DBD11 @ Osaka
2011/Nov./15

Results from T2K Experiment

Shigeki Aoki, Kobe Univ.
for T2K collaboration

Neutrino Oscillation

flavor eigenstates

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

mass eigenstates

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

$\neq 0$?

$$U_{MNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

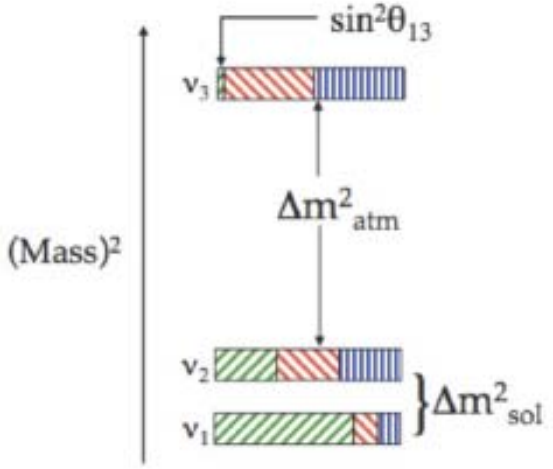
Maki-Nakagawa-Sakata Matrix

"atm. + accel." "reactor + accel." "solar + KamLand"

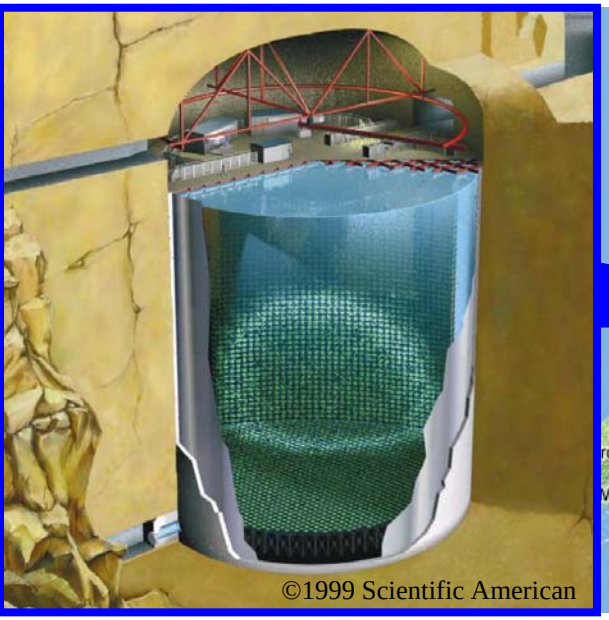
experimental signature using ν_μ beam :

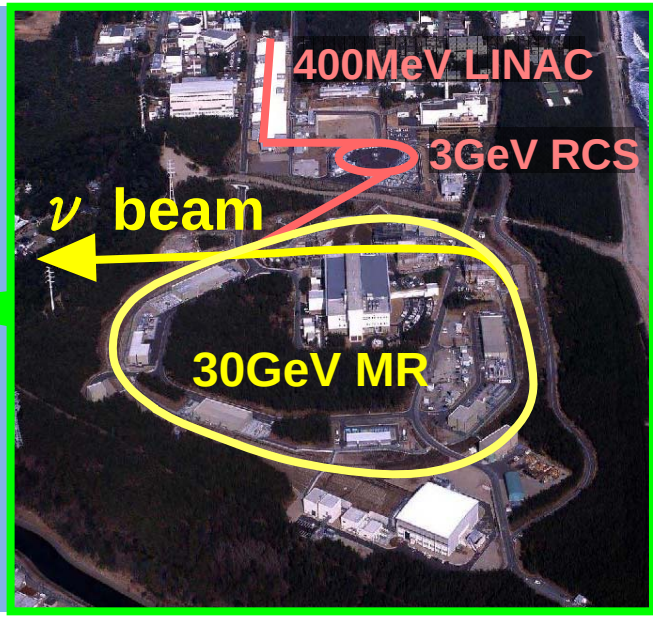
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2\left(1.27\Delta m^2{}_{23}[\mathrm{eV}^2]\frac{L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin\theta_{23} \sin^2\left(1.27\Delta m^2{}_{23}[\mathrm{eV}^2]\frac{L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$



T2K (Tokai-to-Kamioka) Experiment





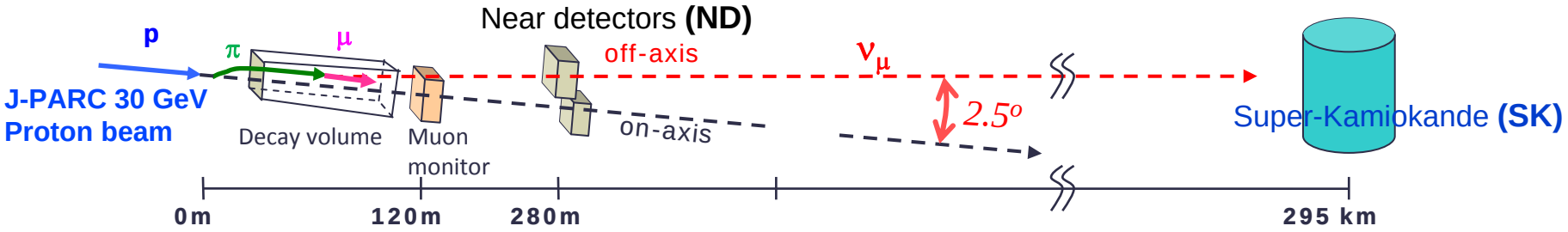
Super Kamiokande
(Far Detector)

J-PARC @ Tokai
- Accelerator Beam
- Beam Monitors
- Near Detectors

Long Baseline Neutrino Oscillation Experiment

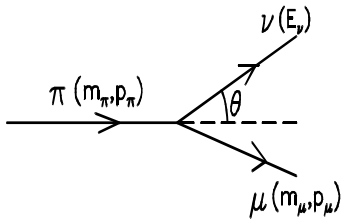
- Search for $\nu_\mu \rightarrow \nu_e$ appearance
  Aim to measure θ_{13}
  ~10 times better sensitivity than CHOOZ limit ($\sin^2 2\theta_{13} < 0.15$)
- Precise measurements of oscillation parameters via ν_μ disappearance
  $\delta(\Delta m^2_{23}) \sim 1 \times 10^{-4}$ eV^2, $\delta(\sin^2 2\theta_{23}) \sim 0.01$

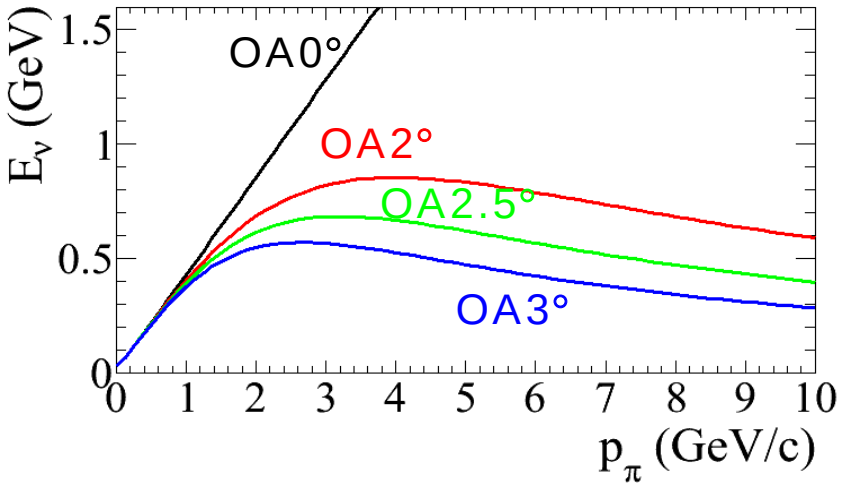
Off-axis beam

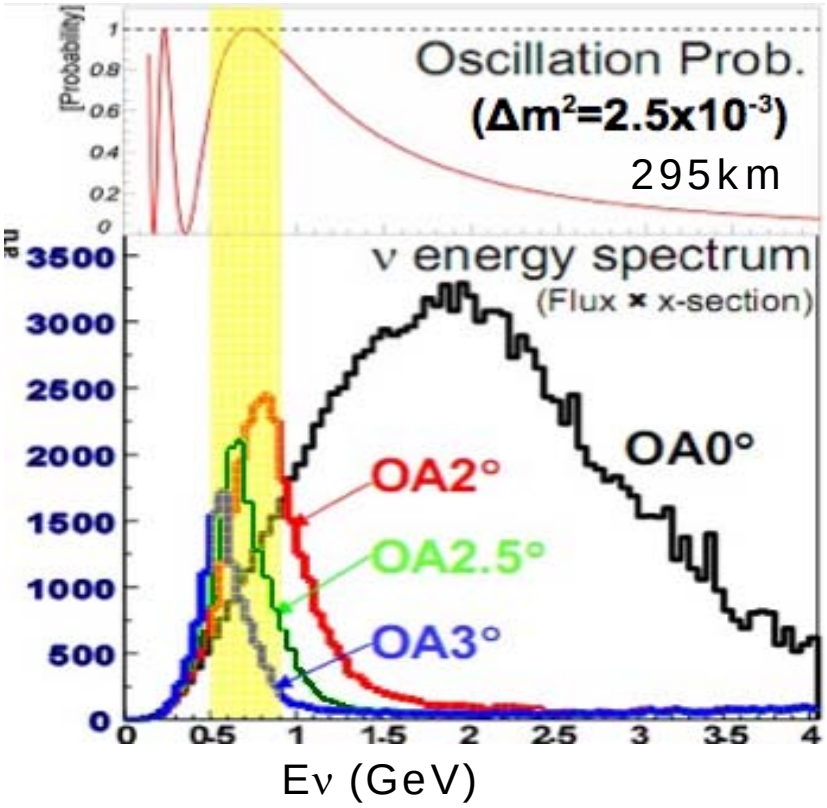


- Intense, narrow-band beam
- Peak Eν tuned for oscillation max. (~0.6 GeV)
- Reduce BG by π^0 from high energy tail
- Important to watch and keep beam direction

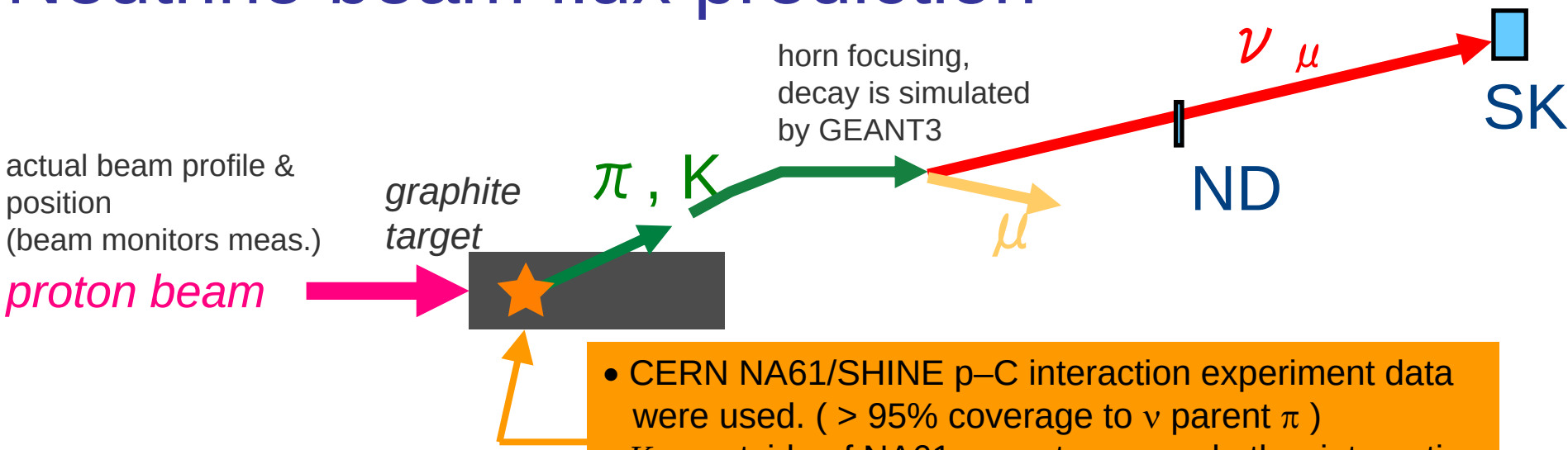
pion decay kinematics



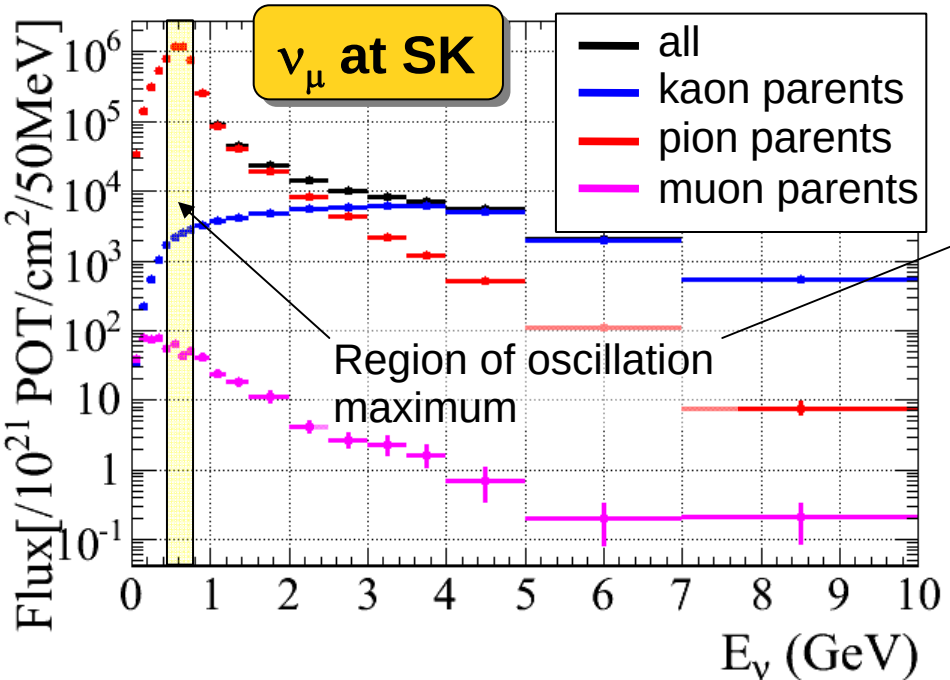


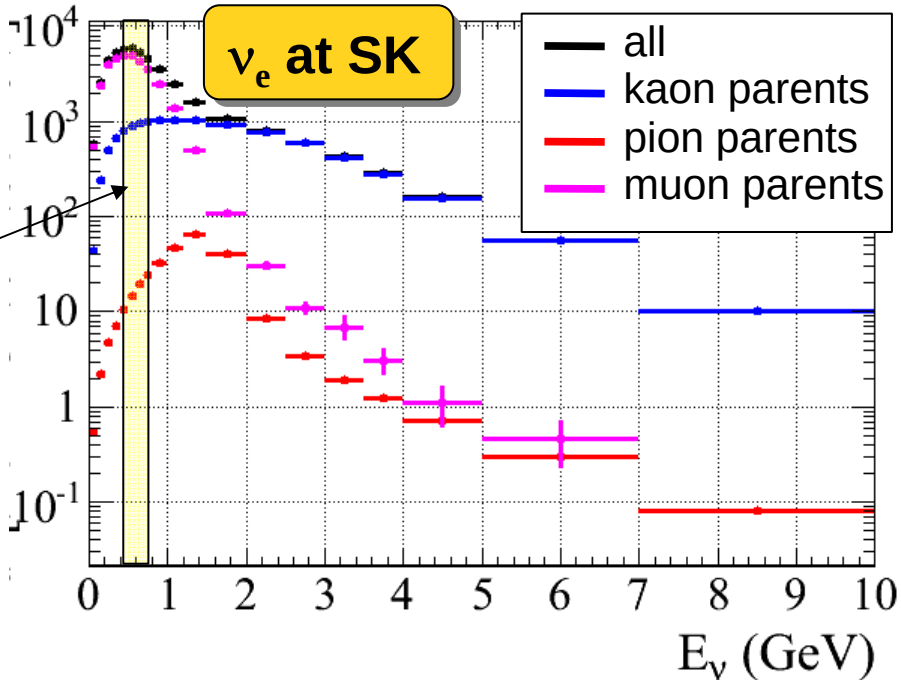


Neutrino beam flux prediction

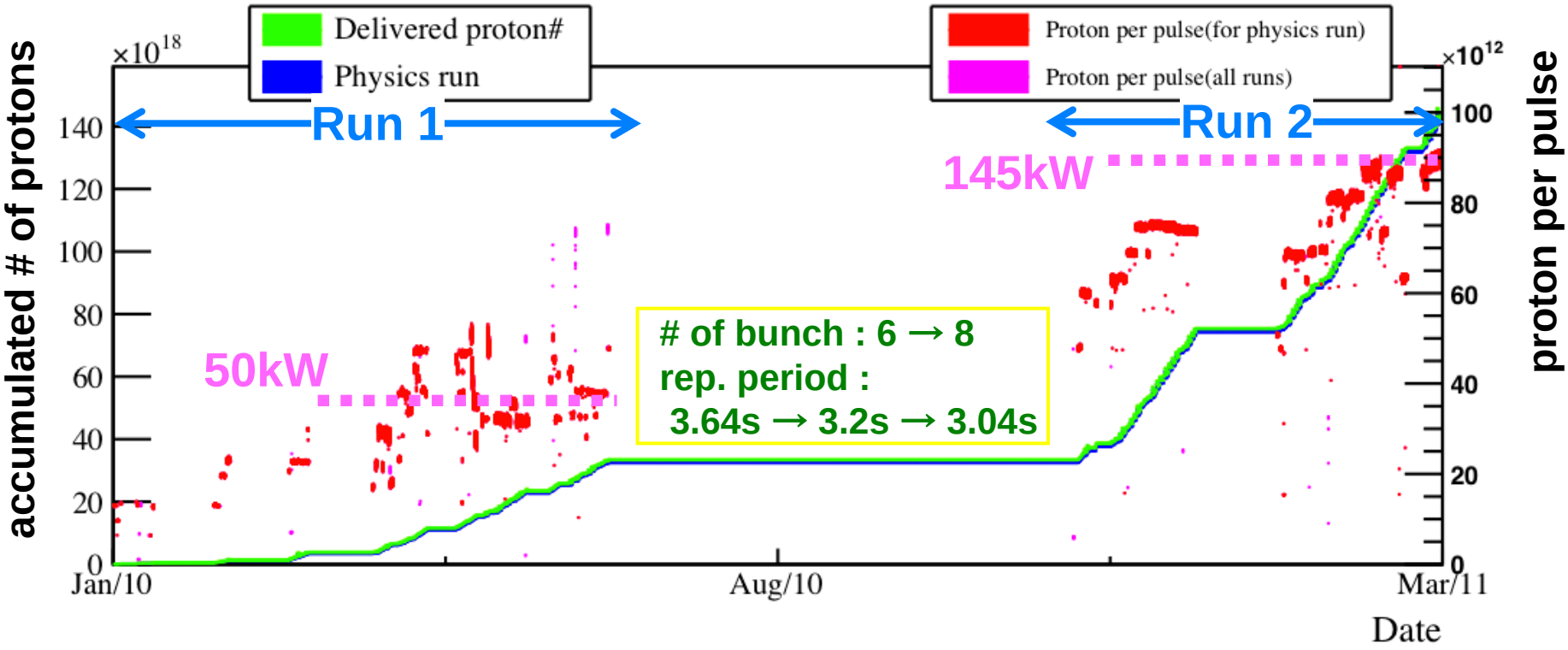


- CERN NA61/SHINE p–C interaction experiment data were used. (> 95% coverage to ν parent π)
- K, π outside of NA61 acceptance, and other interaction in the target were simulated using FLUKA.





Data Taking



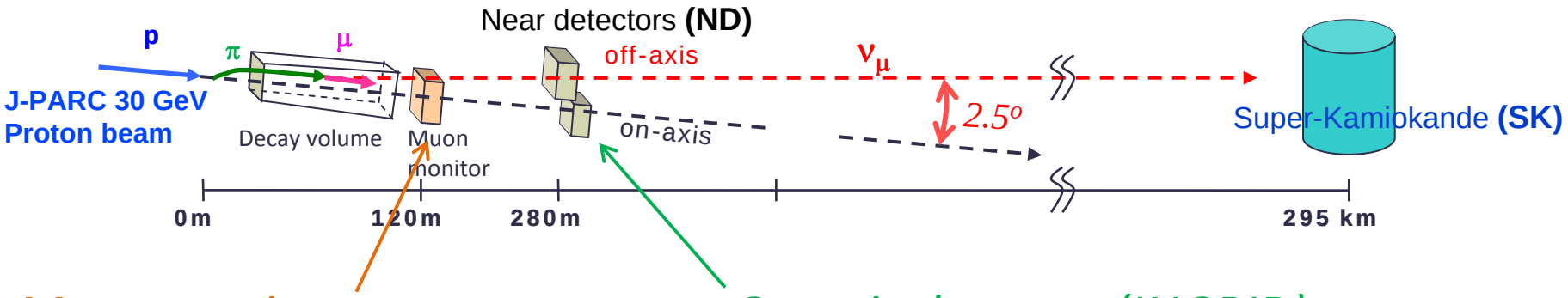
Run 1 (Jan. ’10 - June ’10)

- 3.23 x 10^{19} p.o.t. for analysis
- 50kW stable beam operation

Run 2 (Nov. ’10 - Mar. ’11)

- 11.08 x 10^{19} p.o.t. for analysis
- ~145kW beam operation

1.43 x 10^{20} POT is used for current analysis (2% of T2K’s final goal)

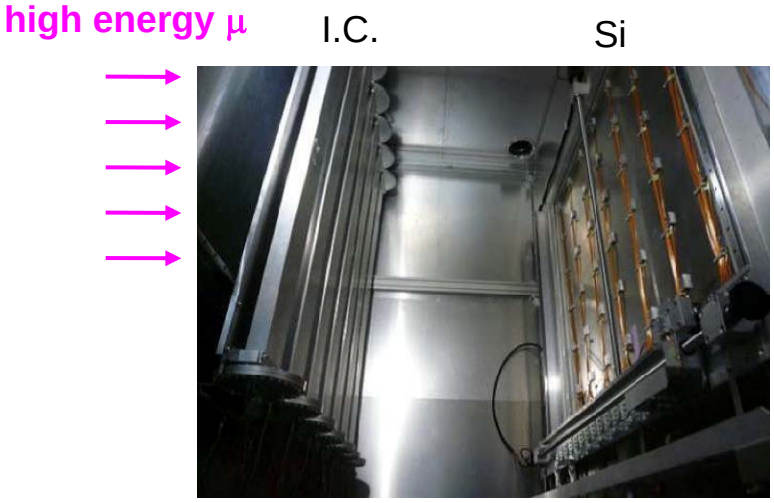


Muon monitor

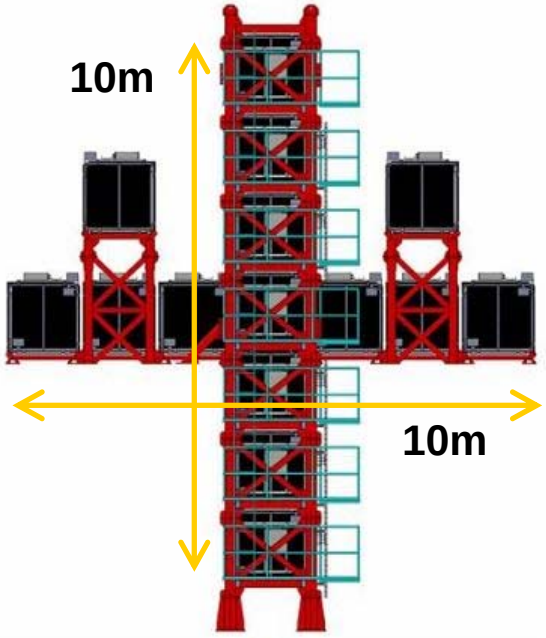
- Si detector + Ionization Chamber
  7×7 array covers 1.5m × 1.5m
- Monitor intensity and profile spill-by-spill

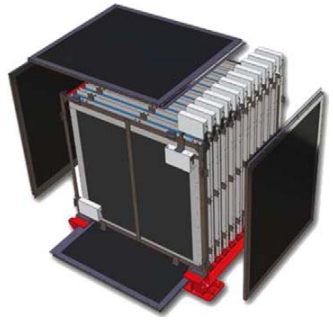
On-axis detector (INGRID)

- Iron + Scintillator detector
  7 (horiz.) + 7 (vert.) + 2 modules
- Monitor ν beam (direction & flux) day-by-day



Muon monitor

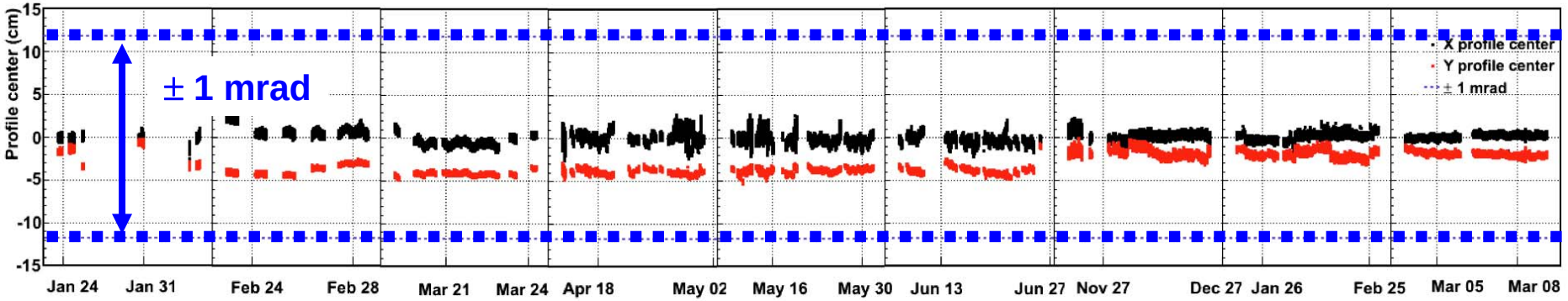




7 ton / module

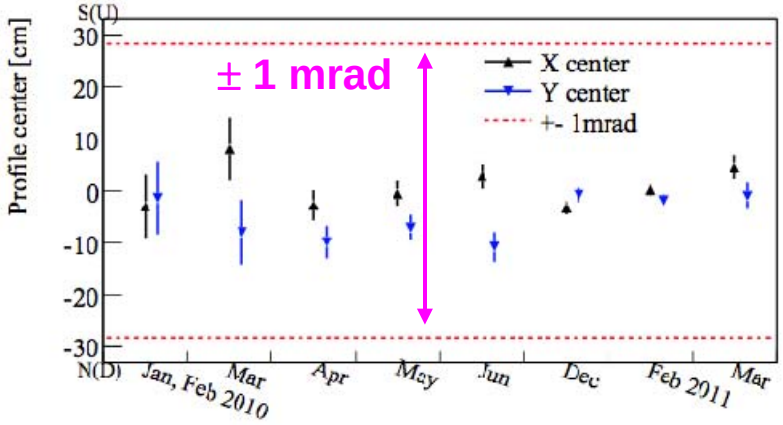
ν beam stability

Muon monitor : Stability of the beam direction

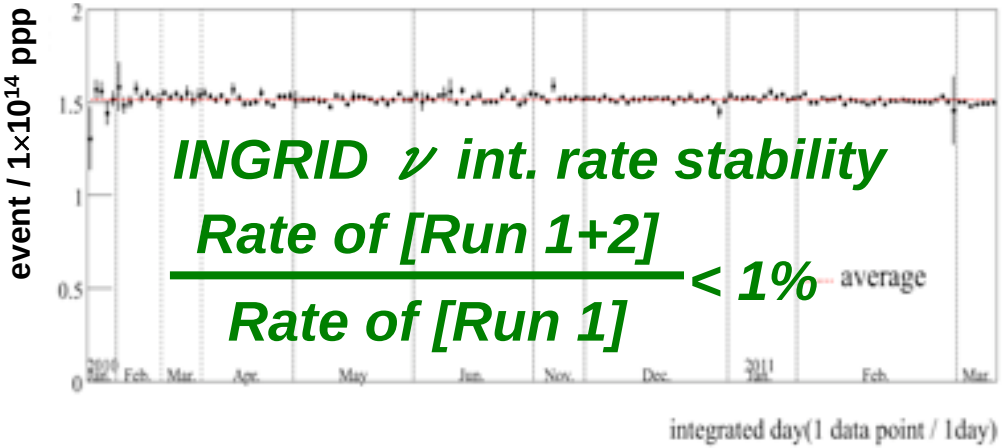


INGRID :

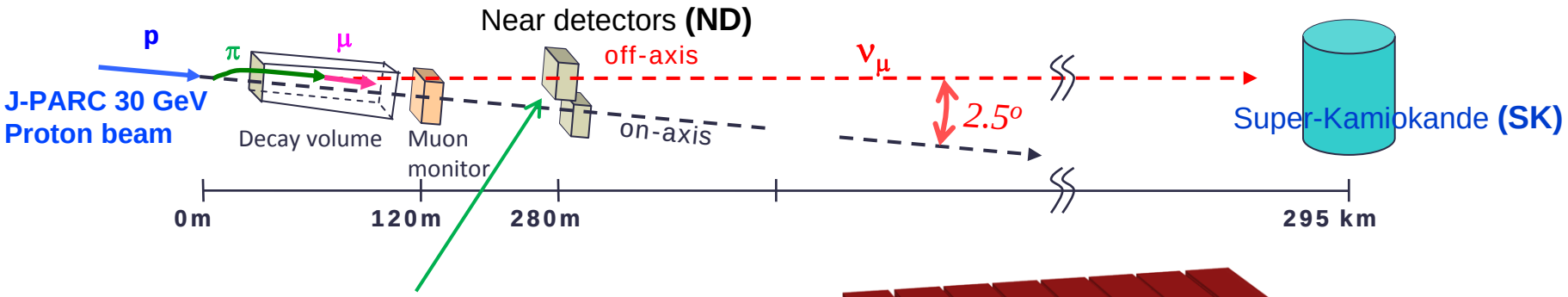
Stability of ν beam direction



Stability of ν interaction rate normalized by # of protons

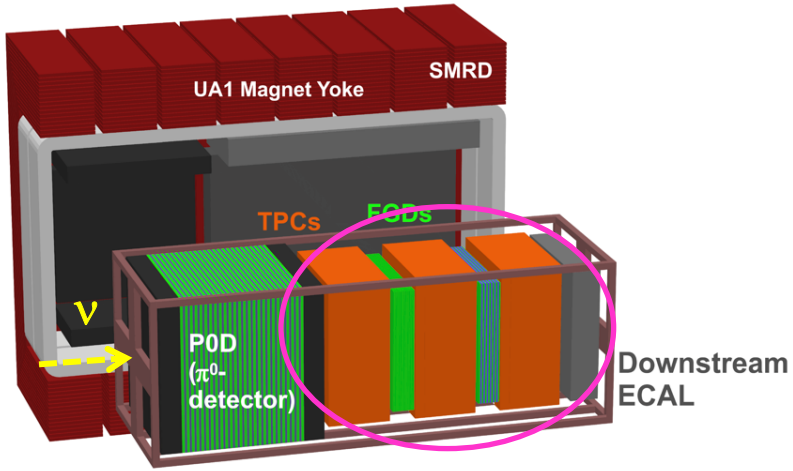


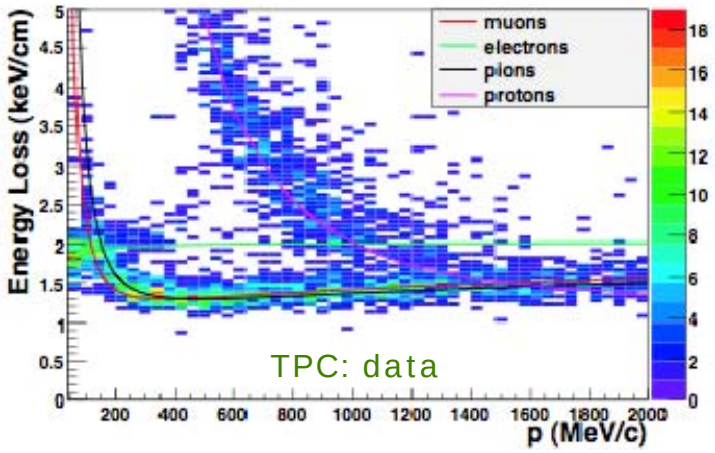
ν beam direction and interaction rates were stable.

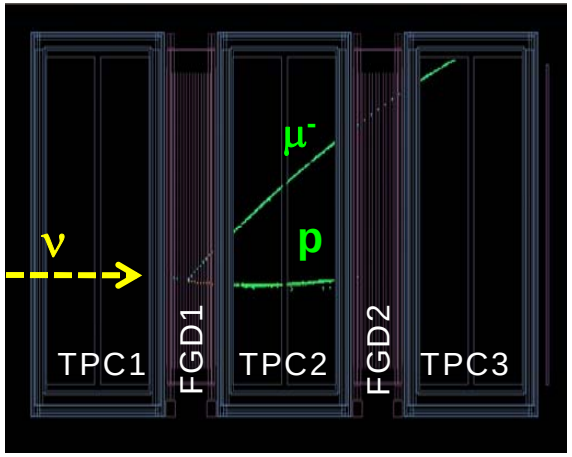


Off-axis detector (ND280)

- Predict interaction rate w/o oscillation
- Fine grained detector (FGD)
  full active for ν int. w/ FV 1.6 ton
- 0.2 T UA1 magnet
- Time projection chamber (TPC)
  Particle ID by dE/dx in gas







Beam measurement at ND280

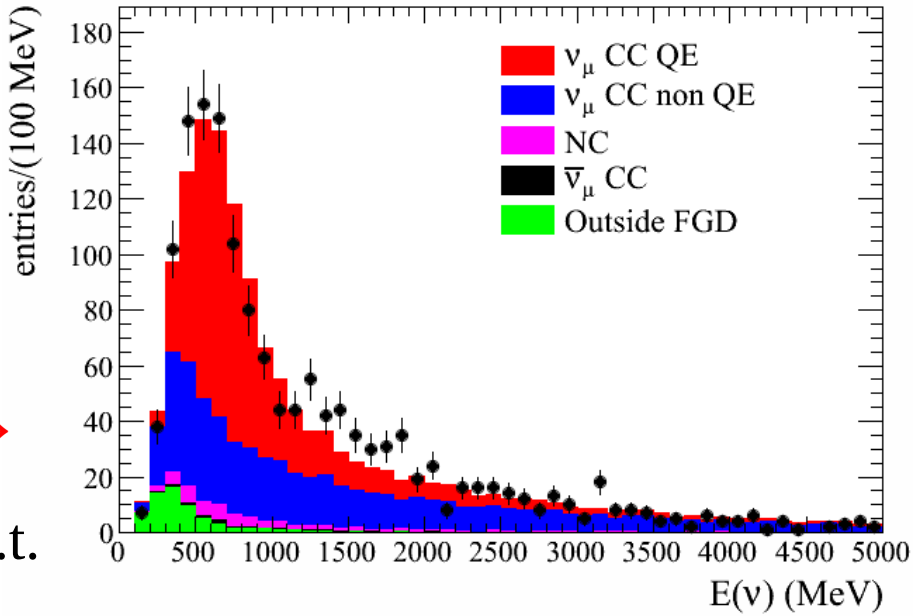
of event expected at SK
without oscillation

$$N_{SK}^{\exp} = N_{SK}^{MC} \frac{R_{ND}^{\mu,\,Data}}{R_{ND}^{\mu,\,MC}}$$

Input number for
oscillation analysis

- **ν_μ inclusive measurement**

  Select events starting in the FGD FV with most energetic negative track identified as μ .
  (90% purity, 38% efficiency)



Data is consistent with MC →

$$R_{ND}^{\mu,\,Data} = 1529 \text{ events} \,/\, 2.9\times10^{19} \text{ p.o.t.}$$

$$\frac{R_{ND}^{\mu,\,Data}}{R_{ND}^{\mu,\,MC}} = 1.036 \pm 0.028\,(\text{stat.}) \,{}^{+0.044}_{-0.037}\,(\text{det.syst.}) \pm 0.038\,(\text{phys. syst.})$$

Beam measurement at ND280

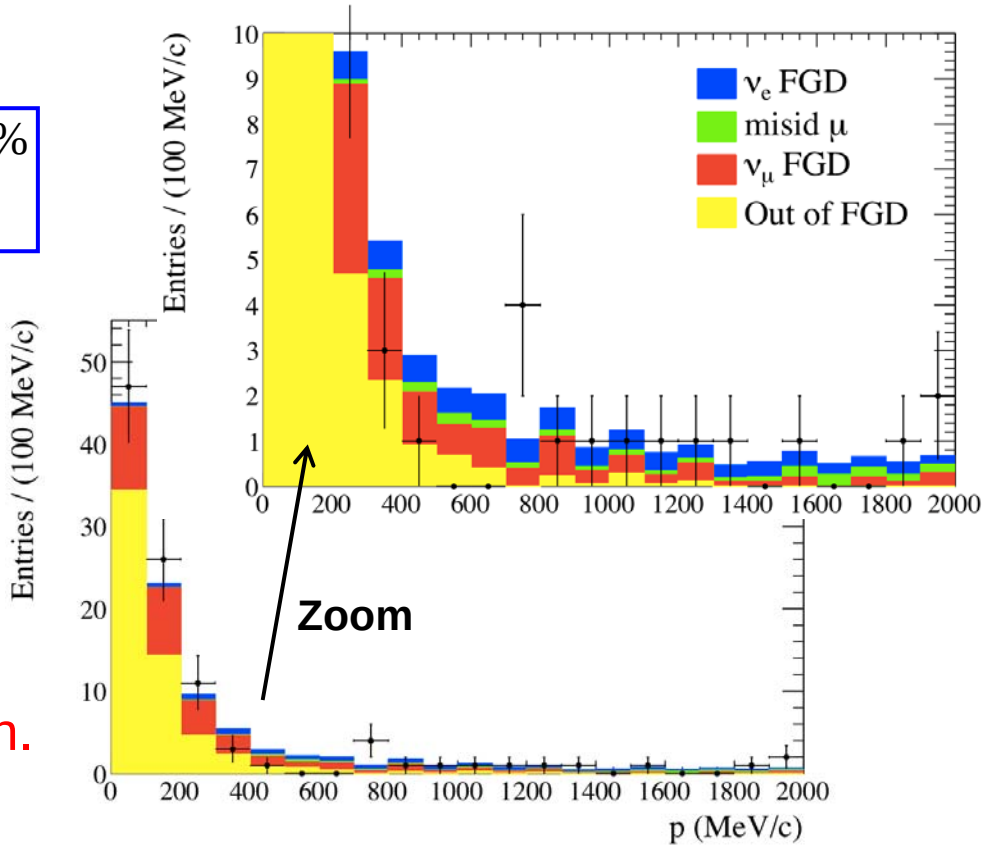
- **ν_e inclusive measurement**

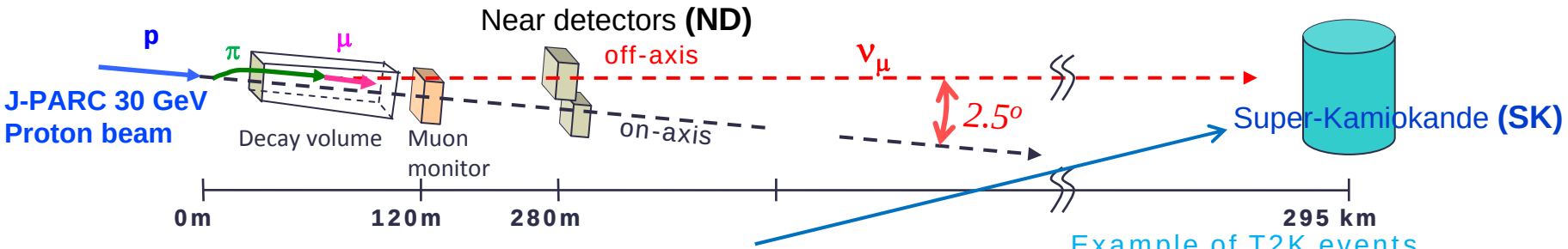
Select electrons by PID from TPC.
BG from mis-ID μ estimated using sand-μ data.
BG from γ conversion constrained by control sample (data).

$$R(\nu_e/\nu_\mu) = (1.0 \pm 0.7(\text{stat.}) \pm 0.3(\text{syst.}))\,\%$$
$$< 2.0\,\% \quad @\ 90\%\ \text{C.L.}$$

$$\frac{(N_{\nu_e}/N_{\nu_\mu})^{\text{Data}}}{(N_{\nu_e}/N_{\nu_\mu})^{\text{MC}}} = 0.6 \pm 0.4(\text{stat.}) \pm 0.2(\text{syst.})$$

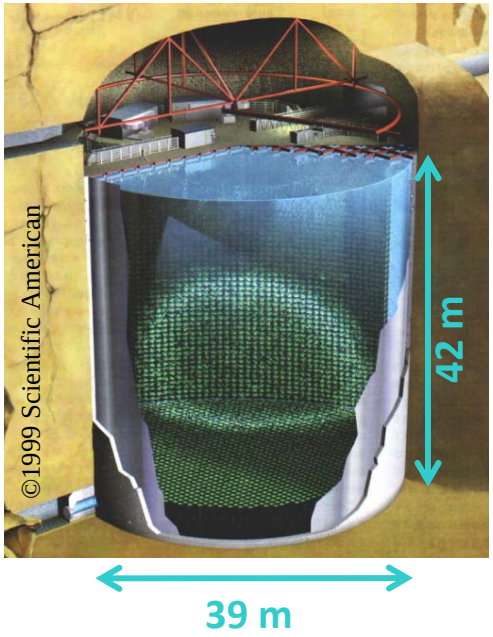
Measured ν_e/ν_μ ratio is consistent with MC expectation.



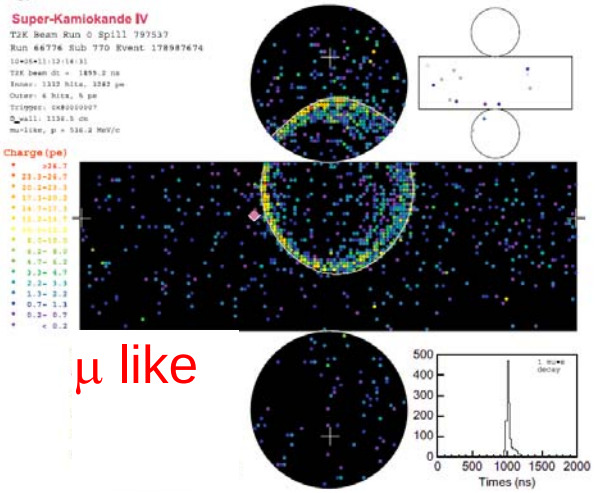


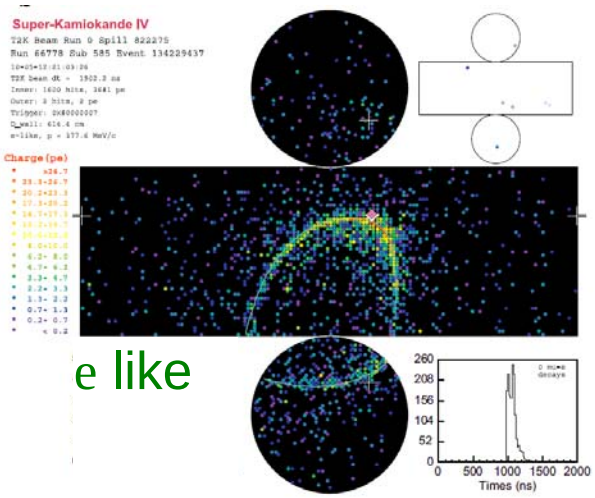
Far detector (Super-Kamiokande)

- Water Cherenkov detector w/ FV 22.5 kton
- Dead Time less DAQ (2008 ~)
- Excellent particle ID for μ/e particle with ~99% efficiency



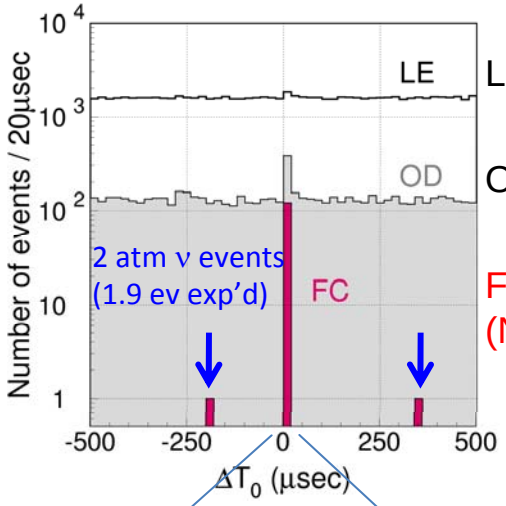
Example of T2K events





SK events

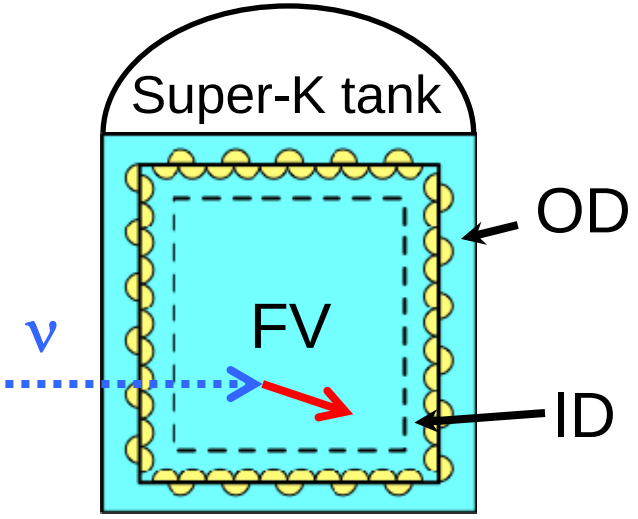
Event timing w.r.t. beam spill



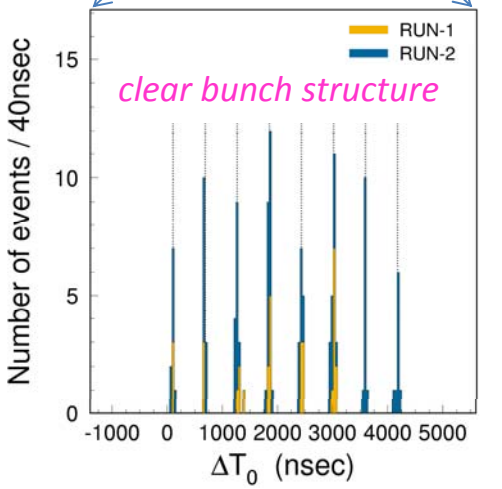
LE : Low Energy events

OD : hits in Outer Detector

FC : Fully Contained
(No activity in Outer Detector)



FV : Fiducial Volume
> 2m from wall

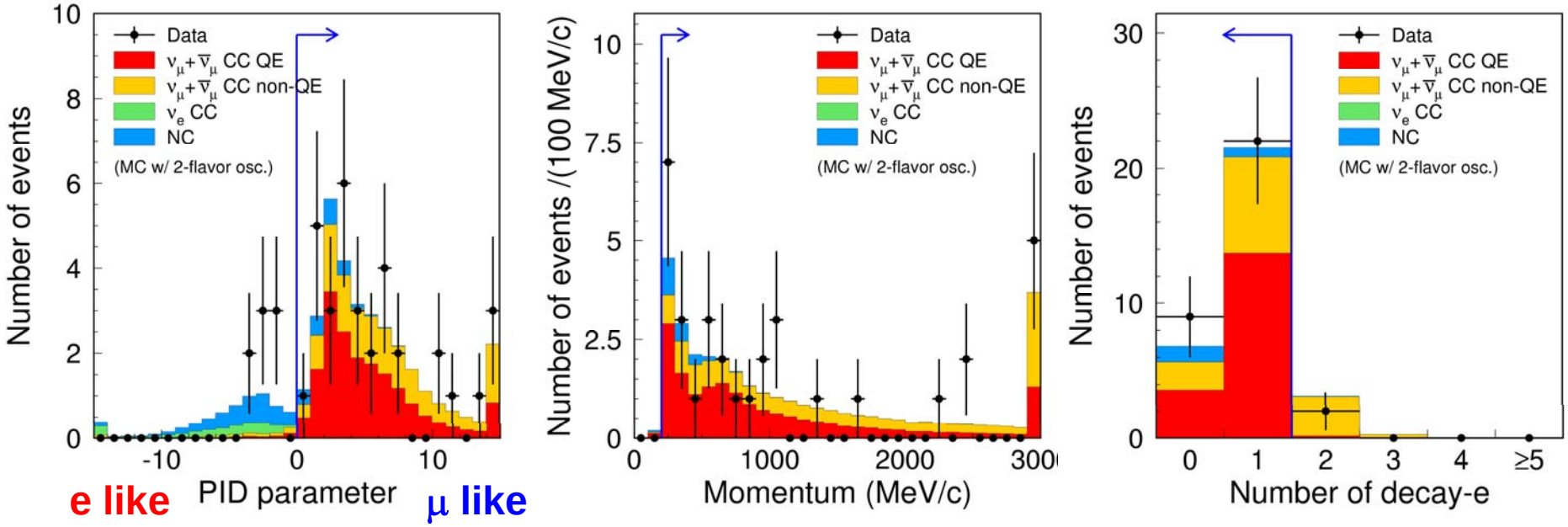


121 events detected

Criteria				# of events	
Fully Containd & beam timing				121	
(FC)	Vertex in FV	total		88	
	(FCFV)	Single Ring	μ-like	33	→ ν_μ cand.
			e-like	8	→ ν_e cand.
		Multi Ring		47	

$\Delta T_0 = T_{GPS}$@SK - T_{GPS}@J-PARC - TOF_c(~985 μ sec)

ν_μ disappearance analysis



Cut Sequence for ν_μ CCQE

Criteria	# of events
single ring μ-like	**33**
muon momentum p_μ > 200 MeV/c	**33**
# of decay electron < 2	**31**

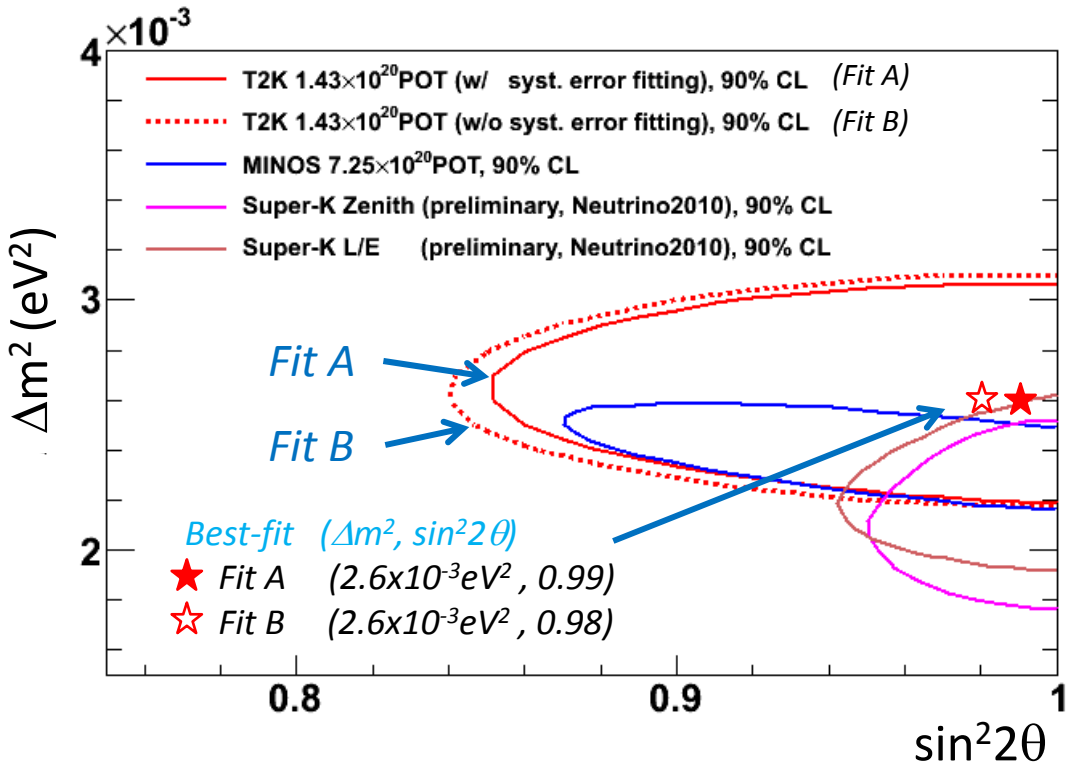
For **null-oscillation** :

103.6 events expected

For **oscillation** with $\sin^2 2\theta_{23}=1$, $\Delta m^2_{23}=2.4\times10^{-3}$ **eV²** :

28.3 events expected

ν_μ disappearance analysis

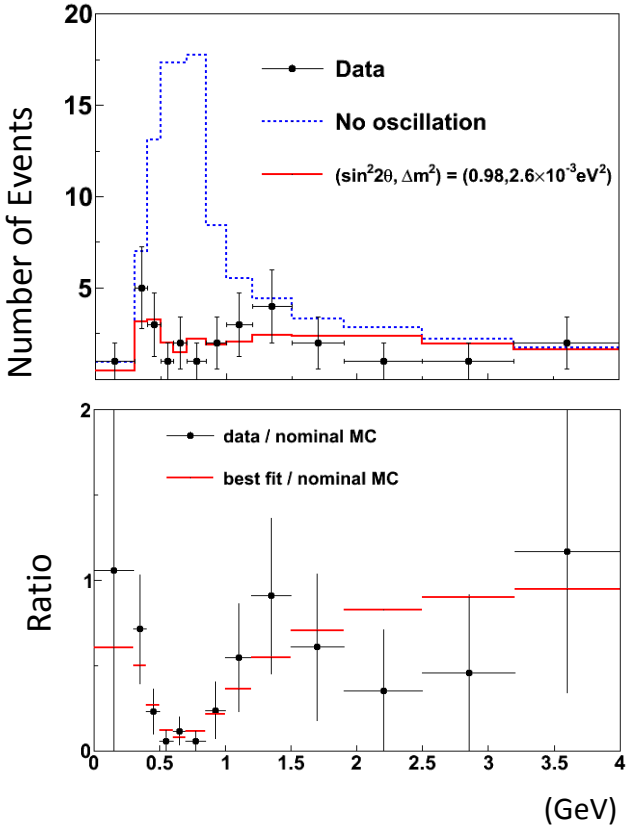


90% C.L. allowed region

	Δm^2 (eV^2)	sin^2(2θ)
Fit A	2.1 ~ 3.1 x 10^{-3}	> 0.85
Fit B	2.1 ~ 3.2 x 10^{-3}	> 0.84

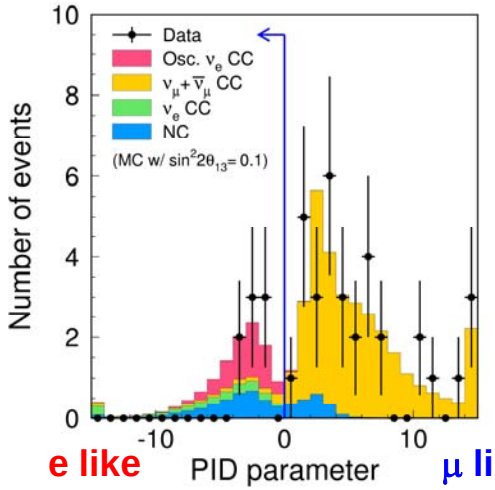
Consistent with MINOS/SK results

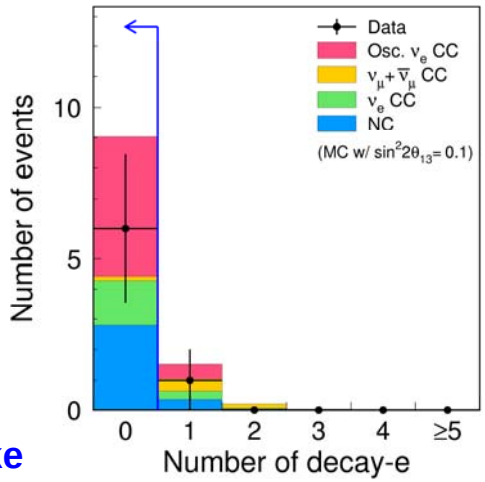
Reconstructed ν energy

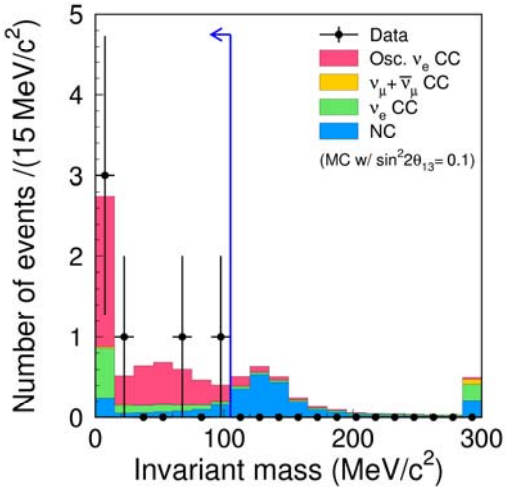


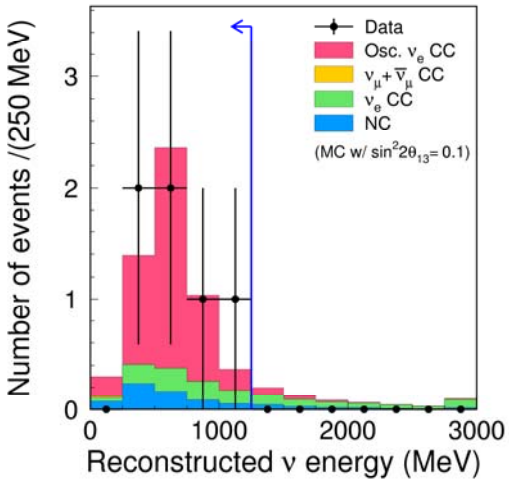
Clear oscillation pattern observed

ν_e appearance analysis









Cut Sequence for ν_e CCQE

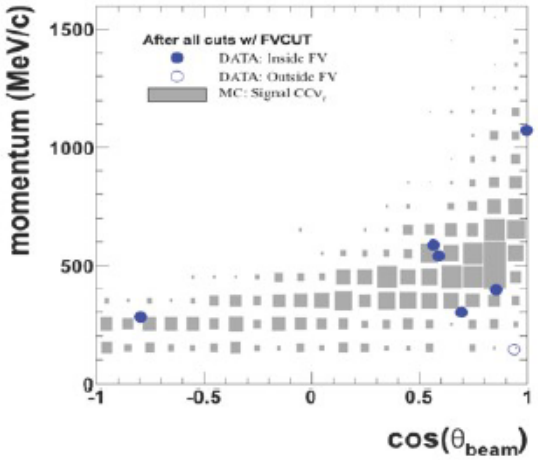
Criteria	# of events
single ring e-like	**8**
E_{vis} > 100 MeV	**7**
No delayed electron	**6**
M_{inv} of 2 ring < 105 MeV/c^2	**6**
$E\nu_{rec}$ < 1250 MeV	**6**

Background breakdown

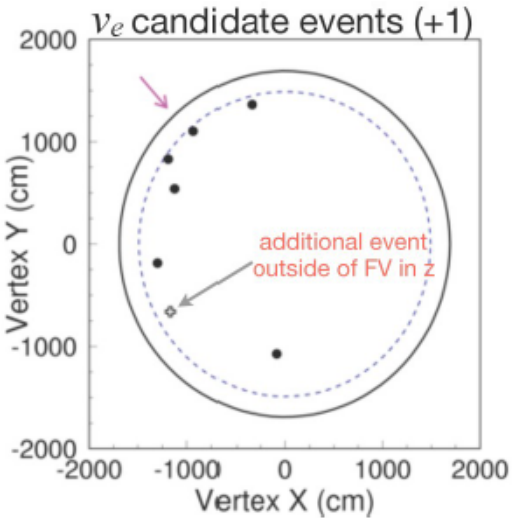
Total	ν_μCC	ν_eCC	NC	solar $\nu_\mu \rightarrow \nu_e$
1.5	0.03	0.8	0.6	0.09

Expected backgrounds: 1.5 ± 0.3

ν_e appearance analysis



Kinematic distribution of nue candidates consistent with numu->nue oscillation



Vertex distribution of nue candidates: KS test of R2 gives 11% probability

6 candidate events with 1.5 expected background

Best fit values:

Normal :

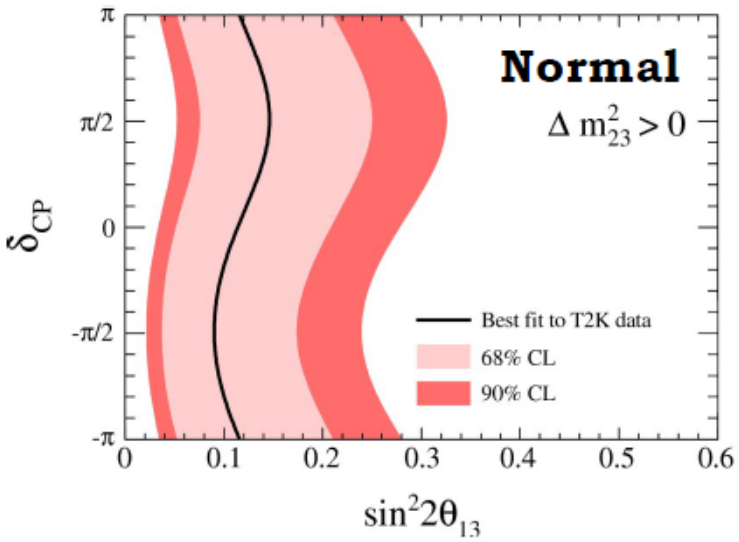
$0.04 < \sin^2 2\theta_{13} < 0.34$

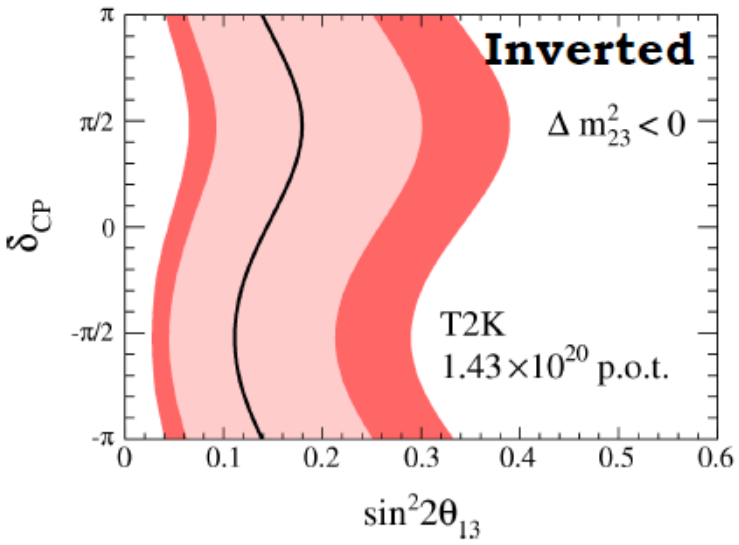
Central value: **0.14**

Inverted :

$0.03 < \sin^2 2\theta_{13} < 0.28$

Central value: **0.11**

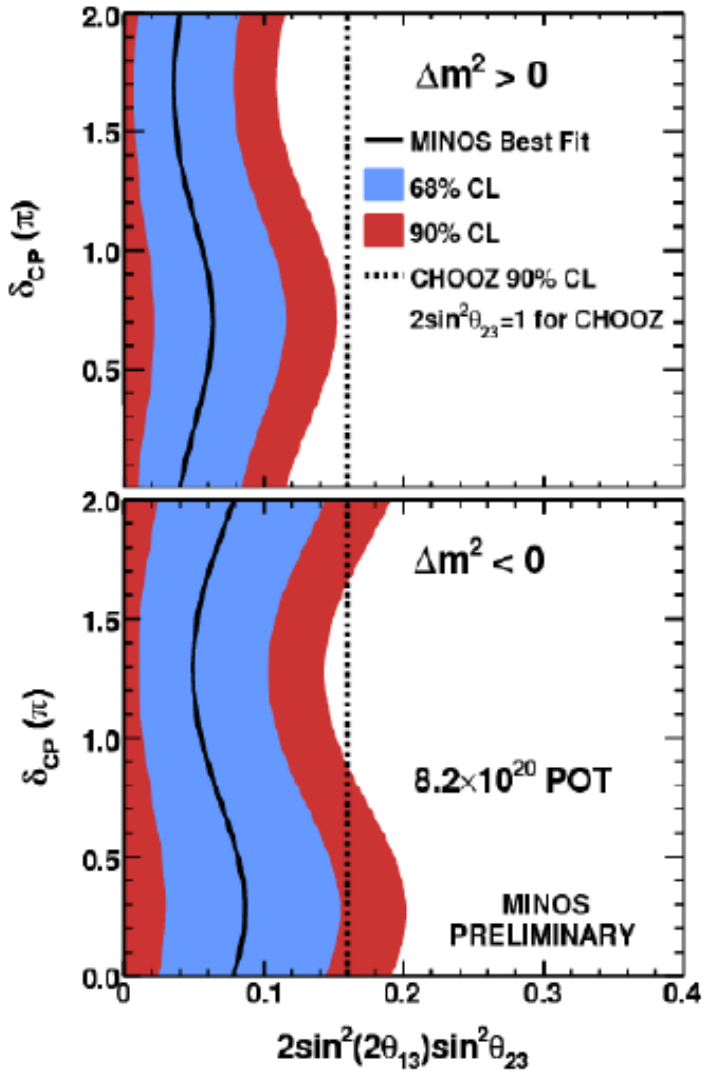


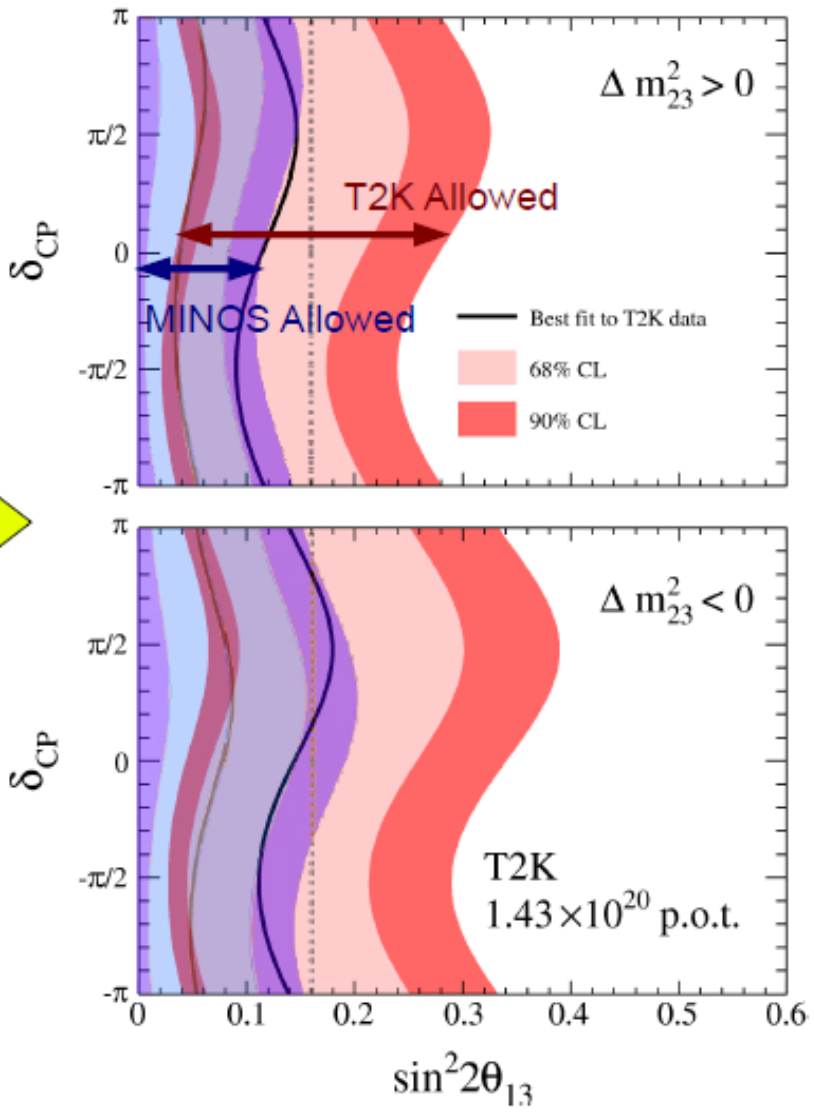


P_{value} of *null* hypothesis: 0.7%

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

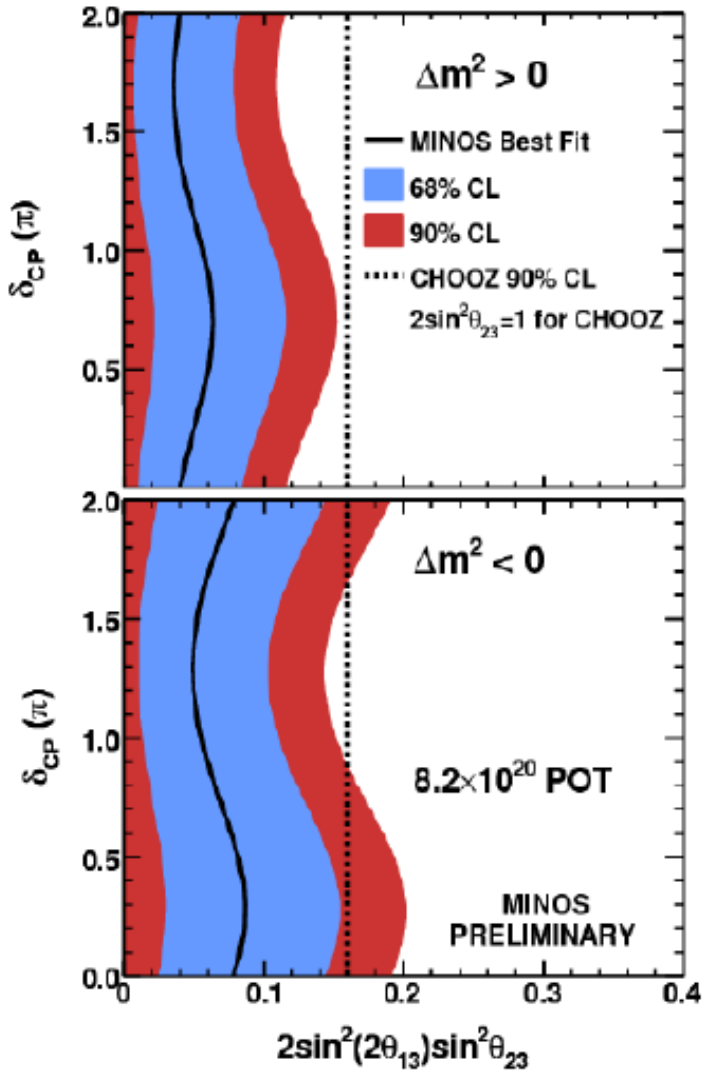
Comparison with MINOS result



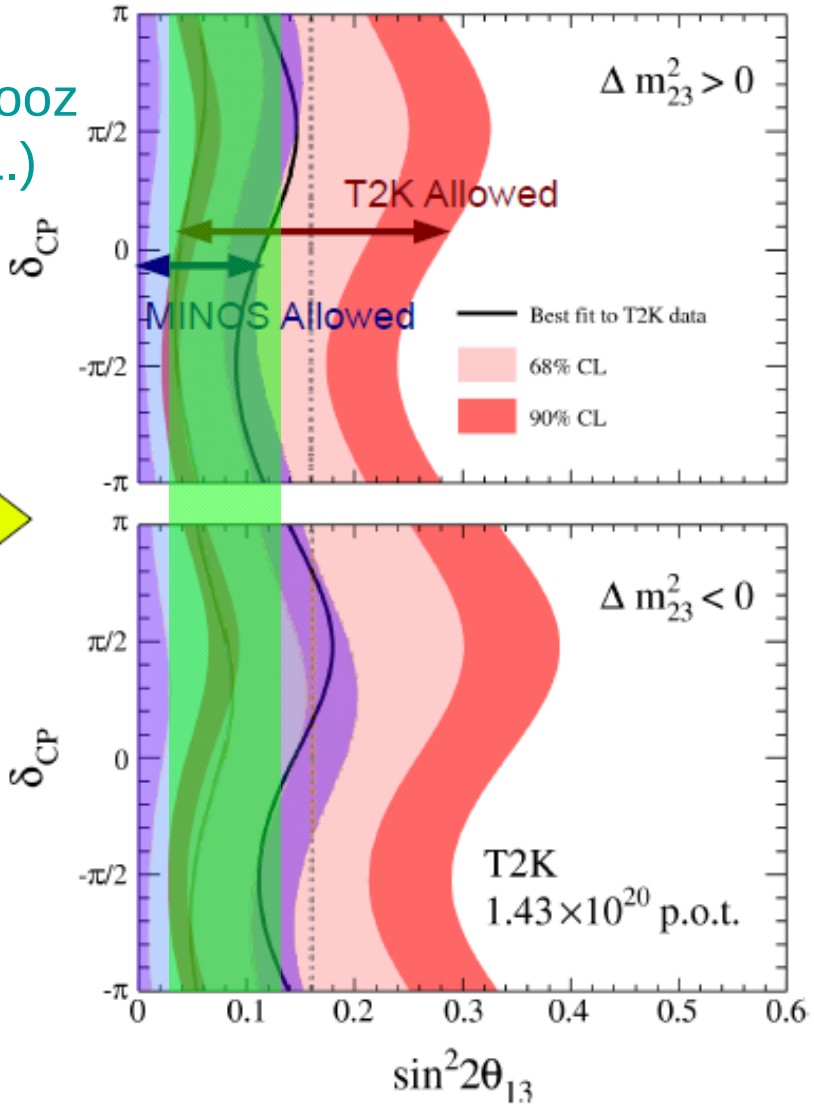


Significant overlap of T2K and MINOS 90% C.L. allowed regions

Comparison with MINOS result



Double Chooz
(68% C.L.)



Significant overlap of T2K and MINOS 90% C.L. allowed regions

Summary

First off-axis experimental ν_e and ν_μ results from T2K,
based on RUN1+2 data (1.43×10^{20} p.o.t.)

New result from ν_μ disappearance analysis

- Observe 31 events for single-ring μ-like (104 events expected w/o osc.)
- 90% C.L. allowed region: $2.1 \times 10^{-3} < \Delta m^2_{23} < 3.1 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} > 0.85$
- Consistent with other ν_μ oscillation results

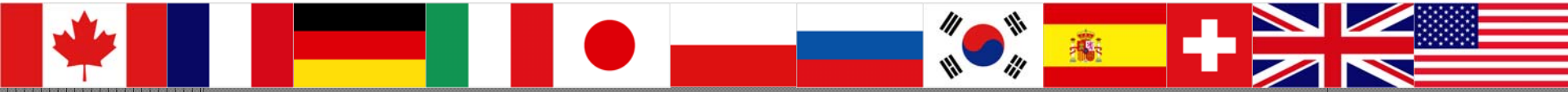
Indication of ν_e appearance consistent with non-zero θ_{13}

- Observe 6 ν_e candidate events when 1.5 ± 0.3 (syst.) BG expected at $\sin^2(2\theta_{13})=0$ (p-value = 0.7% equivalent to 2.5 σ)
- $0.03\ (0.04) < \sin^2(2\theta_{13}) < 0.28\ (0.34)$ at 90% C.L. for normal (inverted) hierarchy (assuming $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV^2, $\delta_{CP}=0$)
- Significant overlap of the allowed region has seen among T2K, MINOS and Double Chooz.

Resume J-PARC operation in Dec. 2011
and restart T2K data taking as soon as possible

T2K Collaboration

~500 members, 59 institutes, 12 countries



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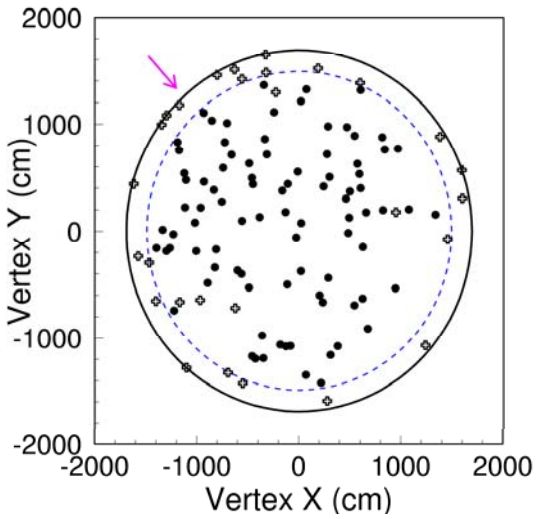
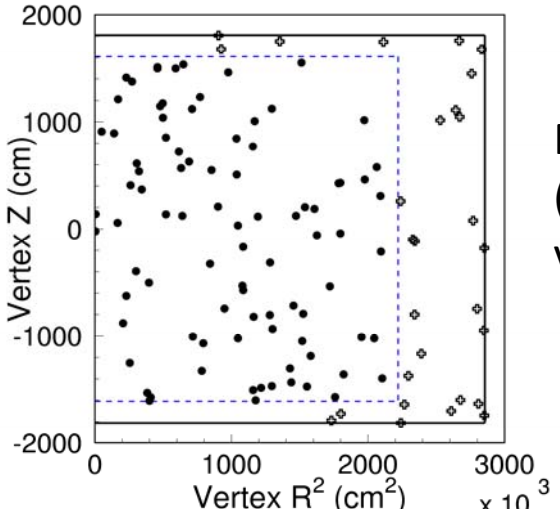
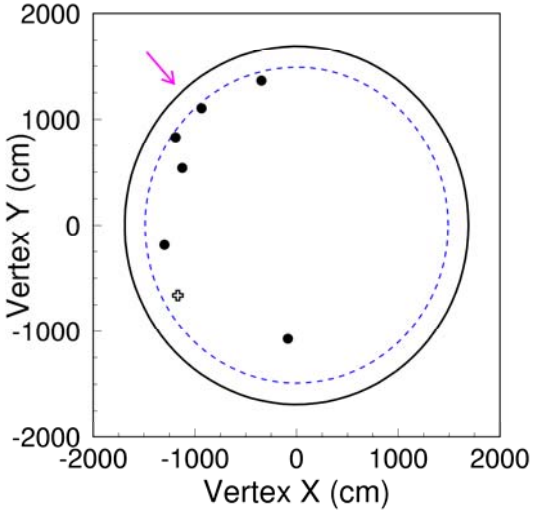
backup

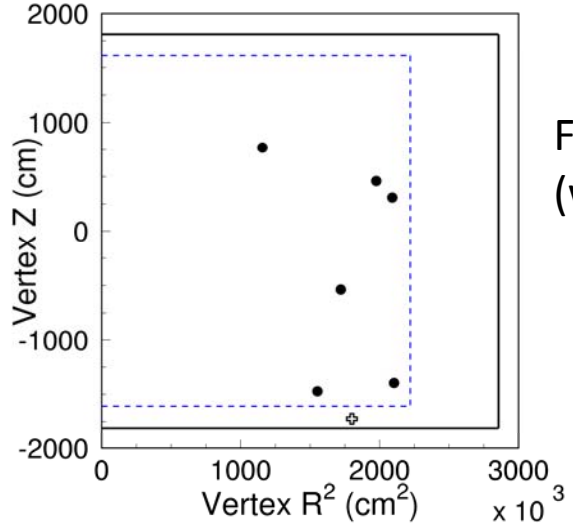
Vertex distributions of T2K FC sample and final sample





Fully-contained (FC) sample
(w/o ν_e selection and fiducial volume cuts)

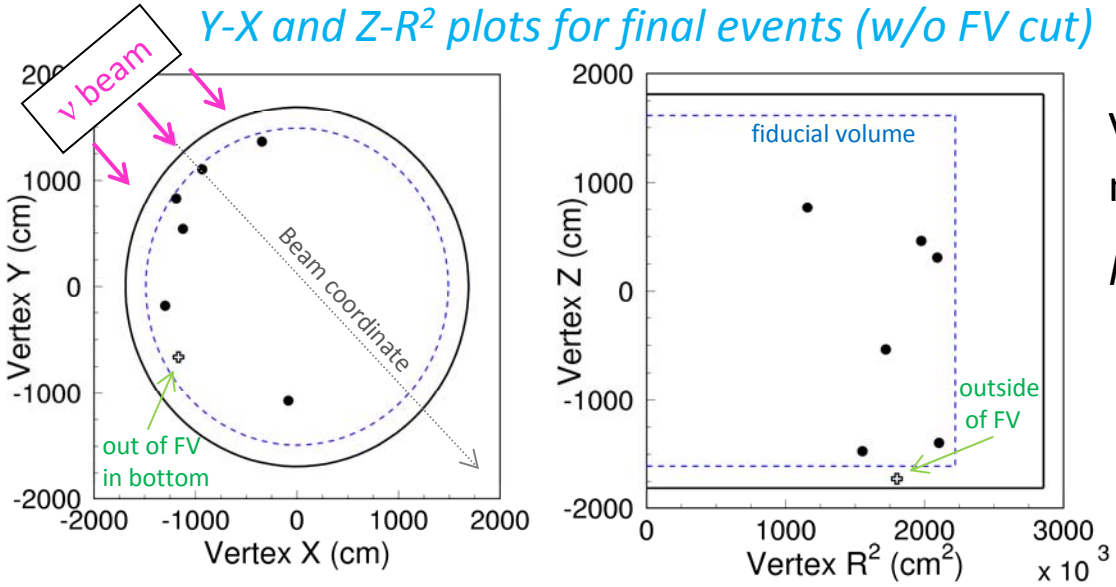




Final sample
(w/o fiducial volume cut)

Vertex distribution

Y-X and Z-R² plots for final events (w/o FV cut)

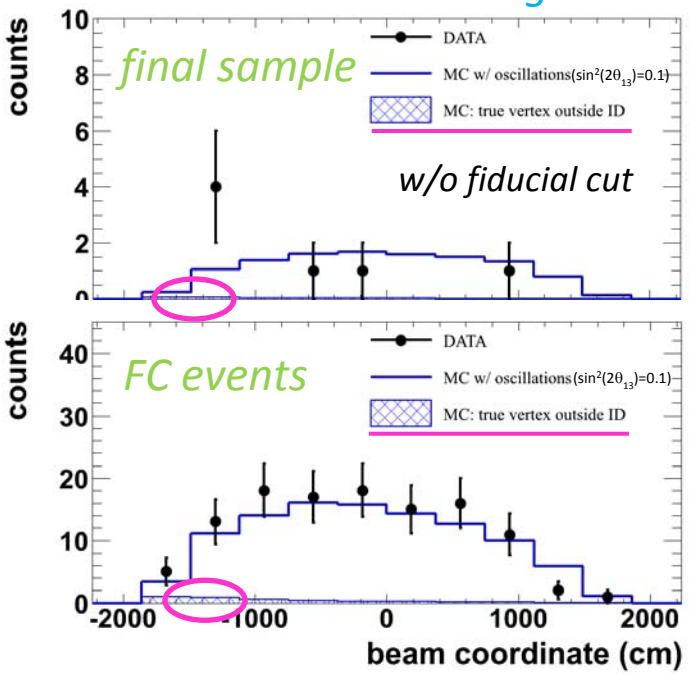


Vertex of these six events are located near fiducial volume edge

K-S test of R² event distribution

→ 3% probability

Vertex distribution along beam dir.



Check distribution of events outside FV
Check distribution of OD events

→ No indication of BG contamination

Simulation study of beam-induced BG by mis-ID μ, π⁰ photon, neutron, K from outside of ID

→ very small (3×10^{-3}) events estimated in FV