

Status and performance of the T2K experiment

Eike Frank
on behalf of the T2K collaboration

**Albert Einstein Center for Fundamental Physics,
Laboratory for High Energy Physics, Bern**

The T2K collaboration



~500 members, 61 Institutes, 12 countries

Canada

TRIUMF
U. Alberta
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
York U.

France

CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany

U. Aachen

Italy

INFN, U. Roma
INFN, U. Napoli
INFN, U. Padova
INFN, U. Bari

Japan

ICRR Kamioka
ICRR RCCN
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Osaka City U.
U. Tokyo

Poland

A. Soltan, Warsaw
H.Niewodniczanski,
Cracow
T. U. Warsaw
U. Silesia, Katowice
U. Warsaw
U. Wroclaw

Russia

INR

S. Korea
N. U. Chonnam
U. Dongshin
U. Sejong
N. U. Seoul
U. Sungkyunkwan

Spain

IFIC, Valencia
U. A. Barcelona

Switzerland
U. Bern
U. Geneva
ETH Zurich

United Kingdom

Imperial C. London
Queen Mary U. L.
Lancaster U.
Liverpool U.
Oxford U.
Sheffield U.
Warwick U.

STFC/RAL
STFC/Daresbury

USA

Boston U.
B.N.L.
Colorado S. U.
Duke U.
Louisiana S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

The T2K experiment



- Long baseline (LBL) neutrino oscillation experiment in Japan
- High intensity off-axis ν_μ beam from Tokai to Kamioka
- Started beam operation 2009, first physics runs in 2010
- Goals:
 - precisely measure θ_{23} and Δm^2_{23} in ν_μ disappearance
 - search for $\nu_\mu \rightarrow \nu_e$ appearance, i.e. non-zero θ_{13} and later on δ_{CP}

Neutrino Oscillation – 3 flavour mixing



Flavor Eigenstates $|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$ Mass Eigenstates

3 mixing angles: θ_{23} , θ_{13} , θ_{12}
1 CP violating phase: δ

Unitary PNMS-Matrix:

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

Atmospheric ν , SK
LBL: K2K, MINOS, T2K...

Reactor ν : CHOOZ
LBL: MINOS T2K, Atm. ν

Solar ν , Reactor ν
SNO, KamLAND, SK

$$\sin^2 \theta_{23} \approx 0.47$$

$$\Delta m_{23}^2 \approx 2.39 \cdot 10^{-3} \text{ eV}^2$$

$$\sin^2 \theta_{13} \approx 0.016$$

δ unknown

$$\sin^2 \theta_{12} \approx 0.32$$

$$\Delta m_{12}^2 \approx 7.7 \cdot 10^{-5} \text{ eV}^2$$

E. Lisi, Prog. in Part. and Nucl. Phys. 64 (2010) 171

- ν_μ disappearance:

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 \theta_{23} \sin^2 \left(1.27 \frac{\Delta m_{23}^2 L}{E} \right)$$

Determine θ_{23} and Δm_{23}^2 precisely

- ν_e appearance:

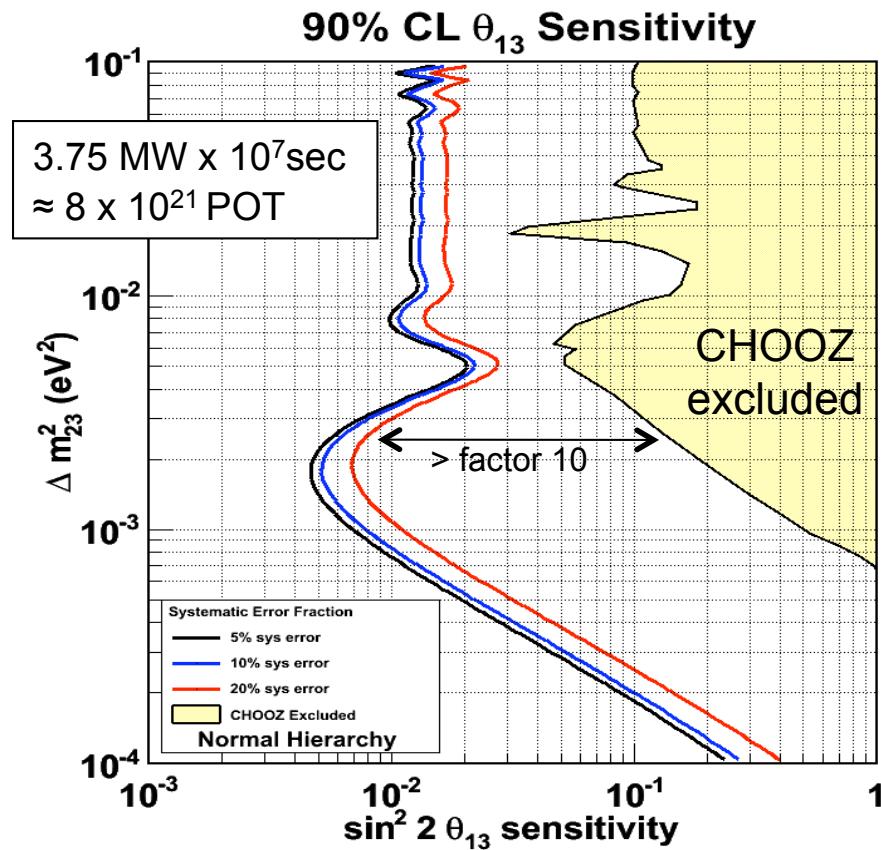
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(1.27 \frac{\Delta m_{13}^2 L}{E} \right)$$

Discover θ_{13} , possible window to δ

Expected Sensitivity of T2K

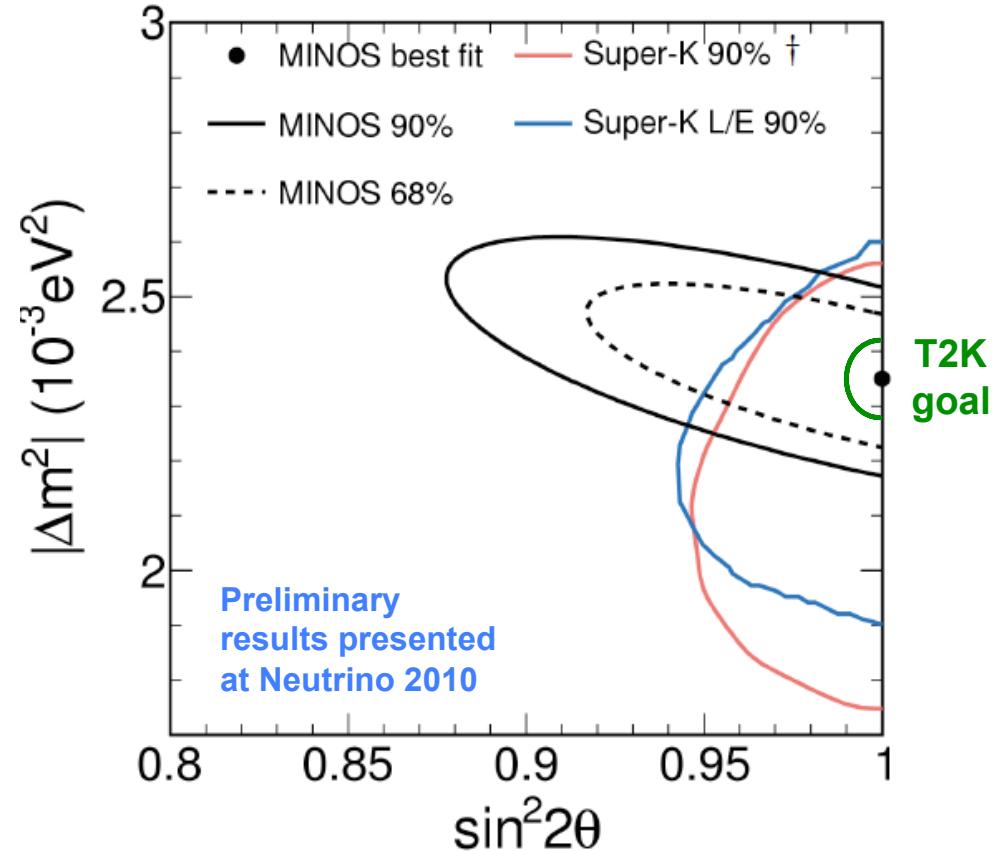


$\nu_\mu \rightarrow \nu_e$ appearance



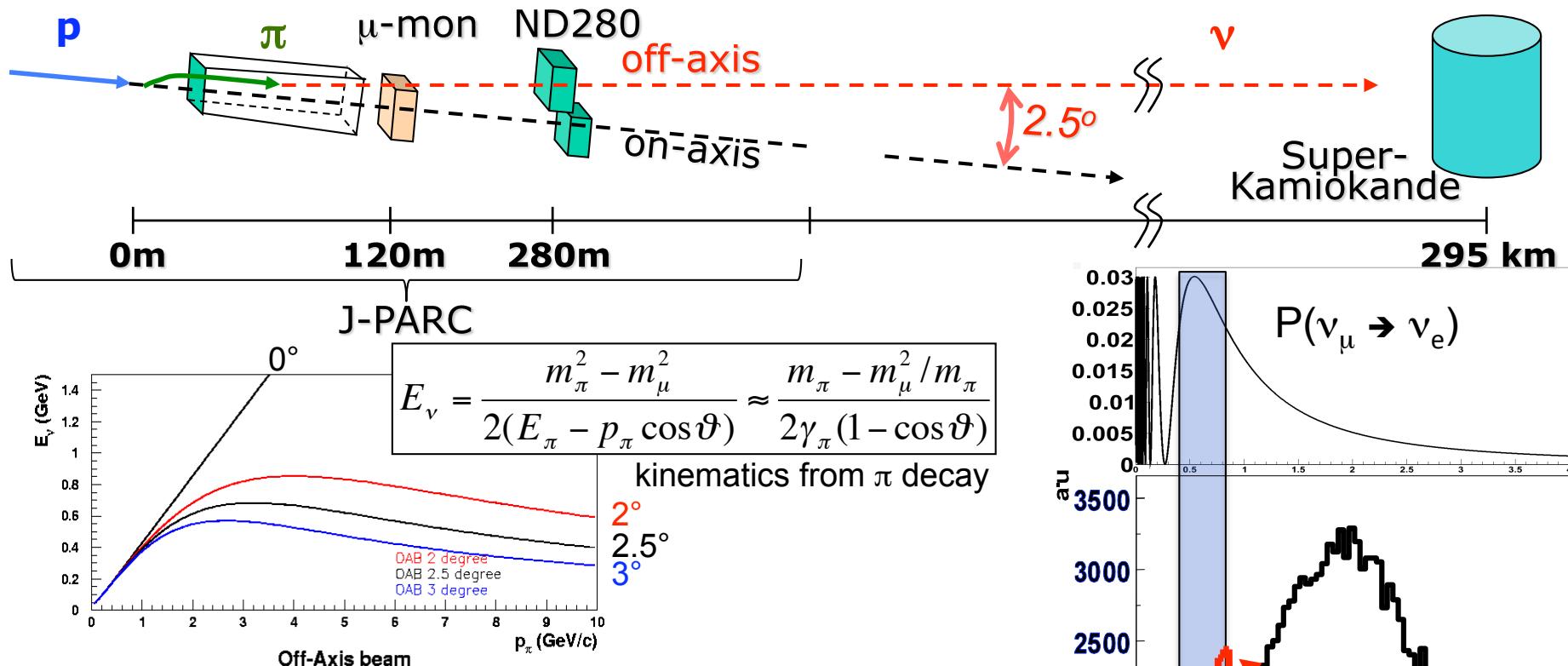
$\delta(\sin^2 2 \theta_{13}) \approx 0.008$,
at $\Delta m_{23}^2 = 2.4 \cdot 10^{-3}$ eV²

ν_μ disappearance



$\delta(\sin^2 2 \theta_{23}) \approx 0.01$,
 $\delta(\Delta m_{23}^2) < 0.1 \cdot 10^{-3}$ eV²

Experimental Setup



- Narrow band **2.5° off-axis beam** at energy tuned to oscillation maximum
- 30 GeV proton beam on Carbon target
- 3 magnetic horns and ~110m long pion decay volume
- Muon monitors after beam dump (fast beam monitoring)
- Near detector complex ND280 (on- and off-axis)
- Far detector Super-Kamiokande (50 kt water Cerenkov)

Analysis Strategy



- Predict **Super-Kamiokande** observations based on:

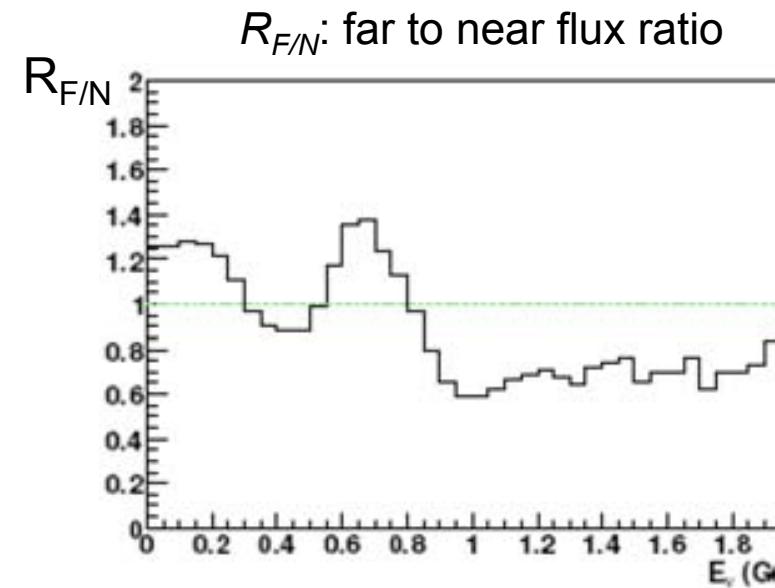
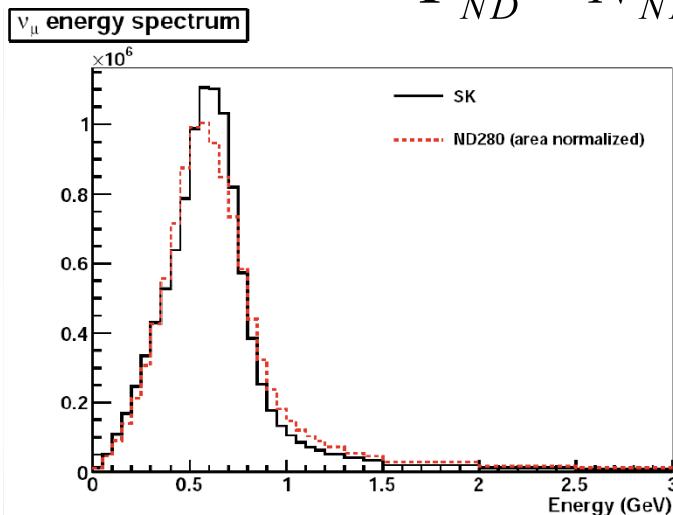
- Near detector measurements: normalization and spectrum of ν -beam
- NA61/Shine** measurements: Hadron production

$$N(E_\nu^{\text{rec}}) = \int \Phi_{SK}^{\text{exp}}(E_\nu^{\text{true}}) \cdot P_{\text{osc}}(E_\nu^{\text{true}}) \cdot \sigma_{SK}(E_\nu^{\text{true}}) \cdot \varepsilon_{SK}(E_\nu^{\text{true}}) \cdot f(E_\nu^{\text{rec}} - E_\nu^{\text{true}}) dE_\nu^{\text{true}}$$

SK-Flux oscillation probability cross section detector efficiency SK Energy resolution

- with fluxes: $\Phi_{SK} = R_{F/N} \cdot \Phi_{ND}$

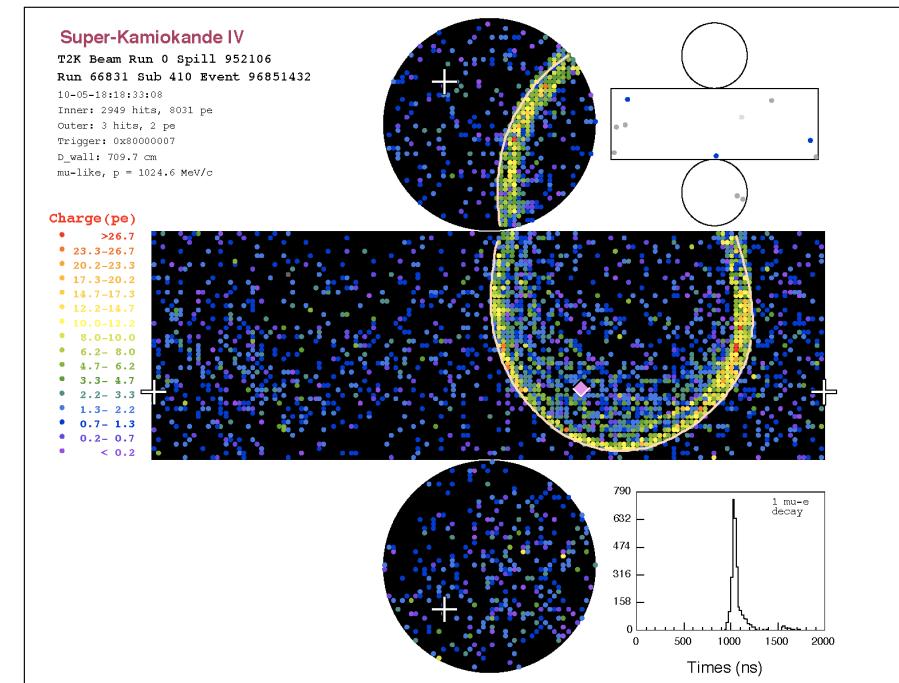
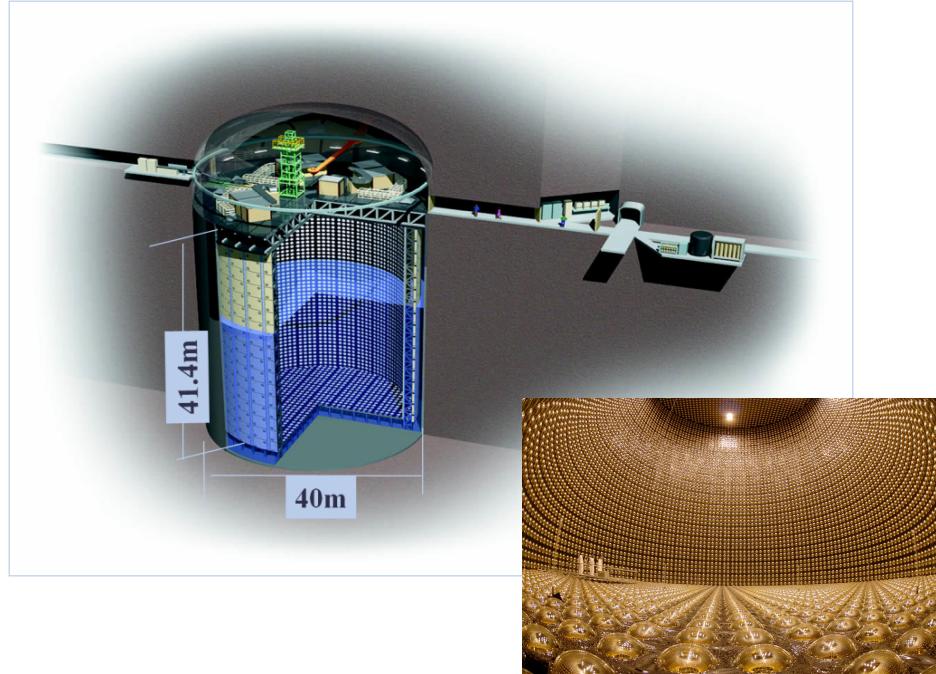
$$\Phi_{ND} = N_{ND}^{\text{obs}} / (\sigma_{ND} \cdot \varepsilon_{ND})$$



Far Detector SK-IV



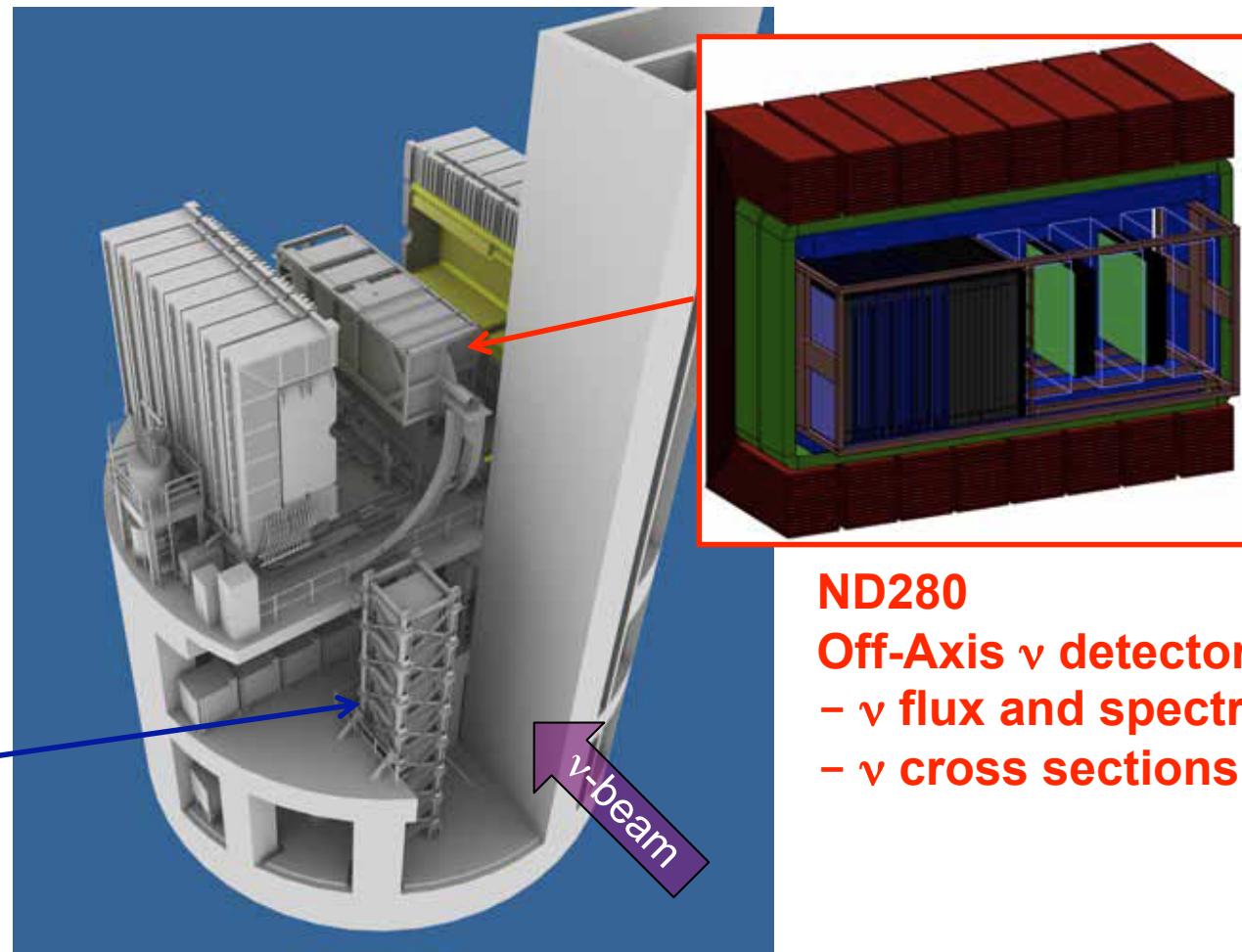
- 22.5kt fiducial volume water Cherenkov detector operational since 1996
- 11129 20" PMTs in inner detector (ID), 1885 8" PMTs in outer detector (OD)
- New readout electronics has been working since 2008 summer.
- Stable & dead time less DAQ system
- SK is working very stably
- Beam related events are selected by event timing using GPS system.



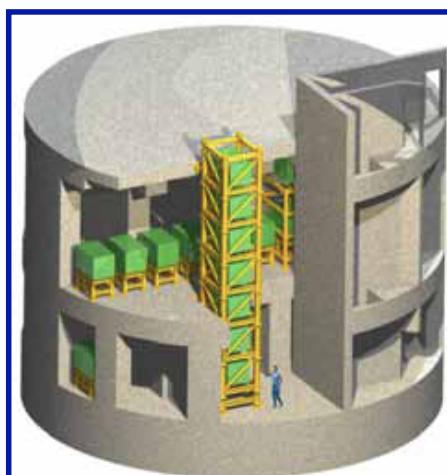
Near detectors



- INGRID: Sandwich calorimeter (iron, plates and scintillator)
- ND280 off-axis: multipurpose detector complex (P0D, TPCs, FGDs, ECal, SMRD)



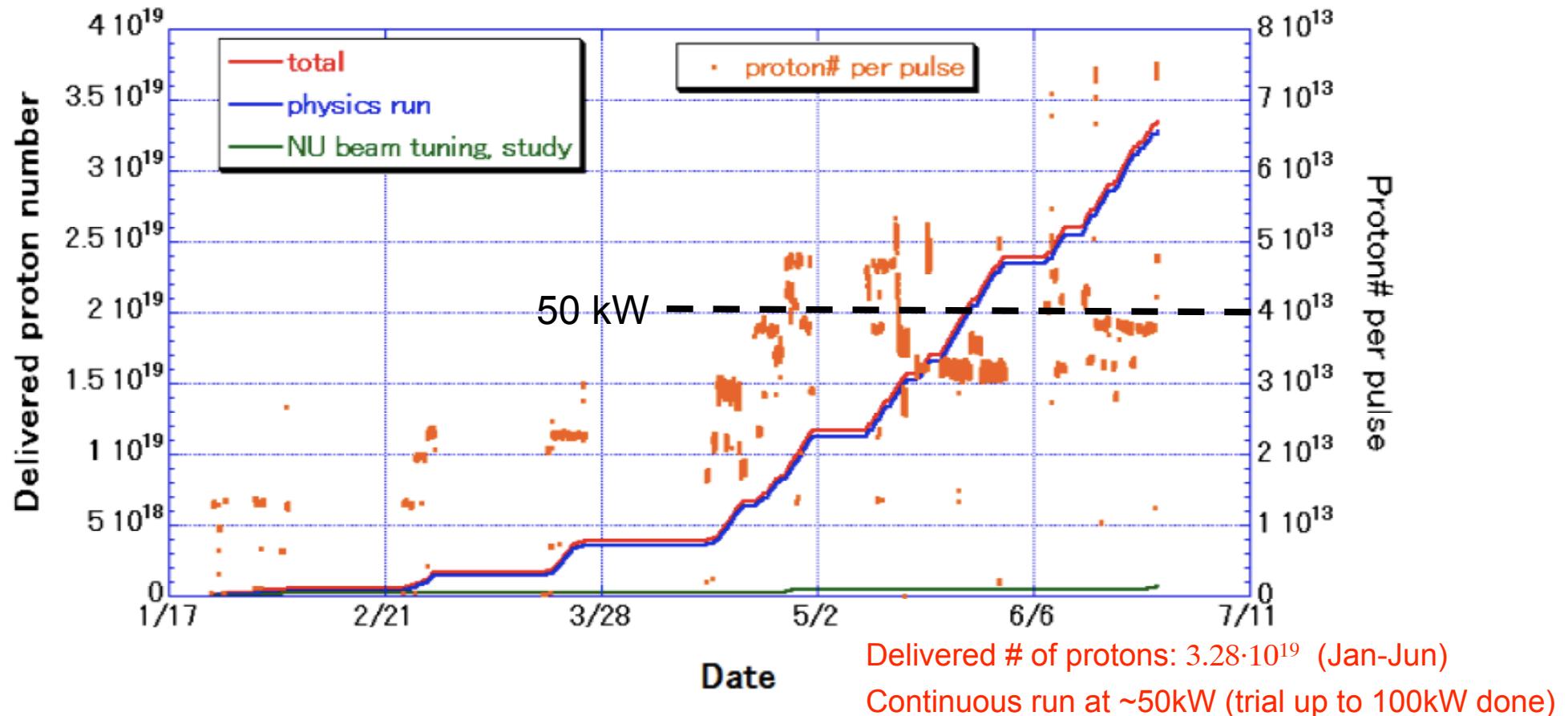
INGRID
On-Axis ν beam monitor



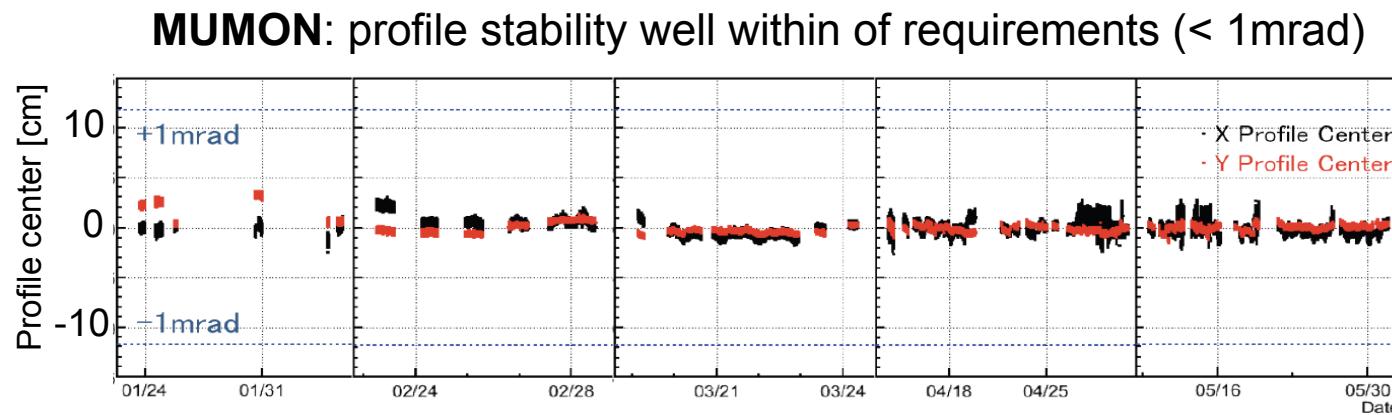
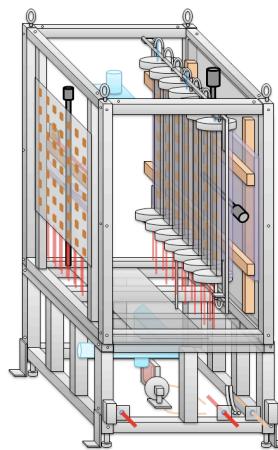
ND280
Off-Axis ν detector:
– ν flux and spectrum
– ν cross sections

Latest milestones

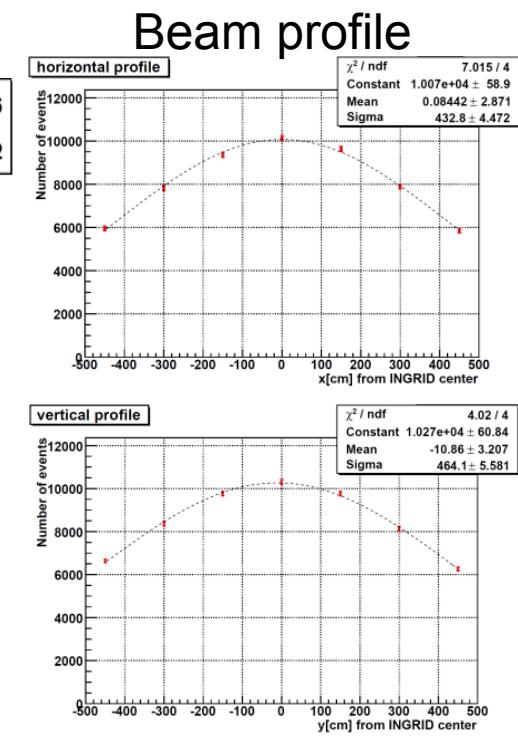
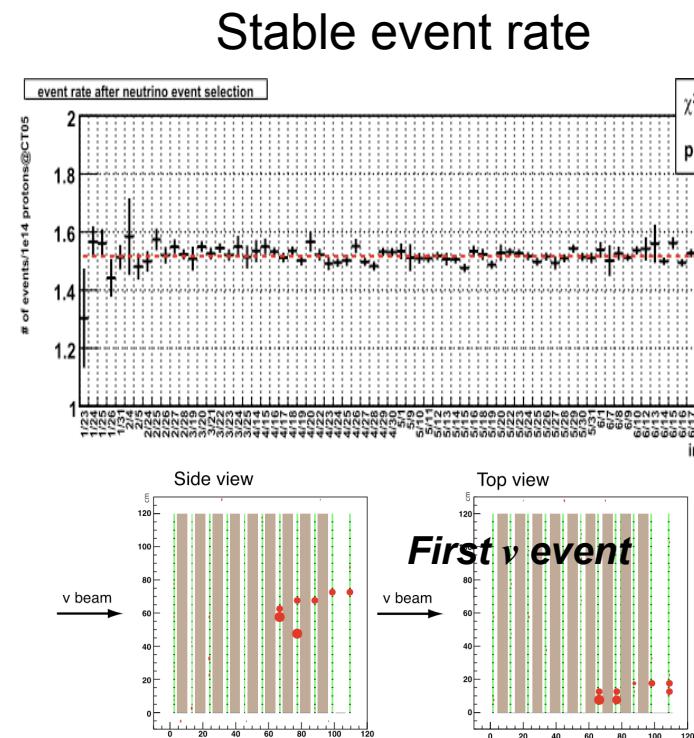
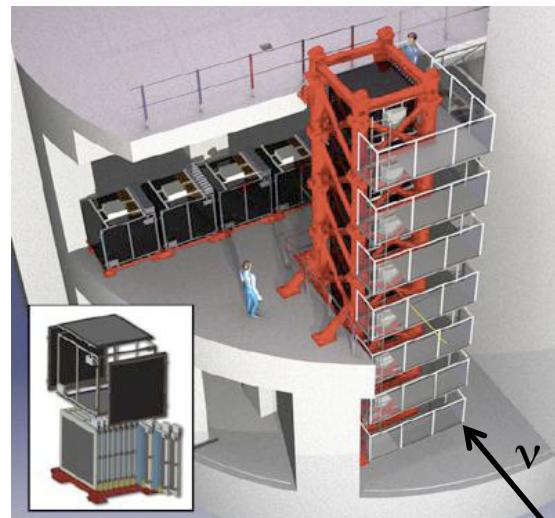
- **March 2009: Beamlime construction completed**
- April 23, 2009: First neutrino beam production and commissioning started
- **January 2010: Data accumulation for oscillation search started!**
- Feb. 24, 2010: First T2K Event in Super-Kamiokande!



Beam monitoring



INGRID

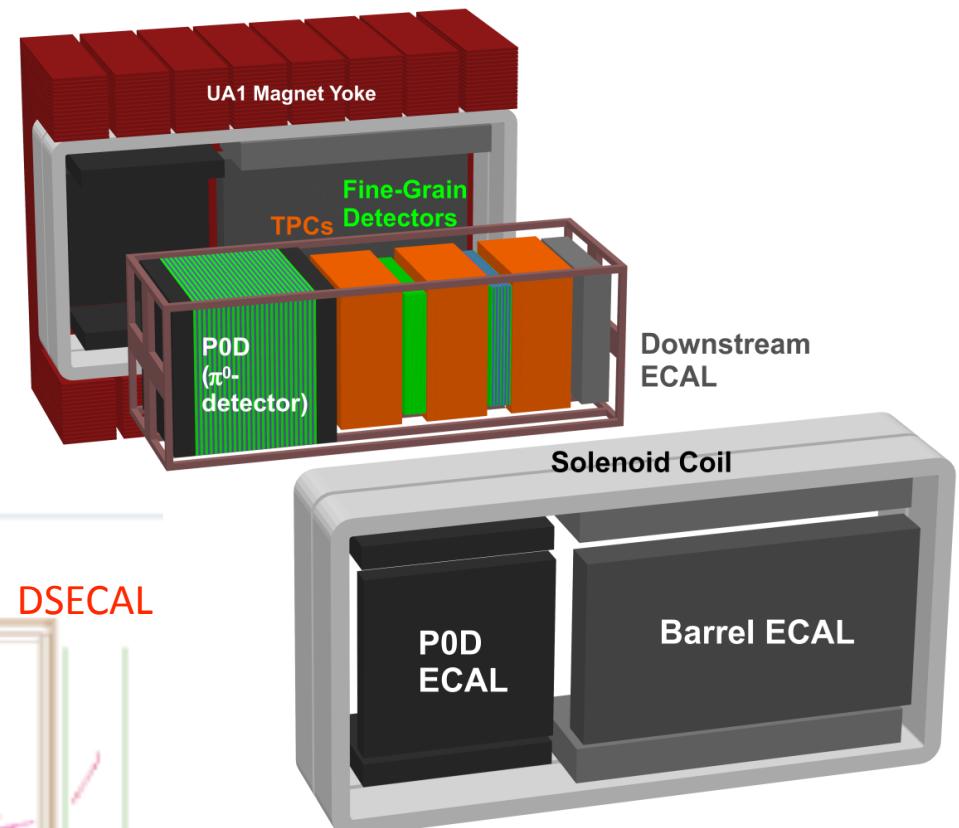


ND280 off-axis

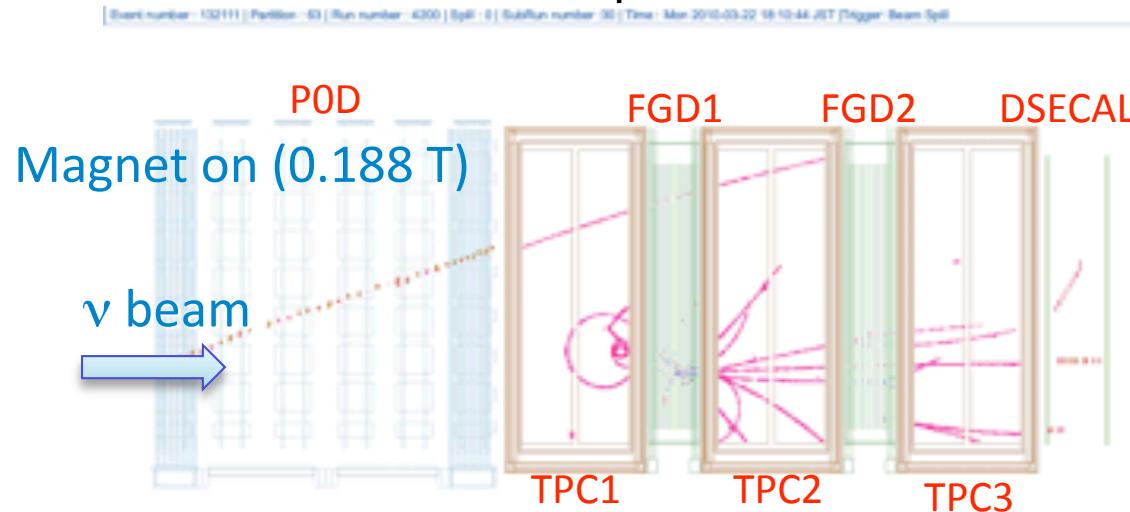


Almost no bad channels

System	Channels	Bad chan.	Fraction
DSECAL	3400	11	0.3%
SMRD	4016	3	0.07%
P0D	10400	7	0.07%
INGRID	8360	8	0.1%
TPC	124416	12	0.01%
FGD	8448	55	0.7%

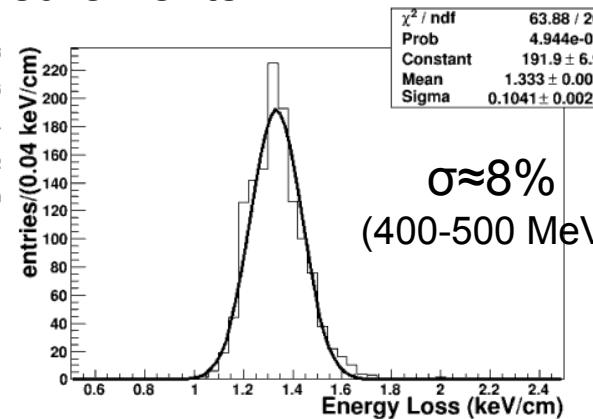
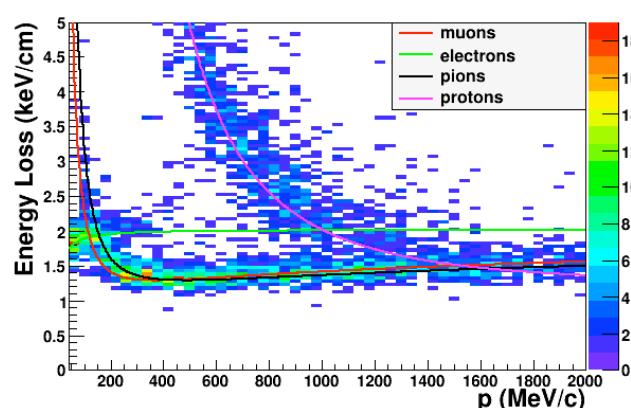


ND280 example event

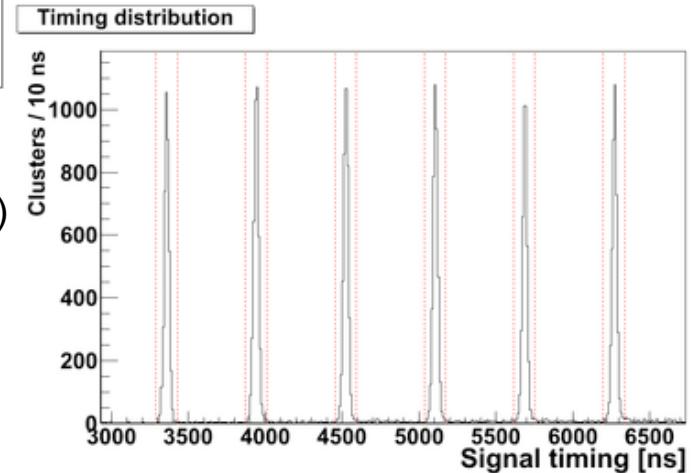


18:10 JST, Mar. 22, 2010

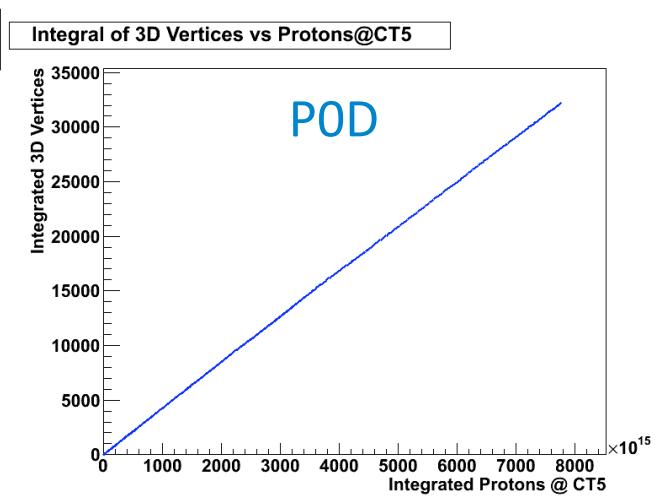
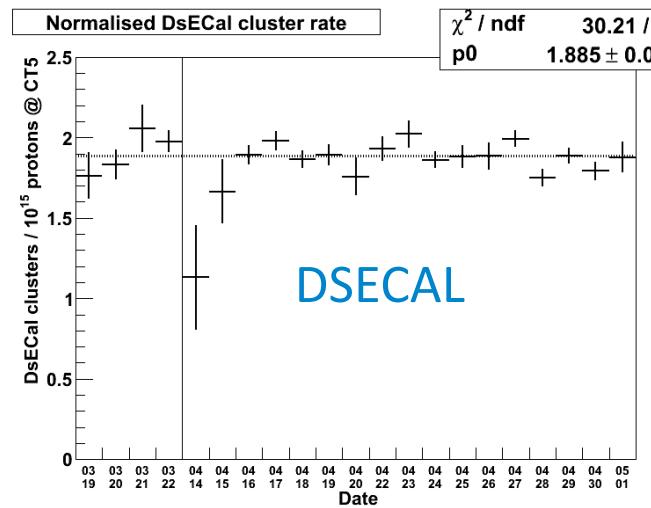
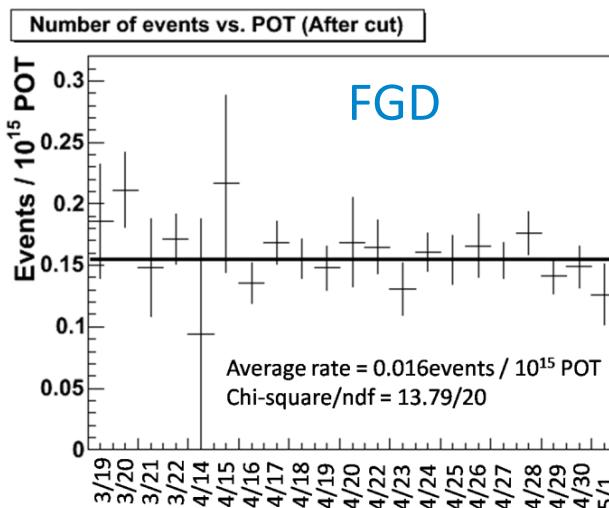
TPC dE/dx measurements



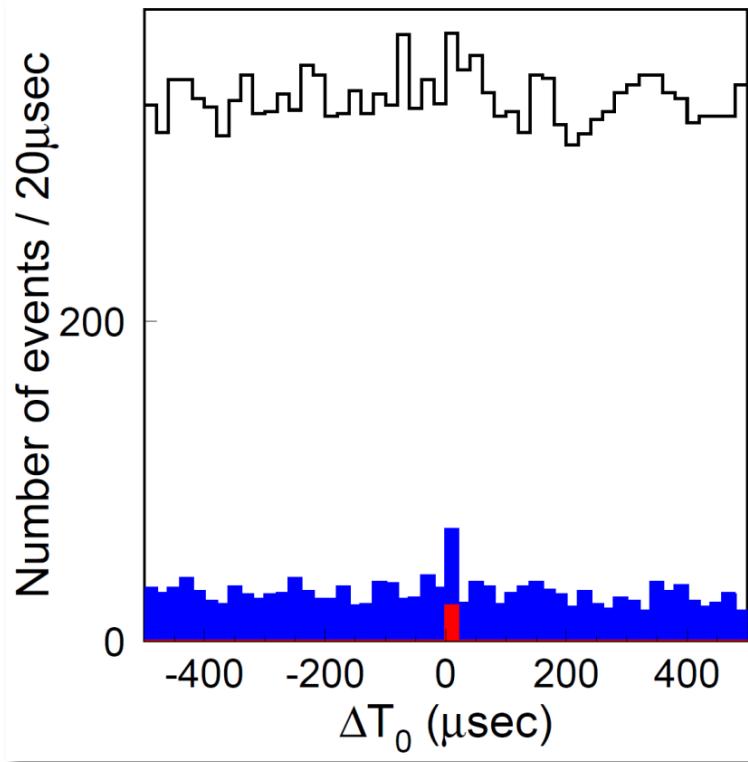
FGD Cluster Timing



Event rates in all subdetectors are stable



33 observed FC events

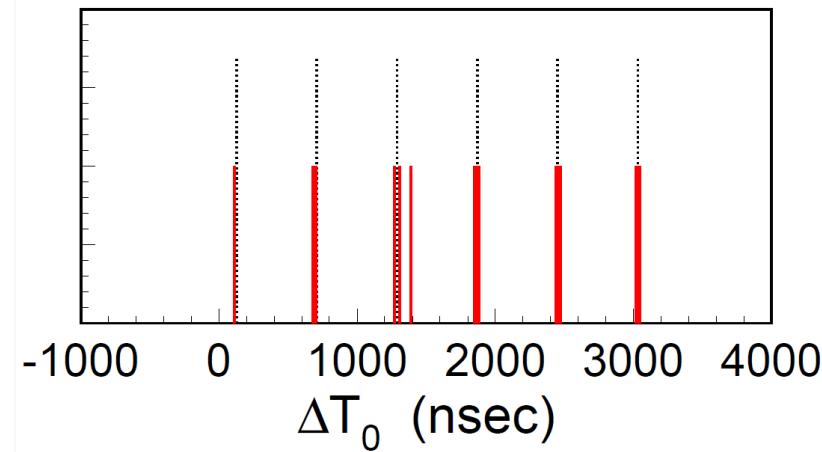


LE: Low energy triggered events

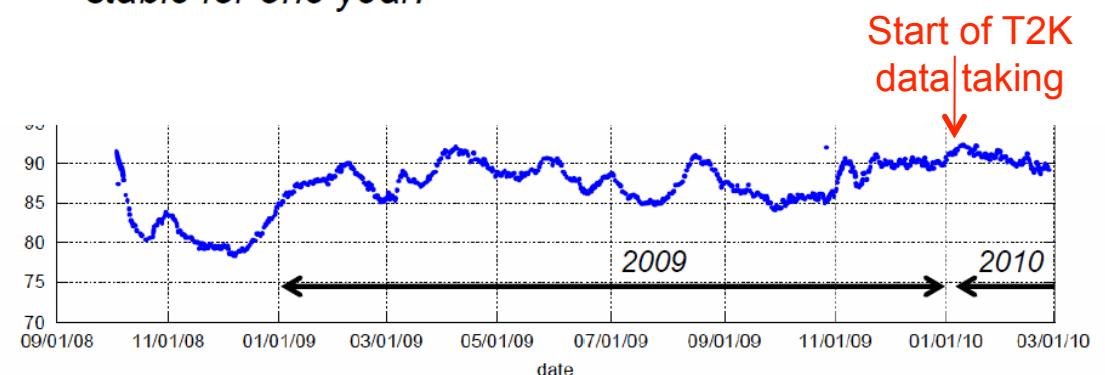
OD: Outer detector events

FC: Fully contained events

Beam structure in event timing



- SK detector is really stable and of high efficiency
 - SK efficiency during beam run is >99% in run 29 and 30.
 - Water quality (light attenuation length) is 90m and is stable for one year.



Summary and Outlook



- Construction completed Mar.2009 as scheduled
- First beam on Apr.23, 2009
- Data taking for oscillation search started in Jan. 2010
 - Continuous operation at ~50kW level
 - Accumulated 3.28E19 protons
 - Observed # of FC events: 33
- After summer shutdown: go from ~100kW towards design power
- Intensive analysis efforts underway to extract physics
- Goals:
 - Accumulate $3.75 \text{ MW} \cdot 10^7 \text{ sec}$
 - Discover ν_e appearance
 - $\sin^2 2\theta_{13}$ down to 0.018 (3σ)
 - Precise measurement of ν_μ disappearance
 - $\delta(\Delta m_{23}^2) \approx 0.1 \cdot 10^{-3} \text{ eV}^2$, $\delta(\sin^2 2\theta_{23}) \approx 1\%$ at 90% C.L.

Backup

SK event selection



- J-PARC neutrino events selected by event timing using GPS
- SK analysis is very well established
 - almost 20 years of experiences with Water Cherenkov detector
- Event selection & cut values are fixed already -> **UNBIASED SELECTION**

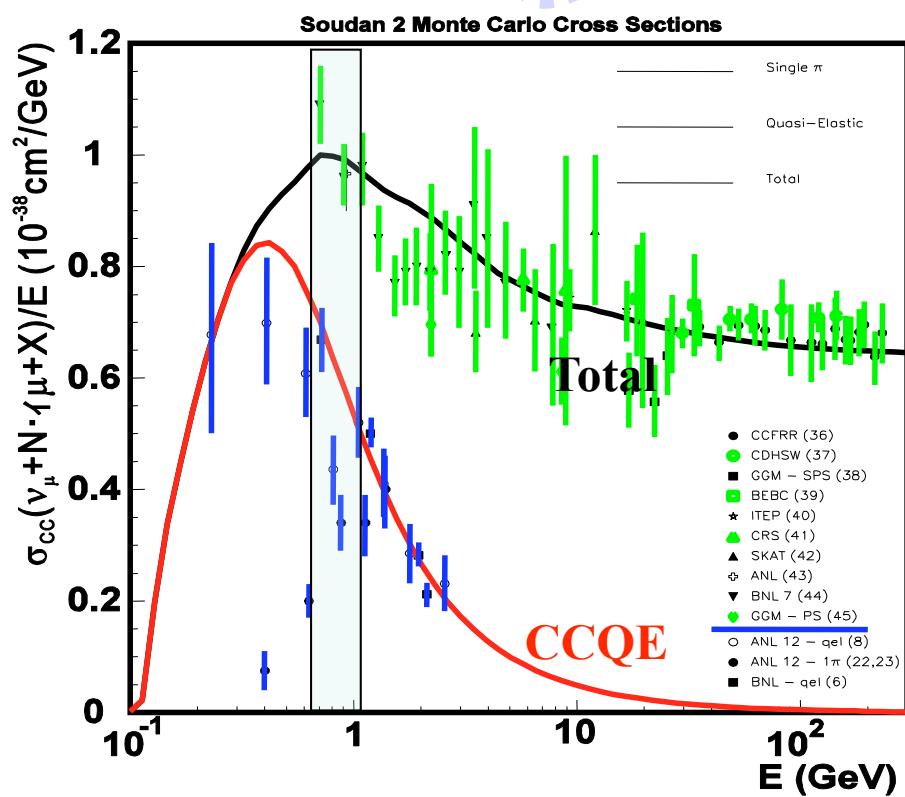
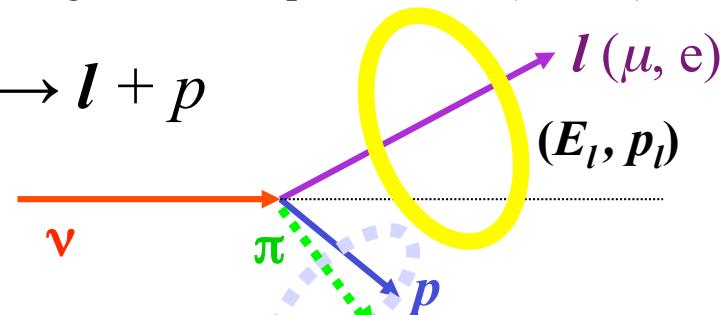
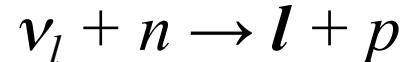
Selection criteria

For ν_μ disappearance analysis	For ν_e appearance search
Timing coincidence with beam timing (+TOF)	
Fully contained (No OD activity)	
Vertex in fiducial volume (Vertex >2m from wall)	
$E_{\text{vis}} > 30 \text{ MeV}$	$E_{\text{vis}} > 100 \text{ MeV}$
# of ring = 1	
μ -like ring	e -like ring
	No decay electron
	Inv. mass with forced-found 2 nd ring < 105MeV
	$E_{\nu}^{\text{rec}} < 1250 \text{ MeV}$

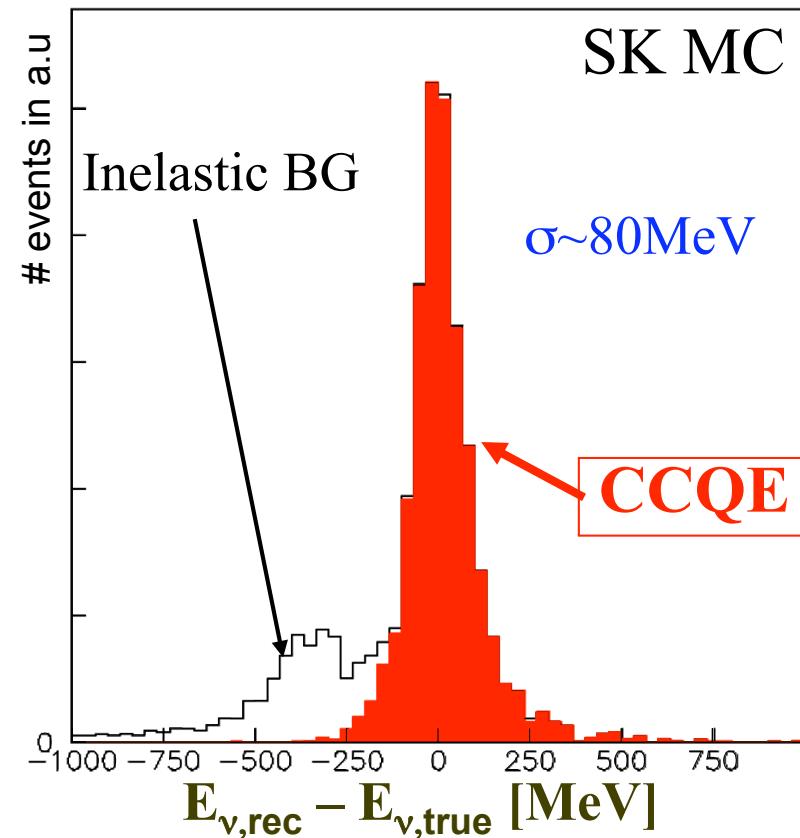
E_ν reconstruction in water Cherenkov



Assume Charged current quasi elastic (CCQE) reaction



$$E_\nu = \frac{m_N E_l - m_l^2/2}{m_N - E_l + p_l \cos\theta_l}$$



What is needed to reach our goal?



- $\nu_{e,\mu}$ reconstruction capability
 - discriminate well ν_μ against ν_e
 - understand background, e.g. π^0 , beam ν_e contamination
-> 10% requirement
- Energy reconstruction in order to determine phase of oscillation (Δm^2)
- Knowledge on ν flux for determining amplitude of oscillation ($\sin^2 2\theta$)
 - NA61/SHINE
 - ND280
- Cross sections for sub-GeV neutrinos

