The T2K Experiment

– study of neutrino oscillations –

CAP Congress 2007

on June 18, 2007

at University of Saskatchewan

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(TRIUMF)

Outline

- Introduction
  - Neutrino oscillation so far and near future
- Overview of the T2K experiment
  - Physics goals and experimental apparatus
  - “To be understood” towards the goals
- Primary and secondary beam
- ND280 measurements
  - Mainly from Canadian contributions
- Schedule and summary

Our knowledge of neutrinos, so far

- Neutrino is one of elementary particles in SM
  - (Almost) massless neutral lepton with spin ½
  - Only (or mostly) left-handed neutrinos
  - Three flavors (active neutrinos) below *Z* boson's 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 by Super-K (1998), confirmed by accelerator neutrino experiments, K2K (2004) and MINOS (2006).
    - Solar ν by Super-K + SNO (2001), confirmed by a reactor neutrino experiment, KamLAND (2002, 2004)
  - Therefore, neutrinos have finite mass and flavor mixing!
  - New era of "neutrino flavor physics"!

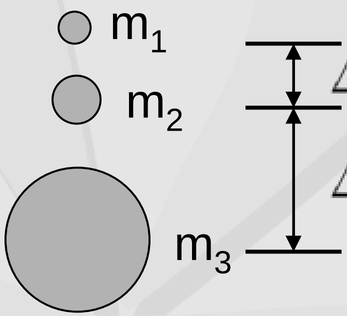
Neutrino flavor mixing

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

Flavor (weak) eigenstate

Mass eigenstate

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



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

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

Atmospheric ν + acc. ν (K2K, MINOS)

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

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

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

Parameters for flavor 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 flavor can change into a neutrino of other flavor once they are mixed, which is called "neutrino oscillation"
  - E.g. in two flavor case for simplicity:

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

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

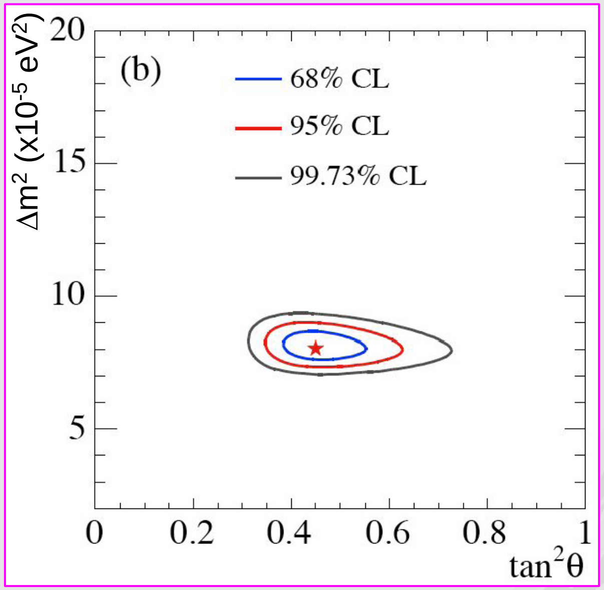
$$P(\nu_\alpha \to \nu_\beta; L) = |\langle \nu_\beta | \nu_\alpha(L) \rangle|^2 = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$

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

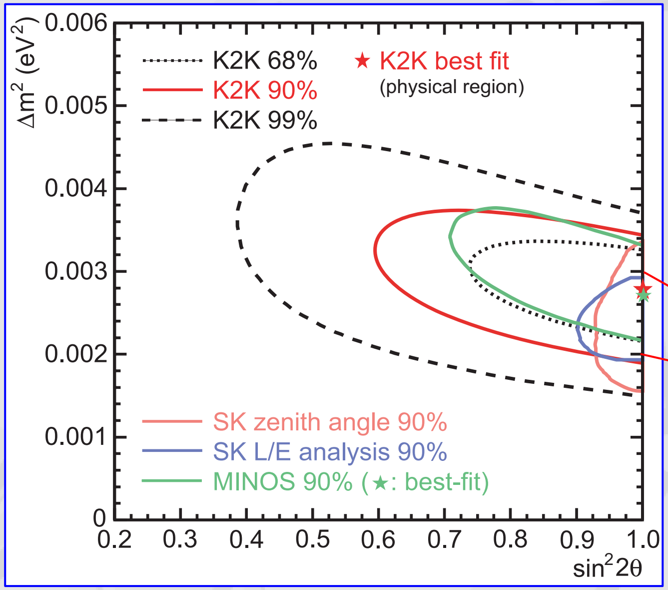
Solar ν region: Δm^2_{12}, θ_{12}



PDG 2006
(Solar + KamLAND
with 2005 SNO NC)

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

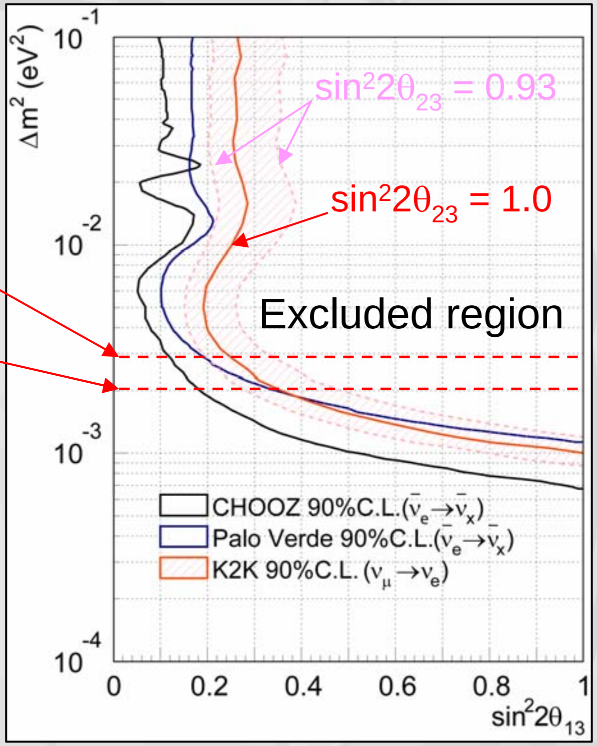
Atmospheric ν region: Δm^2_{23}, θ_{23}



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

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

Δm^2_{13}, θ_{13}



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

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

What's next for the neutrino flavor physics?

- So, current knowledge on the flavor mixing is…

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

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

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

- Next goals to be pursued…
  - Key issues: What is θ_{13}? Is it finite?
    - Search for $\nu_\mu \rightarrow \nu_e$ oscillation

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

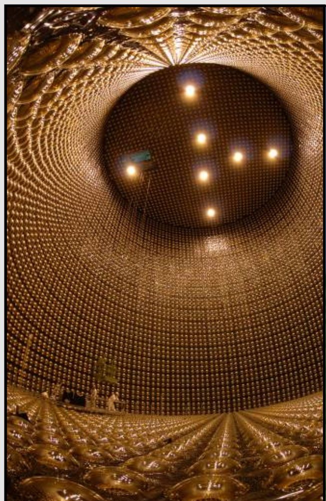
    - Precise measurements for θ_{23}, Δm^2_{23}, …
  - If we find non-zero θ_{13}, then we can go further…
    - Is the CP violated in lepton sector? $A_{\rm CP} \propto P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)$
    - What is the neutrino mass hierarchy? Is $\Delta m^2_{13} < 0$ or > 0?

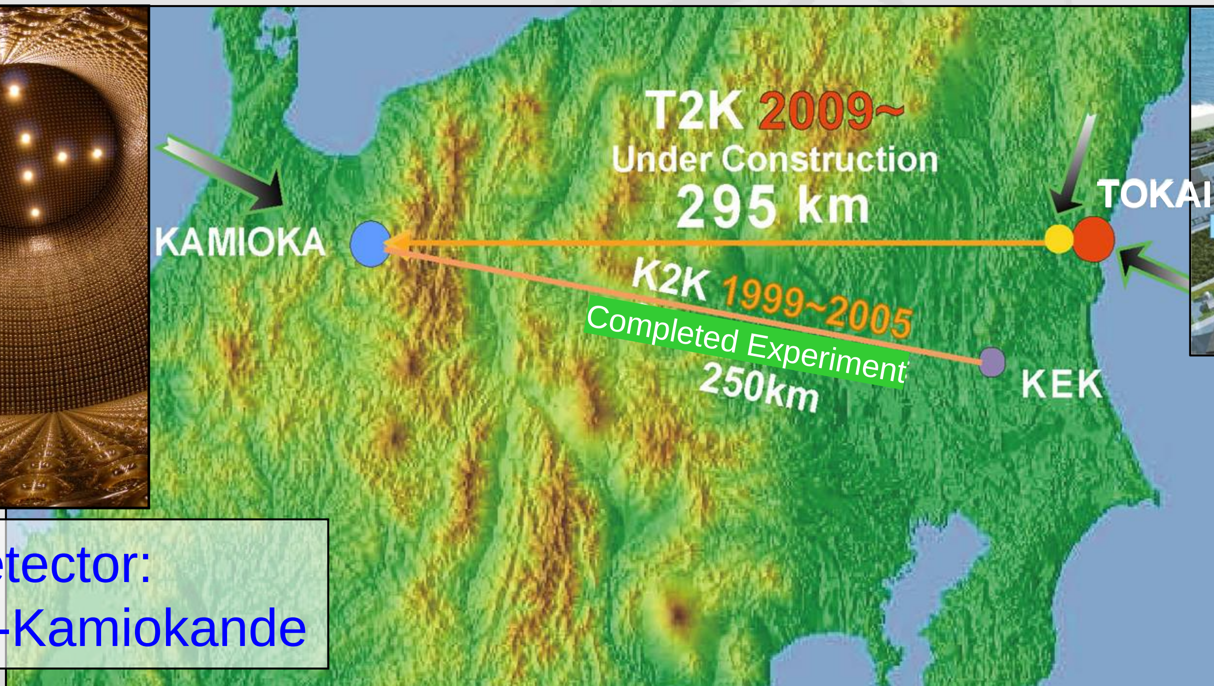
The T2K experiment

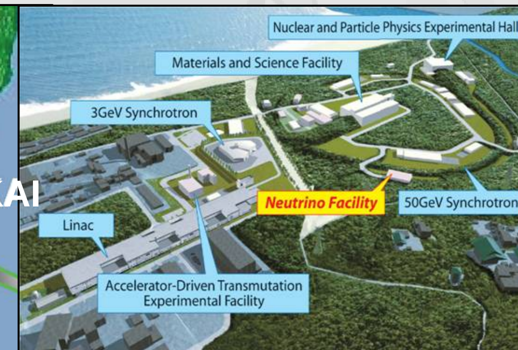
Next generation long baseline neutrino experiment

Neutrino beam from Tokai to Kamioka

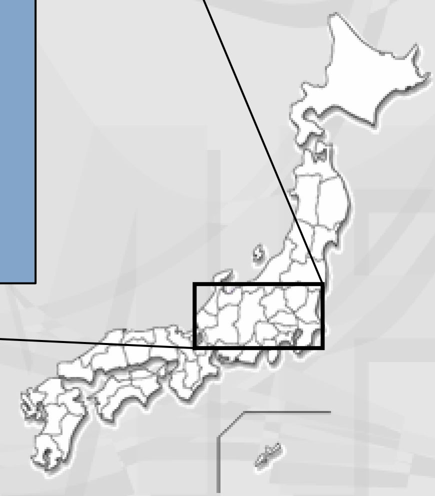
Neutrino beam using
a new accelerator at J-PARC







Far detector:
Super-Kamiokande

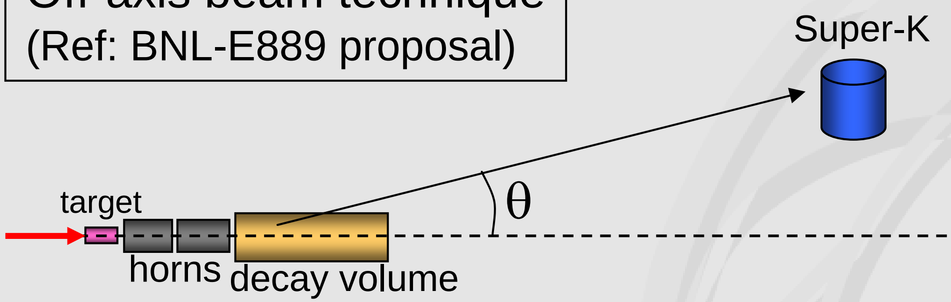


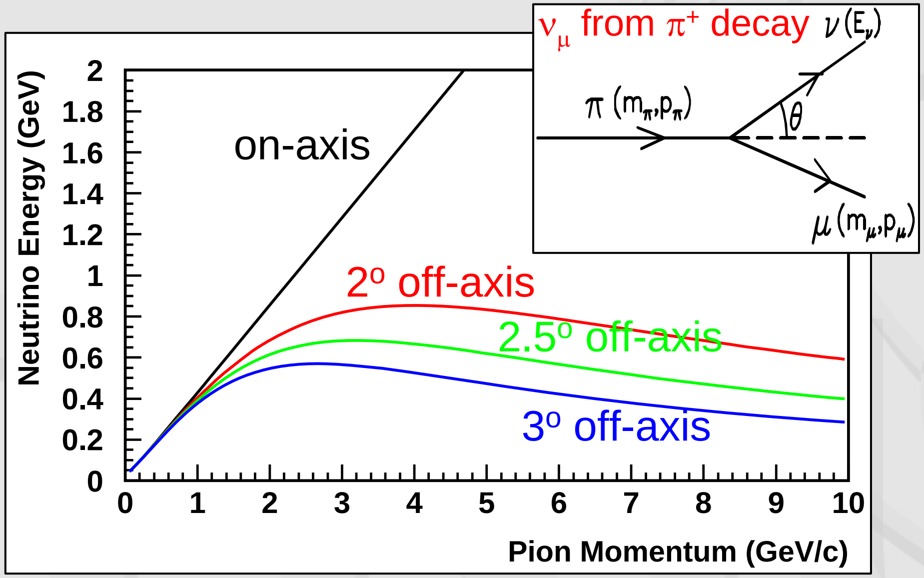
T2K collaboration

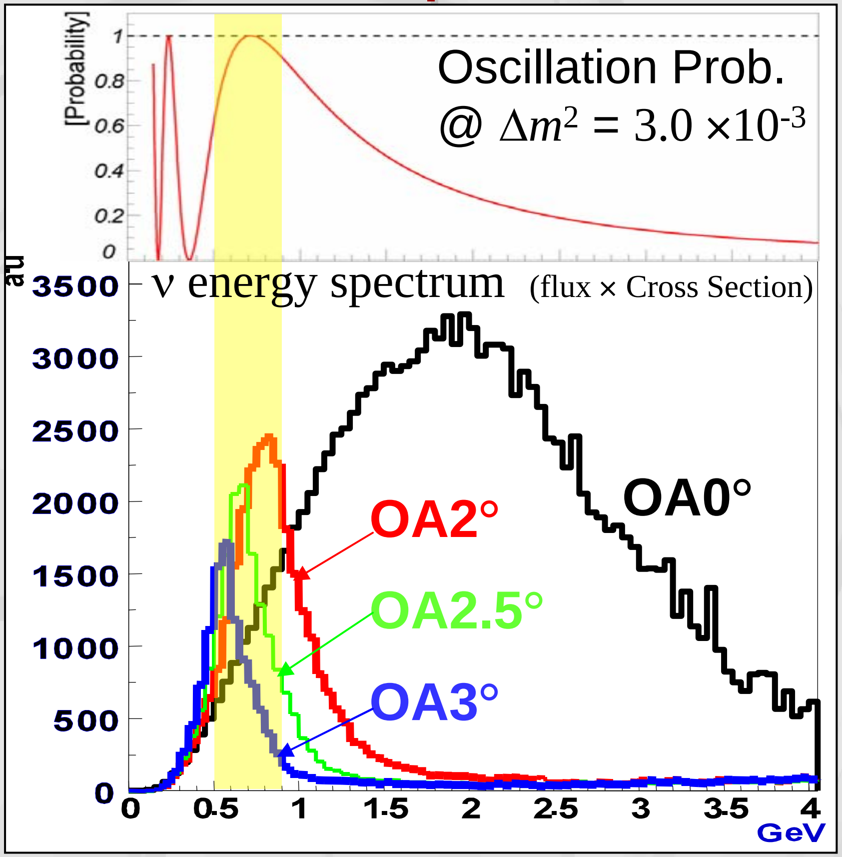
- ~350 members from 12 countries:
  – Japan(66), US(58), Canada(50), France(38), UK(37) Switzerland(31), Poland(22), Korea(13), Russia(12), Spain(11), Itary(9), Germany(2)

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

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



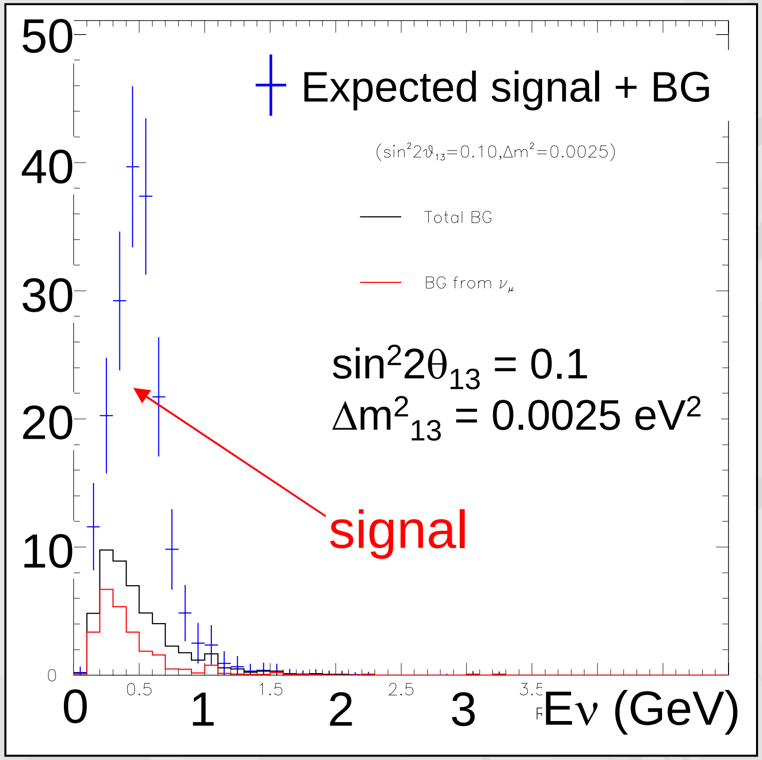


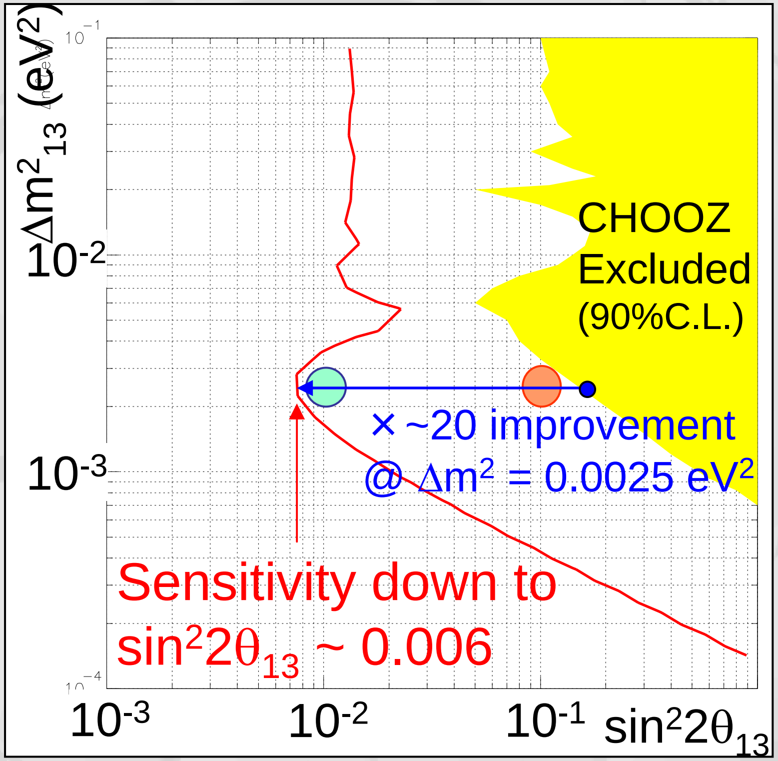


- Quasi-monochromatic energy
- 2–3 times more intense than conventional narrow band beam
- Tuned at oscillation maximum
- Almost pure (> 99%) ν_μ beam

The goals of T2K – ν_e appearance

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



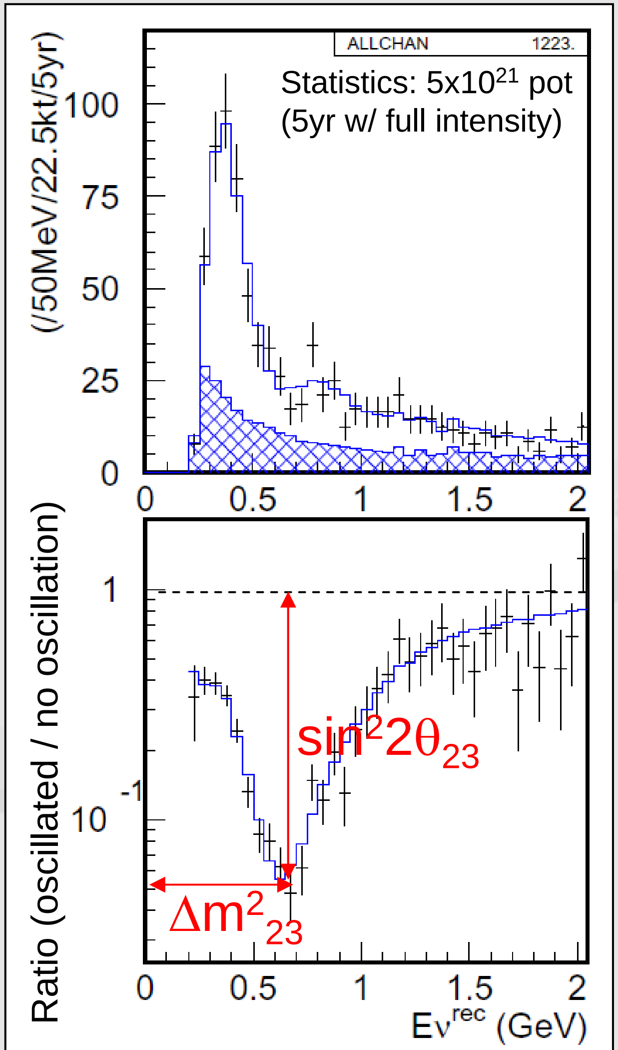


$\sin^2 2\theta_{13}$	Backgrounds			Signal	Signal + BG
	ν_μ induced	Beam ν_e	total		
0.1	10	13	23	103	126
0.01				10	33

(5 years)

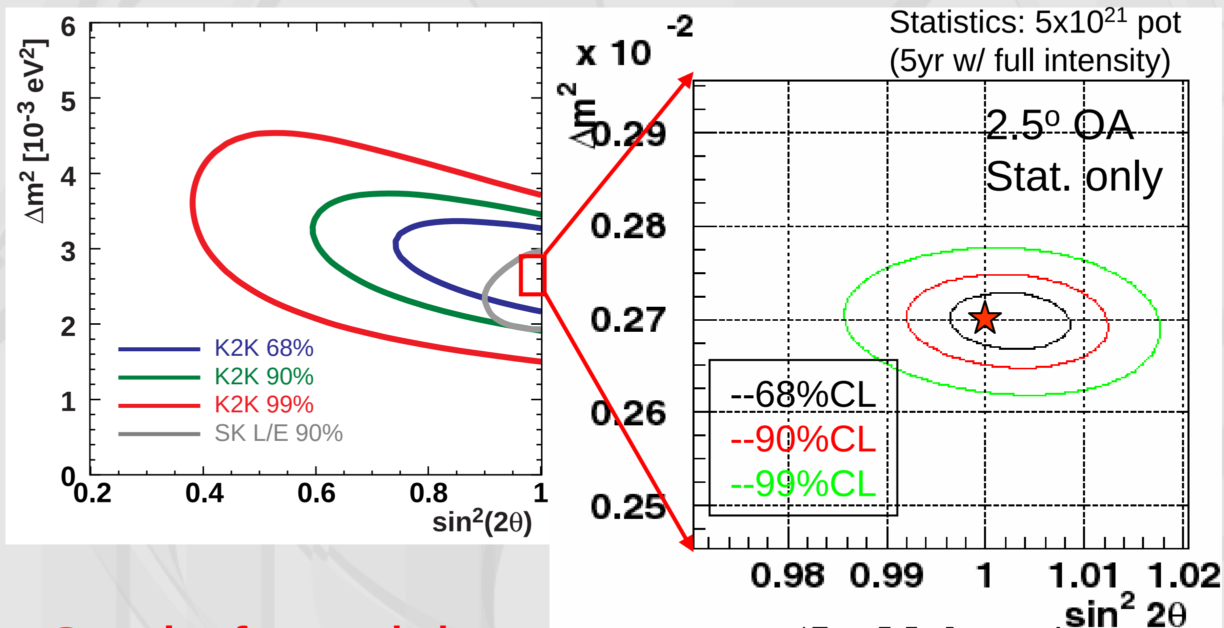
The goals of T2K – ν_μ disappearance

- Precise measurements of ν_μ disappearance



To be measured:

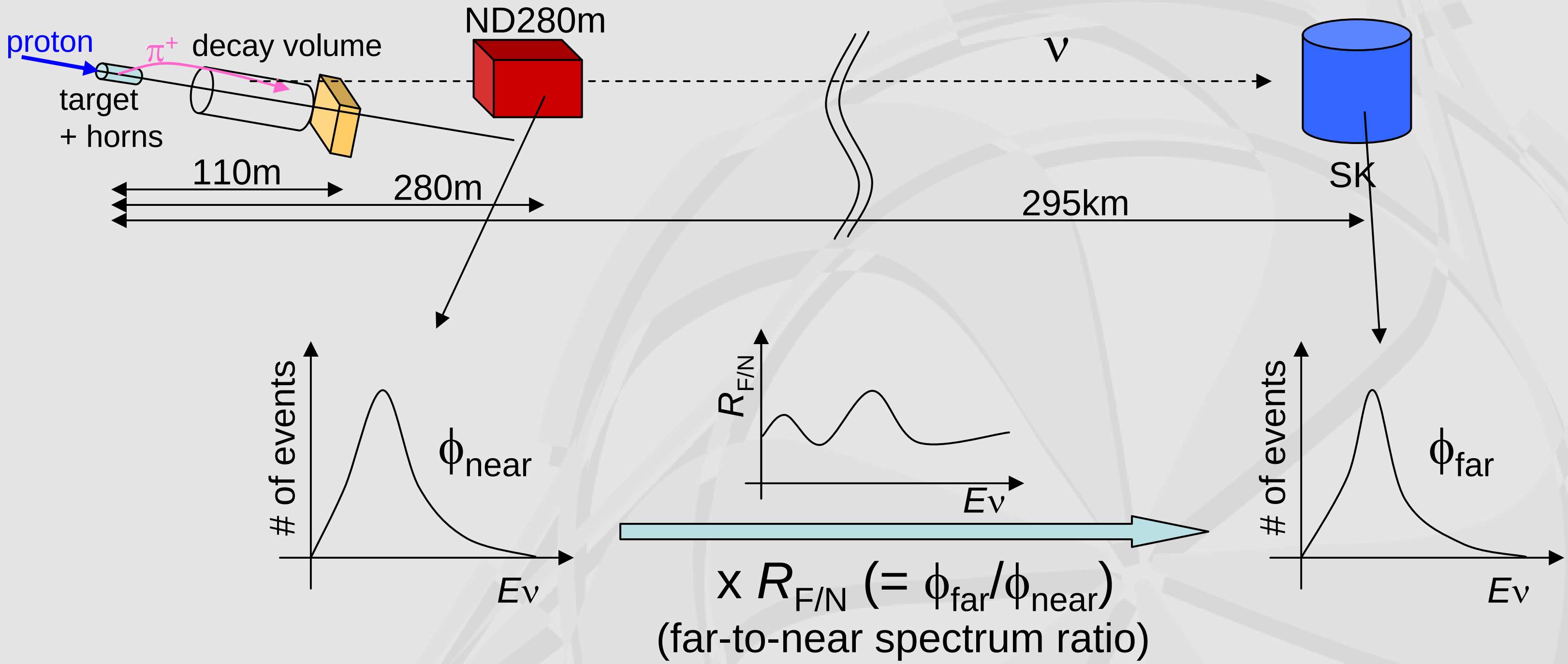
- Oscillation pattern in the energy spectrum
- In particular, re-appearance in low energy region



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

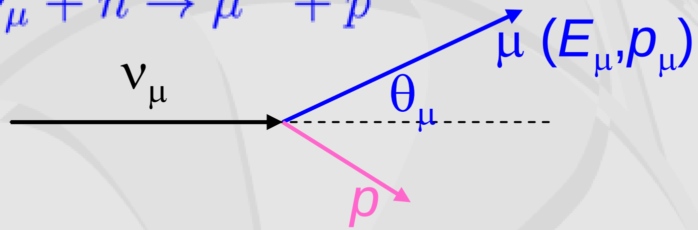
} Key issues!!

Neutrino energy measurement

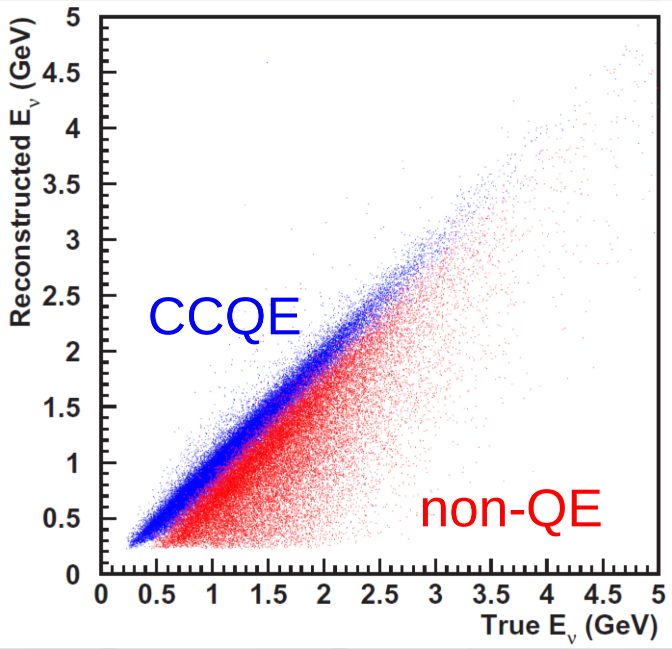
- Use CCQE interaction to reconstruct the energy

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

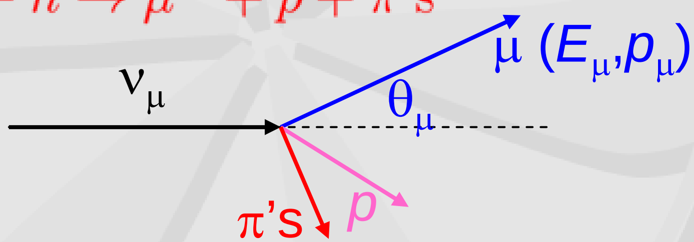
$$\nu_\mu + n \to \mu^- + p$$



- 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)

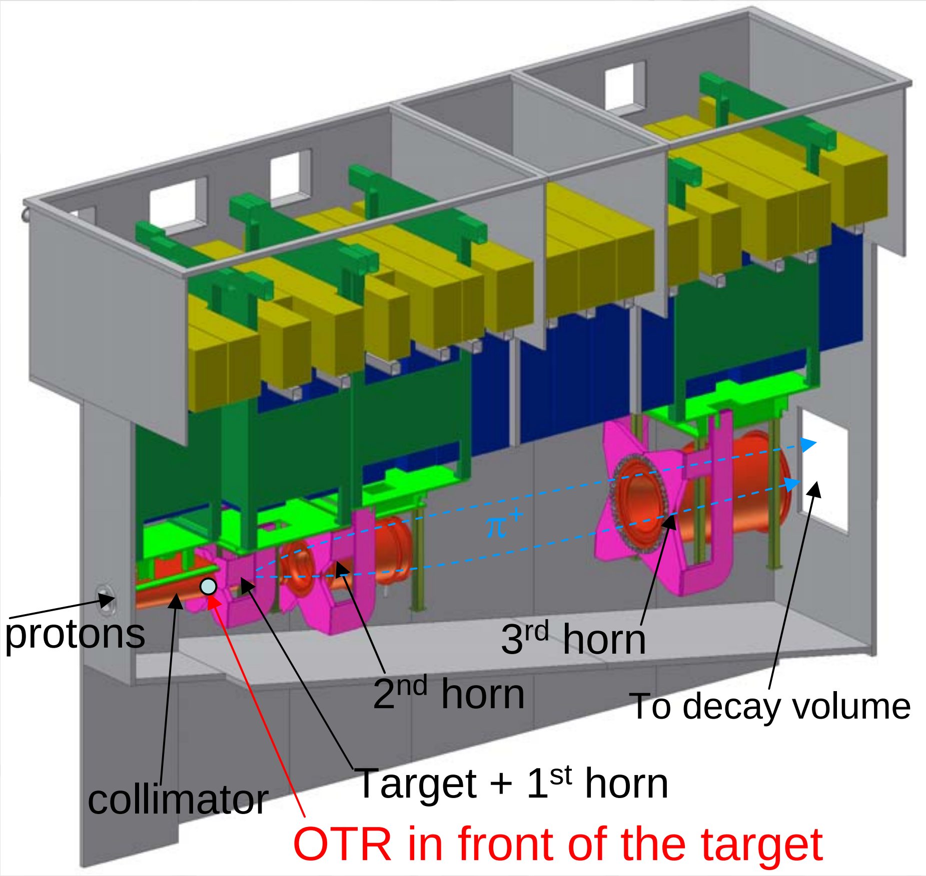
What we need to do to achieve the goals…

- 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

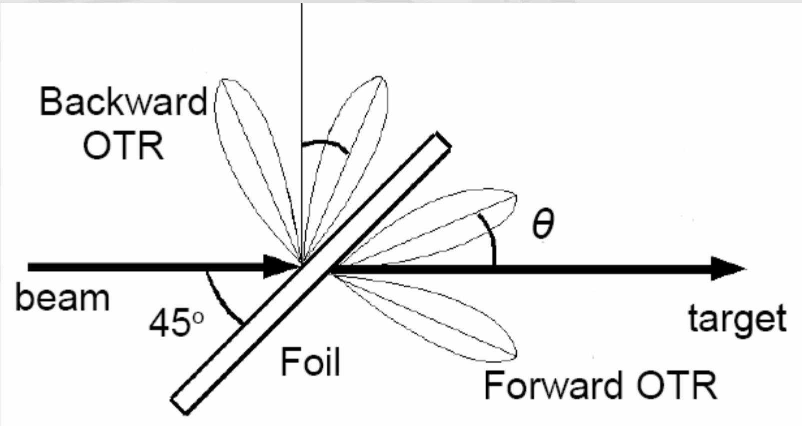
Understanding the primary proton beam

- Primary proton steering:
  - Variation in beam injection into the target changes secondaries' direction, hence the neutrino beam.
  - Measure proton position at target to 1 mm precision:
    - Neutrino energy peak shifts by 2.2 MeV/mm
    - Flux changes by 0.6%/mm
- Optical Transition Radiation (OTR) beam monitor just in front of the target
  - Measure proton position and profile at target
  - Canadian contribution: U of Toronto, York U, TRIUMF



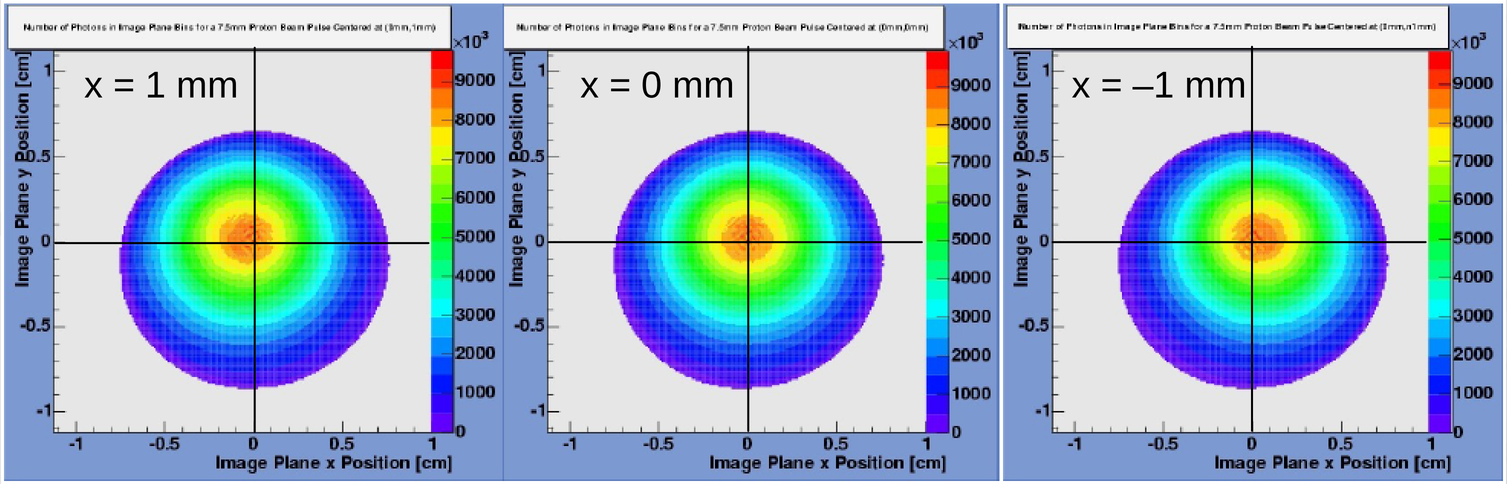
Optical transition radiation beam monitor

- Transition radiation photons are emitted when charged particles pass through a foil.
  - Light yield: ~10^{11} photons/pulse (~10^{14} protons)
  - Read out by optical system
  - 2D image available



- Ray trace simulation of optics shows that:
  - 1mm shift in proton beam position is reconstructable.
  - Simulation is validated by table top optics system

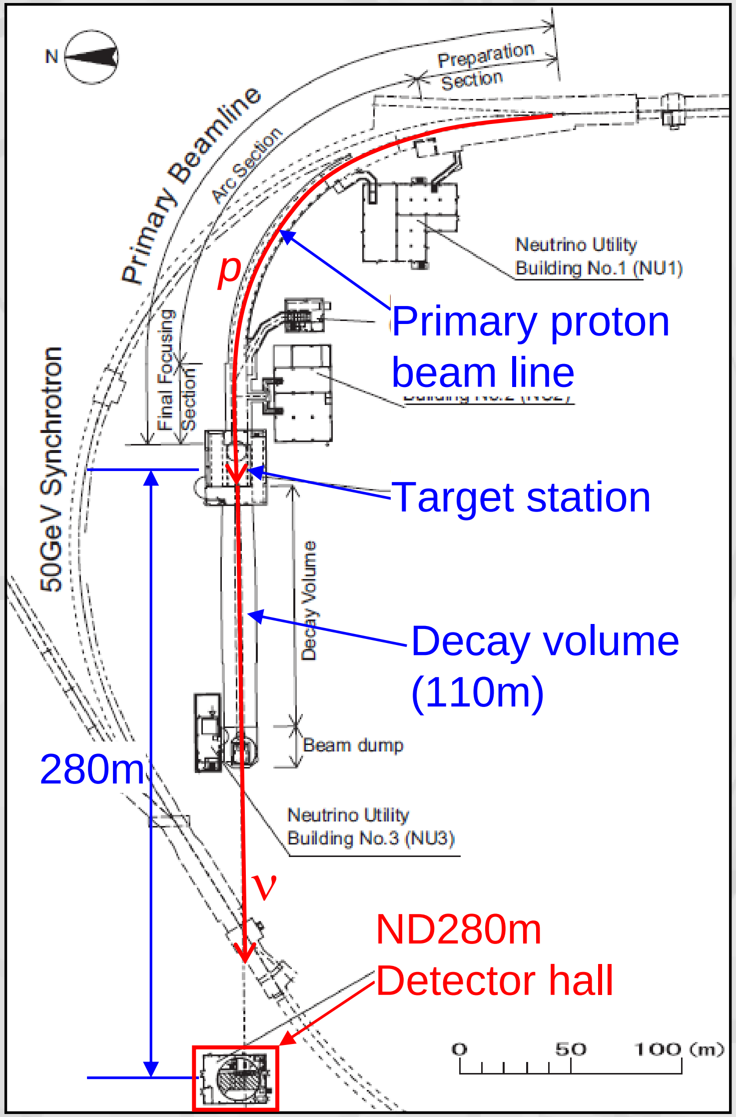
See A. Marino's talk for OTR (Wed. afternoon)



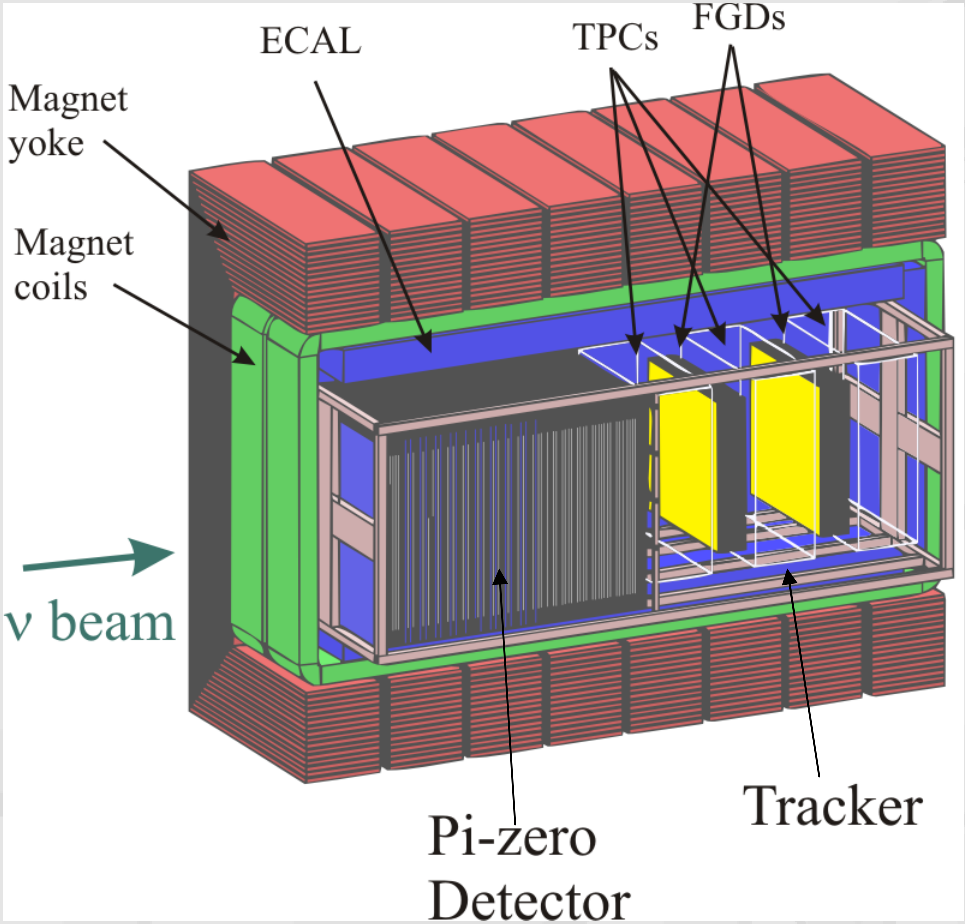
Understanding the neutrino beam properties

Detector complex at 280 m downstream of the target

- On-axis detector: INGRID
  - Monitor the neutrino beam direction
- Off-axis detectors
  - Neutrino flux
  - Neutrino energy spectrum
  - Beam ν_e component
  - Cross-sections for the background processes
    - To study the bias on energy spectrum measurements at ND and SK



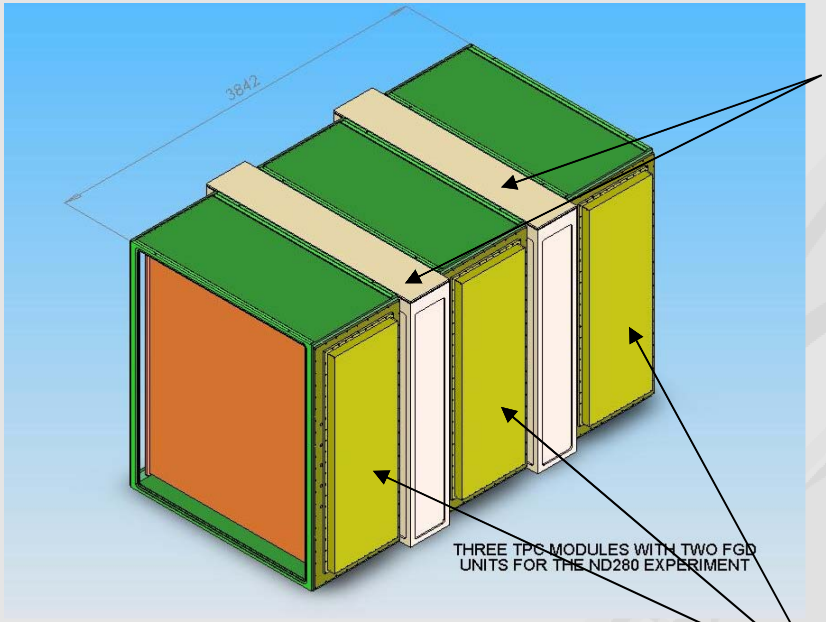
Off-axis detector

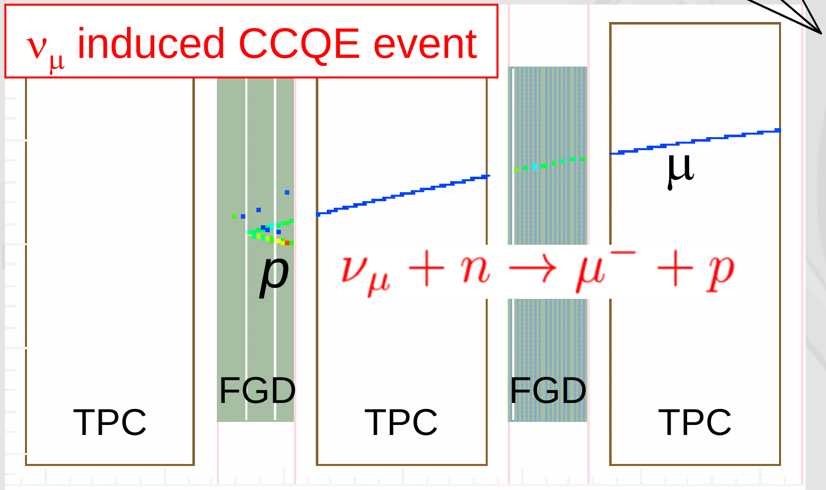


- Pi-zero detector (P0D)
  - To study NCπ^0 production with high statistics
- Tracker
  - To study CC interactions
  - Measure the ν spectrum
- ECAL
  - Detect the EM components from tracker and P0D
  - For π^0 and ν_e studies
- SMRD
  - To measure the energy of μ going sideway
- Housed in UA1 magnet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

The tracker: FGDs + TPCs

Canadian contribution: UBC, UVic, U of Regina, TRIUMF





- 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

  T. Lindner's talk (Wed. morning)
  B. Kirby's talk (Wed. morning)

- 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 (p/μ,π/e)

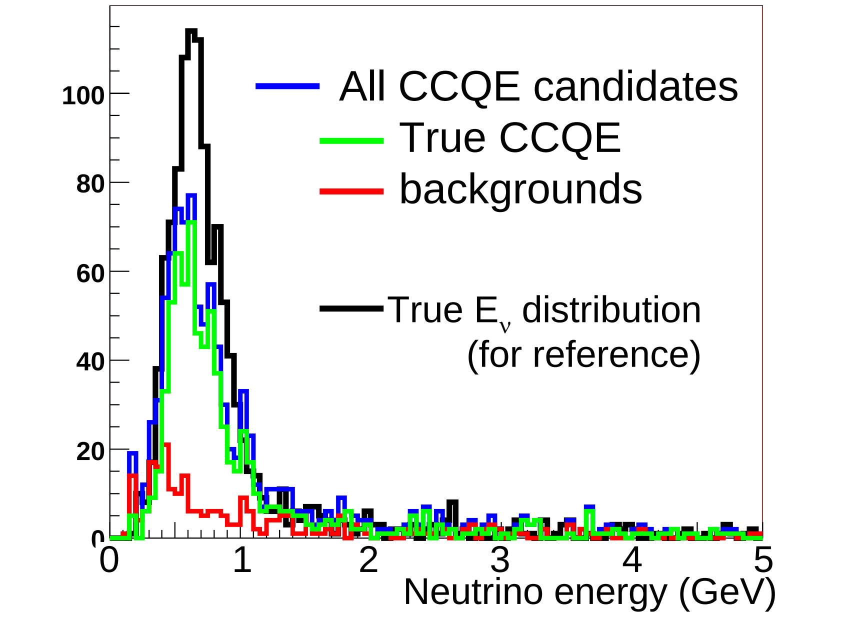
  K. Fransham's talk (after this talk)

ν_μ CCQE measurement in tracker

Preliminary study on CCQE efficiency/purity has been done by using "smeared MC truth" information

- CCQE: $\nu_\mu + n \rightarrow \mu^- + p$
  - Only μ^- and *p* exist in the final state.
  - But, most of B.G. processes contain pions (e.g. CC-1π, CC-multi-π).
- Selection criteria for ν_μ CCQE:
  1. Only one negative track detected in TPC (μ candidate)
  2. No positive π^+/e^+ like track in TPC
  3. No Michel electron in FGD (veto $\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$ decay)
  4. No γ with E > 67 MeV in ECAL (veto $\pi^0 \rightarrow 2\gamma$)

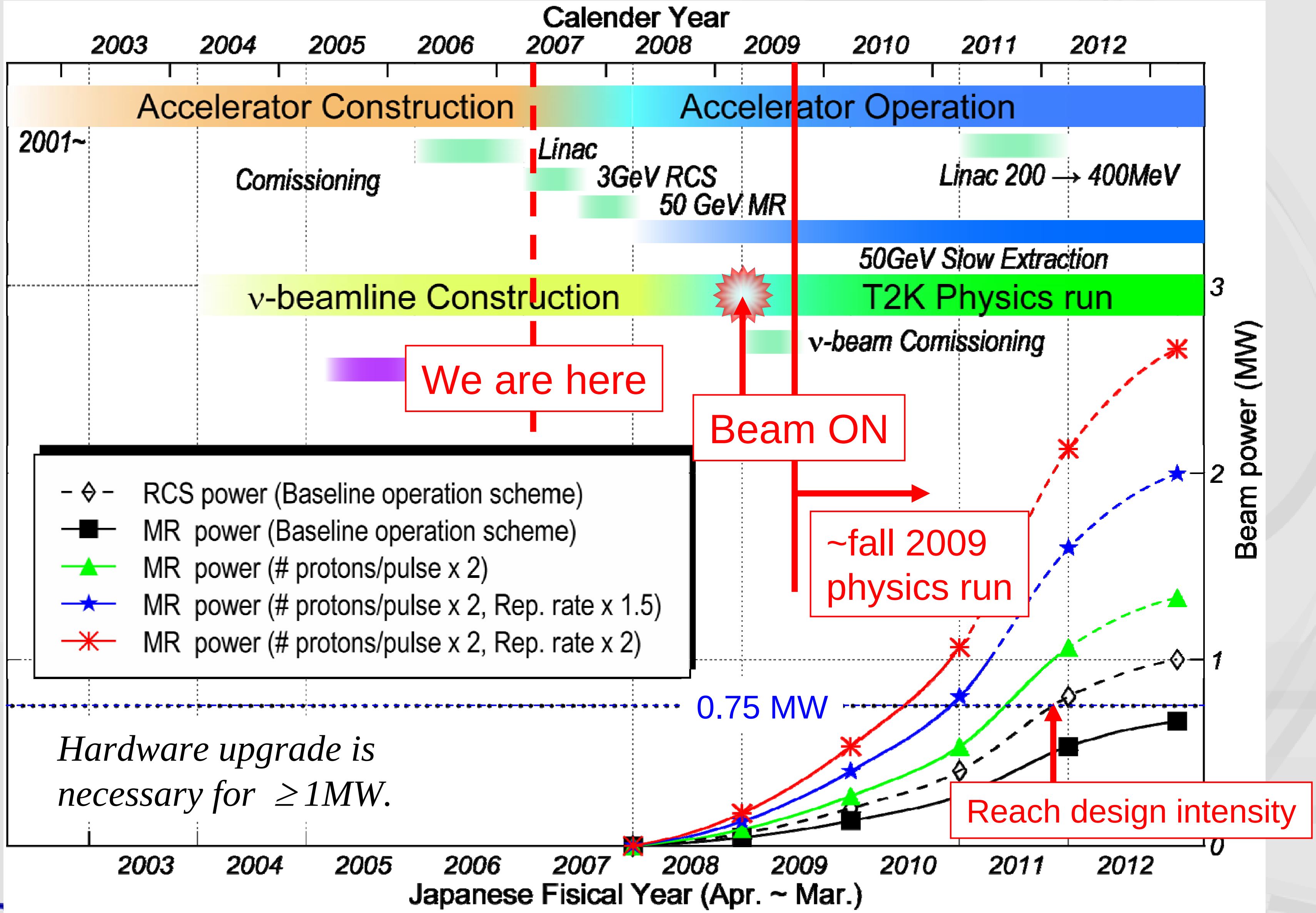
Reconstructed energy spectrum for CCQE candidates



With a set of simple and robust cuts, CCQE can be selected with relatively high efficiency and purity.

- Similar studies for CC-1π^+, NC-1π^+ and ν_e CCQE selections in progress
- Real reconstruction algorithms under development.

T2K time line and possible beam operation



J-PARC accelerator and neutrino beam line under construction

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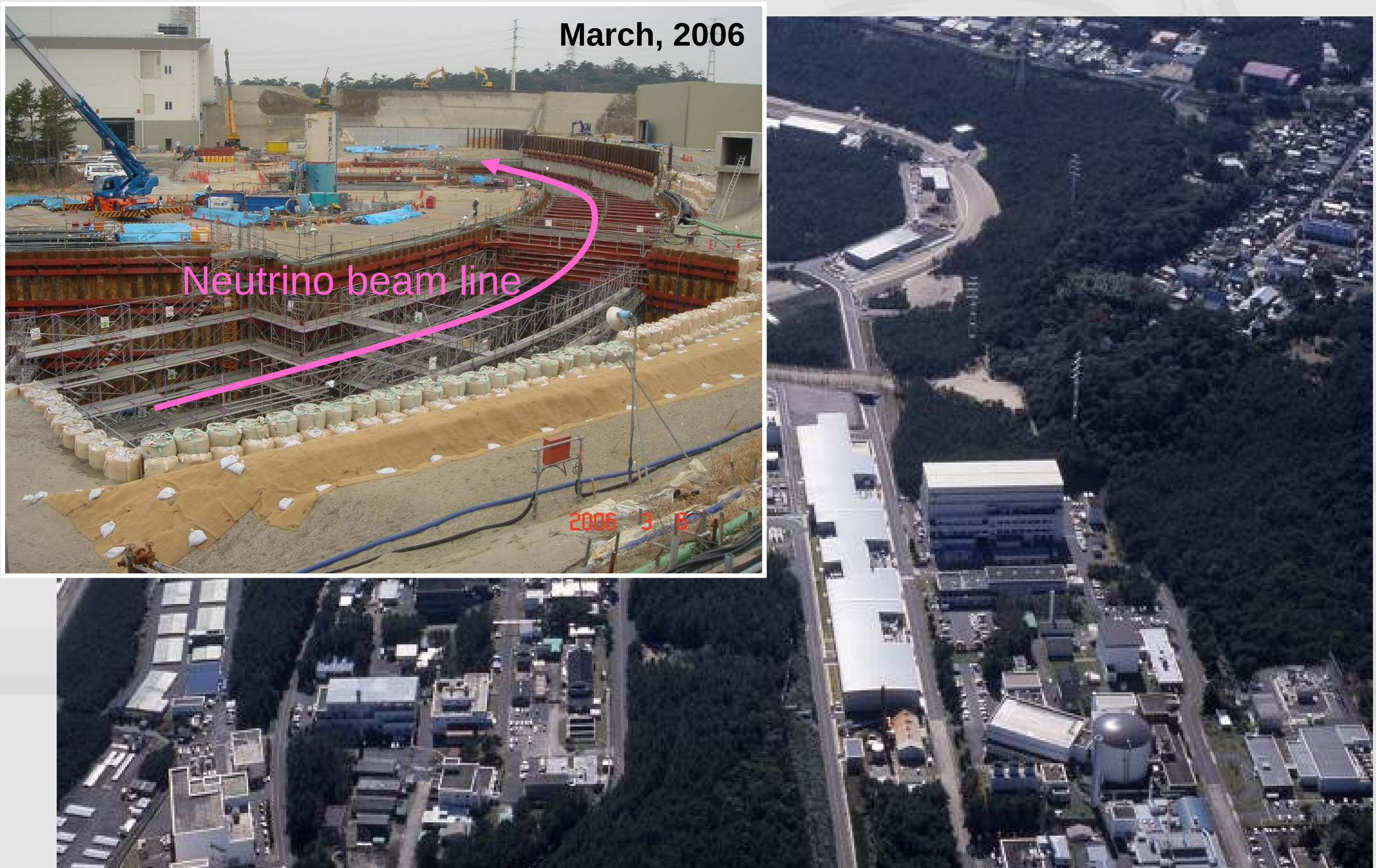

J-PARC accelerator and neutrino beam line under construction

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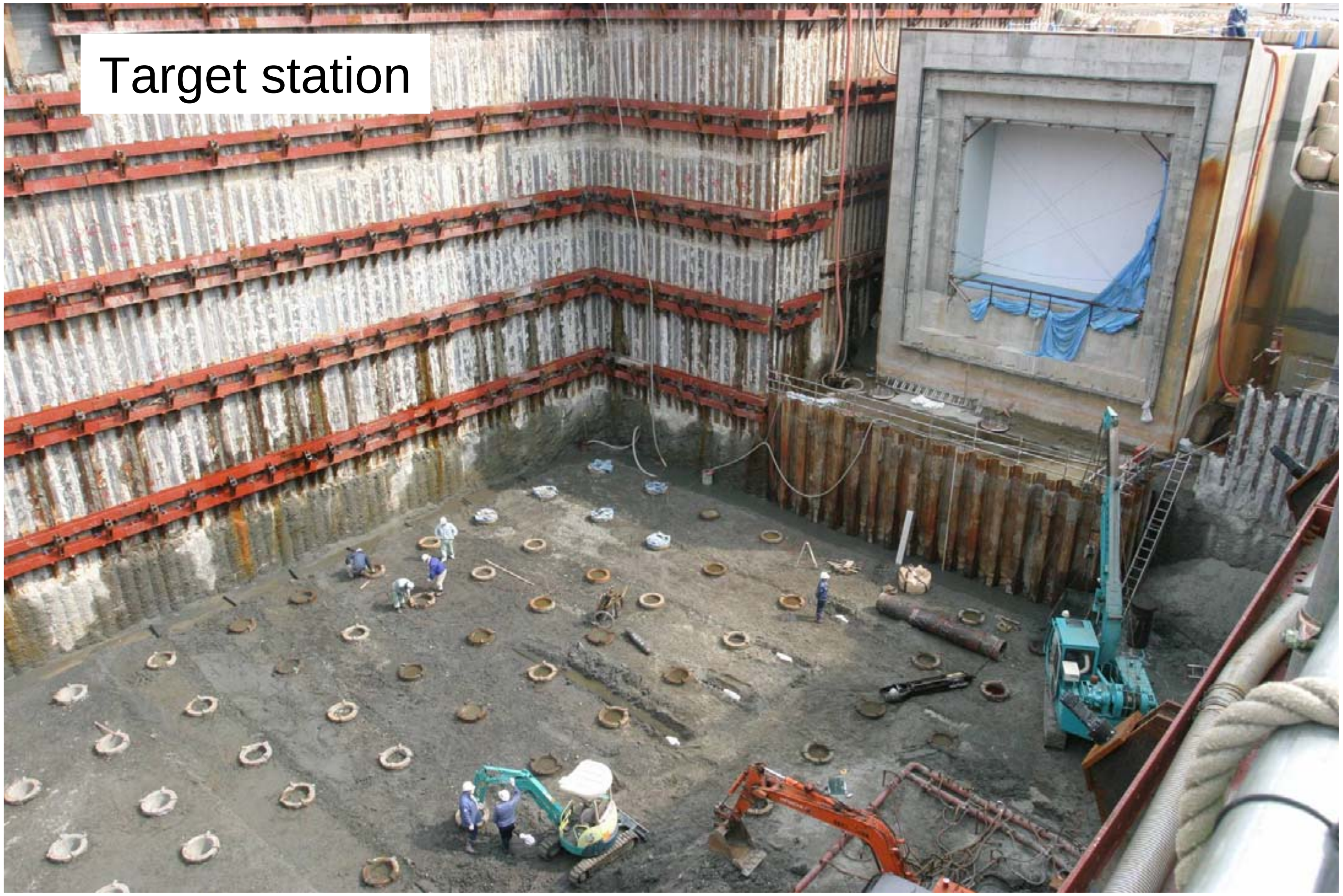
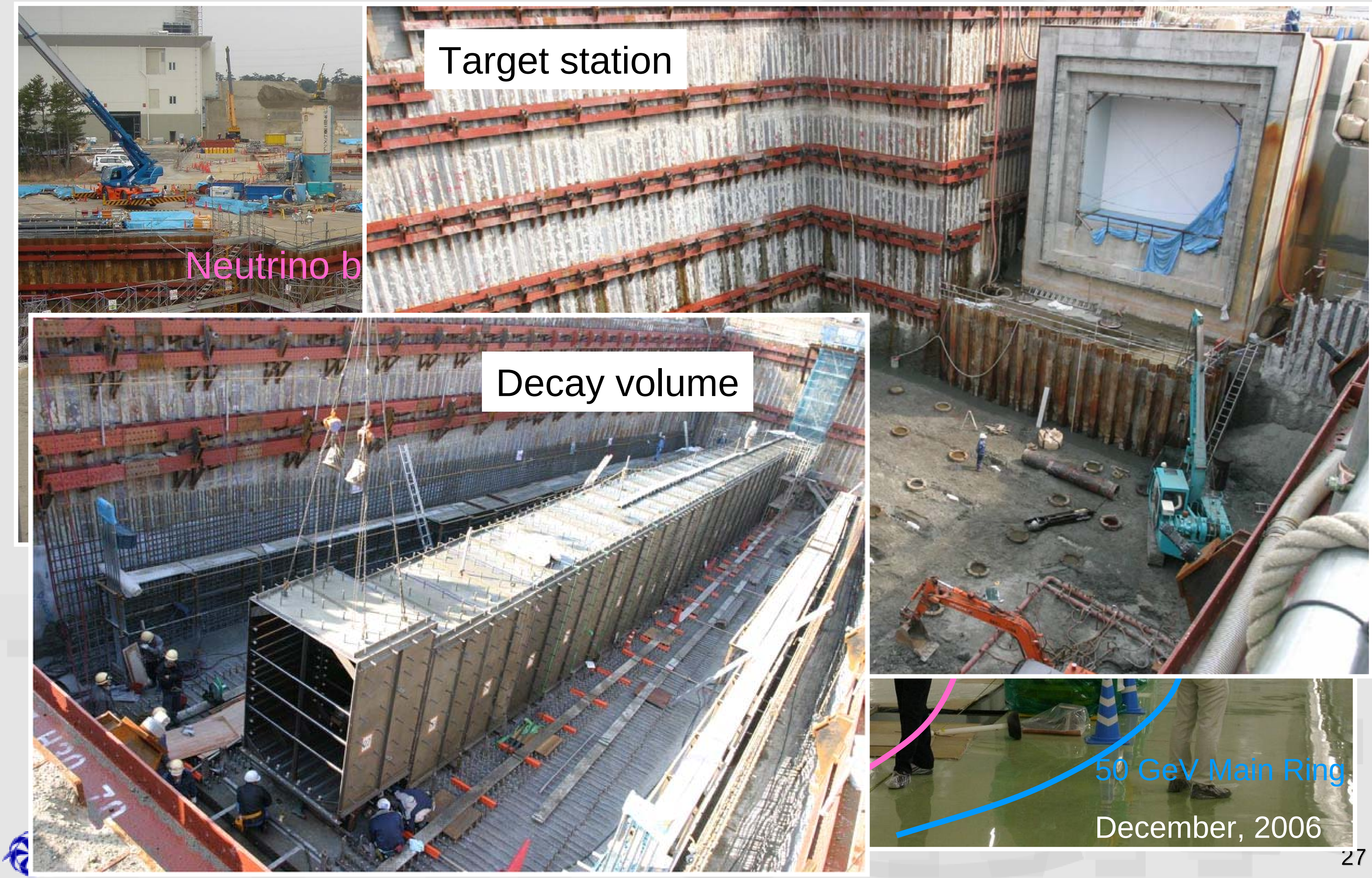
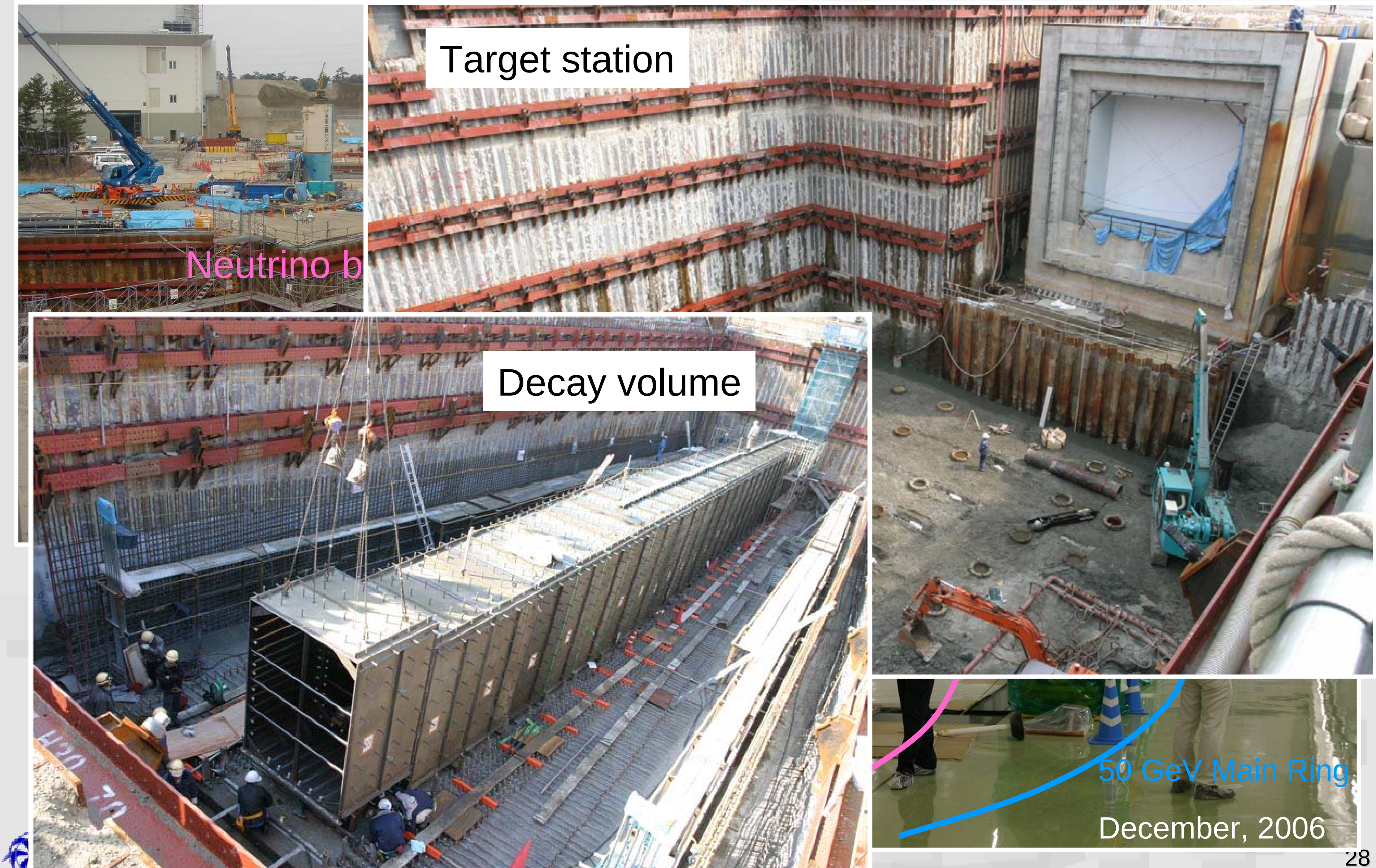


J-PARC accelerator and neutrino beam line under construction



J-PARC accelerator and neutrino beam line under construction



Summary

- Neutrino oscillations have been established in late 1990's and early 2000's
- The next is to measure oscillation parameters precisely and search for non-zero θ_{13}.
- T2K experiment will do the job!
  - To measure the Δm^2_{23} and θ_{23} to a few % precision
  - To search for non-zero θ_{13} down to $\sin^2 2\theta_{13} \sim 0.006$
- J-PARC / T2K status:
  - Accelerator and beam line being constructed.
  - Detector design finalized, being constructed.
  - Beam will start in 2009