Nov. 11th, 2010
@IPMU

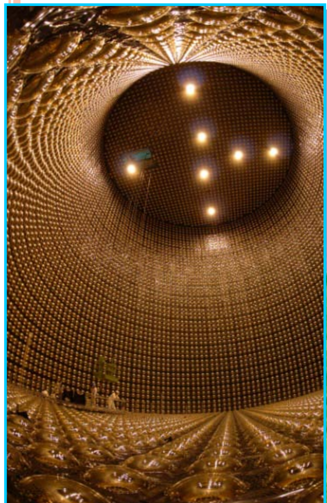
T2K and Beyond

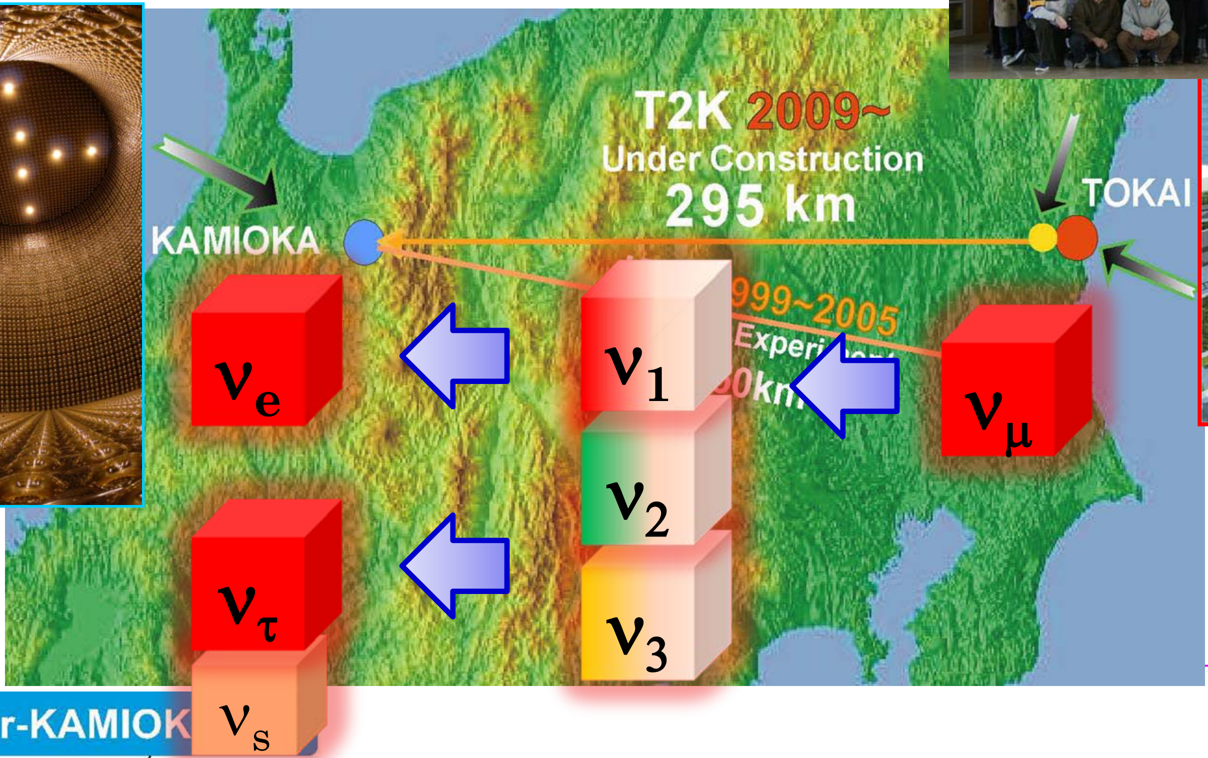
T. Nakaya (Kyoto,IPMU)

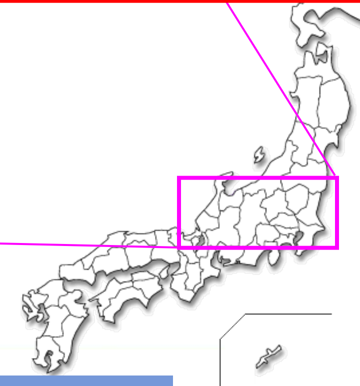
Outline

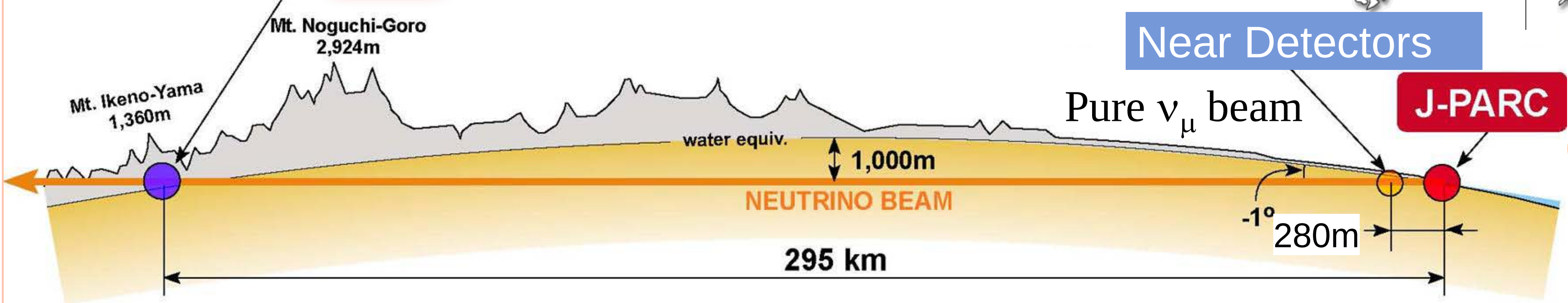
- Introduction to T2K
- Physics Sensitivity
- Experimental Overview
- T2K status
- Beyond

1. Introduction to T2K

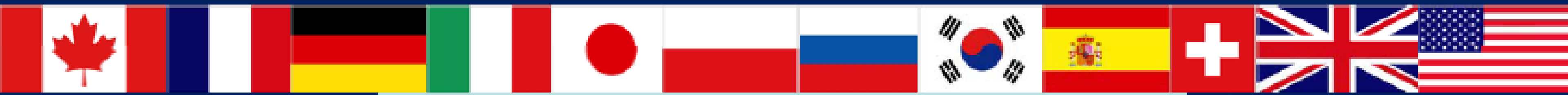








The T2K Collaboration



~500 members, 62 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
- Hiroshima U.
- 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. Wroklaw

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

BIRTH OF T2K

Letter of Intent:
A Long Baseline Neutrino Oscillation Experiment using the JHF 50 GeV Proton-Synchrotron and the Super-Kamiokande Detector

February 3, 2000

—V1.0—

JHF Neutrino Working Group

Y. Itow[1] , Y. Obayashi, Y. Totsuka
Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Tokyo 188-8502, Japan

Y. Hayato, H. Ishino, T. Kobayashi[2] , K. Nakamura, M. Sakuda
Inst. of Particle and Nuclear Studies, High Energy Accelerator Research Org. (KEK), Tsukuba, Ibaraki 305-0801, Japan

T. Hara
Department of Physics, Kobe University, Kobe, Hyogo 657-8501, Japan

T. Nakaya[3] , K. Nishikawa[4]
Department of Physics, Kyoto University, Kyoto 606-8502, Japan

T. Hasegawa, K. Ishihara, A. Suzuki
Department of Physics, Tohoku University, Sendai, Miyagi, 980-8578, Japan

[1] Super Kamiokande Contact Person: itow@suketto.icrr.u-tokyo.ac.jp
[2] Neutrino Beam Contact Person: kobayasi@neutrino.kek.jp
[3] Near Detector Contact Person: nakaya@scphys.kyoto-u.ac.jp
[4] Organizer: nishikaw@neutrino.kek.jp

The JHF-Kamioka neutrino project

Y. Itow[1], T. Kajita[1], K. Kaneyuki[1], M. Shiozawa[1], Y. Totsuka[1], Y. Hayato[2], T. Ishida[2], T. Ishii[2], T. Kobayashi[2], T. Maruyama[2], K. Nakamura[2], Y. Obayashi[2], Y. Oyama[2], M. Sakuda[2], M. Yoshida[2], S. Aoki[3], T. Hara[3], A. Suzuki[3], A. Ichikawa[4], T. Nakaya[4], K. Nishikawa[4], T. Hasegawa[5], K. Ishihara[5], A. Suzuki[5], A. Konaka[6]

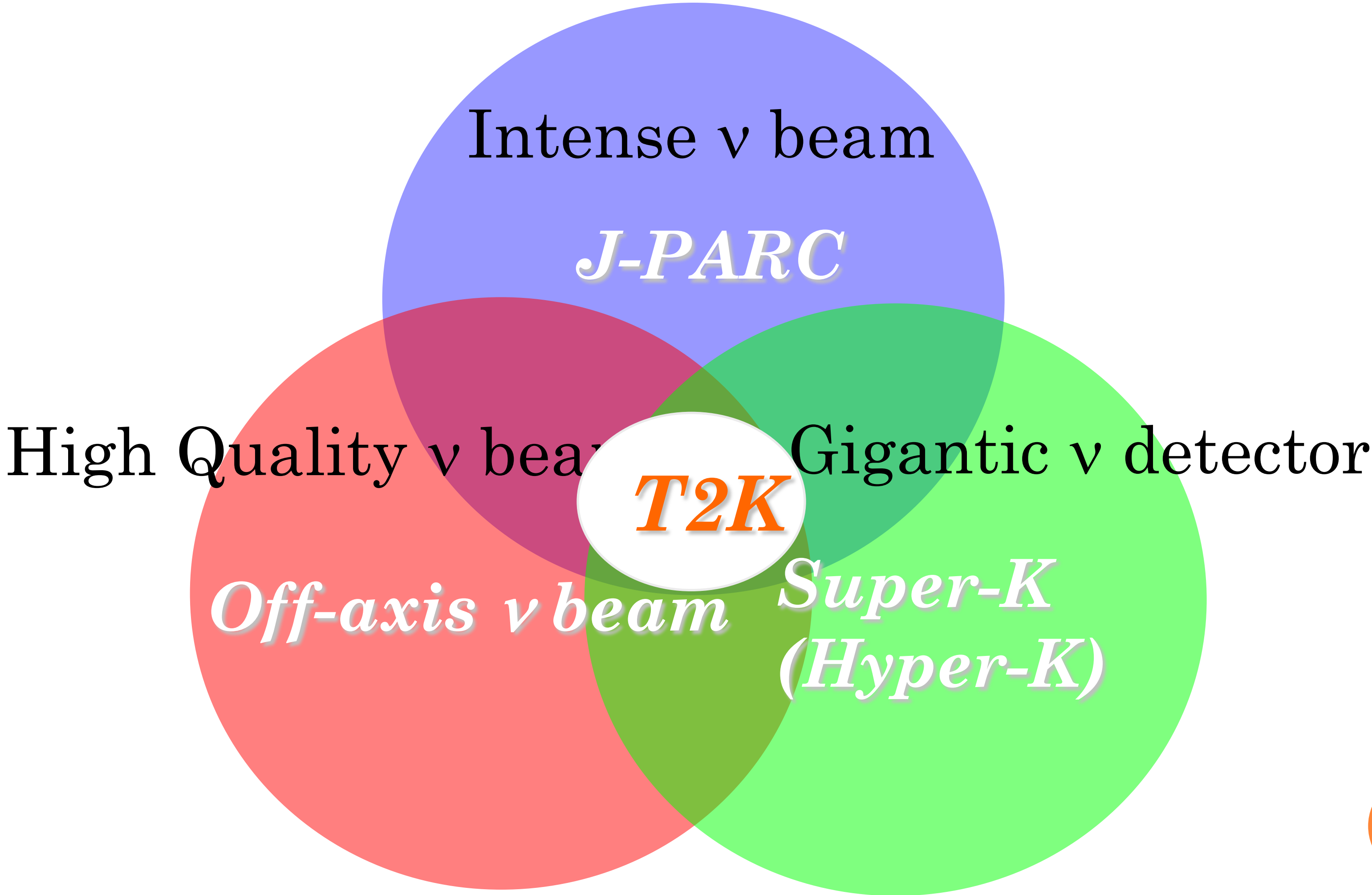
[1] Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan
[2] Inst. of Particle and Nuclear Studies, High Energy Accelerator Research Org. (KEK), Tsukuba, Ibaraki 305-0801, Japan
[3] Department of Physics, Kobe University, Kobe, Hyogo 657-8501, Japan
[4] Department of Physics, Kyoto University, Kyoto 606-8502, Japan
[5] Department of Physics, Tohoku University, Sendai, Miyagi, 980-8578, Japan
[6] TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada, V6T 2A3

Abstract

The JHF-Kamioka neutrino project is a second generation long base line neutrino oscillation experiment that probes physics beyond the Standard Model by high precision measurements of

- **The JHF-Kamioka neutrino project.** hep-ex/0106019
  - *Citation: 690*

T2K Strategy



Mission of T2K

- **Discovery of ν_e appearance !**
  - A **new phenomenon**.
  - Complete the picture of **three generation mixing** scheme.
  - A window to study **CP violation** and mass-hierarchy.
- **Precision measurements of neutrino oscillation.**
  - Confirmation of standard neutrino oscillation scenario.

  => Precise determination of parameters?

  or

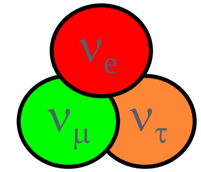
  => ***Probe new physics !***

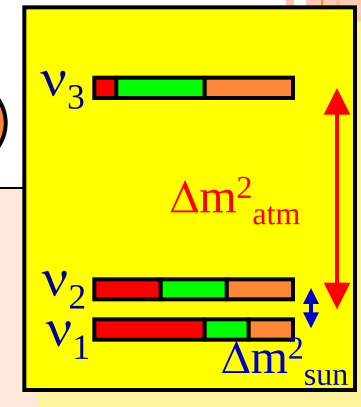
YOUR INTERESTS IN T2K

My personal guesses:

- When will T2K have the results?
- How is the J-PARC accelerator running?
- Is the option of anti-neutrino running?
- Does T2K have the sensitivity to the CP violation and the sign of Δm^2?
- What is the future upgrade (or successor) of T2K?

T2K Physics Sensitivity





Oscillation Probabilities when $\Delta m^2_{12} << \Delta m^2_{23} \approx \Delta m^2_{13}$

- θ_{23} : ν_μ disappearance

$$P_{\nu\mu\to\nu x} \approx 1 - \underbrace{\cos^4\theta_{13}}_{\sim 1} \cdot \sin^2 2\theta_{23} \cdot \sin^2\left(1.27\Delta m^2_{23} L / E_\nu\right)$$

common

- θ_{13}: ν_e appearance

$$P_{\nu\mu\to\nu e} \approx \underbrace{\sin^2\theta_{23}}_{\sim 0.5} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(1.27\Delta m^2_{23} L / E_\nu\right)$$

- δ : CP violation (T2K-beyond)

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \cong$$

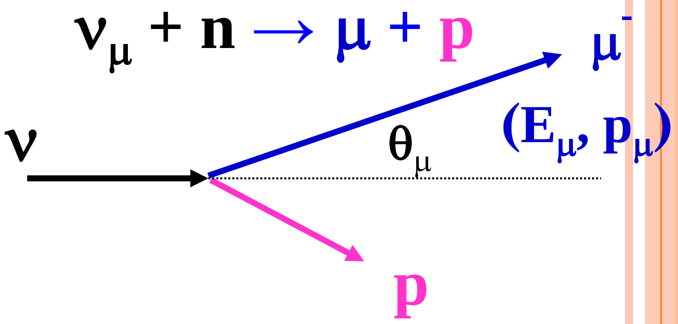
~0.18 ($\sin^2 2\theta_{13}$=0.1)
~0.58 ($\sin^2 2\theta_{13}$=0.01) $\cdot \sin\delta$

NOTE

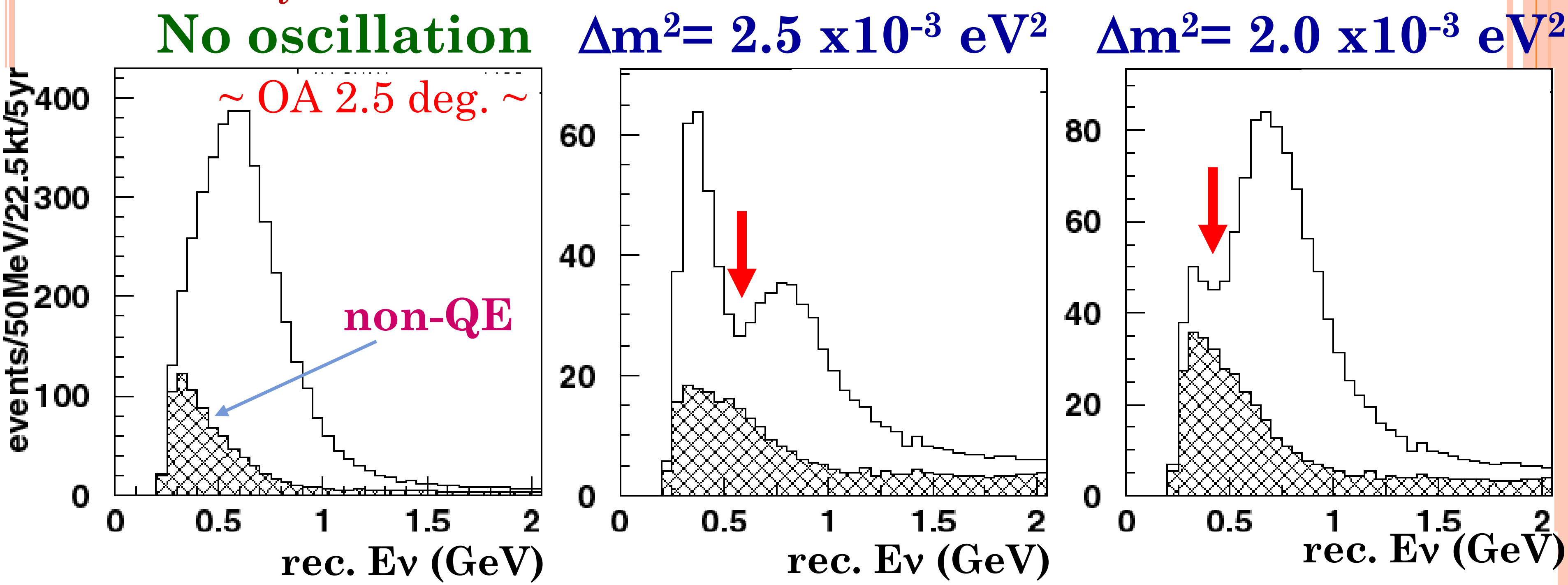
- We are working to update the physics sensitivity based on the current experimental condition with data collected so far. However, they are not ready yet. So, I show the sensitivity in our proposal.
- We plan to have the first physics results soon (target: within JFY2010).

Measurement of θ_{23} , Δm_{23}^2

Use 1 ring μ-like events
(= **Quasi-Elastic** enhanced sample)
to reconstruct neutrino energy.



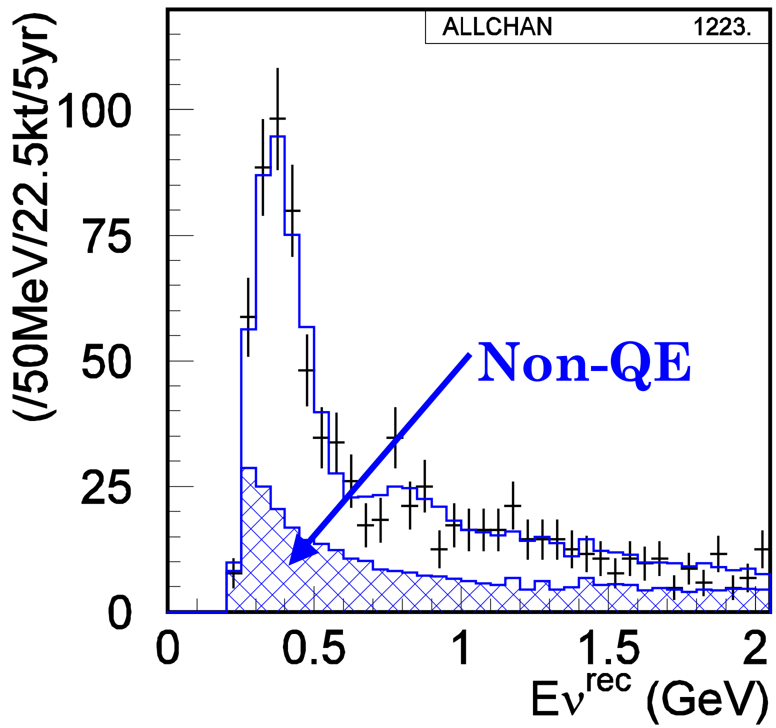
750kW × 5 years



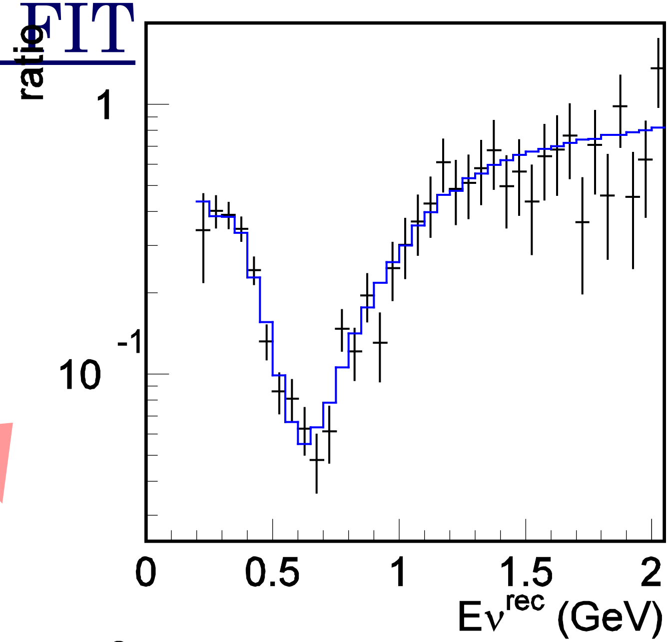
(assuming $\sin^2 2\theta_{23} = 1.0$)

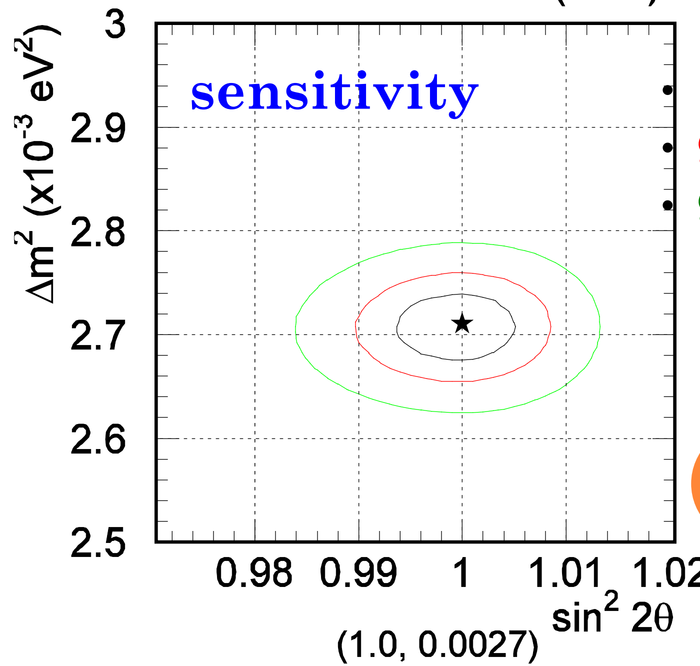
OSCILLATION PARAMETER FIT

Input:
$\sin^2 2\theta_{23}$=1.00
Δm^2= 2.7 x10^{-3} eV^2



Ratio of E_ν to non-oscillation

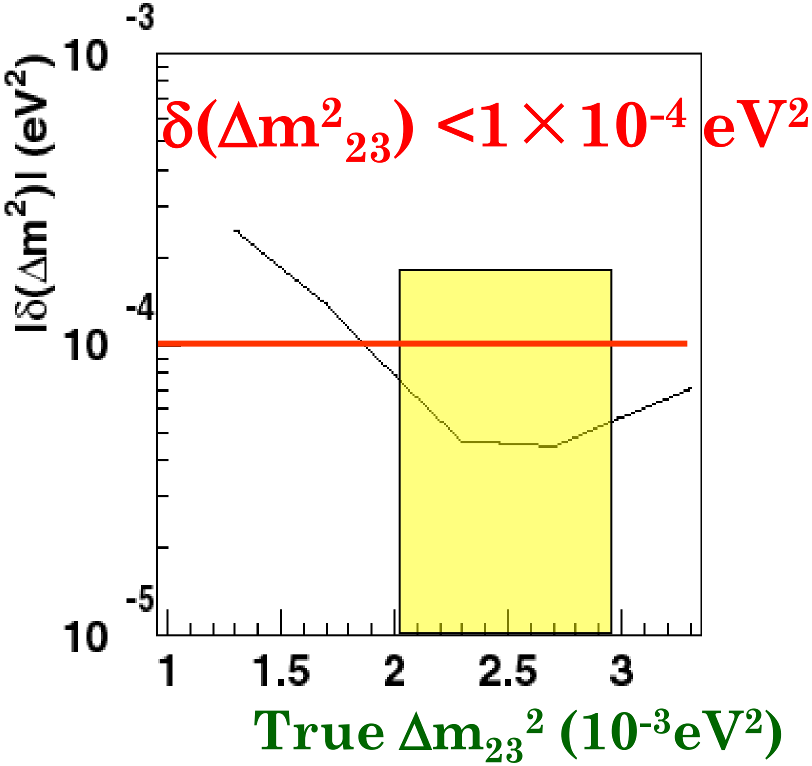


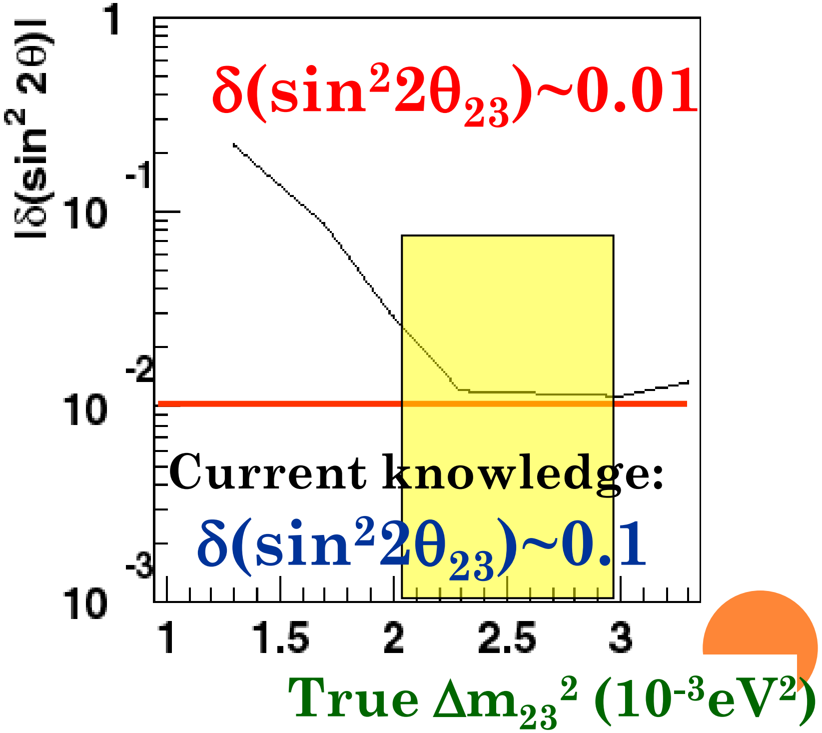


- 1σ
- 90% CL
- 99% CL

T2K-I sensitivity with systematic errors

- normalization (5%)
- non-QE/QE ratio (5%)
- E scale (2%)
- Spectrum shape (20%)
- Spectrum width (5%)





θ_{13} measurement (ν_e appearance search)

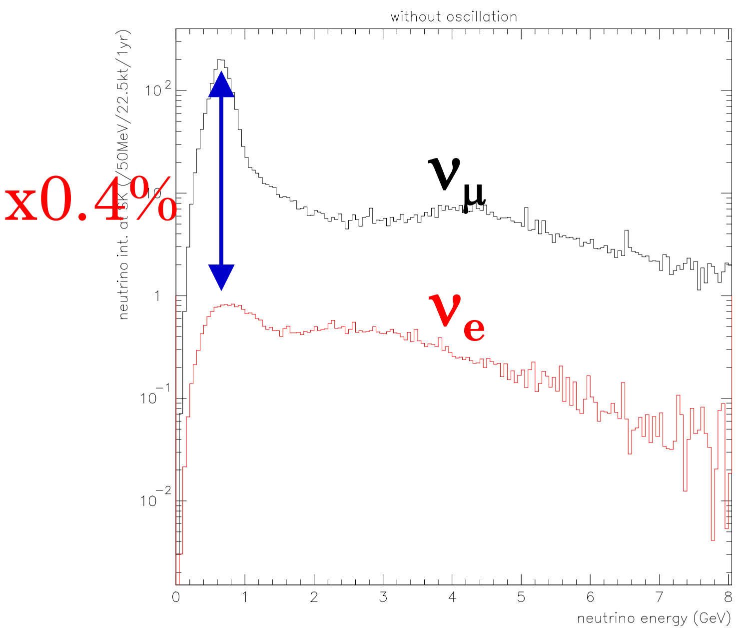
$\sin^2 2\theta_{23}=1$ and $\delta=0$ are assumed.

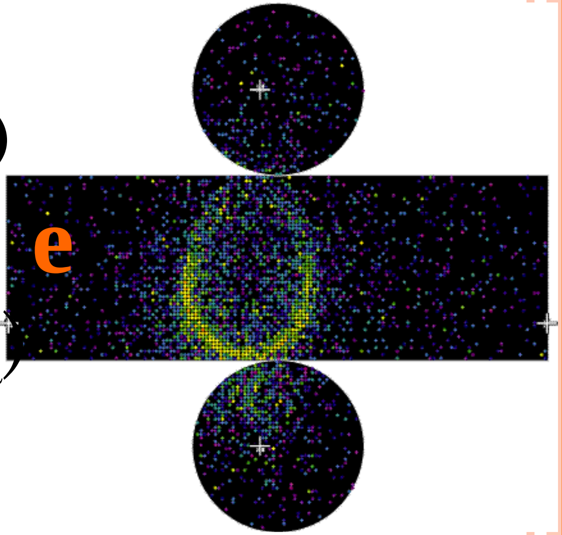
Signal:

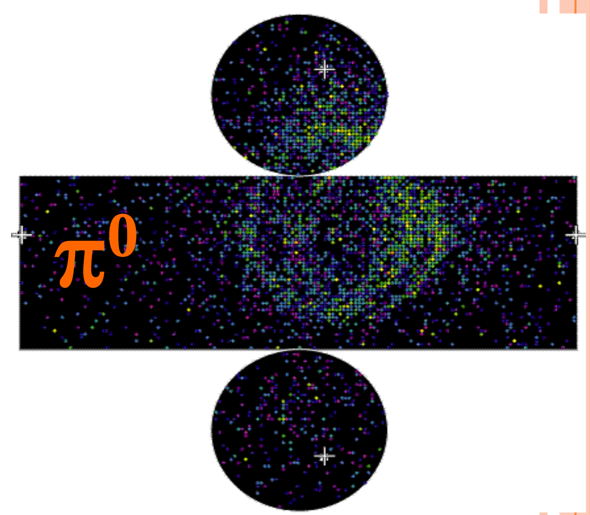
- 1ring e-like event (CC QE sample)

Background:

- beam ν_e contamination (0.4% of ν_μ)
- mis-reconstructed π^0 event

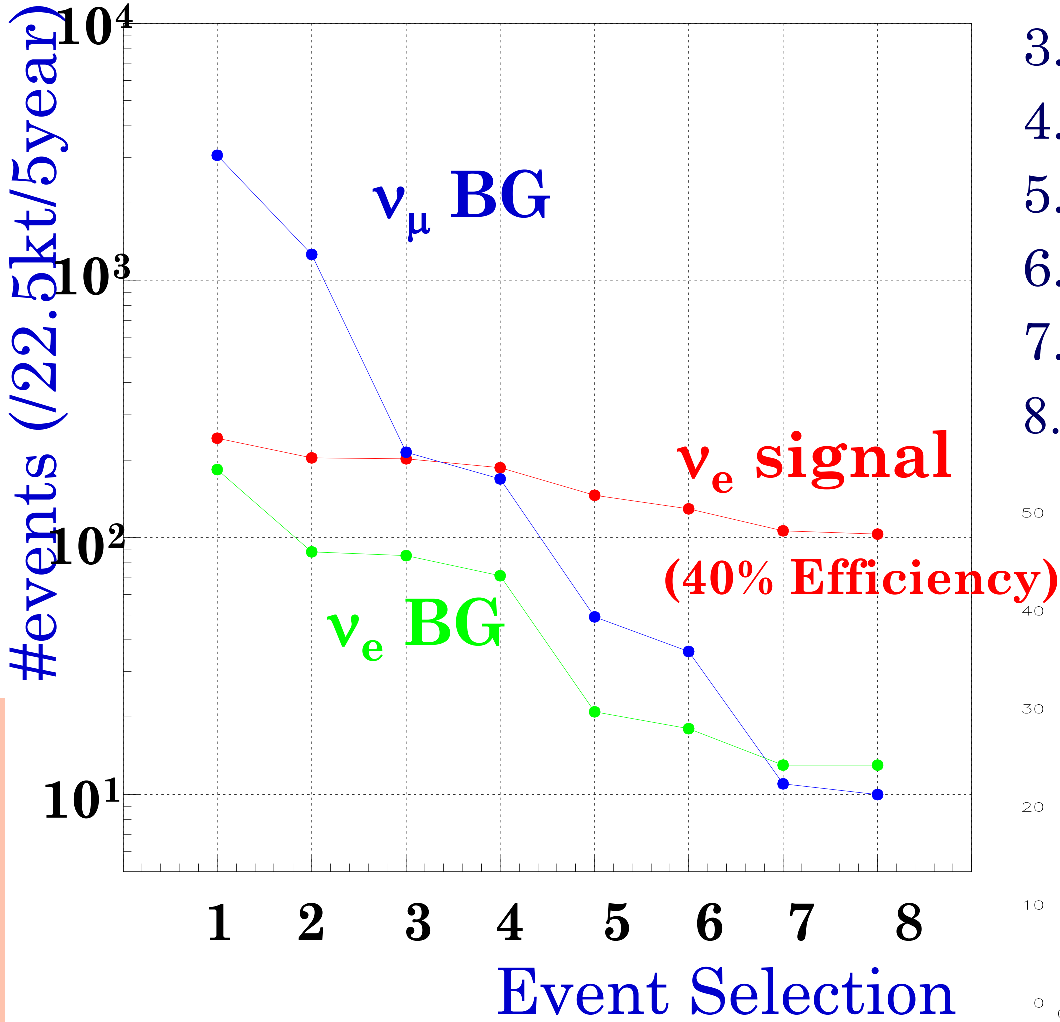




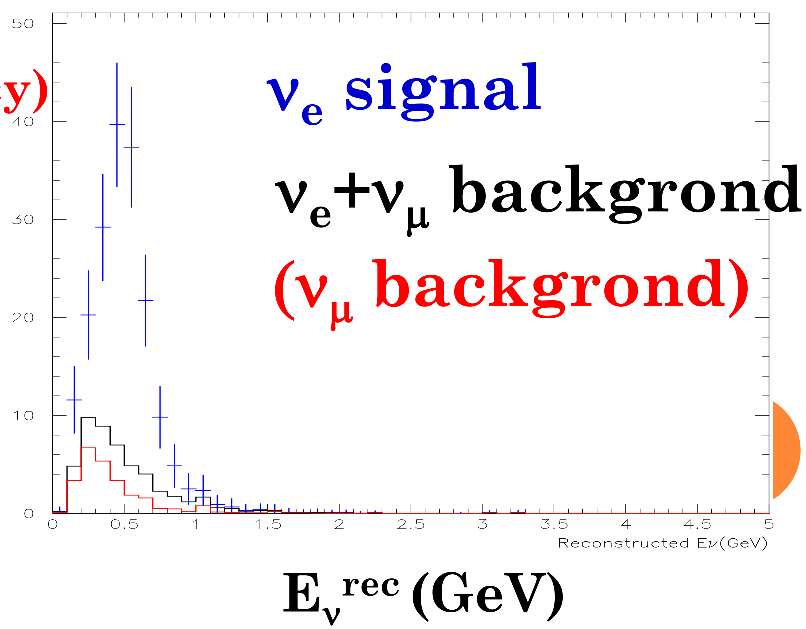


Background Suppression

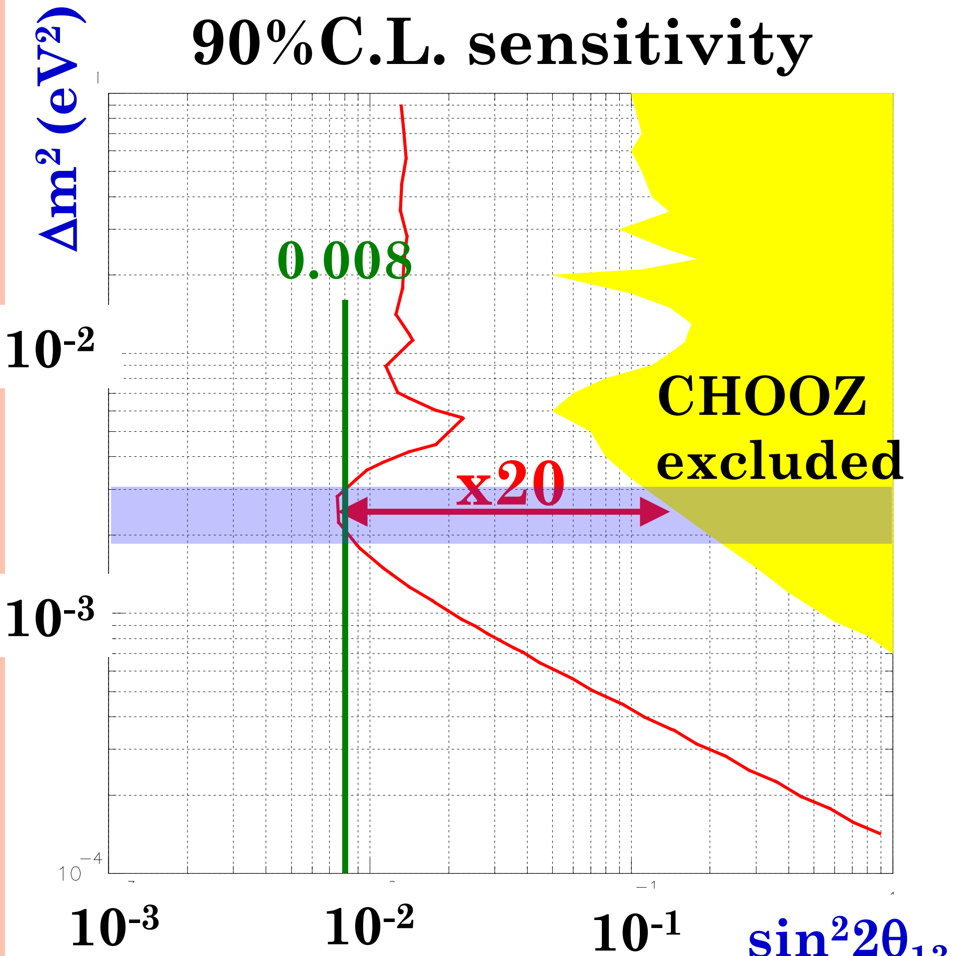
($\Delta M^2 = 2.5 \times 10^{-3} eV^2, \sin^2 2\Theta_{13} = 0.1$)

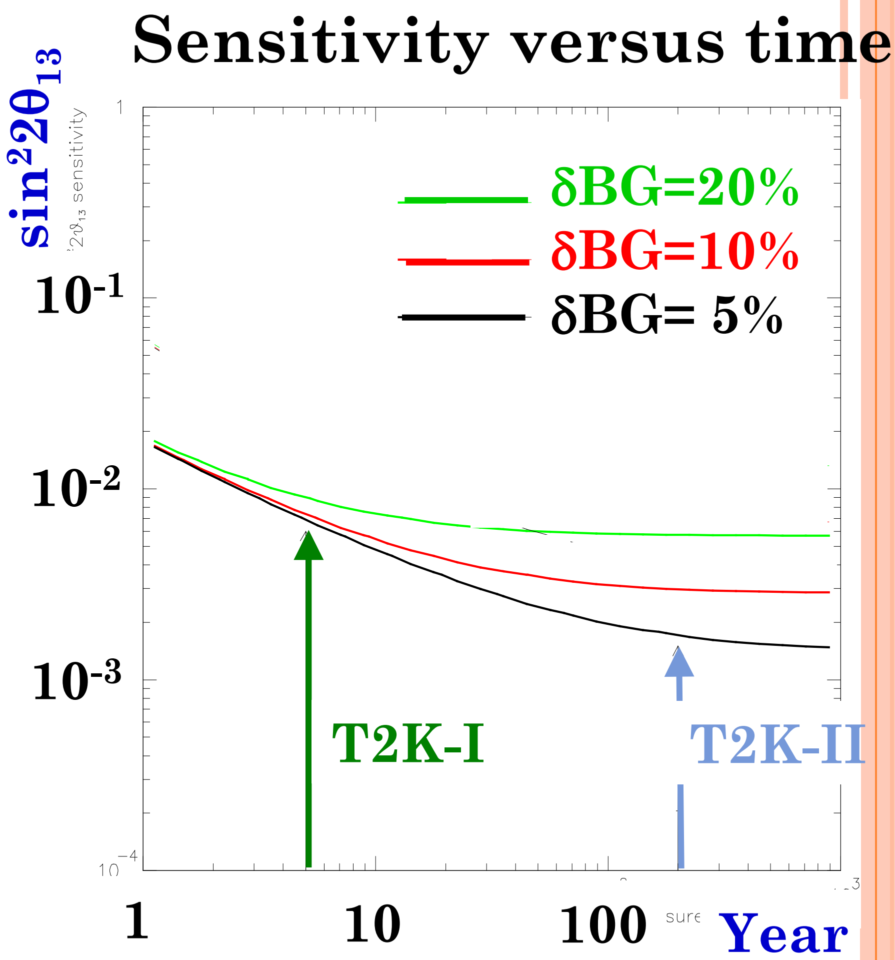


1. FCFV, $E_{vis.}$ >100MeV
2. single ring
3. e-like PID
4. no decay-electron
5. $0.35 < E_\nu^{rec} < 0.85$GeV
6. $\cos\theta_{\nu e} < 0.90$
7. $M_{\pi 0} < 100 MeV/c^2$ (π^0 fitter)
8. $\Delta L < 80$ (π^0 fitter)



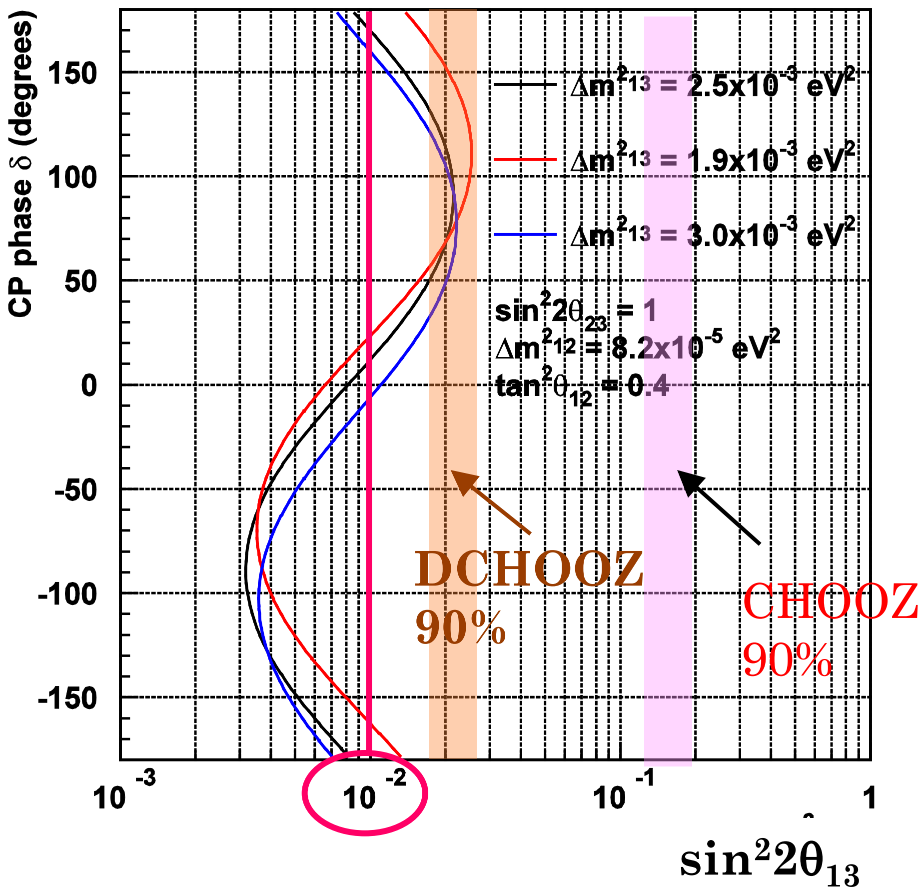
Θ$_{13}$ Sensitivity (w/ ΔBG_{SYS}=10%)

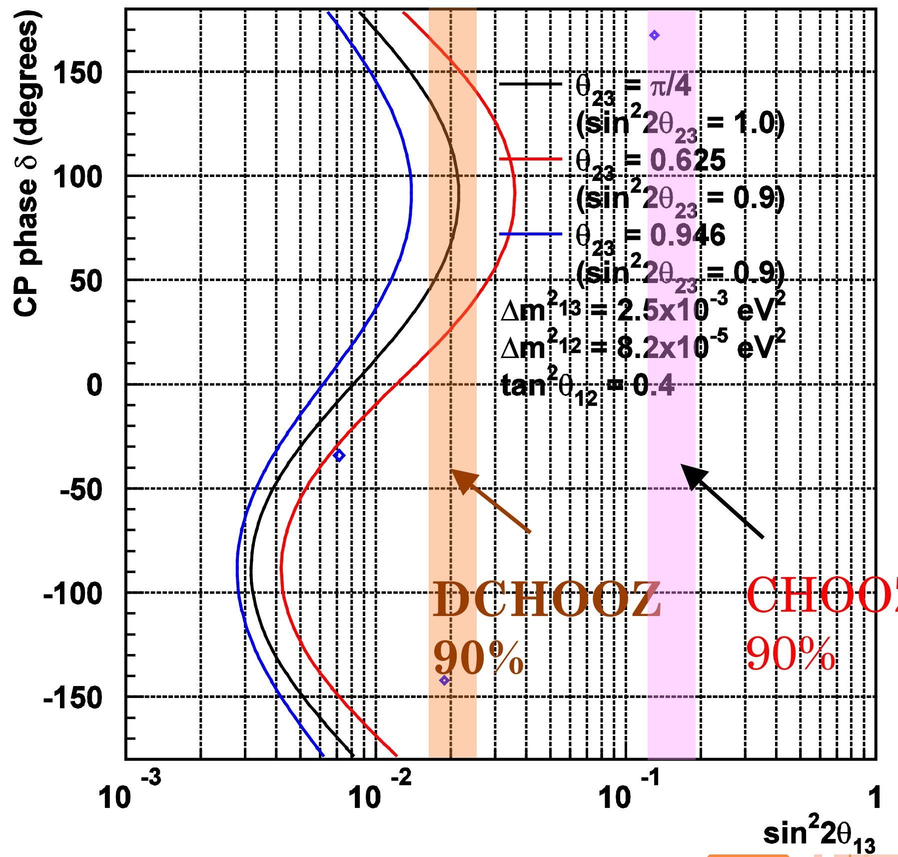




T2K Physics Sensitivity

ν_e appearance
(Strong δ dependence)

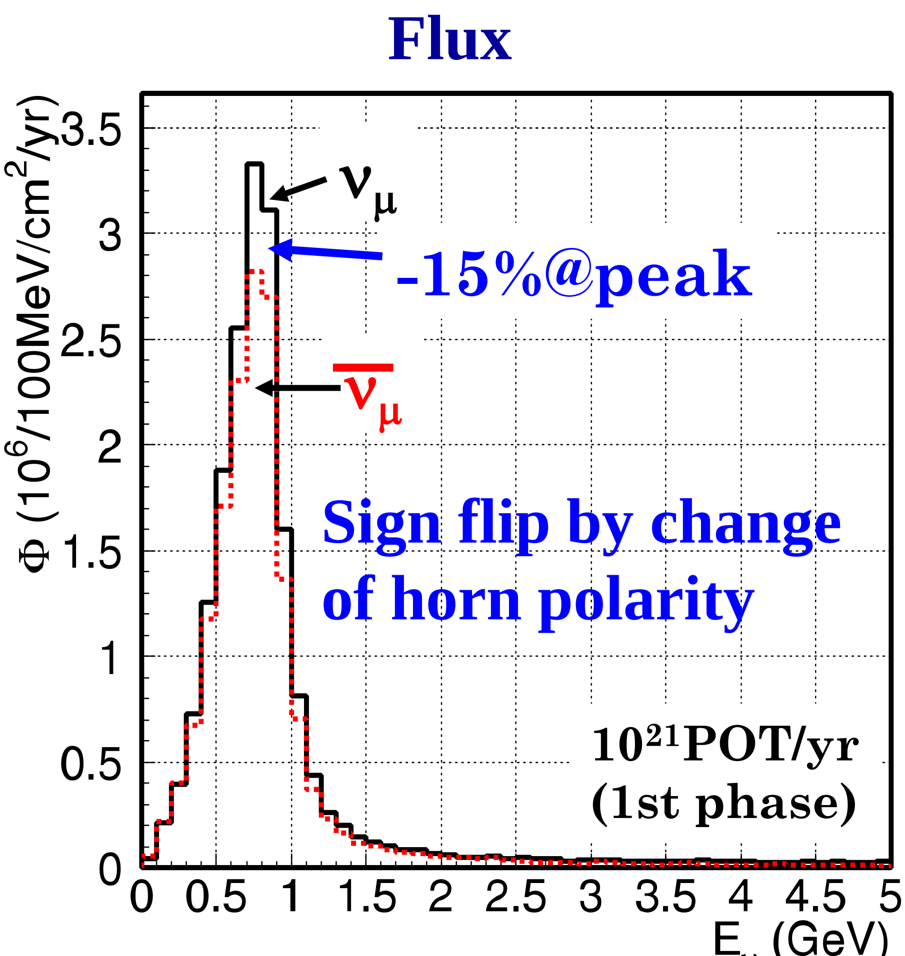


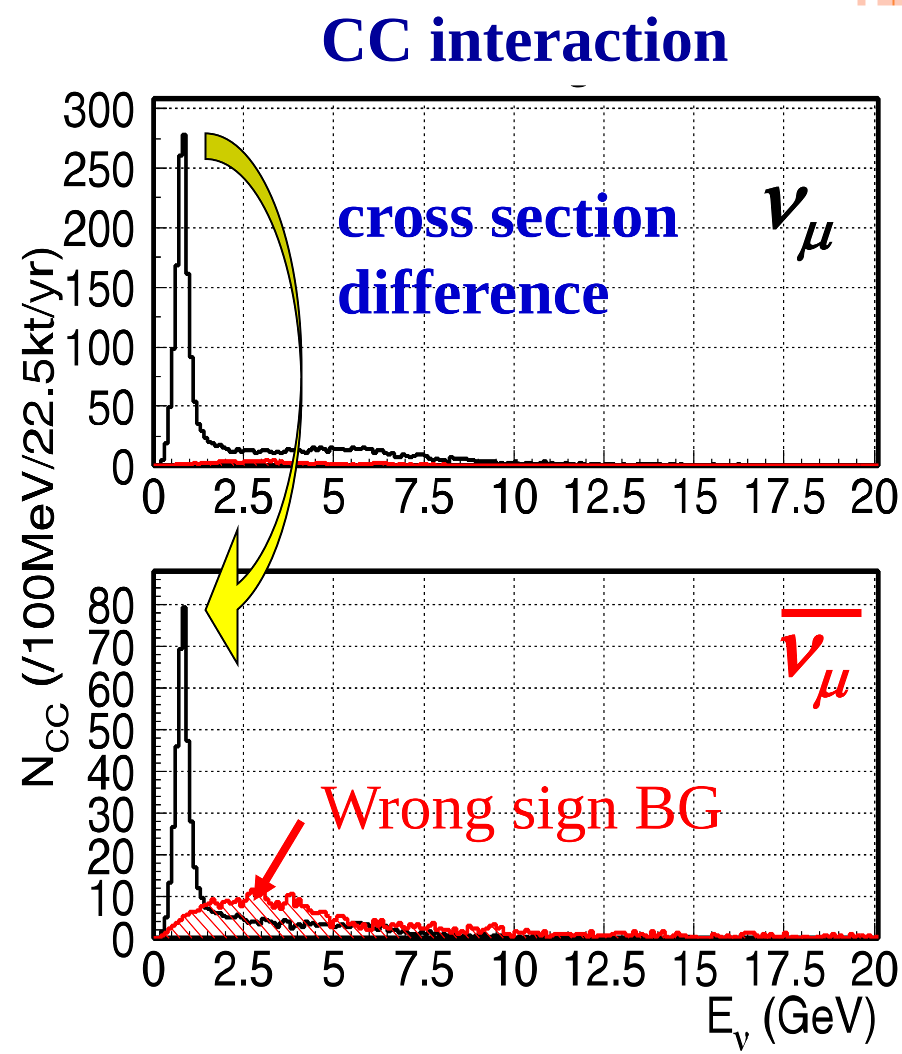


~10 times improvement from CHOOZ

CP violation study *$\bar{\nu}$ beam is an option*

(Note: Old study with 2° off-axis)



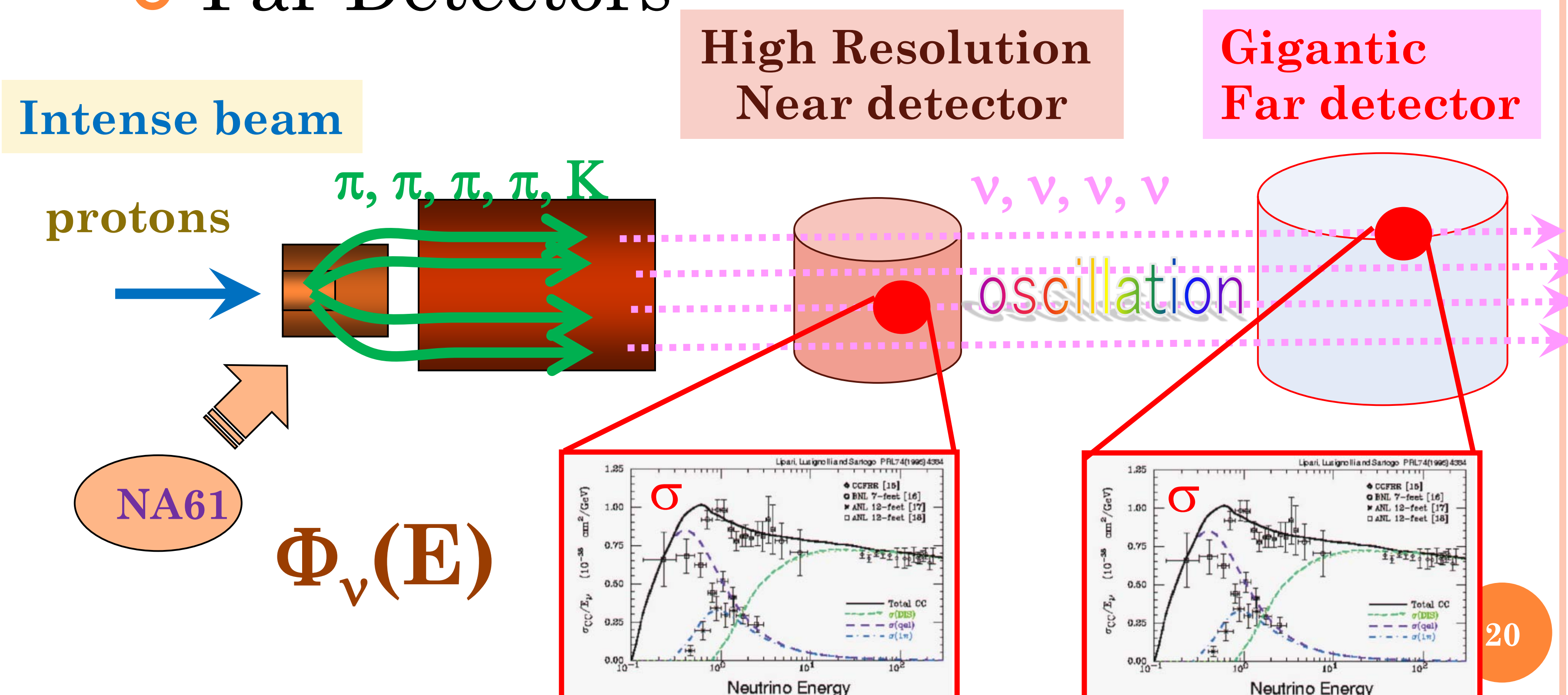


T2K Physics summary with future options

- Probe θ_{13} by looking for ν_e appearance.
- Precision measurements of θ_{23} and Δm^2_{23}.
- Search for sterile neutrinos by measuring the neutral current interactions.
- Look for the difference of between ν oscillation and $\bar{\nu}$.
  - CP violation (δ in the MNS matrix or new interactions)

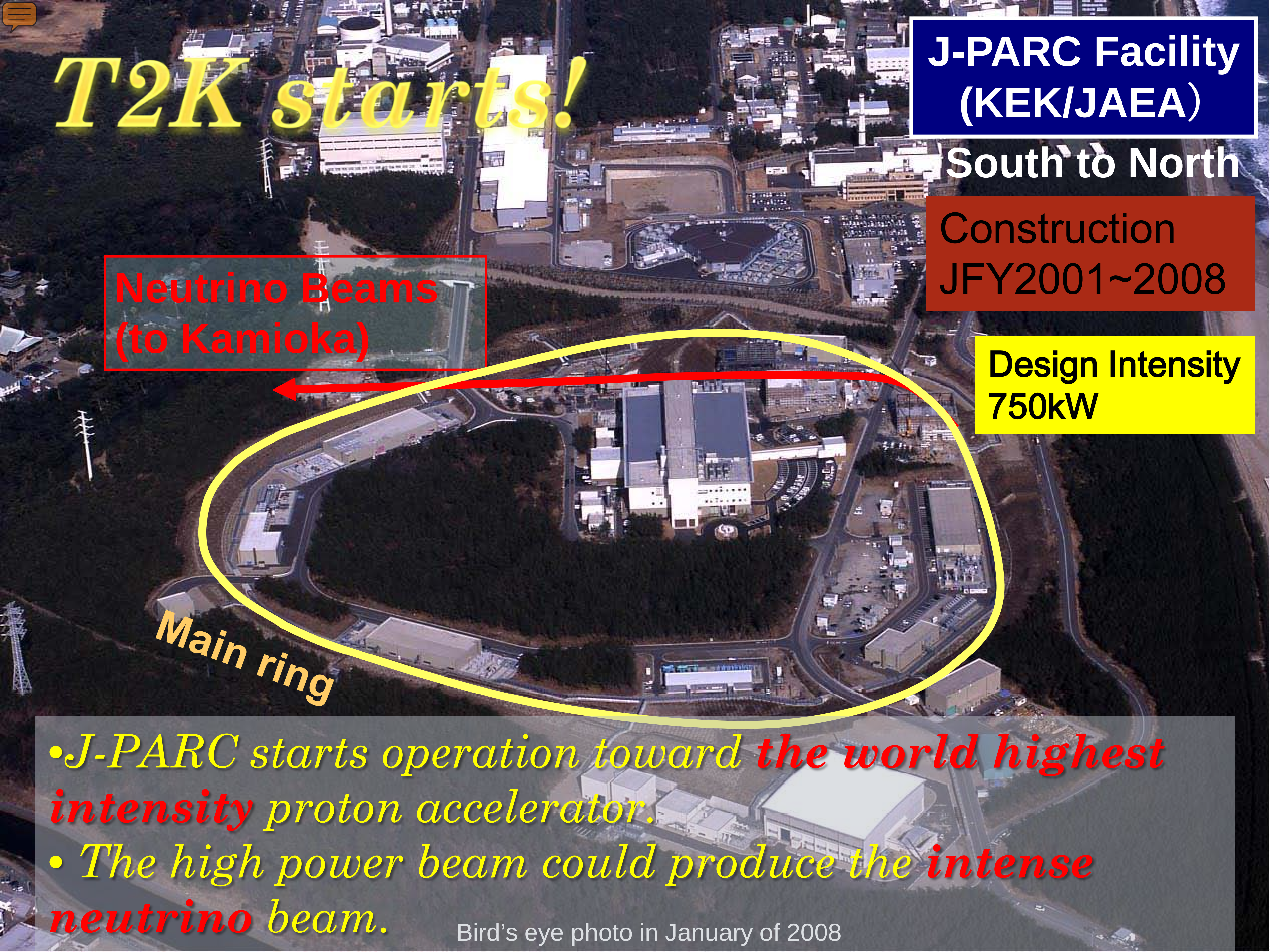
3. Experimental Overview

- Accelerator/Neutrino Beams
- Near Detectors
- Far Detectors



	T2K (construction: 2004~2010)
Accelerator	J-PARC MR 750kW (design) New
Neutrino Beam	2.5 degree off-axis E_{peak}~700MeV New
Near Detector	Fine-Segmented multi-type detectors w/ magnetic field (w/ water target) New
Far Detector	Water Cherenkov 50ktons (22.5 kt fiducial) 295km away
Near/Far extrapolation	Hadron production is measured by CERN NA61 New

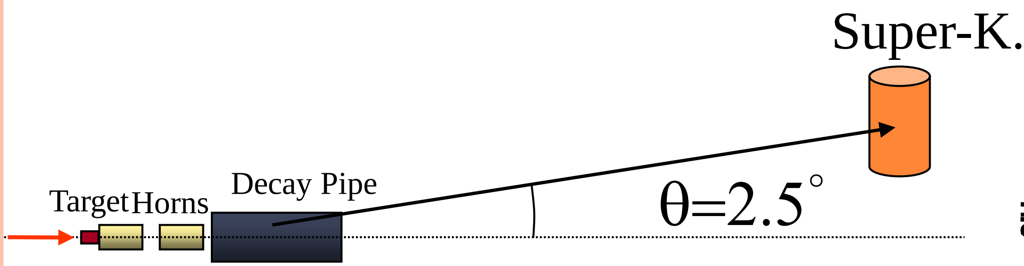
T2K starts!



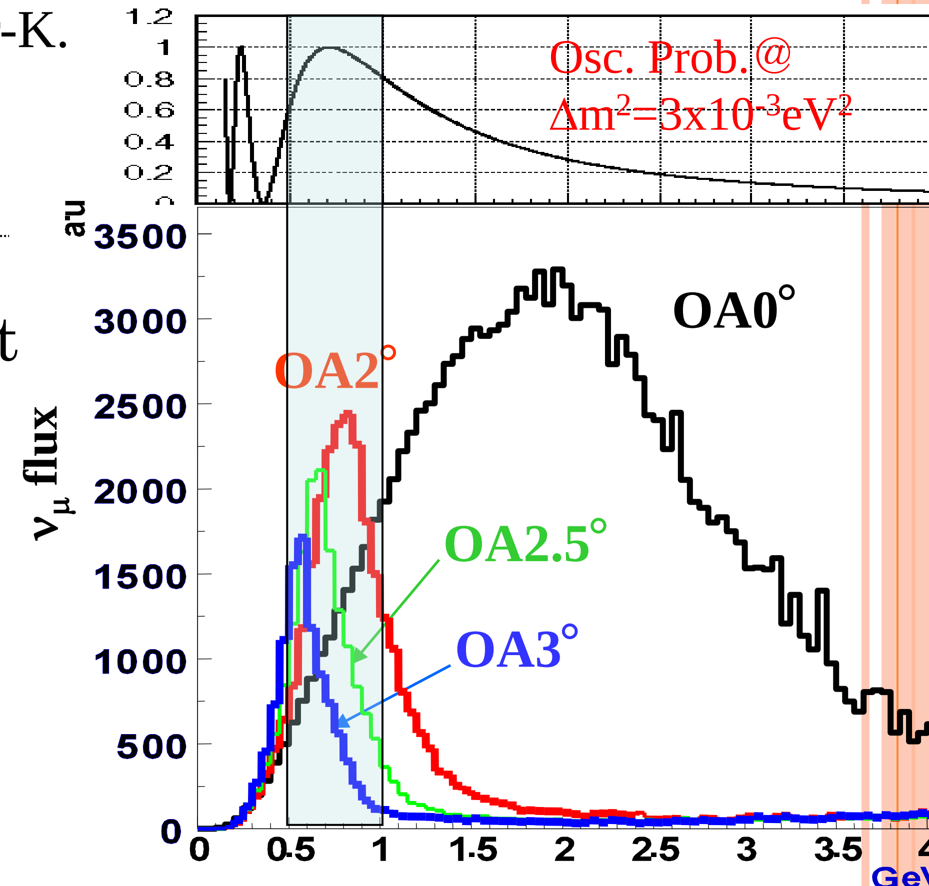
- *J-PARC starts operation toward **the world highest intensity** proton accelerator.*
- *The high power beam could produce the **intense neutrino** beam.*

Bird's eye photo in January of 2008

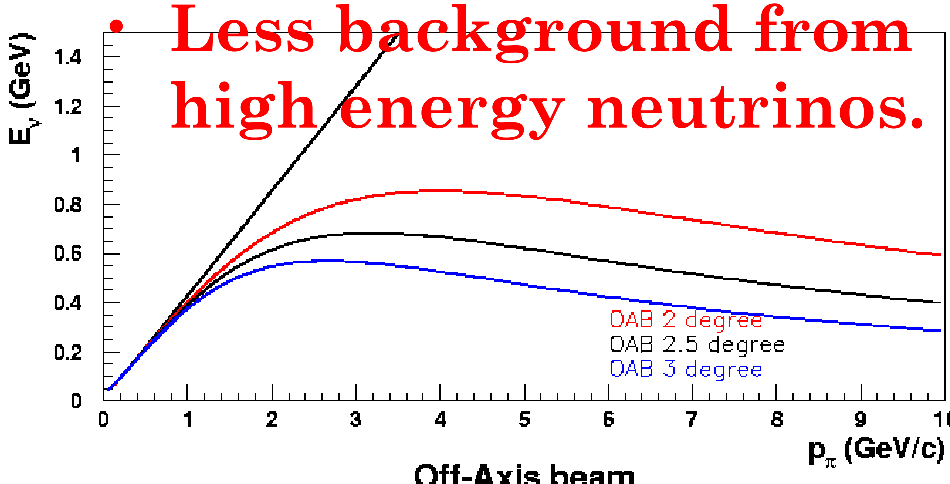
OFF-AXIS ν BEAM CONFIGURATION



◆ **Quasi Monochromatic Beam**

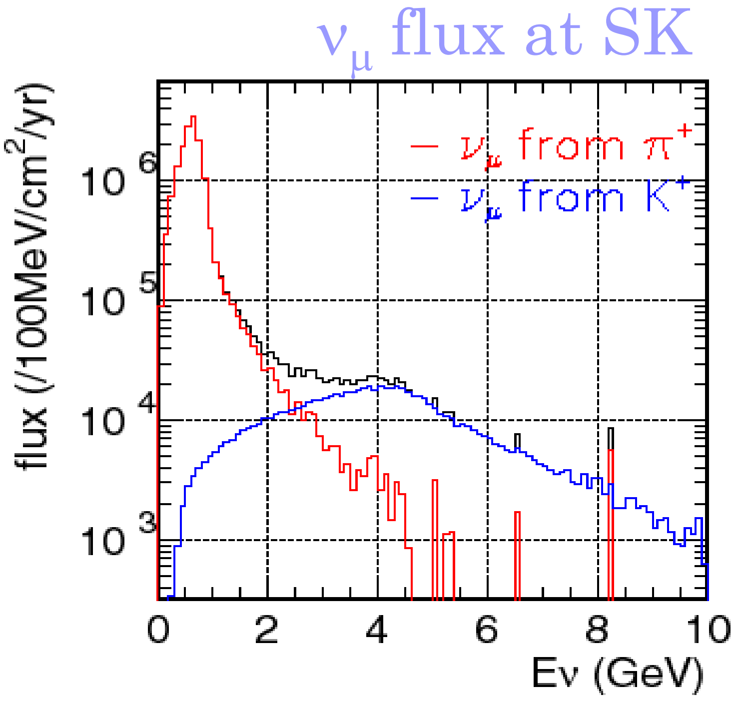


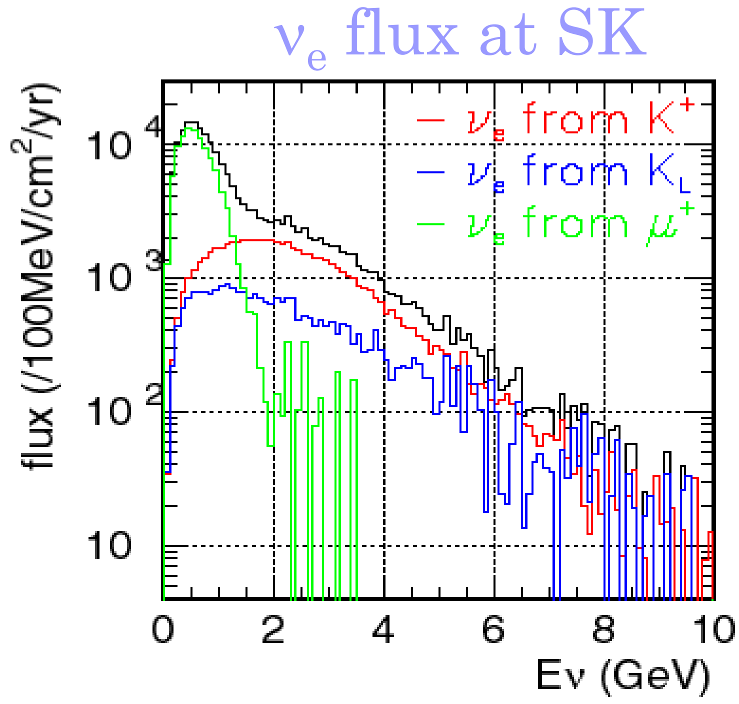
- The ν beam energy is tuned at the oscillation maximum.
  - **Higher signal yield.**
  - **Less background from high energy neutrinos.**



Intense and high-quality neutrino beam

T2K Neutrino production mode





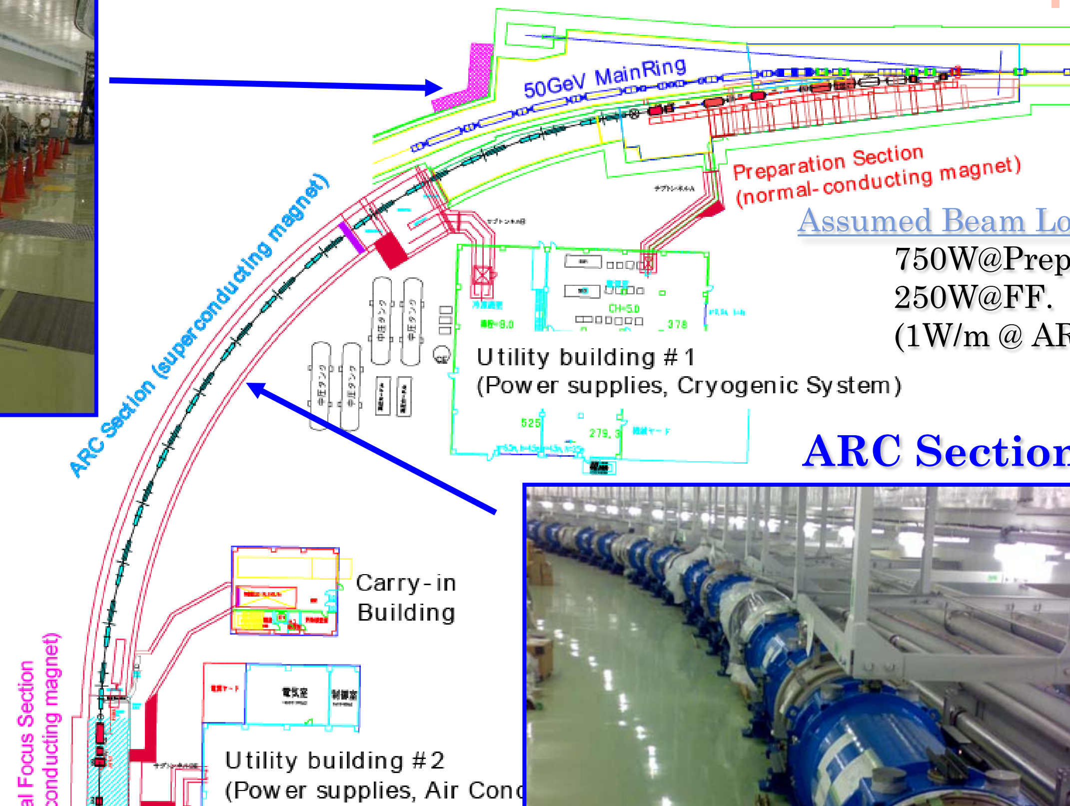
$K / \pi = 0.052$ @SK
$= 0.047$ @ND

$K^+ / K_L / \mu^+ = 32\% / 14\% / 54\%$ @SK
$= 29\% / 13\% / 59\%$ @ND

Primary Beam-line

Preparation Section

Final Focusing Section



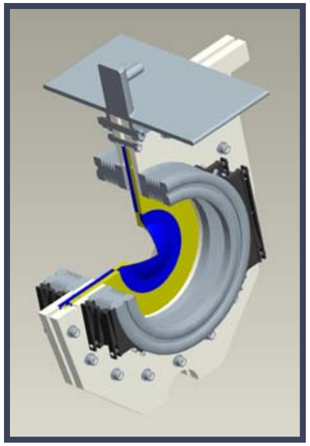
Assumed Beam Loss
750W@Prep.
250W@FF.
(1W/m @ ARC)

ARC Section

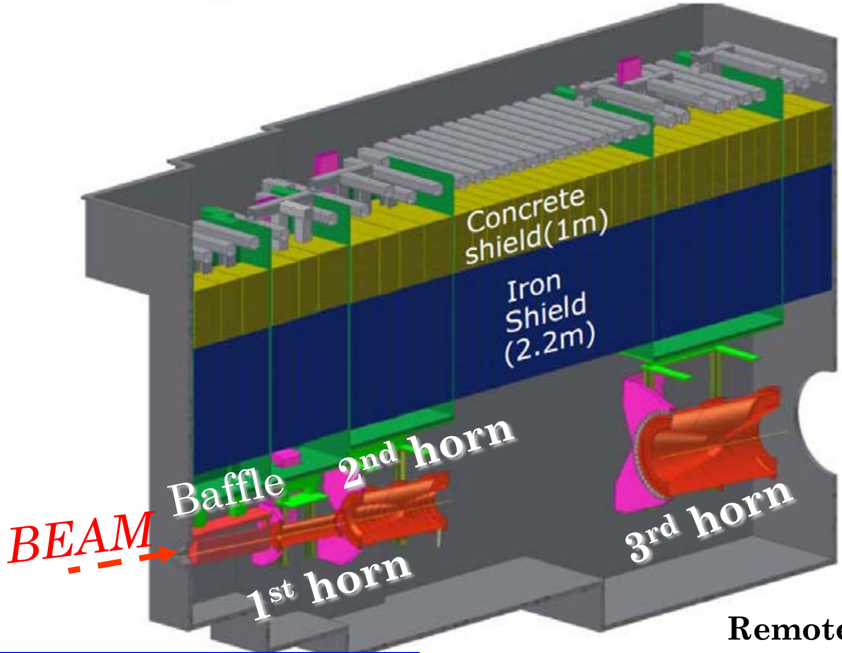
- Beam-line tunnel was completed in December 2006
- Installation finished in 2009

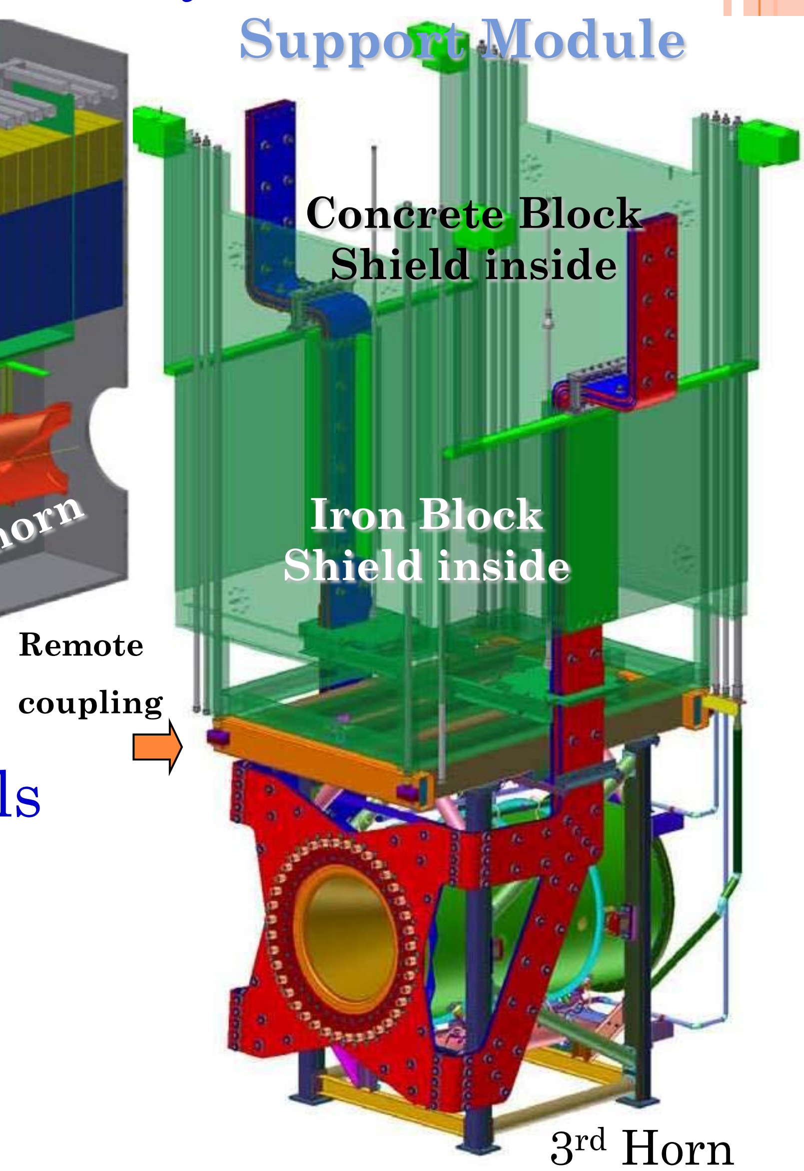
Target Station and horns

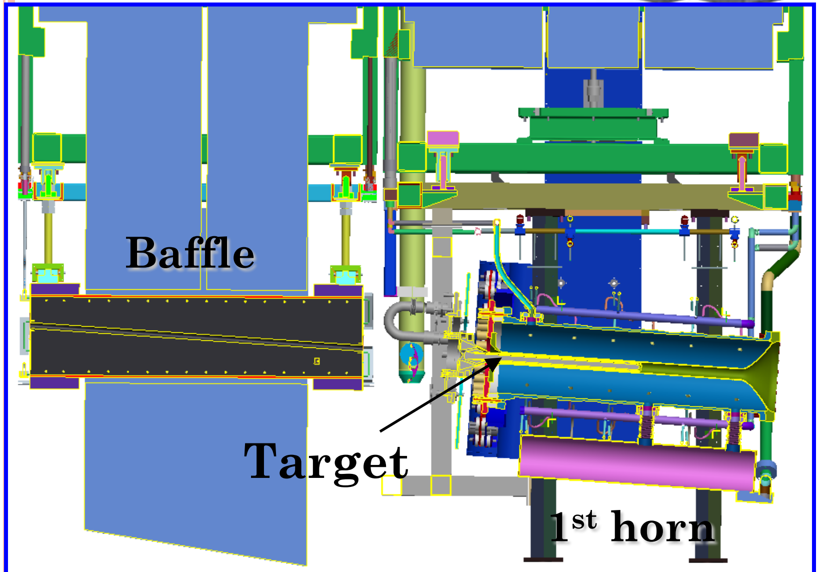
320kA current for the horn system



Beam Window
With pillow seal



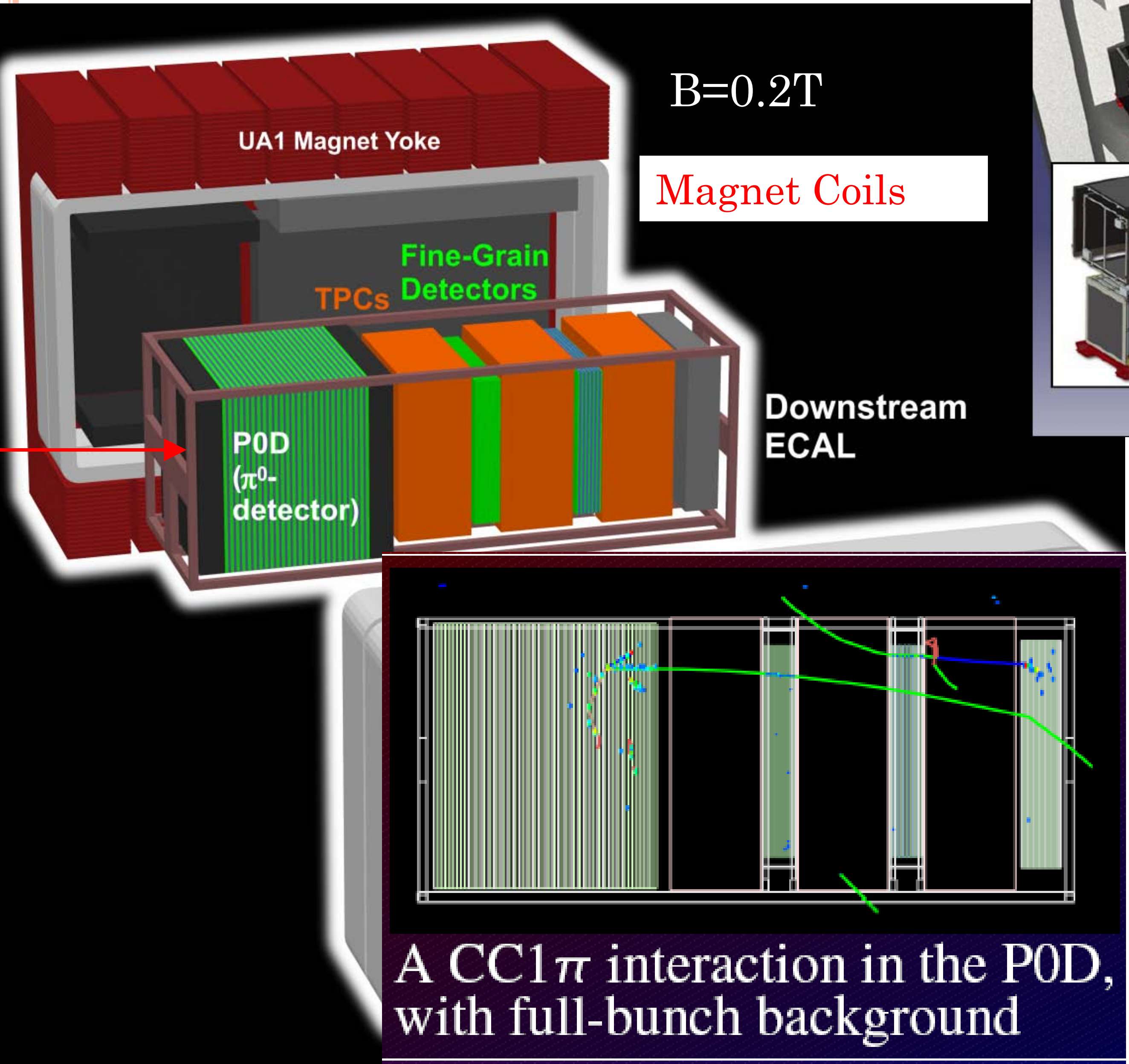


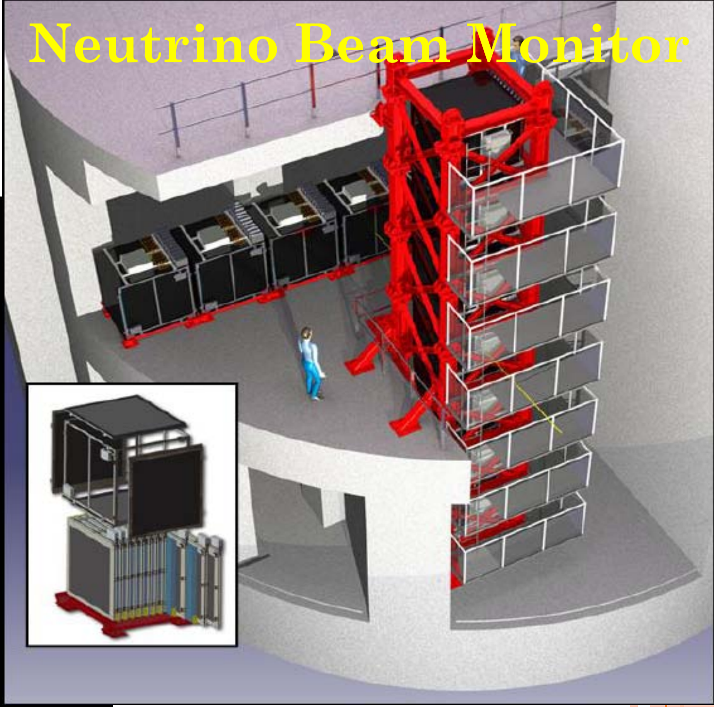


Huge
He vessels

ND280
(Near Neutrino Detectors)

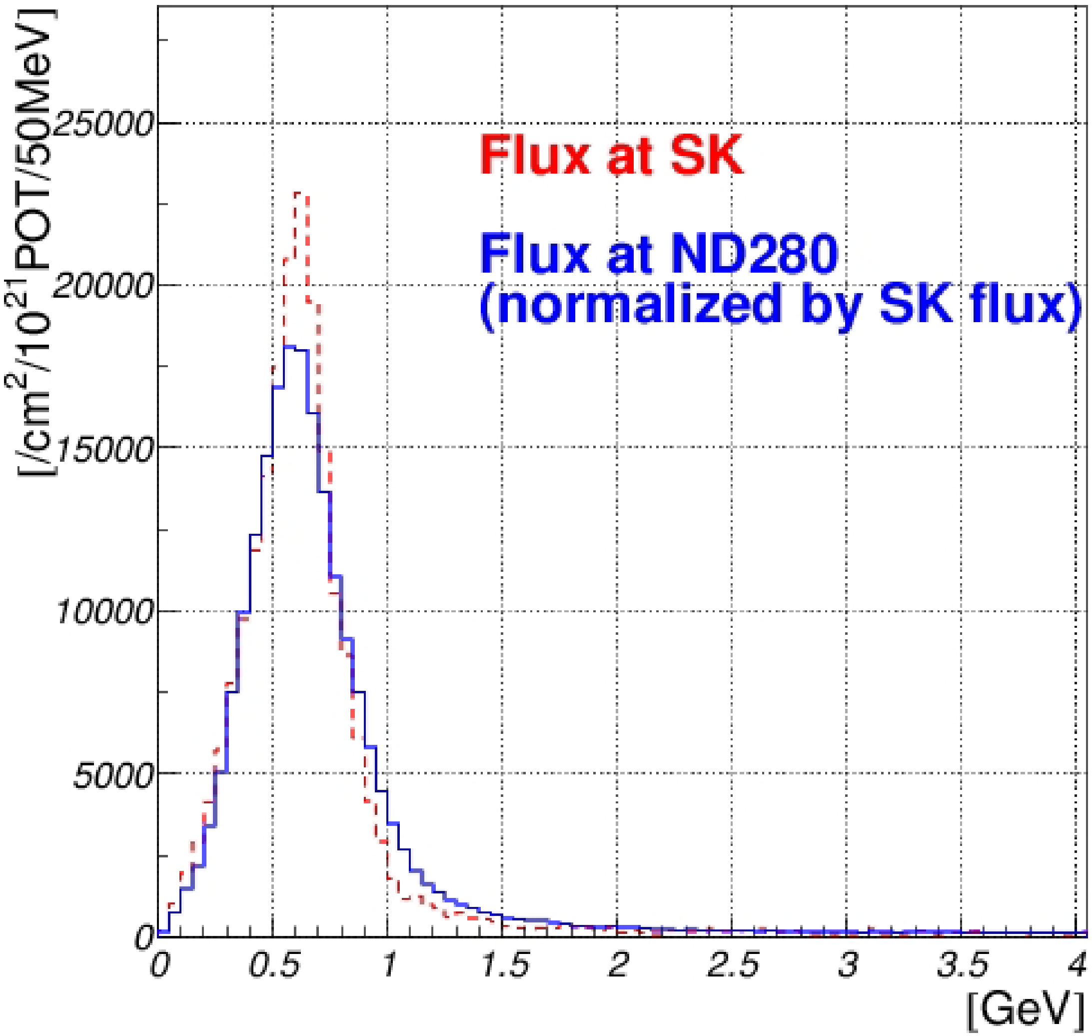
ND280 OFF-AXIS





- Volume:
  - $3.5 \times 3.5 \times 7.0 m^3$
- **P0D:** π^0 Detector
- **FGD+TPC:** Charged Particle tracking
- **EM calorimeter**
- **Side-Muon-Range Detector**

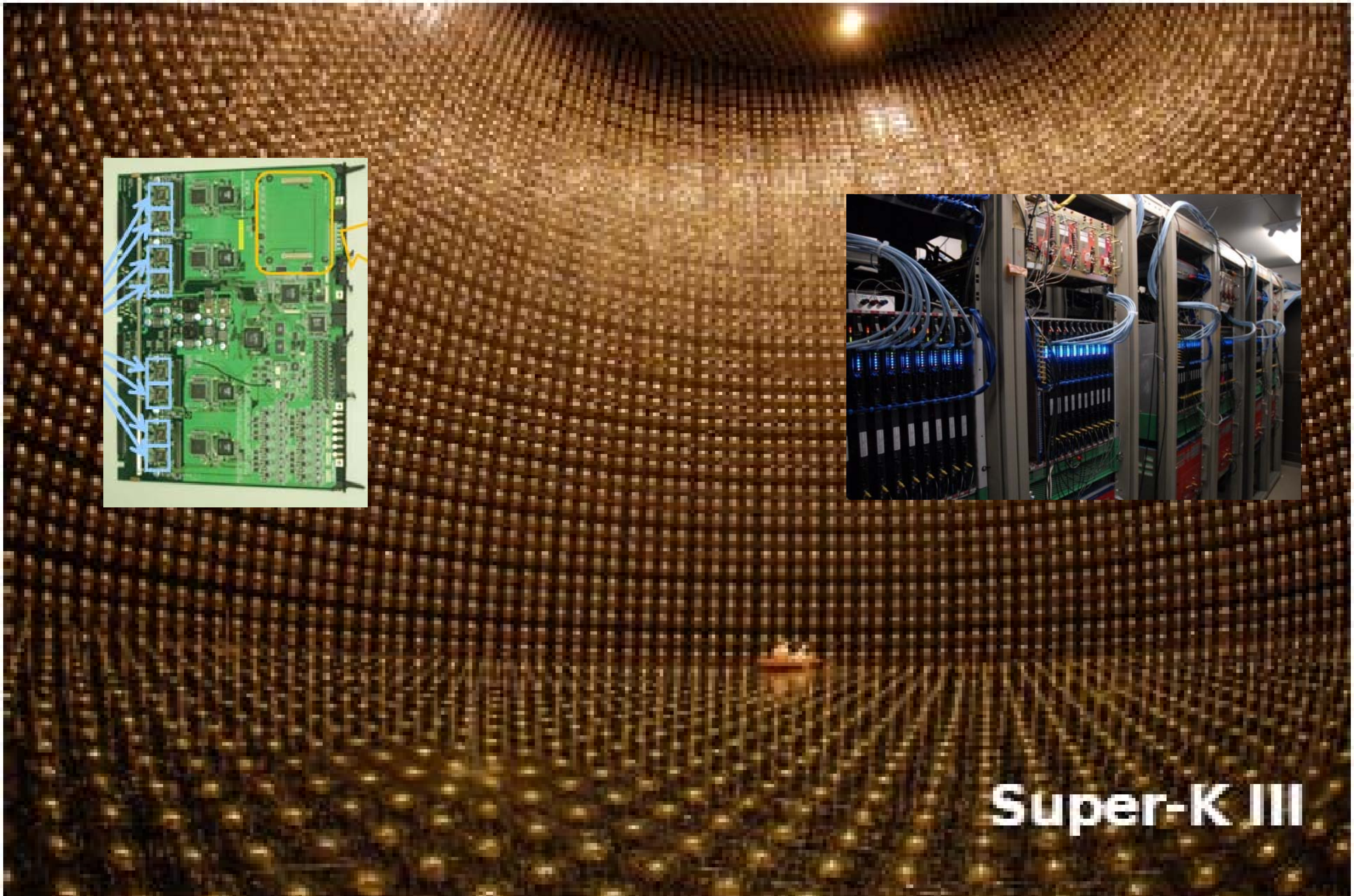
NEUTRINO BEAM SPECTRUM AT SK AND ND280



Off-axis Detector

- Measure ν_μ flux: <5%
- Measure ν_μ energy scale: <2%
- Measure intrinsic ν_e content of beam: <10%
- Measure non-CCQE backgrounds for both ν_μ disappearance and ν_e appearance: <10%
- Magnetic field, fine segmentation, excellent tracking
- Major international contributions
- High complexity and non-trivial integration

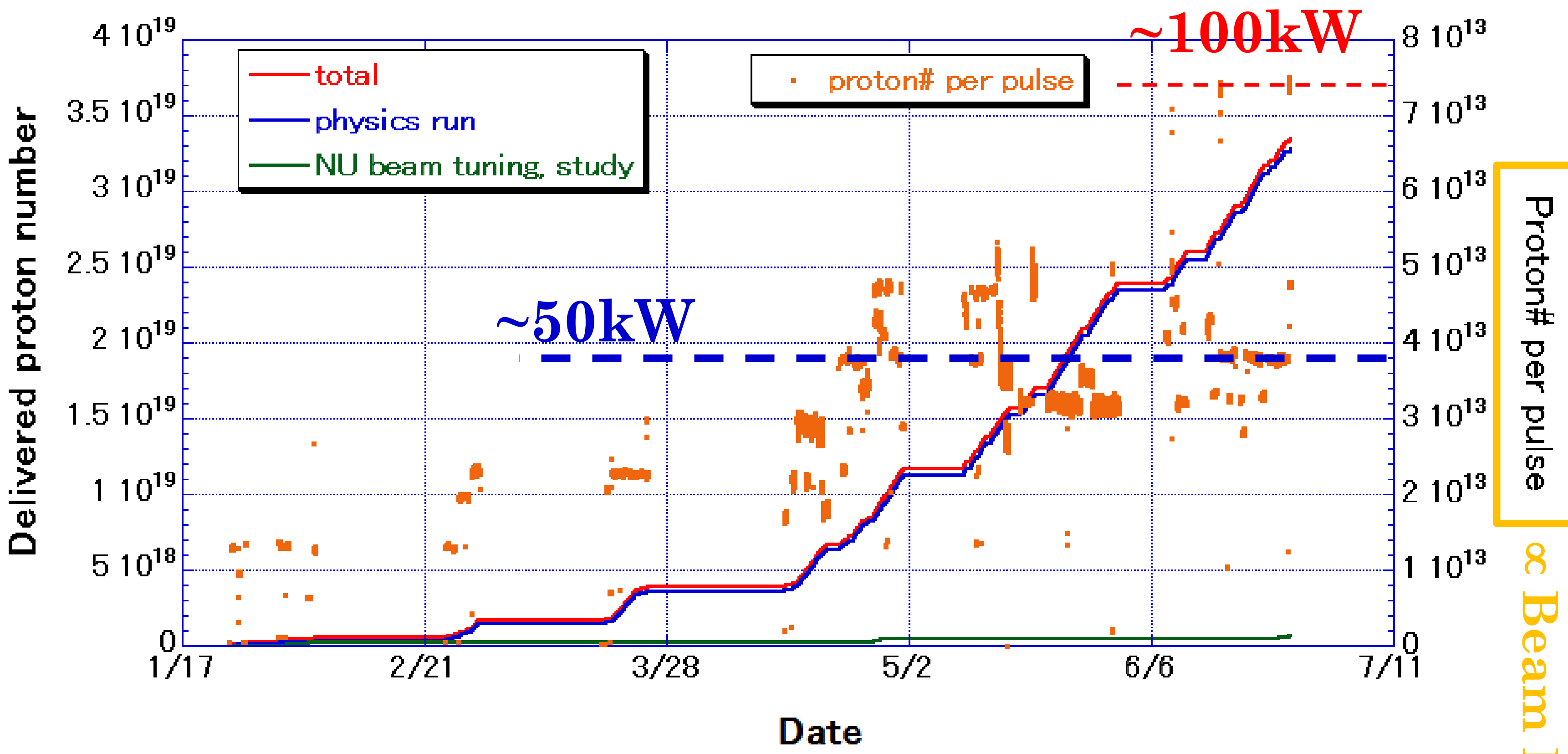
Far Detector: Super-Kamiokande IV



T2K Construction just finished

T2K Status

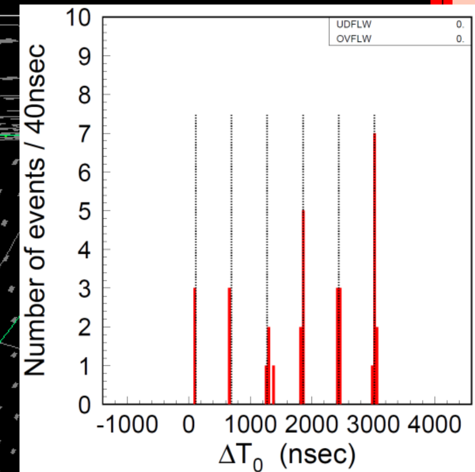
T2K Physics Run begins in 2010.

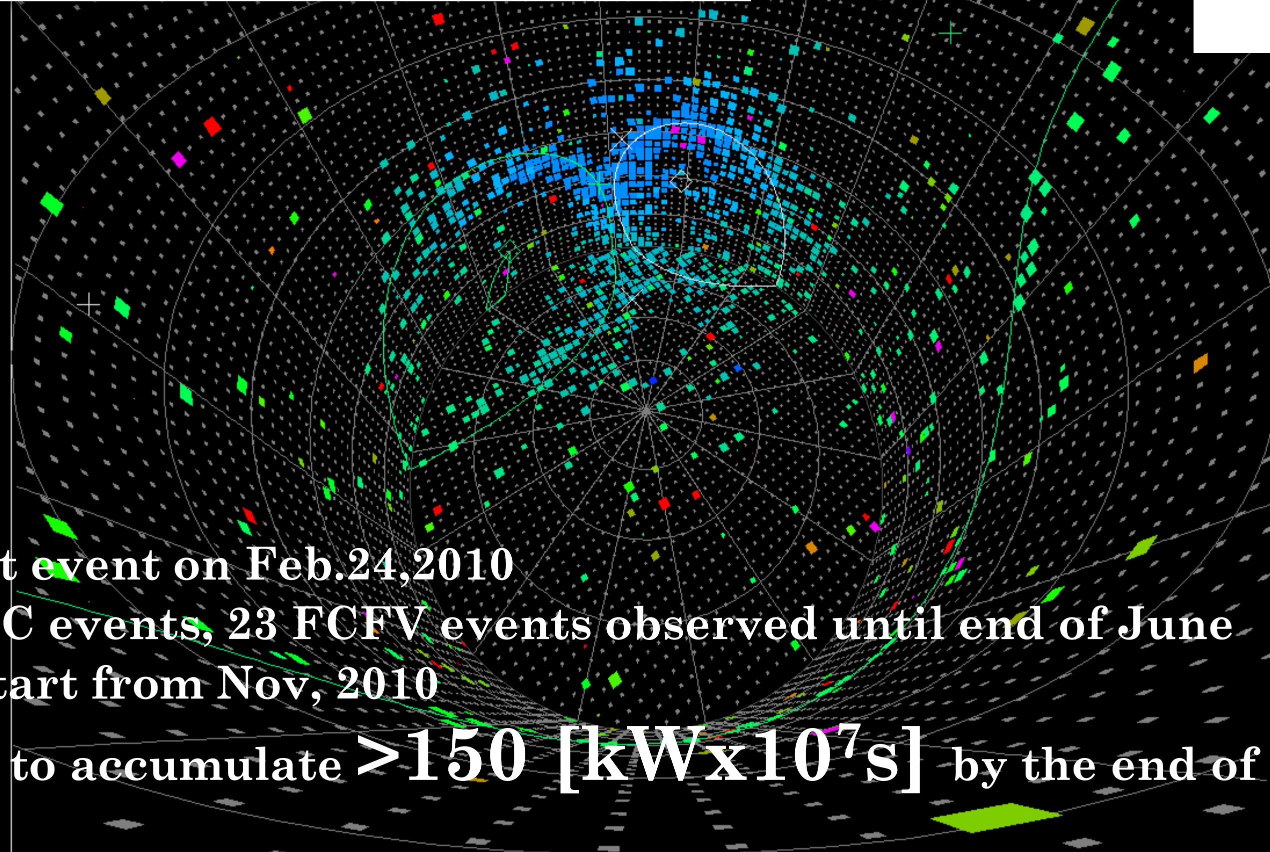


- Delivered POT: 3.35×10^{19} (3.28×10^{19} for physics)
- Continuous run @ ~50kW level
- Trial up to 100kW successful.

Observation at Super-Kamiokande

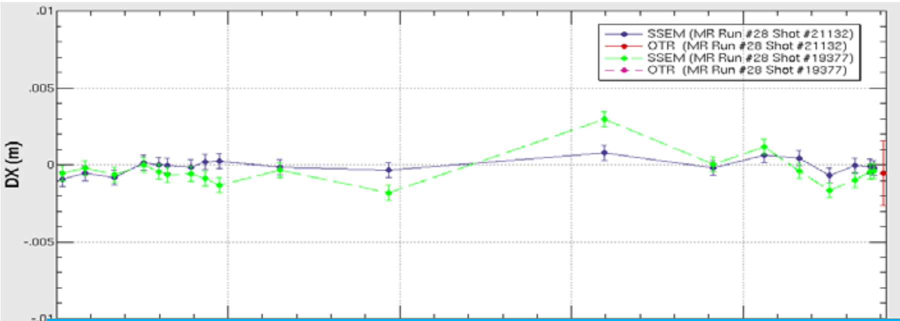
Class / Beam run	ALL	Exp. BG
Fully-Contained (FC)	**33**	0.0094
+ fiducial volume cut + visible ene. > 30MeV (FCFV)	**23**	0.0011



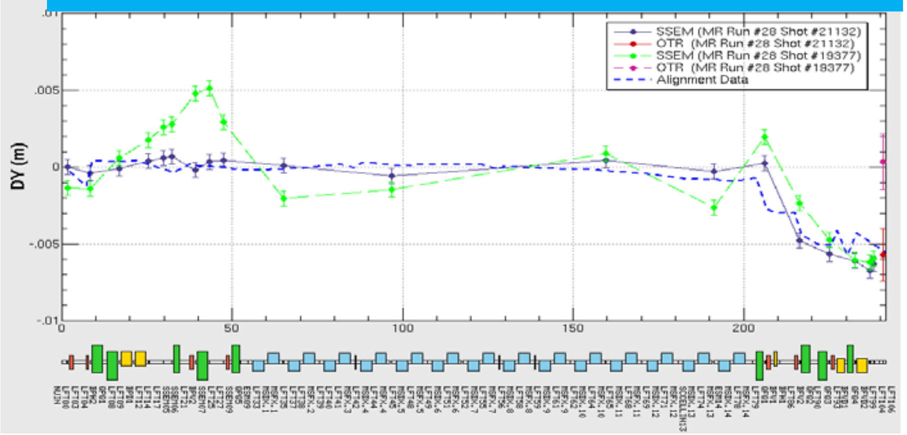


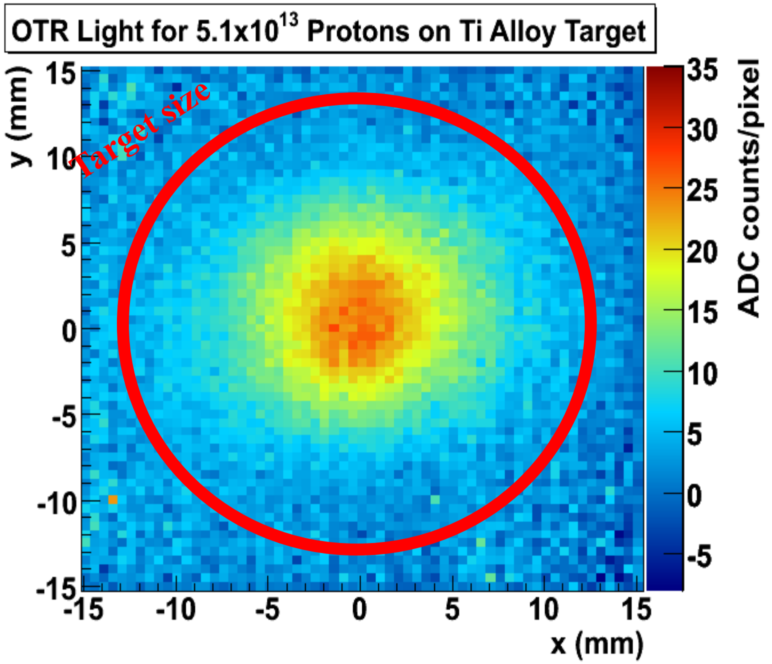
- **First event on Feb.24,2010**
- **33 FC events, 23 FCFV events observed until end of June**
- **Restart from Nov, 2010**
- **Aim to accumulate >150 [kWx10^7s] by the end of June 2011**

First neutrino physics run: Primary beam



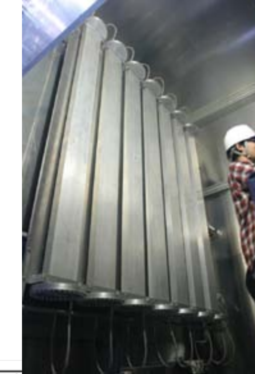
Beam orbit is tuned within 2mm from design orbit.
(Critical for controlling beam loss)

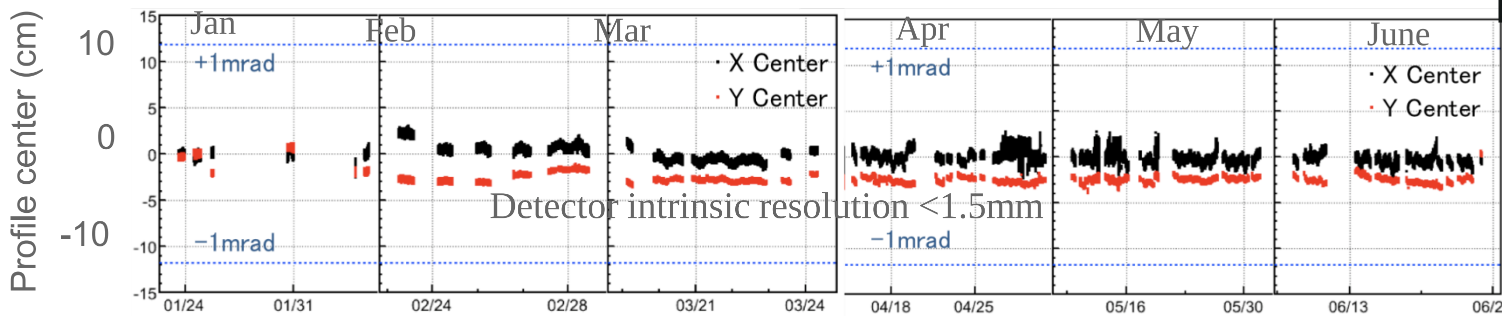


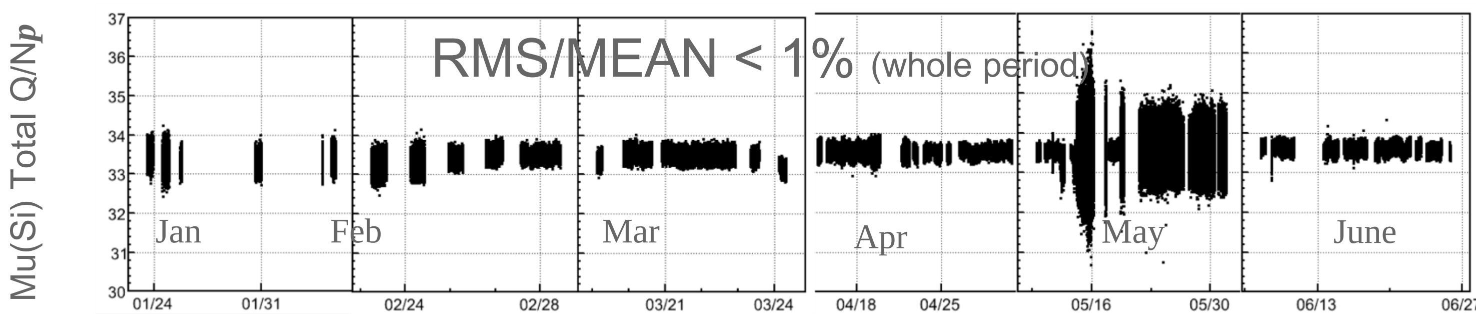


Optical transition radiation detector (OTR) immediately upstream of target:

First neutrino physics run: muon monitor







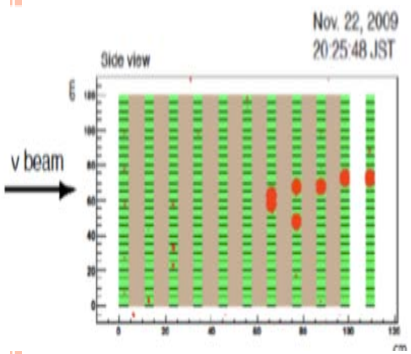
- Muon monitors:
  - Silicon detectors and ionization chambers downstream of hadron absorber
  - Additional emulsion detectors during commissioning runs
- Direction stable to <1 mrad
- Secondary/primary beam intensity ratio stable to 1%

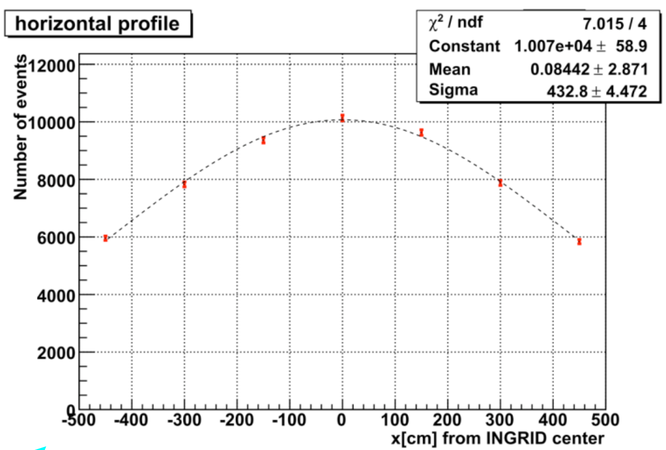
First Neutrino events in J-PARC

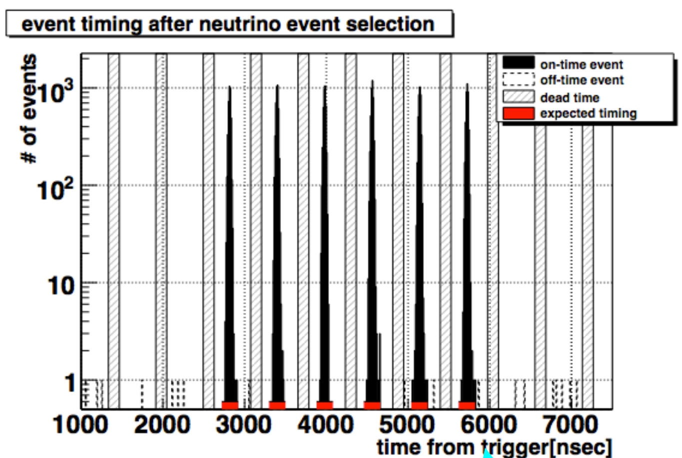
- Nov. 23rd, 2009.

First neutrino physics run:
On-axis neutrino monitor (INGRID)

The first INGRID neutrino candidate

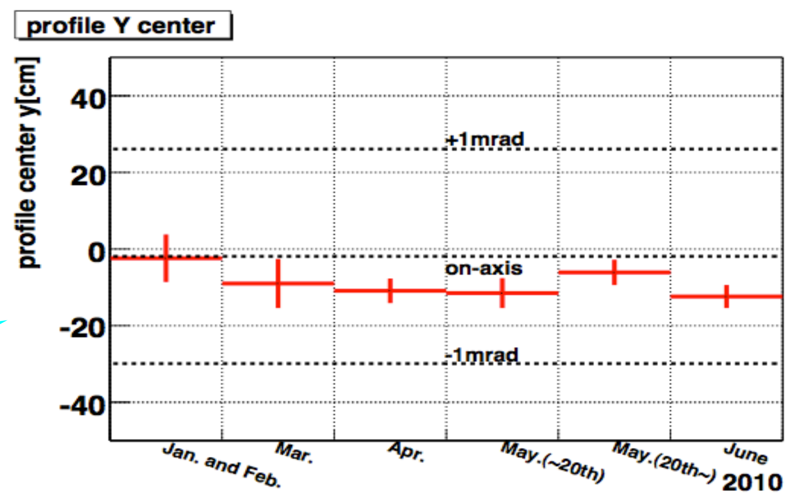






Neutrino event rate shows good symmetry: detectors and beam working well

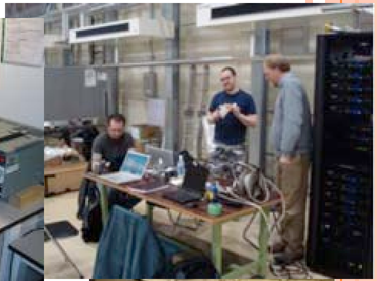
Neutrino timing distribution shows six-bunch structure of primary proton beam



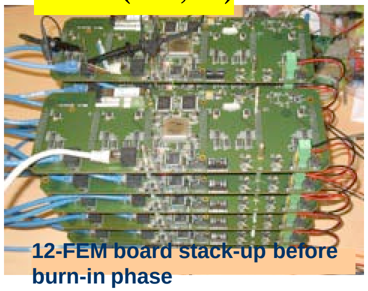
Beam profile center is within 1 mrad requirement

Off-axis Detectors

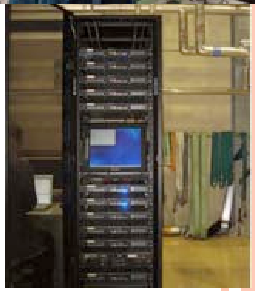
FGD(Canada, Japan)

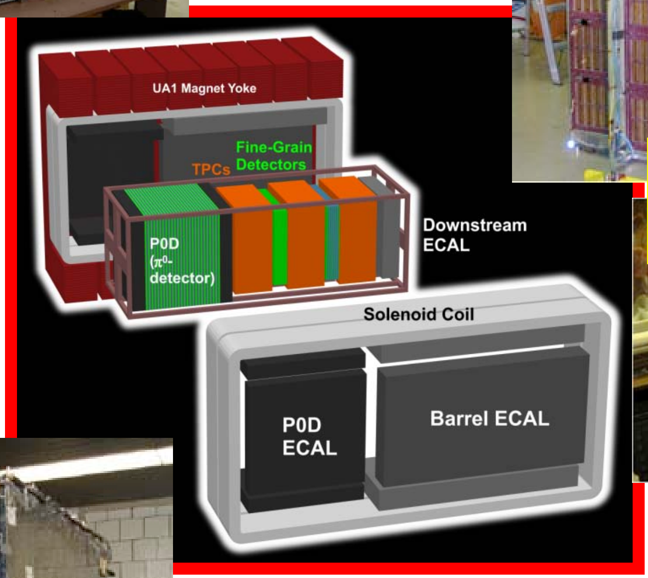


Elec(UK,Fr)



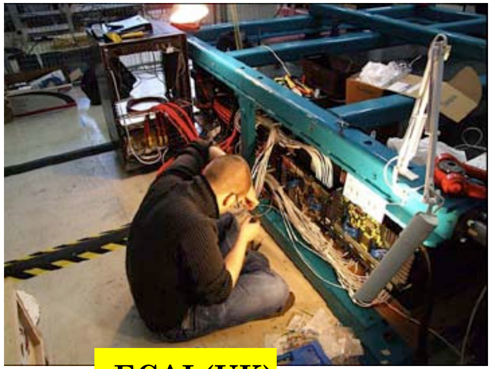
12-FEM board stack-up before burn-in phase





TPC(Canada/France, Spain, Swiss, Italy, German)

P0D(US)



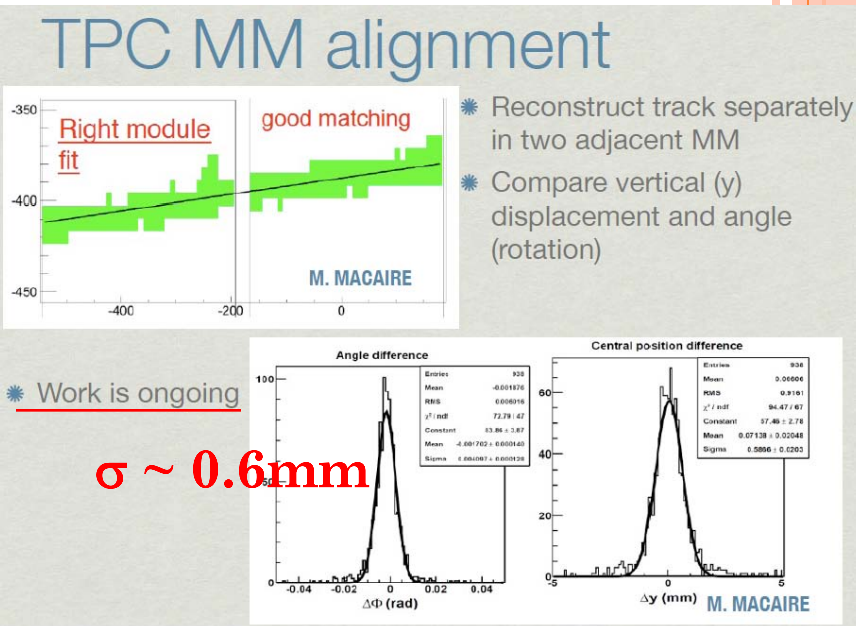
ECAL(UK)

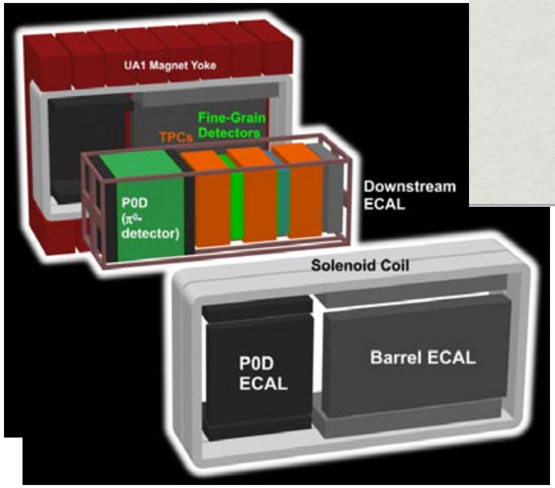
SMRD(Jp,US,Pol,Rus)

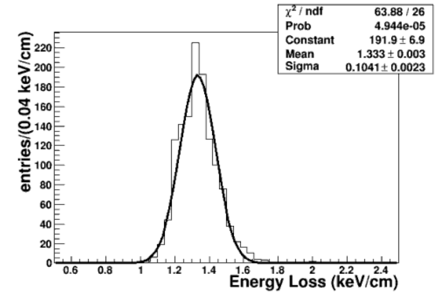
OFF-AXIS DETECTOR PERFORMANCES

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%

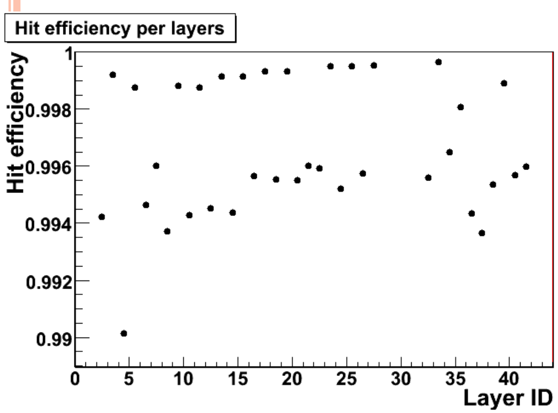
Very small number of bad channels

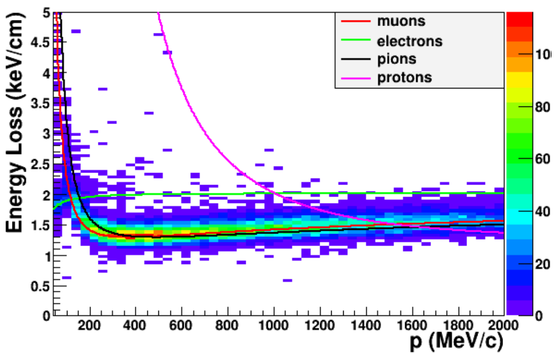


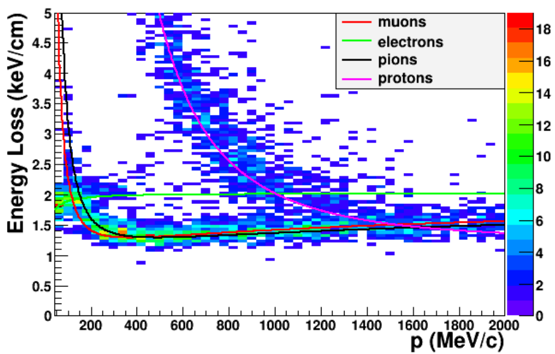




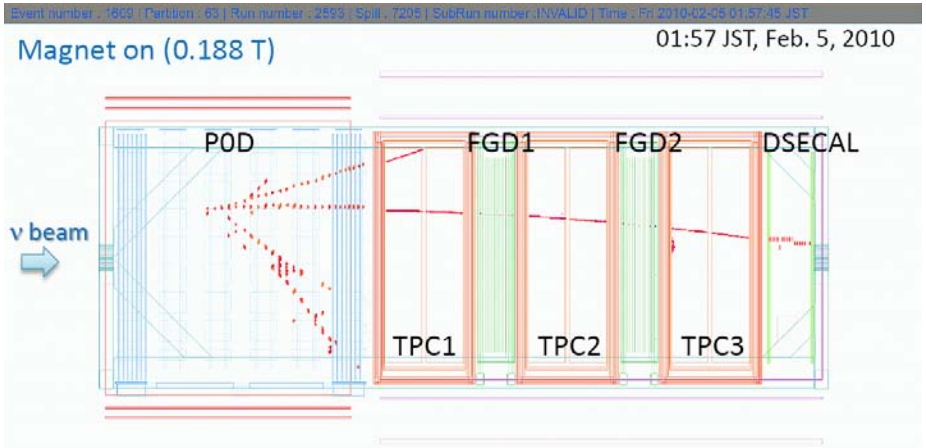
Hit Efficiencies >99%
For all layers (FGD)

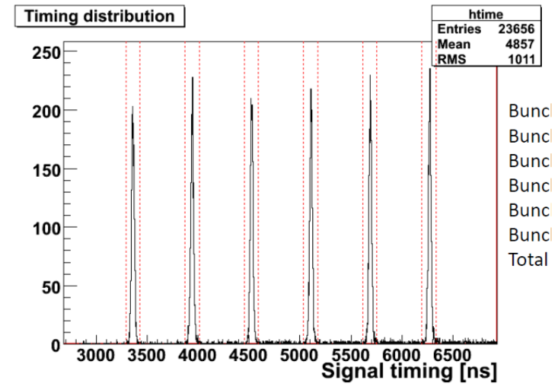


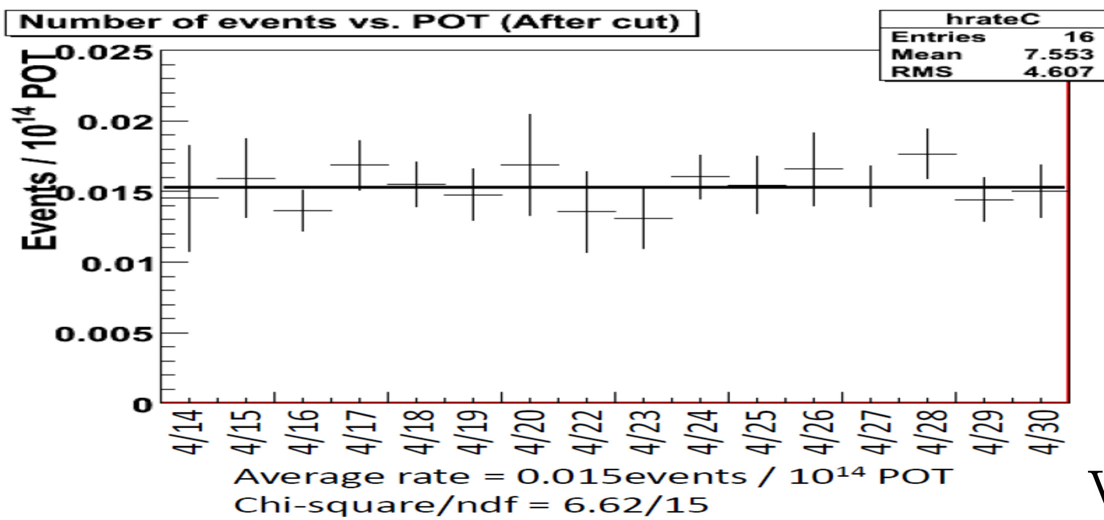


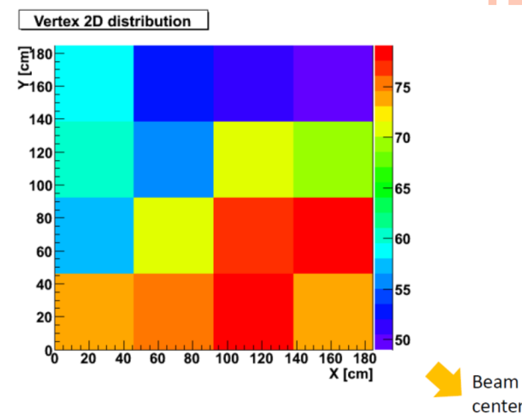


OFF-AXIS DETECTOR MEASUREMENTS



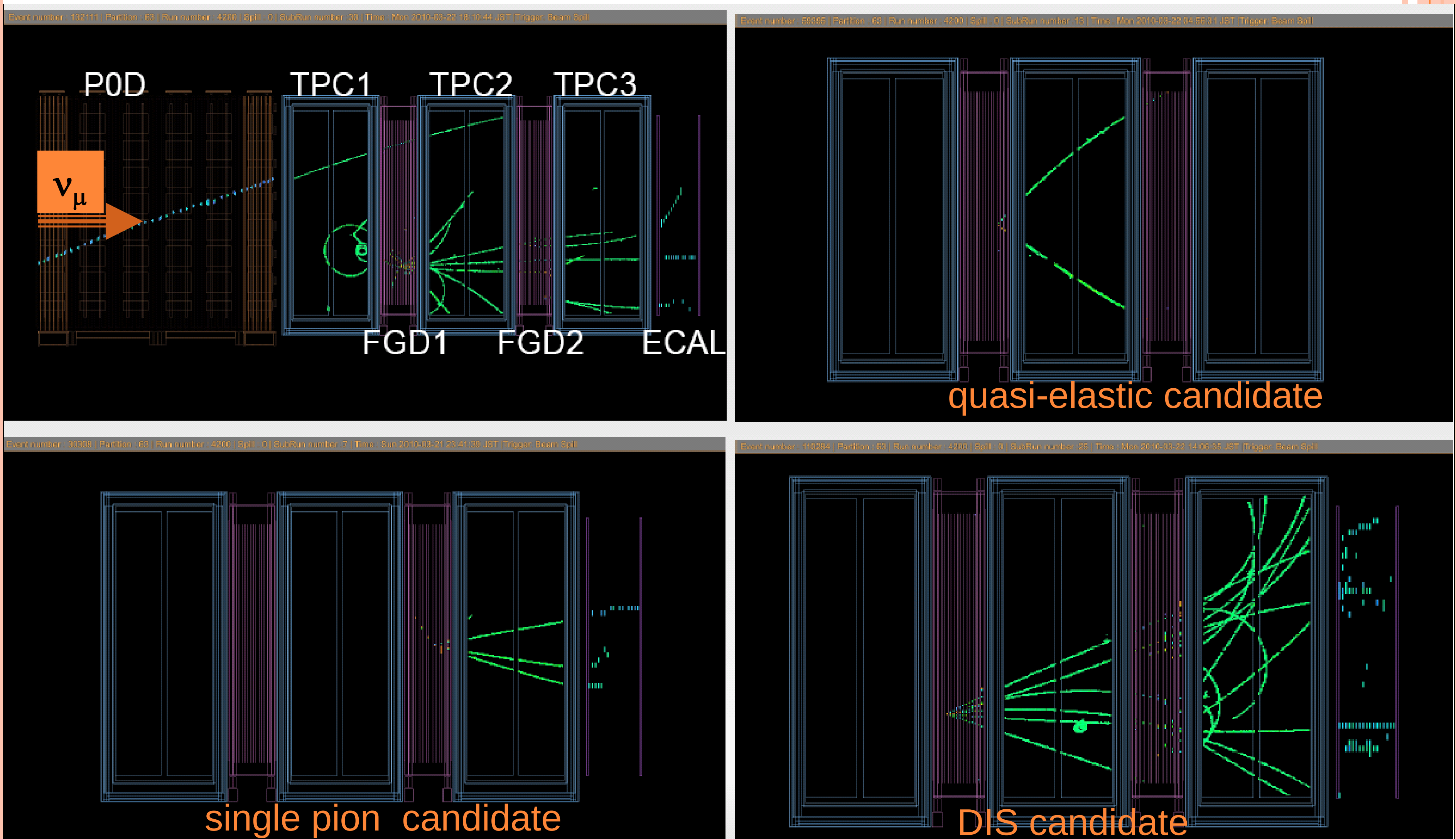






View from Downstream to Upstre

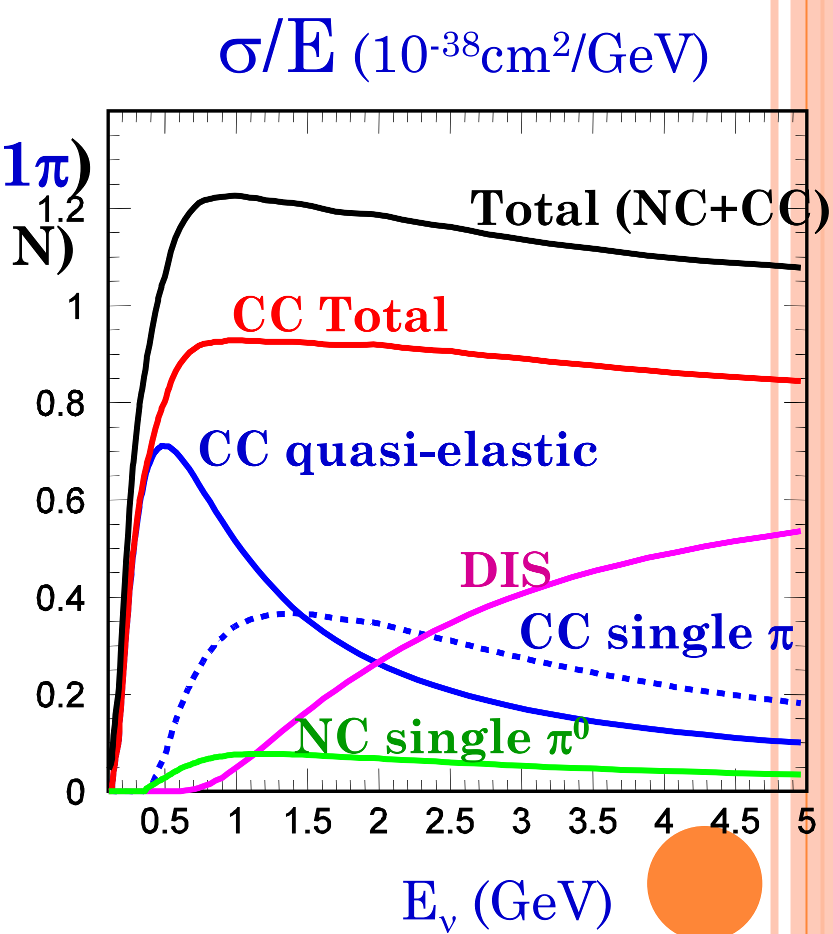
A few ND280 neutrino interaction candidates



Neutrino interactions in the T2K Energy (~1GeV)

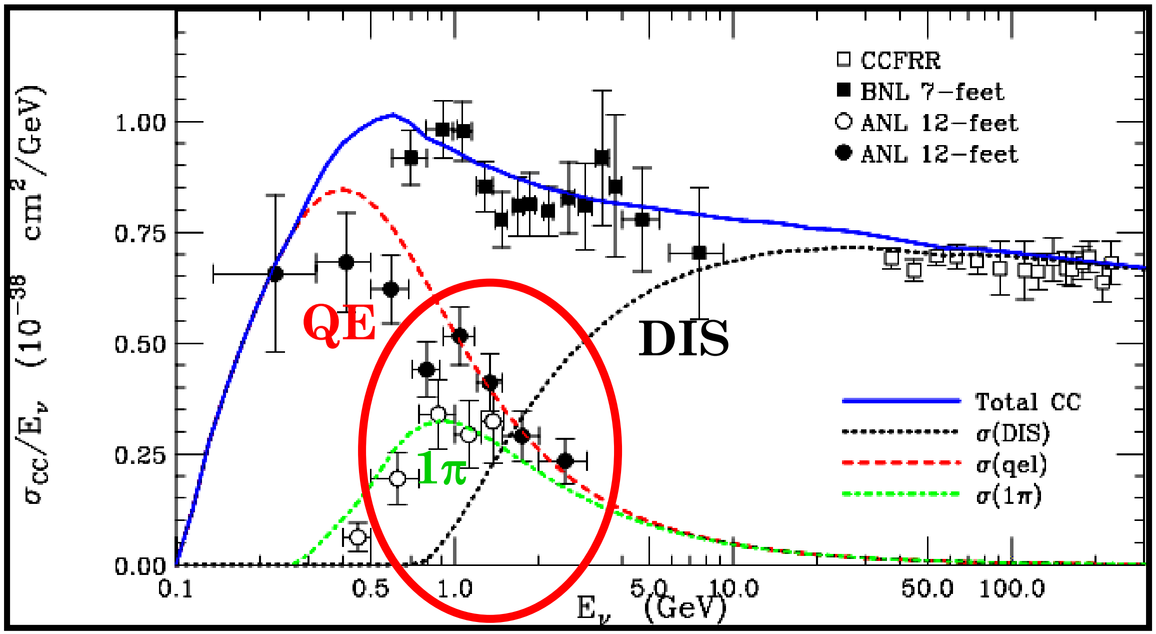
- **CC quasi elastic (CCQE)**
  - $\nu + n \rightarrow \mu^- + p$ (n in N)
- **CC (resonance) single π (CC-1π)**
  - $\nu + n(p) \rightarrow \mu^- + \pi^+ + p(n)$ (n,p in N)
- **DIS (Deep Inelastic Scattering)**
  - $\nu + N \rightarrow \mu^- + m\pi^{+,-,0} + N'$
- **CC coherent π**
  - $\nu + A \rightarrow \mu^- + \pi^+ + A$
- **NC**

+ Nuclear Effects



Existing Data (poor precision) ⇨ Measure them more precisely in T2K

σ_ν in this E range interesting:



MINOS, NuMI

K2K, NOvA

MiniBooNE, SciBooNE, T2K

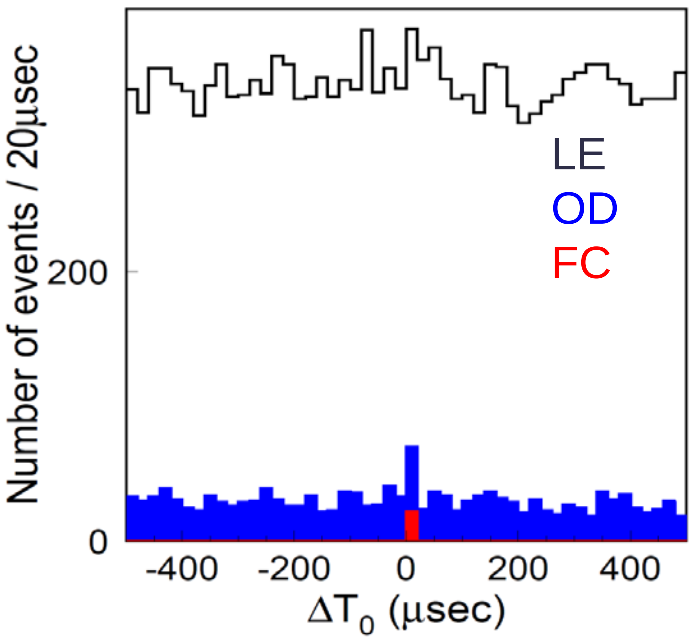
Super-K atmospheric ν

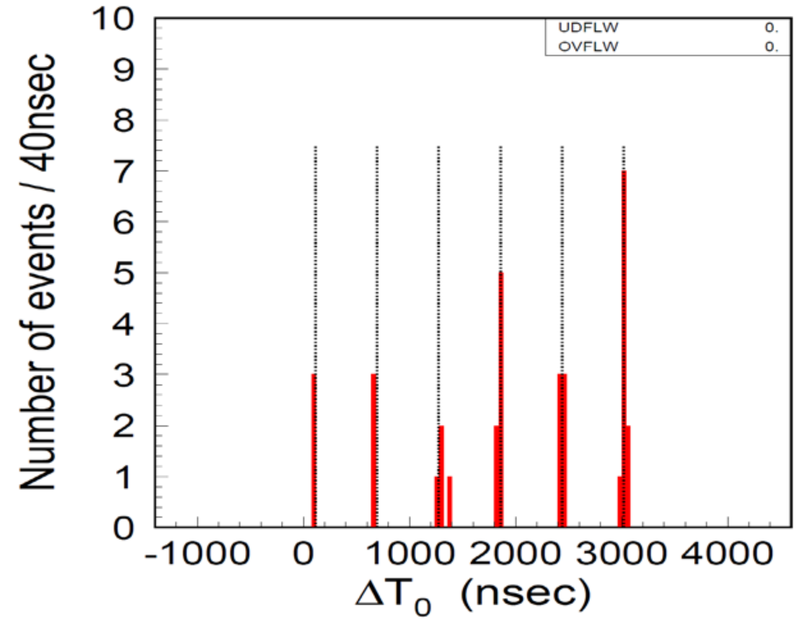
FIRST NEUTRINO PHYSICS RUN: SUPER-KAMIOKANDE

- **J-PARC neutrino events selected by event timing using GPS**
- **SK analysis is very well established**
- **Event selection & cut values fixed before data collection for this run**

ν_μ disappearance analysis	ν_e appearance search
Timing coincidence w/ beam timing (+TOF)	
Fully contained (No OD activity)	
Vertex in fiducial volume (>2m from wall)	
Evis > 30MeV	Evis > 100MeV
Number of rings =1	
μ-like ring	e-like ring
	No decay electron
	Forced 2nd ring: $m_{\gamma\gamma}$<105 MeV
	E_ν^{rec} < 1250MeV

First neutrino physics run: Super-Kamiokande



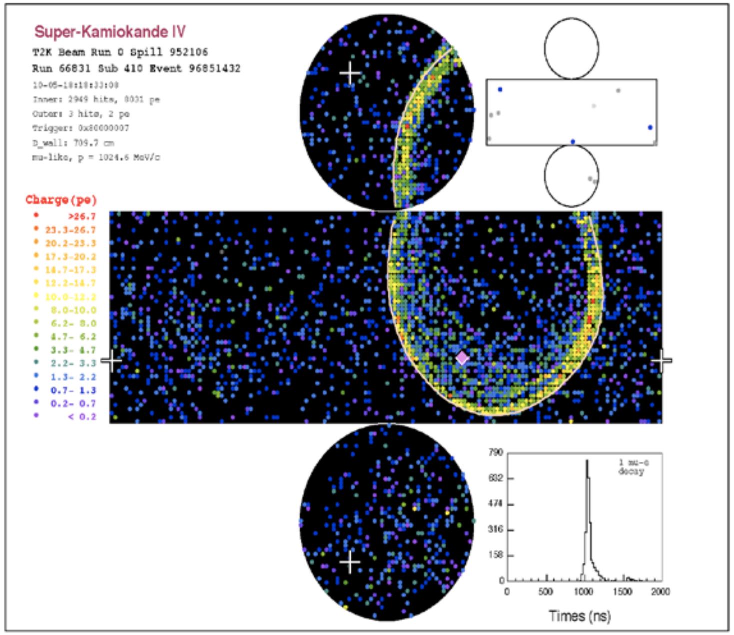


LE: Low energy triggered events
OD: Outer detector events
FC: Fully contained events

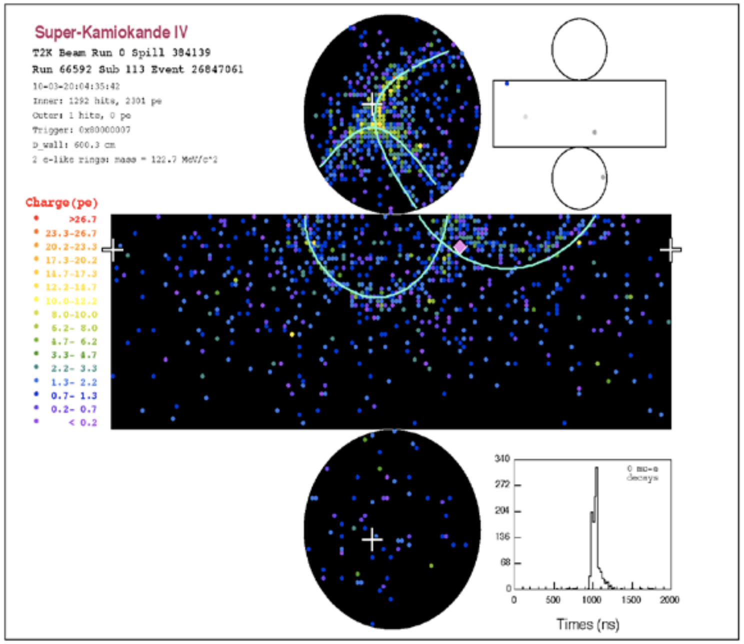
- Event time distribution clearly shows six-bunch beam structure
- 33 FC events and 23 are in the Fiducial Volume.
- Expected non-beam background: ~0.001 events

T2K NEUTRINO EVENTS

Single-ring μ-like event



Two-ring event

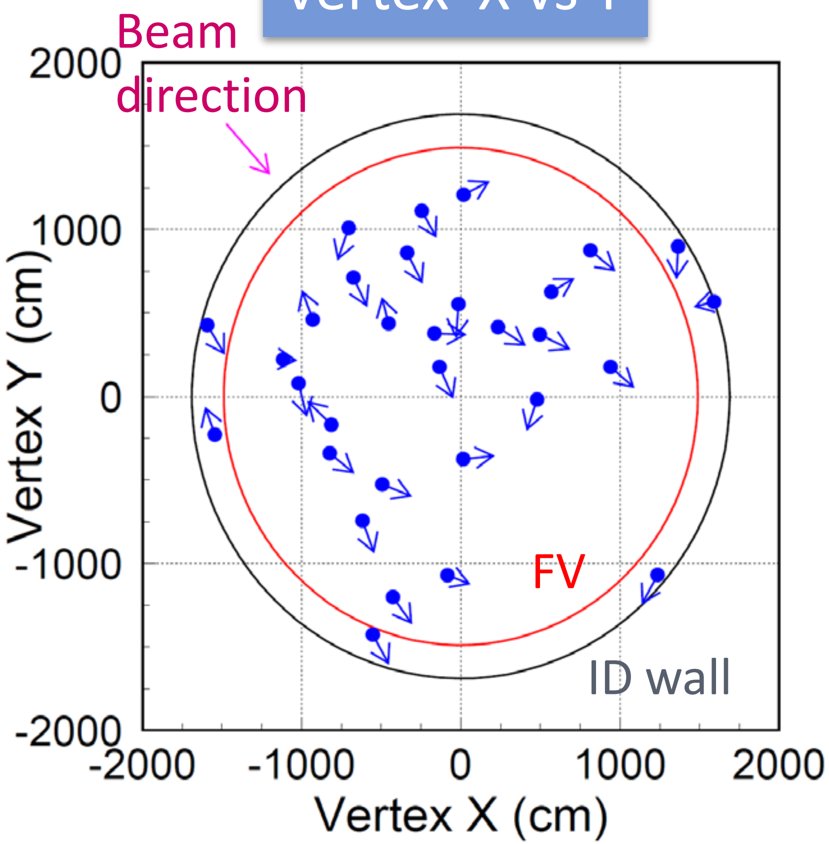


- Pink diamonds are placed on the wall in the beam direction starting from the reconstructed vertex.

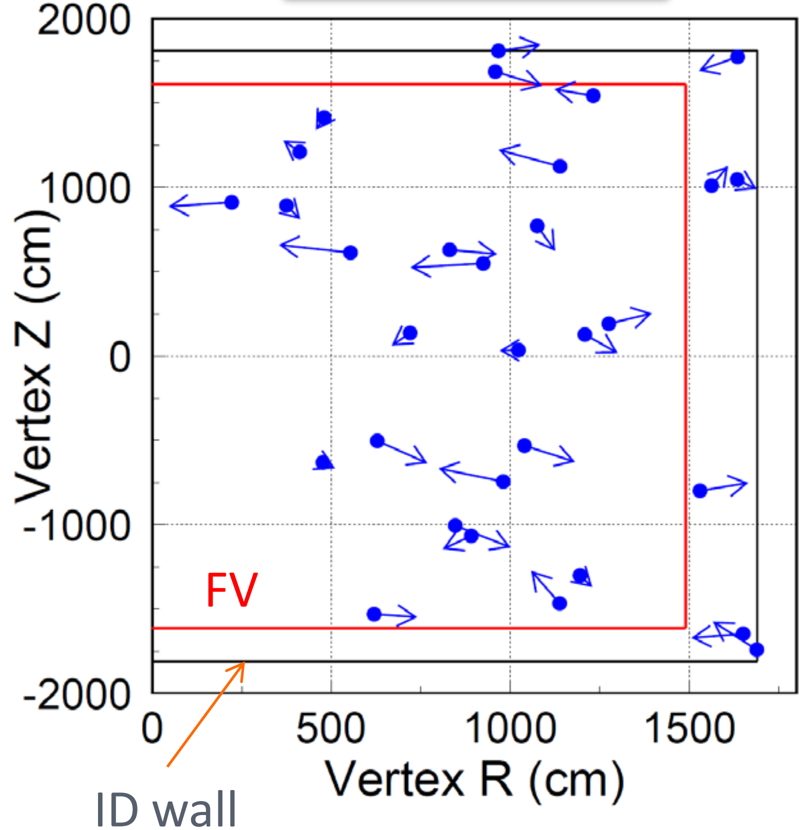
VERTEX AND DIRECTION
(FC, EVIS>30MEV)

Points : Reconstructed event vertex
Arrow : 1st-ring direction

Vertex X vs Y

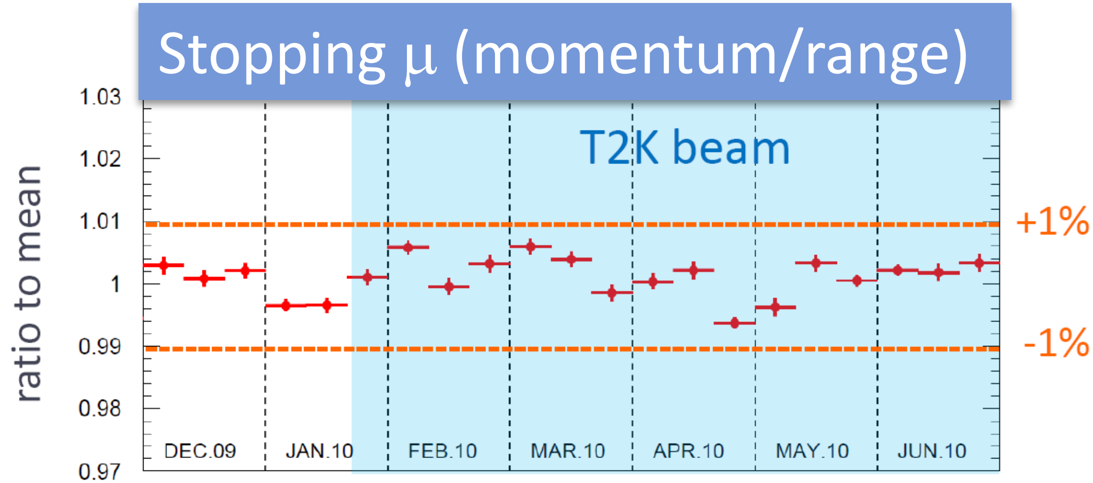


Vertex R vs Z



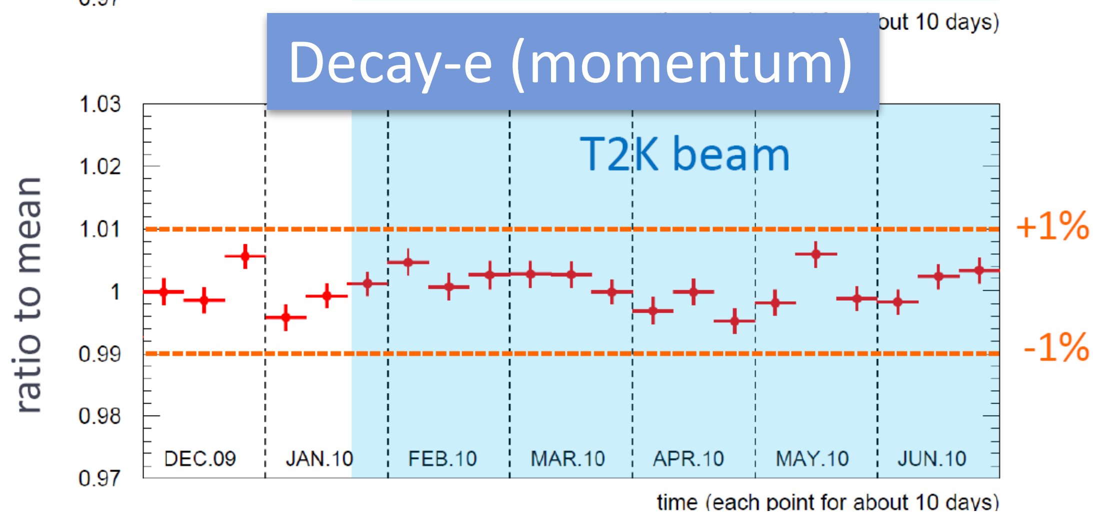
Super-K Energy scale stability for T2K data quality assuarance

Stopping μ (momentum/range)



RMS/MEAN
T2K period : 0.31%
(SK-IV all : 0.39%)

Decay-e (momentum)



RMS/MEAN
T2K period : 0.28%
(SK-IV all : 0.45%)

Energy scale has been quite stable.

Physics Sensitivity of this run

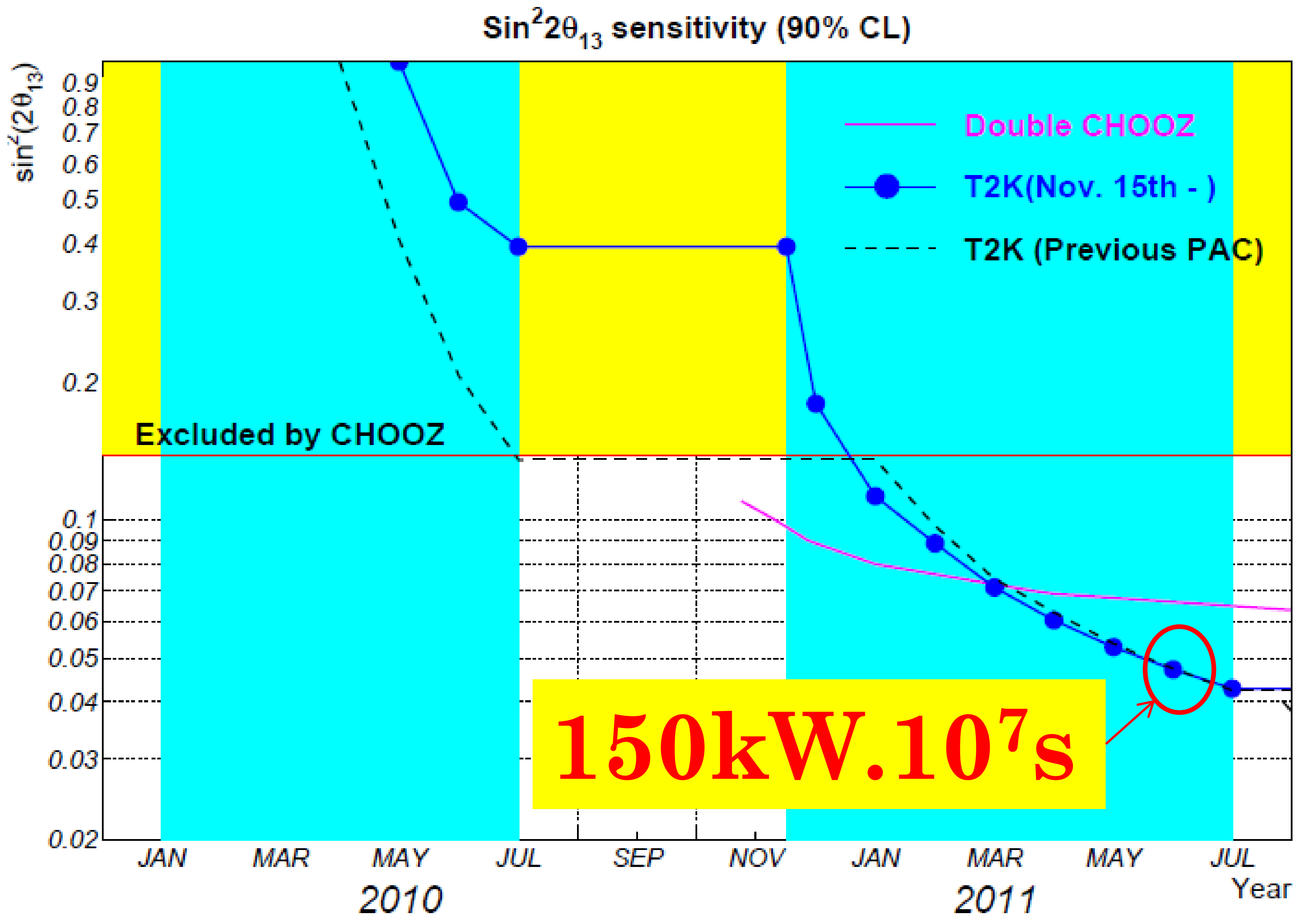
- Physics analysis with the 3.23 E19 POT data is under processed and will be shown soon.
  - Measurements of muon neutrino disappearance
    - **Sensitive to $\sin^2 2\theta_{23}$ and Δm^2_{23}**
  - Search for electron neutrino appearance
    - **Sensitive to $\sin^2 2\theta_{13}$**
- Appealing features
  - High quality data with the off-axis beam to study neutrino oscillations.
    - **Expect the similar sensitivity as that of K2K**

Near term improvement

- The beam power of 2010 Jan.-June run was limited to 50kW by the fast-extraction kicker problem.
  - Fixed during this summer maintenance.
  - 100kW operation was tested and is successful.
- T2K will start running from the next week.
  - 6 bunch → 8 bunch (33% more protons)
  - Acceleration Cycle: 3.64s → 3.2s (14% more protons)

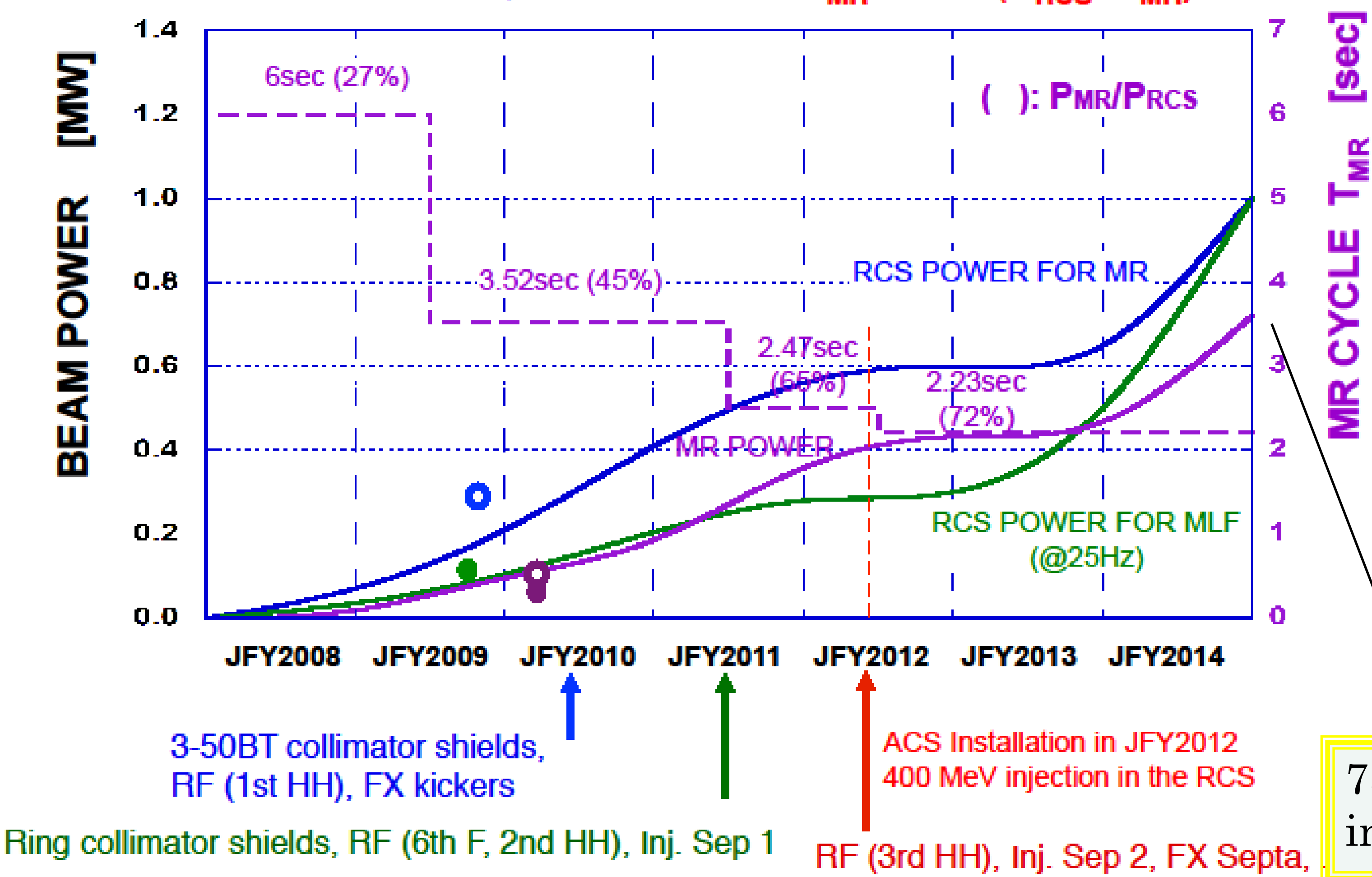
  ⇨ **150kW operation is feasible.**

SHORT TERM GOAL TOWARD 2011



Power upgrade plan of RCS and MR(FX)

For 8 bunches, 30 GeV at MR: $P_{MR}=1.6 \times (P_{RCS}/T_{MR})$



750kW in 2014

Beyond

T2K Beyond

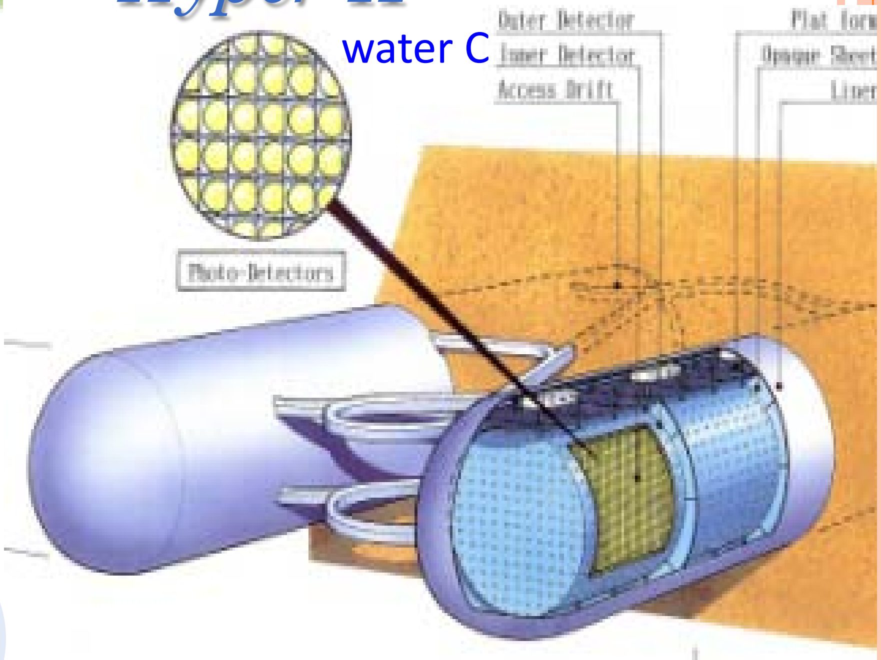
Study Symmetry Violation between ν and $\bar{\nu}$

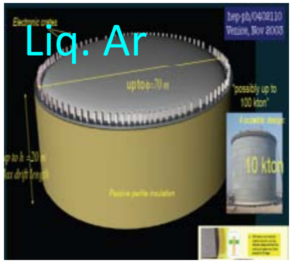
J-PARC Upgrade
KEK Roadmap
→1.7MW

Best Optimization

Huge ν detector
•Water Cherenkov
•Lq. Ar TPC
O(~100k)ton

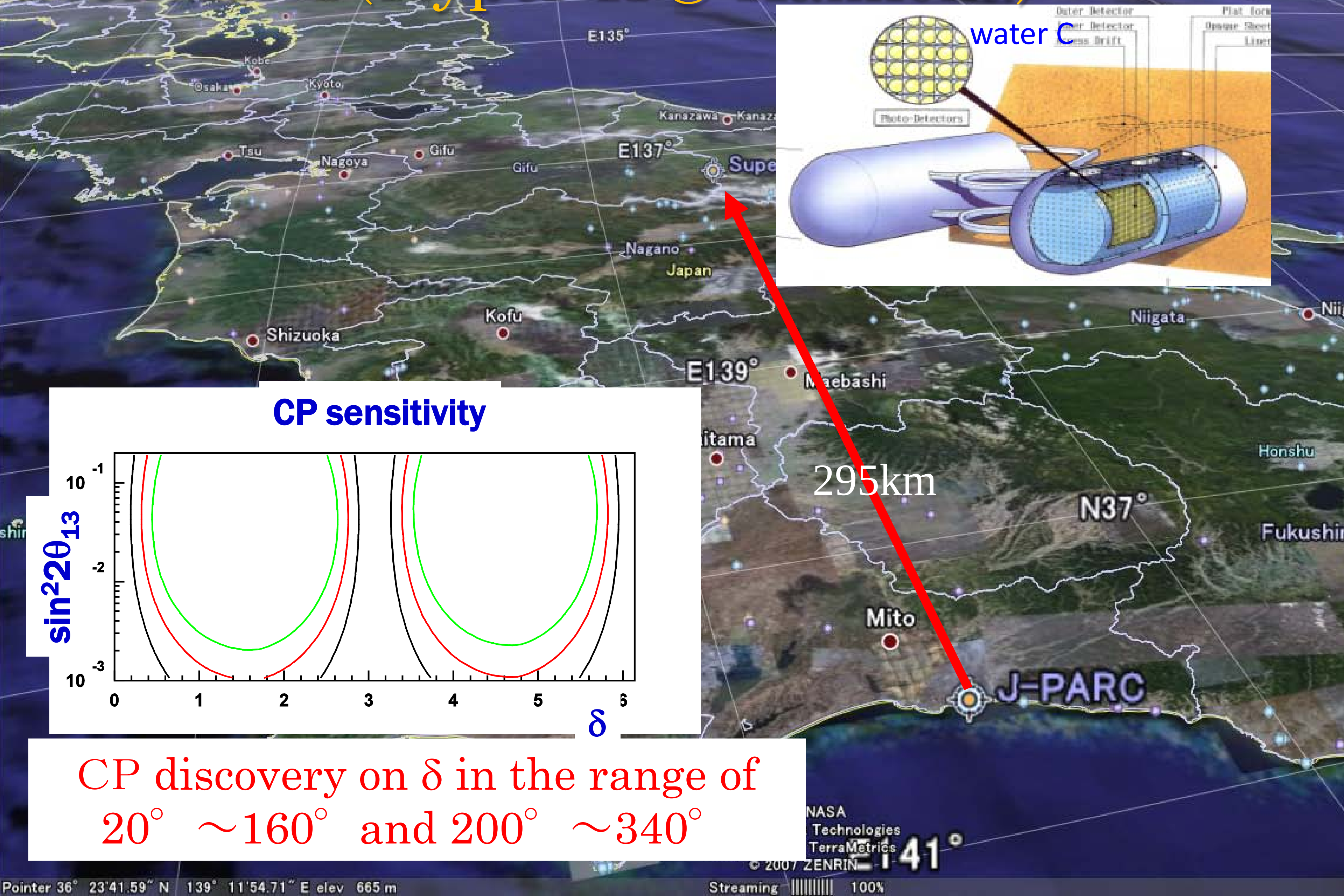
Hyper-K





GUT
Proton Decay

Scenario 1 (Hyper-K @ Kamioka)



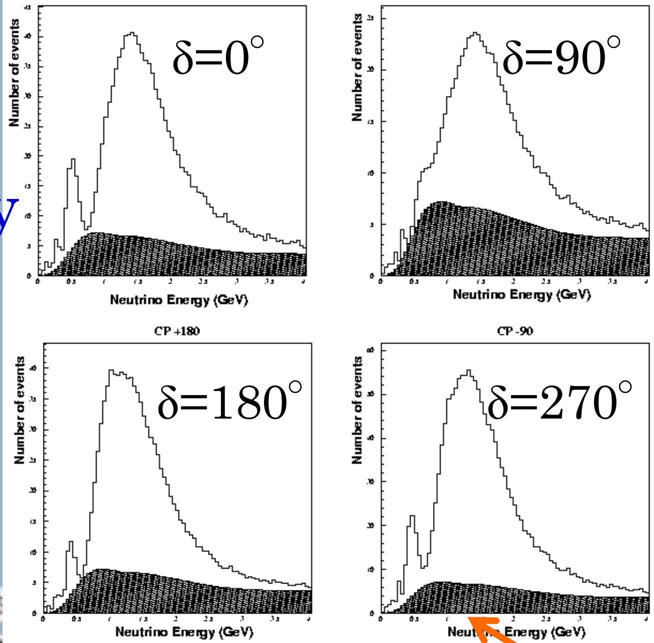
CP discovery on δ in the range of 20° ～160° and 200° ～340°

Scenario 2

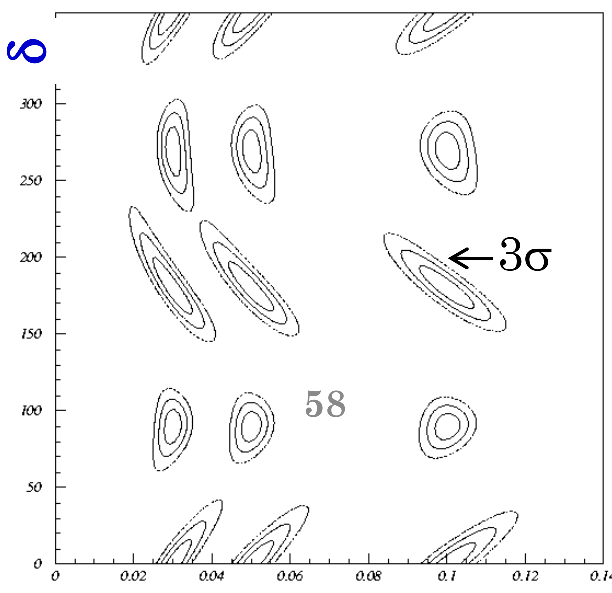
- 100kton Lq. Ar TPC @ 658km
- ν beam only
- Sensitivity to the mass hierarchy

ν_e Spectrum

$\sin^2 2\theta_{13}=0.03$, Normal Hierarchy



CP Measurement Potential

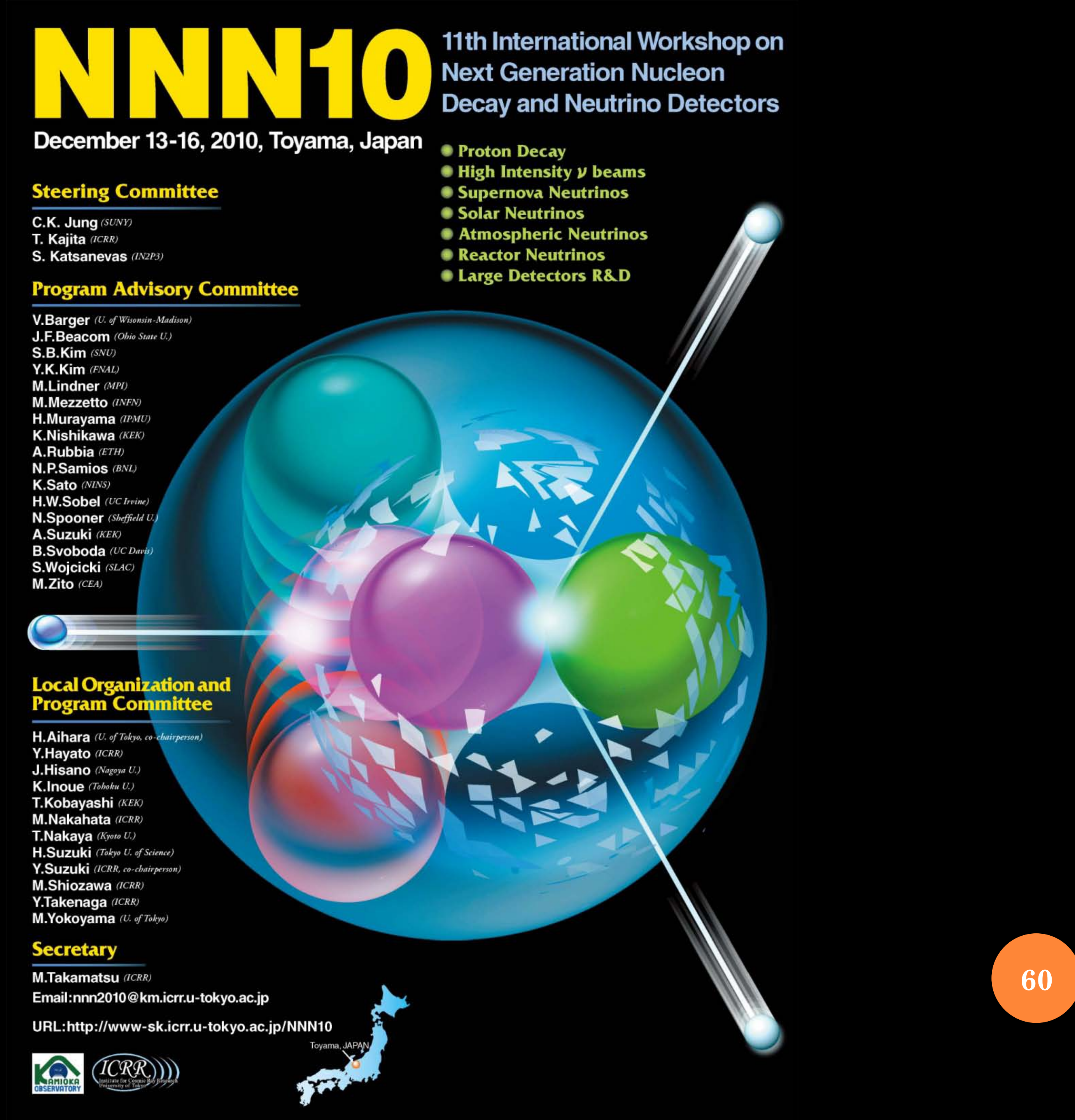


NP08, arXiv:0804.2111

YOUR INTERESTS IN T2K

My personal guesses:

- When will T2K have the results?
  - First results with the similar sensitivity as K2K will come soon.
  - In 2011, the sensitivity will be improved to be $\sin^2 2\theta_{13}$~0.05.
  - After 2011, the sensitivity will be further improved.
- How is the J-PARC accelerator running?
  - Expect the operation with150kW or higher in 2010-2011.
  - Aim the design intensity of 750kW.
- Is it the option of anti-neutrino running?
  - Technically feasible. The physics case should be studied and reviewed by PAC.
- Does T2K have the sensitivity to the CP violation and the sign of Δm^2?
  - The probability of ν_e appearance has the strong CP dependence, but do not have the sensitivity to the sign of Δm^2 with 300km baseline
- What is the future upgrade (or successor) of T2K?
  - J-PARC proton beam power upgrade
  - A Huge Far Detector to probe the proton decay and the ν CP violation.


NNN10
11th International Workshop on
Next Generation Nucleon
Decay and Neutrino Detectors
December 13-16, 2010, Toyama, Japan
Proton Decay
High Intensity ν beams
Supernova Neutrinos
Solar Neutrinos
Atmospheric Neutrinos
Reactor Neutrinos
Large Detectors R&D
Steering Committee
C.K. Jung (SUNY)
T. Kajita (ICRR)
S. Katsanevas (IN2P3)
Program Advisory Committee
V.Barger (U. of Wisonsin-Madison)
J.F.Beacom (Ohio State U.)
S.B.Kim (SNU)
Y.K.Kim (FNAL)
M.Lindner (MPI)
M.Mezzetto (INFN)
H.Murayama (IPMU)
K.Nishikawa (KEK)
A.Rubbia (ETH)
N.P.Samios (BNL)
K.Sato (NINS)
H.W.Sobel (UC Irvine)
N.Spooner (Sheffield U.)
A.Suzuki (KEK)
B.Svoboda (UC Davis)
S.Wojcicki (SLAC)
M.Zito (CEA)
Local Organization and Program Committee
H.Aihara (U. of Tokyo, co-chairperson)
Y.Hayato (ICRR)
J.Hisano (Nagoya U.)
K.Inoue (Tohoku U.)
T.Kobayashi (KEK)
M.Nakahata (ICRR)
T.Nakaya (Kyoto U.)
H.Suzuki (Tokyo U. of Science)
Y.Suzuki (ICRR, co-chairperson)
M.Shiozawa (ICRR)
Y.Takenaga (ICRR)
M.Yokoyama (U. of Tokyo)
Secretary
M.Takamatsu (ICRR)
Email:nnn2010@km.icrr.u-tokyo.ac.jp
URL:http://www-sk.icrr.u-tokyo.ac.jp/NNN10
Toyama, JAPAN
KAMIOKA OBSERVATORY
ICRR


The XXV International Conference on Neutrino Physics and Astrophysics
NEUTRINO 2012
June 3-9 2012 Kyoto, Japan
June 3, Kyoto University Clock Tower Centennial Hall
June 4-9, Kyoto TERRSA
http://neu2012.kek.jp/
Hosted by
The Science Council of Japan (plan)
The Physical Society of Japan
Co-hosted by
Kamioka Observatory, Institute for Cosmic Ray Research (ICRR),University of Tokyo
Kyoto University
High Energy Accelerator Research Organization (KEK)
International Advisory Committee
Local Organizing Committee