The T2K experiment: Status & Future plan

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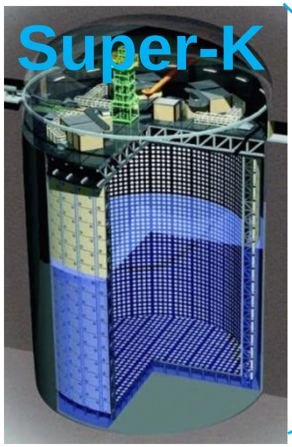
(on behalf of the T2K collaboration)

La Thuile 2011, March 1, 2011

T2K (Tokai to Kamioka)



50-kt water Cherenkov
(22.5 kt fiducial)

30-GeV 750-kW proton beam

- **Long baseline neutrino oscillation experiment**
  - Intense ν_μ beam at J-PARC
  - Near (280 m) /far (295 km) neutrino detectors, ND280/Super-K
- **Goals**
  - Search for $\boldsymbol{\nu_\mu} \rightarrow \boldsymbol{\nu_e}$ (ν_e appearance)
  - Precise measurement of $\boldsymbol{\nu_\mu} \rightarrow \boldsymbol{\nu_x}$ (ν_μ disappearance)

T2K collaboration

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

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
U. Aachen

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

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
U. Silesia, Katowice
T. U. Warsaw
U. Warsaw
U. Wroclaw

Russia
INR

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

Spain
IFIC, Valencia
U. A. Barcelona

Switzerland
ETH Zurich
U. Bern
U. Geneva

UK
Imperial C. L.
Lancaster U.
Liverpool U.
Queen Mary U. L.
Oxford U.
Sheffield U.
STFC/RAL
STFC/Daresbury
Warwick U.

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

Host institutes: ICRR KEK

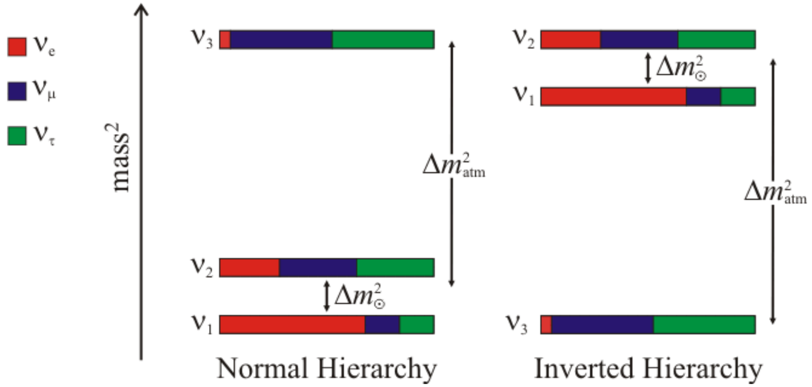
~500 collaborators
59 institutions, 12 countries

Neutrino oscillation

flavor states ≠ mass states

ν mixing ~ 3×3 unitary matrix U_{PMNS}

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



U_{MNS}: 3 mixing angles (θ_{12}, θ_{23}, θ_{13}) + 1 CP phase (δ)
2 mass differences ($\Delta m_{ij}^2 = m_i^2 - m_j^2$)

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

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

What we know so far (90 % C.L.)

- **(1,2)**: $\theta_{12} = 34.4^{+1.3}_{-1.2}$ °, $\Delta m_{12}^2 = 7.59^{+0.19}_{-0.21} \times 10^{-5}$ eV^2 (solar + reactor)
- **(2,3)**: $\theta_{23} = 37^\circ \sim 45^\circ$, $\Delta m_{23}^2 = 2.43 \pm 0.13 \times 10^{-3}$ eV^2 (atmospheric + accelerator)
- **(1,3)**: only upper limit, $\theta_{13} < 11^\circ$ (reactor(CHOOZ) + accelerator)
- δ **/sign of Δm_{atm}^2** : no information

Neutrino oscillation: T2K goals

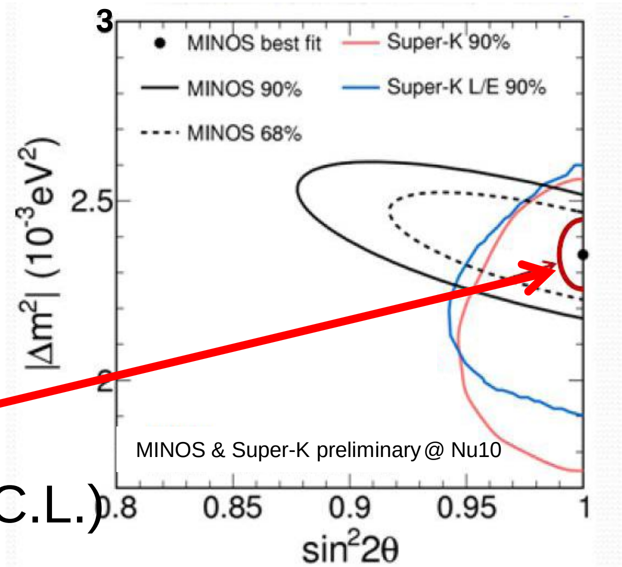
- **ν_μ disappearance**

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2\left(1.27\Delta m_{23}^2 \frac{L}{E}\right)$$

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

T2K goal w/ 3.75 MW × 10^7s:

$\delta(\Delta m_{23}^2) \sim 1 \times 10^{-4}$ eV^2, $\delta(\sin^2 2\theta_{23}) \sim 1\%$ (90% C.L.)



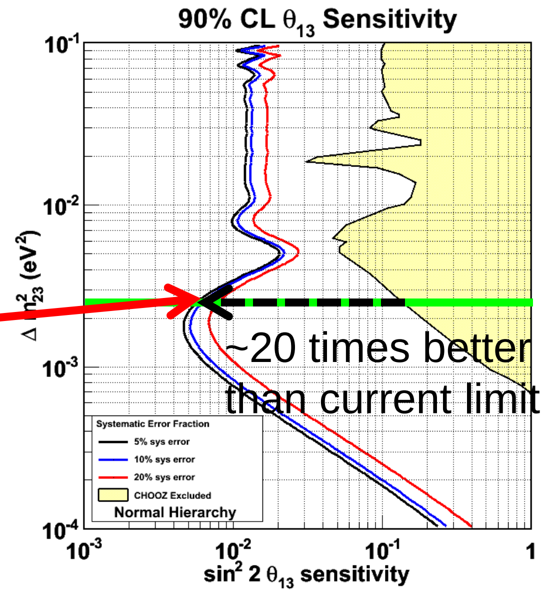
- **ν_e appearance**

$$P_{\mu\to e} \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(1.27\Delta m_{13}^2 \frac{L}{E}\right)$$

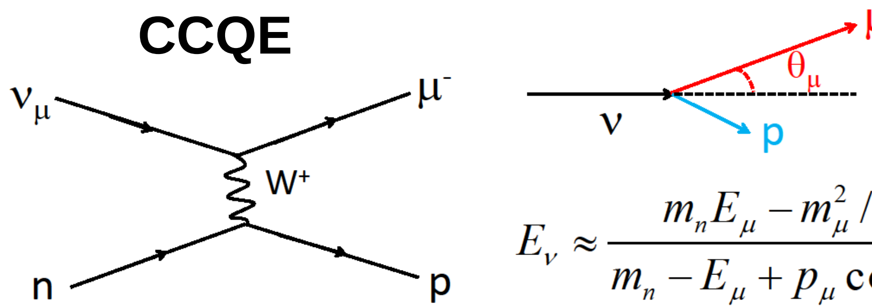
T2K goal w/ 3.75 MW × 10^7s:

$\sin^2 2\theta_{13}$ down to 0.006 (90% C.L.)

($\Delta m^2 \sim 2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1$, $\delta_{CP}=0$, normal hierarchy, 10% syst. error.)



Off-axis beam



$$E_\nu \approx \frac{m_n E_\mu - m_\mu^2/2}{m_n - E_\mu + p_\mu \cos\theta_\mu}$$

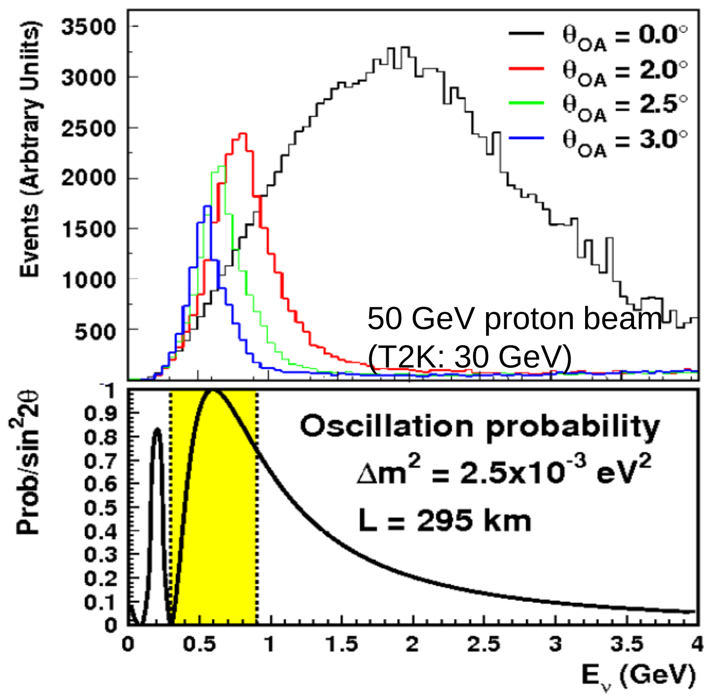
- **T2K**
  - **Oscillation maximum:** L=295km, $\Delta m_{23}^2 \sim 2.4\times10^{-3}$ eV^2 → **E_ν ~ 0.6 GeV**
  - **Signal:** Charged Current Quasi Elastic events(dominant at E_ν ~ 0.6 GeV)
  - **Major background:** Higher energy events with unobserved energy

    → Can be suppressed by off-axis beam configuration

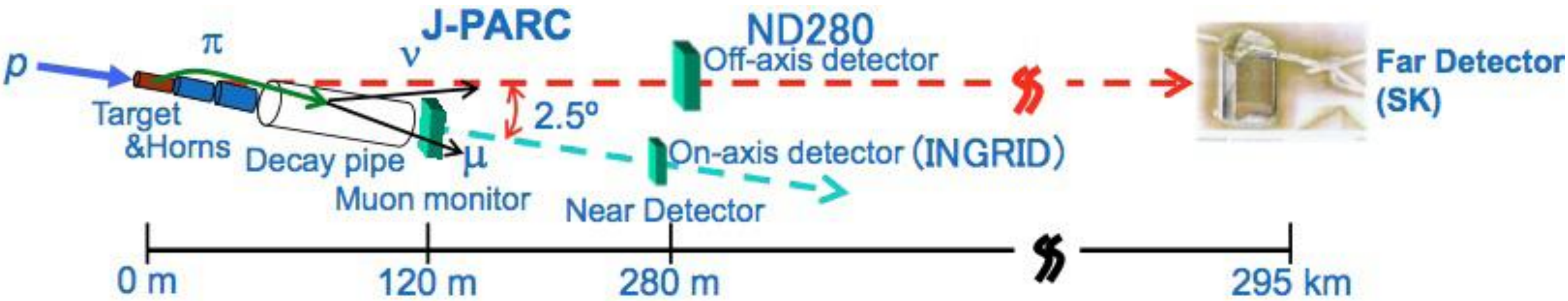
- **E_ν spectrum vs angle**
  - On-axis: large tail at high energy
  - Off-axis: narrow spectrum

    in interesting E_ν region

- **Our choice: off-axis angle = 2.5°**
  - Increase flux at the oscillation maximum
  - Reduce high energy ν background from non-CCQE events

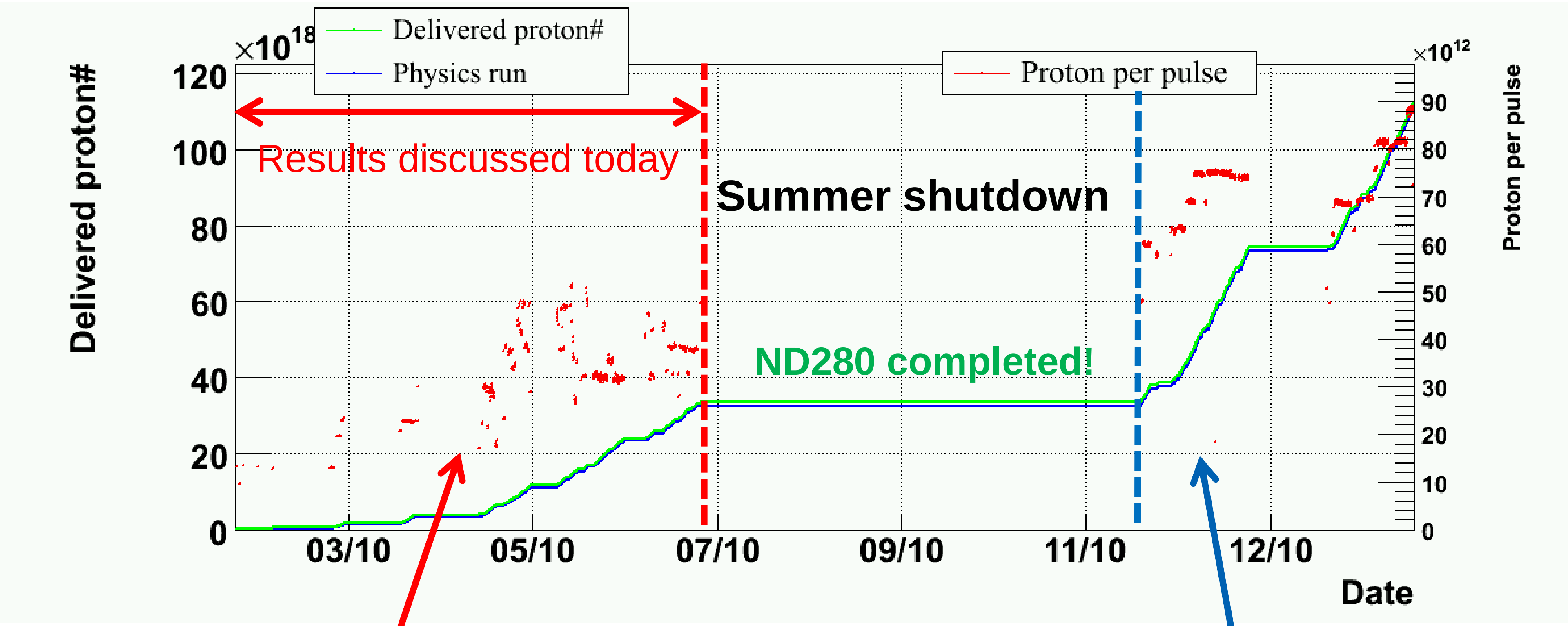


T2K overview



- **Beam monitoring**
  - Primary proton beam monitors (intensity, position, profile)
  - Muon monitor just after decay pipe: beam direction/intensity
- **Near detector@280m**
  - INGRID on-axis: ν beam direction/intensity
  - ND280 off-axis: ν flavor/flux/spectrum/"cross section" measurement
- **Off-axis far detector @295km**
  - Super-Kamiokande: ν flavor/flux/spectrum measurement

Delivered protons



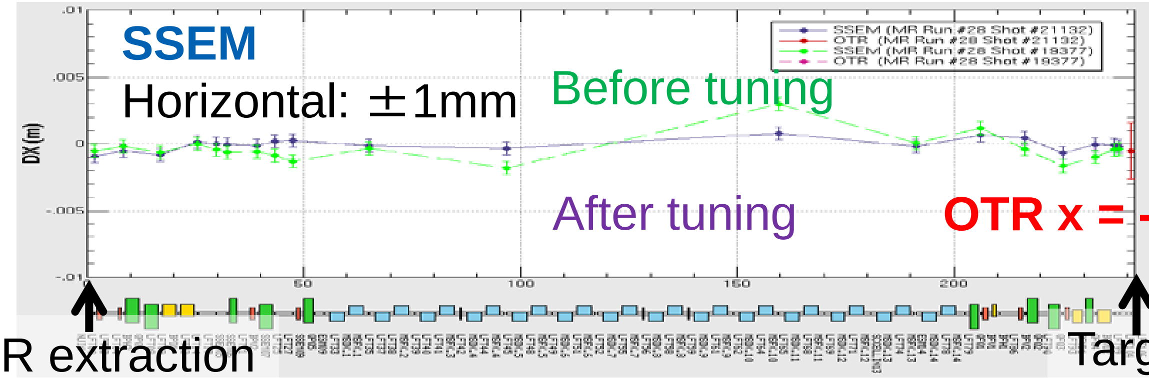
T2K run 1 (Jan. to Jun. 2010)
- **6 bunches/spill**, **3.5 s** spill period
- 3.23×10^{19} POT for T2K analysis
- **~50 kW** operation

T2K run 2 (from Nov. 2010)
- **8 bunches** (new extraction kicker)
- **3.2 s** spill period
- Currently running at ~**135 kW**

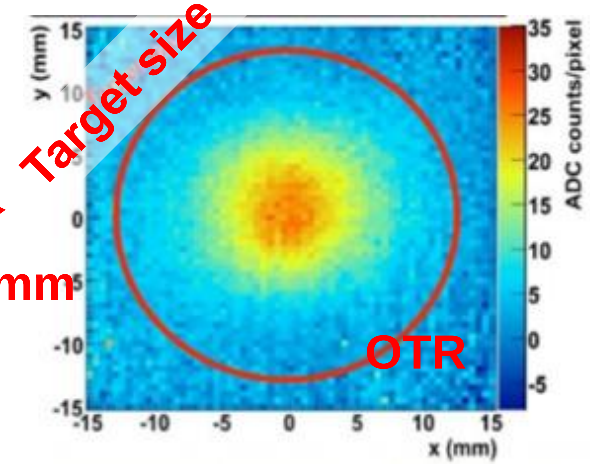
Beam monitor measurements (1)

Primary proton beam monitoring

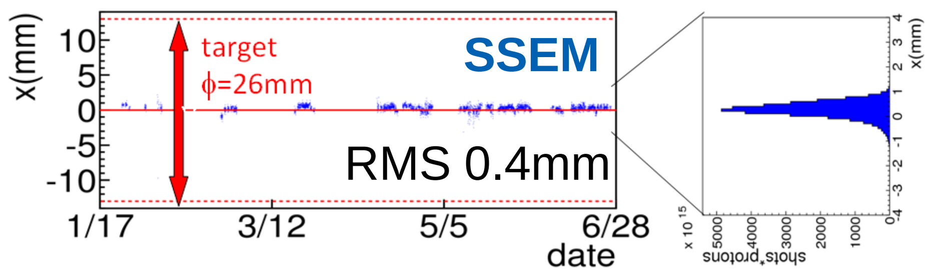
- **Beam orbit:** tuned within 2mm from design orbit.
  (Critical for controlling beam loss)

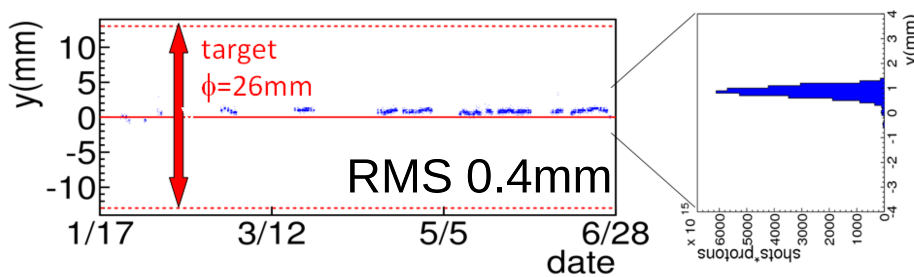


Proton beam hits center of target



- **Beam position on target:**
  Succeeded to control < 1mm during long term operation



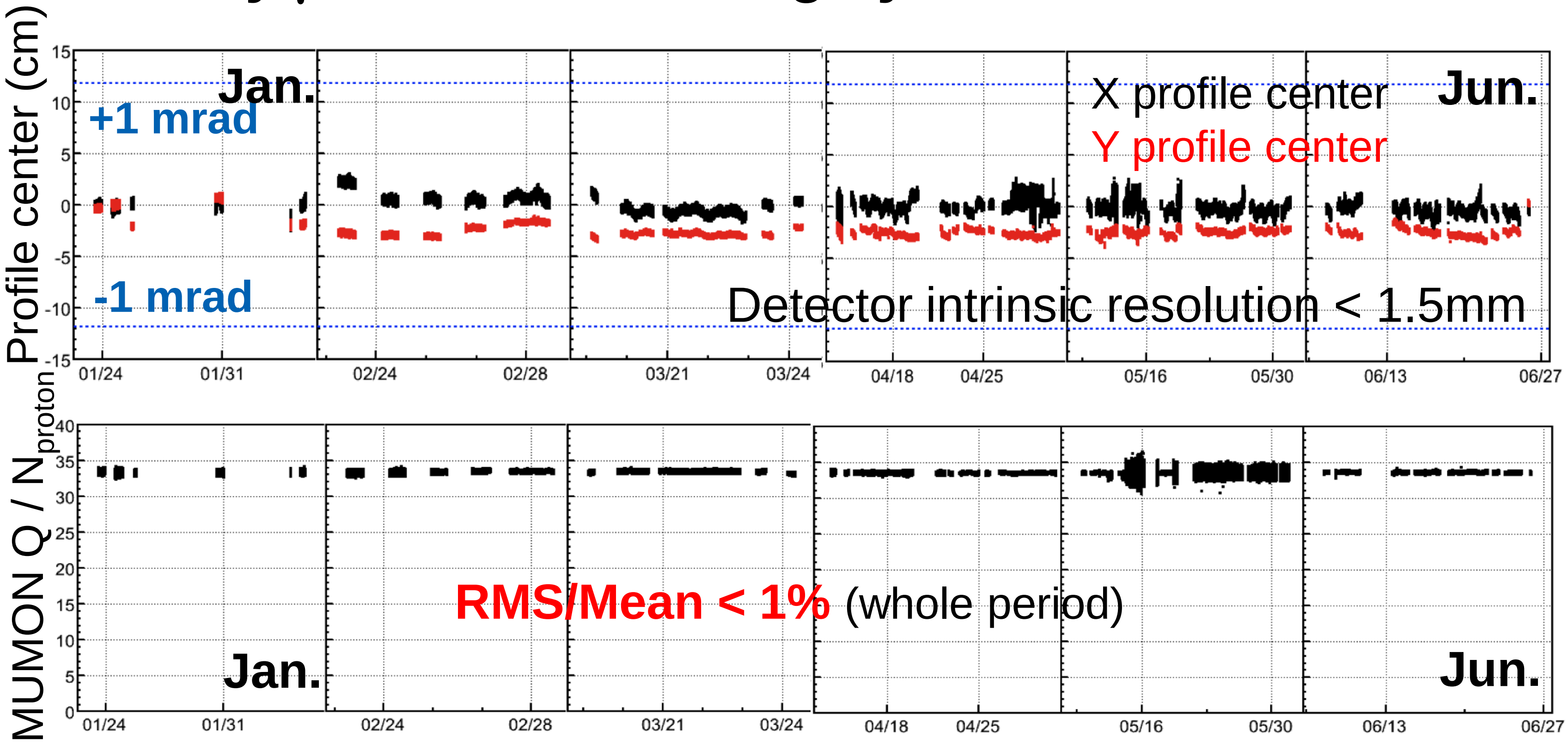


SSEM:
Segmented Secondary Emission Monitor

OTR:
Optical Transition Radiation detector

Beam monitor measurements (2)

Secondary μ beam monitoring by MUMON

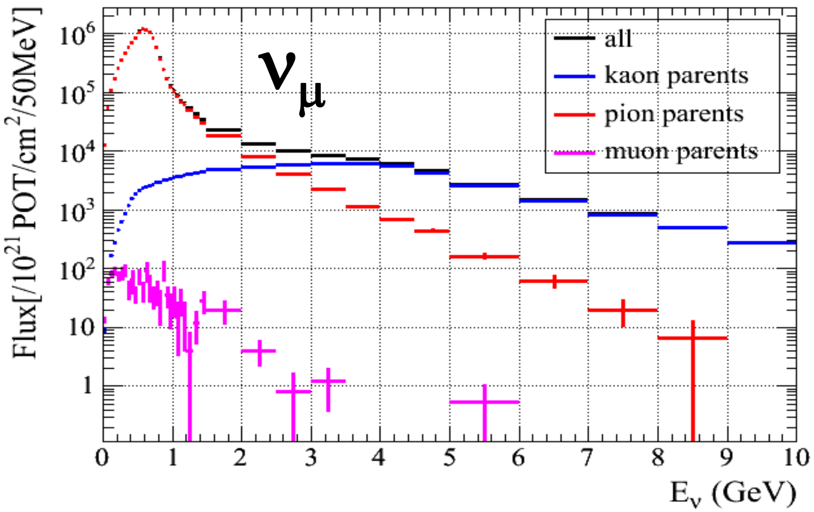


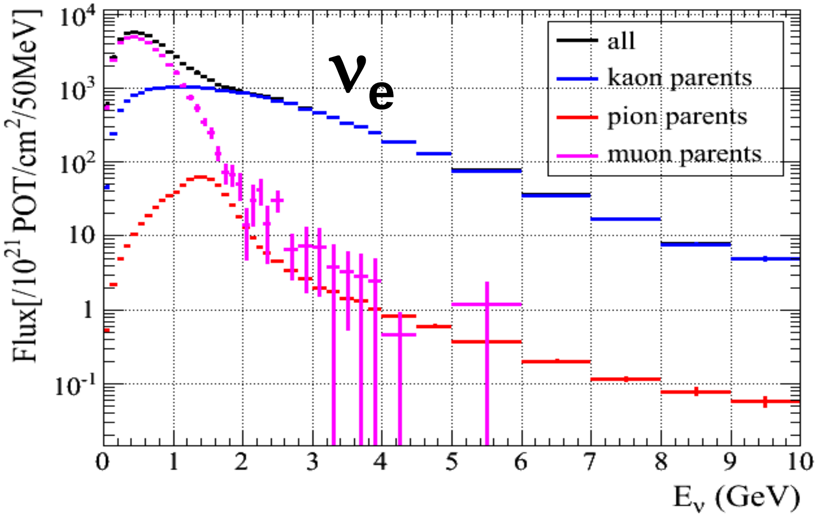
- **Beam direction** is controlled well within **1 mrad**. (1 mrad corresponds to 2% change in the SK flux at the peak energy, E_ν = 0.5 – 0.7 GeV)
- **Secondary beam intensity** (normalized by proton intensity) is stable within **1%** → reflects stability of targeting, horn focussing, etc

Flux prediction

- **T2K neutrino beam simulation**
  - Use information by beam monitor/horn measurements
  - Simulate Proton & Carbon interaction in target
    - Tune the pion production multiplicity and interaction rate based on the recent NA61/SHINE results
  - Track particles exiting from target
  - Simulate neutrino-producing decays

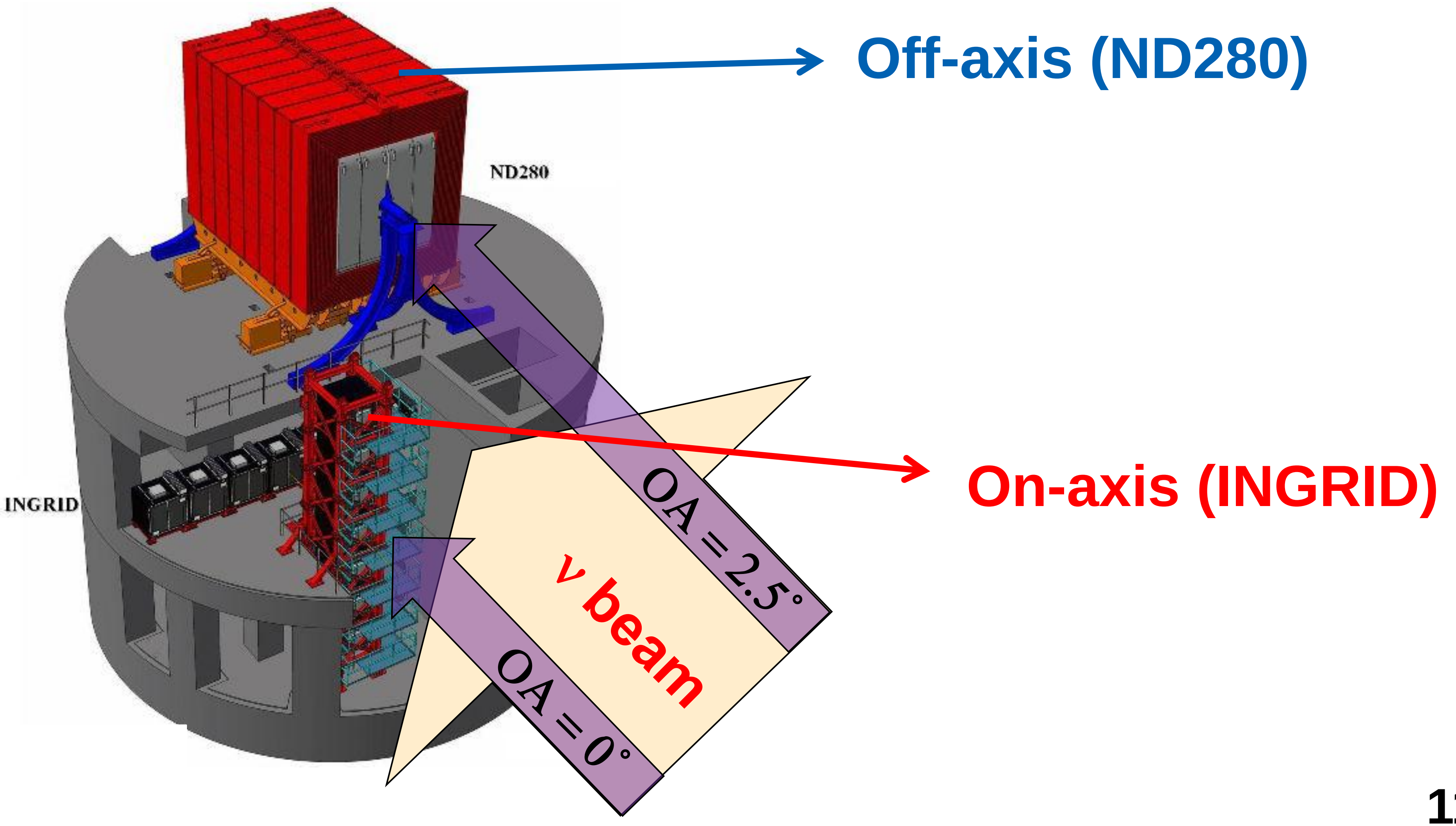
Predicted flux @ SK



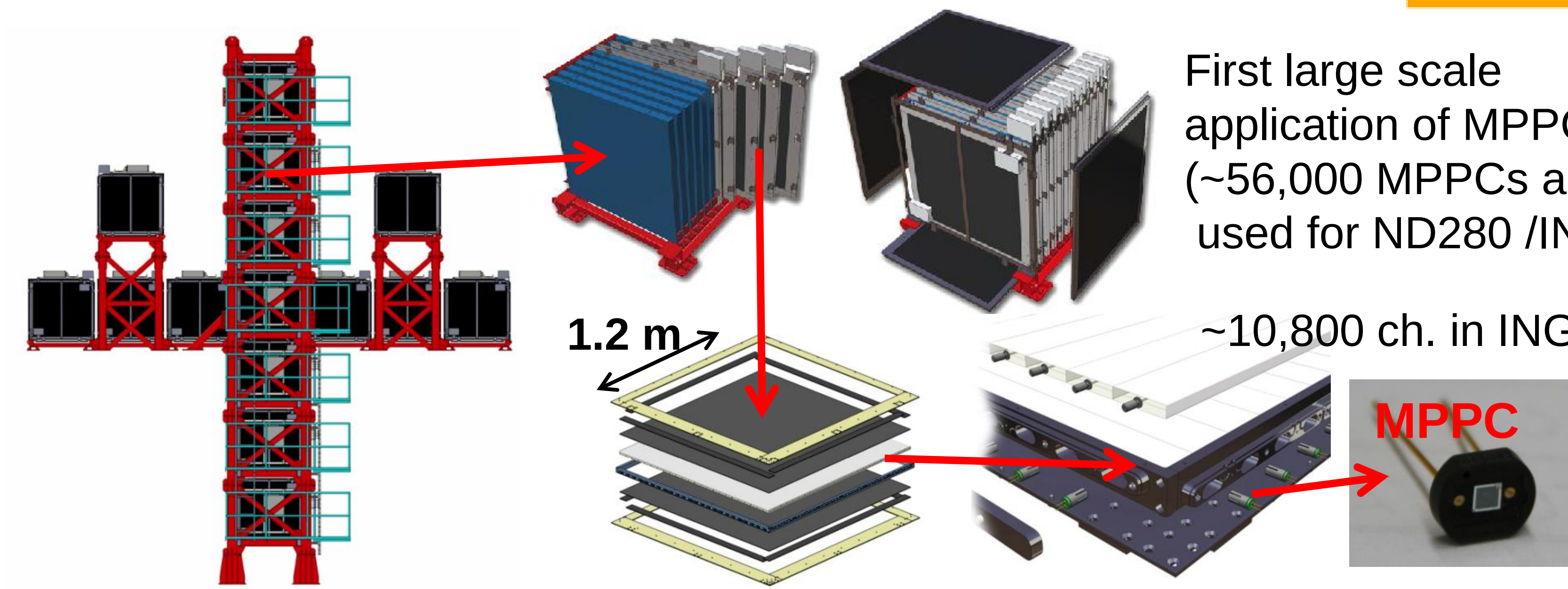


Near Detector at 280m (ND280)

ND280 pit: **280m from proton target**



On-axis neutrino beam monitor (INGRID)



First large scale application of MPPC (~56,000 MPPCs are used for ND280 /INGRID)

~10,800 ch. in INGRID

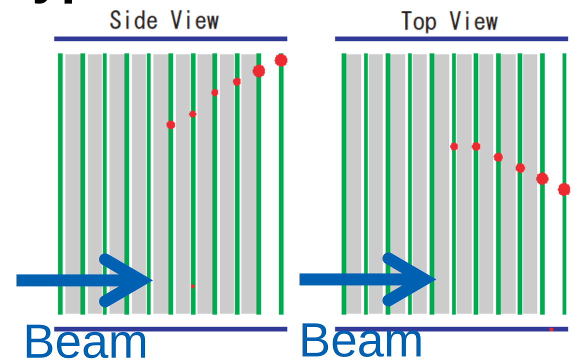
- **14 identical modules + 2 off-cross modules**
  - Beam coverage ~ **10×10 m^2**, Iron target mass ~ **7 ton/module**
  - Sandwiched scintillator/iron planes + veto planes
  - Plastic scintillator + WLS fiber + Multi-Pixel Photon Counter (MPPC)
- **Monitor neutrino beam profile/direction/intensity**
  - ~700 ν interactions/day at 50 kW operation
  - Off-axis angle precision goal is well better than 1 mrad. (1 mrad corresponds to 2% change in the SK flux at the peak energy)

INGRID measurements (1)

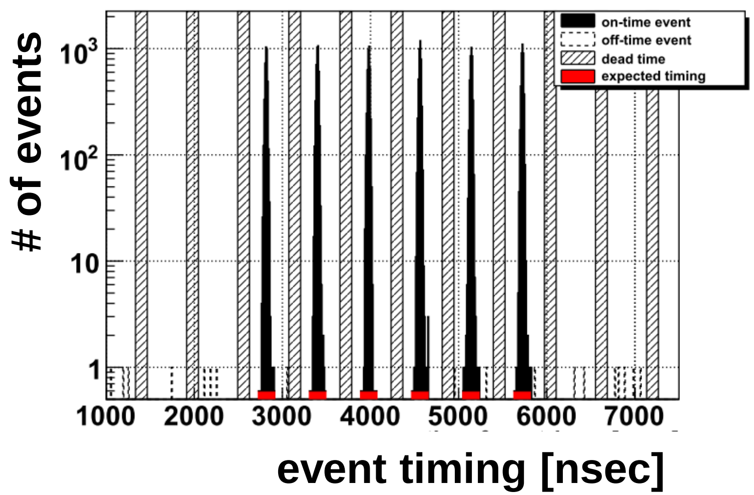
- **Data taking efficiency is 99.9 % during T2K run 1**
- **ν event selection:**

  (1) Tracking → **(2)** veto cut → **(3)** FV cut

Typical ν event

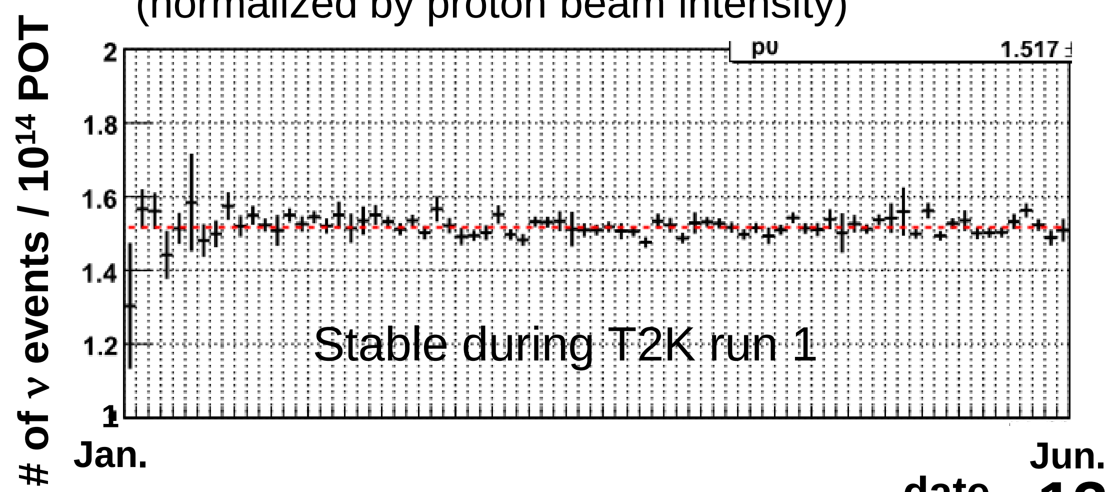


Event timing of ν events



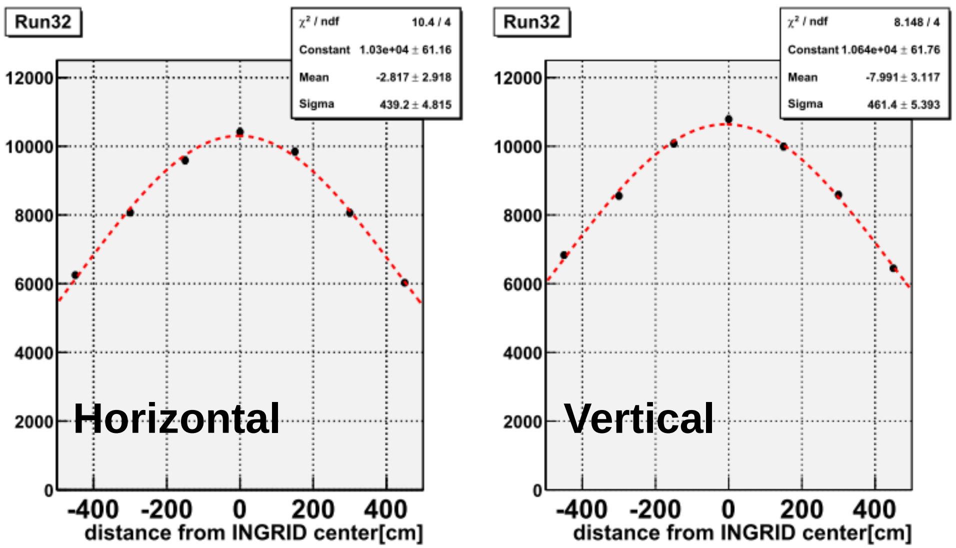
→ Clear 6 bunch structure
(581 ns bunch period)

ν beam intensity
(normalized by proton beam intensity)

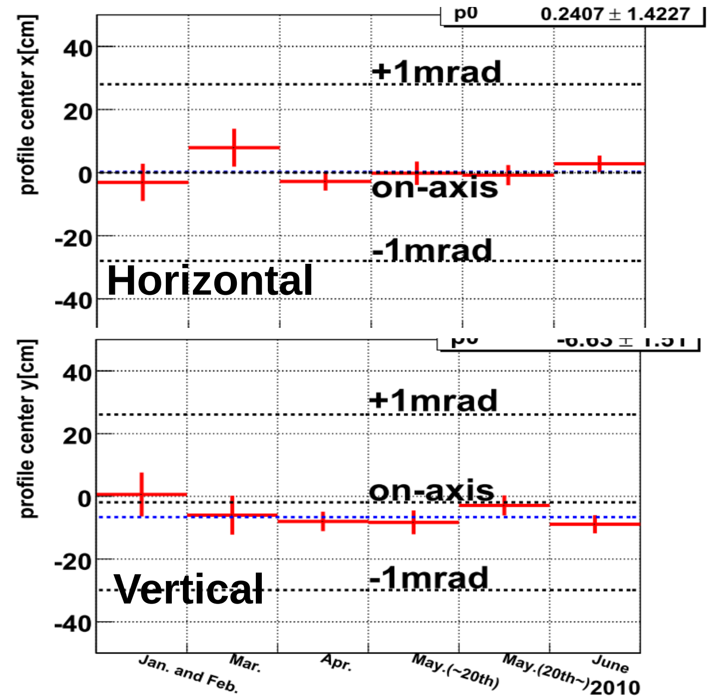


INGRID measurements (2)

ν beam profile



Profile center



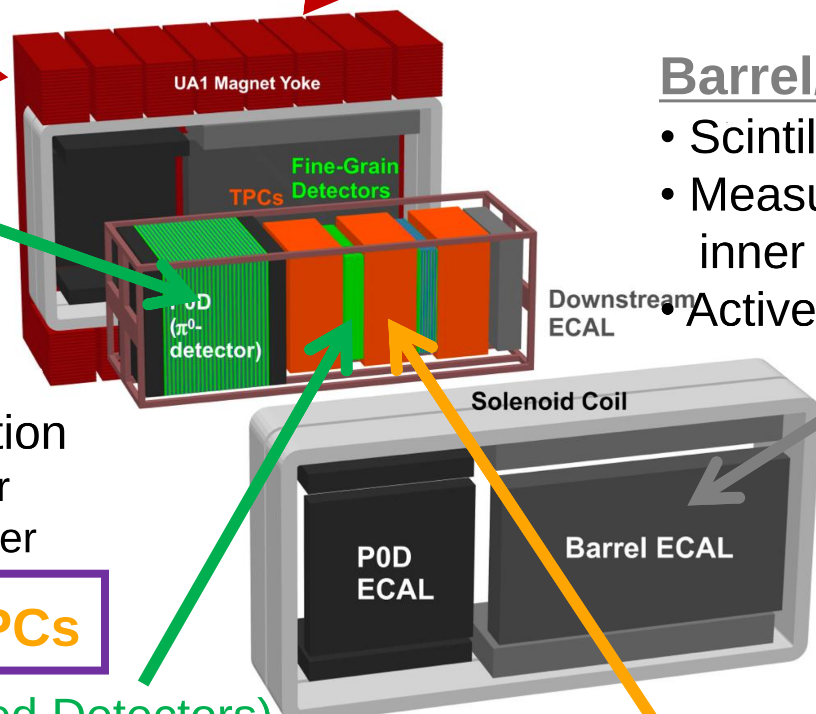
- **Beam center**
  Horizontal = +0.2 ± 1.4(stat.) ± 9.2(syst.) cm
  Vertical = +6.6 ± 1.5(stat.) ± 10.4(syst.) cm (0.1 degree = 49cm @ INGRID)
  → **Off-axis angle = 2.519 ± 0.021 degrees**
- **Event rate:** expectation vs. observation ($R_{data/MC} = N_{data} / N_{MC}$)
  → $R_{data/MC}$ **= 1.073 ± 0.001(stat.) ± 0.040(syst.)**

ND280 off-axis detector overview

Designed for measurement of
- Off-axis spectrum based on CCQE
- Beam ν_e contamination
- Super-K background (NC π^0)

UA1 Magnet
- **0.2 T**

SMRD (Side Muon Range Detector)
- Scintillator planes in magnet yoke
- Detect muons from inner detector
- Momentum measurement



Barrel/DownStream ECAL
- Scintillator planes with radiator
- Measure EM showers from inner detector (γ for NC π^0 etc)
- Active veto

P0D (π^0 Detector)
- Scintillator planes interleaved with water & lead/brass layers
- Optimized for γ detection
- Mass: 16.1 tons w/ water
  13.3 tons w/o water

Tracker: FGDs+TPCs

FGDs (x2) (Fine Grained Detectors)
- Provide full active target mass
- FGD1: Scintillator planes ~ 1 ton
  FGD2: Scinti. & water planes ~ 0.5 & 0.5 ton

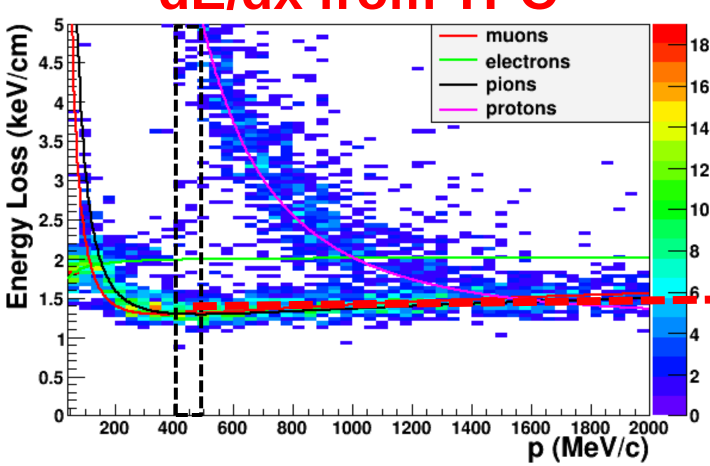
TPCs (x3) (Time Projection Chambers)
- Measure charged particles from FGD/P0D
- Good PID via dE/dx measurement

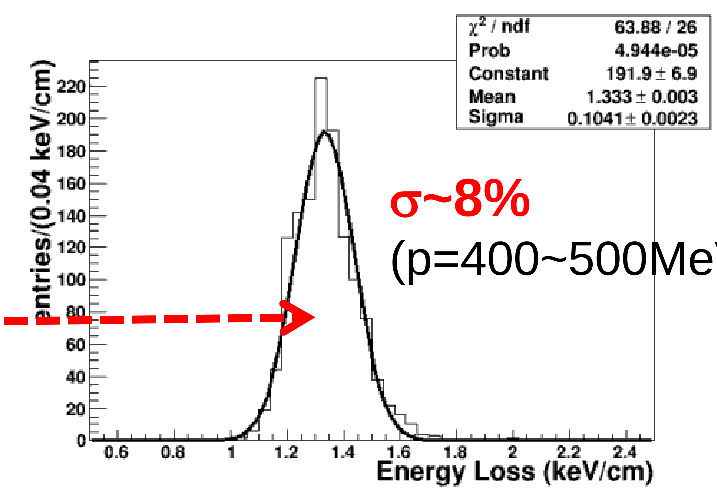
ND280 off-axis performance

Very small number of bad channels
(after ~1 year operation)

Detector	Channels	Bad ch.	Bad fraction
ECAL (DSECAL)	22,336 (3,400)	35 (11)	0.16% (0.32%)
SMRD	4,016	7	0.17%
P0D	10,400	7	0.07%
FGD	8,448	20	0.24 %
INGRID	10,796	18	0.17 %
TPC	124,416	160	0.13 %

dE/dx from TPC



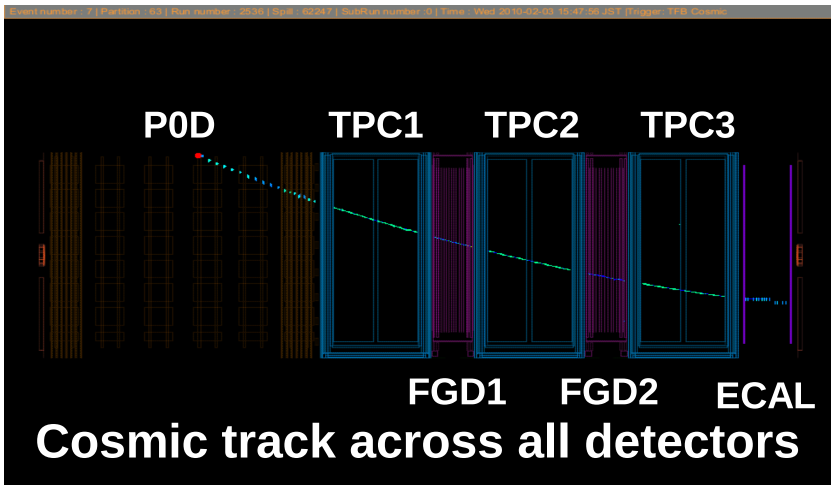


σ~8%
(p=400~500MeV/c)

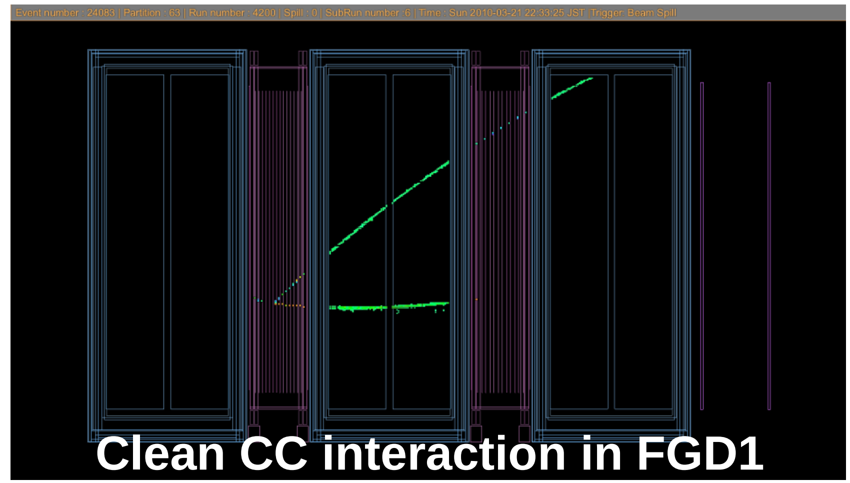
ND280 off-axis neutrino event display

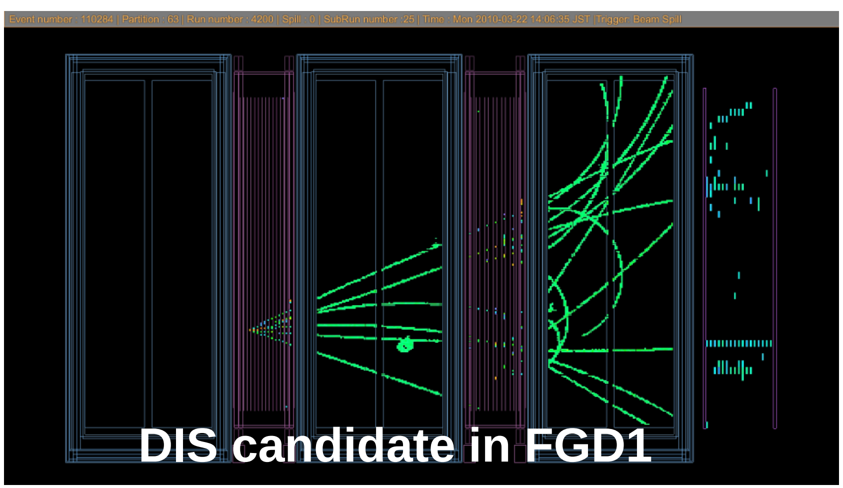
- **Data taking efficiency is 96.7 % during T2K run 1**

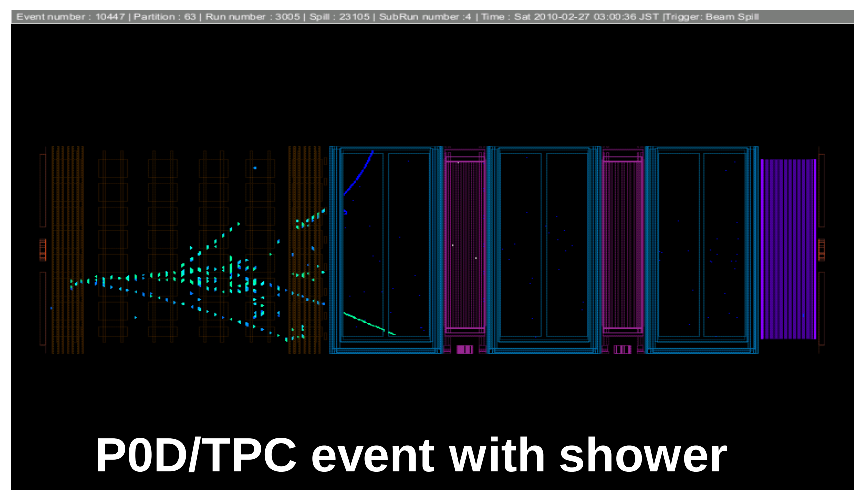
ND280 event displays



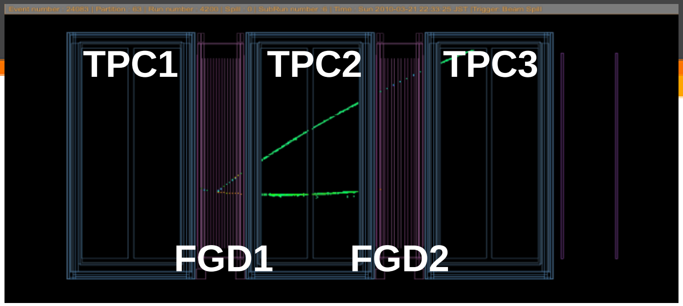
Cosmic track across all detectors


Clean CC interaction in FGD1


DIS candidate in FGD1


P0D/TPC event with shower

ND280 off-axis CC measurement w/ FGD and TPC

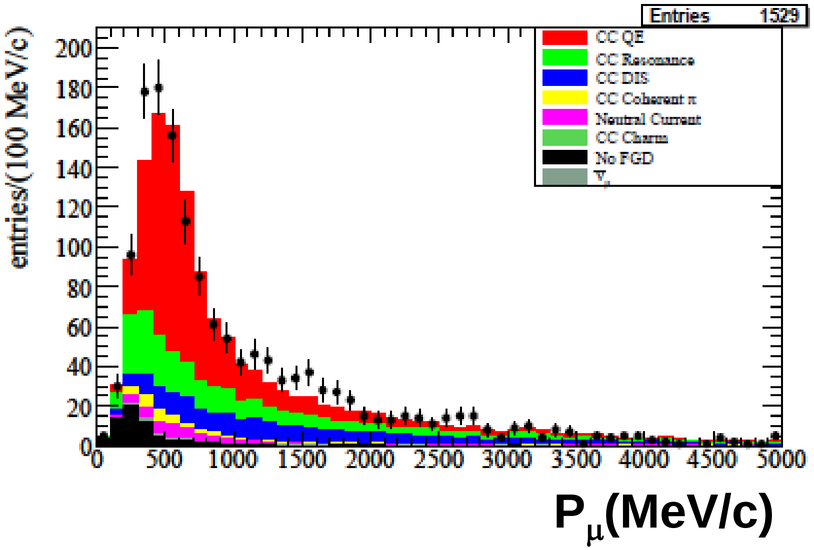


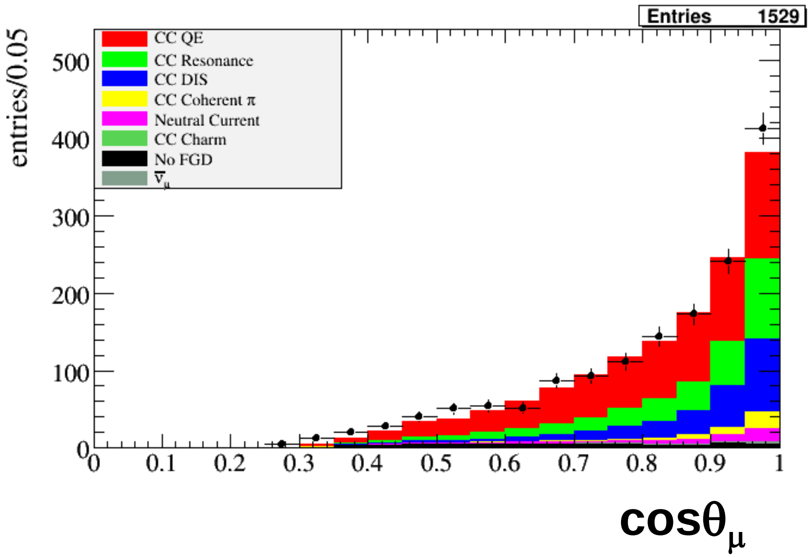
- **CC event selection**

  (1) TPC1 has no track

  (2) TPC2 (or 3) has ≥ 1 track with negative charge (to select μ)

  (3) Track in TPC2 (or 3) starts from FV of FGD1 (or 2)



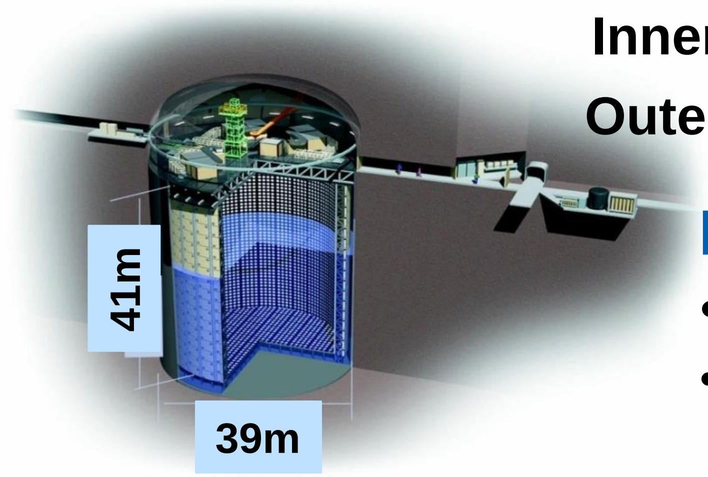


- **Event rate:** expectation vs. observation ($R_{data/MC} = N_{data} / N_{MC}$)

$$R_{data/MC} = 1.061 \pm 0.028\text{(stat.)} {}^{+0.044}_{-0.038} \text{(det. syst.)} \pm \text{under review (phys. model)}$$

Far detector: Super-Kamiokande

50 kT Water Cherenkov detector (22.5 kT fiducial mass)



Inner detector: 11,129 PMTs (20 inch)

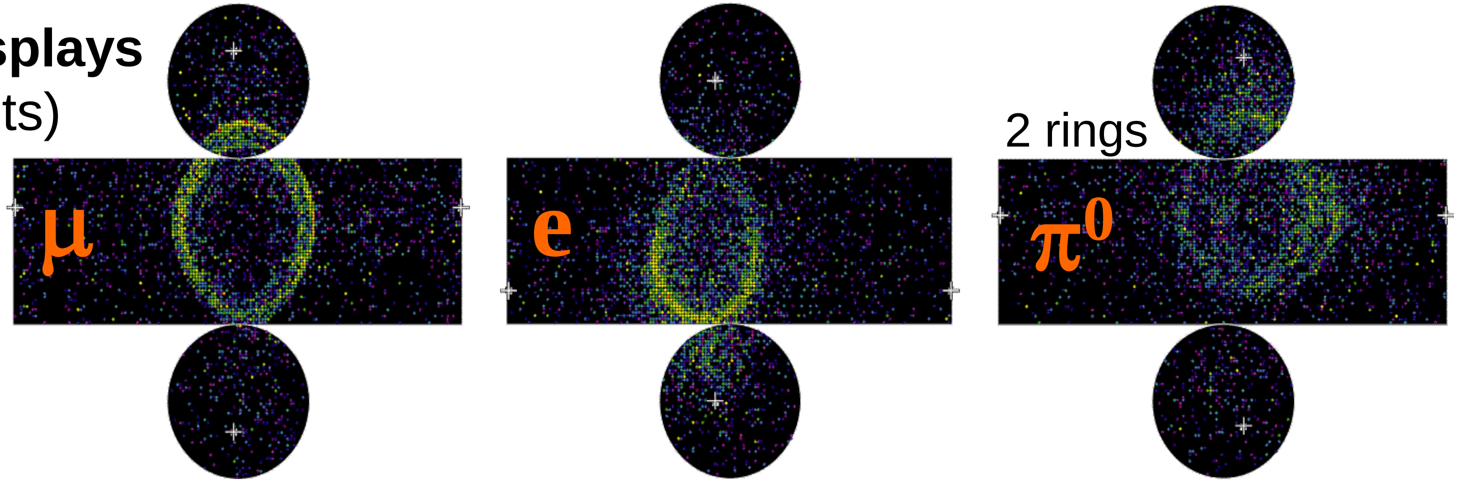
Outer detector: 1,885 PMTs (8 inch)

New electronics/DAQ (since 2008)

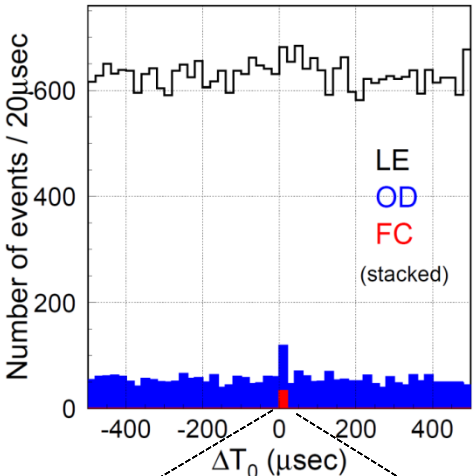
- Stably running
- Deadtime-less DAQ
  → Improve e-tagging (from μ decay) efficiency

Good e-like(shower ring)/μ-like separation: mis-PID probability ~ 1%

Event displays
(MC events)



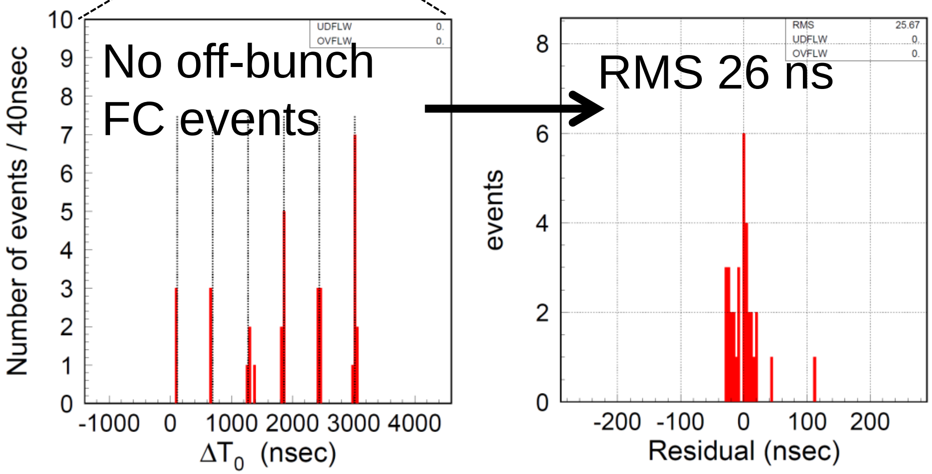
Observed T2K beam-induced events at SK



Identify beam-induced events with GPS

- Transfer beam spill information in real time
- Compare GPS time stamps of beam/SK trigger

LE: Low energy triggered events
OD: Outer detector events
FC: Fully contained events



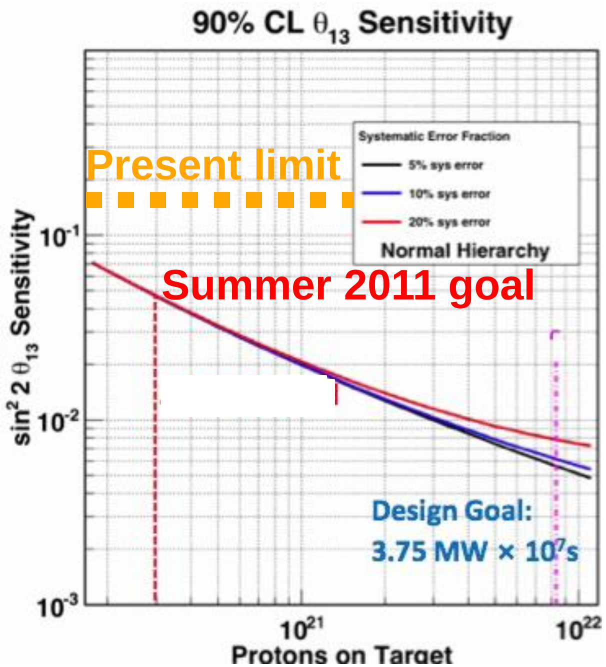
Cuts	Observed events	Expected BG
Fully Contained (FC)	33	~0.01
FC + FV cut + E_{vis} > 30 MeV	**23**	~0.001

ΔT_0=SK trigger time
- beam trigger time

Summary and outlook

- **T2K run 1:** Jan. – Jun. 2010
  - Continuous beam at **~50 kW**, accumulated **3.23×10^{19} POT**
  - Observed **23 events (FCFV) at Super-K**
  - **First physics results soon!**
- **T2K run 2:** Nov. 2010 – summer 2011
  - Currently running at **135 kW**
  - Goal: **150 kW x 10^7 s (~3×10^{20} POT)**

    $\sin^2(2\theta_{13}) < 0.05$ (90% C.L. sensitivity)



- **T2K Goal**
  - Accumulate **3.75 MW $\times10^7$ s**
  - **Discover ν_e appearance**: $\sin^2 2\theta_{13}$ down to 0.006 (90% C.L.)
  - **Precise measurement of (2,3):** $\delta(\Delta m_{23}^2) \sim 1\times10^{-4}$ eV^2, $\delta(\sin^2 2\theta_{23}) \sim 1\%$

Backup slides

- Presentation: 20min.
- Q&A: 5min.

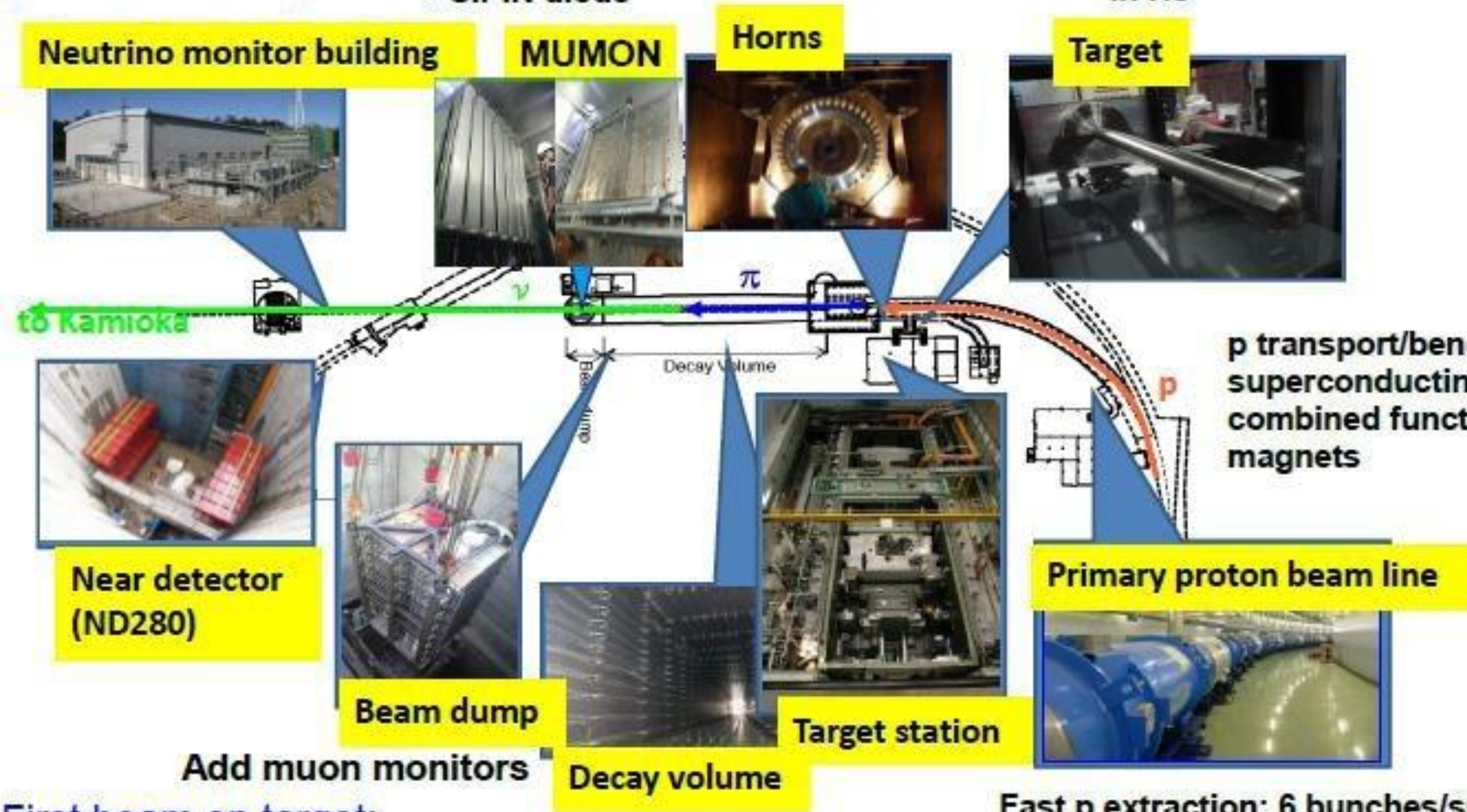
Neutrino Beam Facility

Conventional beam:
$p+C \rightarrow \pi \rightarrow \nu+\mu$

Muon monitors:
Ionization chambers
+ SiPIN diode

3 focusing horns
(250 kA)

Target:
graphite (ø26mm x 90cm)
in He



p transport/bending:
superconducting
combined function
magnets

Add muon monitors

First beam on target:
April 23, 2009

Decay volume (110 m)
He filled

Fast p extraction: 6 bunches/spill,
581 ns separation, 3.5 s spill period

T2K oscillation analysis strategy

N_{SK}: number of reconstructed events at SK (* integral over E_ν^{true})

$$N_{SK}\left(E_\nu^{rec}\right) = \phi_{SK}^{\exp}\left(E_\nu^{true}\right) \times \sigma\left(E_\nu^{true}\right) \times P_{osc}\left(E_\nu^{true}\right) \times \varepsilon_{SK}\left(E_\nu^{true}\right) \times f\left(E_\nu^{rec}, E_\nu^{true}\right)$$

Beam flux | **Cross section** | **Oscillation probability** | **Detector efficiency** | **Detector response**

- **N_{SK} is predicted using**

ND280 flux

$$\phi_{ND} = N_{ND}^{obs} / \left(\sigma_{ND} \times \varepsilon_{ND}\right)$$

← **Normalization & Spectrum from Near detector measurement**

SK flux

$$\phi_{SK} = R_{SK/ND} \times \phi_{ND}$$

← **Hadron production measurement at NA61**

Far to Near extrapolation factor

Compare prediction with observation → **Oscillation parameters**