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CERN Colloquium
CERN Auditorium

Indication of Electron Neutrino Appearance in the T2K experiment and its long-term implications

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High Energy Accelerator Research Organization (KEK)
&
J-PARC Center
For T2K collaboration

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- Introduction of T2K experiment
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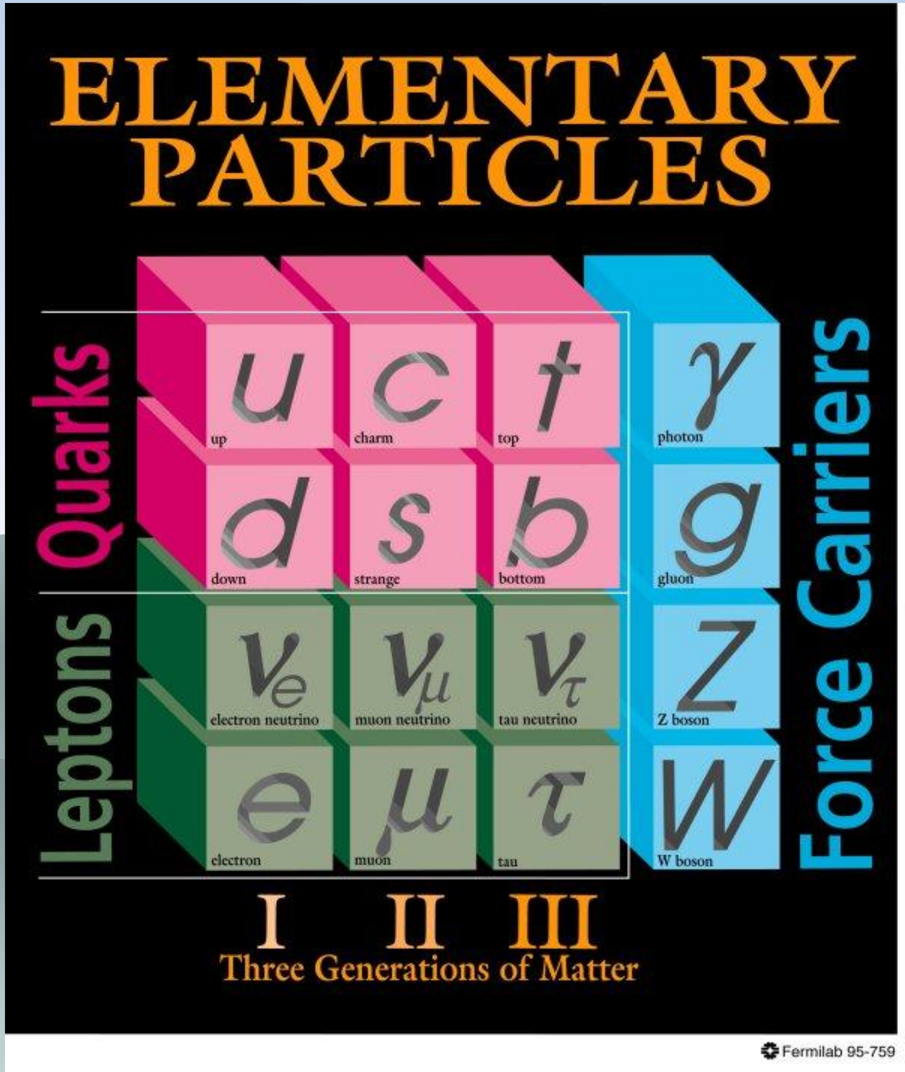
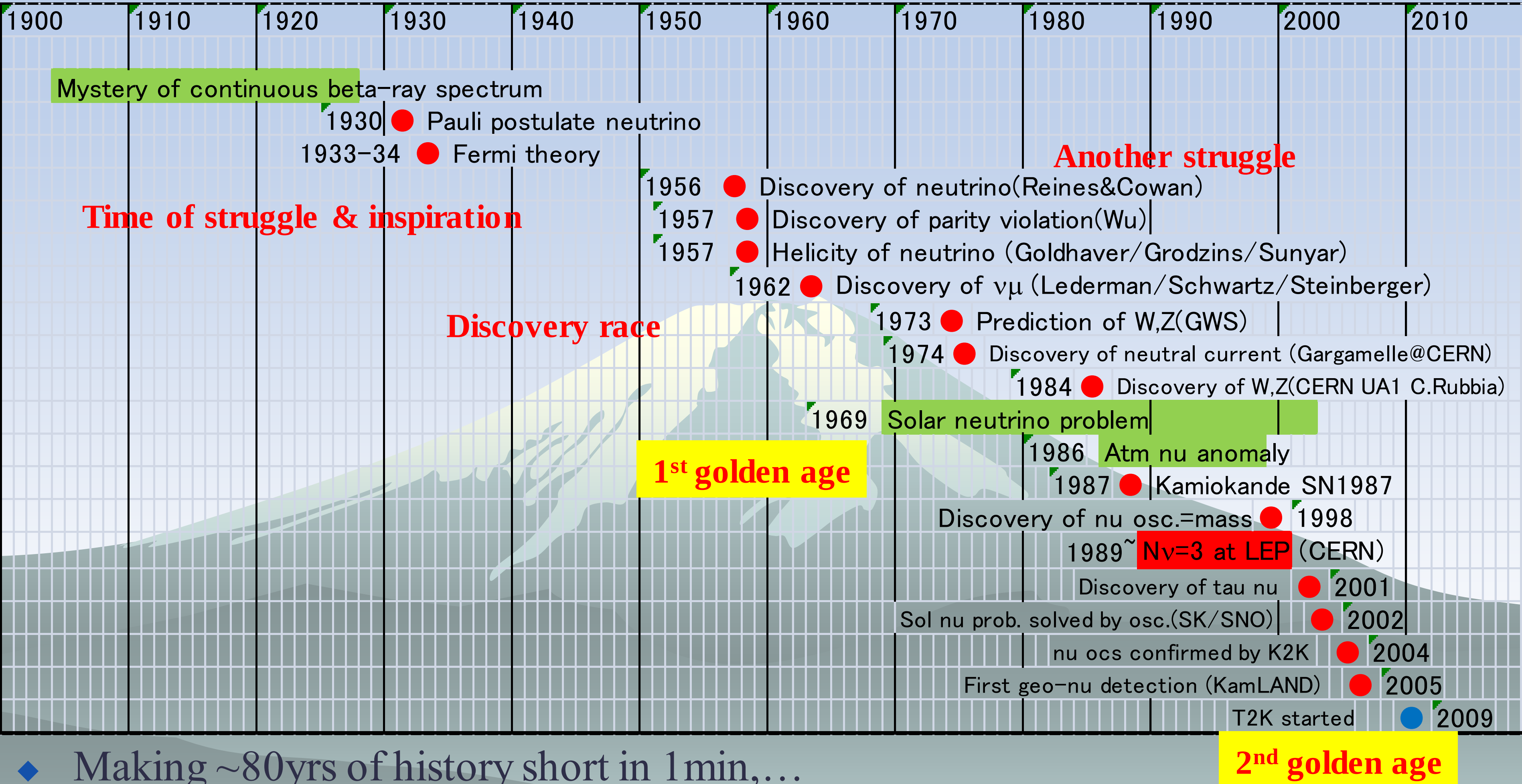
Neutrinos in the present standard model



- 3 types (flavors)
- Has no electric charge
  - Only interact weakly
- Mass has been assumed to be 0 in the standard model

Brief history of neutrino



- Making ~80yrs of history short in 1min,…
- "Mysteries" of neutrino has been fascinating particle physicists for all the time
- But still many mysteries remain which are suspected to hold a key to another breakthrough
- Thus probably continue to fascinate particle physicists another many years

Neutrino physics situation

- Especially since 1998, neutrino physics has made great progress
  - Discovery of oscillation (ν_μ disappearance) in atm ν by SK (98)
    - Confirmation in acc ν beam by K2K(2004)/MINOS(2006)
  - ν_e disappearance ($\rightarrow \nu_\mu/\nu_\tau$) established by solar neutrino measurements by SNO/SK (2002)
    - Confirmation in reactor ν by KamLAND (2004)
  - OPERA observed first ν_τ appearance candidate (2010)
- Surprises (=Mysteries) are
  - Neutrino has really finite (but small) mass: First evidence of violation of Standard Model
  - Neutrino has finite (but big) flavor mixing (unlike quarks)
    - Lepton flavor is violated
- Unraveling full nature of neutrino could provide breakthrough to approach our goals of particle physics

Toward one of big goals of particle physics: Origin of Matter-dominated Universe

Sakharov's 3 conditions

- Baryon number violation
  - Proton decay
- CP violation
  - Quark CPV seems not sufficient
  - Lepton CPV may contribute
- Non-equilibrium

Neutrino might play essential role

Neutrino oscillation

- Quantum mechanical effect
- Flavor of neutrino changes to other flavor during flight
- Only occur when neutrino has finite mass
- The way of changing depend on mass, (energy/flight distance) of neutrino
- Strong tool to explore neutrino mass and mixing

Mu neutrino

Tau neutrino

3 flavor mixing of neutrinos

Flavor eigenstates — Mass eigenstates

ν_e, ν_μ, ν_τ — m_1, m_2, m_3

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

Pontecorvo-Maki-Nakagawa-Sakata Matrix (CKM matrix in lepton sector)

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

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

Atm/Acc — Acc/Reactor — Sol/Reactor

6 independent parameters govern oscillation

θ_{12}, θ_{23}, θ_{13}, δ

Δm_{12}^2, Δm_{23}^2, Δm_{13}^2

$\Delta m_{ij} = m_i^2 - m_j^2$

Present knowledge

Δm^2_{21} $(7.65^{+0.23}_{-0.20})\ 10^{-5}\ \mathrm{eV}^2$

$\sin^2\theta_{12}$ $0.304^{+0.022}_{-0.016}$

Sol/Reactor

$|\Delta m^2_{31}|$ $(2.40^{+0.12}_{-0.11})\ 10^{-3}\ \mathrm{eV}^2$

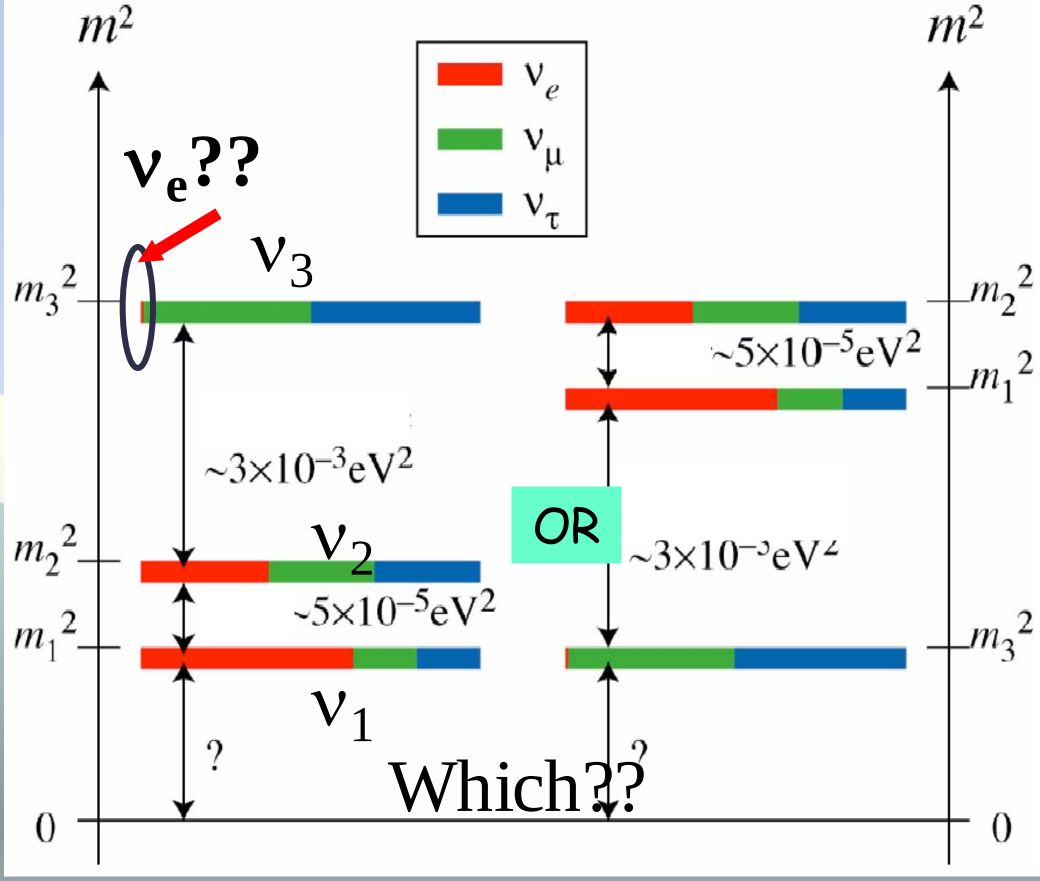
$\sin^2\theta_{23}$ $0.50^{+0.07}_{-0.06}$

Atm/Acc

$\sin^2\theta_{13} < 0.056$ @ 3σ

Schwetz, Tortola, Valle, New J.Phys.10:113011,2008

δ unkown



NEUTRINOS

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

QUARKS

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

Big diff from KM matrix

Today's Questions in neutrino physics

- Last unknown mixing θ_{13}. 3flavor mixing picture valid?
  - ➔Long baseline Accelerator neutrino experiments
  - ➔Reactor neutrino experiments

T2K

- CP symmetry violated?
  - Could be a hint to solve origin of matter in universe
  - ➔ Long baseline Accelerator neutrino experiments
- Mass hierarchy
  - ➔ Long baseline Accelerator neutrino experiments
- Absolute mass?
  - ➔Tritium beta decay spectrum
  - ➔neutrino-less double beta decay
- Neutrino is Dirac? Or Majorana?
  - ➔ neutrino-less double beta decay

Why θ_{13}?

$\nu_\mu \rightarrow \nu_e$ appearance and CPV

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \ (1 - 2S_{13}^2)\right)$$

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$

CPV

$$+4S_{12}^2 C_{13}^2 \{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\} \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$

Sol term

CPV effect $\propto \sin\delta \cdot s_{12} \cdot s_{23} \cdot s_{13}$ **Unknown!**

($\sin\theta_{12}$~0.5, $\sin\theta_{23}$~0.7, $\sin\theta_{13}$<0.2)

The size of θ_{13} decides future direction!

Tokai-to-Kamioka (T2K) experiment

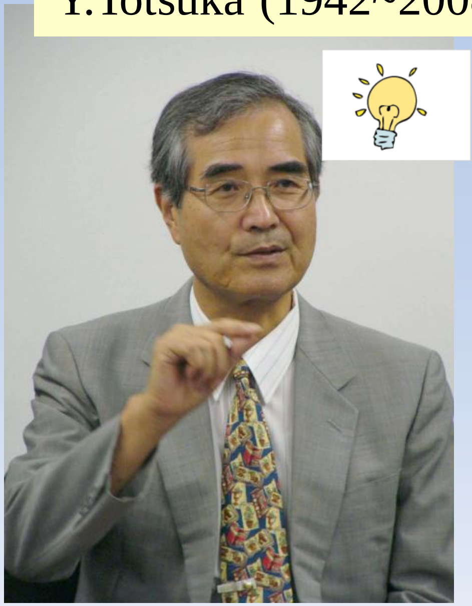
The 1st experiment w/ J-PARC ν facility

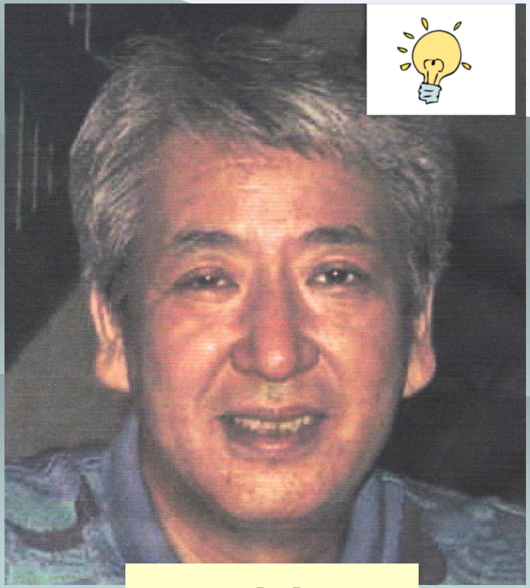
- High intensity ν_μ beam from J-PARC MR to Super-Kamiokande @ 295km
- **Discovery of νe appearance → Determine θ_{13}**
  - Last unknown mixing angle → Prove 3 flavor mixing
  - **Open possibility to explore CPV in lepton sector**
- Precise meas. of ν_μ disappearance → θ_{23}, Δm_{23}^2
  - Really maximum mixing? Any symmetry? Anything unexpected?

Milestones

- 1999: Nishikawa&Totsuka proposed to measure ν_e appearance as a next critical step toward CP measurement
- 2000: Letter of Intent
- April 2004:
  - Officially approved by Japanese Government and 5yr Construction started
  - T2K international collaboration officially formed
  - Spokesperson: K.Nishikawa
- **March 2009: Construction completed as scheduled**
- 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!

Y.Totsuka (1942~2008)





K.Nishikawa

The T2K Collaboration

~500 members, 59 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. Wroklaw

Russia
INR

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

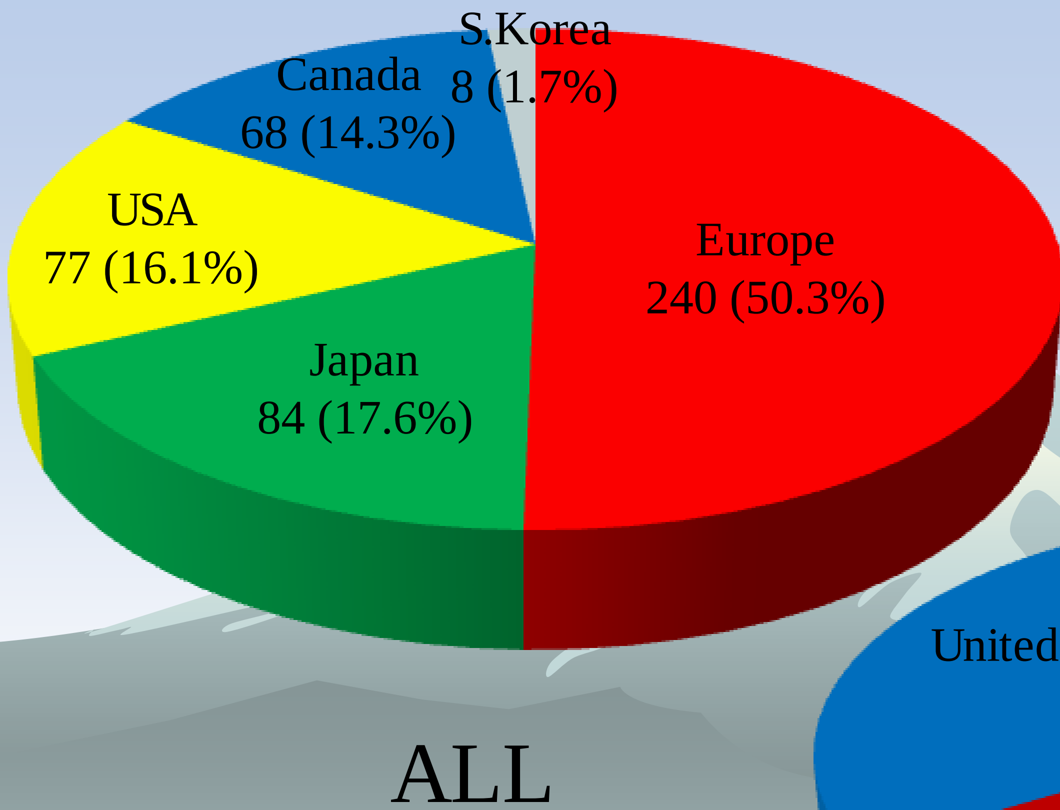
Spain
IFIC, Valencia
IFAE(Bacelona)

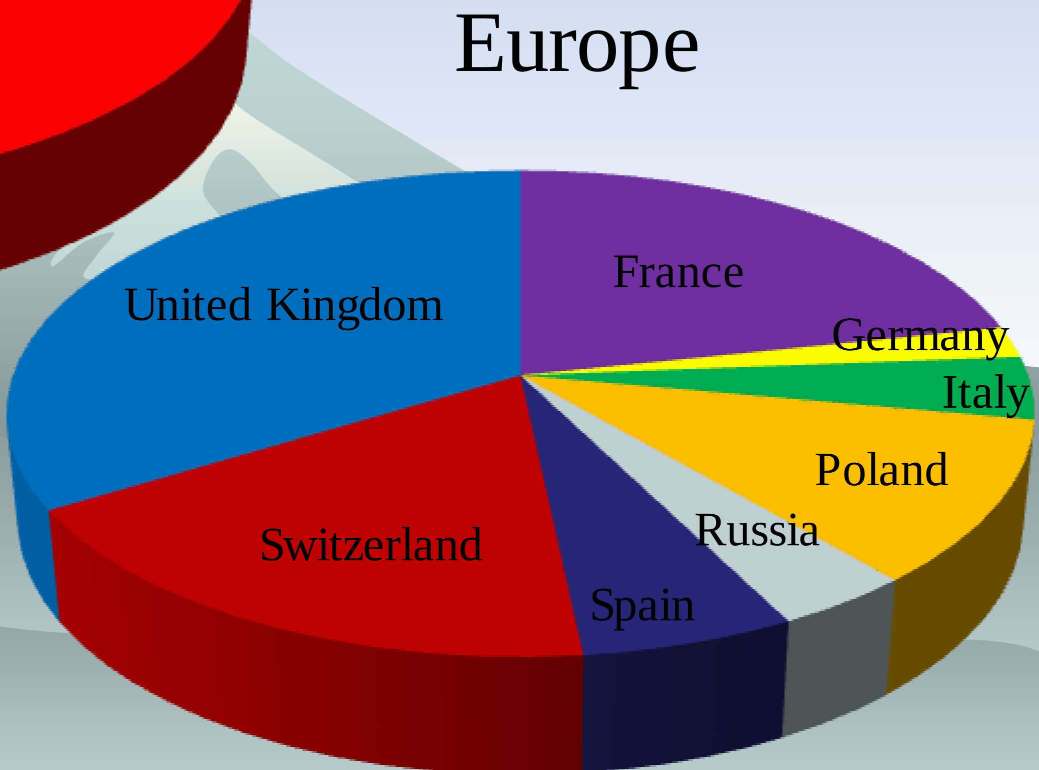
Switzerland
U. Bern
U. Geneva
ETH Zurich

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

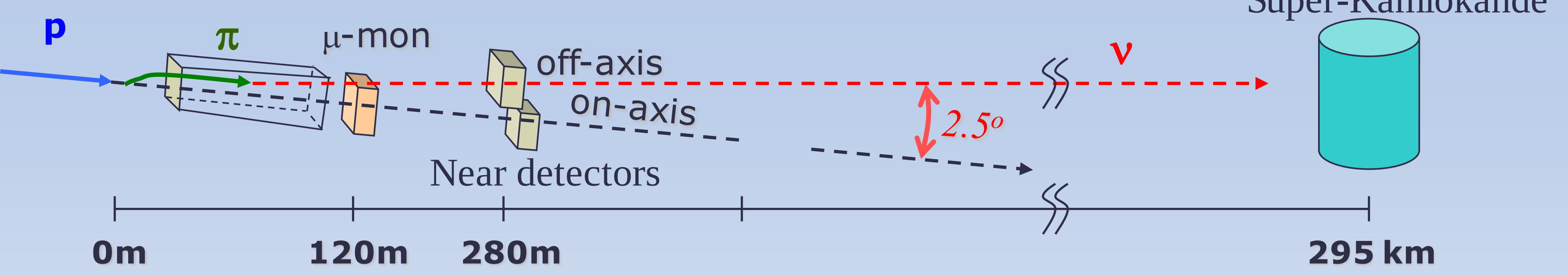
Participants for T2K



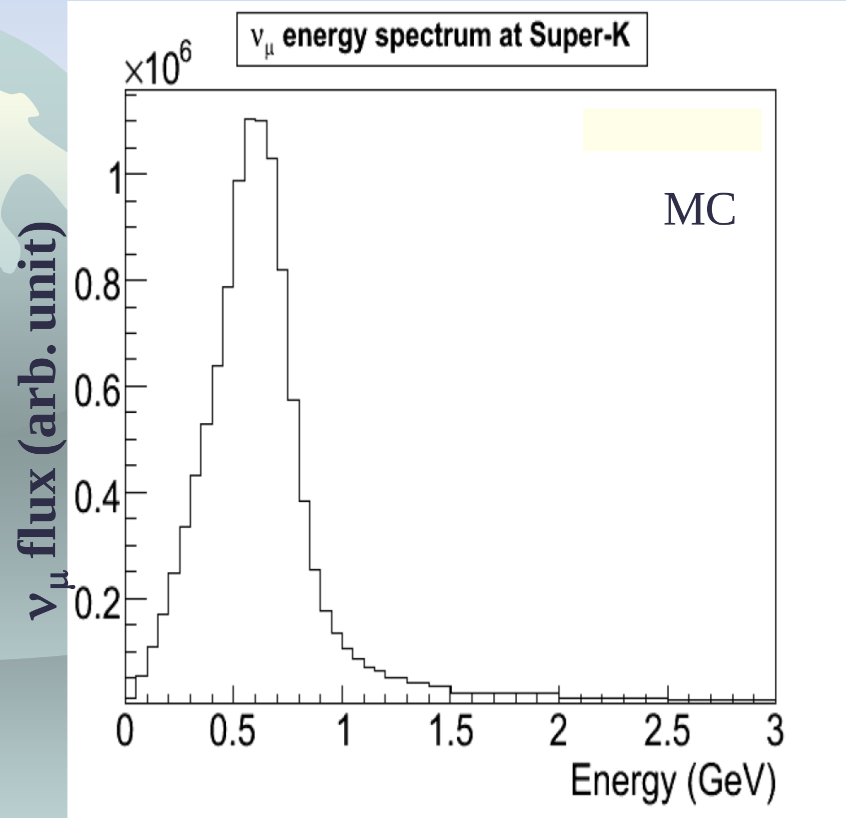


Experimental setup

Overview

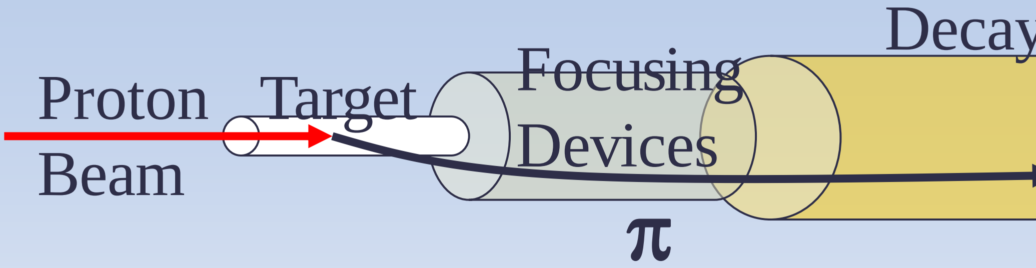


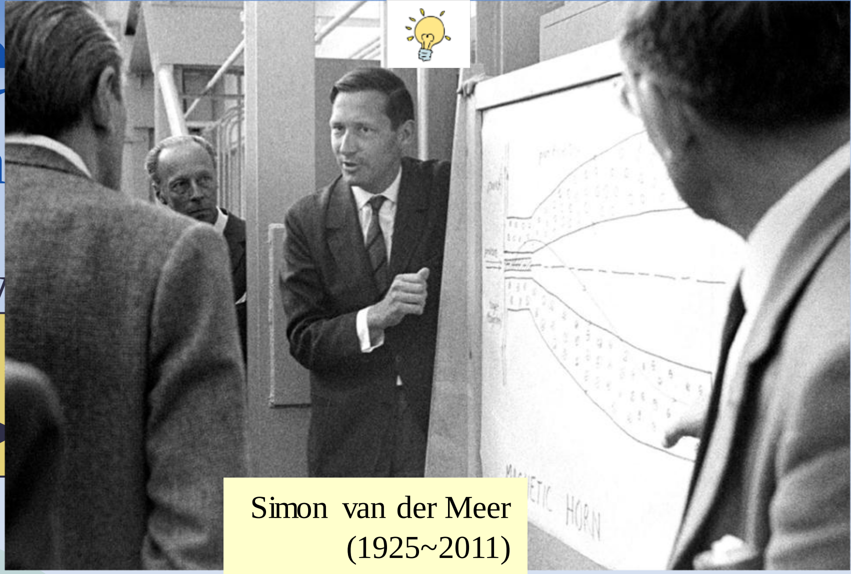
- **30GeV proton beam from MR to produce neutrino beam**
- **Beam is 2.5 deg off-axis from far detector direction**
- **Muon monitors @ ~120m**
- **Near detector @280m**
  - On-axis detector "INGRID"
  - Off-axis (toward SK direction)
- **Far detector Super-Kamiokande @ 295km**



How to make ν_μ be

(Conventional horn focused bea

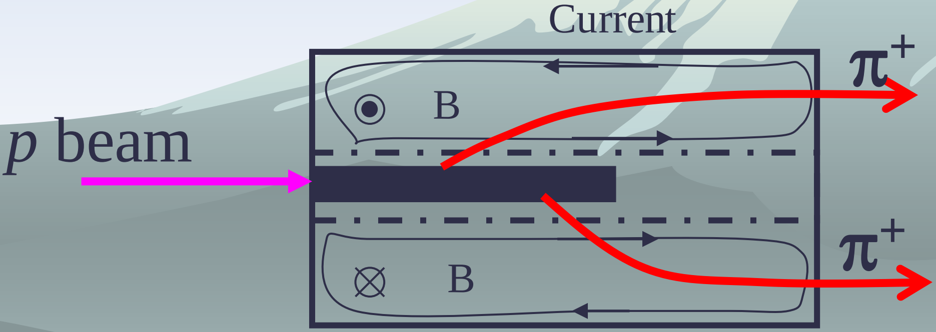


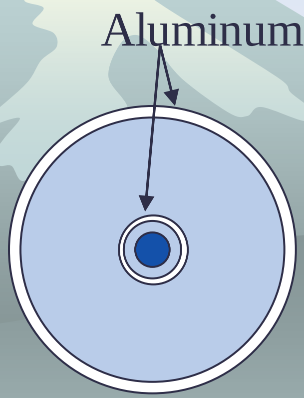


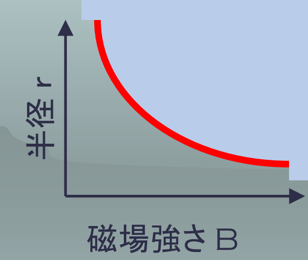
Simon van der Meer (1925~2011)

Focusing device: **Electromagnetic Horn**

Beam Dump





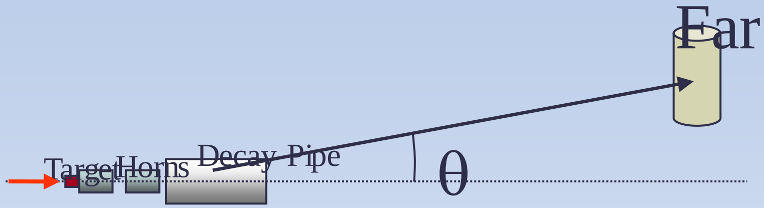


$$B = 4.3\,T\ ,\ r = 15\,mm,\ I = 320kA$$

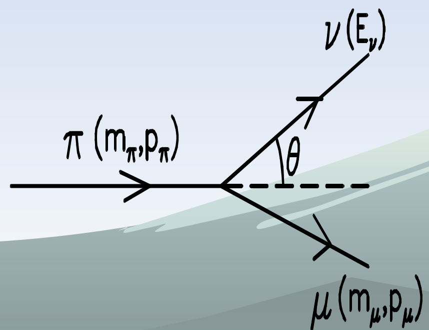
- Pure ν_μ beam ($\gtrsim$99%)
- ν_e ($\lesssim$1%) from $\pi \rightarrow \mu \rightarrow e$ chain and K decay(K_{e3})
- $\nu_\mu/\bar{\nu}_\mu$ can be switched by flipping polarity of Horns

Off-axis (OA) beam
High intensity narrow band beam

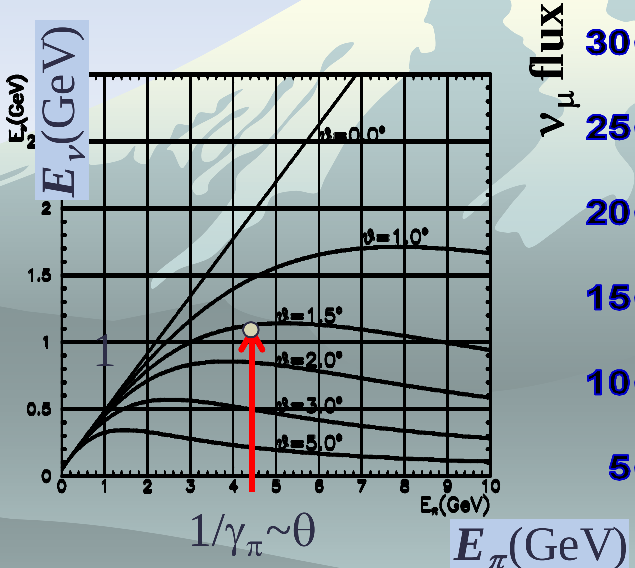
(ref.: BNL-E889 Proposal)



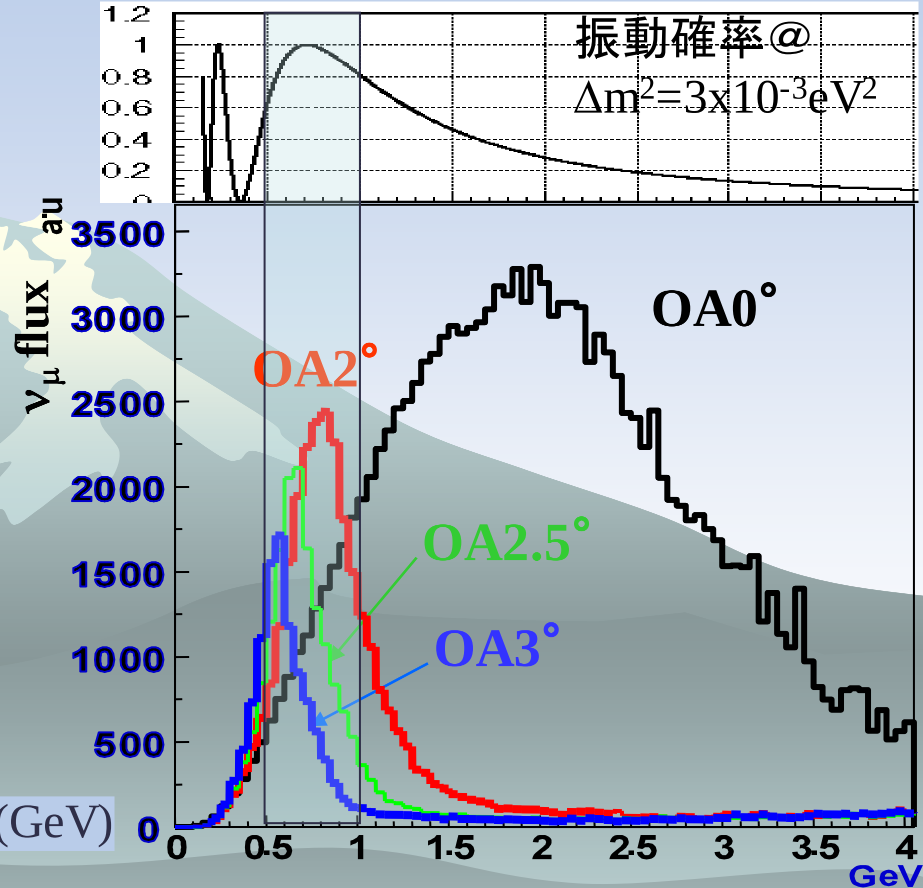
Decay Kinematics



$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)}$$



$$E_\nu^{\max}[\mathrm{GeV}] \approx \frac{30}{\theta[\mathrm{mrad}]}$$

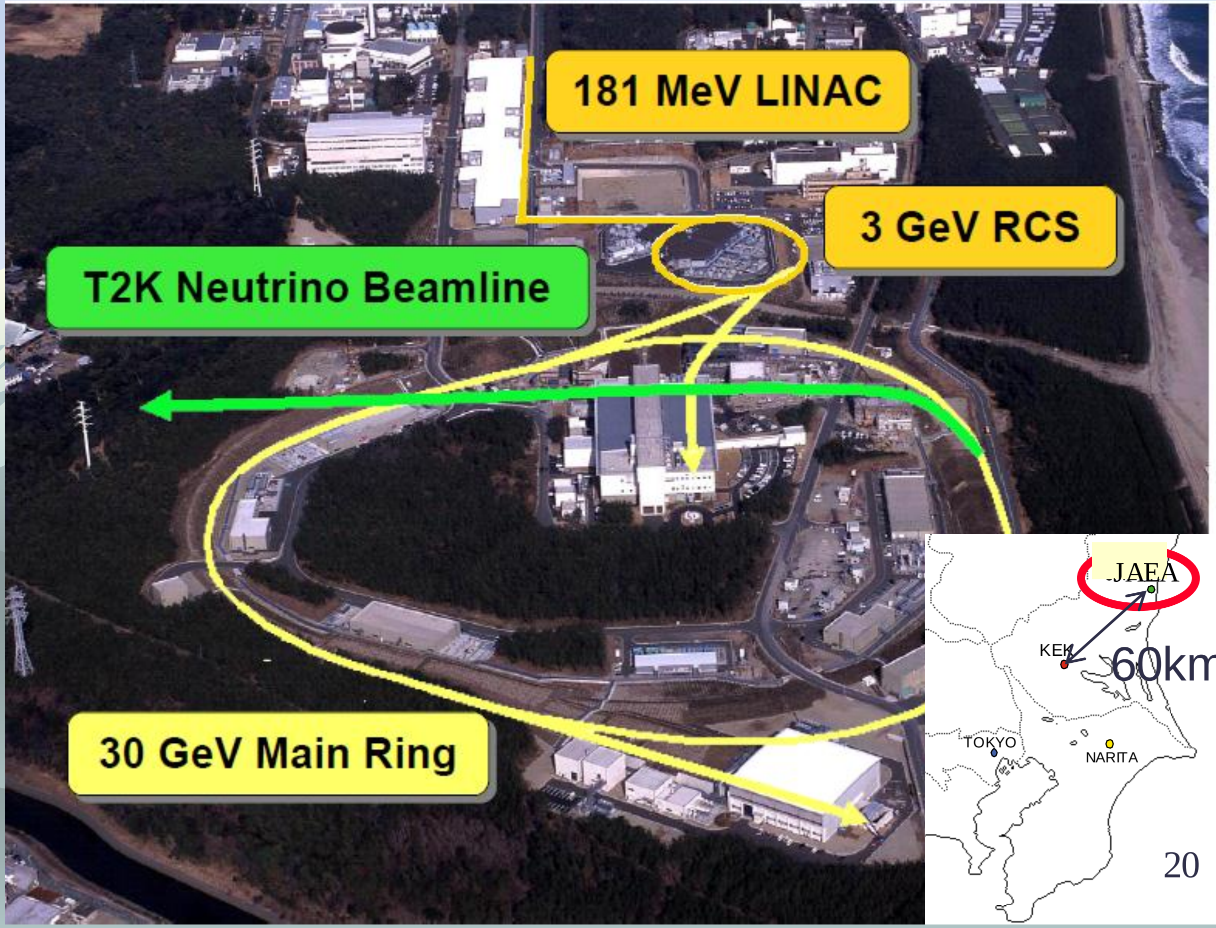


- Increase statistics @ osc. max.
- Decrease background from HE tail

J-PARC

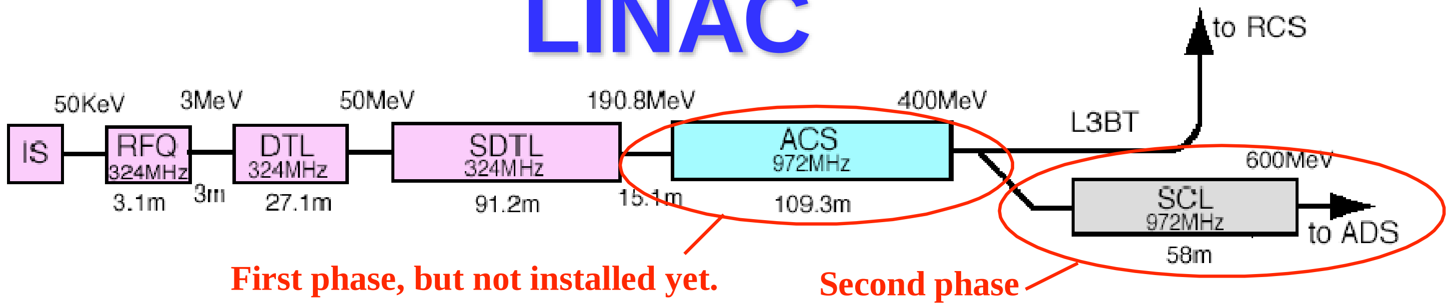
Japan Proton Accelerator Research Complex

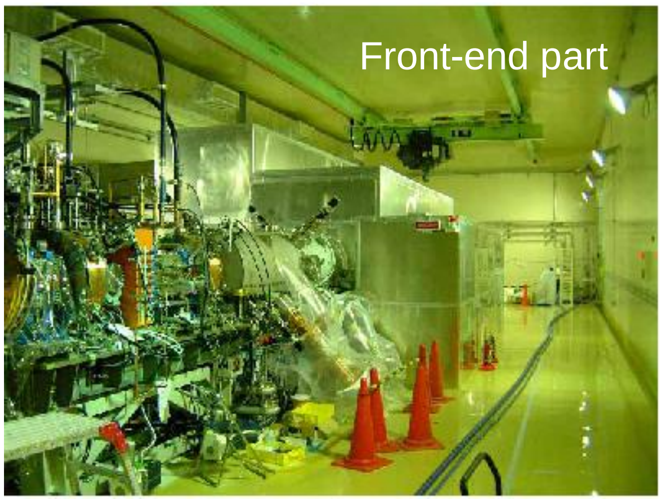
- Located in Tokai-village, 60km N.E. of KEK
- Completed in 2009
- Design goal
  - RCS: 1MW
  - MR: 750kW



Joint project of KEK & Japan Atomic Energy Agency (JAEA)

LINAC





Ion source, LEBT, RFQ,
MEBT(2 choppers, 2 bunchers)

- **Particle:** **H^-**
- **Energy:**
  - **on day-one** **181 MeV**
  - **with ACS** **400 MeV**
- **Peak current:**
  - **at 181 MeV** **30 mA**
  - **at 400 MeV** **50 mA**
- **Repetition:** **25 Hz**
- **Pulse width:** **0.5 msec**

- Stable operation at 15~20mA/500usec pulse width achieved
- Longer continuous operation w/o Ion source maintenance are being tried. >1000hr @16mA achieved
- Upgrade 400MeV is delayed to 2013

T.Kobayashi (KEK)

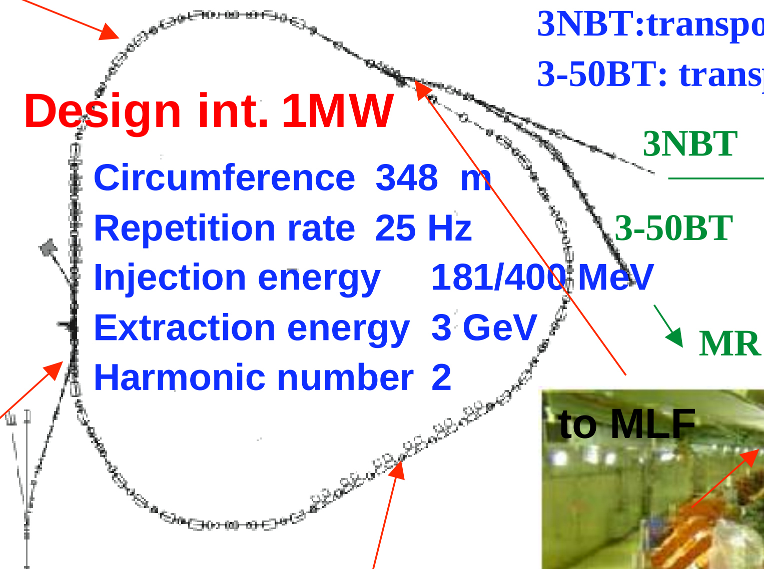
3GeV-RCS

Neutron/Muon source and booster of the MR.

Two beam transport lines

3NBT:transport line to the MLF

3-50BT: transport line to the MR



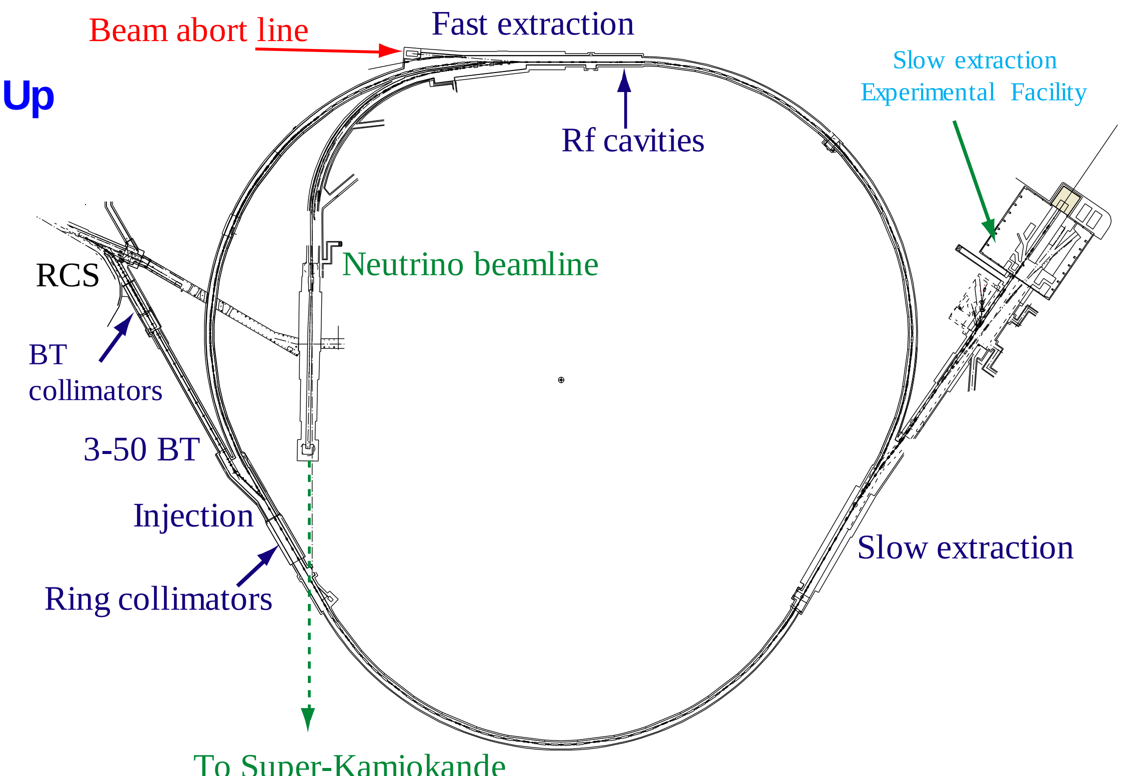
Design int. 1MW

- Circumference 348 m
- Repetition rate 25 Hz
- Injection energy 181/400 MeV
- Extraction energy 3 GeV
- Harmonic number 2

- 200kW stable beam provided for MLF
- 300kWequiv beam provided for MR
- 420kW high power test succeeded (99.5% transmission), ready for providing to MR

MR

Circumference	**1567.5 m**
Repetition rate	**～0.3 Hz@Start Up**
Injection energy	**3 GeV**
Extraction energy	**30 GeV**
Superperiodicity	**3**
h	**9**
No. of bunches	**8 (6 in day 1)**
Transition γ	**31.7(imaginary)**
Typical tune	**22.4, 20.8**
Transverse emittance	
At injection	**~54 πmm-mrad**
At extraction	**~10 πmm-mrad**
Beam power	**0.75MW**

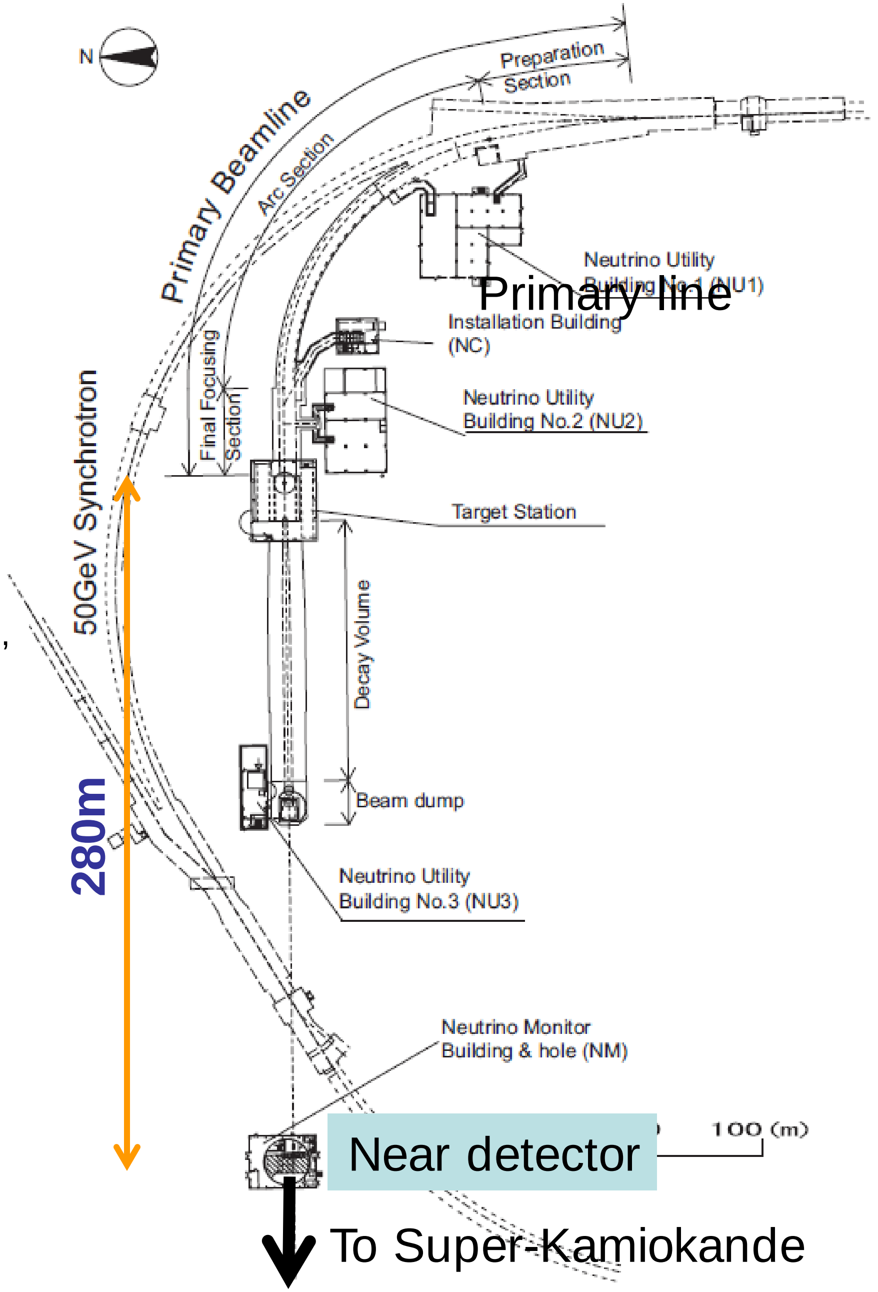


- Stable operation at 145kW realized (Mar,2011)
  - Np=1.1x10^{13}/bunch, Nbunch=8 ➔ 0.9x10^{14} PPP, 3.04sec cycle
- Currently limited by beam loss at injection due to dirty pulse shape of injection kicker magnets
  - ➔ Will be replaced during present shutdown and be fixed
- Toward design intensity and higher
  - For higher PPP: Space charge (RF HH)
  - For higher rep rate: PS, RF
  - Collimator upgrade

T.Kobayashi (KEK)

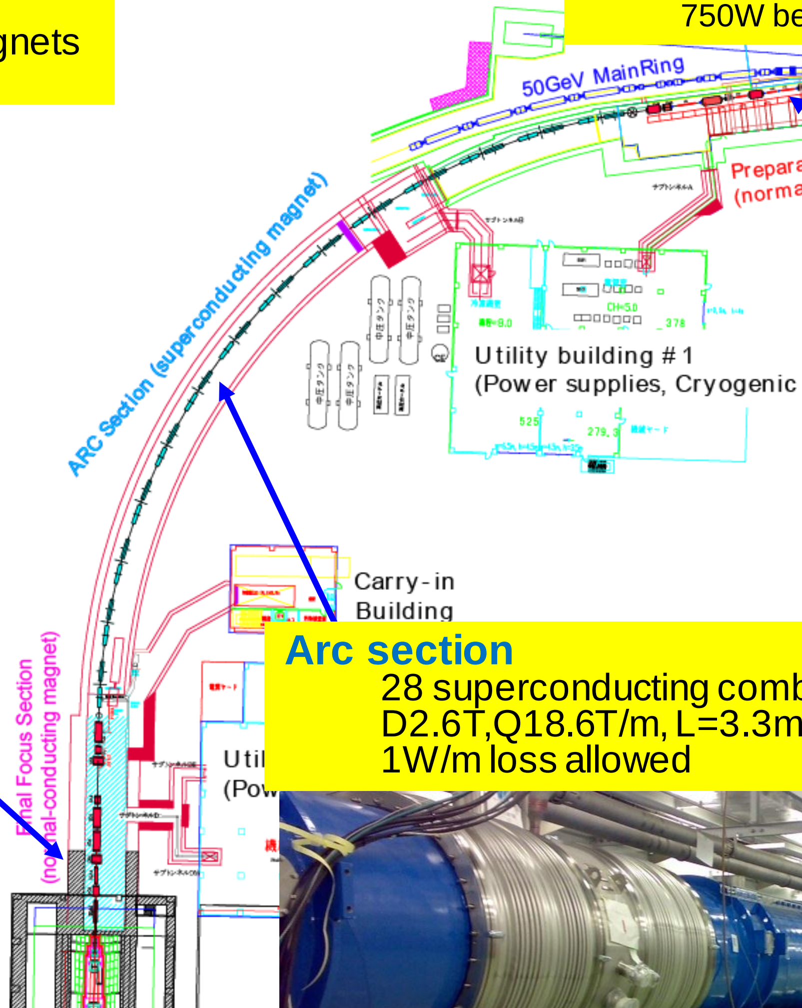
J-PARC Neutrino Beam

- **Conventional horn focused beam**
- **First application of off-axis beam**
  - Adjustable off-axis angle 2~2.5deg.
  - 2.5 deg at Day1
- **First MW-capable beamline**
  - Design intensity is 750kW with safety factor
  - Parts which can never be upgraded later are designed for Multi-MW (3~4MW)
    - Shielding and cooling capacity of target station, decay volume, beam dump
- **First application of superconducting combined function magnet**
- Key issues
  - Beam loss
  - Remote/quick maintenance of activated components
  - Radio active waste



Primary beamline

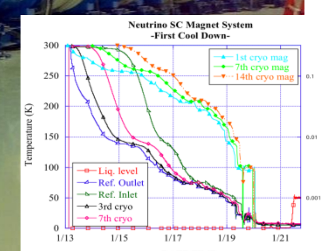
Final focusing (FF) section
10 normal conducting magnets
250W loss shield



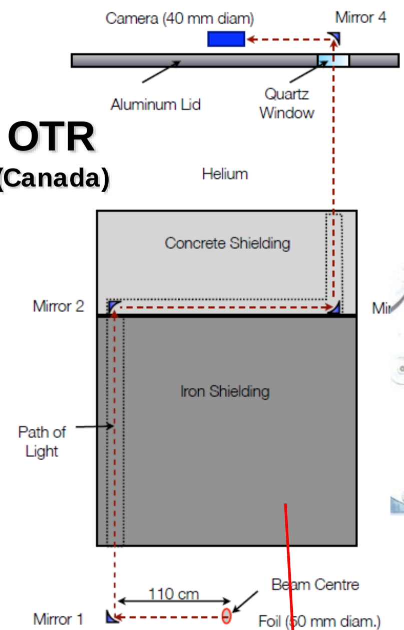
Preparation section
11 normal conducting magnets
750W beam loss shield

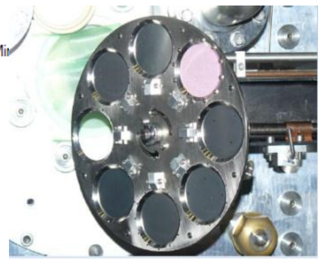
Arc section
28 superconducting combined function magnets
D2.6T,Q18.6T/m, L=3.3m
1W/m loss allowed

3 corrector mags (from US)
MSS from Saclay
CERN cooperation



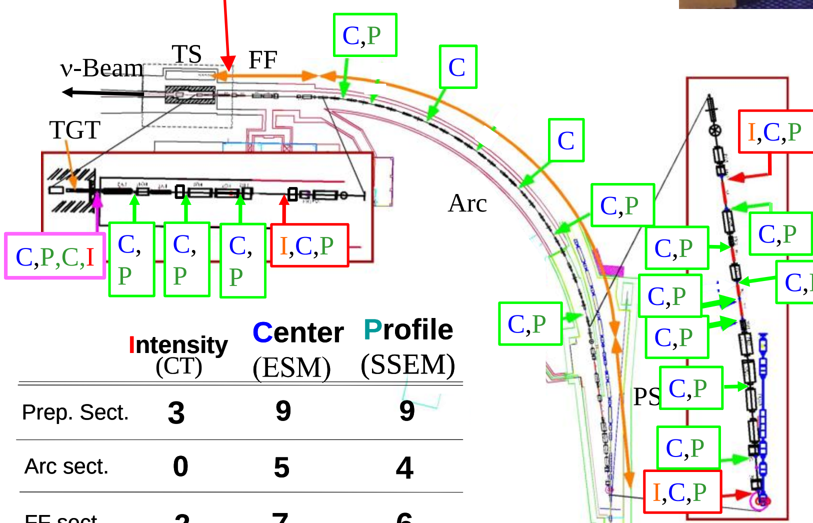
Beam Monitors





ESM

CT



	Intensity (CT)	Center (ESM)	Profile (SSEM)
Prep. Sect.	3	9	9
Arc sect.	0	5	4
FF sect.	2	7	6

Beam loss monitor will be placed along the beam line.

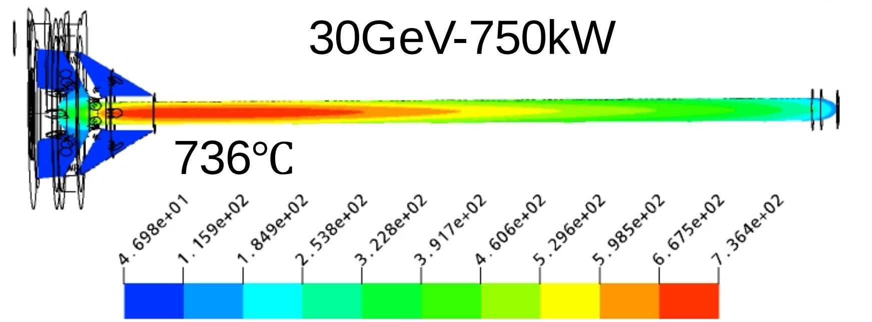
- Position:
  - 21 x Electrostatic monitors
- Profile
  - 19 x Segmented Secondary Emission monitors
- Intensity
  - 5x Current Transformers
- Loss
  - 50 x proportional counters
- Targetting
  - Optical Transition Radiation detector (Canada)
- Elec.: from US/Korea/Jp
- Beam timing: GPS (US)

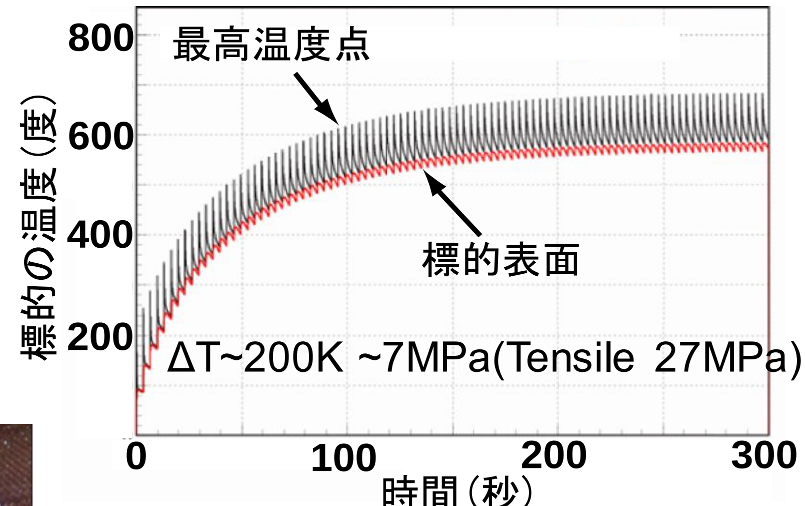
SSEM

5μm^{t} Ti foil strips

Target

- Isotropic Graphite (IG-430) 1.8g/cm3
- 26mm(D)x900mm(L)
  - 1.9 int len. (70% int.),
- Heat load: 58kJ/spill (~20kW)
- Thermal shock stress (ΔT~200K) ~ 7MPa (< tensile strength 37MPa)
- Forced flow Helium gas cooling in Ti-alloy(Ti-6 A1-4V) container
  - Higher temp = less rad. damage
  - O2 < 100ppm to avoid Oxidization (burn!) → to keep S.F.>2 for 5 yrs
- Remote maintenance
- Design done by KEK/RAL





Electromagnetic horns

- 3 horn system
- 320kA design (now 250kW)
  - 0.7ms for 1st horn
  - 2ms for 2nd/3rd (series)
- Max field: 2.1T
- Al alloy (A6061-T6)
- Heat load ~11kW@1st horn (beam+Joule)
- Water cooled.
- Design max thermal stress: 25MPa (Lorentz+Thermal) (cf. tensile stren. 282MPa)
- Fully remote maintenance

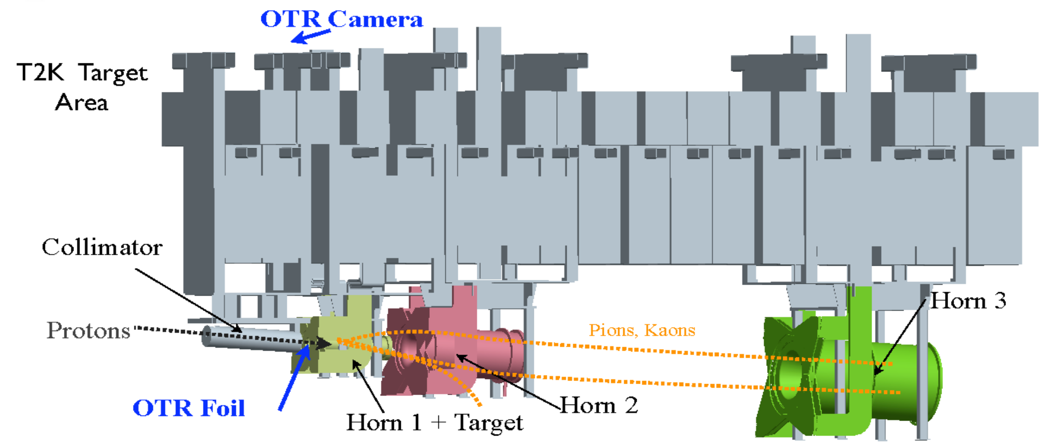
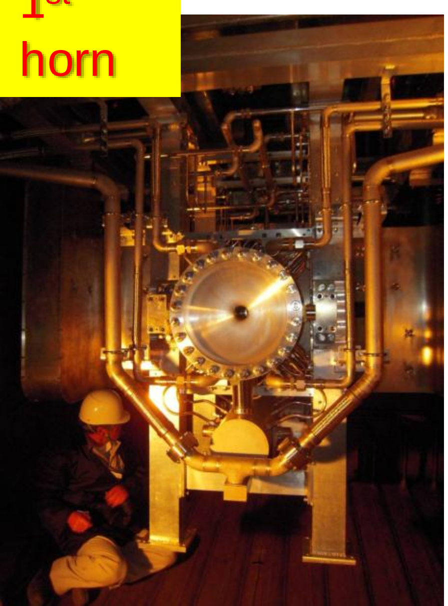


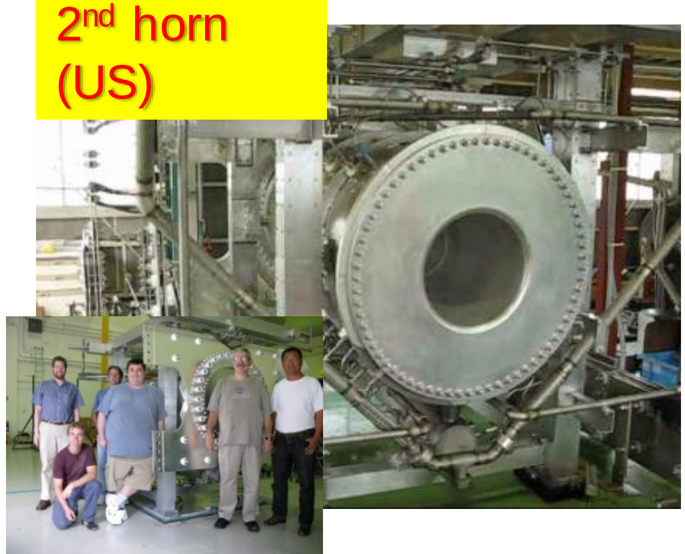
Table 3.8: Heat Load to the horns in unit of kJ/pulse.

	radiaion		Joel's heat	total
	inner-conductor	outer-conductor		
1st horn	23.6	15.6	3.3	42.5(11kW)
2nd horn	6.7	12.3	3.8	22.8(6.3kW)
3rd horn	2.0	4.0	2.5	8.5(2.4kW)

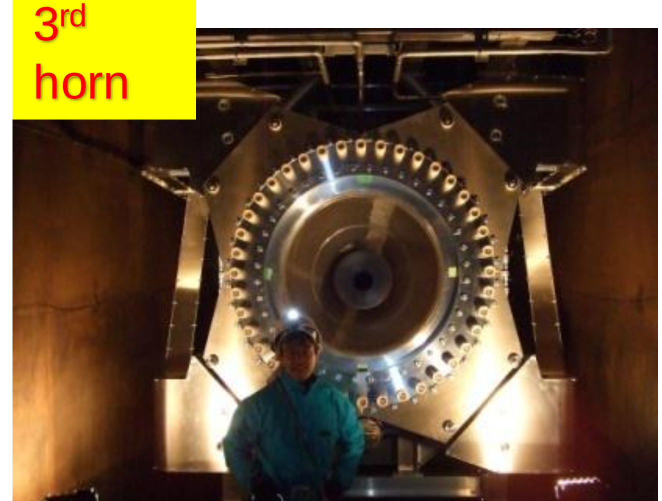
1st horn



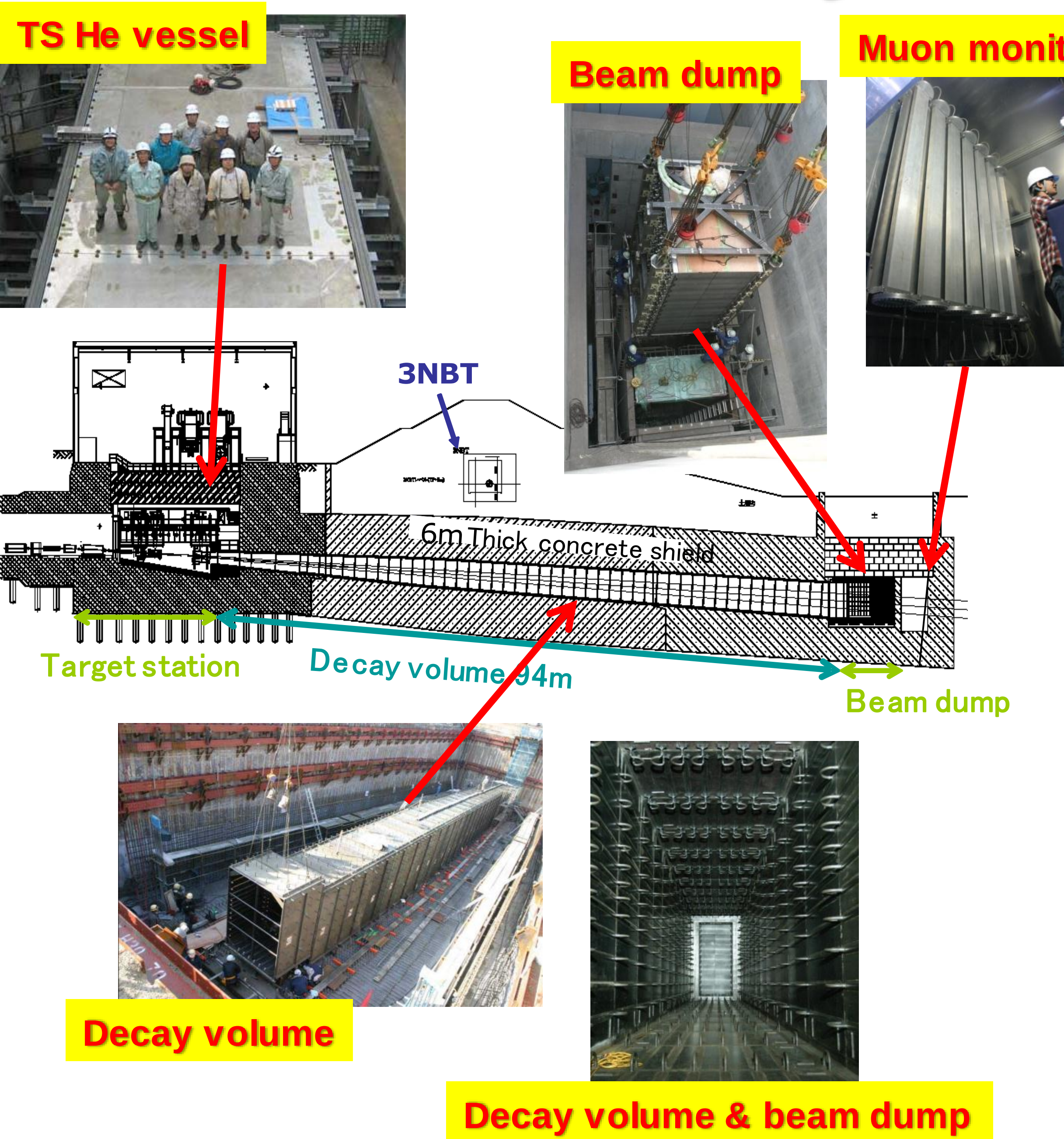
2nd horn (US)



3rd horn

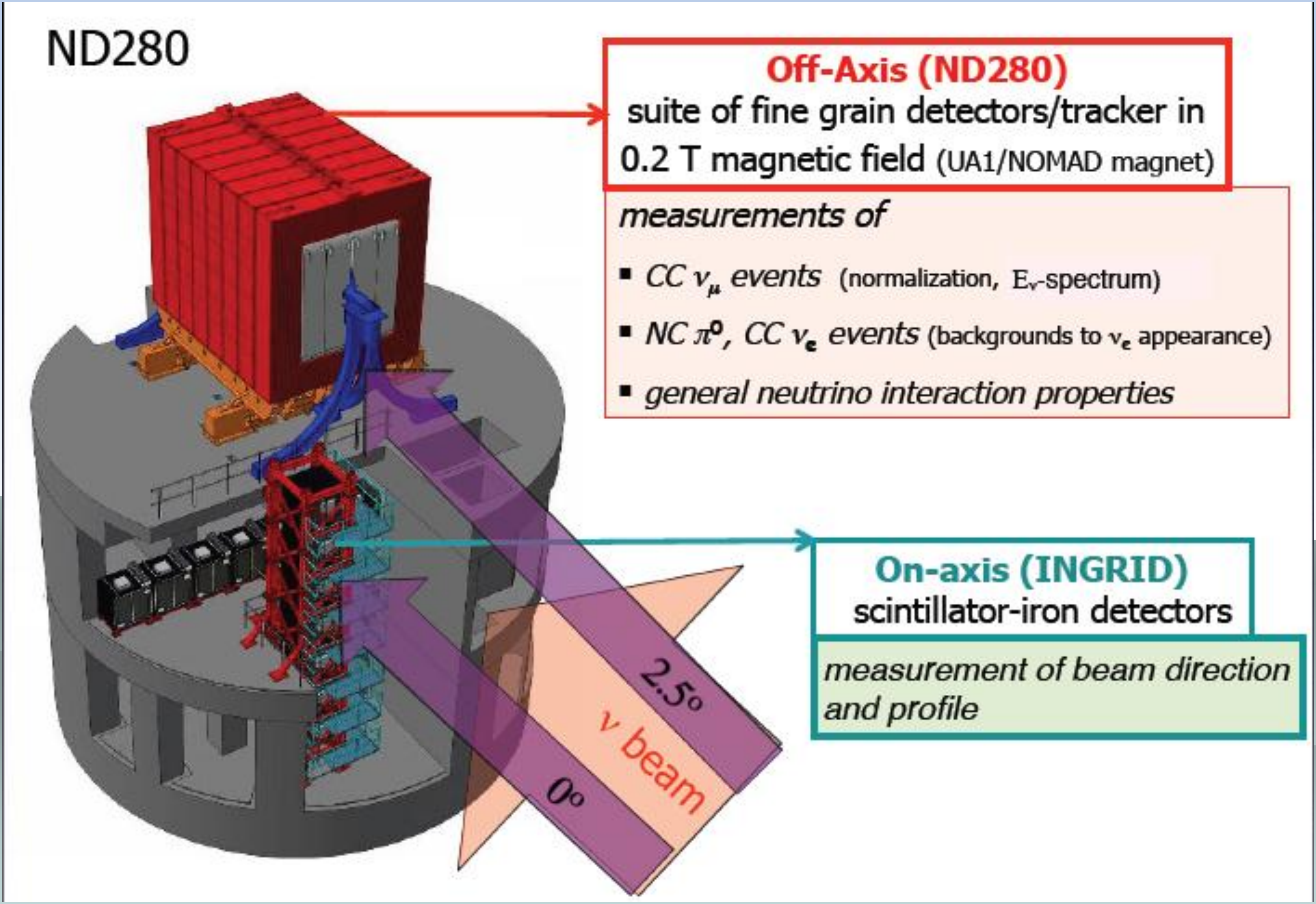


Secondary beamline



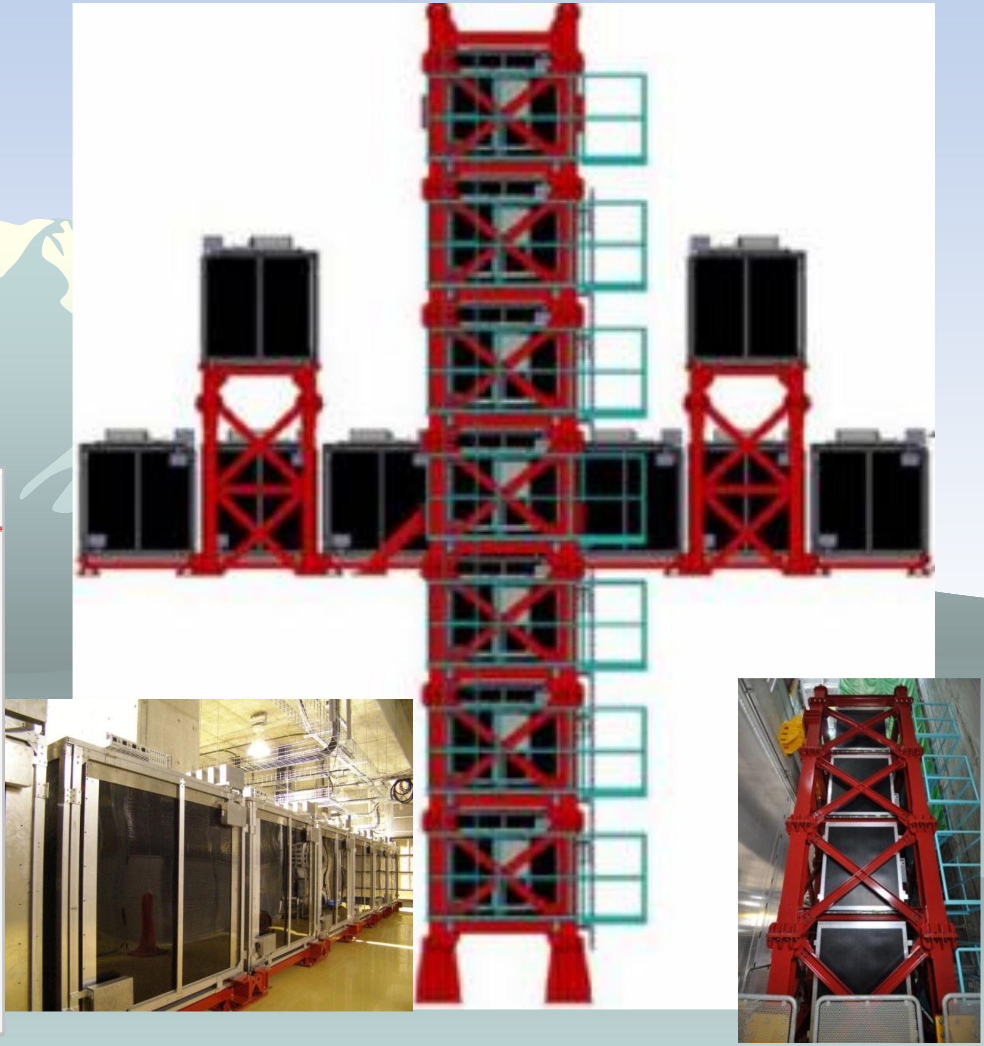
- Heat load (@750kW)
  - TS ~300kW
  - DV ~150kW
  - BD ~240kW
- Whole volume filled w/ He gas (~1000m^3)
  - Reduce NOx & ^{3}H
  - Reduce pion abs.
- All inner surfaces water cooled
  - Concrete upto ~100deg
  - Periodically waste with dilution (obey law)
- Beam dump
  - Graphite blocks
  - Water-pipe casted Al block attached to both side
  - Upto 3MW beam
- Muon monitor
  - 5GeV thresh.
  - Ionization chamber & Si
  - 7x7 grid each
  - Monitor dir/int spill-by-spill
  - Emulsion

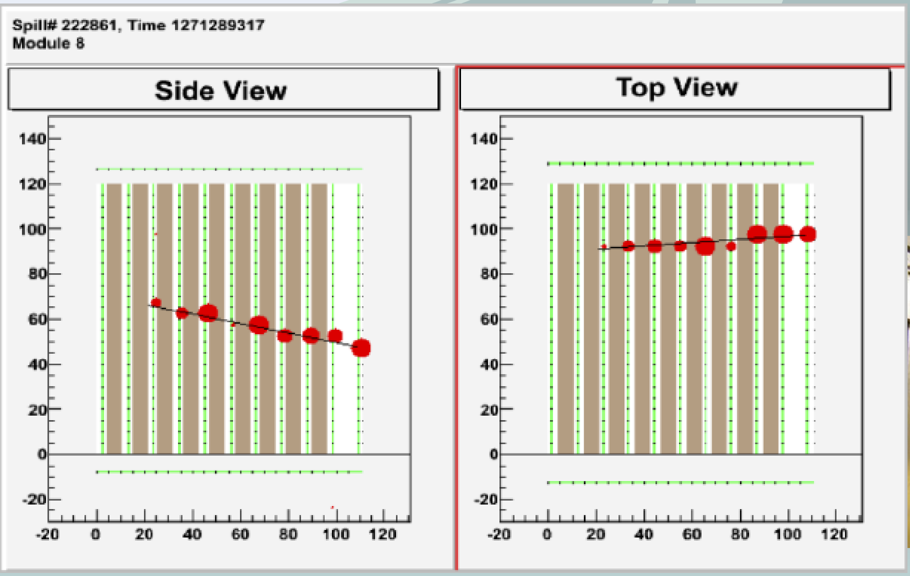
Near detectors



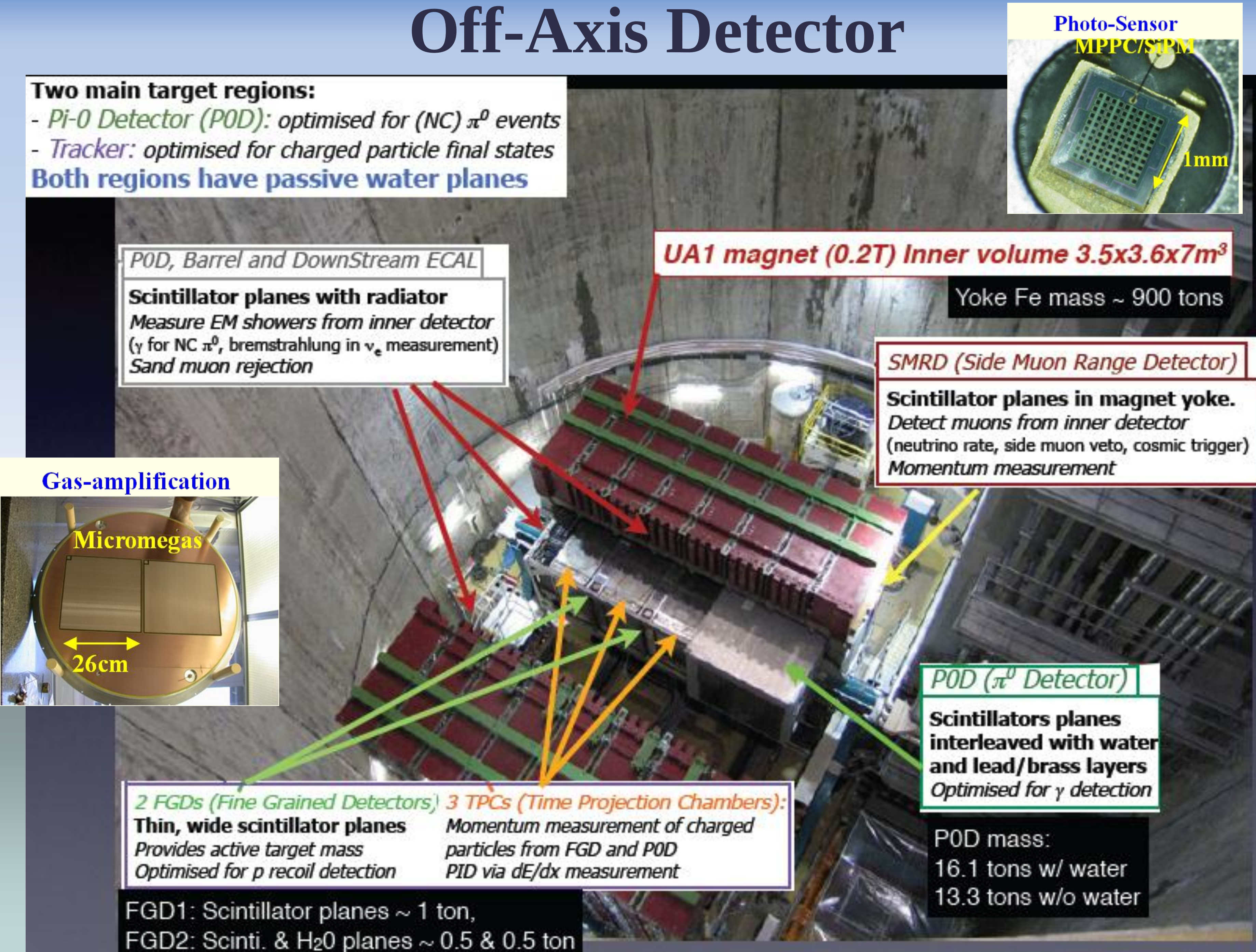
INGRID detector

- Placed on beam axis at 280m from target
- Iron plates + Scintillator bar tracker
- Measure neutrino interaction rate & beam profile
  - Monitor beam intensity & direction

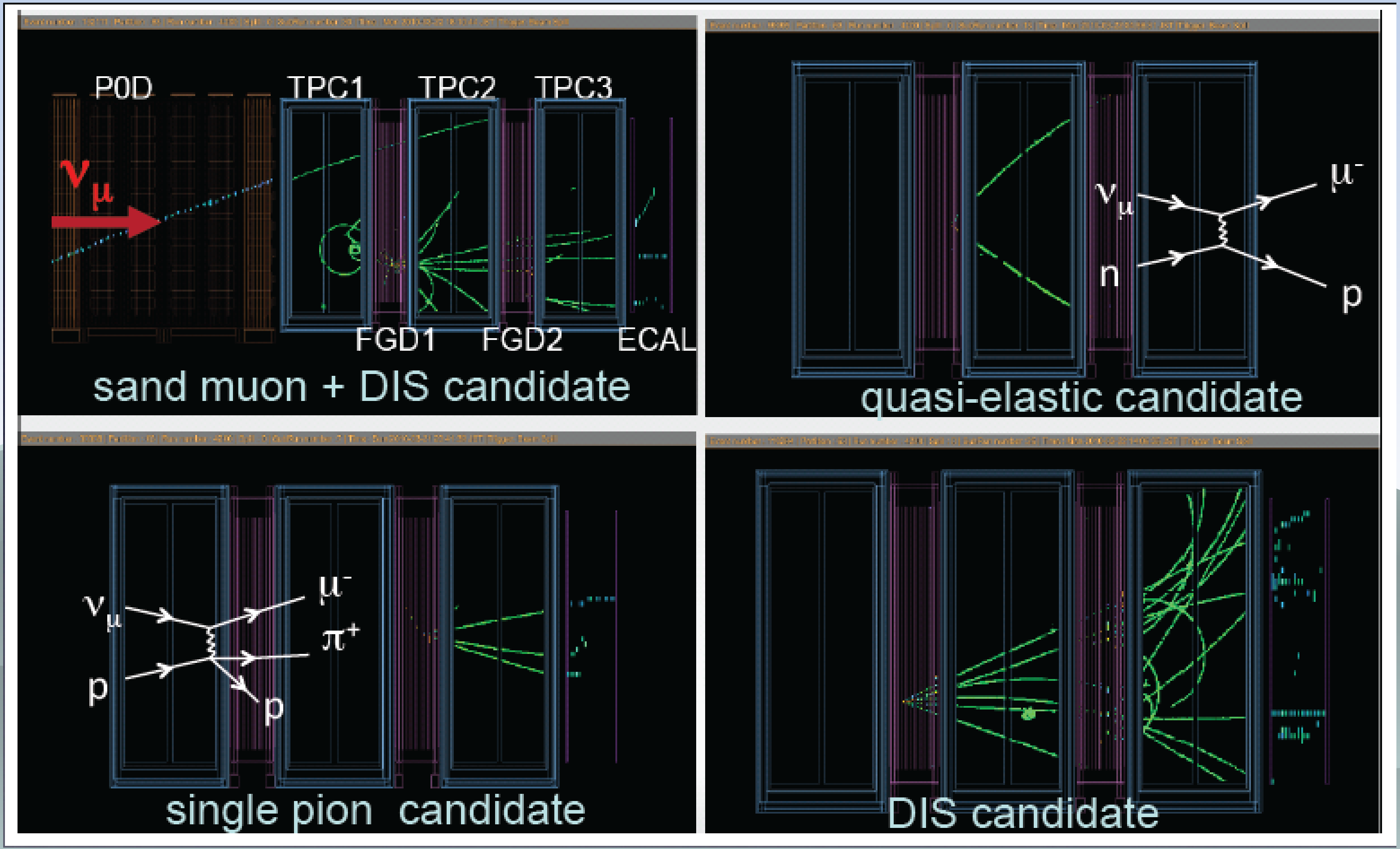




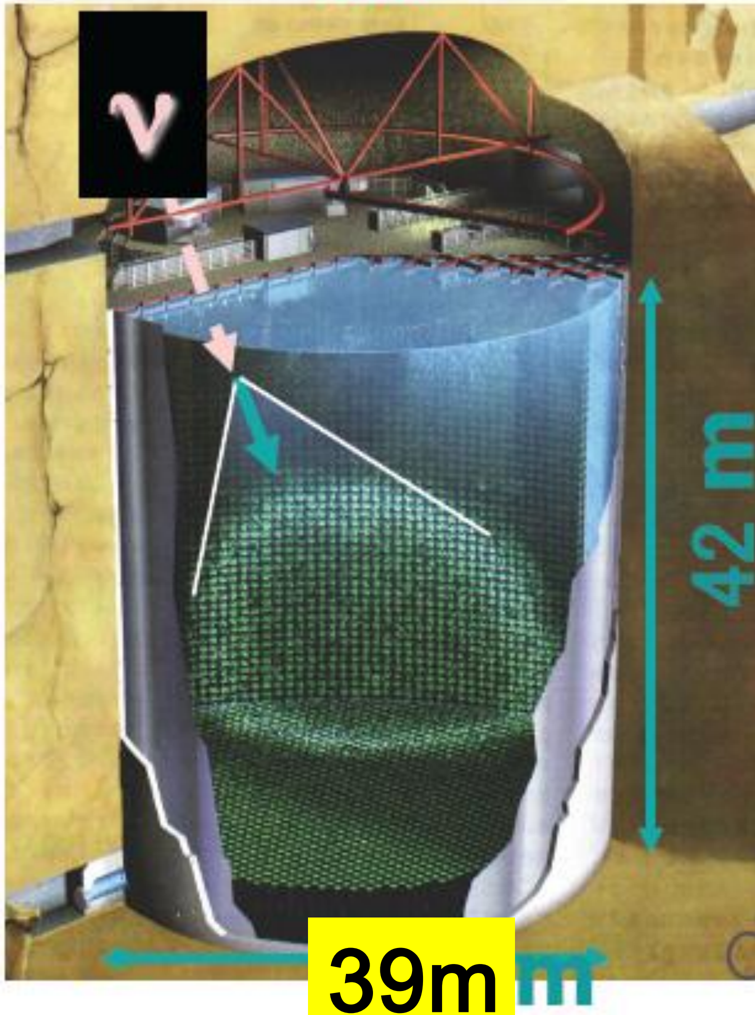
Off-Axis Detector



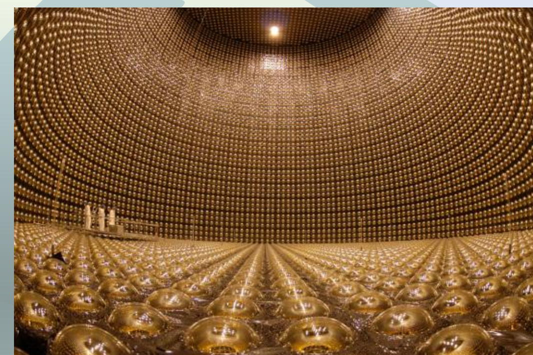
ND280 off-axis event gallery

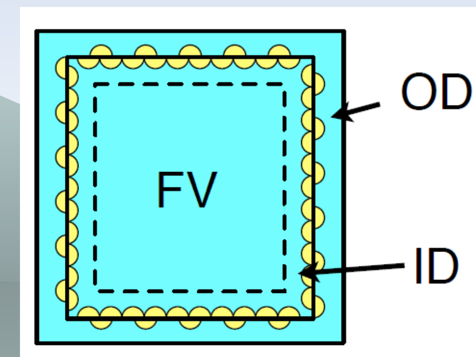


Far Detector: Super-Kamiokande

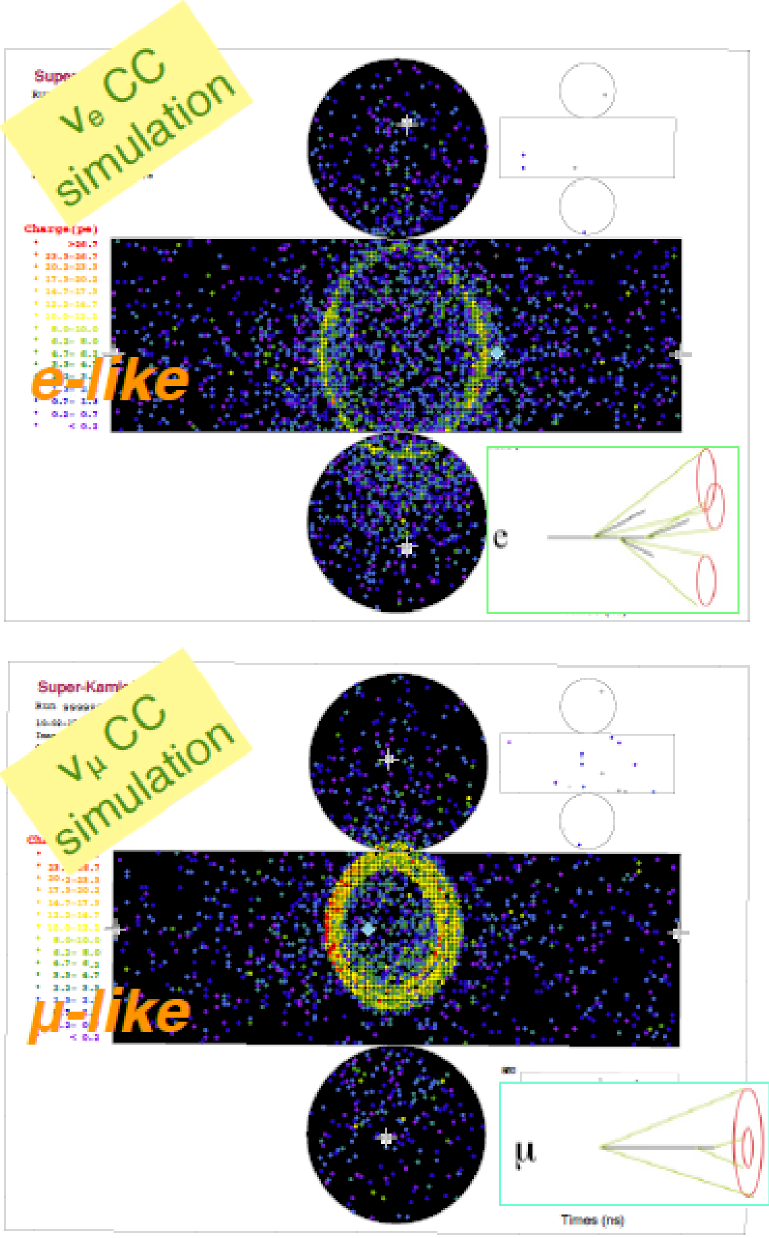


- Water Cherenkov detector operational since 1996
- Total volume: 50kton (Fiducial volume: 22.5kton)
- 11129 20" PMTs in inner detector (ID)
- 1885 8" PMTs in outer detector (OD)
- New dead time less readout electronics since 2008 summer.
- T2K event trigger by accelerator timing sent online

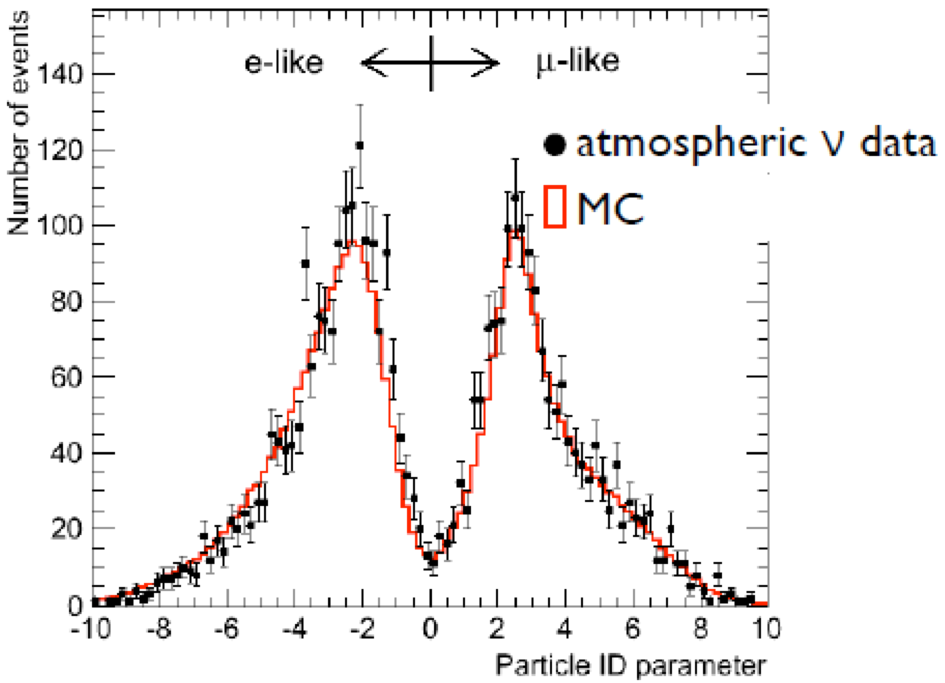




Electron-like and muon-like event at SK



Particle identification using ring shape & opening angle



Probability that μ is mis-identified as electron is ~1%

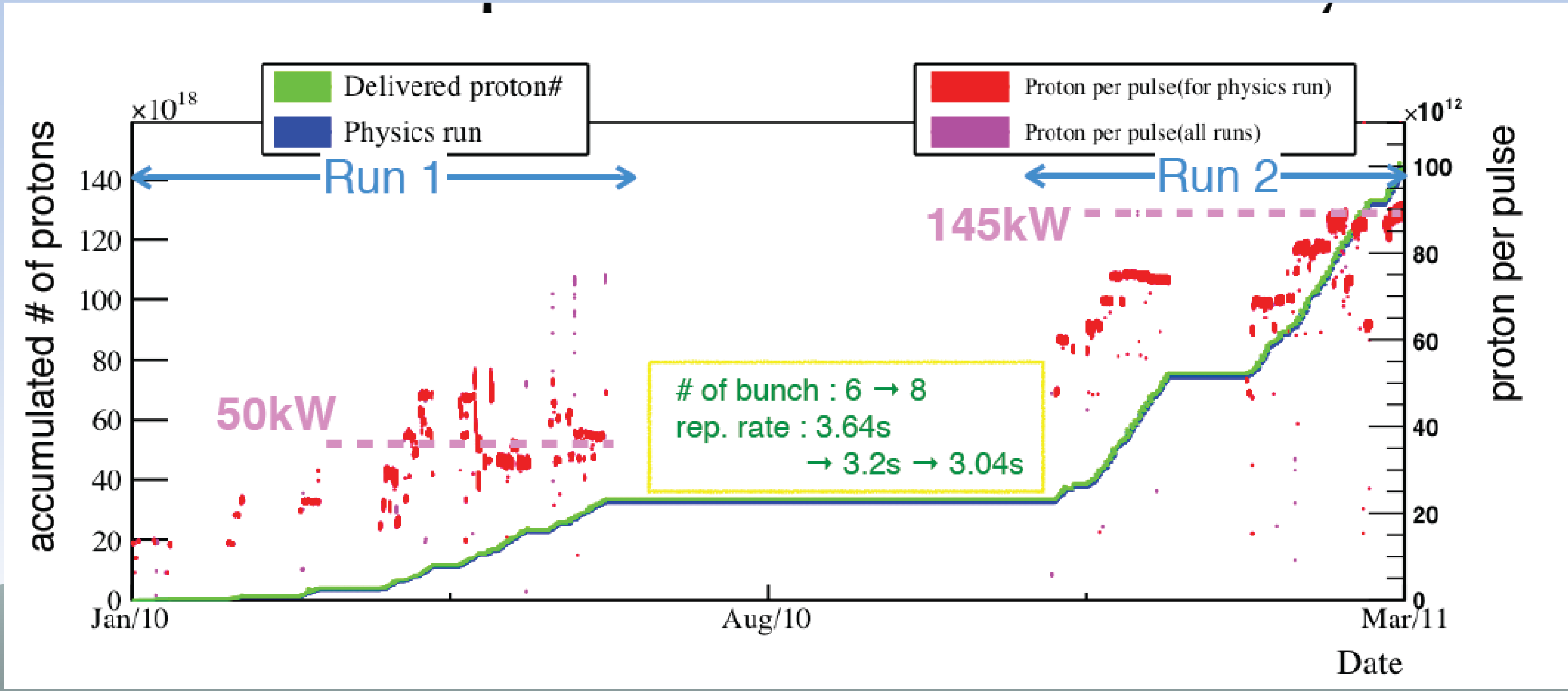
First beam!

First shot after turning on SC magnets at 19:09, Apr.23, 2009

Muon monitor signal

First observation of muons produced in neutrino beamline

Delivered proton

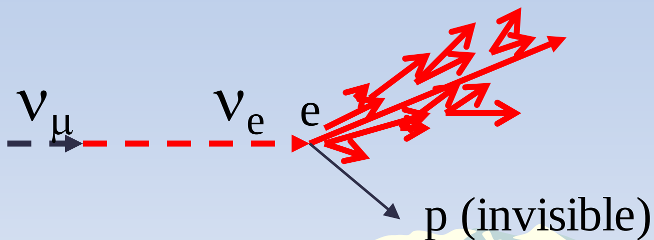


- Started physics data taking Jan, 2010
- Stable beam operation at 145kW achieved
- By Mar.11, 2011, 1.43x10^{20} (~70 [kW・1e7s]) delivered
- All data taken was analyzed

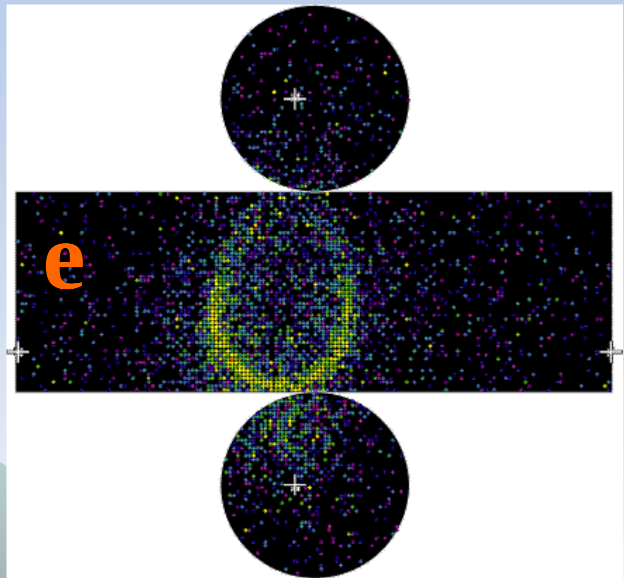
$\nu_\mu \rightarrow \nu_e$ appearance search

Signature

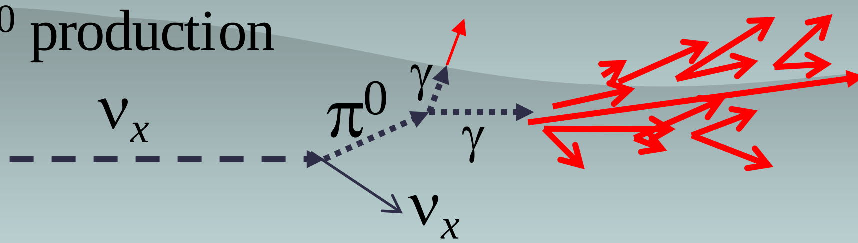
- **Signal: ν_eCCqe (ν_e+n→e+p)**

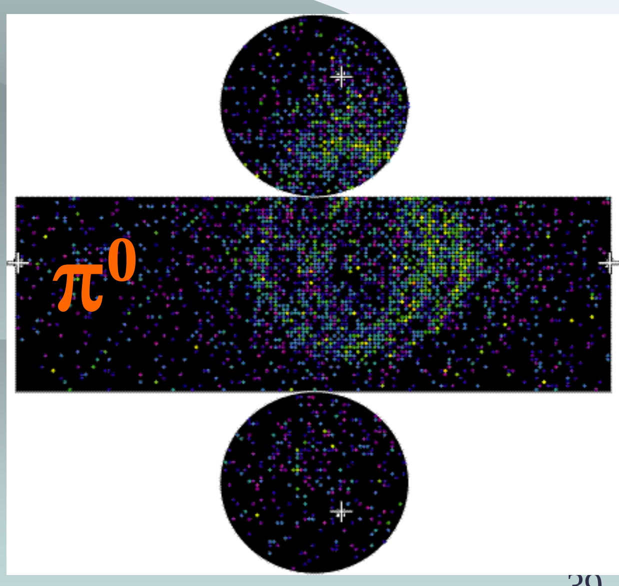


  - Dominant reaction < 1GeV
  - Single EM shower
    - No decay electron (from μ or π)
  - With same E_ν dist as orig. ν_μ



- **Background**
  - Beam intrinsic ν_e (~1%)
    - Different (broad) energy distribution
  - NC π^0 production





    - π^0→2γ with 1 hidden EM shower

Analysis overview

Expected # of events at SK

$$N_{SK}^{\exp} = N_{SK\nu e\mathrm{SIG}}^{\exp}\left(\theta_{13}, \Delta m_{13}^{2}\right) + \underbrace{N_{SK\nu e\mathrm{BEAM}}^{\exp} + N_{SK(\nu\mu+\mathrm{NC})}^{\exp}}_{\mathrm{BG}}$$

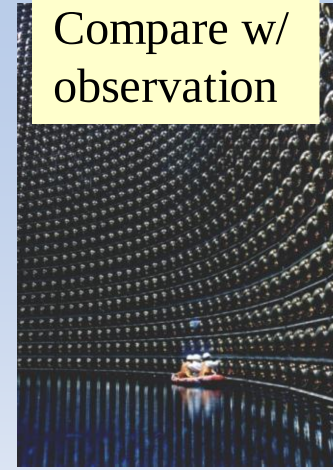
$$N_{SK}^{\exp} = \frac{N_{ND}^{obs}}{N_{ND}^{MC}} \times N_{SK}^{MC}$$

SK MC pred normalized by ND meas

Int xsec — Det. eff.

$$= N_{ND}^{obs} \times \frac{\sum_{reaction} \int \Phi^{SK} \cdot P_{osc}\left(\theta_{13}, \Delta m_{13}^{2}\right) \cdot \sigma_{reaction}^{H2O} \cdot \varepsilon_{SK}\, dE_{\nu}}{\sum_{reaction} \int \Phi^{ND} \cdot \sigma_{reaction}^{ND} \cdot \varepsilon_{ND}\, dE_{\nu}}$$

Compare w/ observation

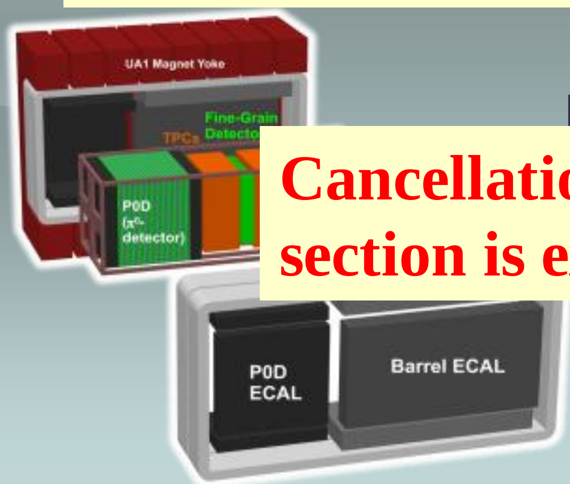


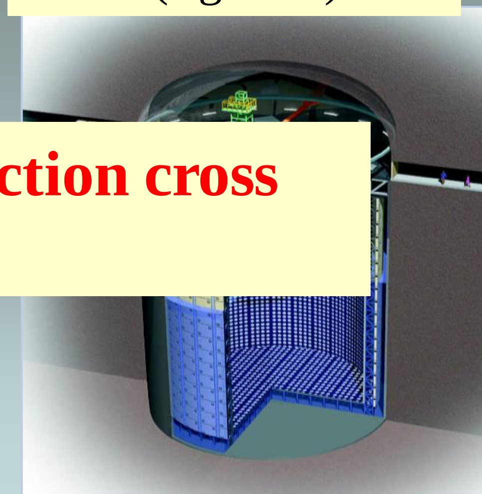
ND meas extra ted by far/near extrap on ratio

Predict expected # of events(sig&BG)

Measure # of CC int at ND

Predict nu flux & Near→far extrapolation





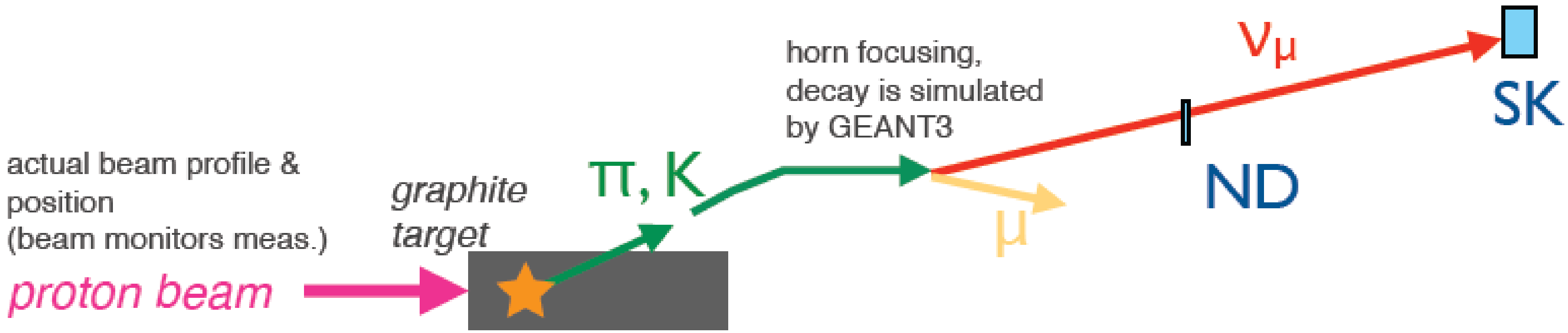
Cancellation of flux normalization, interaction cross section is expected!

CERN NA61 play critical role!

Beam prediction

T2K Neutrino beam simulation based on Hadron production measurements

$$\frac{\int \Phi^{SK}_{\nu_\mu}(E_\nu)\cdot P_{\nu_\mu\to\nu_e}(E_\nu)\cdot\sigma(E_\nu)\cdot\epsilon_{SK}(E_\nu)\;dE_\nu}{\int \Phi^{ND}_{\nu_\mu}(E_\nu)\cdot\sigma(E_\nu)\cdot\epsilon_{ND}(E_\nu)\;dE_\nu}$$

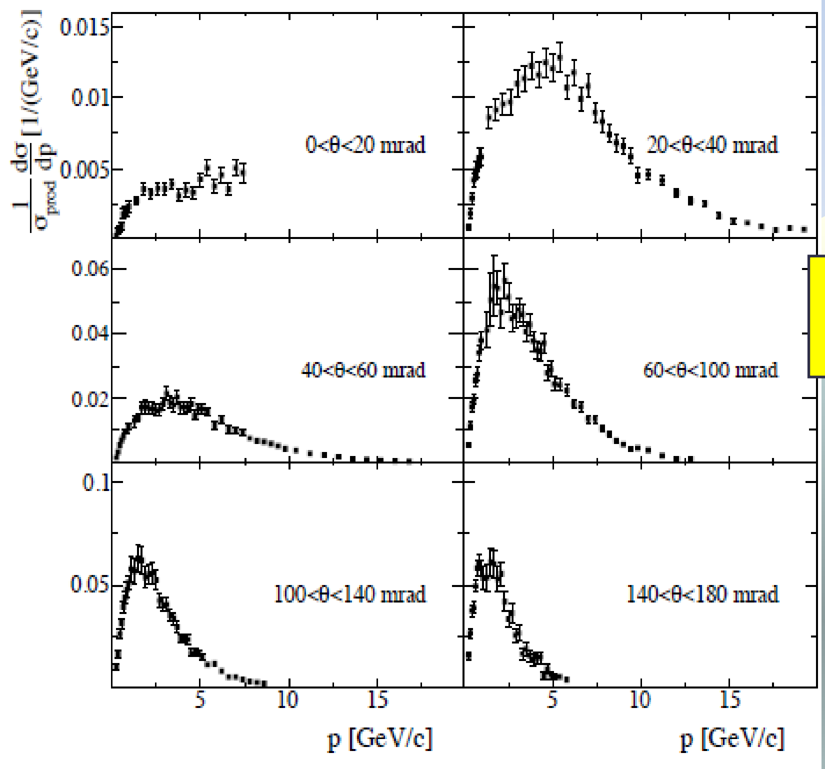


Hadron production in 30GeV proton + C

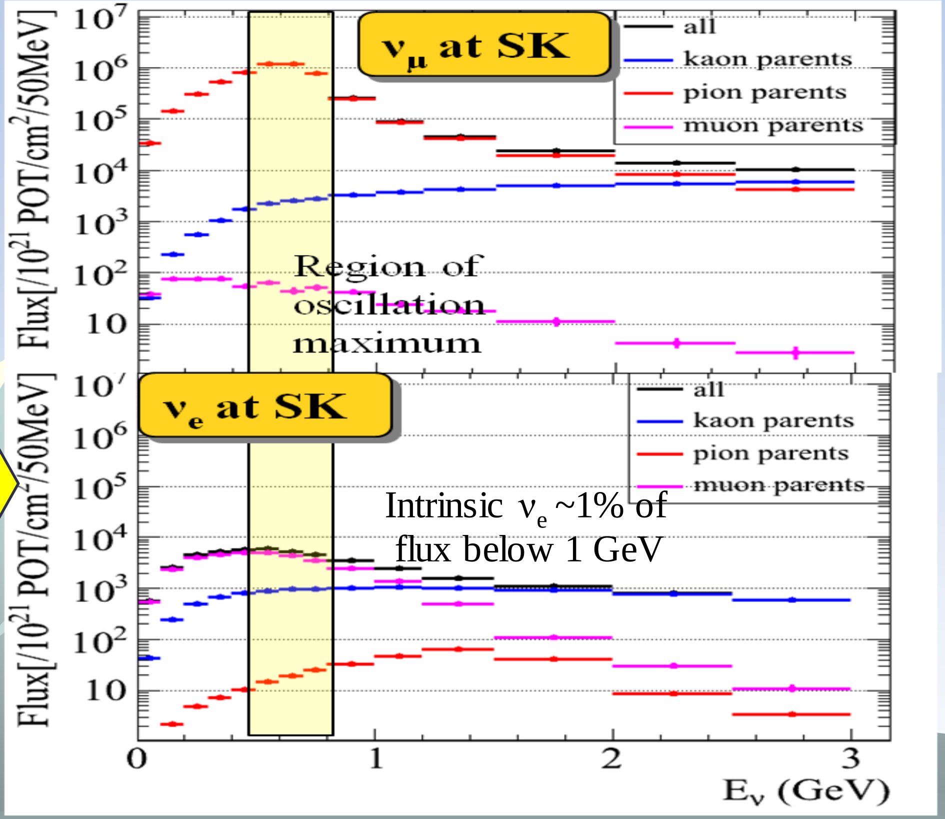
- ***Use CERN NA61/SHINE pion measurement (large acceptance: >95% coverage of ν parent pions)***
- *Kaon, pion outside NA61 acceptance, other interaction in the target were based on FLUKA simulation*
- *Secondary interaction x-sections outside the target were based on experimental data*

Beam prediction w/ CERN/NA61 results

NA61 Results of pion production from 2007 thin (~2cm) target data



N.Abgrall et al., arXiv:1102.0983[hep-ex]
Accepted for publication in Phys. Rev.C(2011)



Error from beam uncertainty

$$\delta N_{ND}^{MC} = 15.4\%$$

$$\delta N_{SK}^{MC} = 16.1\%$$

$$\delta\left(N_{ND}^{MC} \Big/ N_{SK}^{MC} \right) = 8.5\%$$

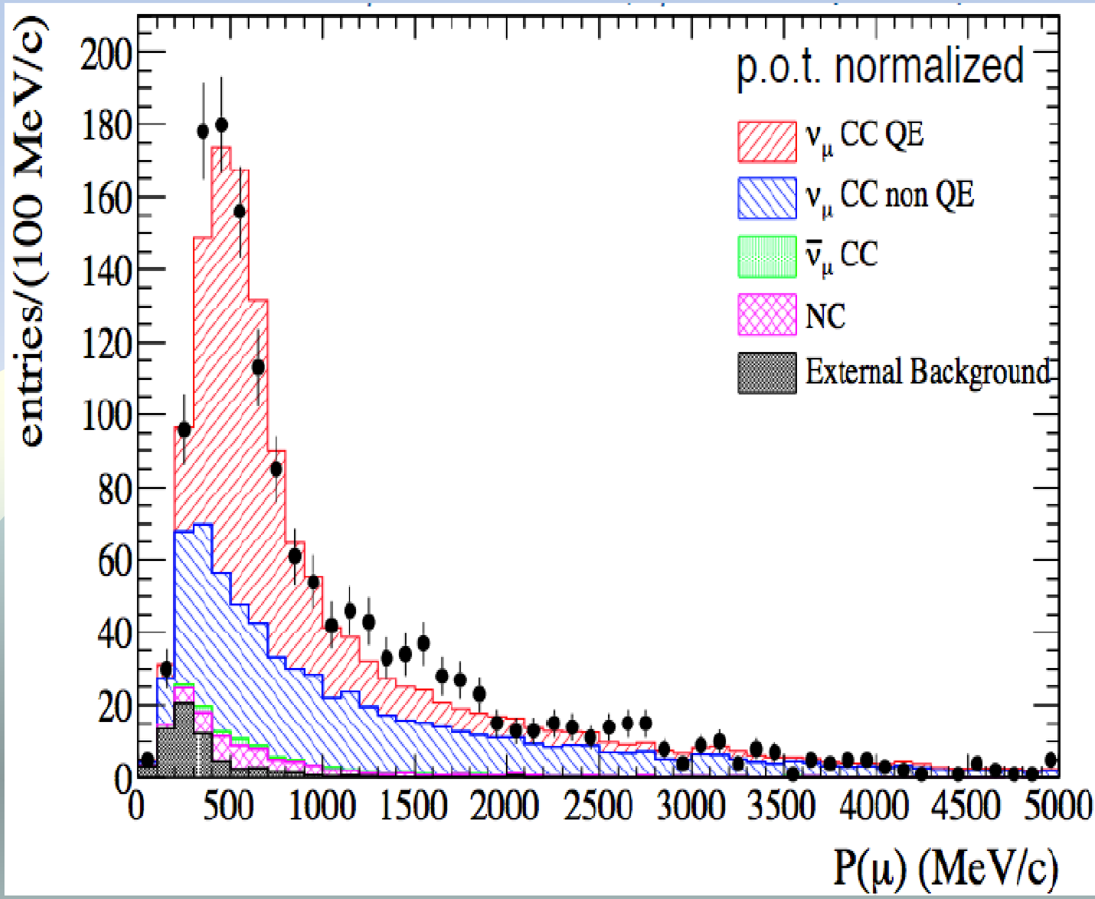
- Cancellation in ratio prediction thanks to near&far correlation
- Kaon uncertainty is dominant (7.6% out of 8.5%) ➔ will be improved by NA61 Kaon results

Off-axis near detector measurement

- To give normalization factor

$$N_{SK}^{exp} = \boxed{\frac{N_{ND}^{obs}}{N_{ND}^{MC}}} \times N_{SK}^{MC}$$

- Measure # of ν_μ CC inclusive events
  - Select events w/ vertex in FGD attached to a muon track in TPC
  - 90% ν_μCC (50% ν_μCCqe)
- Used data Run1 (2.88×10^{19} POT)

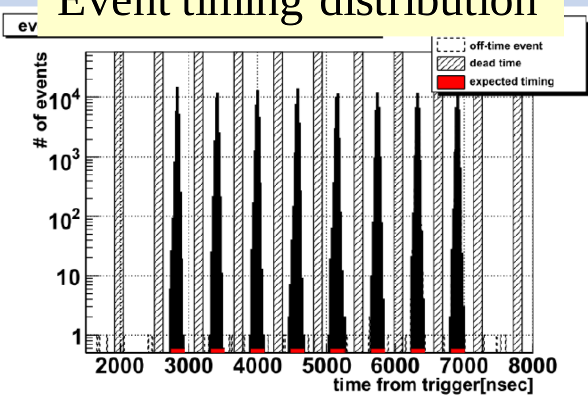


$$N_{ND}^{obs} = 1529 \text{ evts}$$

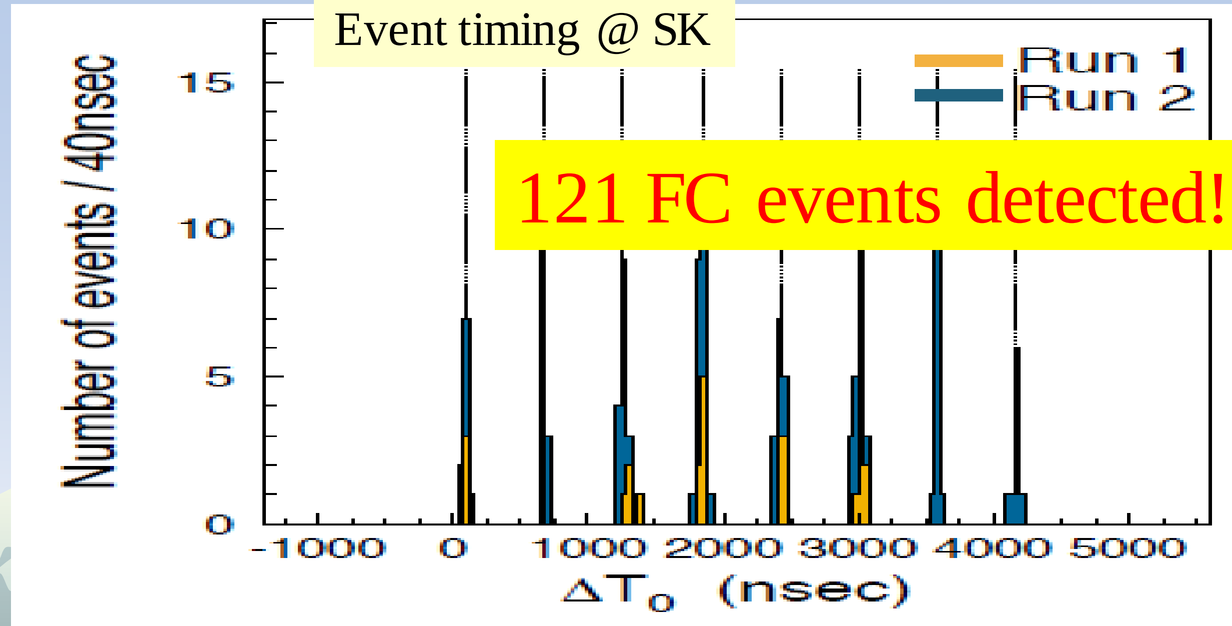
$$\frac{N_{ND}^{obs}}{N_{ND}^{MC}} = 1.036 \pm 0.028(\text{stat})^{+0.044}_{-0.037}(\text{det.syst}) \pm 0.038(\text{phys.model})$$

Event selection (1) timing

Near detector (INGRID)
Event timing distribution



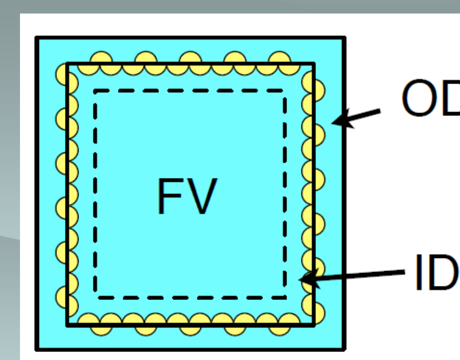
Event timing @ SK



121 FC events detected!

$\Delta T_0 = T_{GPS}@SK - T_{GPS}@J\text{-}PARC - TOF(\sim 985\mu sec)$

- Clear bunch timing structure of J-PARC!!
- **121 Fully Contained(FC) events detected (FC: hits in ID only, no OD hits)**
- Non-J-PARC neutrino contamination in 12us time window: 0.023 events

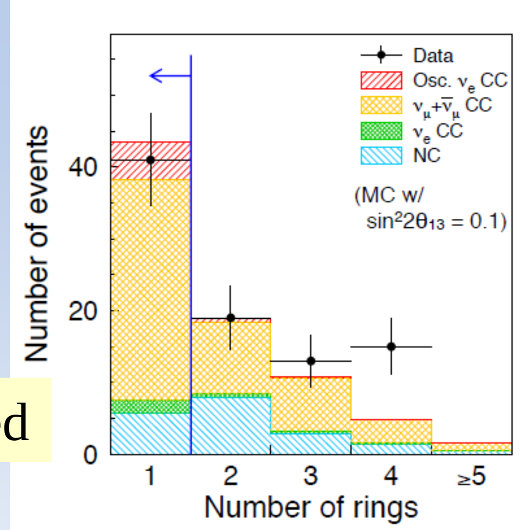


Event selection (2)

2.Single ring

➔Enhance CCqe

41 events remained

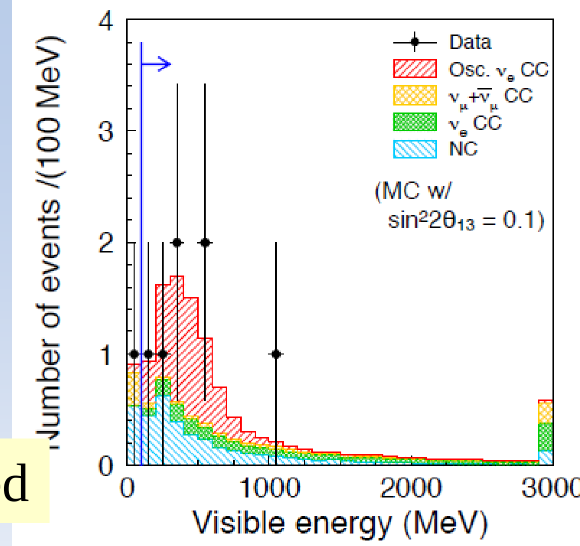


4.Visible energy > 100 MeV

➔

Suppress NC background and electrons from μ decay

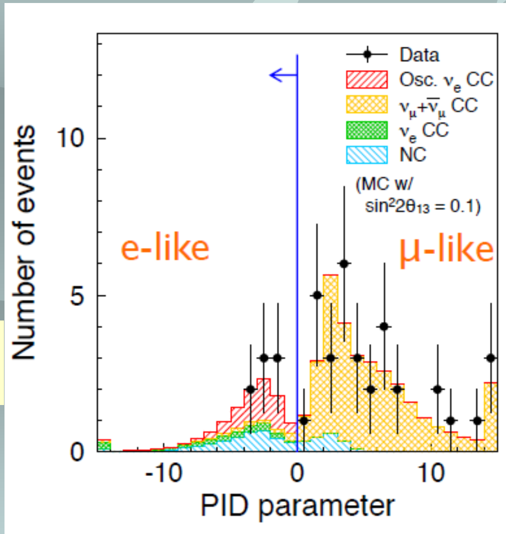
7 events remained



3. PID is e-like

➔Enhance ν_e CC

8 events remained

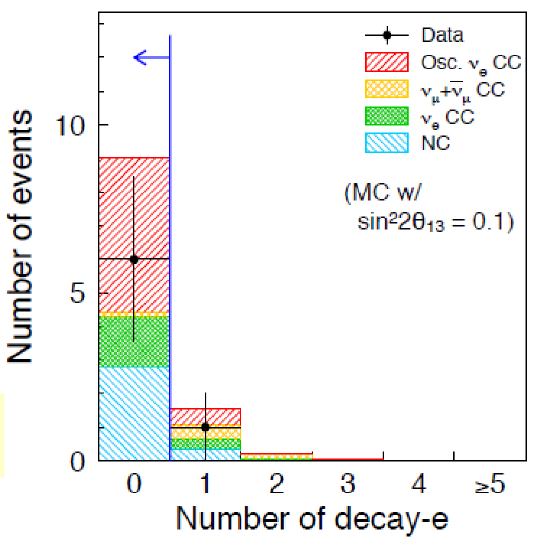


5.No decay-e (delayed e)

➔

Suppress invisible π or μ

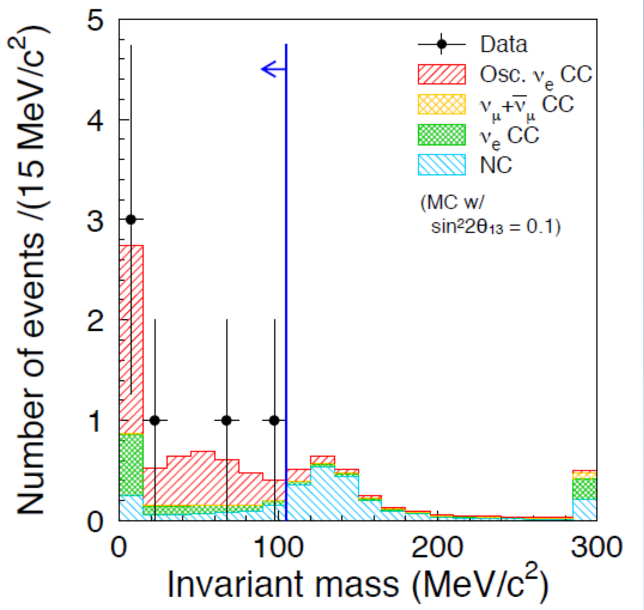
6 events remained



Event Selection (3)

6. Invariant mass of already found 1 e-like ring + additional forced-reconstructed e-like ring M_{inv} < 105MeV/c^2

➔ Reject remaining π^0 background



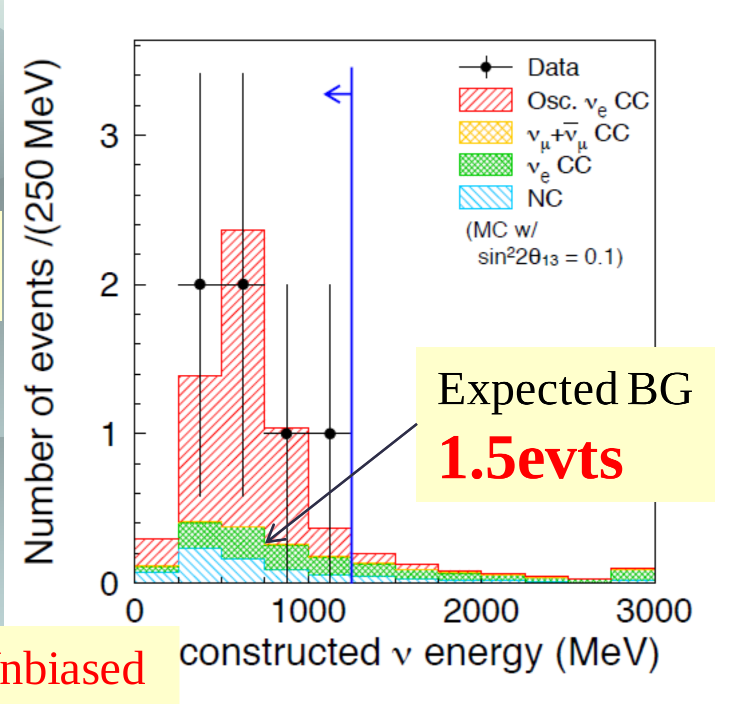
6 events remained

7. Reconstructed neutrino energy < 1250 MeV

- Reject higher energy intrinsic beam background from kaon decays

6 final candidate events remained!

Signal Efficiency = 66%
Background Rejection:
77% for beam ν_e
99% for NC



Expected BG
1.5evts

Selection criteria & cut values are fixed before analysis. Unbiased

Systematic error

Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
(1) Beam flux	$\pm 8.5\%$	$\pm 8.5\%$
(2) ν int. cross section	$\pm 14.0\%$	$\pm 10.5\%$
(3) Near detector	$^{+5.6}_{-5.2}\%$	$^{+5.6}_{-5.2}\%$
(4) Far detector	$\pm 14.7\%$	$\pm 9.4\%$
(5) Near det. statistics	$\pm 2.7\%$	$\pm 2.7\%$
Total	$^{+22.8}_{-22.7}\%$	$^{+17.6}_{-17.5}\%$

Further improvements are planned. Eg. Inclusion of NA61 Kaon results, etc

Smaller error for larger S/N

$$N^{exp}_{SK\ tot.} = 1.5 \pm 0.3 \text{ events}$$

for $\sin^2 2\theta_{13}=0$ (w/ 1.43×10^{20} p.o.t.)

Number of events summary

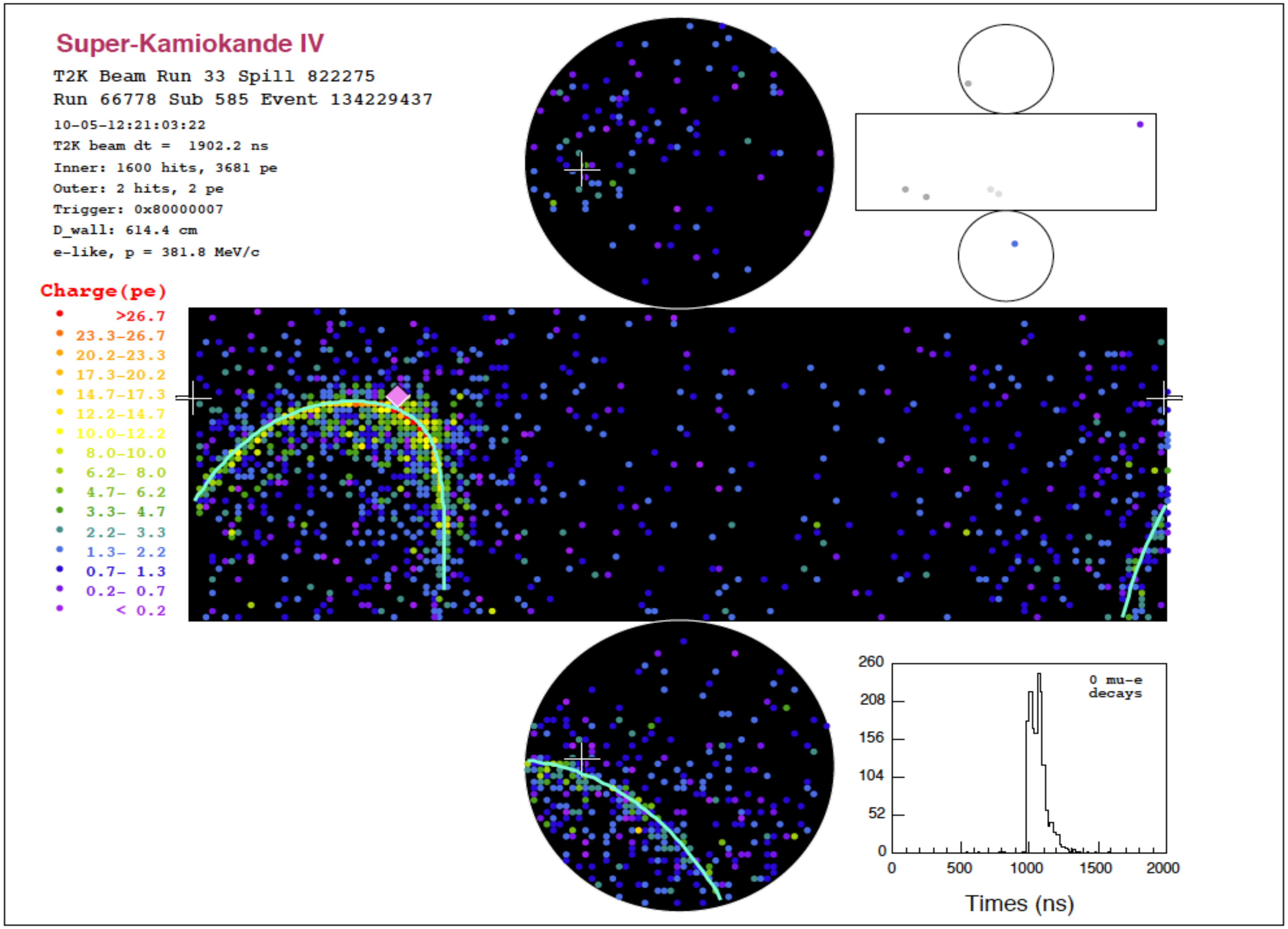
	Total	Beam νe	NC	$\nu_\mu \rightarrow \nu_e$ (sol term)
Expected BG $\sin^2 2\theta_{13} = 0$	1.5 ± 0.3	0.8	0.6	0.1
Observed	6			

Probability to observe six or more events if $\theta_{13}=0$:

0.007

(**2.5 σ** significance)

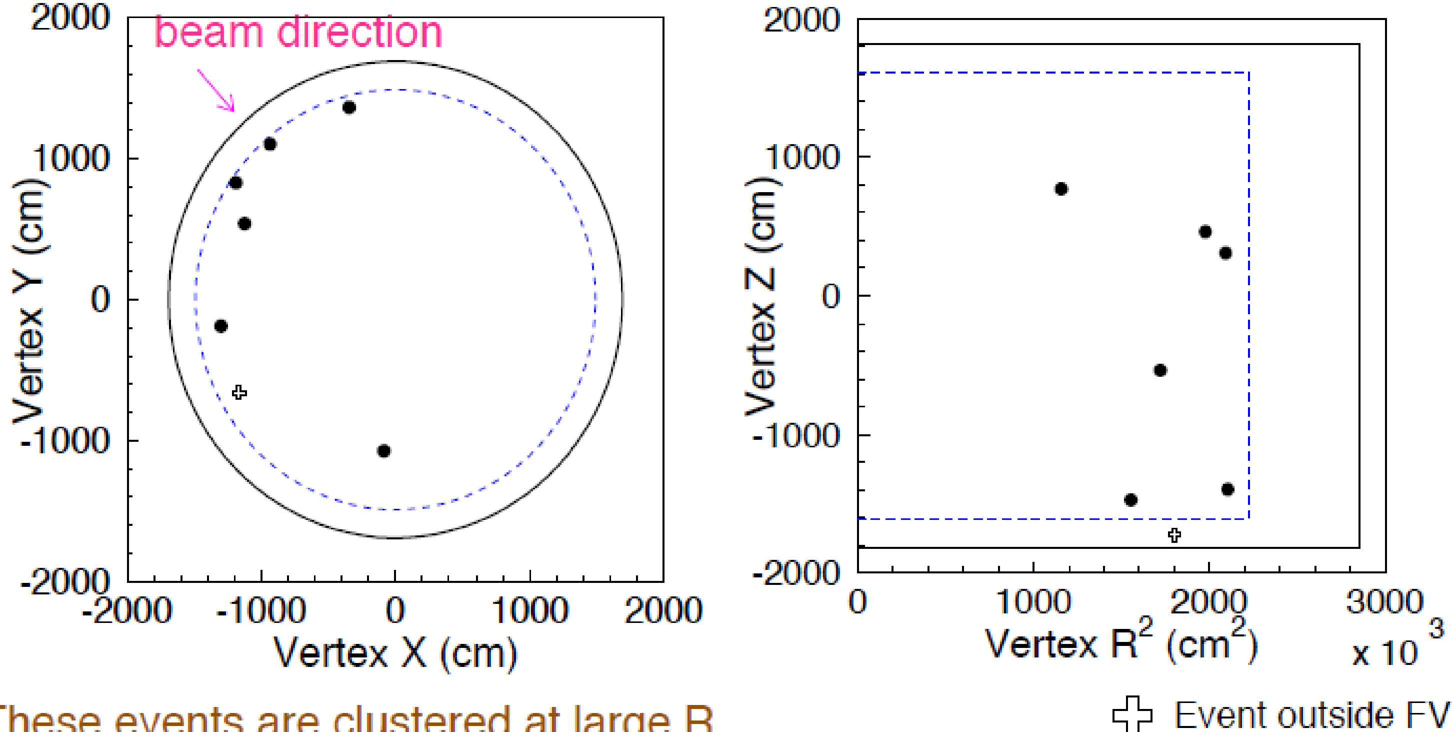
A candidate



	D_{wall} (cm)	Ring-counting likelihood	PID parameter	E_{vis} (MeV)	POLfit mass (MeV/c^2)	E_ν^{rec} (MeV)
#1	614.4	-5.7	-1.2	381.8	29.9	485.9

Vertex distribution

Vertex distribution of ν_e candidate events

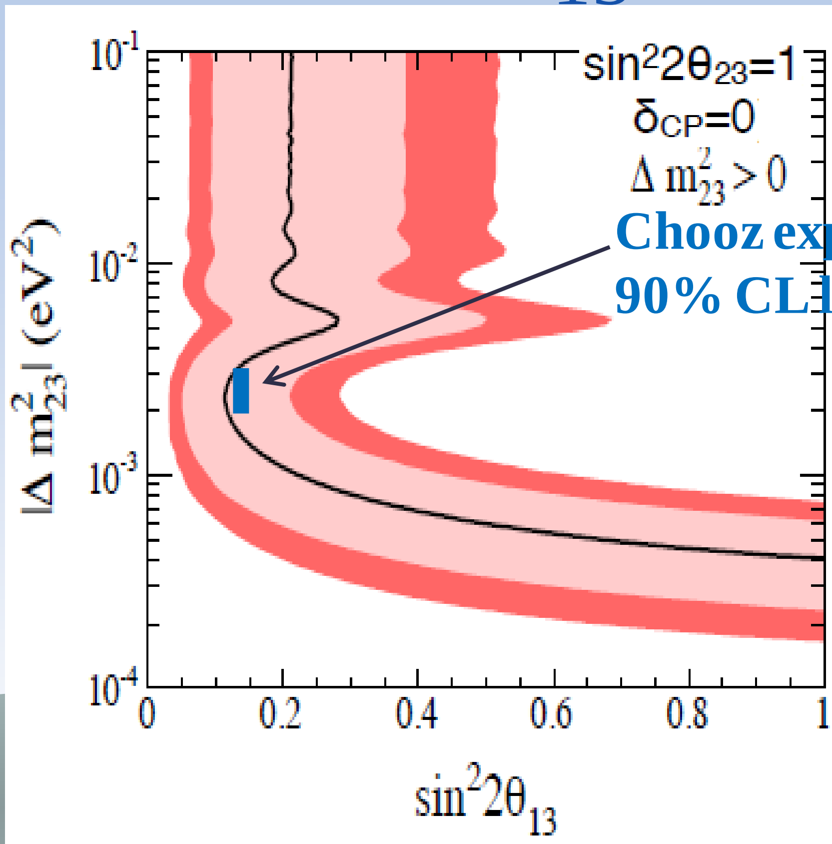


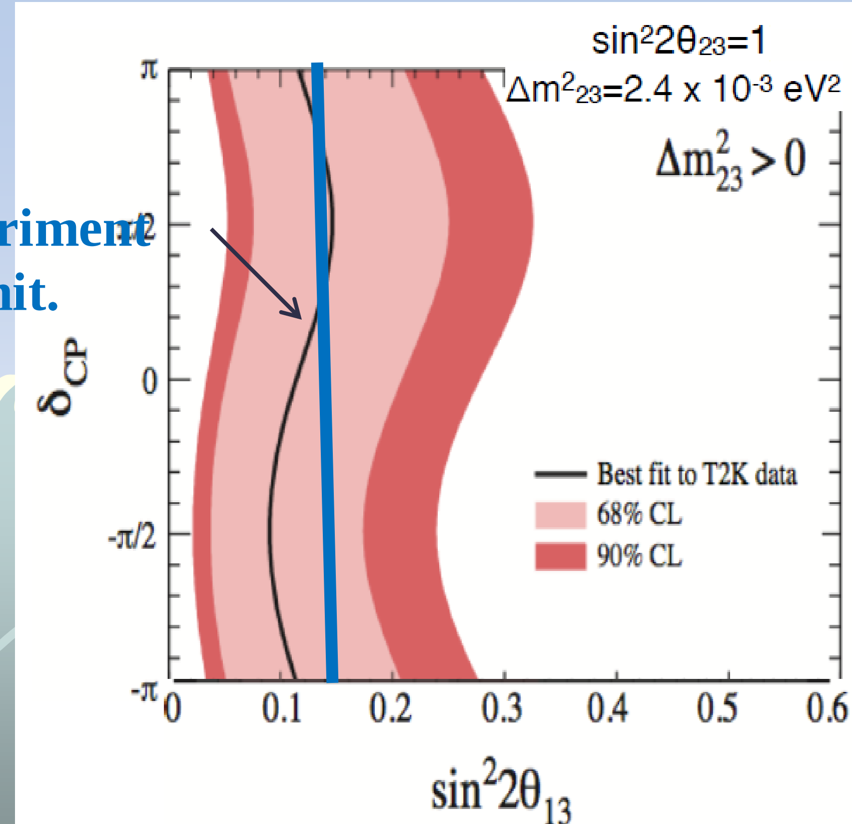
These events are clustered at large R

→ Perform several checks. for example

- * Check distribution of events outside FV → no indication of BG contamination
- * Check distribution of OD events → no indication of BG contamination
- * K.S. test on the R^2 distribution yields a p-value of 0.03

θ_{13} measurements





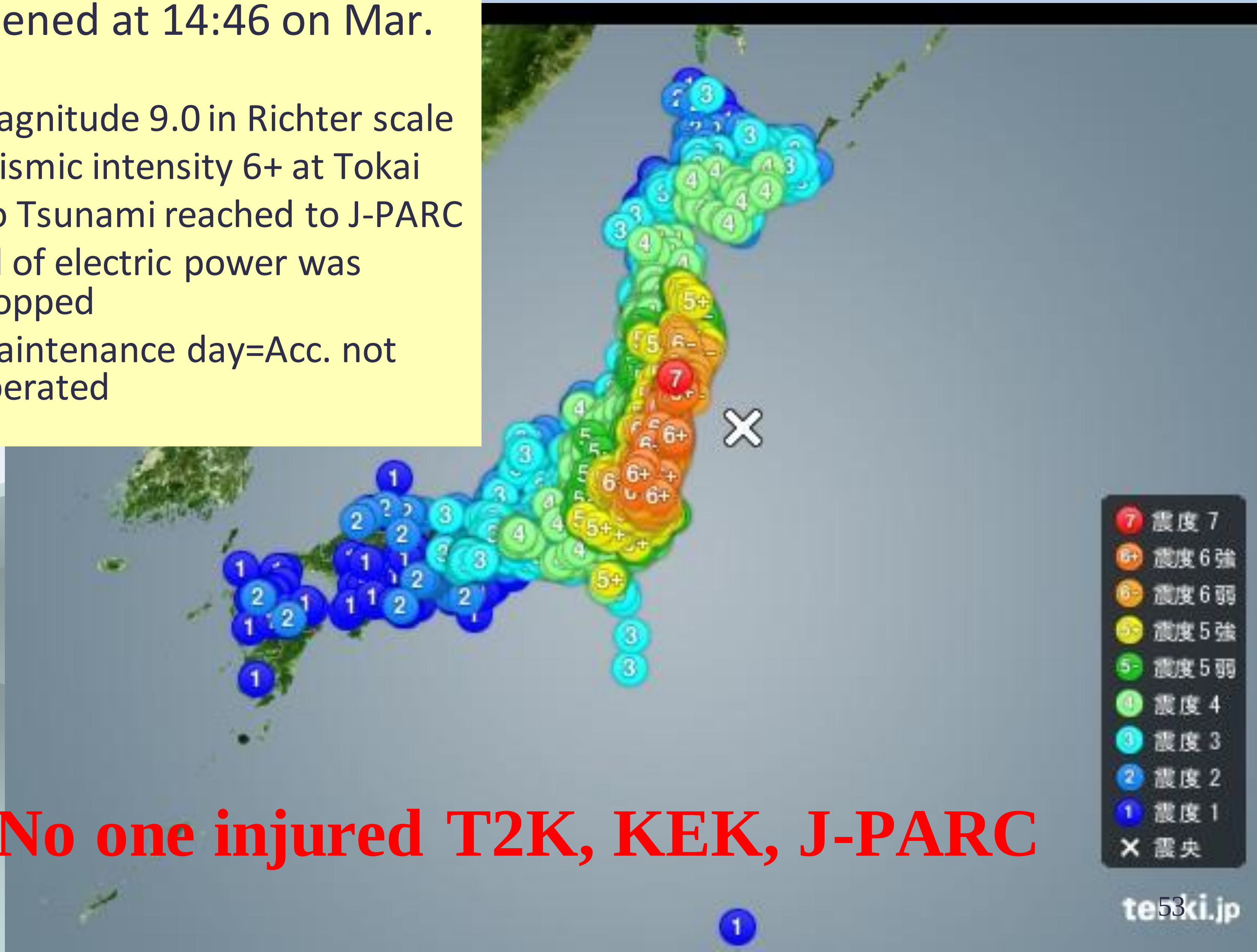
($\Delta m_{23}^2>0$)		($\Delta m_{23}^2<0$)
$0.03 < \sin^2 2\theta_{13} < 0.28$	90% CL range	$0.04 < \sin^2 2\theta_{13} < 0.34$
$\sin^2 2\theta_{13} = 0.11$	Central value	$\sin^2 2\theta_{13} = 0.14$

assuming $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$

J-PARC&T2K status & prospects

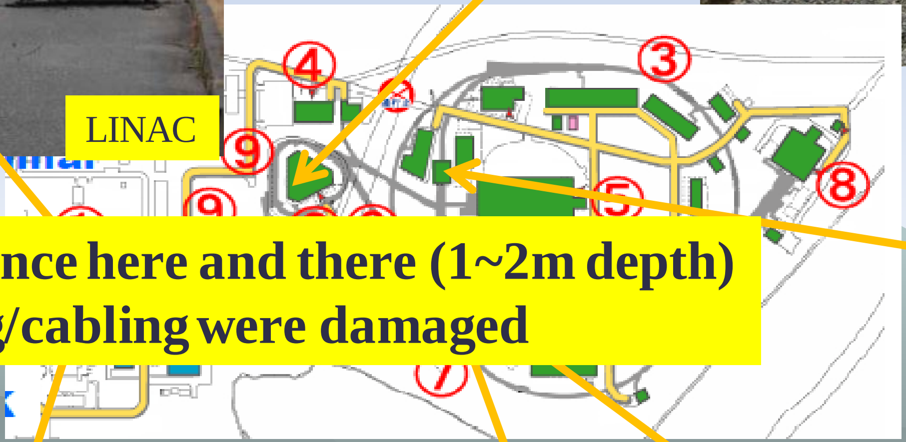
Earthquake on Mar. 11th

- Happened at 14:46 on Mar. 11th
  - Magnitude 9.0 in Richter scale
  - Seismic intensity 6+ at Tokai
  - No Tsunami reached to J-PARC
  - All of electric power was stopped
  - Maintenance day=Acc. not operated



◆ **No one injured T2K, KEK, J-PARC**

Ground level damages

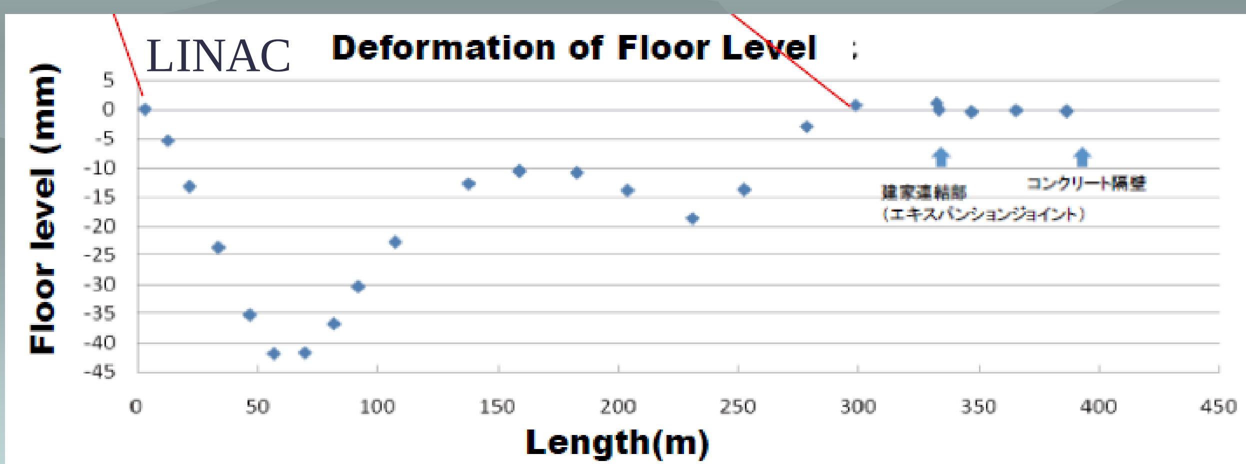


Severe subsidence here and there (1~2m depth)
Near by piping/cabling were damaged

Being rapidly repaired

Equipments

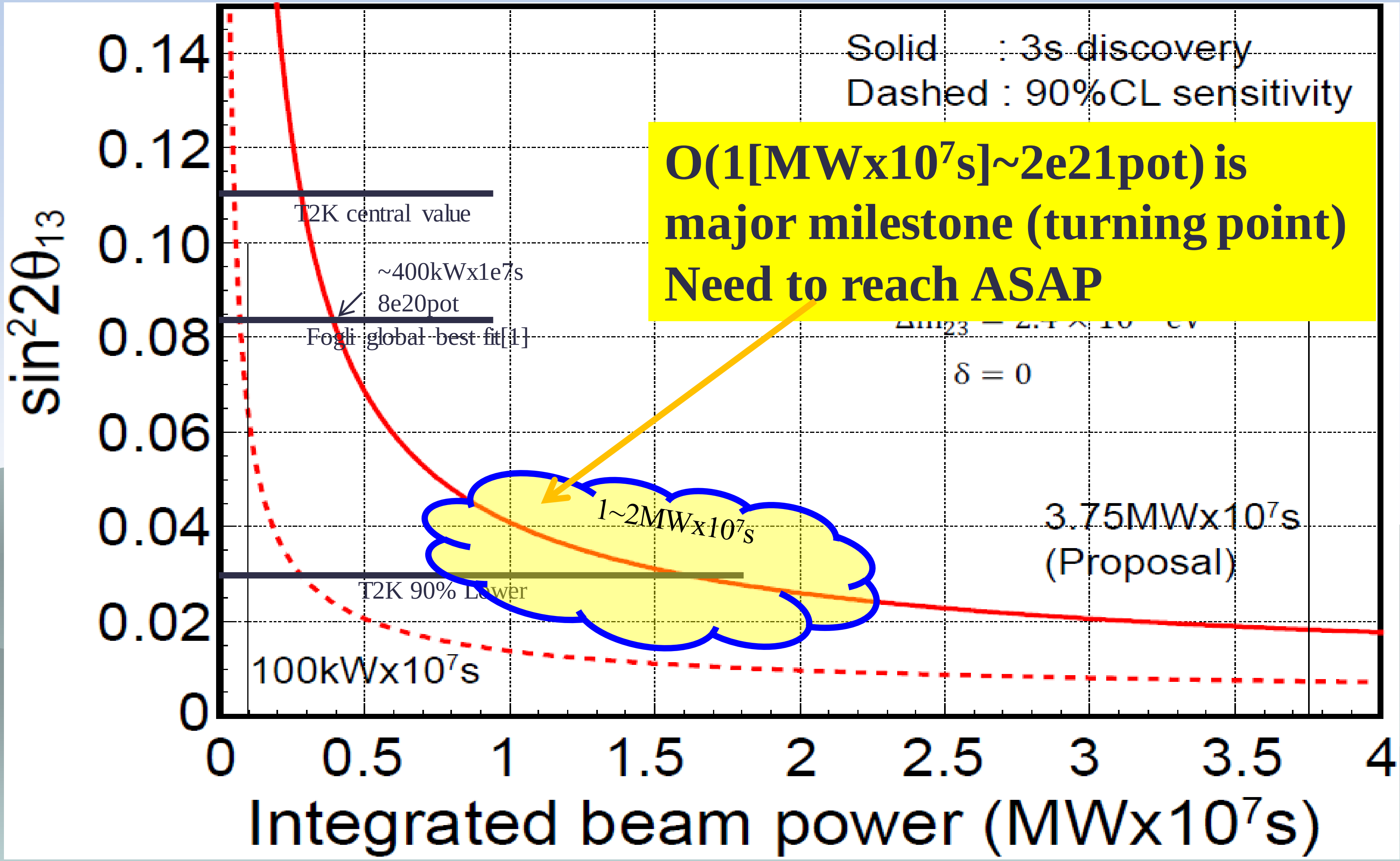
- Generally no fatal damages
- LINAC floor, MR tunnel side pit, Near detector bottom floor once submerged under water
  - Fixed in a few weeks
  - No serious damages on components
- Tunnel moved or bent ~ several cm
  - Major alignment of many components need to be done



J-PARC Plan

- We will resume J-PARC operation in Dec. 2011
- We plan to have >2 "cycle"(~month) beam for users within JFY2011 (by the end of Mar,2012)
- LINAC energy recovery from 181MeV to 400MeV originally scheduled in 2012 was delayed to start July 2013
  - User's needs to take longer beam after long shutdown by the earthquake
  - Delay of preparation caused by earthquake

T2K Expected sensitivities



[1] G.L.Fogli, et.al, arXiv:1106.6028v1 [hep-ph]

Future milestones

- Highest priority is to firmly establish non-zero θ_{13} and its precise determination as quickly as possible

- We have **70** [kWx10^7s] = 1.43e20 pot

We aim to have

- By Summer 2013: **~0.5** [MWx10^7s] ~ 1e21pot
  - Conclude non-zero θ_{13}
  - >5sigma for present T2K central value
- Within a few yrs : **~ 1** [MWx10^7s] ~ 2e21pot
  - > 3sigma for $\sin^2 2\theta_{13} > 0.04$
- Approved goal : **3.8** [MWx10^7s] ~ 8e21pot
  - > 3sigma for $\sin^2 2\theta_{13} >\sim 0.02$

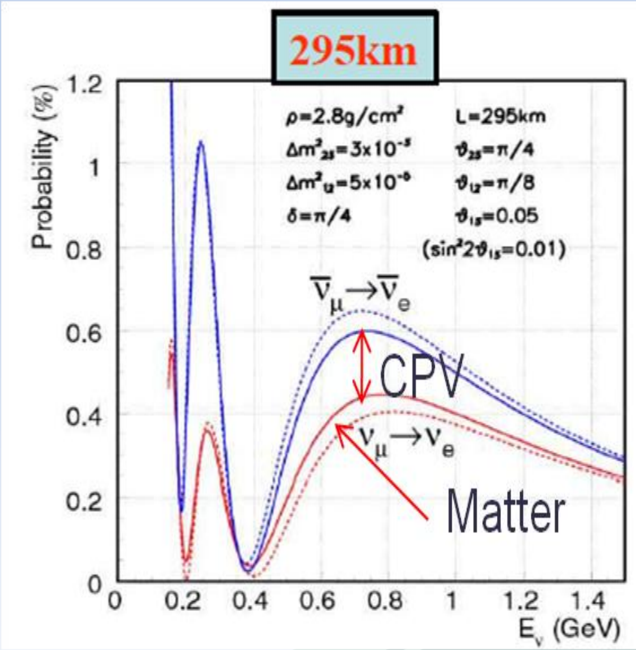
T2K official part is up to here

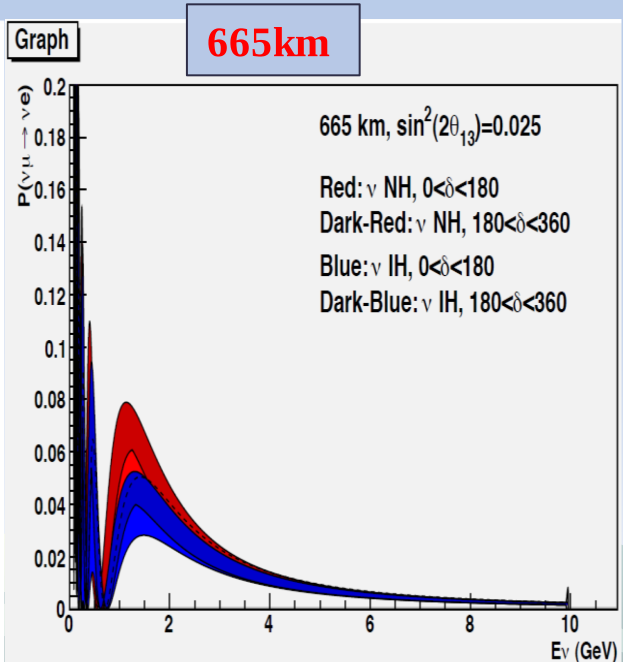
Implication on Future

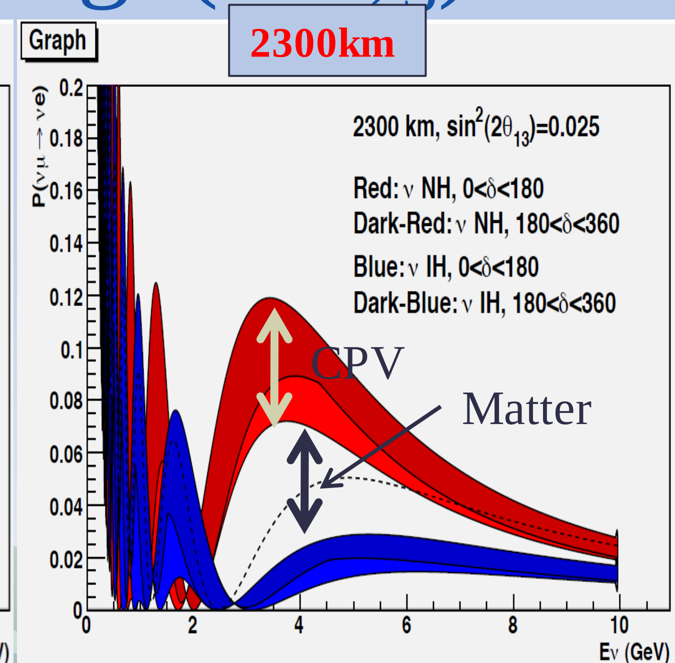
- If $\sin^2 2\theta_{13} > \sim 0.01$
  - Conventional Multi-MW super beam long baseline experiment will be really promising to explore CPV in lepton sector
  - We need to put even more effort to formulate the future project in this direction as soon as possible
- IF not
  - Need "ideal" beam such as Neutrino Factory or beta beam to probe CPV

- Therefore, confirming the indication of large θ_{13} by T2K is a very important and urgent issue

How to measure CPV & sign(Δm_{23})







- **νe appearance energy spectrum shape**
  - Peak position and height for 1st, 2nd maximum and minimum
  - Measure both sinδ & cosδ terms ➔ can discriminate 0deg vs 180deg
- **Difference between νe and $\overline{\nu e}$ behavior**
  - Sensitive to any mechanism to make asymmetry (No assumption)
  - Basically measure sinδ term
- **Distance:**
  - Larger L Matter effect large ➔ Sensitive to sign(Δm_{23}) too
  - Smaller L (lower E): Purer CPV measurement

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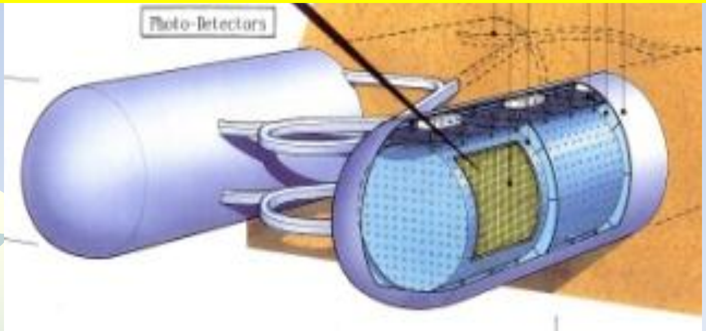
Essential requirements for CPV discovery

- **Order of magnitude higher statistics from present generation experiments**
- **➔**
- **High intensity beam (Multi-MW)**
  - Increase statistics
- **High sensitivity huge detector**
  - Increase statistics
  - Increase signal efficiency
  - Reduce background
  - Reduce systematic errors
  - Should also capable for proton decay detection

“Available” technologies for huge detector

Good at Wideband beam

Good at low E (<1GeV)
narrow band beam



Liq Ar TPC

- Aim O(100kton)
- Electronic “bubble chamber”
  - Can track every charged particle
  - Down to very low energy
- Neutrino energy reconstruction by eg. total energy
  - No need to assume process type
  - Capable upto high energy
- Good PID w/ dE/dx, pi0 rejection
- Realized O(1kton)

Water Cherenkov

- Aim O(1000kton)
- Energy reconstruction assuming Ccqe
  - Effective < 1GeV
- Good PID (μ/e) at low energy
- Cherenkov threshold
- Realized 50kton

Possible experimental configuration

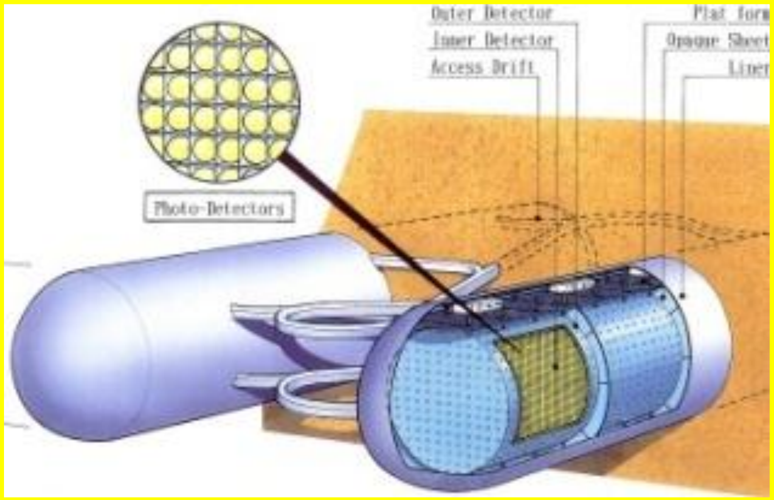
- Multi-MW beam + Longer distance O(1000km)+ Wide band beam + LiqAr
  - Energy spectrum measurement
  - Cover both 1st and 2nd peaks
  - Possible to determine "everything" in 1 shot
    - CPV
    - Hierarchy
    - θ_{23} octant

- Multi-MW beam + Shorter distance (a few 100km) + Low energy narrow band beam + Water Cherenkov
  - Nue/nuebar asymtery of 1st peak
  - Possible to determine
    - CPV
  - Need external input to discriminate mass hierarchy (such as atm nu)

- To realize, international cooperation is essential
  - Europe (LAGUNA) and Japan are pursuing these options coherently

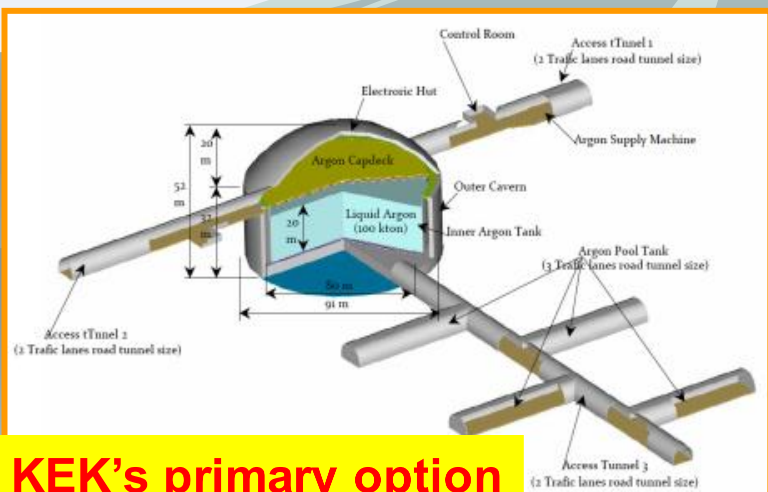
Scenarios in Japan

Kamioka L=295km OA=2.5deg



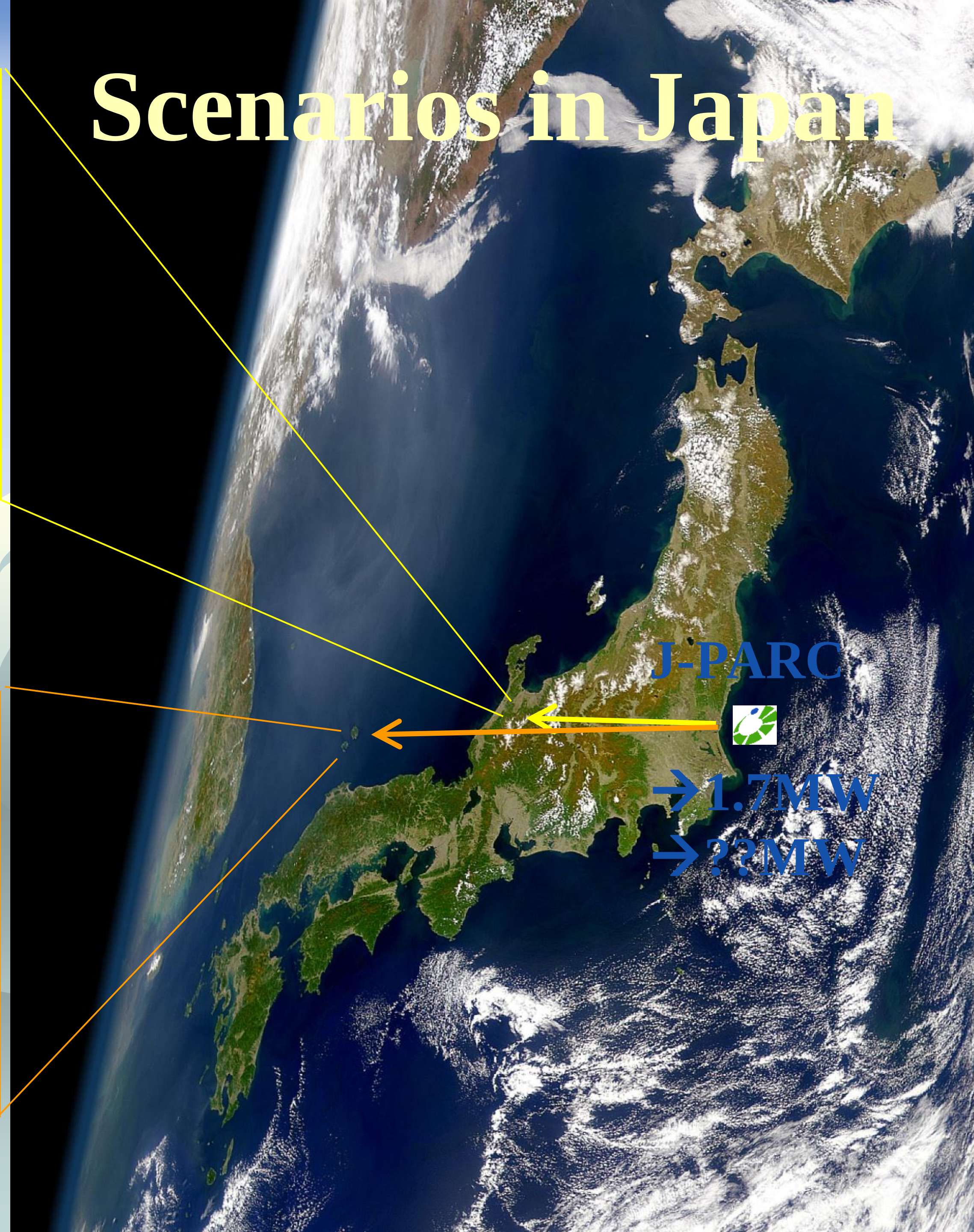
Okinoshima L=658km OA=0.78deg

Almost On-Axis



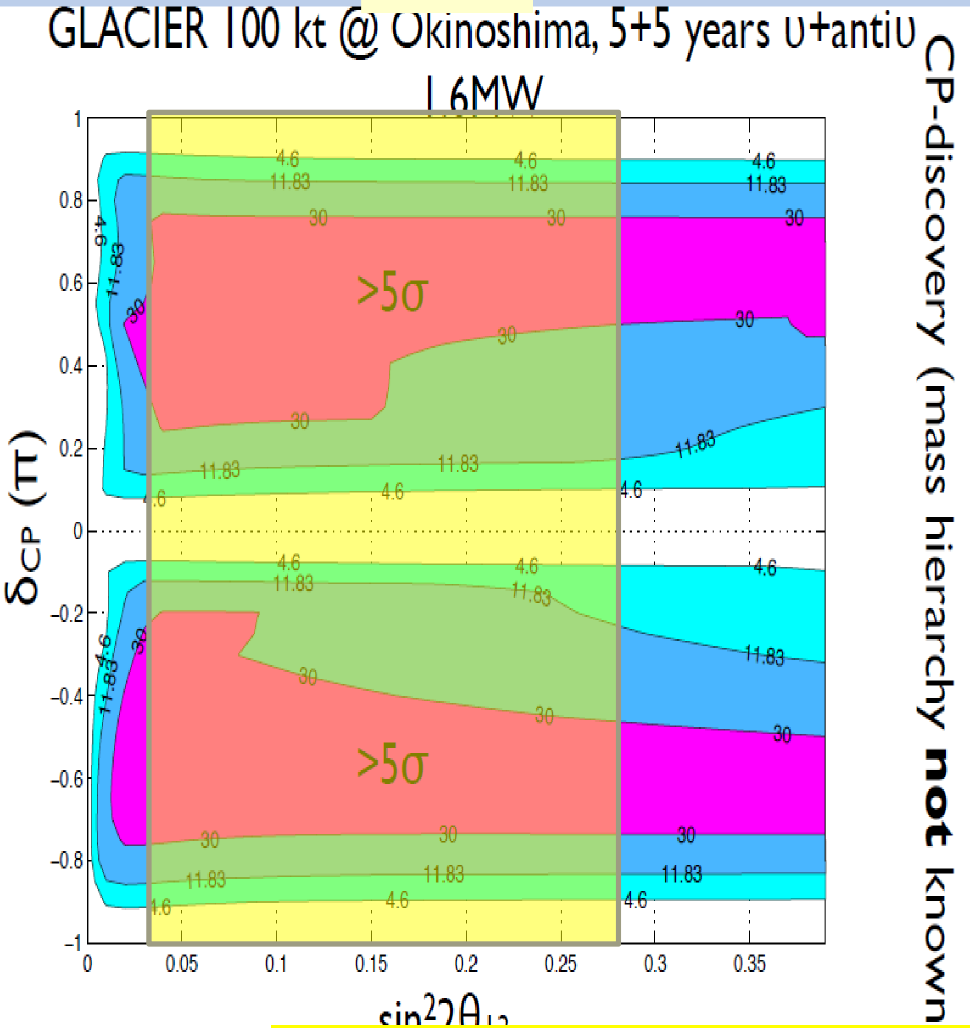
KEK's primary option

P32 proposal (Lar TPC R&D)
Recommended by J-PARC PAC
(Jan 2010), arXiv:0804.2111

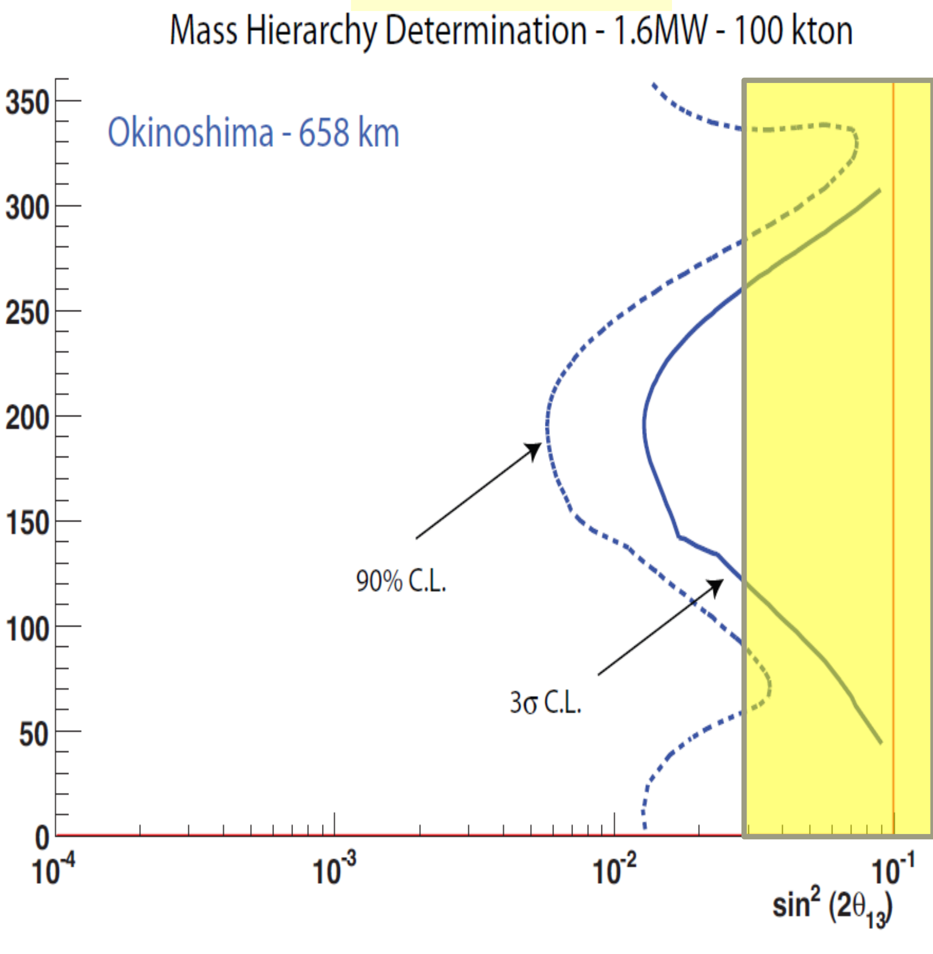


Physics potential

CPV



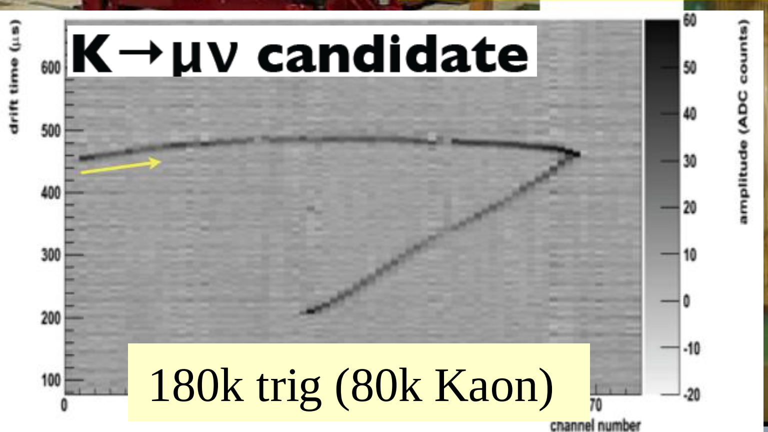
Hierarchy



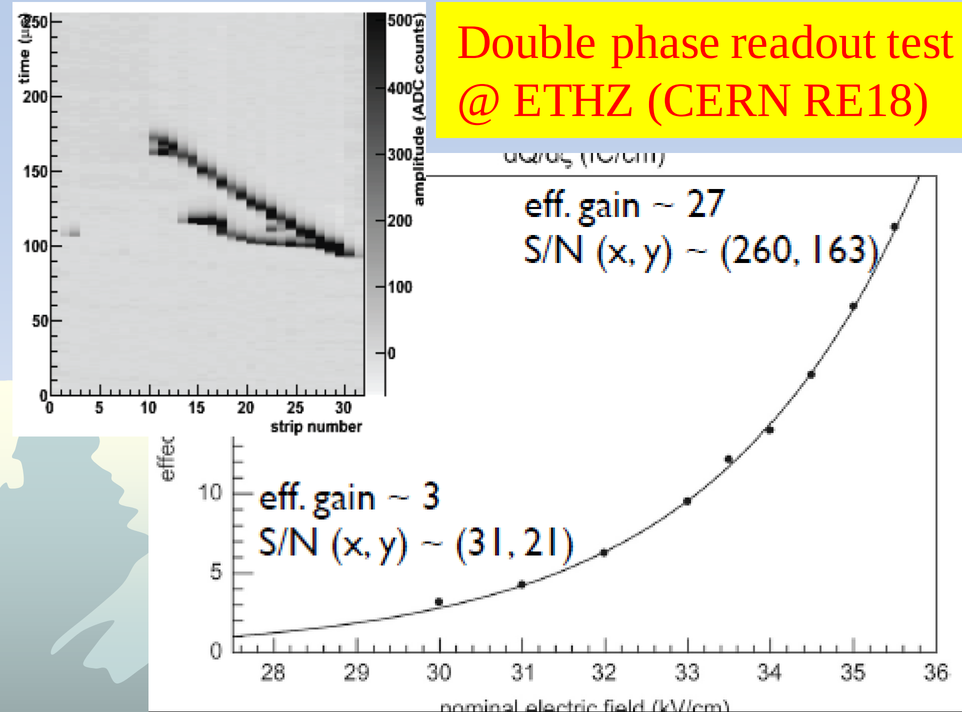
. 10: Mass hierarchy discrimination at 90%C.L. and 3σ for 5+5 years neutrino-antineutrino runs.

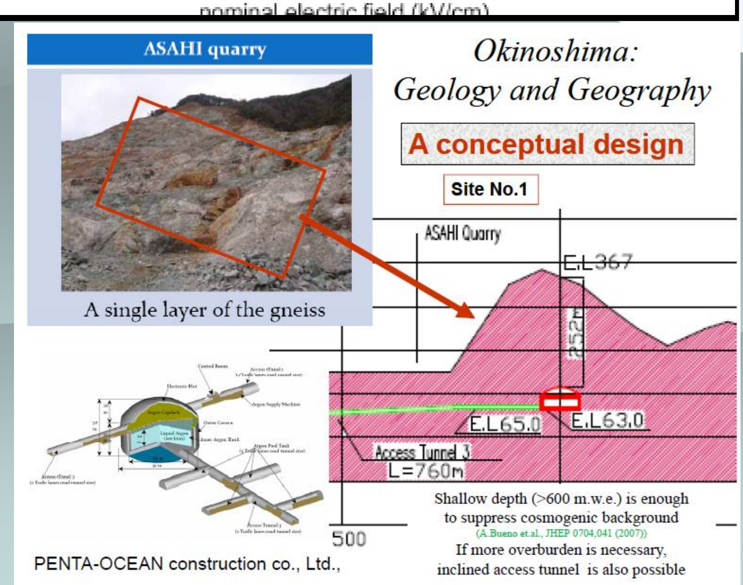
- Very good chance both to detect CPV & determine sign(Δm_{23})

R&D toward realizing 100kt LArTPC



Double phase readout test
@ ETHZ (CERN RE18)





Summary

- T2K reports new results on $\nu_\mu \to \nu_e$ oscillations based on 1.43 x 10^{20} p.o.t. (2% exposure of T2K's goal)
  - Expected number of events is 1.5 ± 0.3 ($\sin^2 2\theta_{13} = 0$)
  - 6 candidate events are observed
  - Under θ_{13}=0 hypothesis, the probability to observe 6 or more candidate events is 0.007 (equivalent to 2.5σ significance)
  - 0.03 (0.04) < $\sin^2 2\theta_{13}$ < 0.28 (0.34) at 90% C.L. for normal (inverted) hierarchy (assuming Δm^2_{23}=2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$=1, δCP=0)
  - To appear in PRL (arXiv:1106.2822v1)
- We will resume J-PARC operation in Dec,2011 and restart T2K data taking as soon as possible
- ν_μ disappearance result with full data set will be reported at EPS conf. next week

Summary (2)

- Impact of T2K result on future project was briefly discussed
  - With large $\sin^2 2\theta_{13}$ (>0.01), detection of CPV with conventional beam method (w/ Multi-MW & huge high sensitivity detector) becomes promising!!
- KEK is pursuing and making R&D on huge Liq Ar detector at further distance in close cooperation with European initiative, LAGUNA

Acknowledgements

- T2K is a CERN recognized experiment (RE13)
- We thank CERN on
  - Donation of UA1/NOMAD magnet
  - Infrastructure for detector preparation
  - CERN test beam for detectors
  - Micromegas production and test by CERN TS/DEM group
  - Various technical, administrative support on detector preparation, especially for UA1/NOMAD magnet related issues
  - CERN-KEK cooperation on super conducting magnet for neutrino beam line
  - Fruitful exchange of information on beam line (K2K & T2K)
  - Warm word and donation for the earthquake
- We also thank NA61 Collaboration
  - Successful collaboration