Status of the T2K experiment

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2007/June/13, DBD07

1. Introduction
2. T2K experiment
   - Features and Prospects
   - Hadron-production measurement
3. Short summary of the construction status
4. Summary

Neutrino oscillation

- neutrino flavor mixing

flavor eigenstates — mass eigenstates

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

(Simplified two-flavor case)

$\Delta m^2 = m_1^2 - m_2^2$ in eV^2 — traveling distance in km

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left[\frac{1.27\Delta m^2 L}{E_\nu}\right]$$

neutrino's energy in GeV

$$U_{\alpha i} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

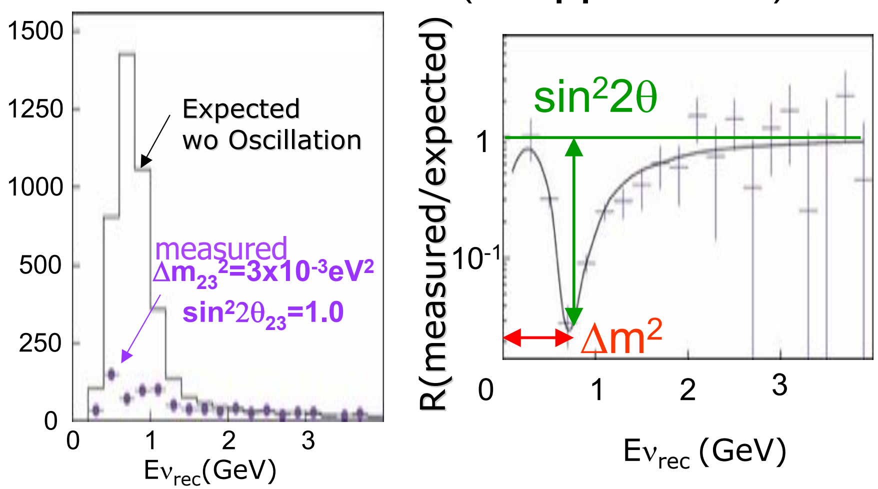
- **Reduction of ν_α**
- **Distortion of $E_{\nu\alpha}$ spectrum**
- **Appearance of ν_β**

Observed by several experiments

⇩

Neutrino has mass and its flavor is mixing

Fixed distance (disappearance)



Three flavor mixing

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \mathrm{diag}(1, e^{i\alpha}, e^{i\beta})$$

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

$$\Delta m_{12}^2 + \Delta m_{23}^2 + \Delta m_{31}^2 = 0$$

- present knowledge

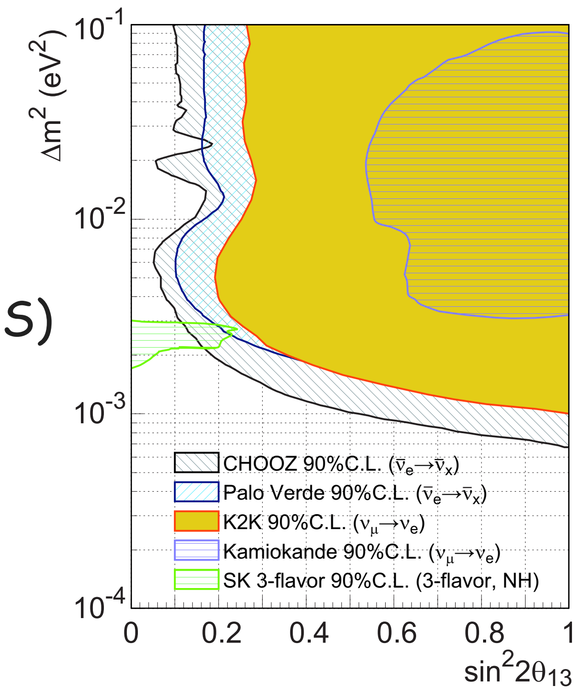
$\Delta m^2_{solar} = 8 \times 10^{-5}$ eV^2
$\sin^2(2\theta_{12}) = 0.86$
(KamLAND + solar ν)

$\Delta m^2_{atm} = (2.2 \sim 3.0) \times 10^{-3}$ eV^2
$\sin^2(2\theta_{23}) > 0.92$
(SK atm.-ν, K2K,MINOS)

$\sin^2(2\theta_{13}) < 0.15$
@$\Delta m^2 = 2.5 \times 10^{-3}$eV^2
(CHOOZ)

δ : unknown

sign(Δm^2_{atm}) : unknown



What does T2K aim for ?

1. discovery of a finite θ_{13}

- open the possibility to measure CPV phase δ
- important interplay with mass ordering and $0\nu\beta\beta$

$$|m_{ee}| \equiv \left| \sum_i m_i U_{ei}^2 \right|$$

effective mass

$U_{e3} = s_{13}e^{-i\delta}$

NEUTRINOS

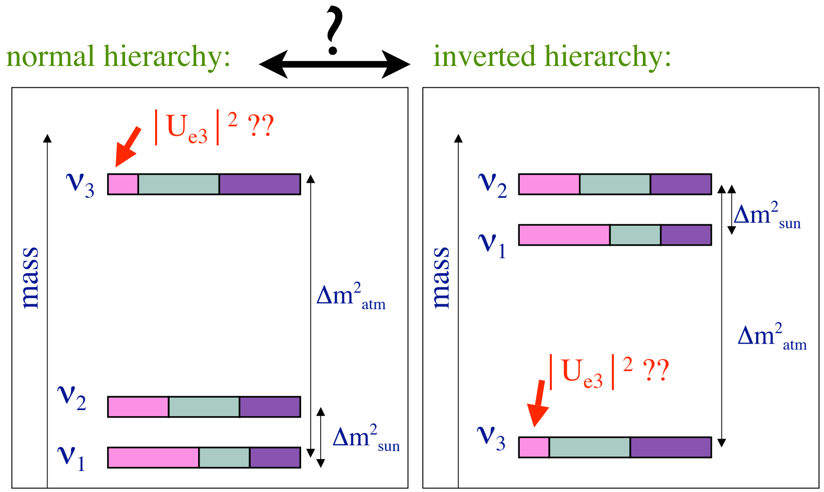
$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

2. precise measurement of other parameters

- Is θ_{23} maximal mixing ?

3. CPV in lepton sector

→ hint on Baryon# asymmetry of Universe



T2K experiment (J-PARC E11)

~T2K: Tokai to Kamioka LBL Neutrino Oscillation Experiment~

- T2K 1st-phase
  - ✓ ***discovery of a finite θ_{13} by observing ν_e appearance***
    - measure ν_e app. in T2K-I → δ (CPV) in T2K 2nd-phase
  - ✓ ***precise measurement of θ_{23}, Δm^2_{23} by ν_μ disappearance***

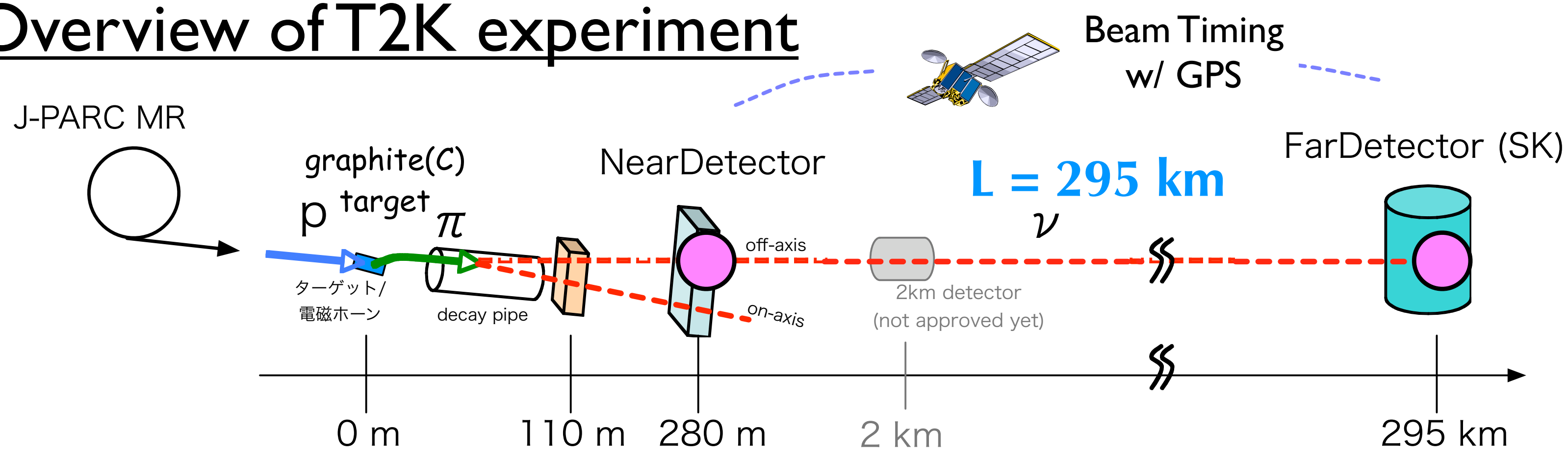
Construction of new ν beam-line / detectors : 2004~2008

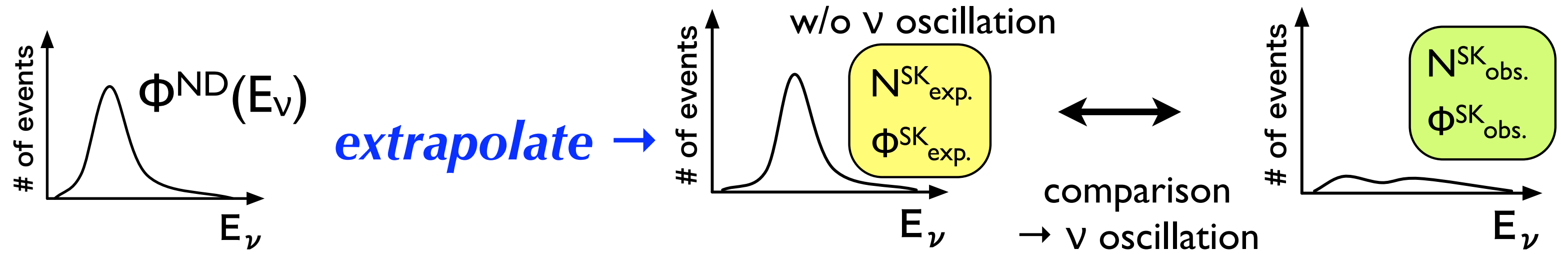
Experiment : 2009 ~

SK
(ready for T2K)

J-PARC 750kW
(under construction)

Overview of T2K experiment





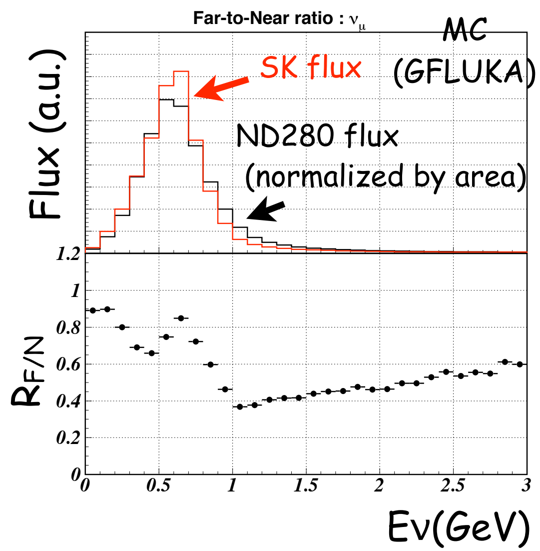
- **observable = $\Phi(E_\nu)$ x $\sigma(E_\nu)$** CC interaction

  FNAL SciBoone exp.

- **To extrapolate Φ^{SK} is a key issue**
  - $\Phi^{SK}(E_\nu) \neq \Phi^{ND}(E_\nu)$ even w/o oscillation due to effect of non-point like source

$$\Phi^{SK}_{exp.}(E_\nu) = R_{F/N}(E_\nu) \times \Phi^{ND}(E_\nu)$$

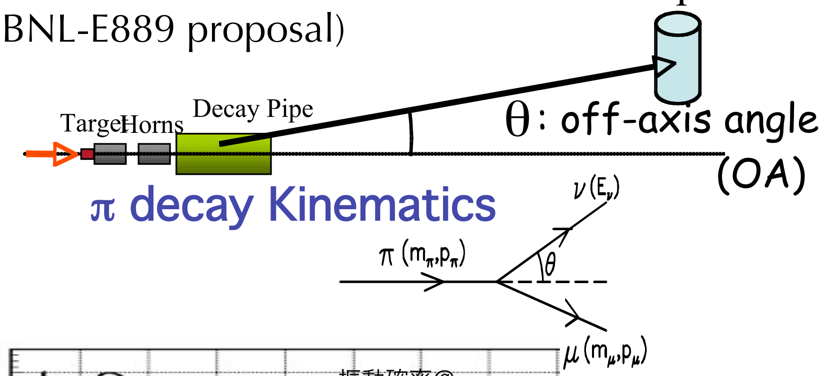
Hadron production measurement

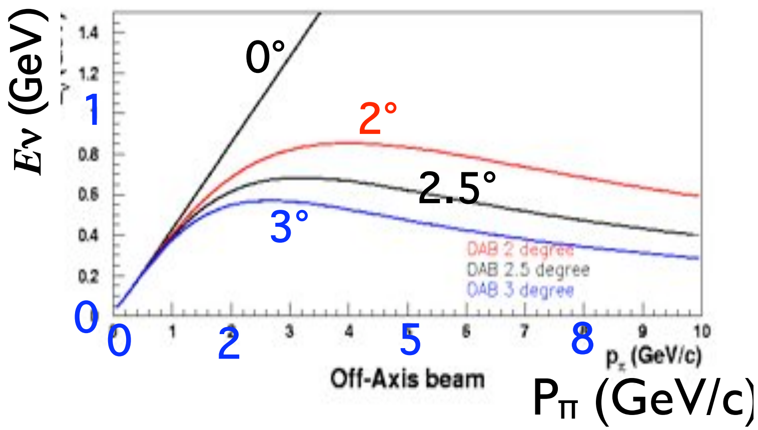


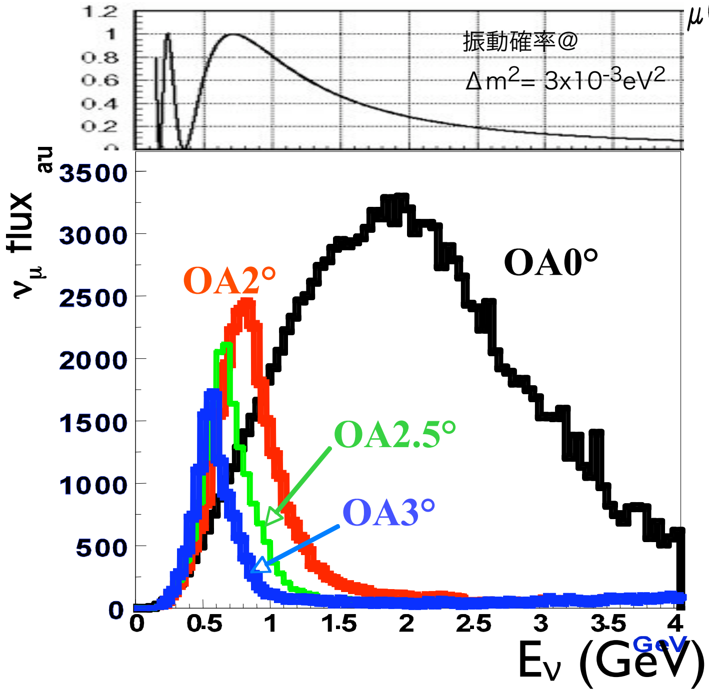
Narrow-band intense neutrino beam

- Off-axis beam method

(ref. BNL-E889 proposal)







L = 295 km
Δm^2_{23} = (2.2~3.0) x 10^{-3} eV^2

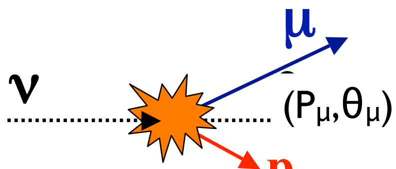
➡ ***Oscillation max.***
E_ν = 0.5~0.7 GeV

- ✓ set E_ν peak @osc. max. (OA 2.5°)
  - x 2~3 intense than OA 0°
  - ~2200 ν_μ int. in total (~1600 ν_μ CC int.) for 1yr * 22.5kt(SK)
- ✓ small high energy ν tail → reduce bkg. to CCQE
- ✓ ν_e ~0.4% at ν_μ peak

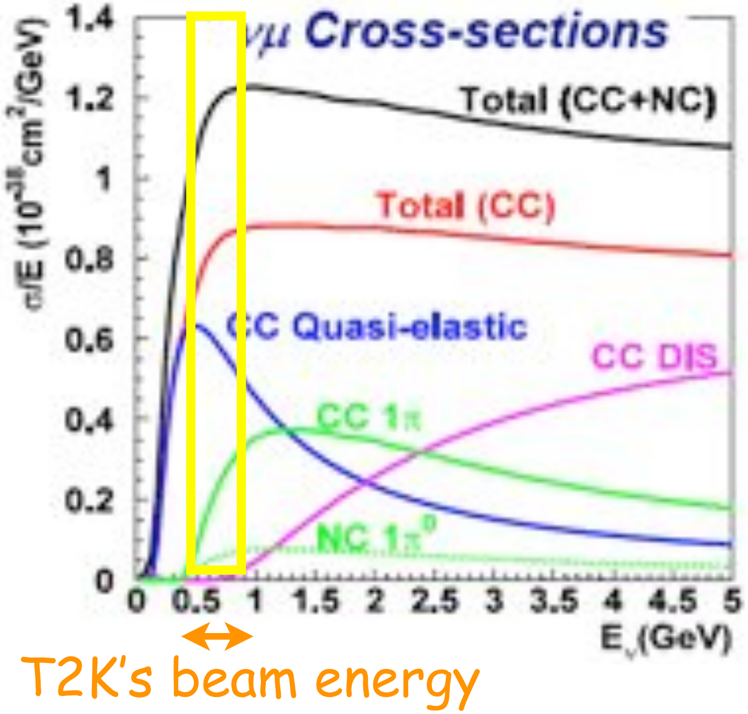
ν Energy Reconstruction

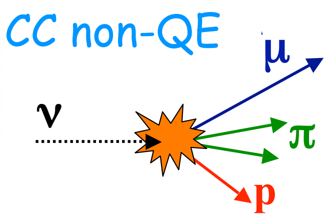
- Energy Rec. is possible for **CC Quasi-Elastic (CCQE)**

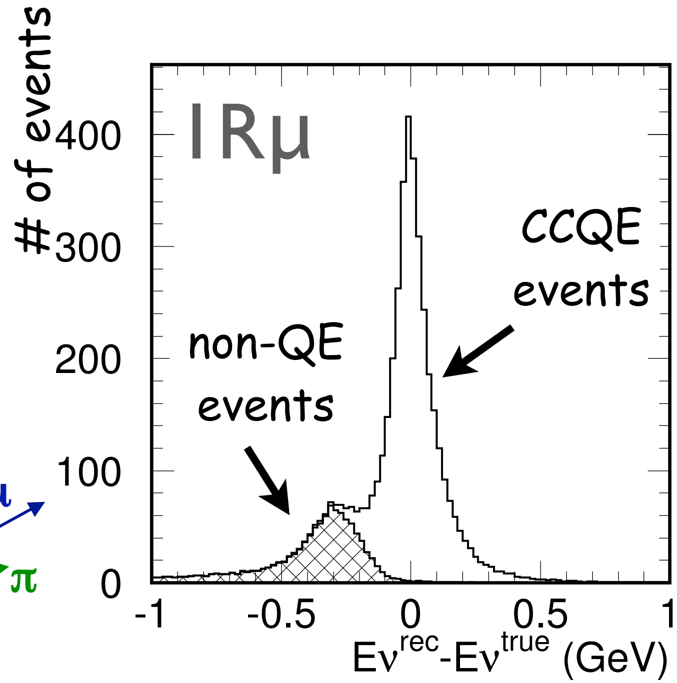
$$E_\nu^{rec} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$



CCQE: $\nu_{\mu(e)} + n \rightarrow \mu(e) + p$

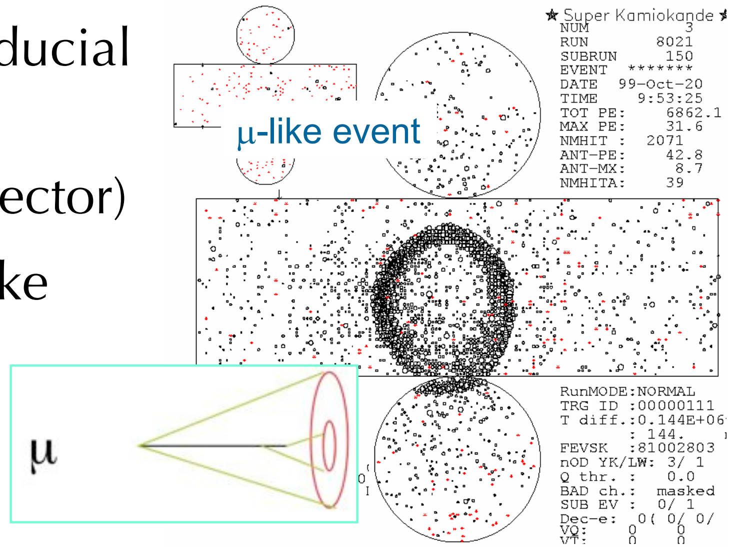


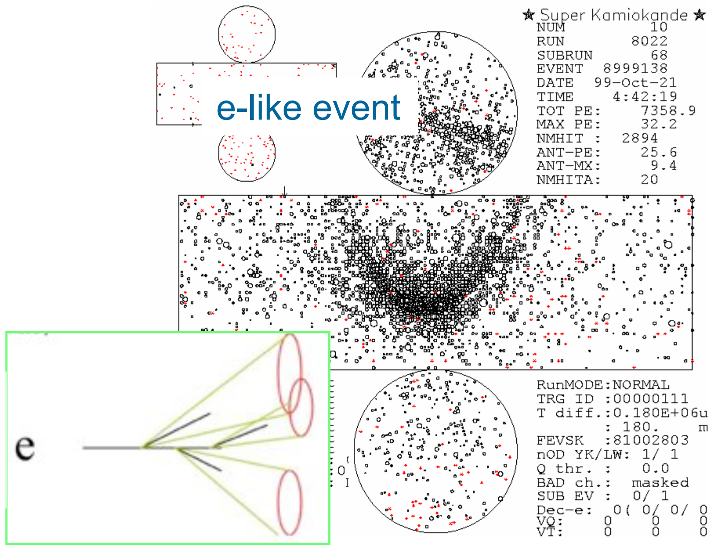




Super Kamiokande (far detector)

- 50 kton water Cherenkov detector (fiducial volume: 22.5 kton)
  - ~10000 x 20 inch PMTs (inner detector)
- good hit-ID: e-like(shower ring) / **μ**-like
- δE_{scale} ~ 2%





Physics prospects

1. θ_{13} measurement by ν_e appearance
2. precise measurement of $(\theta_{23}, \Delta m^2_{23})$
3. Hadron-production measurement

θ_{13} measurement by ν_e appearance

- simplified probability of $\nu_\mu \rightarrow \nu_e$ $\Delta m^2_{31} = \Delta m^2_{32} >> \Delta m^2_{12}$

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13}) \sin^2\theta_{23} \sin\left[1.27\Delta m^2_{31} L/E\right]$$

common as ν_μ disappearance

- However, more exact $P(\nu_\mu \rightarrow \nu_e)$ composes not only θ_{13} but also other unknown parameters

θ_{13} term CPV term

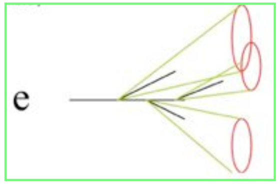
$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31} - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21} + \ldots$$

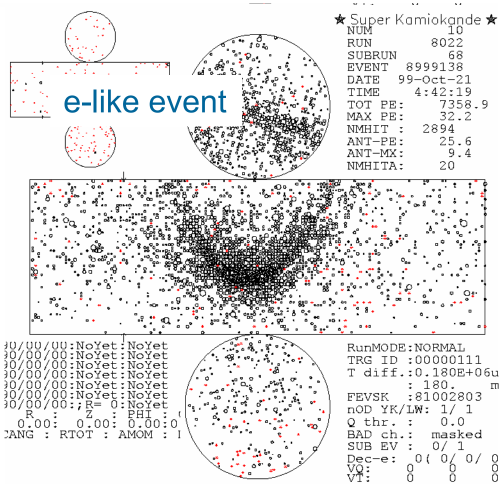
T2K observable: $P(\nu_\mu \rightarrow \nu_e)$ → $\sin^2(2\theta_{13})$

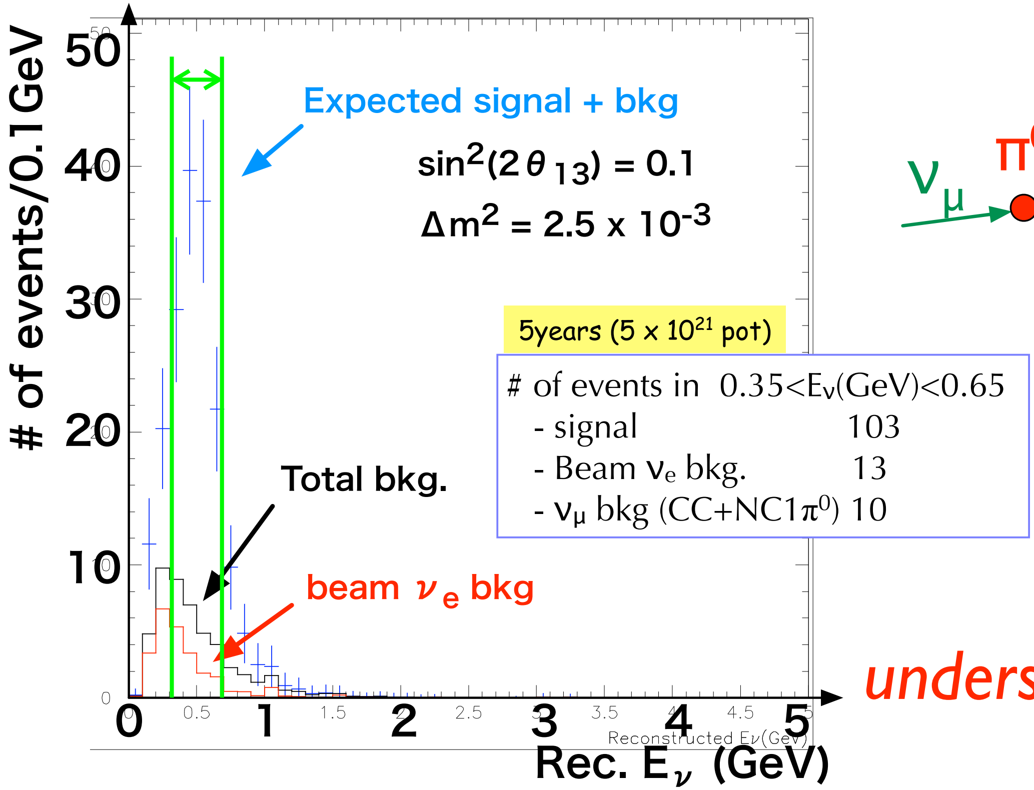
some ambiguities due to unknown parameters, but more sensitive than the current limit

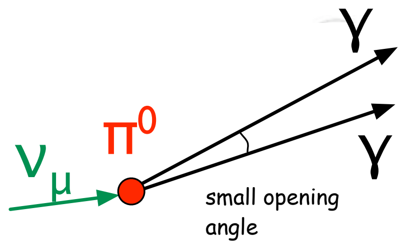
and, it is possible to measure CPV by $\dfrac{P(\nu_\mu \to \nu_e) - P(\overline{\nu_\mu} \to \overline{\nu_e})}{P(\nu_\mu \to \nu_e) + P(\overline{\nu_\mu} \to \overline{\nu_e})}$ *in T2K-II*

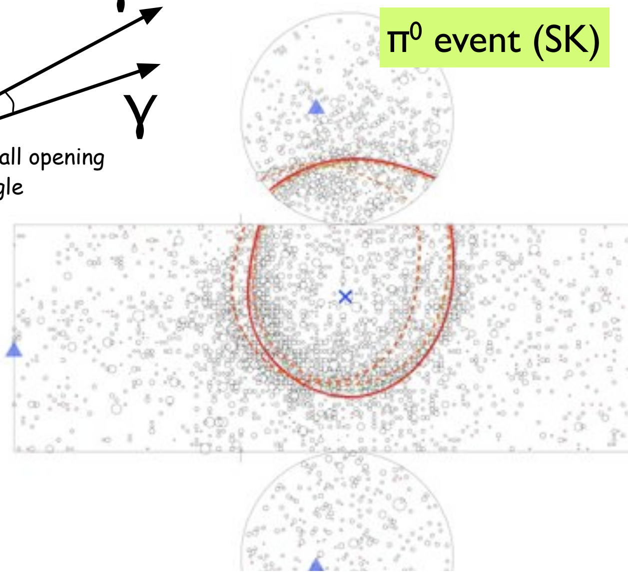
- ν_e appearance
  - signal : e^- from ν_e CCQE
  - background
    - beam intrinsic ν_e
    - ν_μ NC1π^0, in which π^0 is mis-ID as e^-









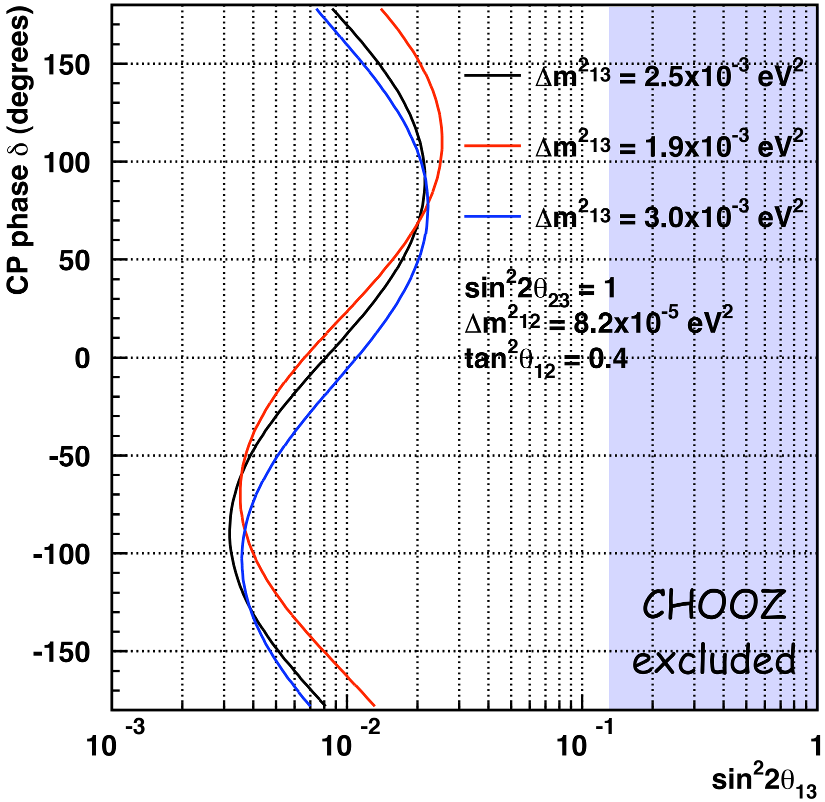


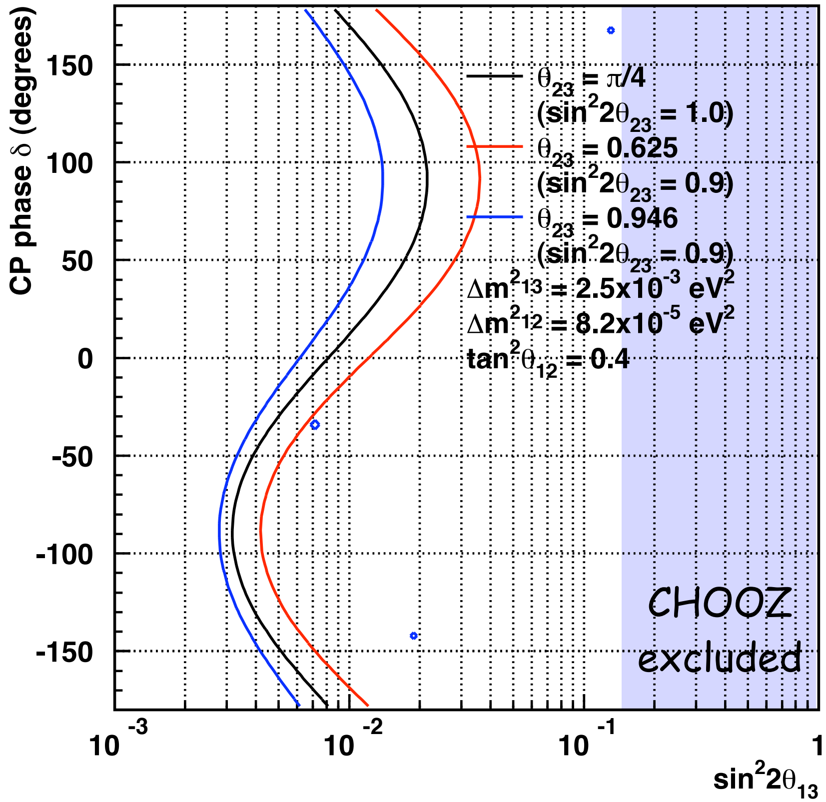
understanding bkg. is a key issue

Expected sensitivity of θ_{13}

- > x10 improvement from CHOOZ results for almost any δ

$\sin^2(2\theta_{13}) = 0.008$ (90% C.L.) for $\delta=0$, $\Delta m^2_{13}=2.5\times10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$





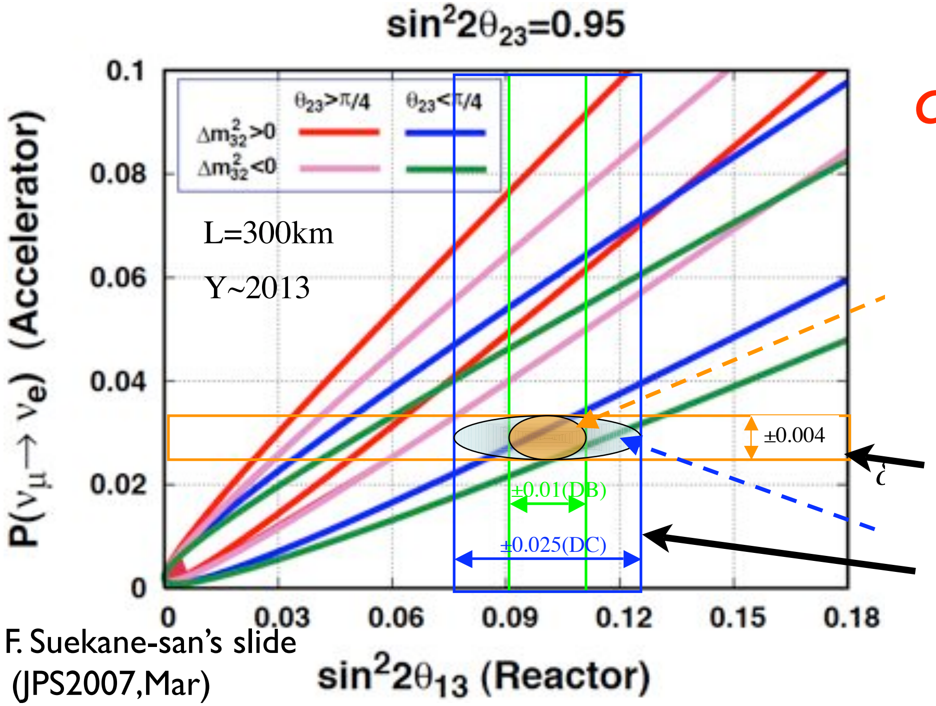
90%C.L. sensitivity @5years (5×10^{21} pot) w/ stat. + 10% bkg. systematic error

Complementary measurement of θ_{13}

- Reactor Experiment (DoubleChooz, DayaBay, RENO ...)
  - ν_e disappearance → **pure $\sin^2 2\theta_{13}$ measurement**

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta_{13} \cdot \sin^2(1.27\Delta m^2_{31} L/E) + O(\Delta m^2_{21}/\Delta m^2_{31})$$

  - not sensitive to CPV phase δ



from F. Suekane-san's slide (JPS2007,Mar)

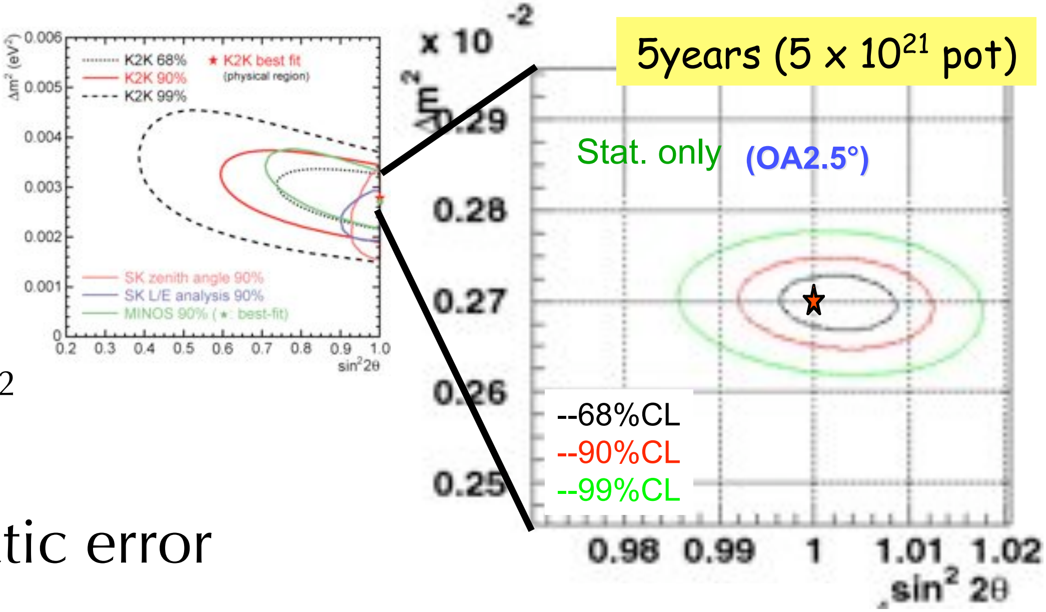
comparison both results

↓

δ, *sign(Δm^2_{31}), $\sin\theta_{23}$*

precise measurement of $(\theta_{23}, \Delta m^2_{23})$

- ν_μ disappearance
- goal
  - $\delta(\sin^2 2\theta_{23}) \sim 0.01$
  - $\delta(\Delta m^2_{23}) \sim < 1 \times 10^{-4}\ \mathrm{eV}^2$

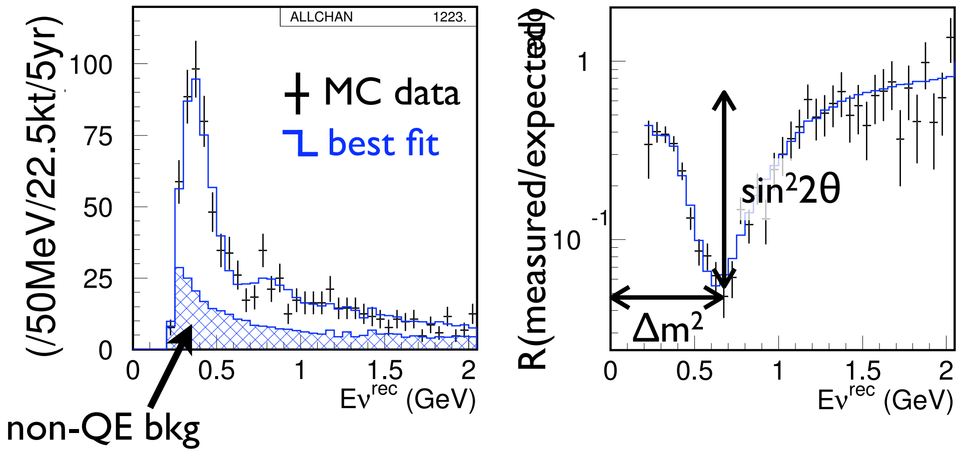


<u>Requirements</u> on systematic error

- Non-QE/QE ratio : <5%
- Energy scale : <2%
- **flux normalization : <10%**
- **Spectrum shape : <20%**
- **Spectrum width : <10%**

required errors on $\Phi^{SK}_{exp.}(E_\nu)$

$(\sin^2 2\theta, \Delta m^2) = (1.0, 2.7 \times 10^{-3}\ \mathrm{eV}^2)$

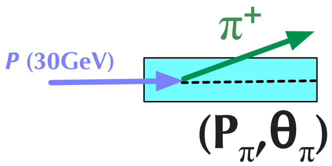


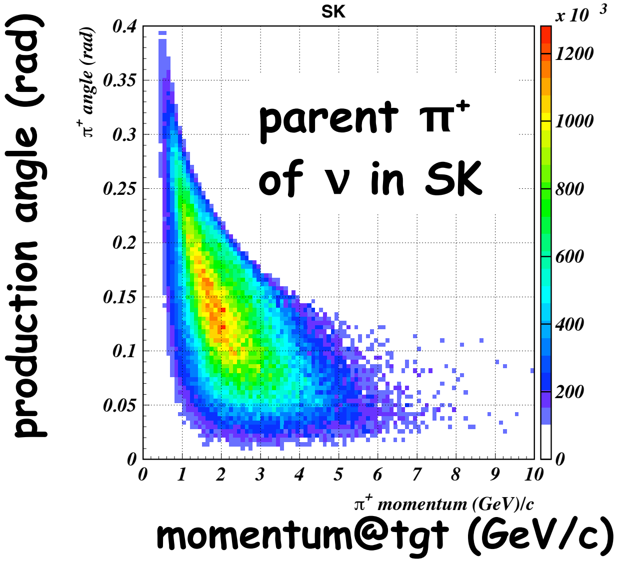
Hadron-production measurement

- expect $\Phi^{SK}_{exp}(E_\nu)$ precisely in order to reduce syst. errors
- $\Phi^{SK}_{exp.}(E_\nu) = \mathbf{R_{F/N}}(E_\nu) \times \Phi^{ND}(E_\nu)$
  - $R_{F/N}(E_\nu)$ is sensitive to hadron-production distribution
- Requirements on the accuracy of $R_{F/N}(E_\nu)$
  - ν_e app.: $\delta(N_{bkg}) < 10\%$ ⇨ $\delta R_{F/N}(E_\nu) < 2\sim3\%$
    E_ν: 0-1GeV and 1-10GeV
  - ν_μ disapp.: required errors on Φ^{SK}_{exp} ⇨ $\delta R_{F/N}(E_\nu) < 2\sim3\%$
    E_ν: 0-1.5GeV, 100MeV/bin
- There are no measurements of 30GeV ~ 50GeV p+C

Experimental measurement of the hadron-production is necessary !!

- Requirements on hadron-production measurements
  - **Measure (P_π,θ_π) distribution** with <10% stat. error for each 150MeV/c x 20mrad bin in the region: $0.3 < P_\pi(\text{GeV/c}) < 10$ and $0 < \theta_\pi(\text{mrad}) < 400$





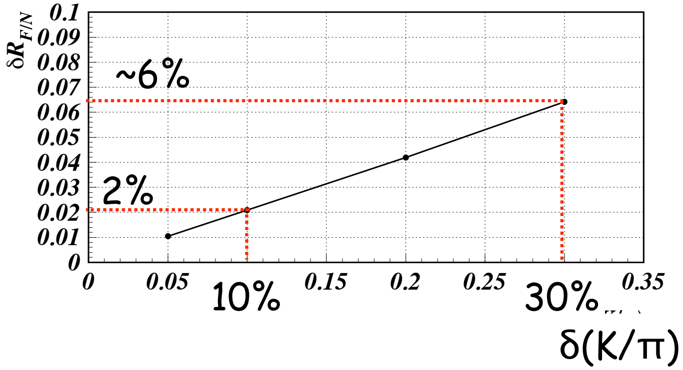
→ $\delta R_{F/N}(E_\nu) < 2\sim3\%$

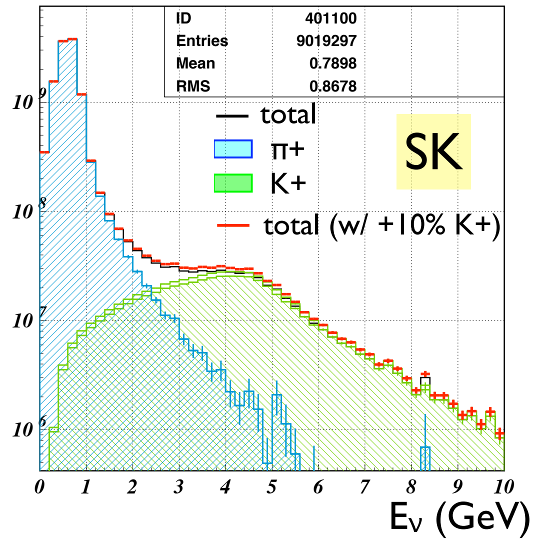
Eν: 0-1.5GeV,100MeV/bin

  - **Measure K/π ratio** with <10% accuracy
    - high energy ν_μ (→NC1π^0 bkg.) from K decay

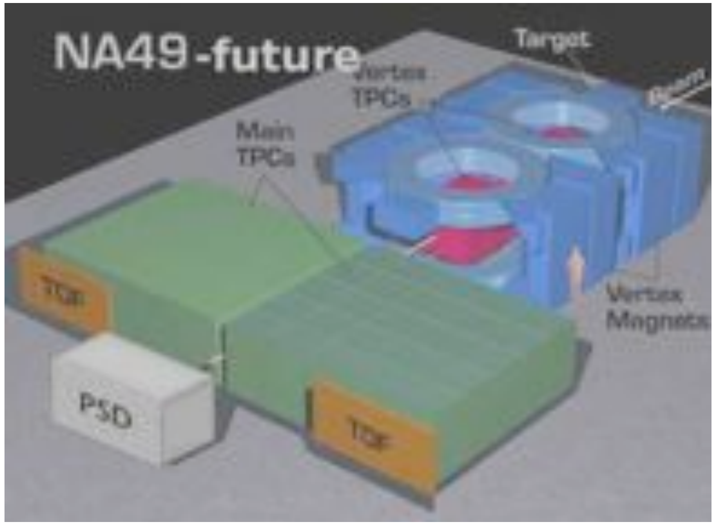
↓ $\delta R_{F/N}(E_\nu) < 2\sim3\%$

Eν: 0-1GeV and 1-10GeV





CERN NA61 Experiment



- Detector w/ Large acceptance
  - TPC w/ magnetic field + TOF
  - PID(p,K,π ..) w/ dE/dx and TOF
- **p+C for T2K in 2007** (,2008)
  - thin(1cm), thick(10cm,90cm) targets
  - **beam time in 2007 fall (29days) ← devoted for T2K purpose**
- Impact of NA61

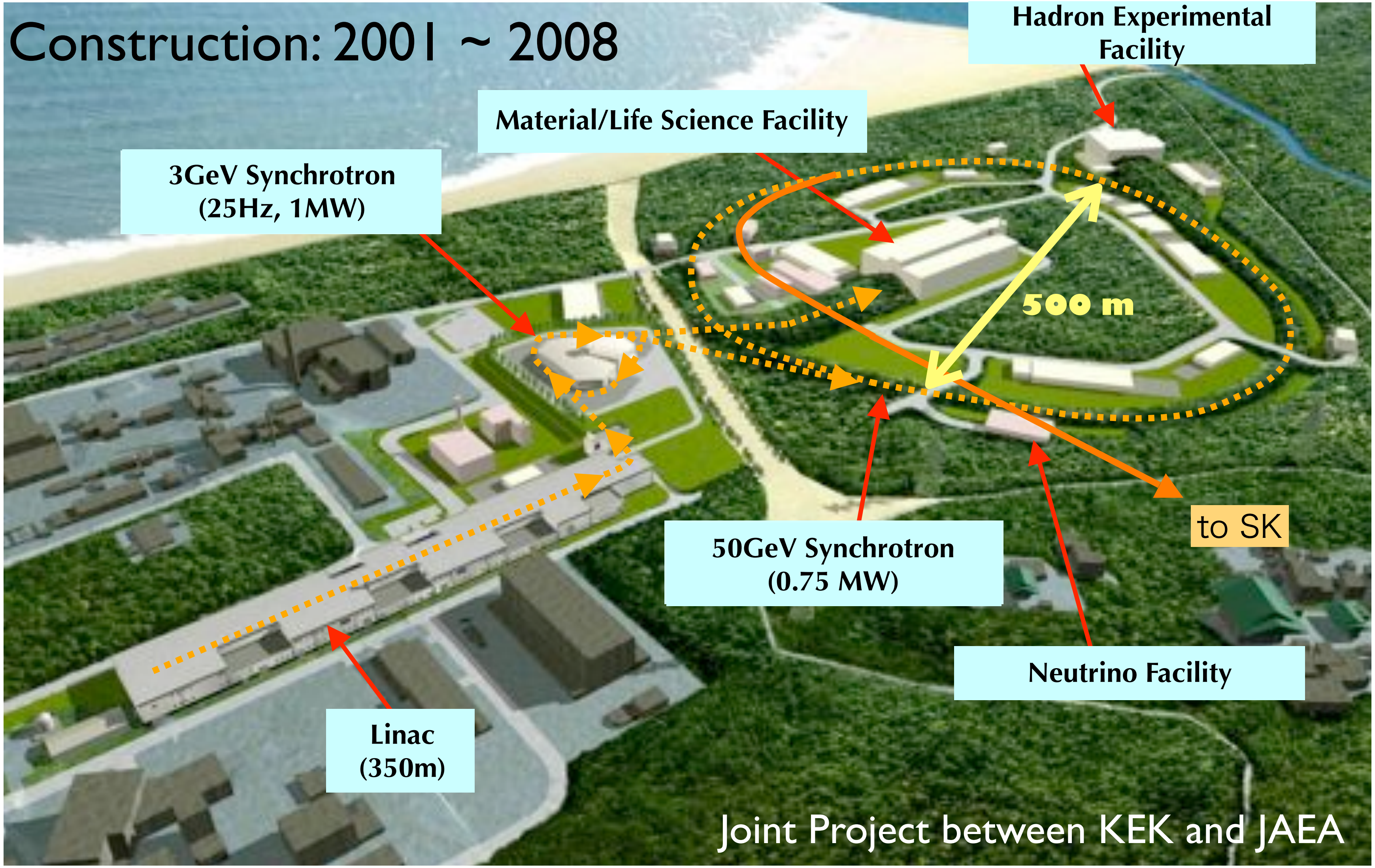
	T2K goal	Error from $R_{F/N}$ w/ NA61
δN_{bkg} for νe app.	**10%**	**< 4%**
$\delta(\sin^2 2\theta_{23})$	**1%**	**0.5%**
$\delta(\Delta m^2_{23})$ [x10^{-4} eV^2]	**< 1**	**0.15**

→ get ready for T2K which starts in 2009

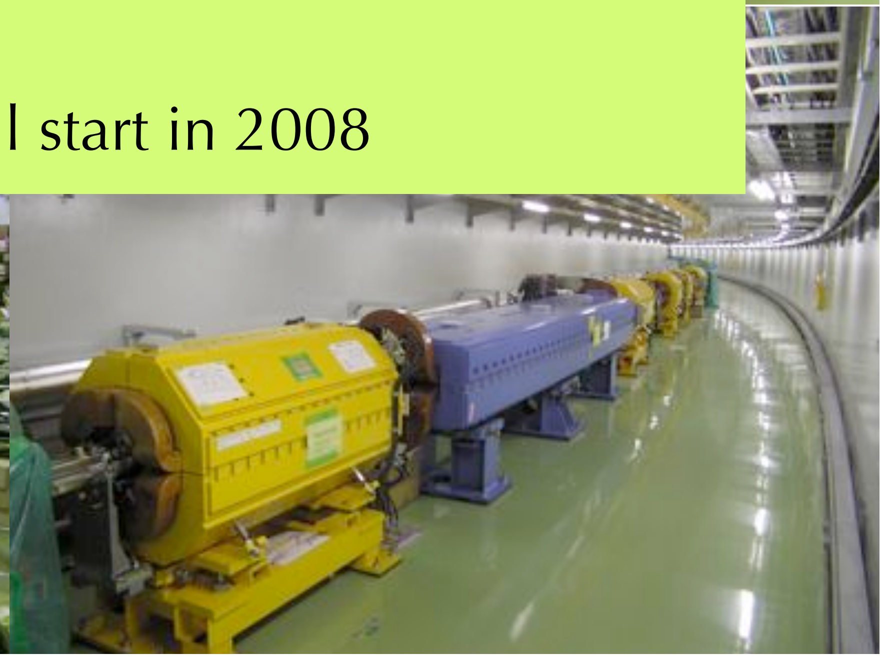
Construction status

J-PARC

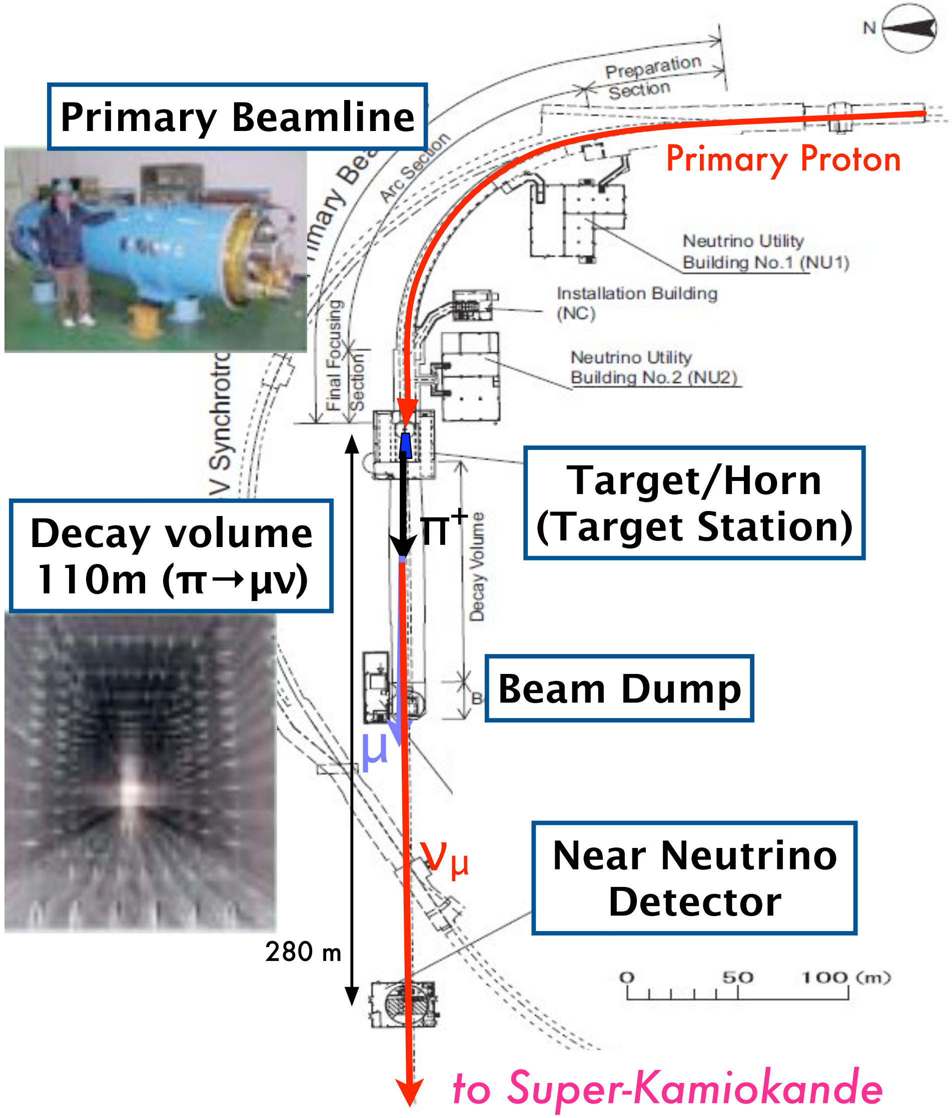
(Japan Proton Accelerator Research Complex)



- Construction & Commissioning are in progress
  - **Linac successfully accelerated up to the design energy of 181MeV**
- MR commissioning will start in 2008



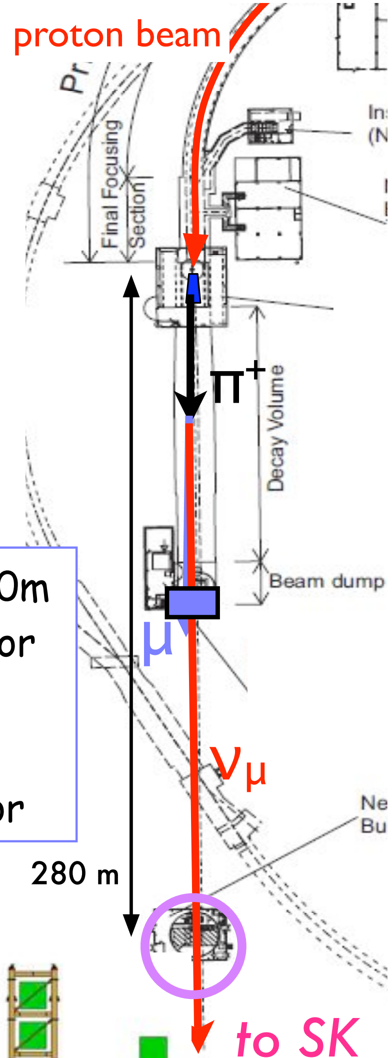
Neutrino Facility at J-PARC



Beam-line construction
2004.Apr ~ 2009.Mar
First Beam in 2009.Apr

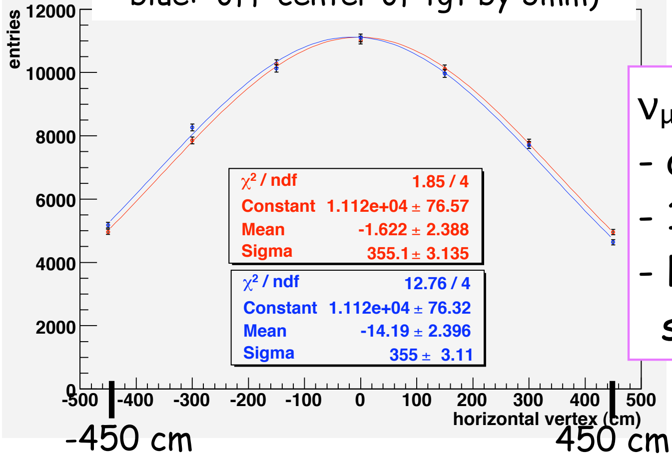
Beam direction

- Requirement on the beam direction **< 1 mrad**
  - reduce syst. error of Δm^2_{23} caused by δE_ν
  - δ(p beam pos. on target) < 1mm
- beam-line alignment using GPS
- monitor direction of the μ and ν_μ

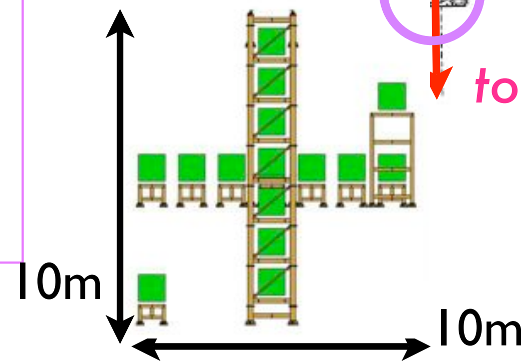


muon monitor @ ~110m
- IC & semi-conductor array
- 150 cm x 150cm
- spill by spill monitor

1 month data w/ 1% beam
(red: p beam hits the center of tgt,
blue: off-center of tgt by 3mm)

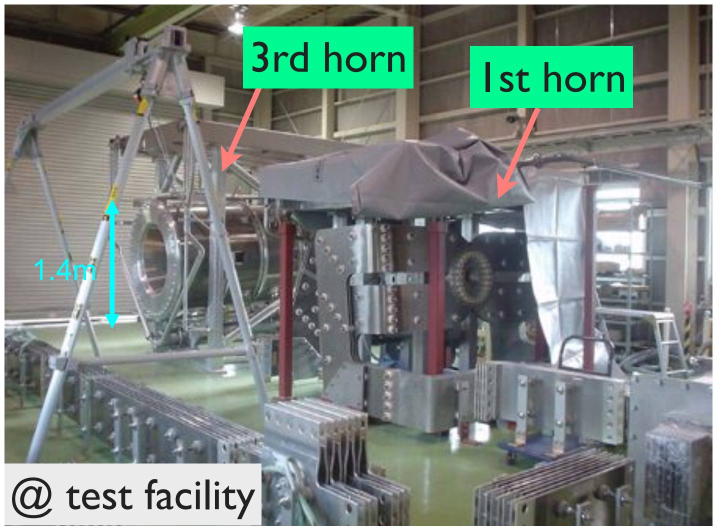


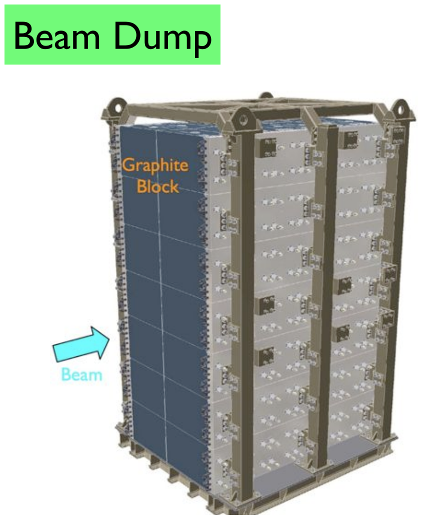
ν_μ beam monitor @ 280m
- on-axis of ν_μ beam
- 10m x 10m
- Fe/Scintillator sandwich x 16



A New Neutrino Beam line with MW fast ext. beam

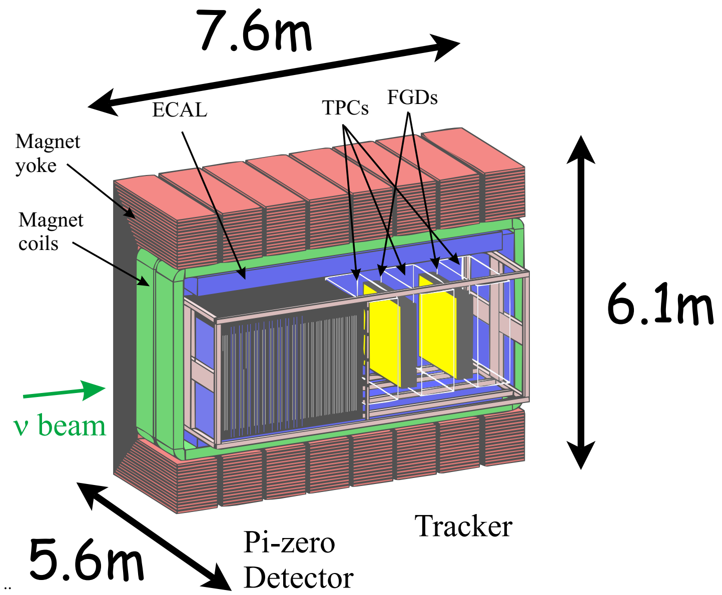
- Technical challenges
  - Thermal shock → use graphite for target and beam dump
  - Heat load → water cooling everywhere
  - Radiation → shield & remote maintenance
- Construction & final R&D of each component are in progress

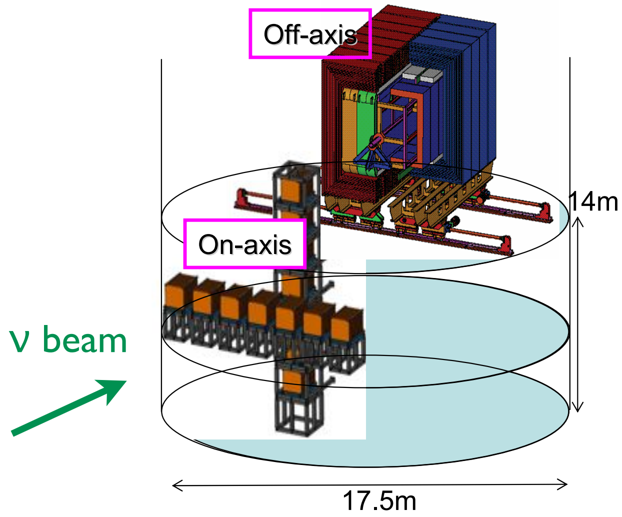




Near Detectors @ 280m

- Off-axis detector
  - measure ν beam energy, flux and flavor contents
  - study ν cross section (water/carbon)
  - Tracker(FGD,TPC), Pi0 detector and EM calorimeter in the UA1 magnet (0.2T)
- On-axis detector
  - ν beam direction monitor
- Beam/detector commissioning will start with on-axis detector in Apr/2009
  - commissioning of off-axis detector in the fall of 2009





Summary

- T2K **Start from Apr/2009**
  - off-axis beam → E_ν ~ sub-GeV & SK as far detector
  - discover a finite θ_{13} >x10 improvement
    - if we measure ν_e app. in T2K-I → CPV in T2K-II
    - complementary with Reactor experiment
    - interplay with mass ordering and $0\nu\beta\beta$
  - precise measurement: $\delta(\sin^2\theta_{23})\sim 1\%$, $\Delta m^2_{23} < 1 \times 10^{-4}$ eV^2
  - new hadron-production measurement: CERN NA61
- Construction of Accelerators and Neutrino Facility at J-PARC are in progress