Recent results from the T2K experiment

Edoardo Mazzucato, CEA Saclay

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T2K : Tokai to Kamioka

A long baseline neutrino oscillation experiment

- Well established now that neutrinos have non-zero masses since they oscillate
- Flavor eigensates $(\nu_e, \nu_\mu, \nu_\tau) \neq$ mass eigenstates (ν_1, ν_2, ν_3)
- Neutrino oscillations described by $\Delta m^2_{ij} = m_j^2 - m_i^2$ and the Pontecorvo-Maki-Nakagawa-Sakata (**PMNS**) matrix

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

T2K goal is to measure precisely $P(\nu_\mu \rightarrow \nu_\mu)$ and $P(\nu_\mu \rightarrow \nu_e)$

- Neutrinos raise many other questions : What are their absolute mass ? Dirac or Majorana particles ? Is CP violated in the leptonic sector? Are neutrinos faster than light ?

Neutrino mixing

atmospheric *solar*

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\, e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\, e^{-i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

ν oscillations governed by 6 parameters : θ_{12} , θ_{23} , θ_{13} , Δm^2_{12} , Δm^2_{23} and δ_{CP}

$\theta_{23} \sim 46° \pm 4°$
$|\Delta m^2_{23}| \sim (2.4 \pm 0.1) \times 10^{-3}\ eV^2$
(SK, K2K, MINOS, T2K)

$\theta_{13} < 11°$ at 90% CL (CHOOZ)
T2K, MINOS, DCHOOZ:
indication of $\theta_{13} > 0$!

$\theta_{12} \sim (33.6 \pm 1.1)°$
$\Delta m^2_{12} \sim (7.6 \pm 0.2) \times 10^{-5}\ eV^2$
(SNO, KAMLAND)

T2K goals:

Expected sensitivity with full T2K proposal statistics (3.75 MW × 10^7 s)

- **Measurement of the mixing angle θ_{13} through ν_e appearance:**

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13}) \sin^2\theta_{23} \sin^2(1.27\Delta m^2_{31} L/E_\nu)$$

$\delta(\sin^2(2\theta_{13}) \sim 0.008$ at 90% C.L.

A non-zero value of θ_{13} would open the road to future investigations of leptonic CP violation (δ_{CP}) and the mass hierarchy problem

- **Precision determination of θ_{23} and Δm^2_{23} by observing ν_μ disappearance:**

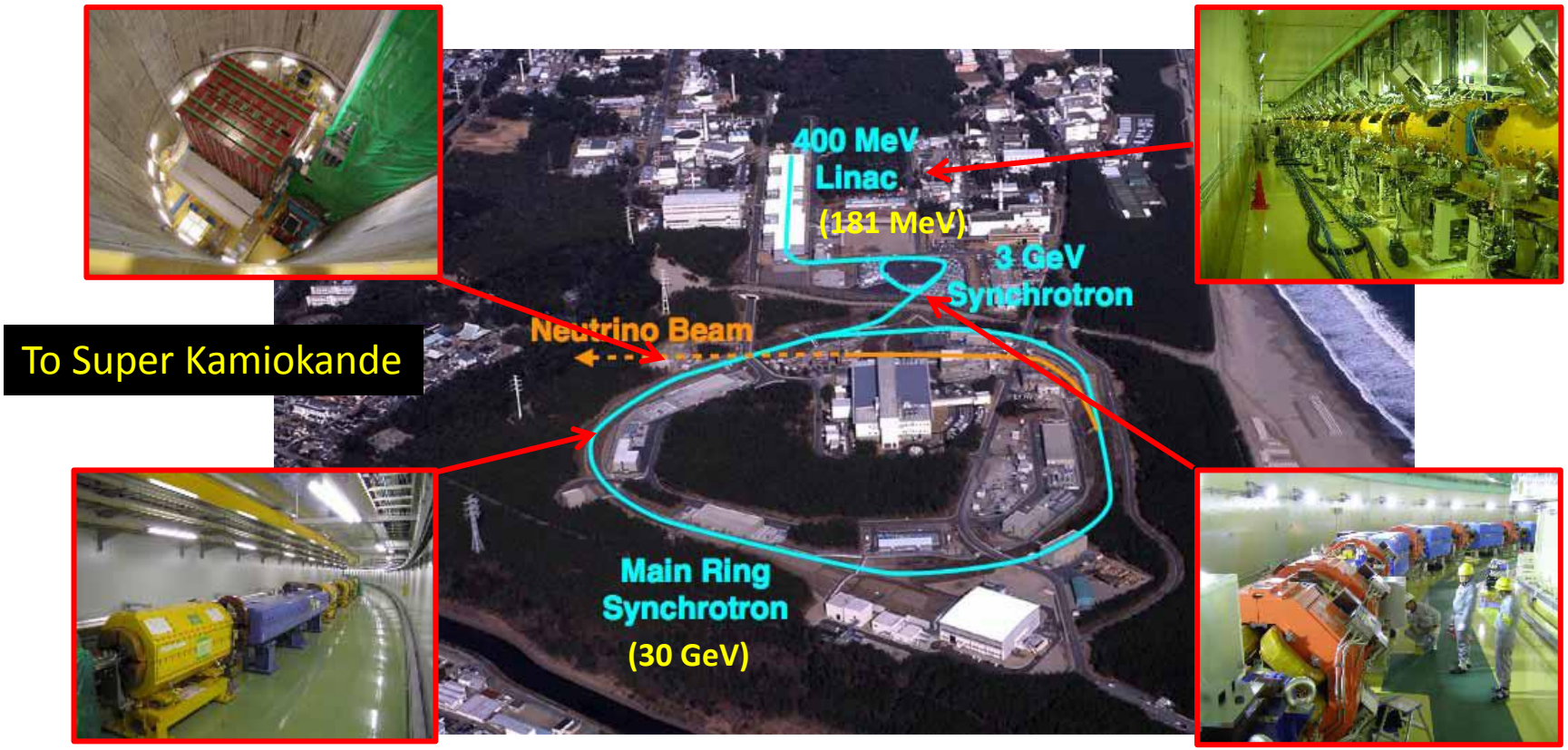
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2(1.27\Delta m^2_{23} L/E_\nu)$$

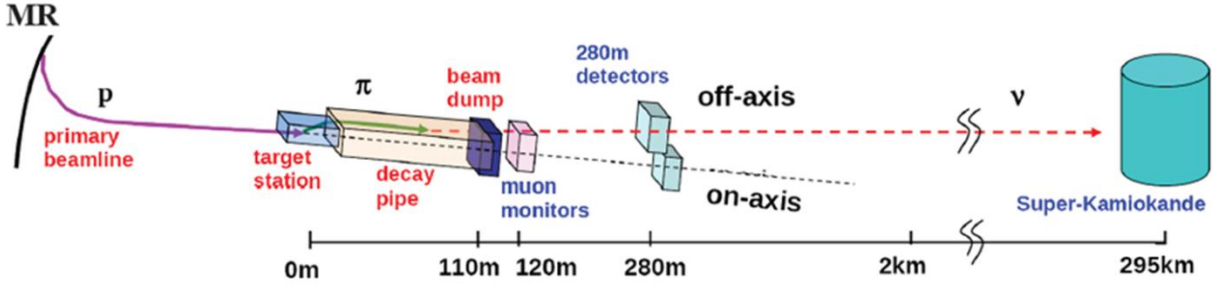
$\delta(|\Delta m^2_{23}|) \sim 1 \times 10^{-4}\ eV^2$
$\delta(\sin^2(2\theta_{23})) \sim 1\%$

The T2K Collaboration

~ 500 members, 59 national institutes, 12 countries

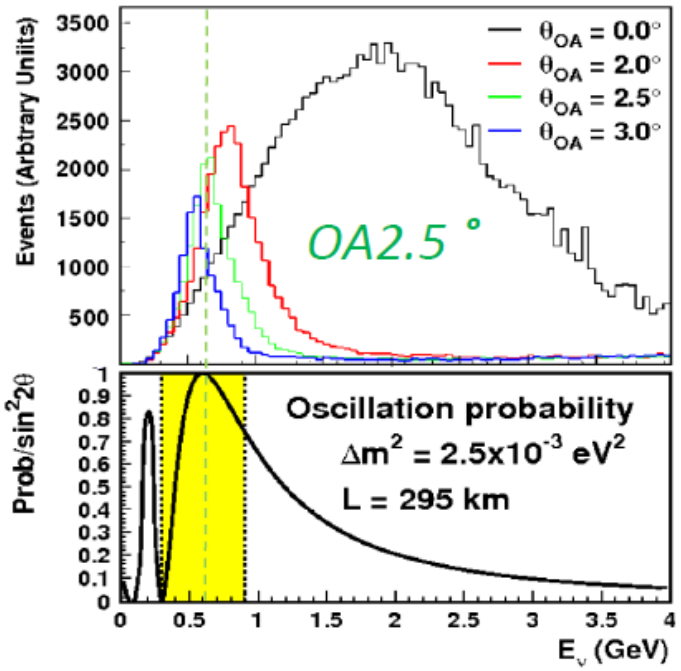
J-PARC neutrino facility

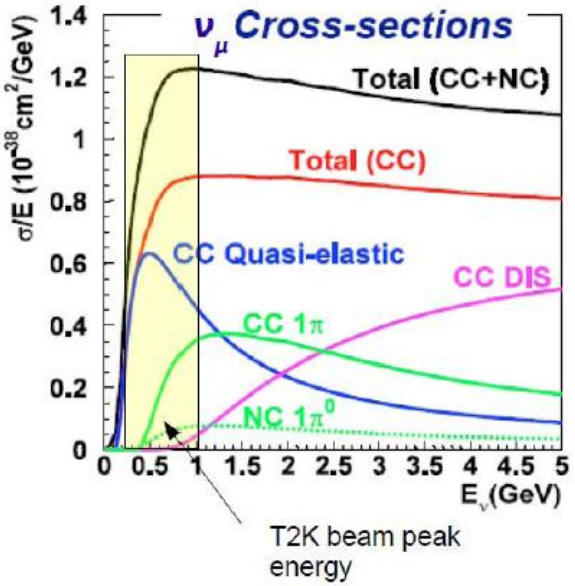




Off-axis technique

- The T2K detectors are located 2.5° w.r.t. beam axis
- Off-axis technique gives a narrow ν spectrum peaked at ~ 600 MeV
- Optimized energy spectrum for maximal oscillation probability
- Small ν_e contamination





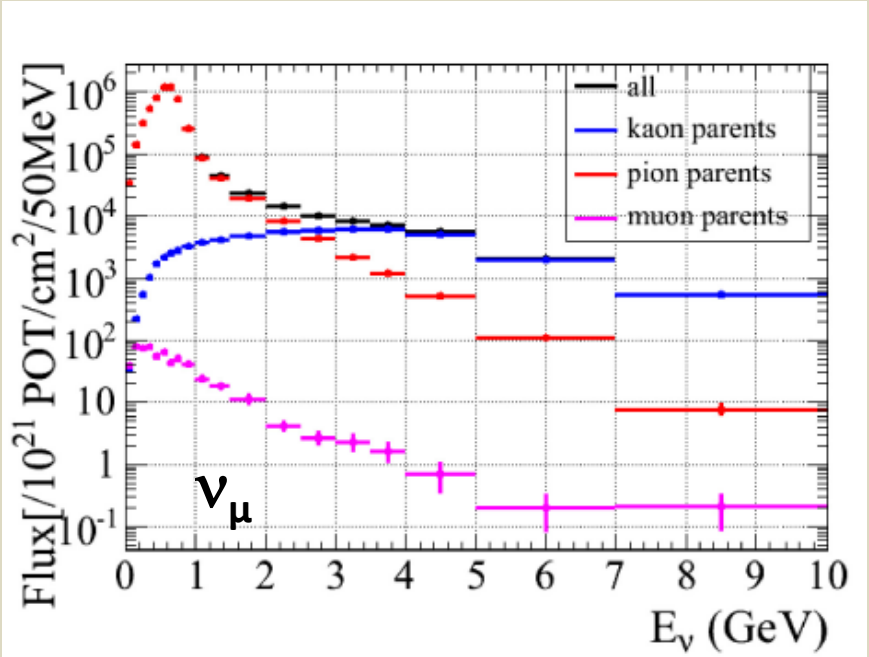
- Below 1 GeV, **charged current** interactions are dominated by **quasi-elastic** process **(CCQE)**

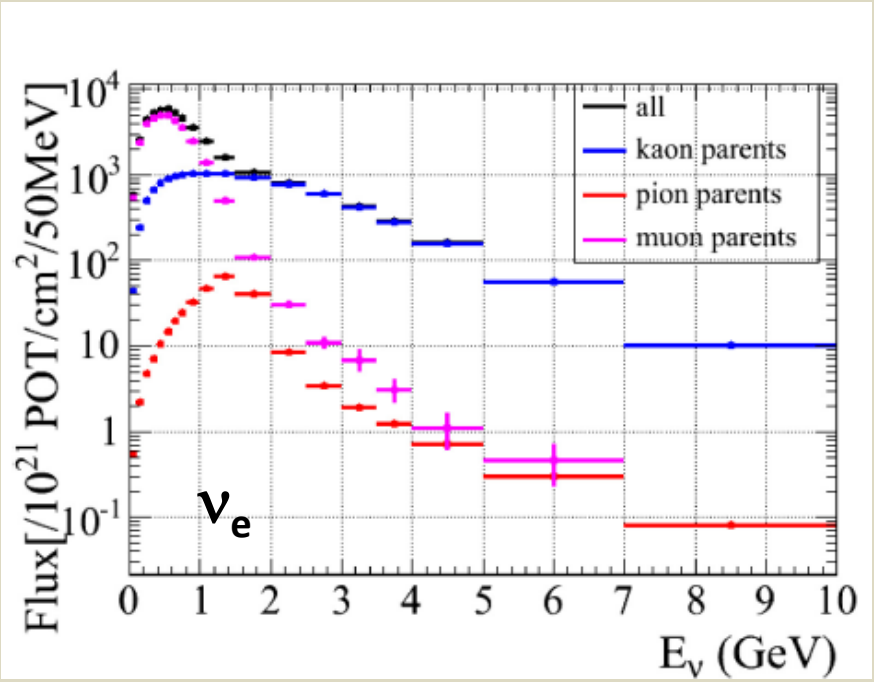
$$\nu_l + n \rightarrow p + l^- \quad (l = e, \mu)$$

- E_ν precisely determined from the lepton momentum vector
- Small energy tail reduces contributions from other processes (NC, CC1π, DIS …)

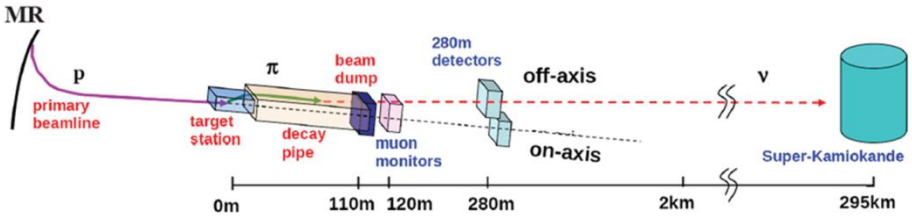
Neutrino fluxes at SK

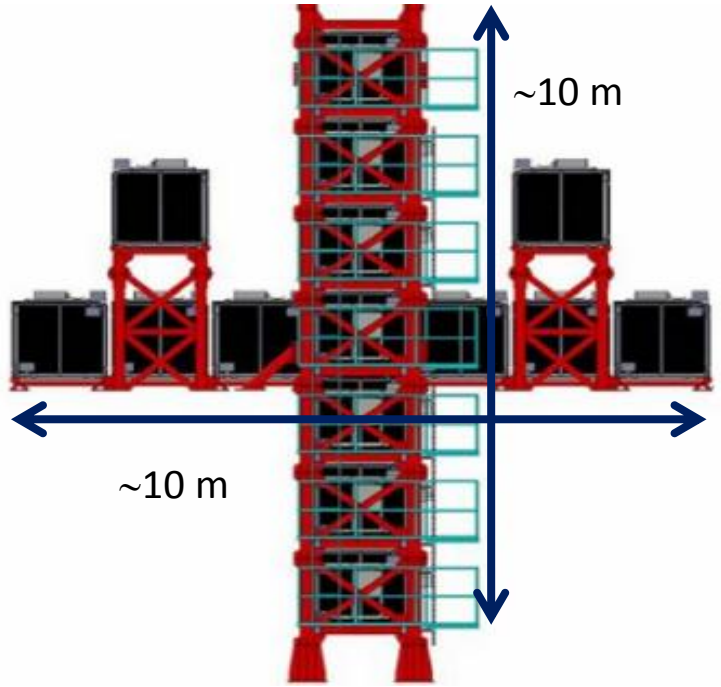
Predictions based on NA61 (CERN) pion production data + FLUKA





INGRID on-axis detector

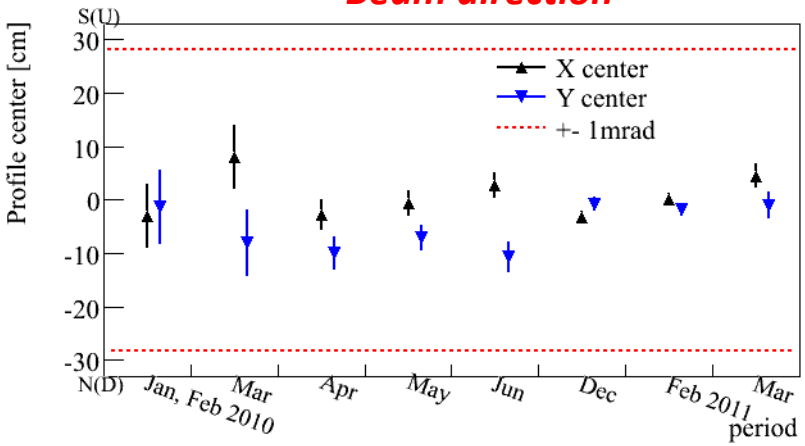




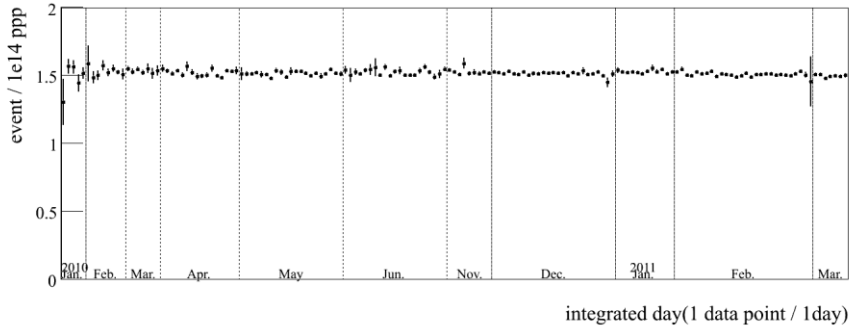
Monitors the ν beam direction and intensity

- 16 iron/scintillator modules (7.1 tons of iron /module)
- physics requirement for beam direction stability < 1 mrad

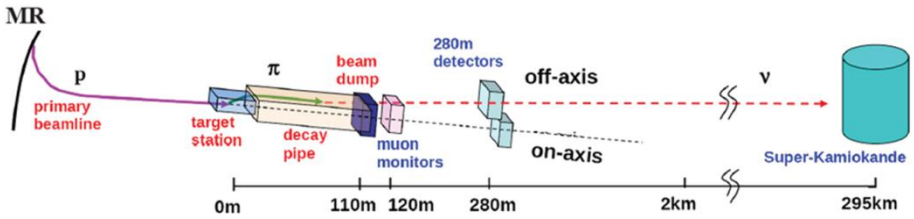
Beam direction

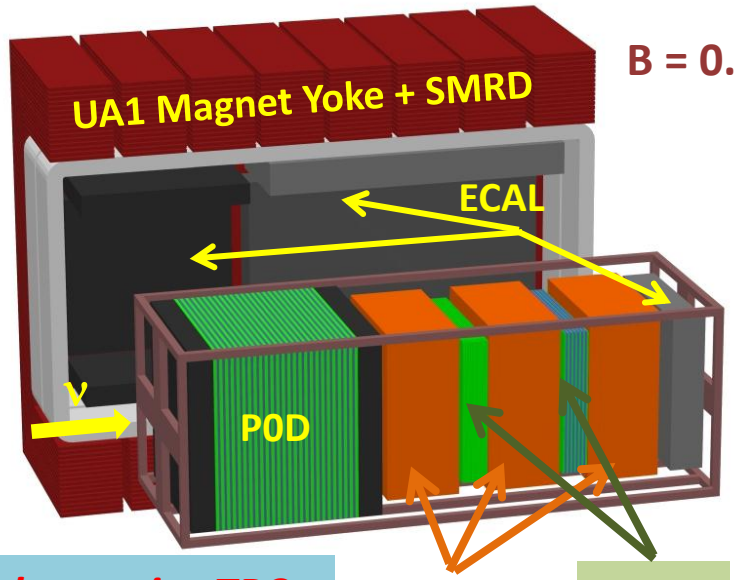


ν event rate



ND280 off-axis

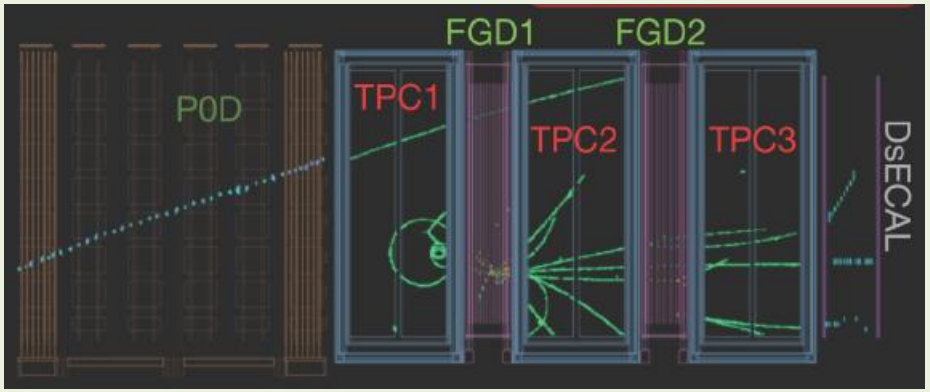




Measurement of :

- *energy spectrum and flux of ν beam*
- *ν_e contamination in the beam*
- *rates for exclusive ν interactions (CCQE, CC1π, NC, DIS, …)*

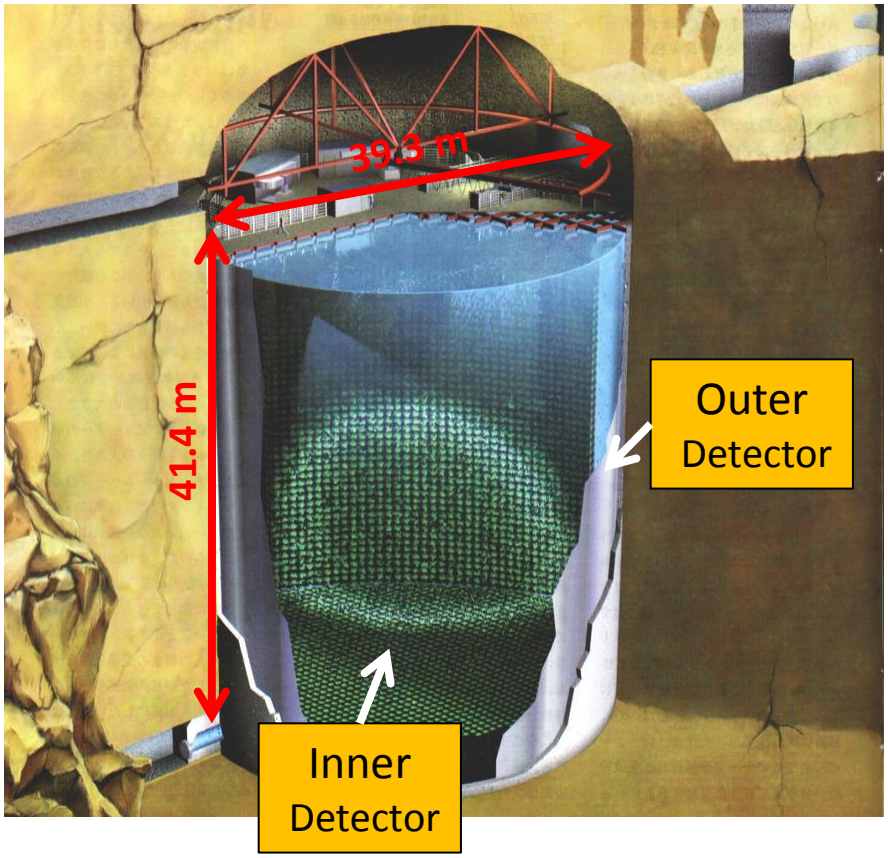
First large-size TPCs based on MPGDs !
(Georges Vasseur's talk)



- *ND280 Tracker provides the most accurate measurement of the ν energy spectrum from CCQE events.*
- *Particle Identification (e, μ, π, p)*

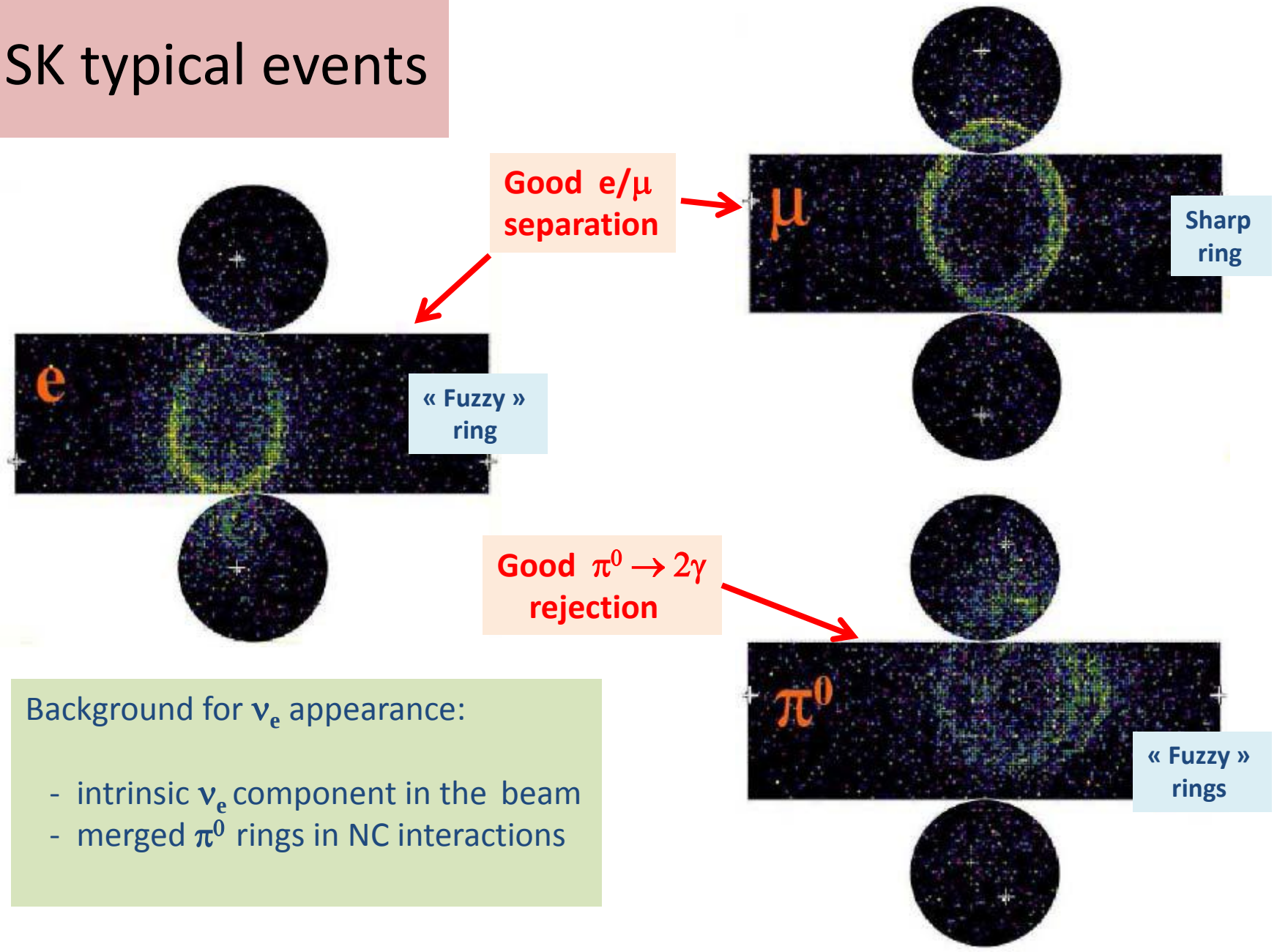
Far detector: Super-Kamiokande (SK-IV)

Mozumi mine



- 50kT Water Cerenkov detector
- Fiducial volume: 22.5kT
- Inner (ID) and Outer (OD) Detectors separated optically
- Inner Detector (ID):
  - 11129 PMTs (ϕ=20in)
  - 40% coverage
- Outer Detector (OD):
  - 1885 PMTS (ϕ=8in)
- SK-IV running since Sept. 6th / 2008 with new front-end electronics
- Excellent e/μ separation (< 1%)

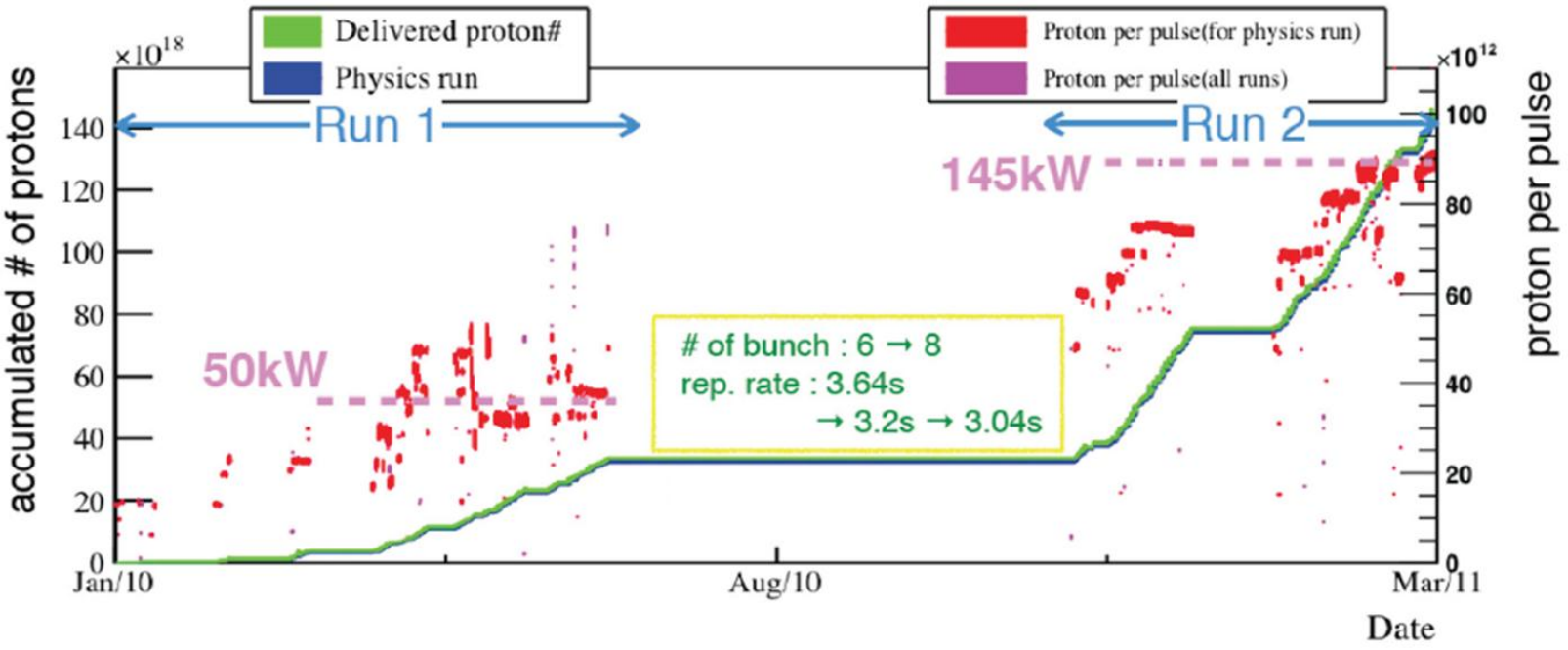
SK typical events



Background for ν_e appearance:

- intrinsic ν_e component in the beam
- merged π^0 rings in NC interactions

Data taking



- Data taking for physics started in January 2010 and ended on March 11th, 2011 due to the earthquake.
- At the end of Run 2, stable operation at 145 kW was achieved.
- Run1 + Run 2 total dataset : **1.43 x 10^{20} POT** (protons on target). This amount of data represents **~2%** of the T2K proposal goal.

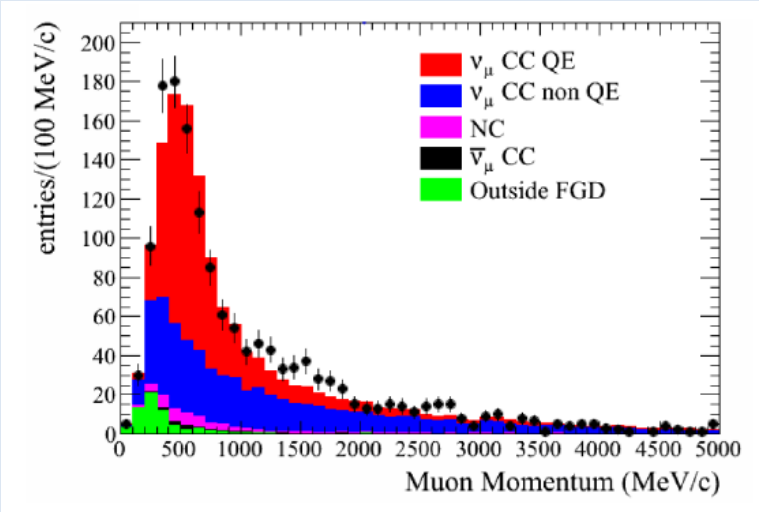
Oscillation Analysis Strategy

- To measure appearance/disappearance probabilities , need to compute the expected number of events at SK
- Use ND280 off-axis detector as normalization to reduce systematics from beam flux, ν cross-sections

Number of events at SK computed by Monte Carlo
(depends on beam flux, cross sections, input oscillation parameters, detector efficiencies ...)

Expected number of events at SK

$$N_{SK}^{exp} = \frac{N_{ND}^{\mu,data}}{N_{ND}^{\mu,MC}} \times N_{SK}^{MC}$$



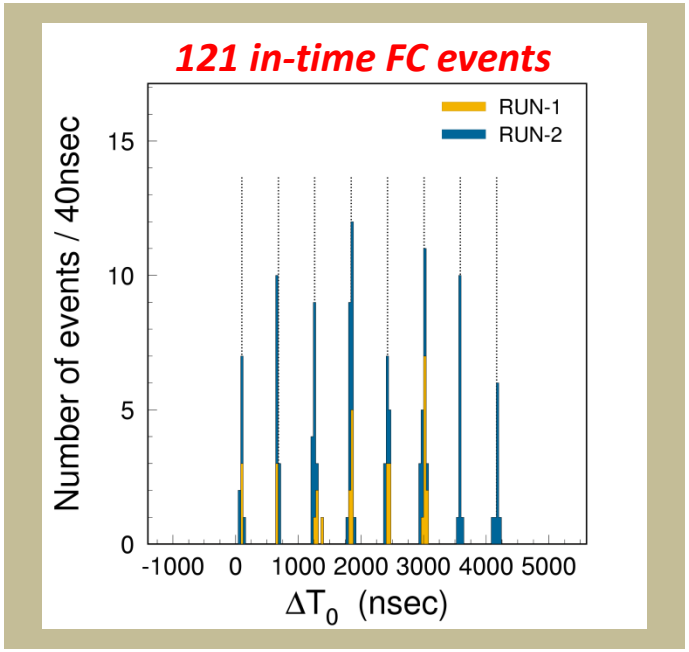
Measurement of ν_μ inclusive CC interactions in the ND280 Tracker from Run 1

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

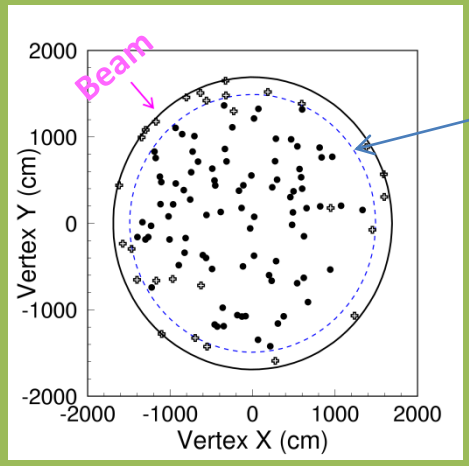
ν_μ disappearance

ν_μ selection at SK

- Selection cuts tuned using MC and atmospheric data
- Time cut : -2 to +10 μs window on GPS time, synchronized between J-PARC and SK

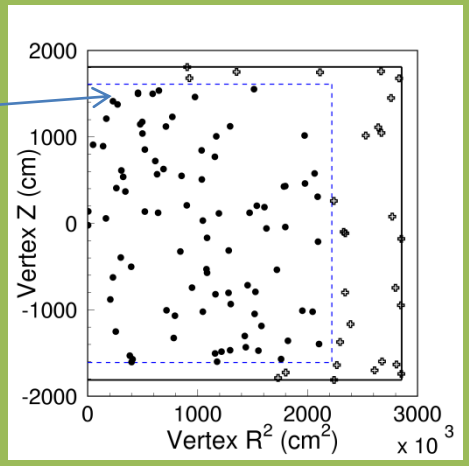


Select fully contained (FC) events in the fiducial volume (FV)
No activity in Outer Detector (OD)



Fiducial Volume

FC events (E_{vis} > 30 MeV)



Enriched sample of CCQE ν_μ interactions

MC events normalized to POT

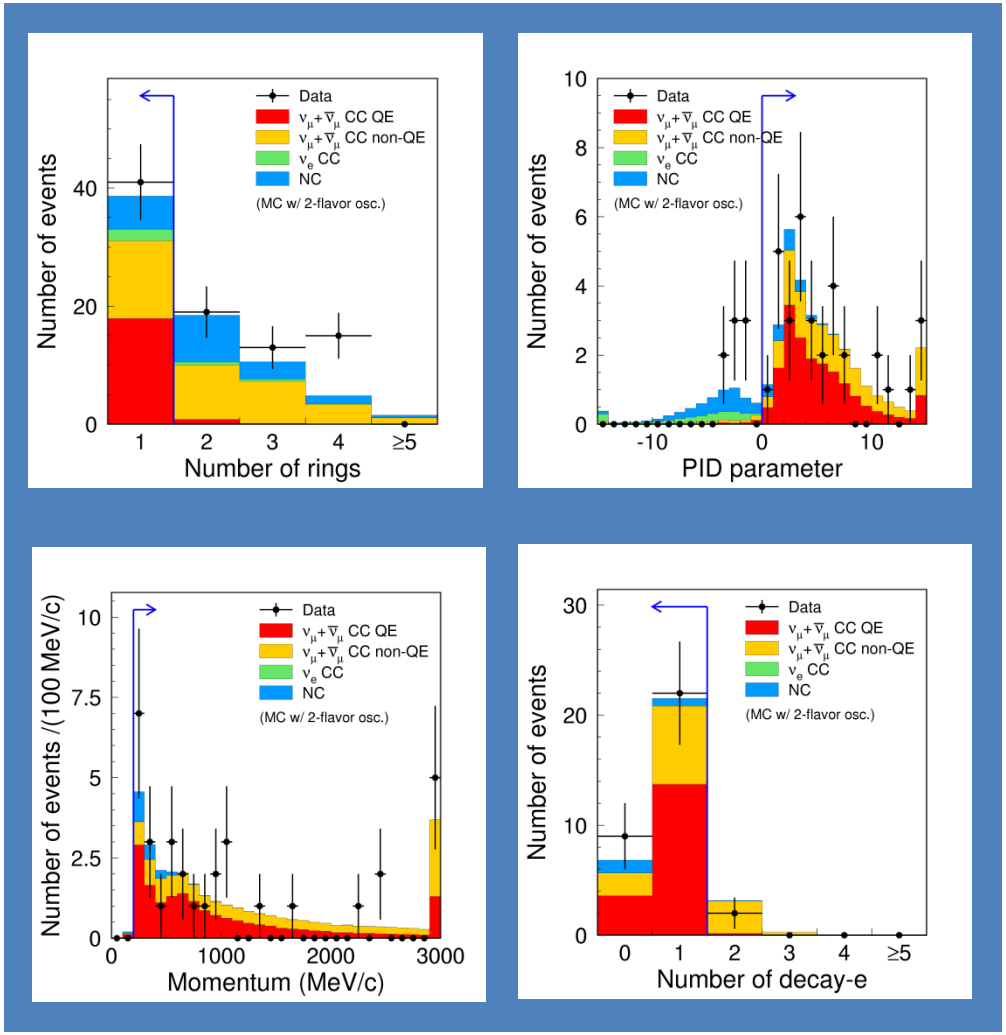
$\sin^2 2\theta_{23} = 1.0$, $\Delta m^2_{23} = 2.4\times10^{-3}$ eV^2

	Data	MC w/ 2-flavor oscillation					MC w/o osc.
		Total	ν_μCCQE	ν_μCC non-QE	ν_eCC	NC	
Interaction in FV	-	141	24.0	43.7	3.2	71.0	243
FCFV	88	74.1	19.0	33.8	3.0	18.3	166
Single-ring	41	38.7	17.9	13.1	1.9	5.7	120
μ-like	33	32.0	17.6	12.4	< 0.1	1.9	112
P_μ > 200 MeV/c	33	31.8	17.5	12.4	< 0.1	1.9	111
N(decay-e) ≤ 1	31	28.4	17.3	9.2	< 0.1	1.8	104
Efficiency	-	20 %	72 %	21 %	0.4 %	3 %	43 %

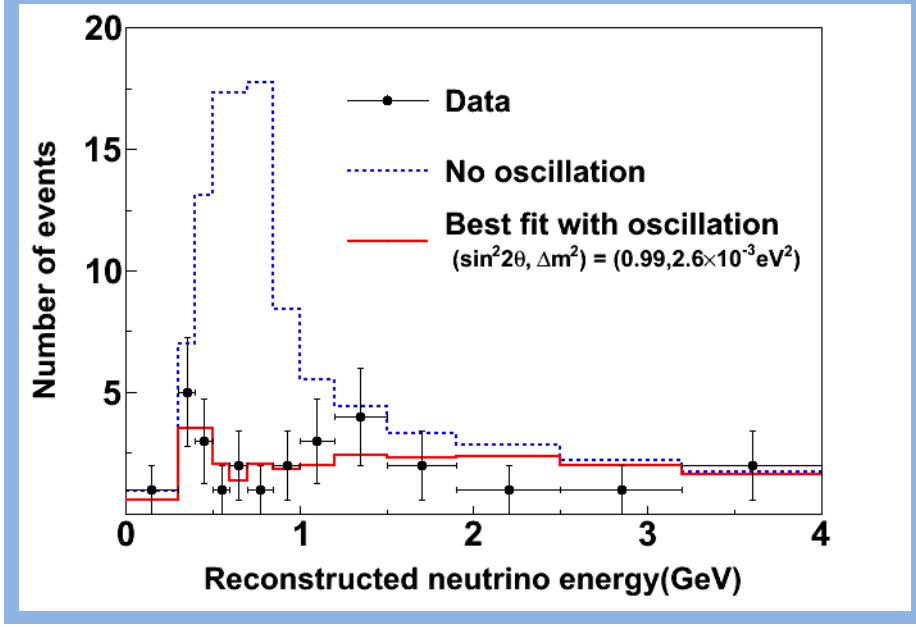
31 remaining events after all cuts

- CCQE efficiency : 72%
- CCQE purity : 61%

Expect 104 ± 17 events if no oscillation!



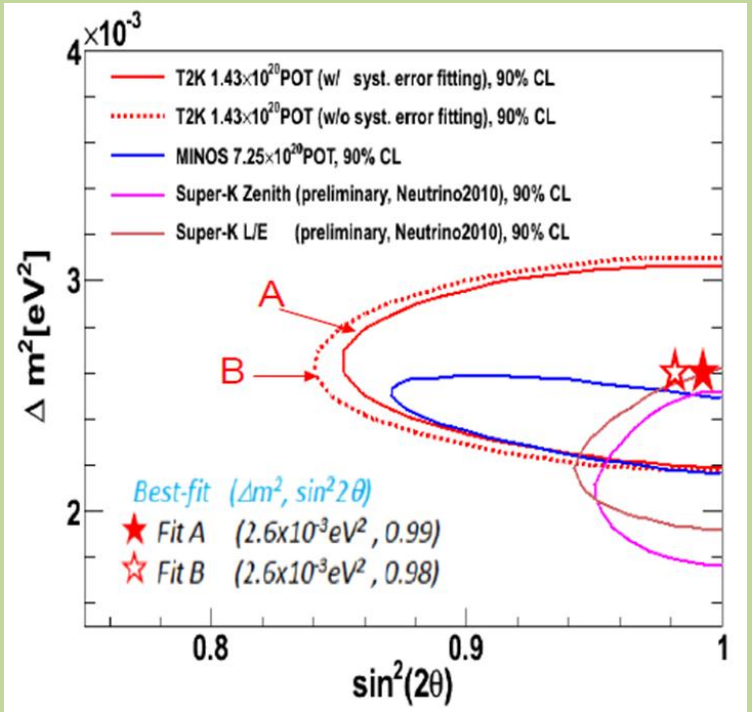
ν_μ disappearance results



Disappearance clearly observed in the ν energy distribution.

Shows power of off-axis technique!

No oscillation hypothesis excluded at 4.5 σ



T2K fits are consistent with SK (atmospheric) and MINOS (accelerator) results

Publication in preparation

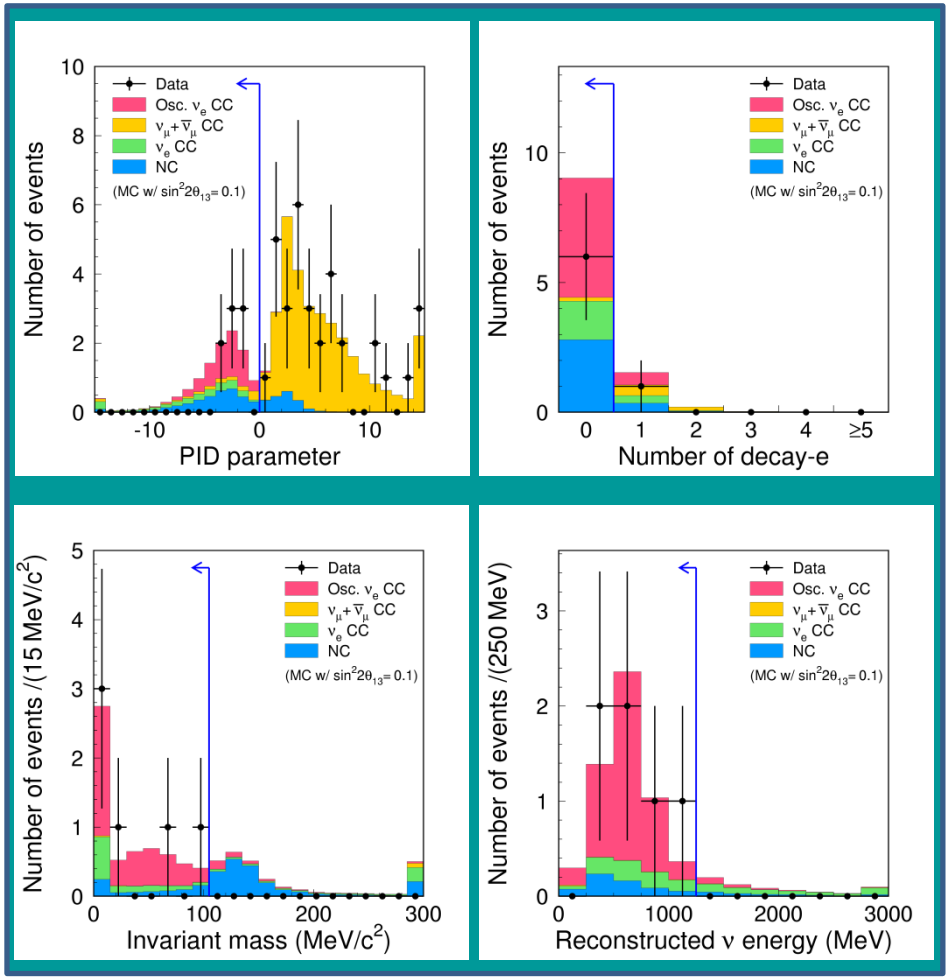
ν_e appearance

ν_e selection

$|\Delta m^2_{23}| = 2.4 \times 10^{-3}$ eV², $\sin^2(2\theta_{23}) = 1$ and $\delta_{CP} = 0$

Expected N_{SK} for $\sin^2 2\theta_{13} = 0.1$

	Data	BG expectation				$\nu_\mu \rightarrow \nu_e$ expect.
		Total	ν_μCC	ν_eCC	NC	
Interaction in FV	-	141.3	67.2	3.1	71.0	6.2
FCFV	88	73.6	52.4	2.9	18.3	6.0
Single-ring	41	38.3	30.8	1.8	5.7	5.2
e-like	8	6.6	1.0	1.8	3.7	5.2
E_{vis} > 100 MeV	7	5.7	0.7	1.8	3.2	5.1
No decay-e	6	4.4	0.1	1.5	2.8	4.6
M_{inv} < 105 MeV/c²	6	1.9	0.04	1.1	0.8	4.2
E_ν^{rec} < 1250 MeV	6	1.3	0.03	0.7	0.6	4.1
Efficiency	-	1 %	< 0.1 %	23 %	1 %	66 %



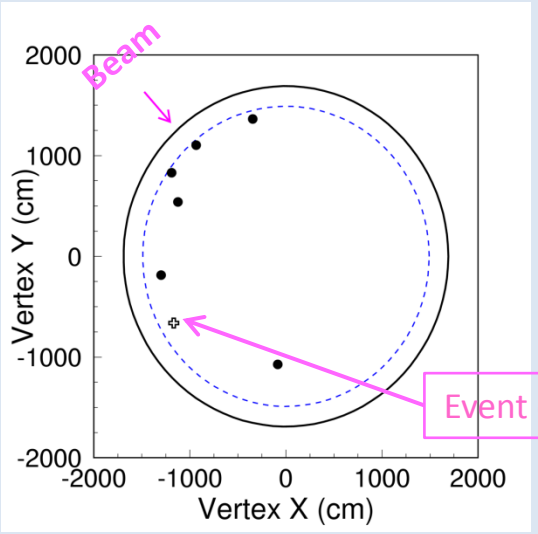
6 candidate events pass all cuts

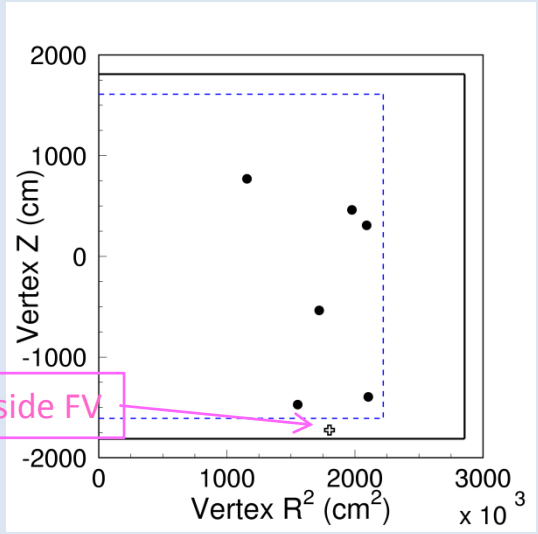
Expected number of events for $\sin^2 2\theta_{13} = 0$:

$N_{SK} = 1.5 \pm 0.3$ (syst) events

ν_e contamination in the beam measured at ND280 to be < 2% at 90% C.L.

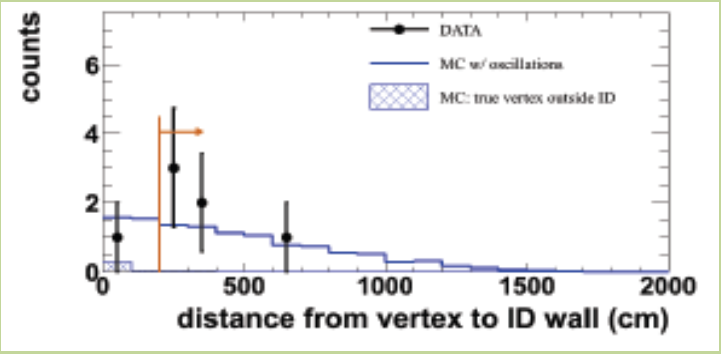
Vertex distribution





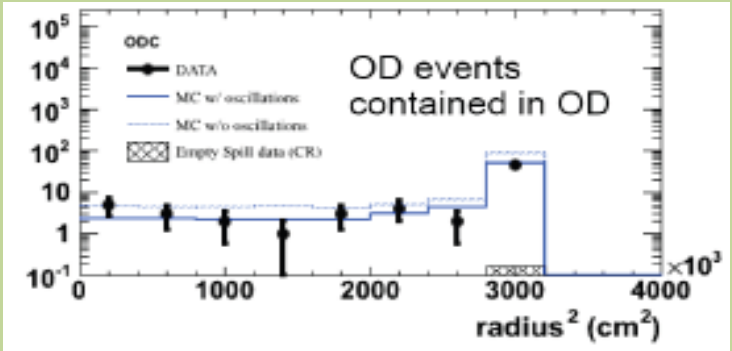
- The candidate events are located at large R
- A Kolmogorov-Smirnov test gives 3% p-value for such a R^2 distribution

Distribution of events outside FV



No indication of background contamination

Distribution of events in Outer Detector



ν_e appearance results

Published in Phys. Rev. Lett. 107 041801 (2011)

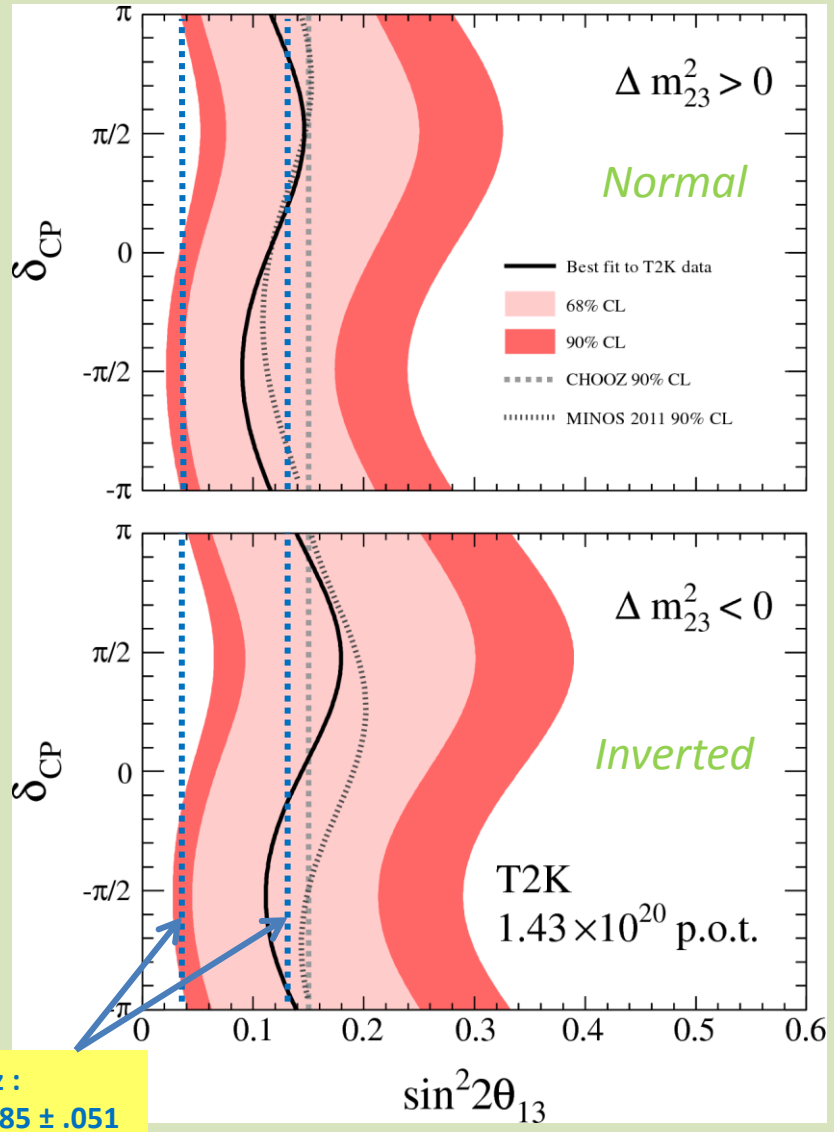
$|\Delta m^2_{23}| = 2.4 \times 10^{-3}$ eV², $\sin^2(2\theta_{23}) = 1$ and $\delta_{CP} = 0$

90% C.L. (Feldman-Cousins method) intervals and best fit values :

Normal: $0.03 < \sin^2(2\theta_{13}) < 0.28$, $\sin^2(2\theta_{13}) = 0.11$

Inverted: $0.04 < \sin^2(2\theta_{13}) < 0.34$, $\sin^2(2\theta_{13}) = 0.14$

Null oscillation disfavored at 2.5σ

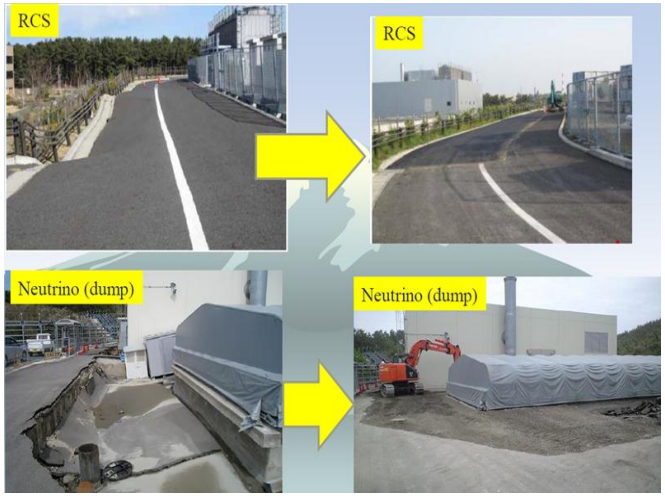


Double Chooz : $\sin^2(2\theta_{13}) = .085 \pm .051$

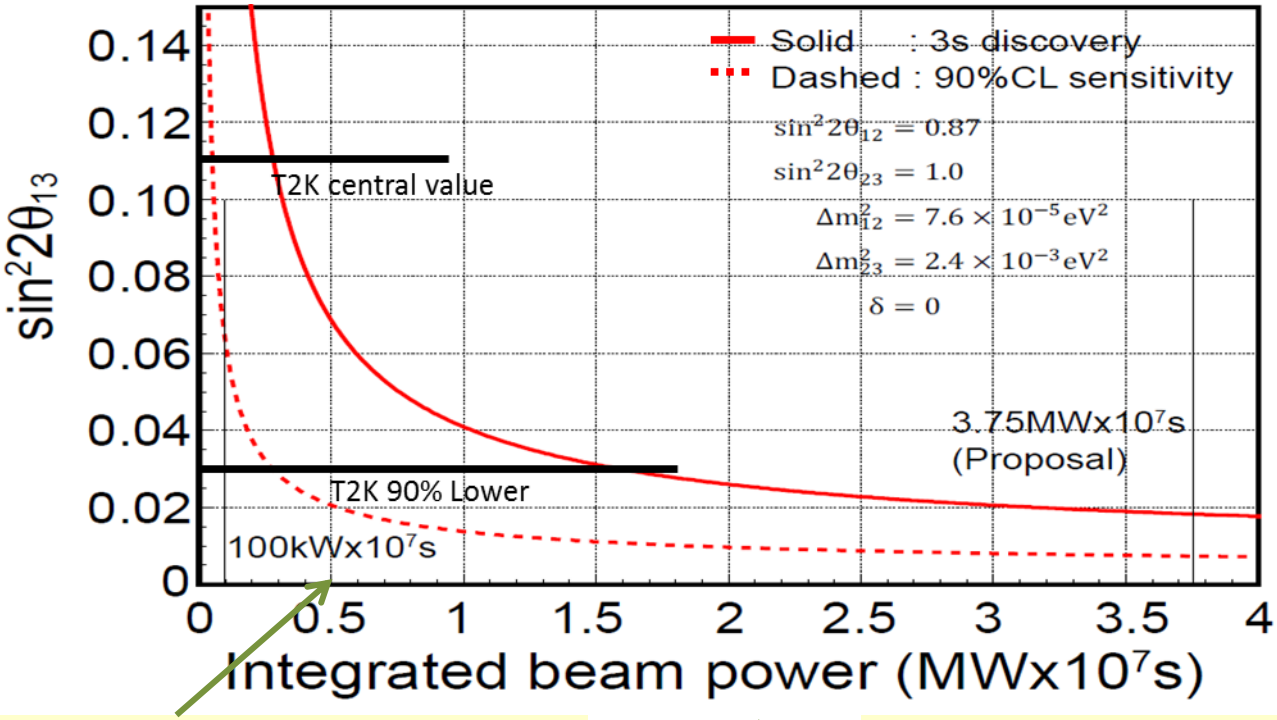
Near future of T2K

- J-PARC has now recovered from March 11th earthquake.
- No serious damage to the accelerator and the ND280 detectors. SK not affected at all.
- Accelerator status :
  - Magnets and beam monitors have been re-aligned.
  - Beam commissioning will start next week.
  - Goal is to restart at 100 kW.
- ND280 status:
  - Detectors under maintenance.
  - All sub-detectors have been tested sucessfully.
  - Magnet open until end of the year.
  - Commissioning will start early in January 2012.

Data taking for physics should resume by end of January 2012



Expected sensitivity to $\sin^2 2\theta_{13}$



Milestone : 10 ^{21} POT (~500kW × 10^{7}s) by summer 2013

Exclusion of $\theta_{13} = 0$ at 5σ at the best fit value of $\sin^2(2\theta_{13}) = 0.11$

The main goal of T2K is the determination of θ_{13}