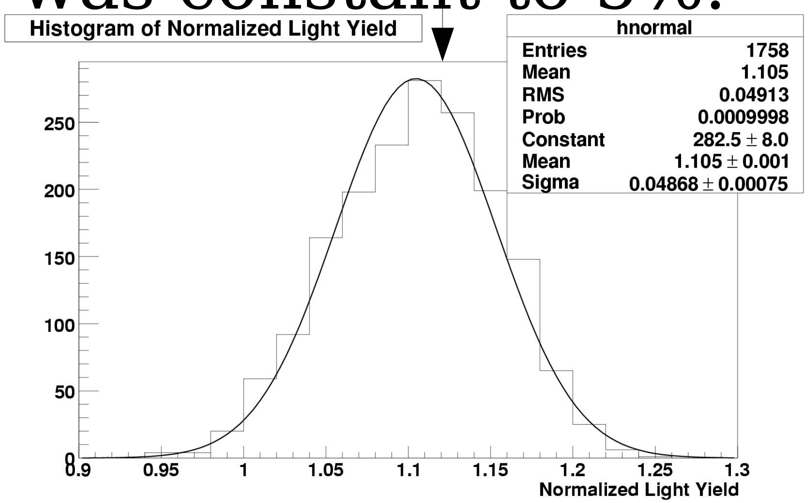
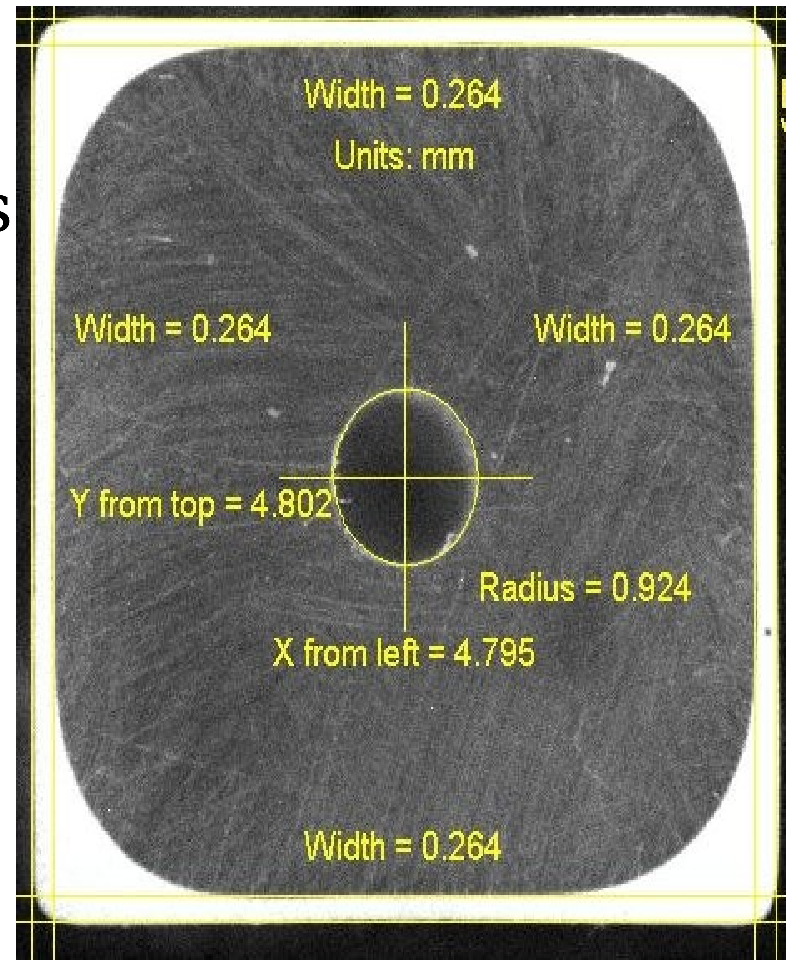
Tracker - FGD

- each FGD: $2 \times 2 \times 0.3$ m^3 target volume
- scintillator bars: $1 \times 1 \times 200$ cm^3 arranged in alternating x-y planes
  - fine segmentation needed to track low energy protons, in order to distinguish CCQE and non-elastic
- the back FGD will contain water layers
  - initially 3~cm passive water layers between each x-y scintillator plane
  - active program to produce water-based scintillator for a future upgrade
- plan to use “SiPM” devices for readout

Scintillator Quality Control

- Periodically checked Ti02 coating width and size/position of WLS fibre hole.
- Used automated scanner check light output from bars using Ru-106 source; found that bar-to-bar light yield was constant to 5%.

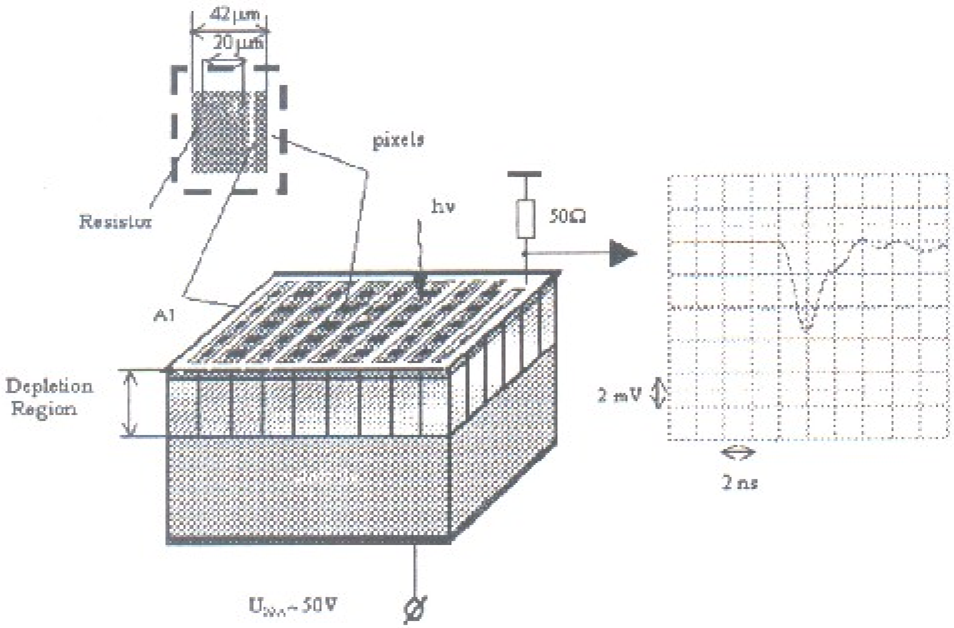


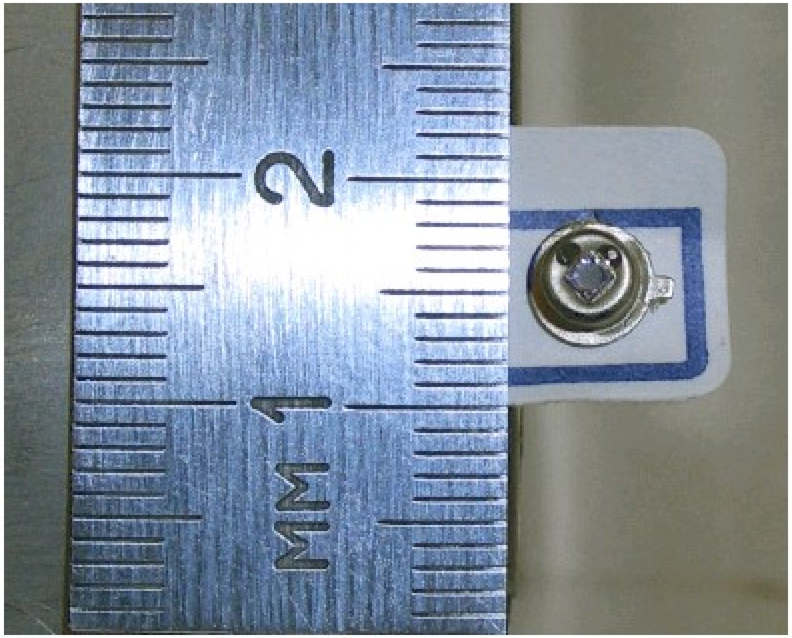


XY Module Construction

- Each module consists of an X layer, a Y layer and two G10 skins.
- Considerable R/D was done for module glueing procedure.
- Metal jig was constructed to ensure that X and Y layers were aligned and perpendicular.

Silicon Photomultiplier





WLS Fibres and Silicon Photon Counters

- Procurement and testing of WLS fibres being done at University of Regina.
- Fibres are presently at Fermilab being mirrored at one end

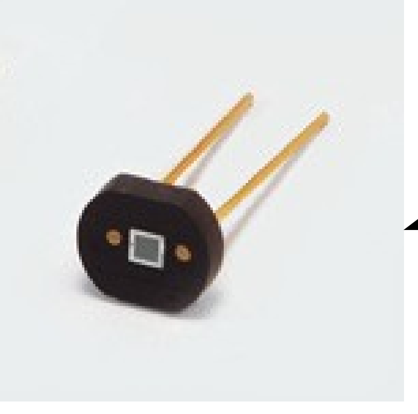


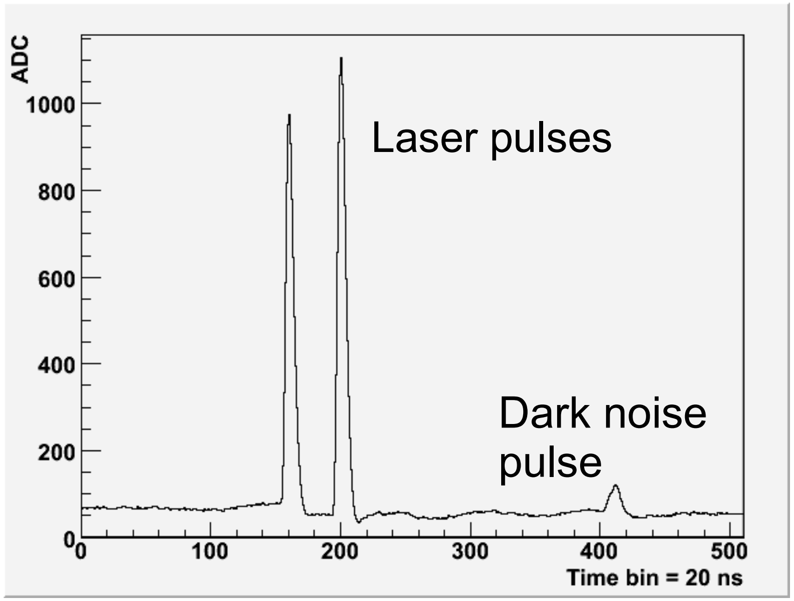
Photo from product catalogue

- Kyoto University handling purchase of silicon photon counters.
- T2K is the first large experiment to use this type of sensor.
- Results of our tests have been very positive; devices such as Hamamatsu MPPC will satisfy all our requirements.

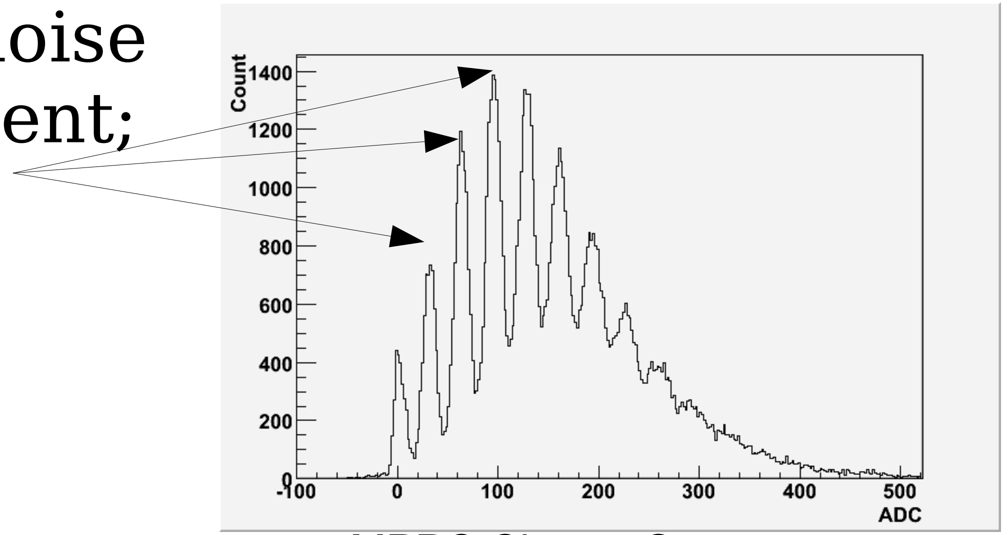
FGD Electronics

• MPPC signal is shaped and digitized by ASIC designed by TPC/Saclay collaborators.

• Currently testing ASIC prototype. Signal to noise of electronics is excellent; can easily distinguish single photoelectrons.



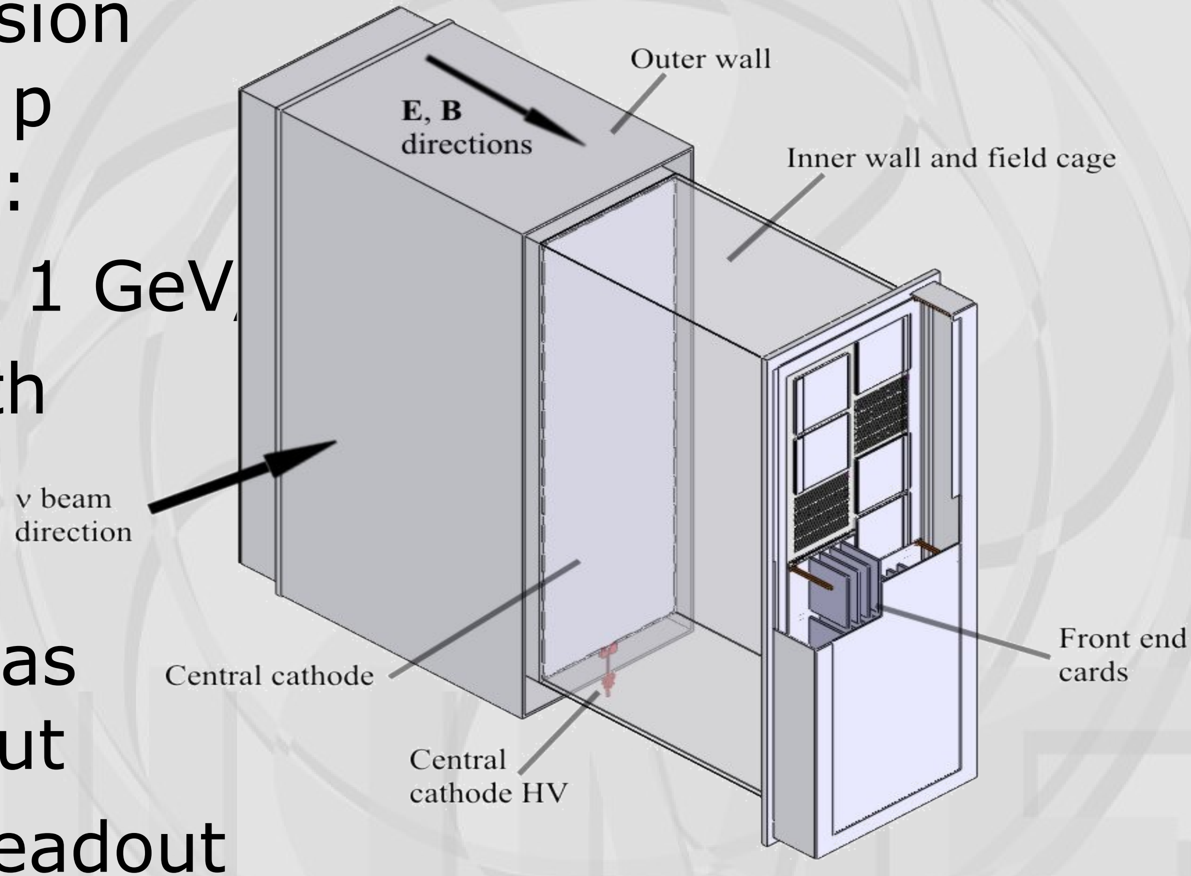
ASIC waveform example



MPPC Charge Spectrum

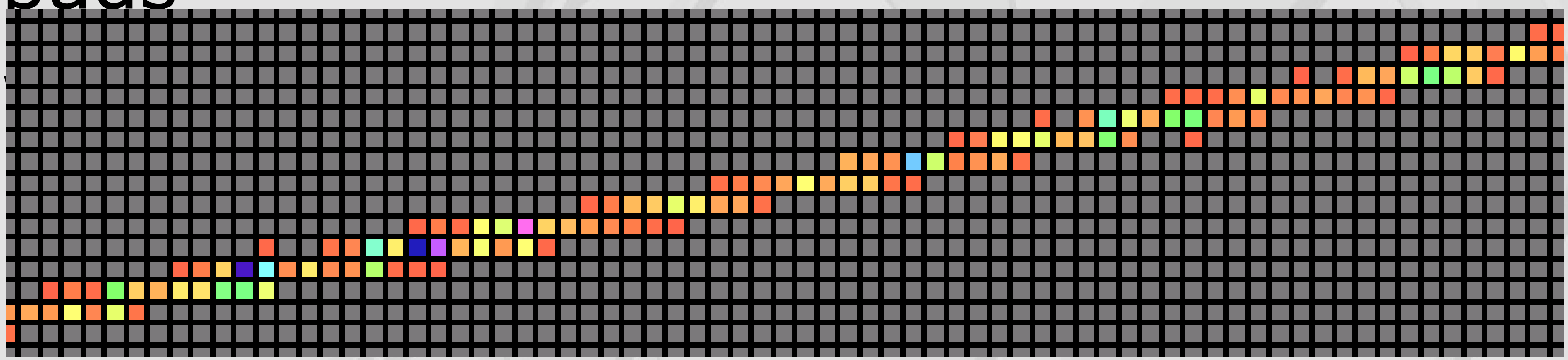
Tracker - TPC

- use a low diffusion gas to achieve p resolution goal:
  - 10% for p < 1 GeV/
- double wall with field cage as inner wall
- micropattern gas detector readout
- custom ASIC readout electronics



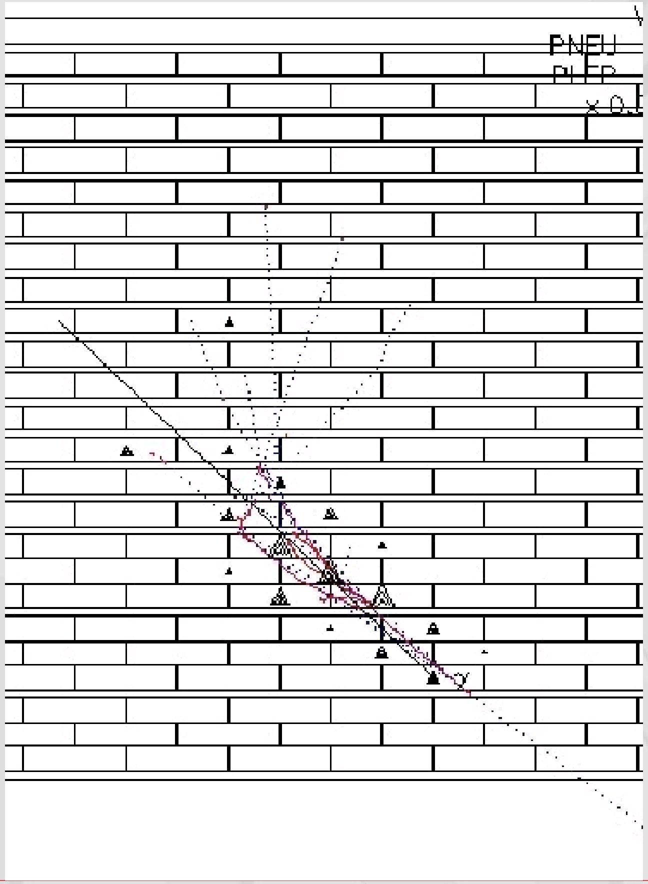
Tracker - TPC

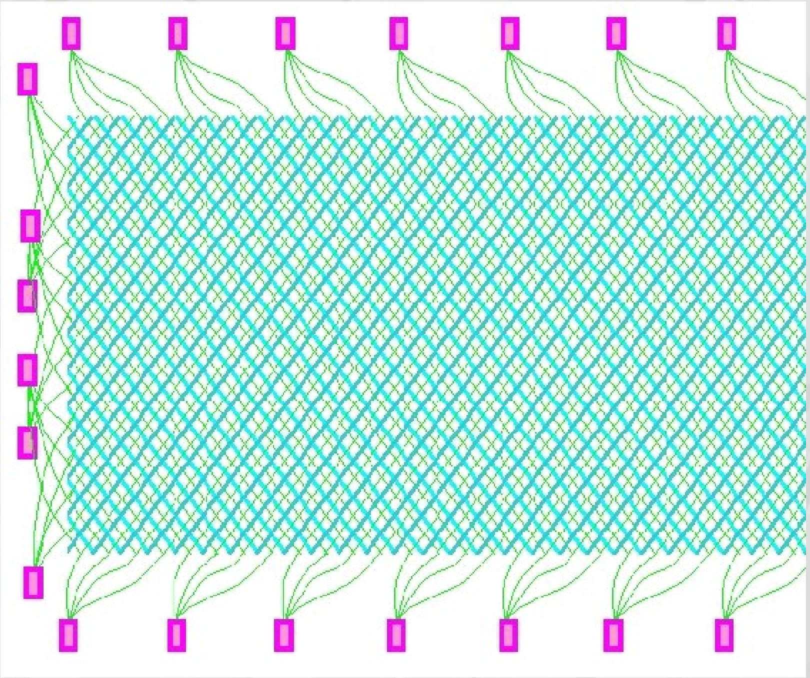
- readout segmented into 8×8 mm^2 pads



ECAL

- segmentation schemes under study





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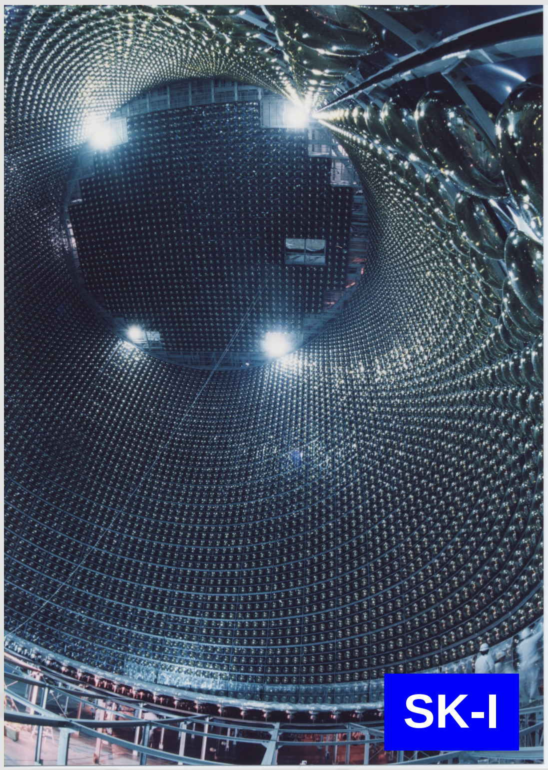
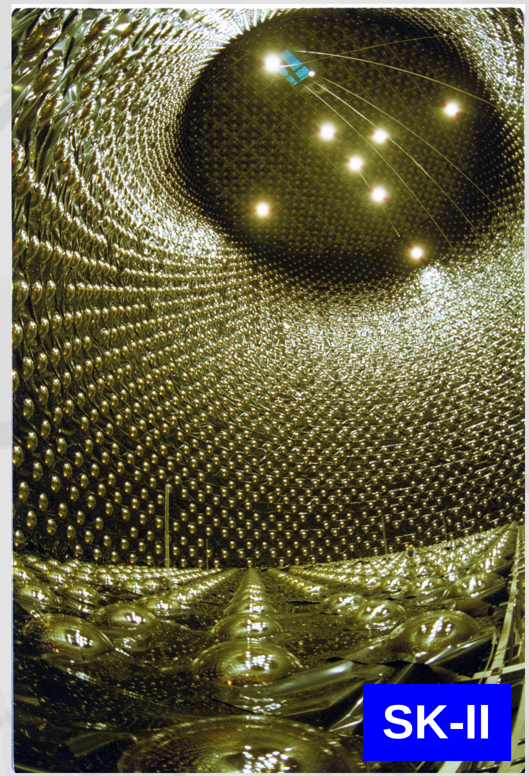
Super-Kamiokande history

1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007

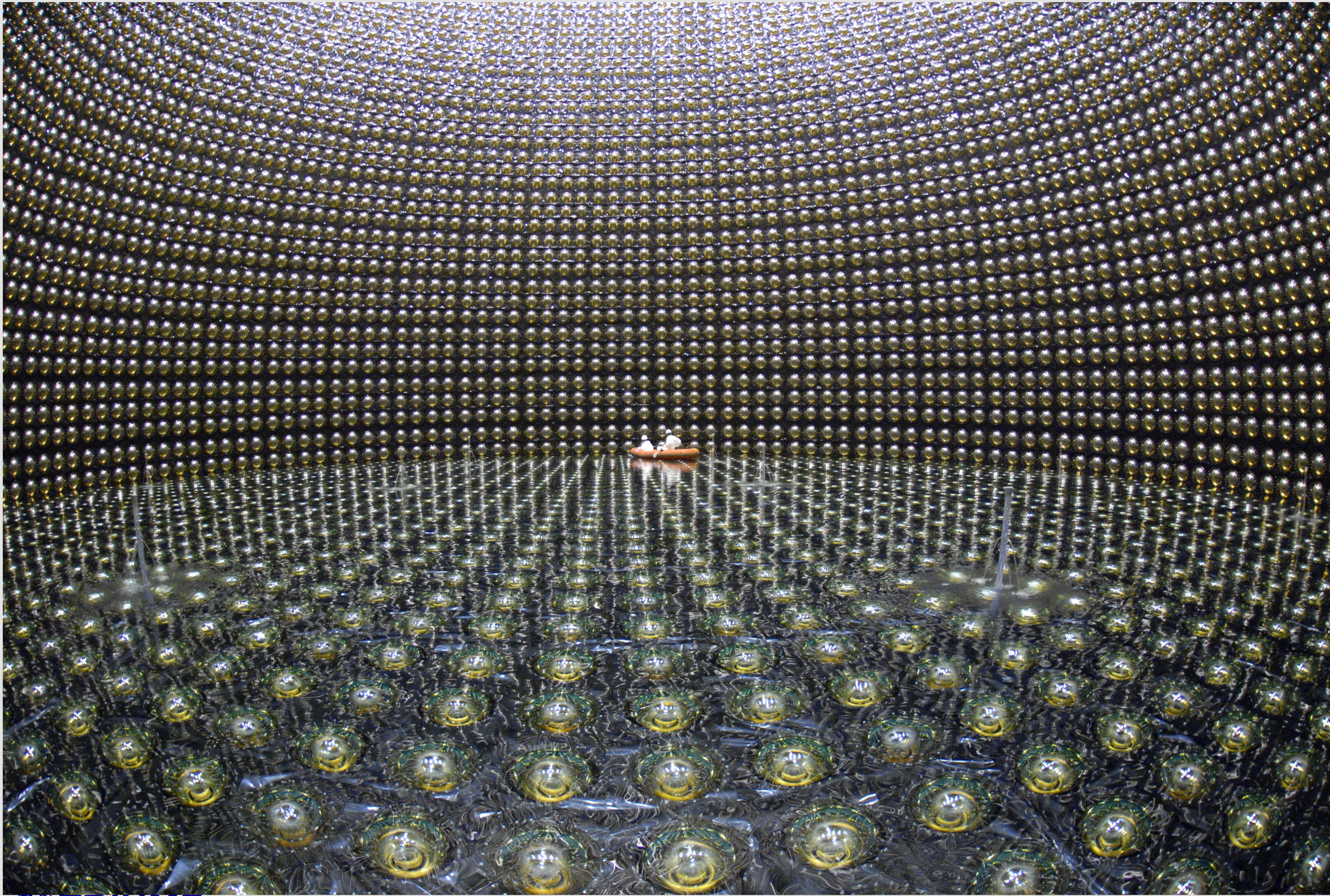
SK-I — accident — SK-II — reconstruction — SK-III



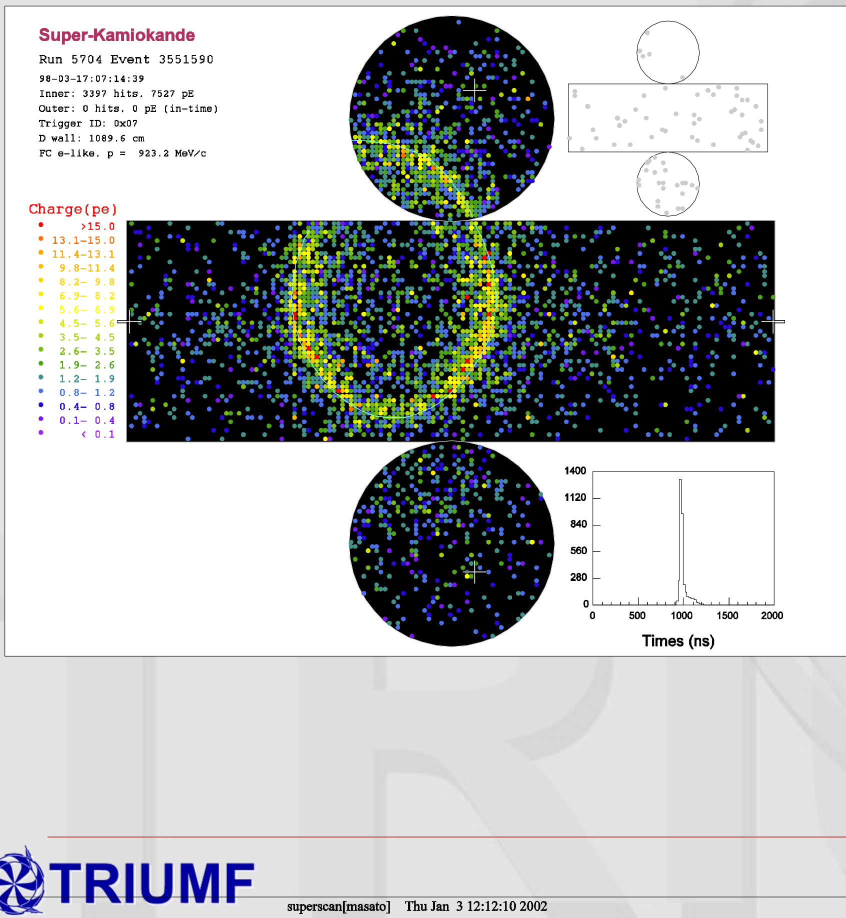


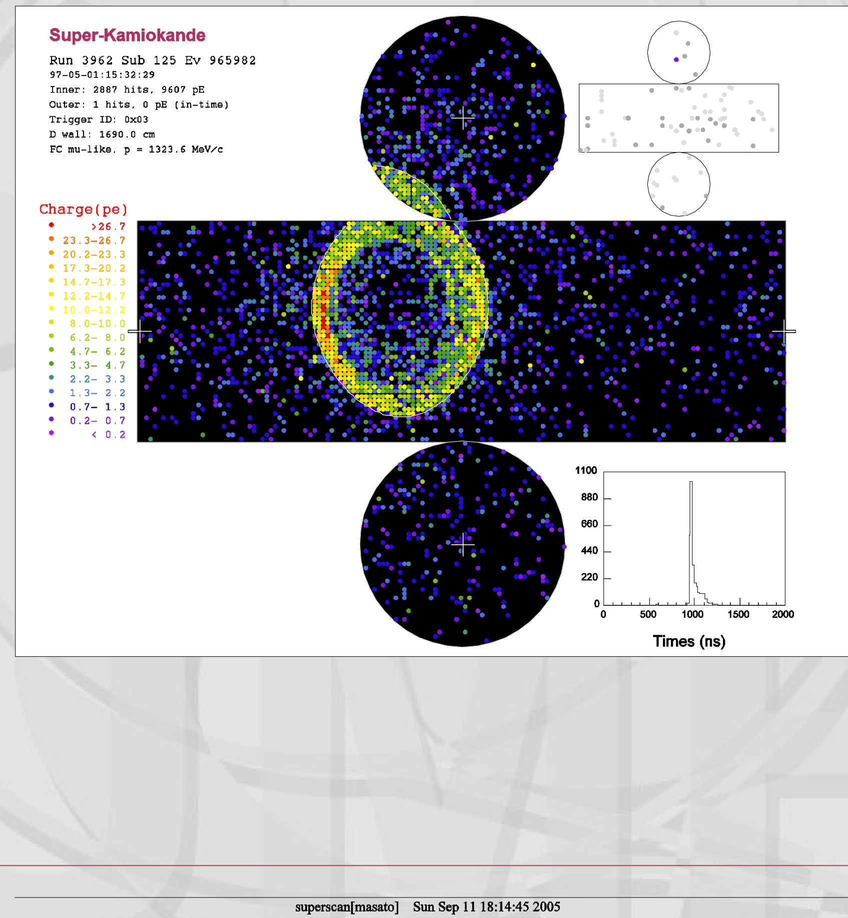
plastic vessel

SK-I		SK-II
11,146	number of inner detector PMTs	5,182
40 %	photocathode coverage	19 %



e/μ separation @ SK





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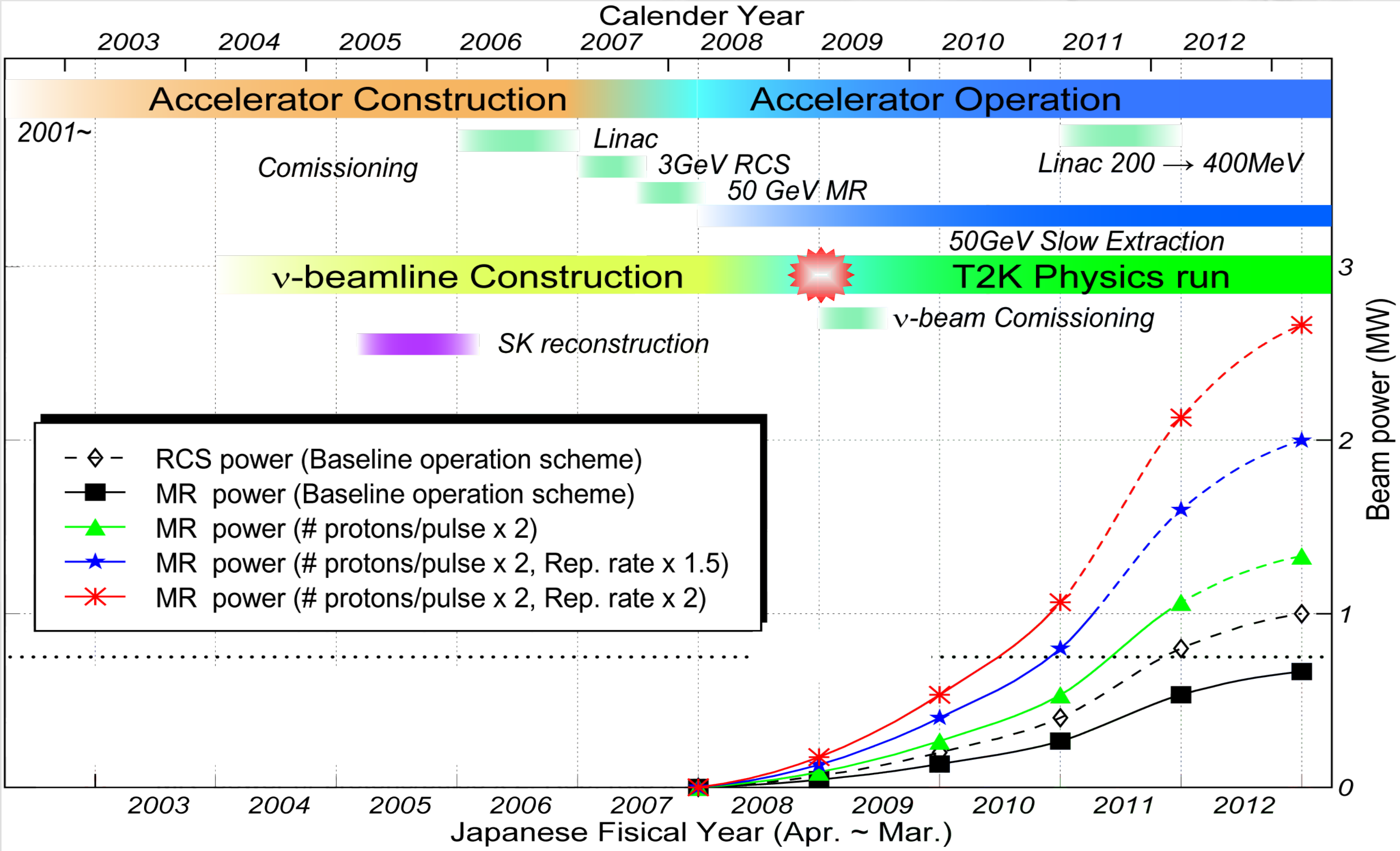
T2K time lines

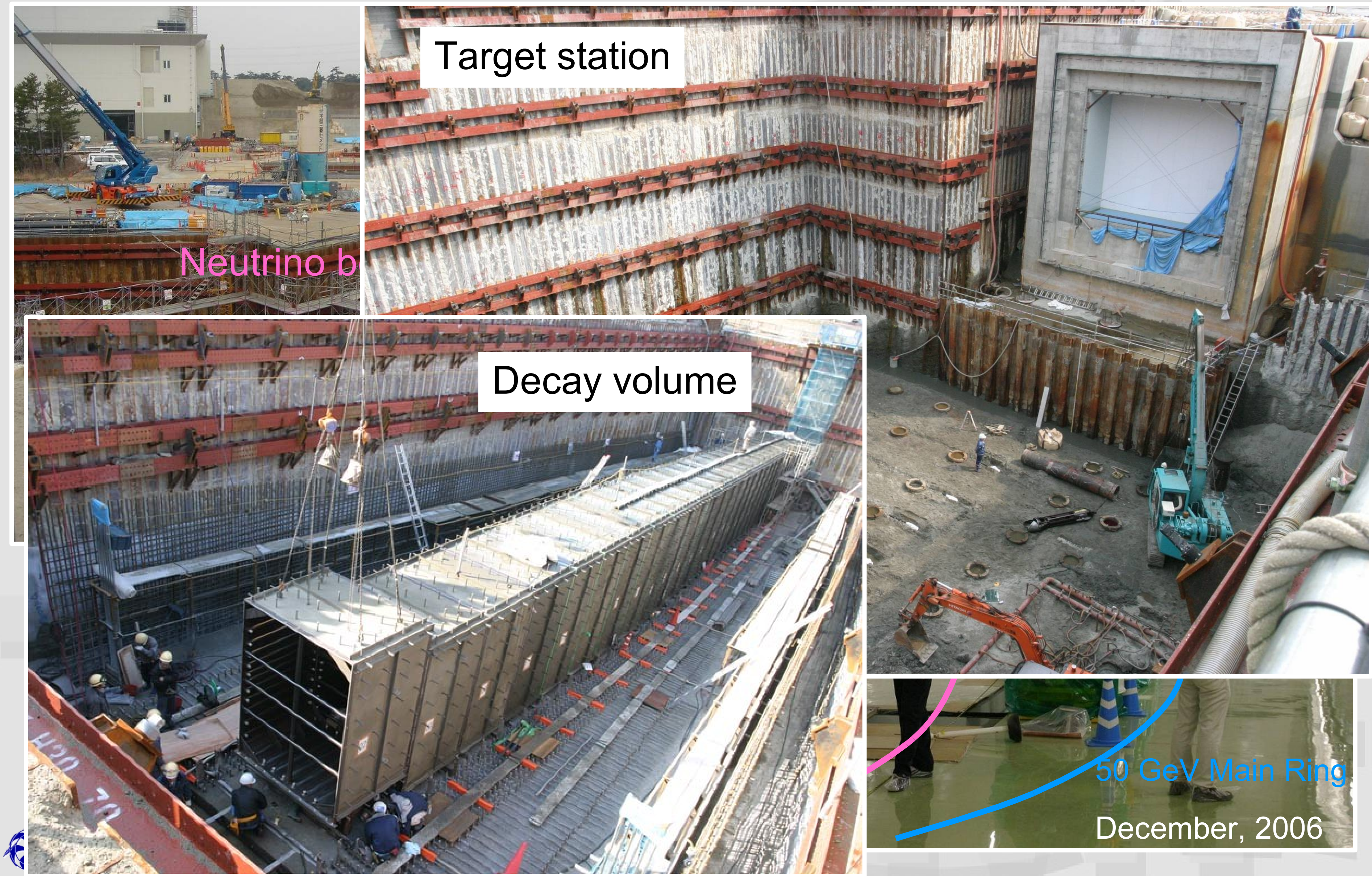


- ➡ Beam line construction started Apr. 2004
- ➡ ND280 pit construction start Jul. 2007
- ➡ UA1 magnet installation Apr. 2008
- ➡ Completion of ND280 building Mar. 2009
- ➡ Neutrino beam line commissioning Apr. 2009
- ➡ T2K data taking starts Apr. 2009
- ➡ ND280 Commissioning Oct. 2009
- ➡ ND280 Data taking Nov. 2009...

J-PARC accelerator and neutrino beam line under construction

TRIUMF

J-PARC accelerator and neutrino beam line under construction



Summary

Neutrino oscillations were established in late 1990's and early 2000's

Next step is to measure oscillation parameters precisely and search for non-zero θ_{13}.

T2K experiment will do the job!

- Measure the Δm^2_{23} and θ_{23} to a few % precision
- Search for non-zero θ_{13} down to $\sin^2 2\theta_{13} \sim 0.006$

J-PARC / T2K status:

- Accelerator and beam line under construction.
- Detector design finalized, under construction.
- Beam will start in 2009

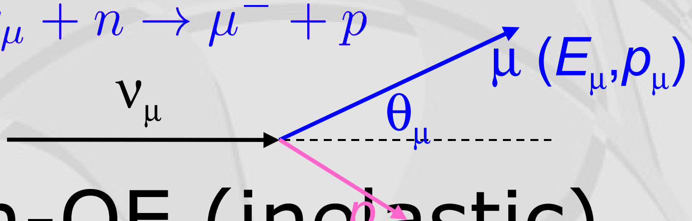
Extra slides

Neutrino energy measurement

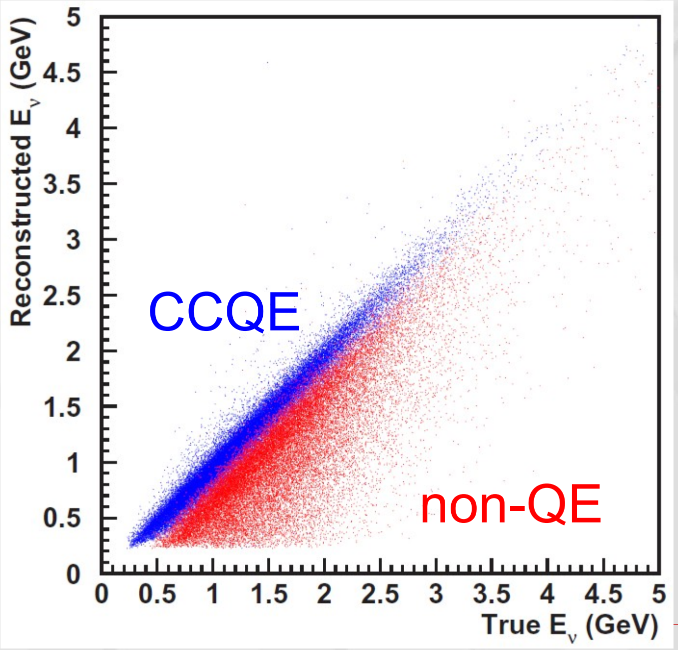
- Use CCQE interaction to reconstruct the energy

$$E_\nu^{\text{rec.}} = \frac{m_N E_\ell - m_\ell^2/2}{m_N - E_\ell + p_\ell \cos\theta_\ell}$$

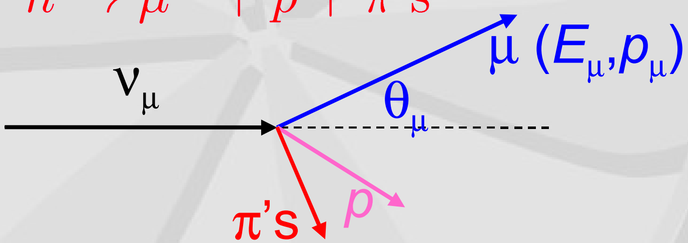
$$\nu_\mu + n \to \mu^- + p$$



- Backgrounds are non-QE (inelastic) interactions



$$\nu_\mu + n \to \mu^- + p + \pi\text{'s}$$



Rate(E_ν) = flux×σ → Flux(E_ν)

To estimate the energy spectrum,
we need to understand σ(QE) and σ(non-QE)

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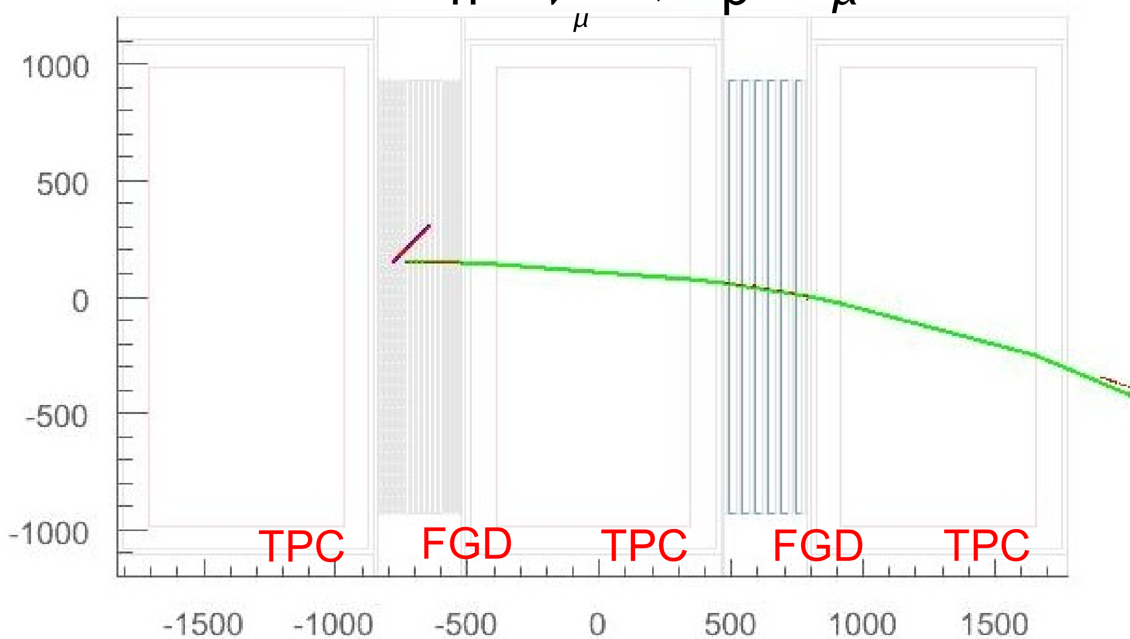
FGD Physics Requirements

- FGD provides the target mass for neutrino interactions in Tracker.
- FGD must also provide reconstruction and particle identification of short tracks that stop in FGD.
- In particular, must distinguish protons from pions; pion tagging will use Michel electrons, charge deposition.

Simulated CCQE neutrino interaction:

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

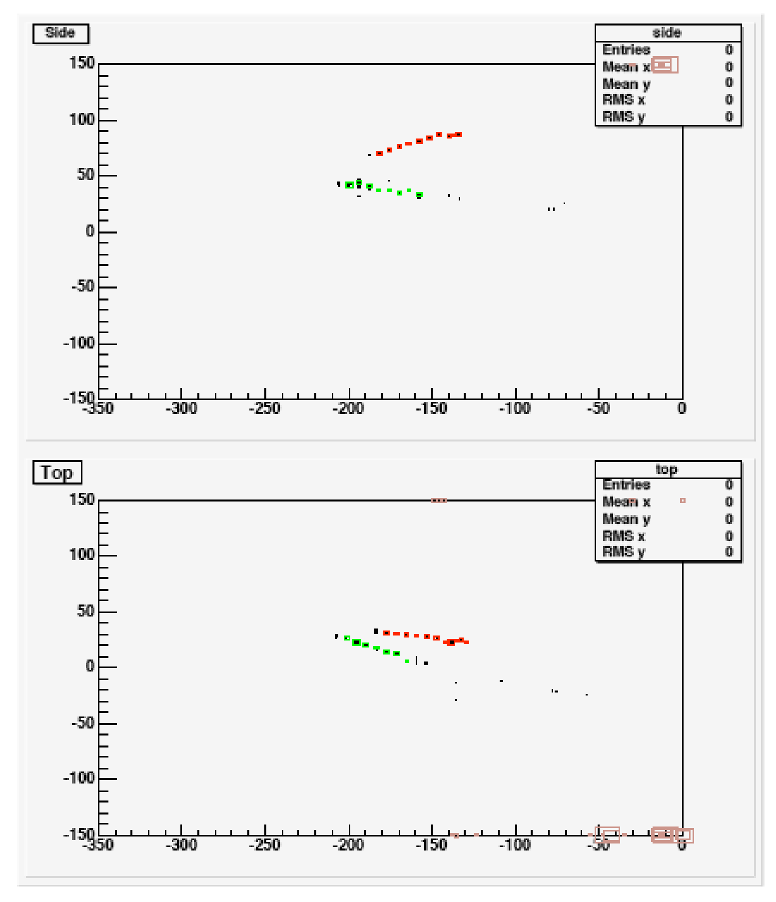


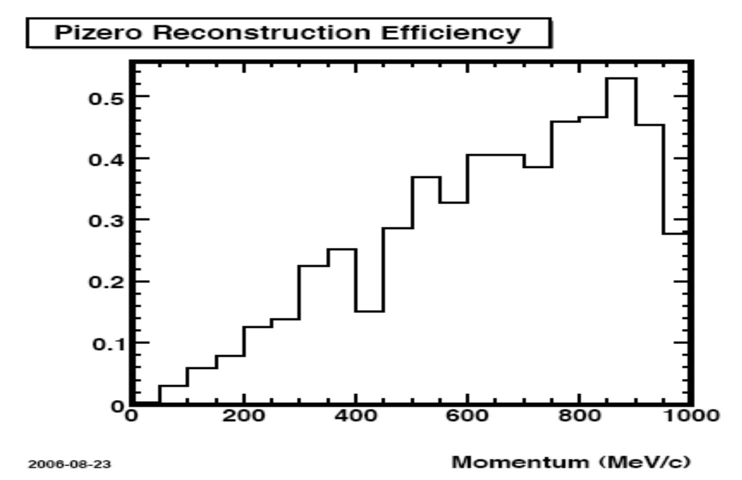
P0D : NCπ^0 measurement

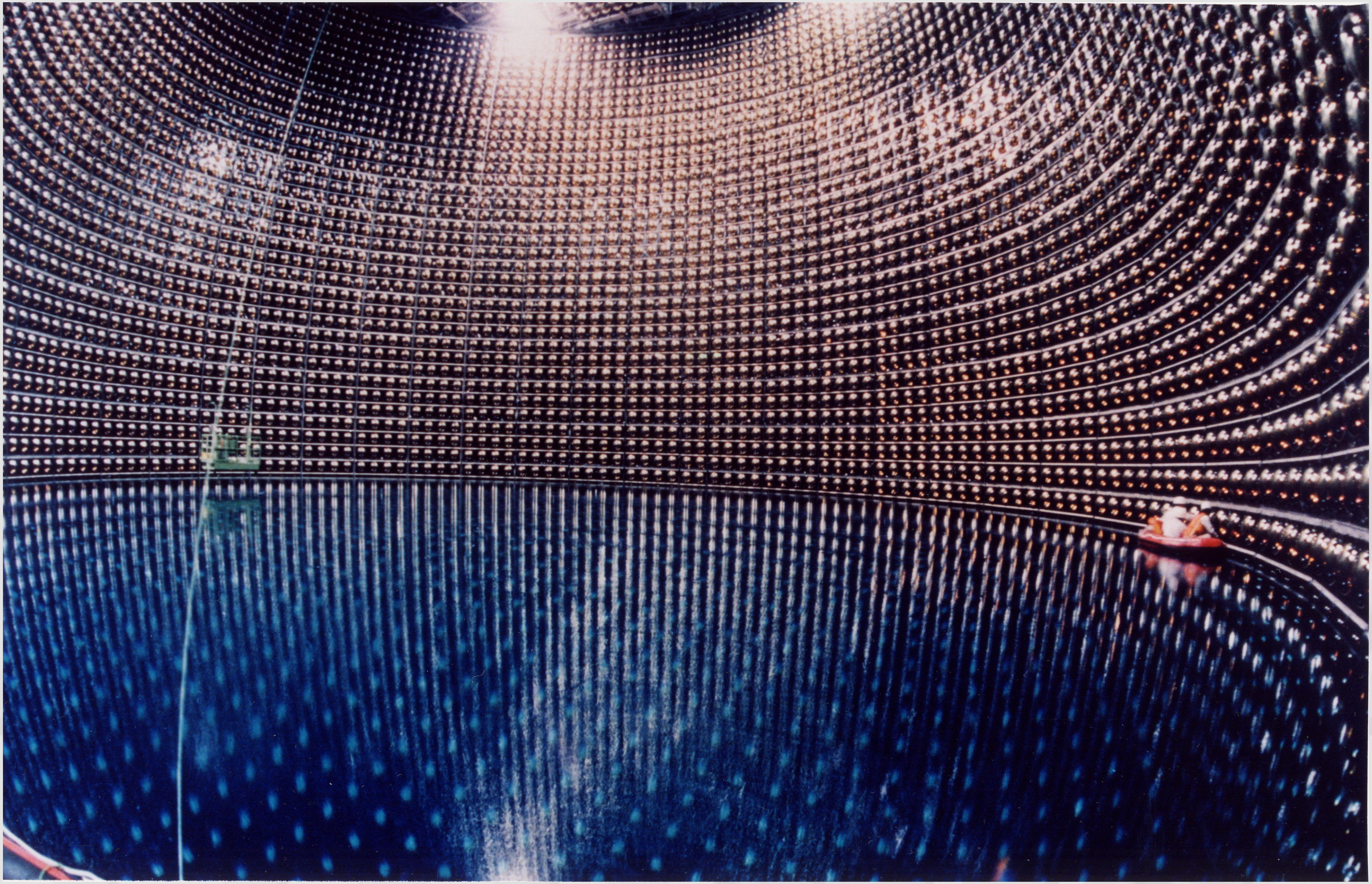
$\gamma 1$
$\gamma 2$

➡ Dedicated to appearance backgrounds

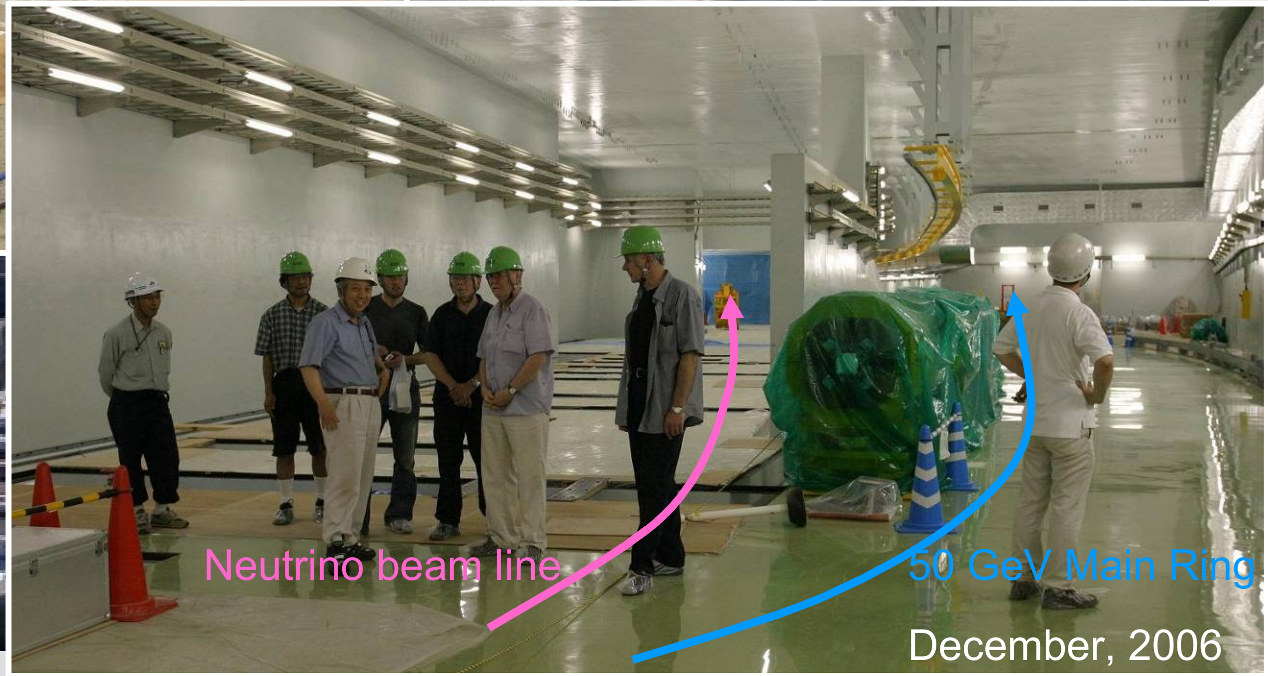
- **1.7x10^4 NC-Res1π^0** events in H_2O target per year
- **~6000 π^0 reconstructed**
- **Water in/out** periods : C/H_2O differences
- Inclusive NC/CC production
- Beam ν_e







J-PARC accelerator and neutrino beam line under construction



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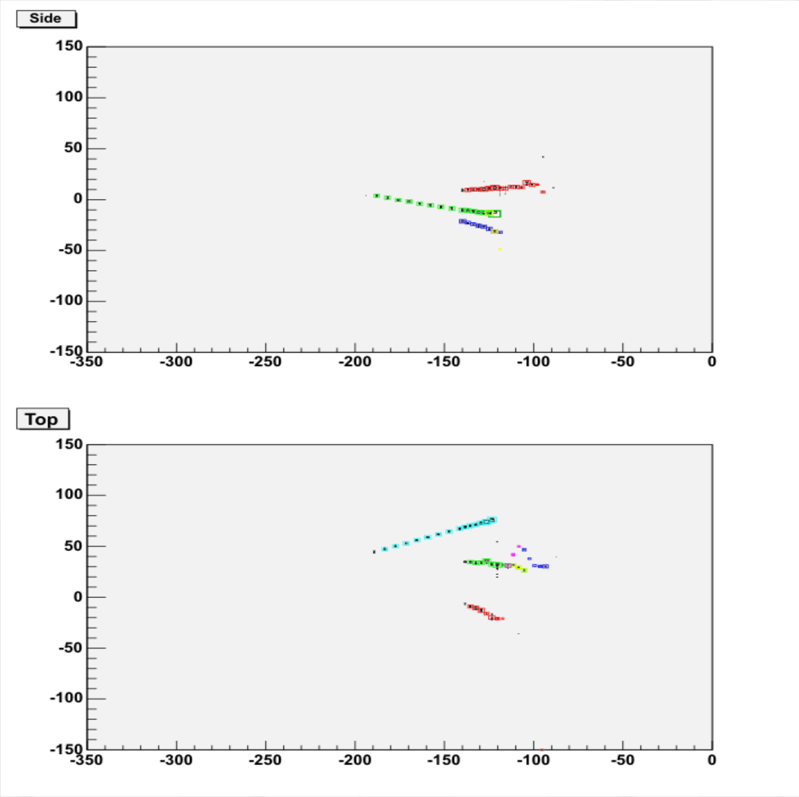
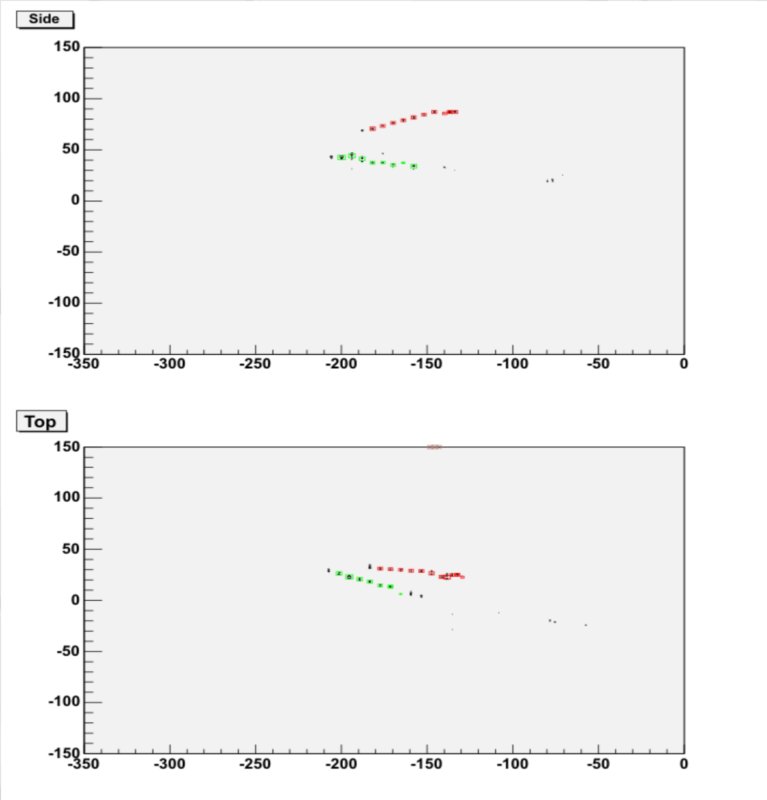
J-PARC accelerator and neutrino beam line under construction

TRIUMF

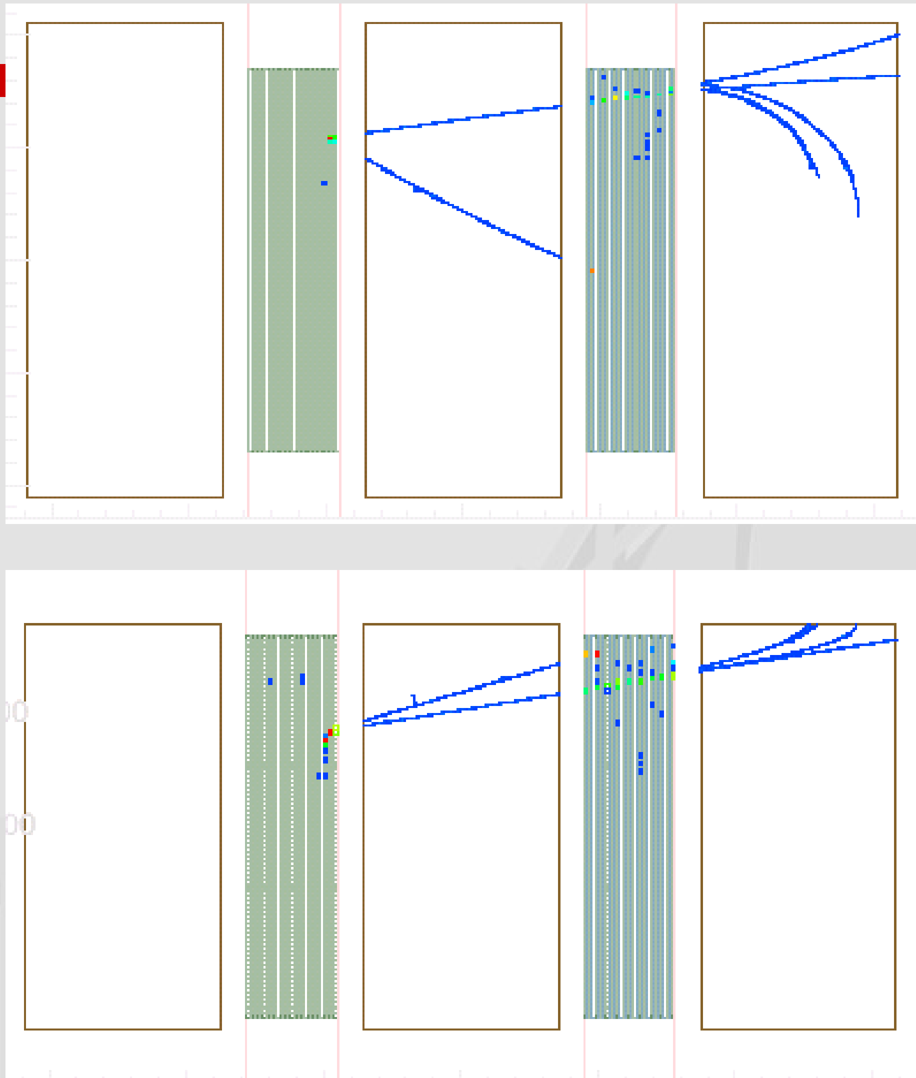
Pi-zero detector

- Typical NC single π^0 production events:





Tracker – ν_e CC event



Event No.: 13 Reaction code: 1 Position in File: 13

Primary Vertex [mm]: (423, 543, 985)

Located in

Basket_0/TRK_0/Active_1/ScintX1_145/bar_39527

Informational particles

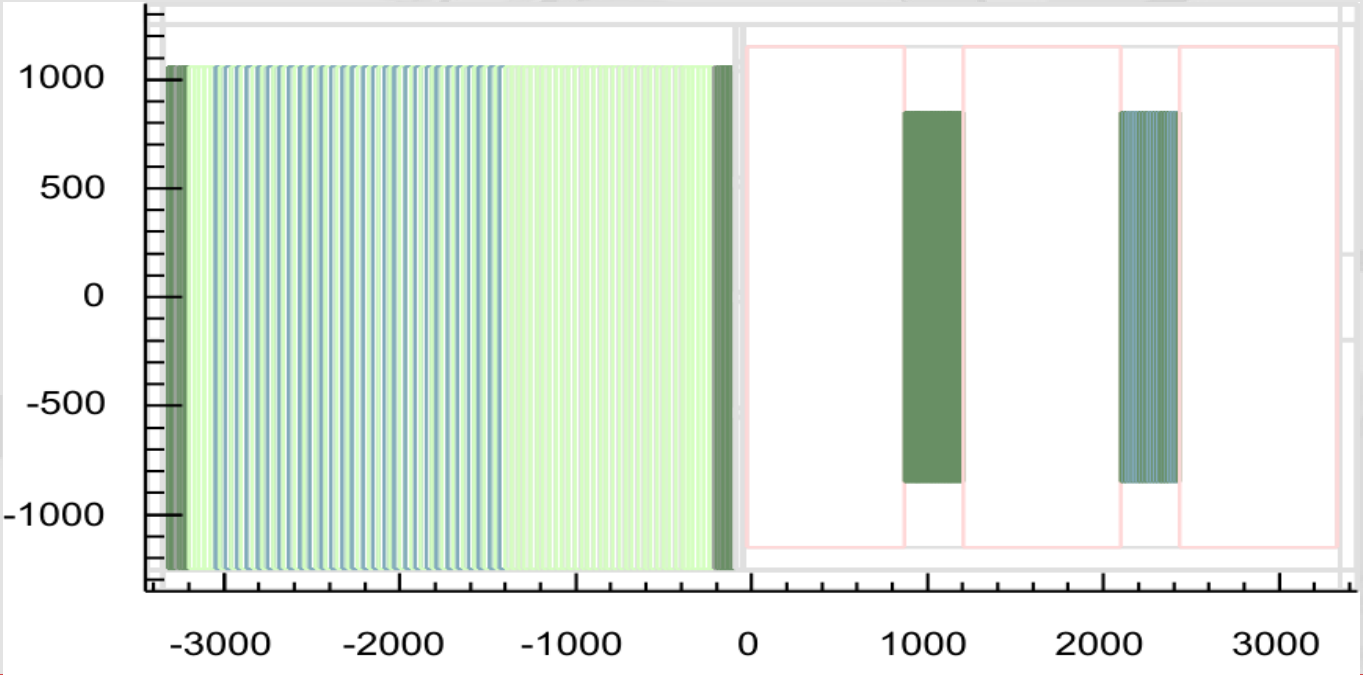
ν_e (12)	Trk -1,	KE= 2893 MeV
n (2112)	Trk -1,	KE= 0 MeV

Primary particles

e^- (11)	Trk 1,	KE= 2578 MeV
n (2112)	Trk 2,	KE= 46 MeV
p (2212)	Trk 3,	KE= 15 MeV
p (2212)	Trk 4,	KE= 117 MeV
p (2212)	Trk 5,	KE= 86 MeV
p (2212)	Trk 6,	KE= 14 MeV
γ (22)	Trk 7,	KE= 4 MeV

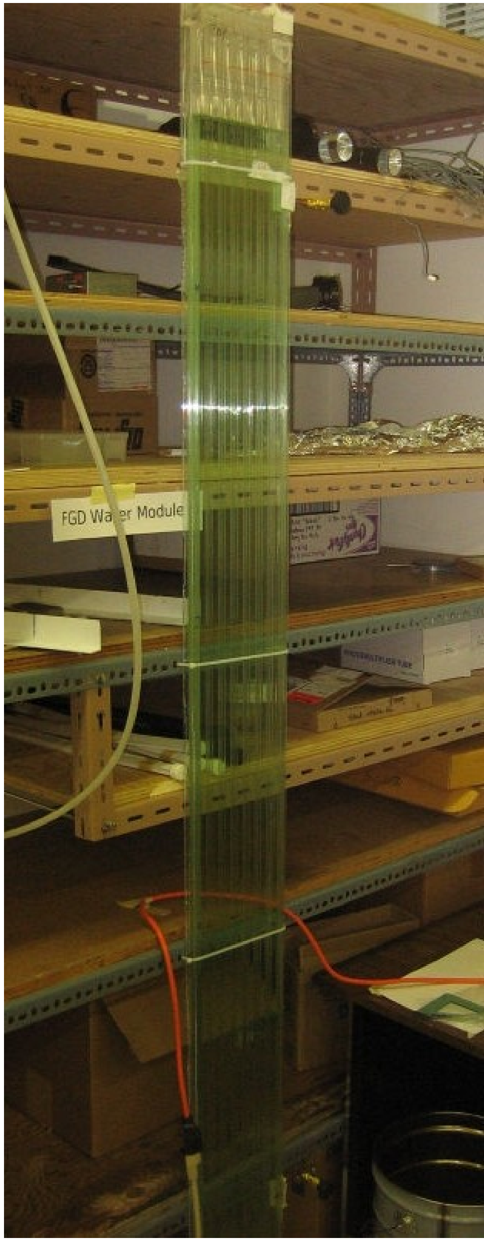
Tracker

- consists of solid active target modules (FGD) and gas time projection chamber modules (TPC)



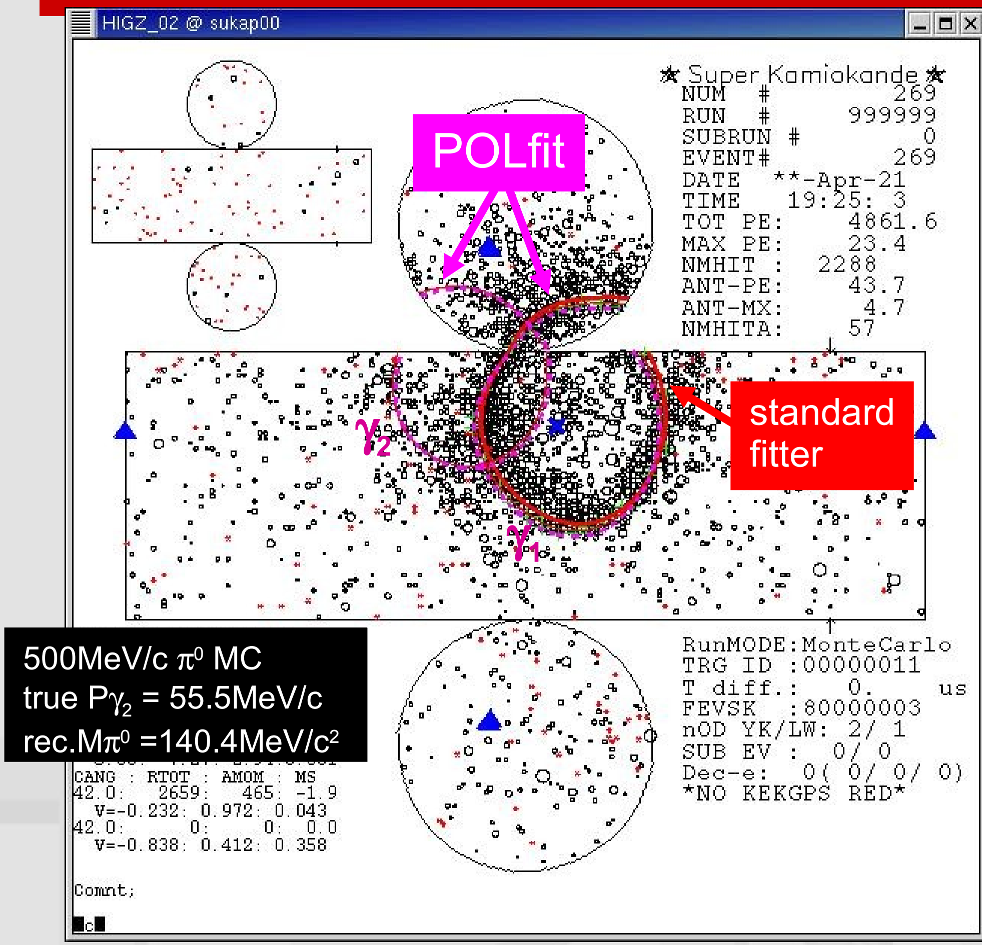
Water Module Testing

- Second FGD is composed of water layers interleaved with scintillator.
  - Must measure CCQE cross-section on water, since SuperK is water-based detector.
- Using commercial polycarbonate water panels.
- Water panels will be connected to a sub-atmospheric pressure water circulation system (to mitigate the effects of any leak).



Water Module Test Setup

POLfit (π^0 fitter)

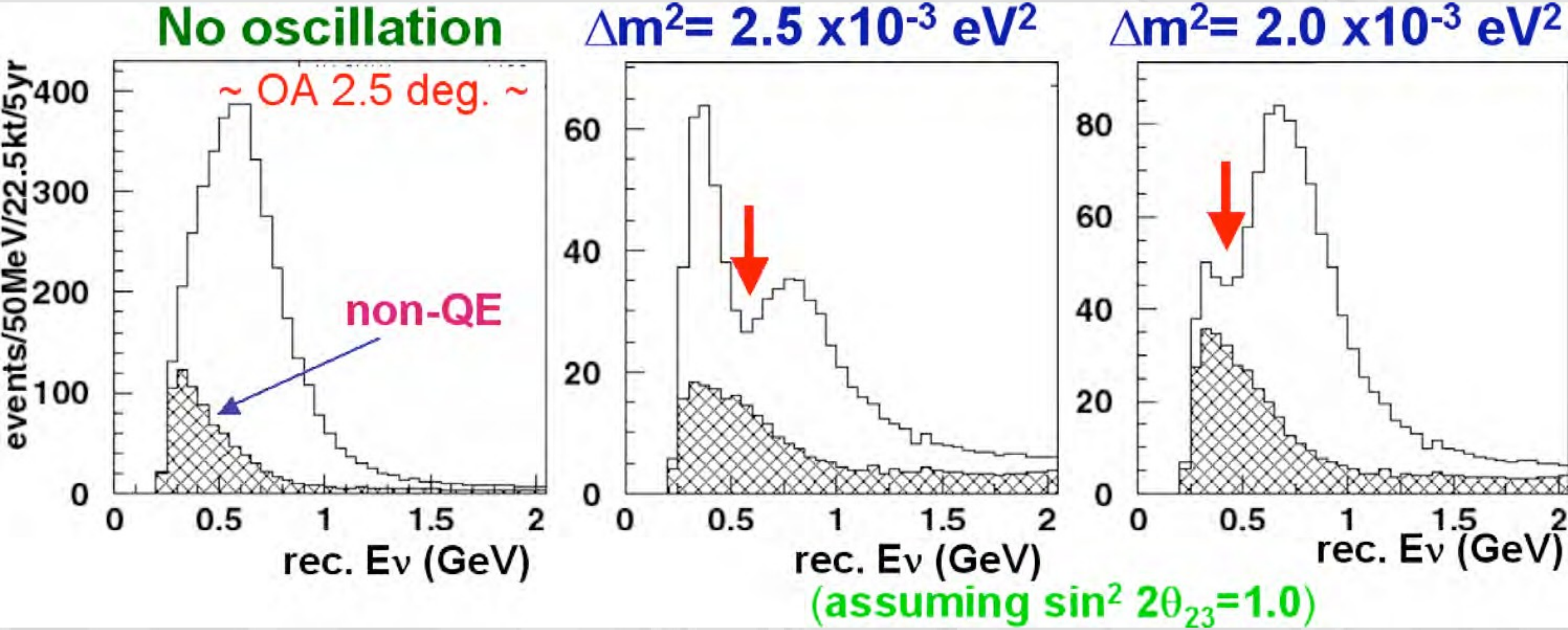


force to find 2^{nd} γ-ring

↓

identify and reject asymmetric decay π^0 BG in 1R-e sample

- input:
  vertex, 1^{st} ring dir., total E_{vis}
- output:
  $M_{\gamma\gamma}$, ΔL(π^0like-elike)

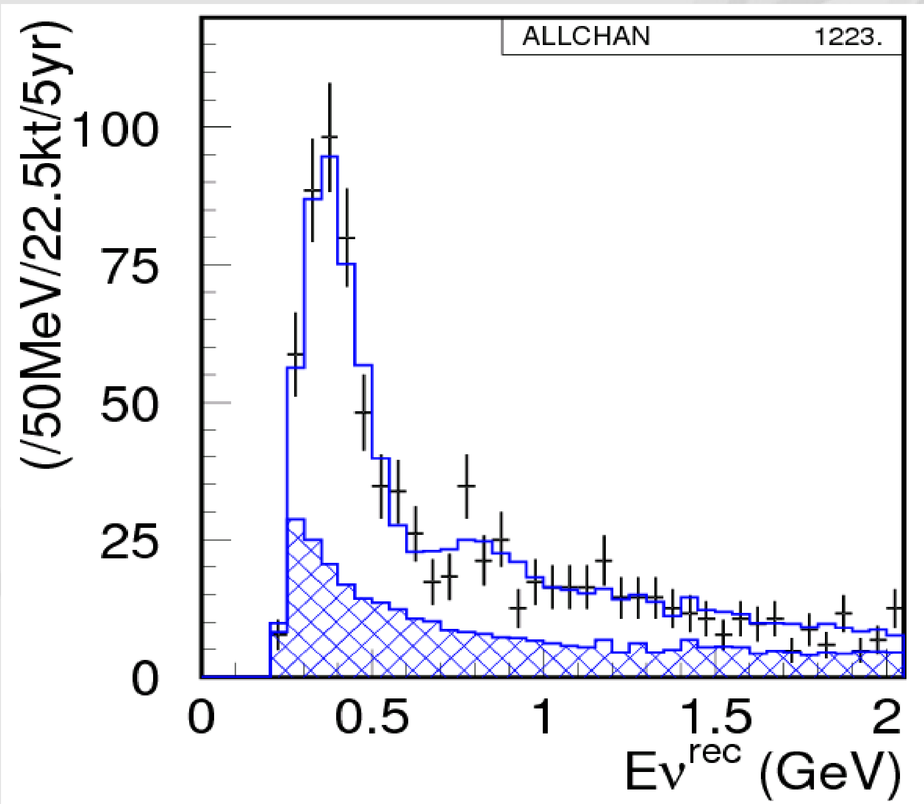


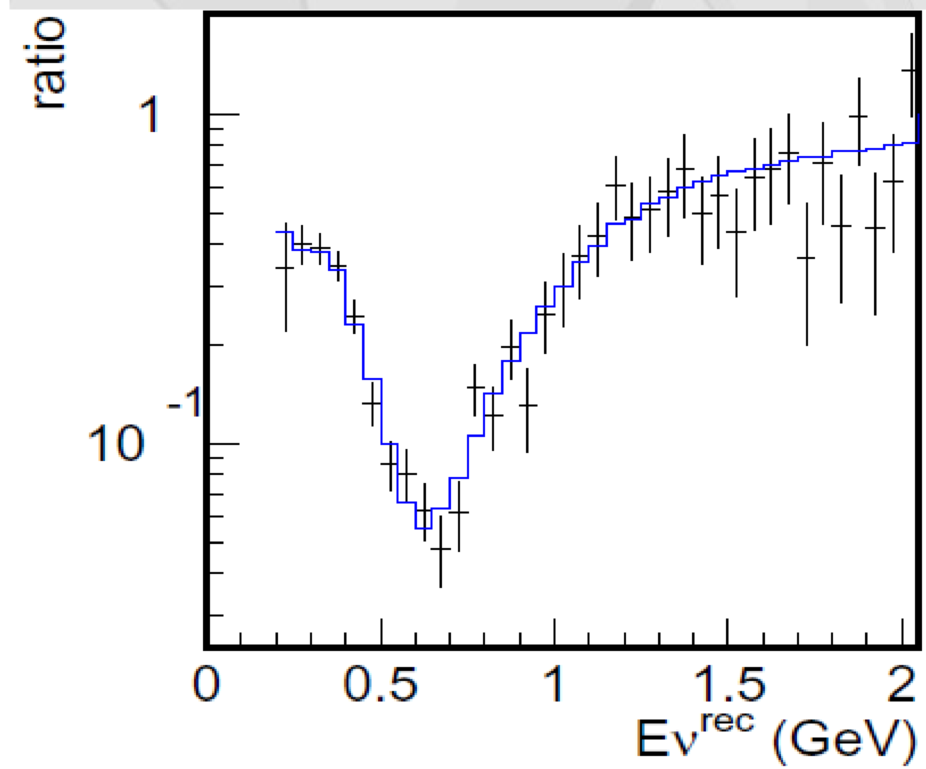
No oscillation
Δm²= 2.5 x10⁻³ eV²
Δm²= 2.0 x10⁻³ eV²
events/50MeV/22.5kt/5yr
~ OA 2.5 deg. ~
non-QE
rec. Eν (GeV)
rec. Eν (GeV)
rec. Eν (GeV)
(assuming sin² 2θ23=1.0)

muon disappearance

<u>Goal of precision</u>

– $\delta(\sin^2 2\theta_{23}) \sim 0.01 \delta(\Delta m^2_{23}) < 10^{-4}\ eV^2$





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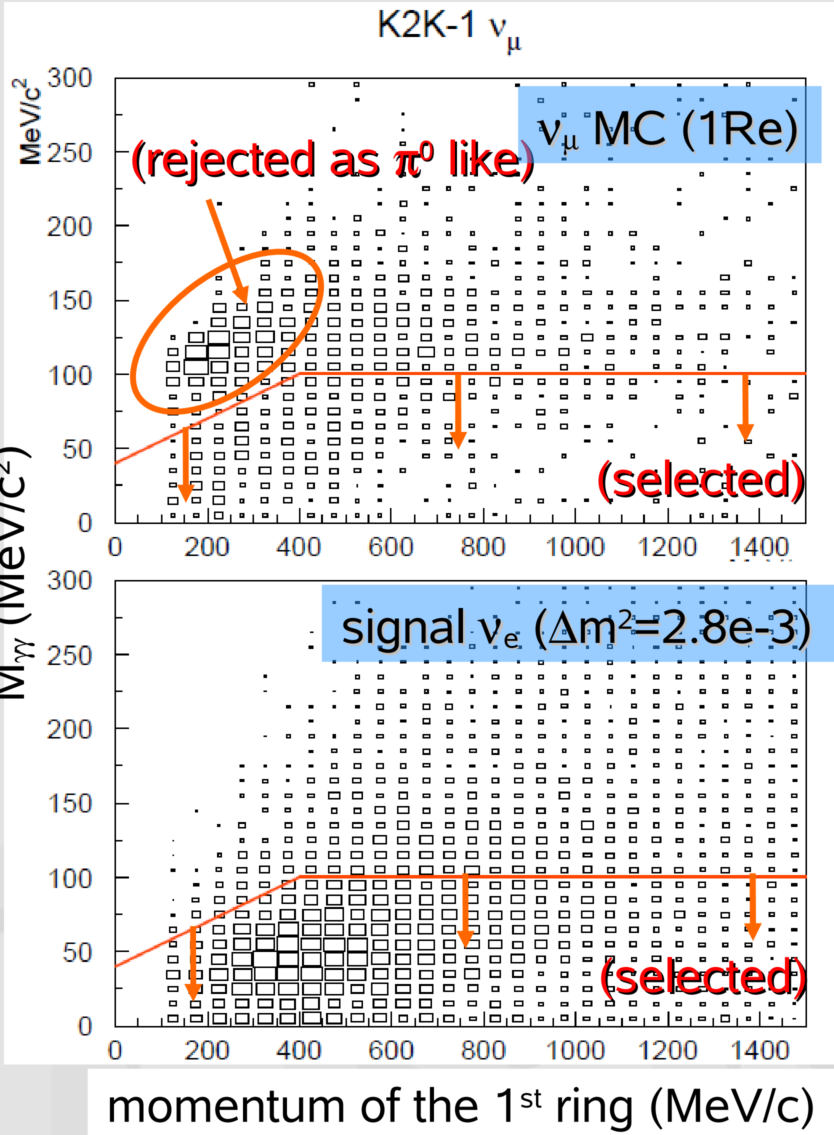
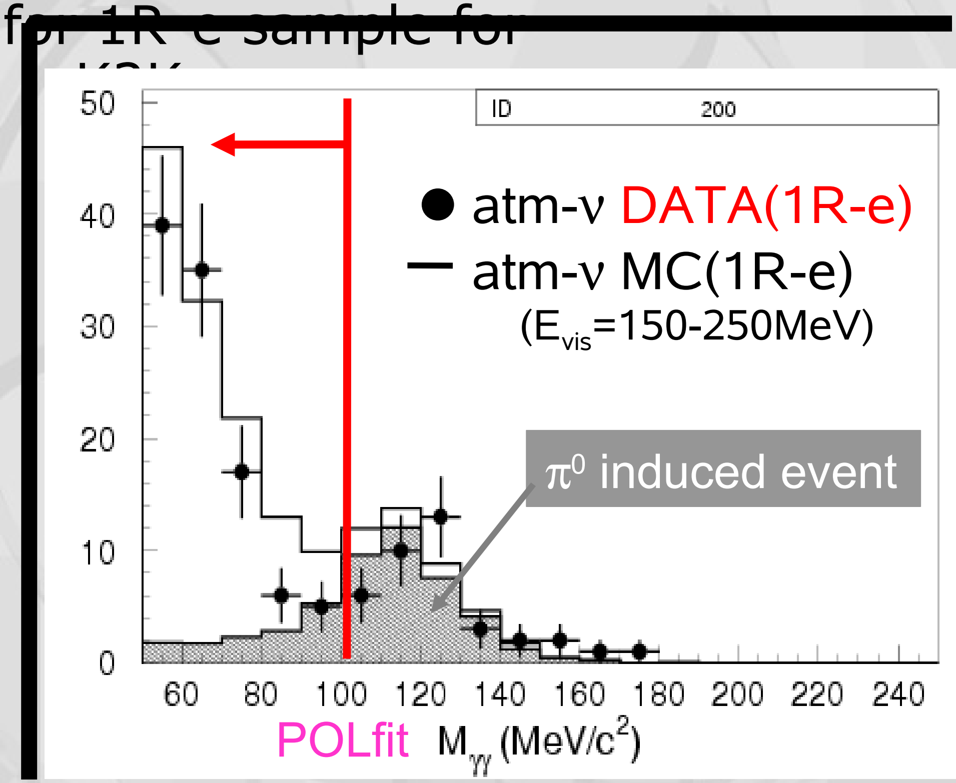
e/π^0 separation @ SK



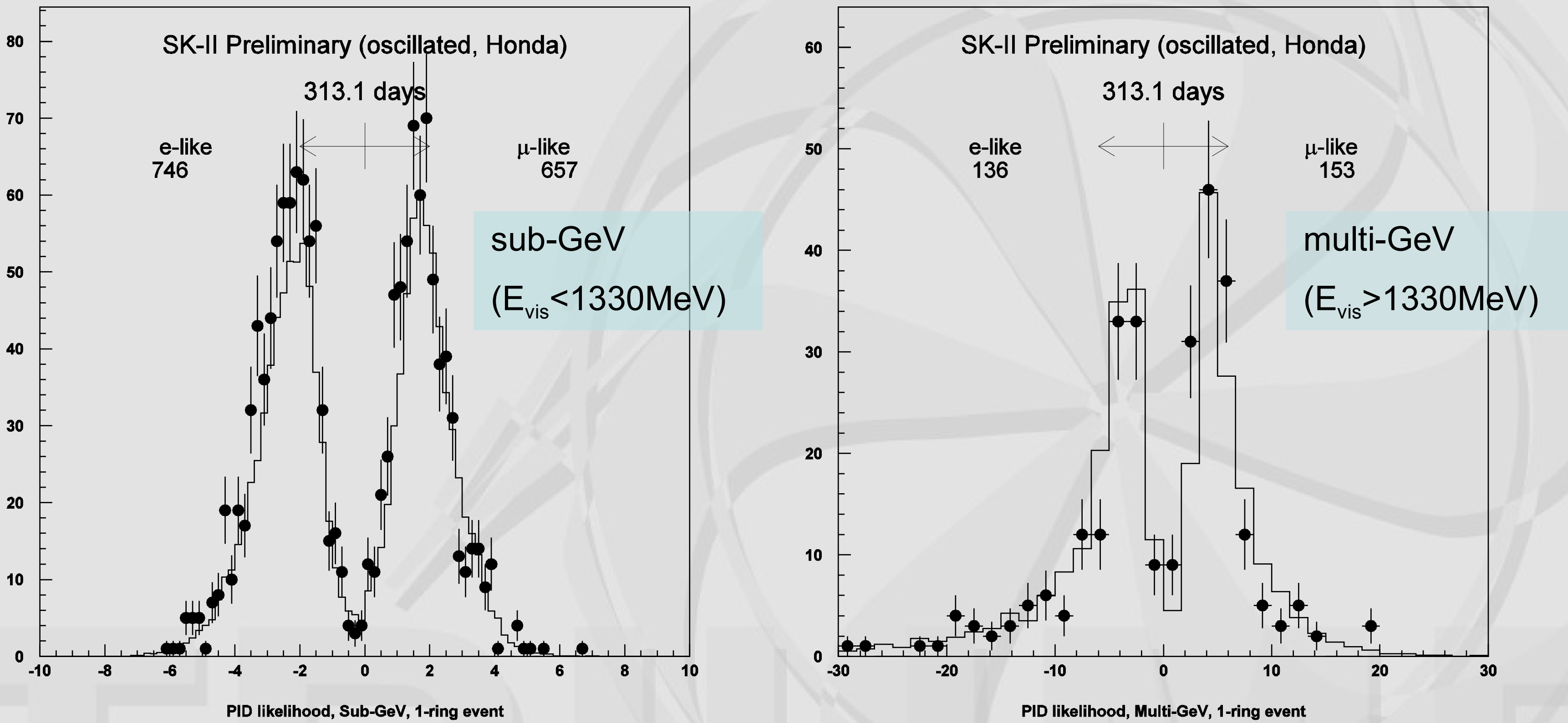
70% π^0 rejection and 30% signal efficiency loss

for 1R e sample for K2K



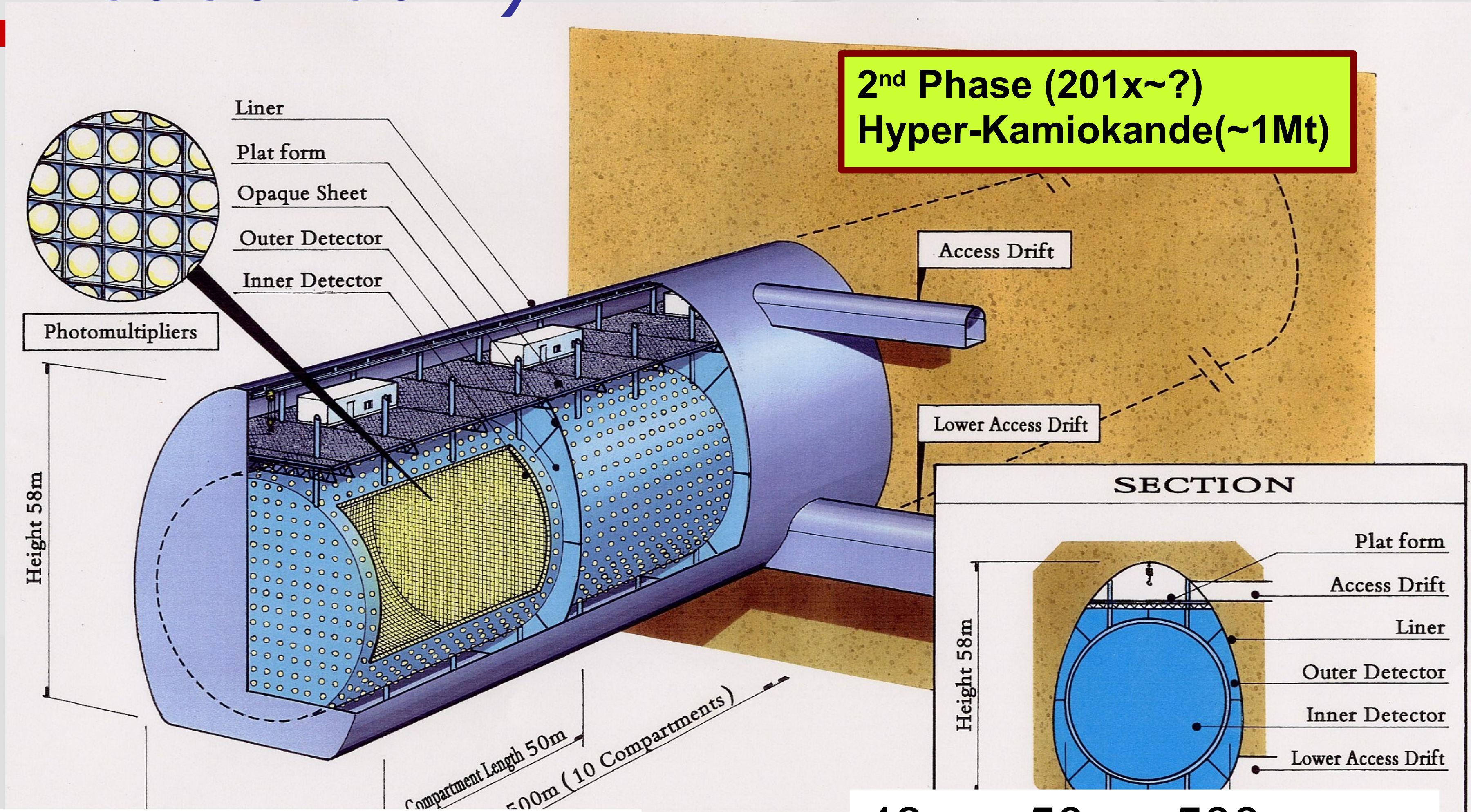
e/μ separation @ SK

- atm-ν DATA(1R)
  - atm-ν MC(1R)



An experiment with test beams also confirmed PID capability: PL B374(1996)238

Phase 2 (if θ_{13} can be measured.)

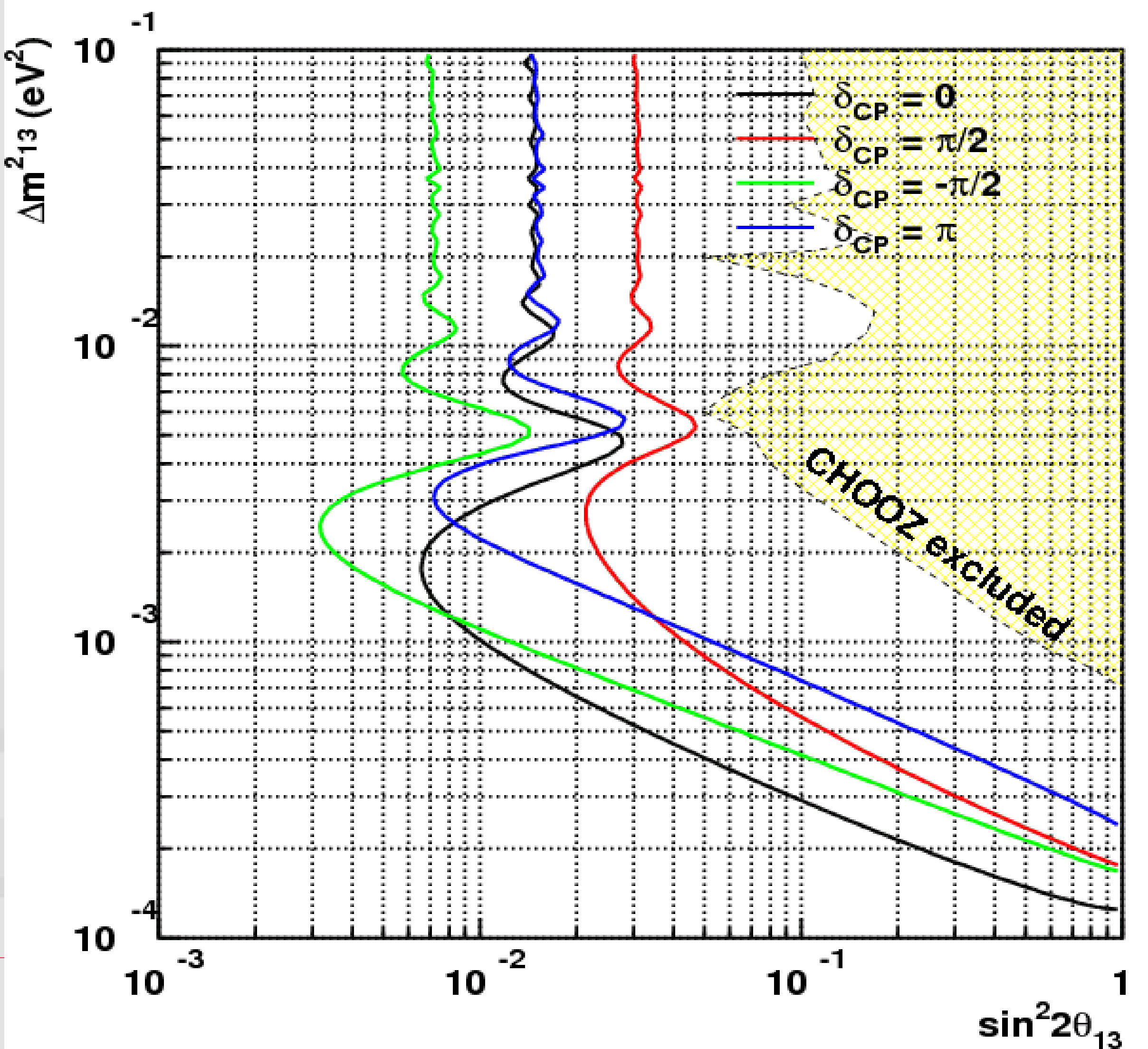


nucleon decay search
CP violation measurement

48m × 50m ×500m,

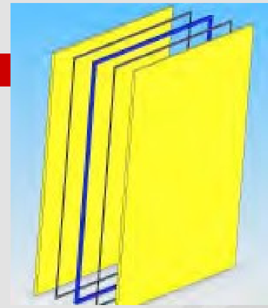
Total mass = 1 Mton

sensitivity to θ_{13}



TRIUMF

ND280 Off-Axis: P0D region



Pi0 detector(P0D)

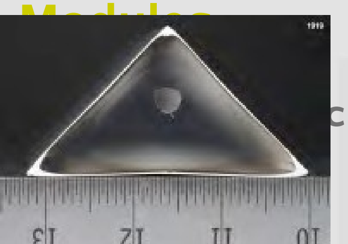
Target

40 X-Y Pb/plastic planes
40% H_20 Passive
6t fiducial mass
10560 total channels

Surrounding Calorimeter (PECAL)

Coarse Pb/Plastic (4x1cm bar)
10cm thick ~5.0X0
γ catcher
MIP tagging
~2k Channels

P0D Up/Central Calorimeters Modules



cker planes