Neutrino Oscillation Results from T2K

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on behalf of the T2K Collaboration

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Neutrino Oscillations

Neutrino flavor eigenstates related to mass eigenstates by PMNS mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

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

CPV phase δ

Implies oscillation between flavors with probability:

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum_{i>j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

What we know:

θ_{23}, Δm^2_{23} – from atmospheric and accelerator neutrino experiments

θ_{12}, Δm^2_{12} – from solar and reactor neutrino experiments

What we don't know:

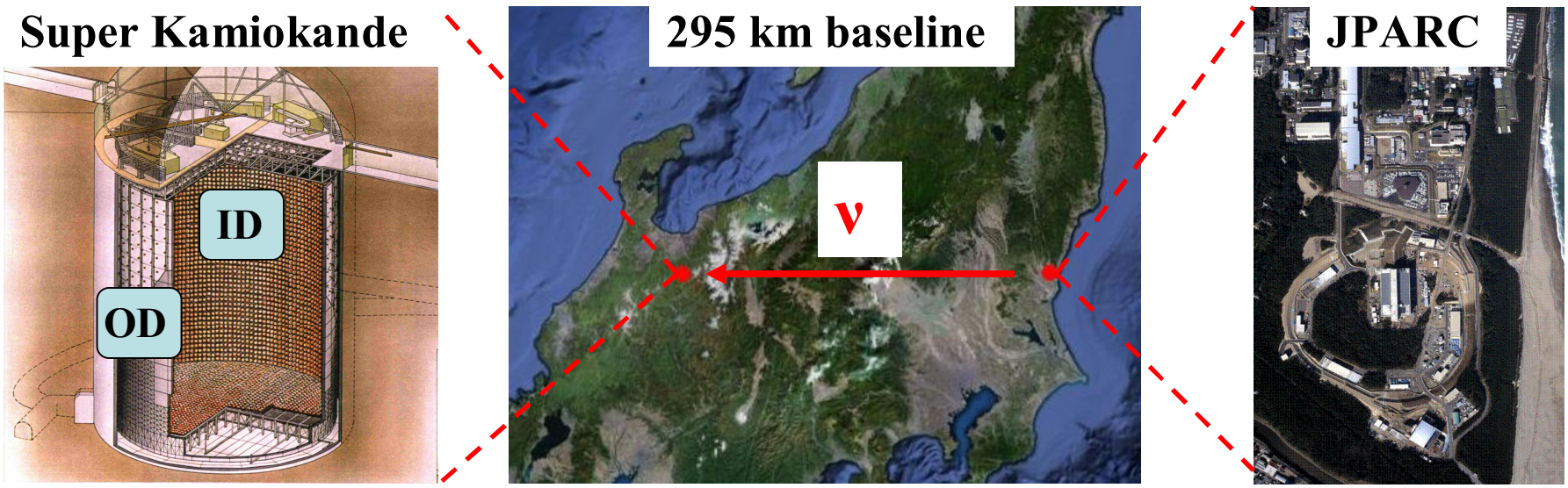
Sgn(Δm^2_{23}) – normal or inverted hierarchy | **δ** – need non-zero θ_{13}

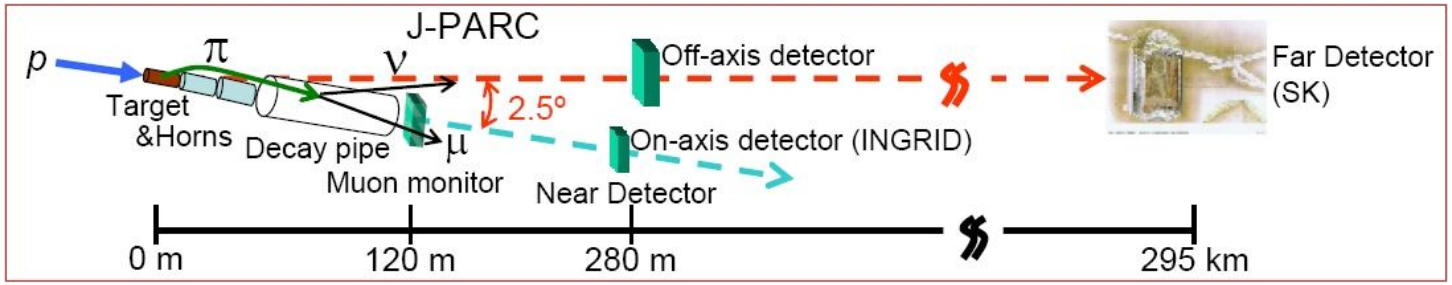
θ_{13} – Can measure via $\nu_\mu \to \nu_e$ oscillation: $P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E_\nu}$

T2K Collaboration

~500 Members, 58 Institutes, 12 Countries

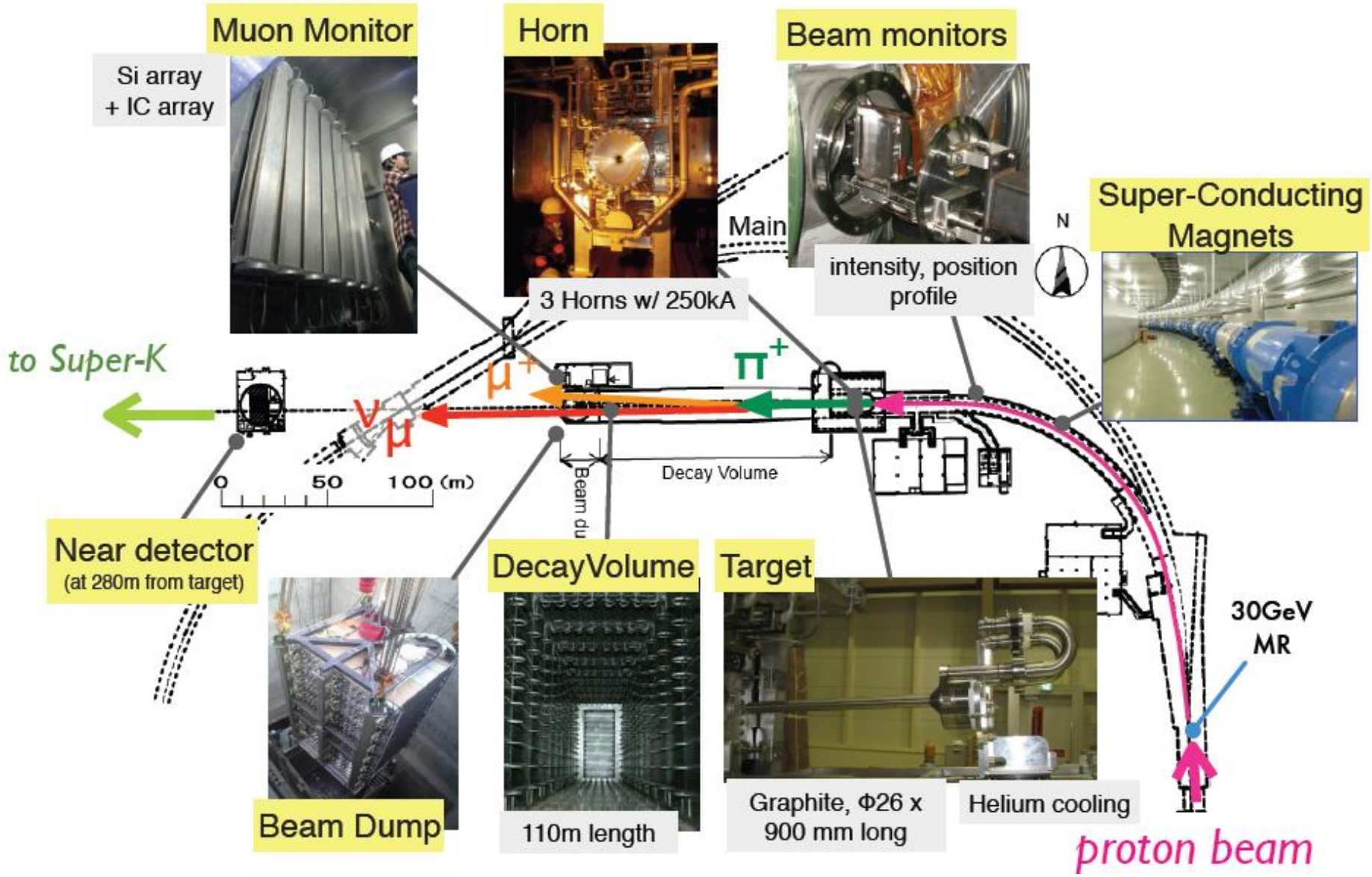
T2K Experiment



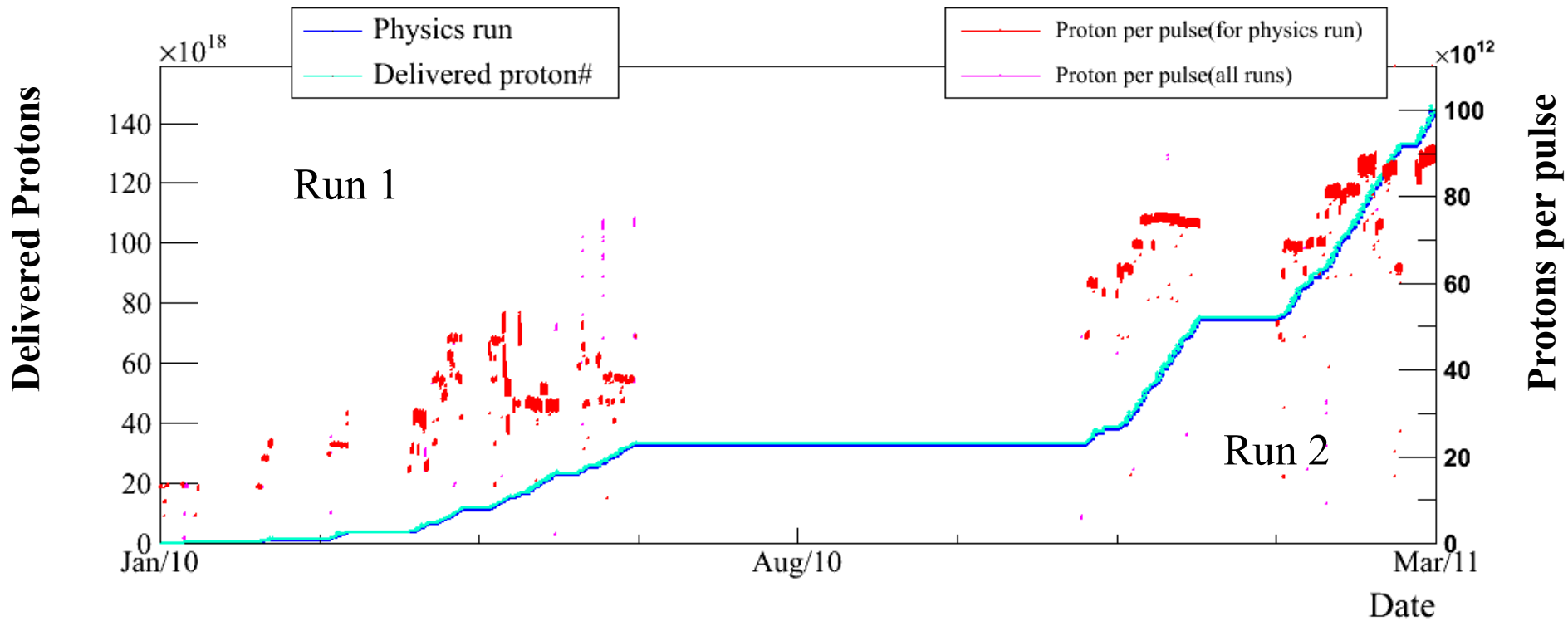


- ν_μ beam produced at JPARC in Tokai, Japan
  - 2.5 degree off axis to exploit π decay kinematics → narrow band beam
- Super Kamiokande serves as the far detector
- Primary physics goals:
  - Discovery of ν_e appearance → non-zero θ_{13}
  - Precision measurement of ν_μ disappearance → θ_{23}, Δm^2_{23}

T2K Neutrino Beamline



Run 1 + Run 2 Dataset



Run 1 (Jan – June 2010)

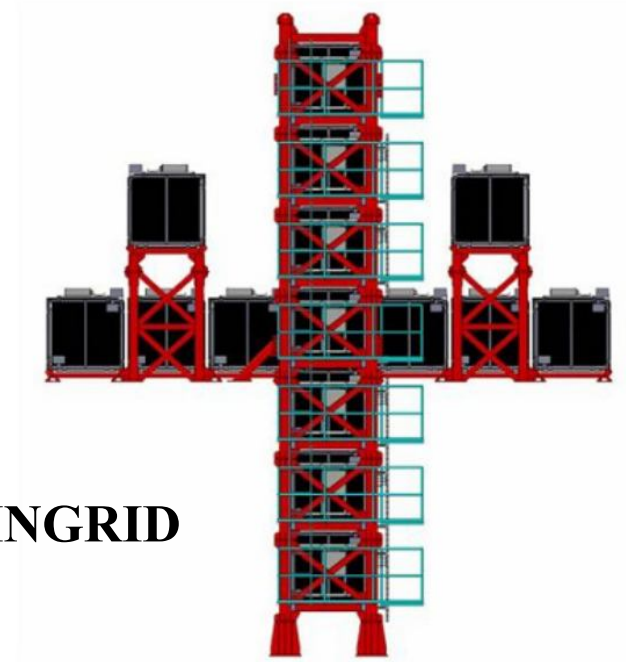
- 3.23×10^{19} p.o.t delivered

Run 2 (Nov 2010 – March 2011)

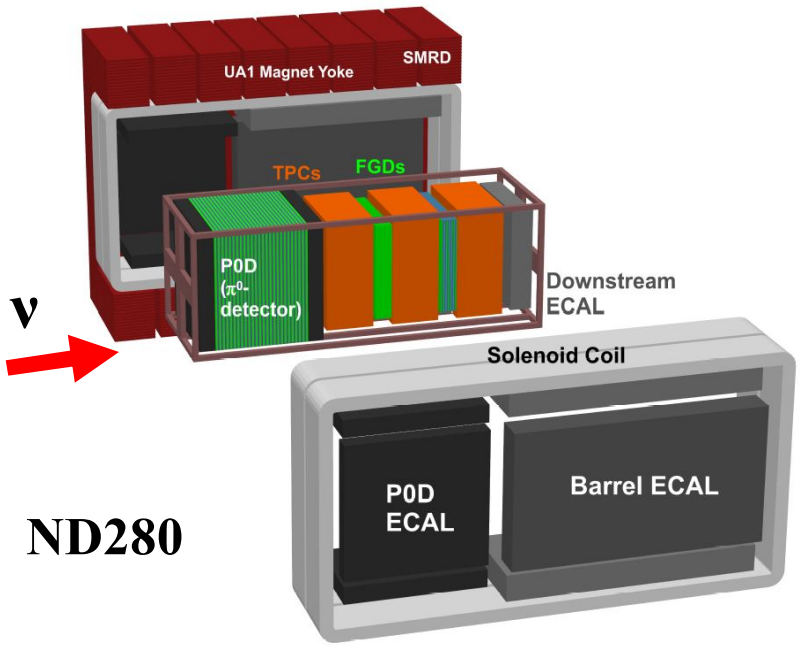
- 11.08×10^{19} p.o.t delivered
- Achieved 145 kW beam operation
- Ended 3/11/2011 due to earthquake

Total p.o.t 1.43×10^{20} , Less than 2% of T2K final goal

T2K Near Detectors



INGRID



ND280

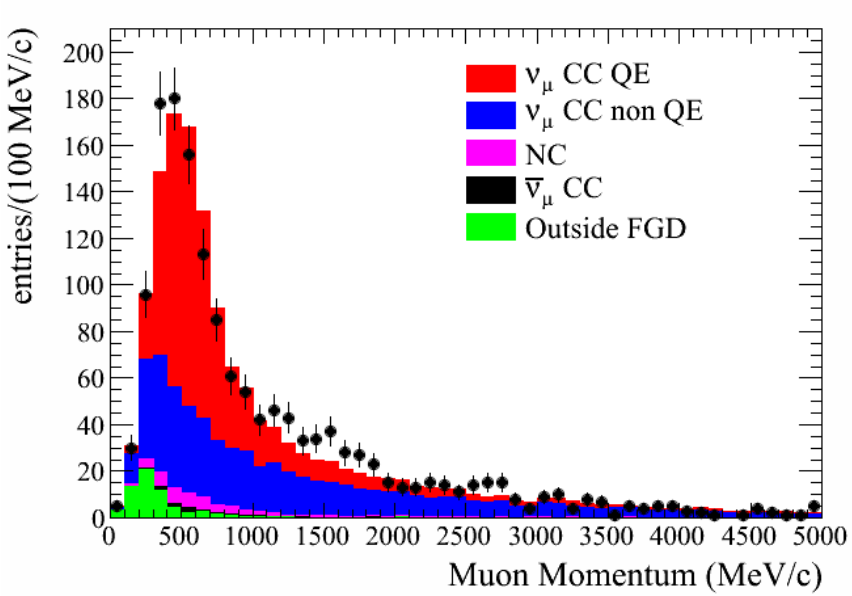
INGRID detector

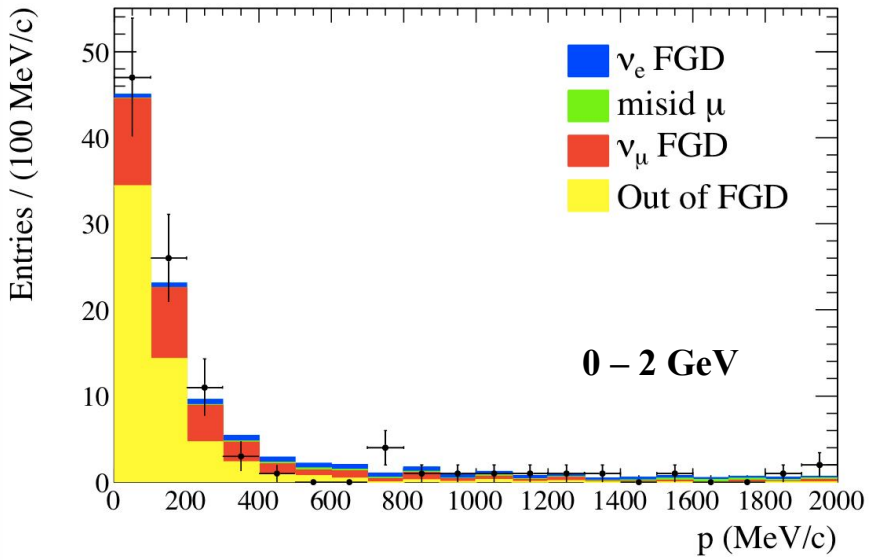
- On axis near detector at 280 m
- 16 iron/scintillator modules
- Provide day-to-day monitoring of neutrino beam stability in rate, profile and direction

ND280 off-axis near detector

- 2.5° off-axis, 280 m from beam origin
- Detectors installed in recycled UA1 magnet
- Provide measurements of neutrino spectra prior to oscillation
- Provide cross-section measurements of important background channels

Near Detector Measurements





ν_μ CC Inclusive

- Select tracks beginning in FGD and identified as μ-like by the TPC
- Measured data/MC ratio provides normalization of expected number of events at SK

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

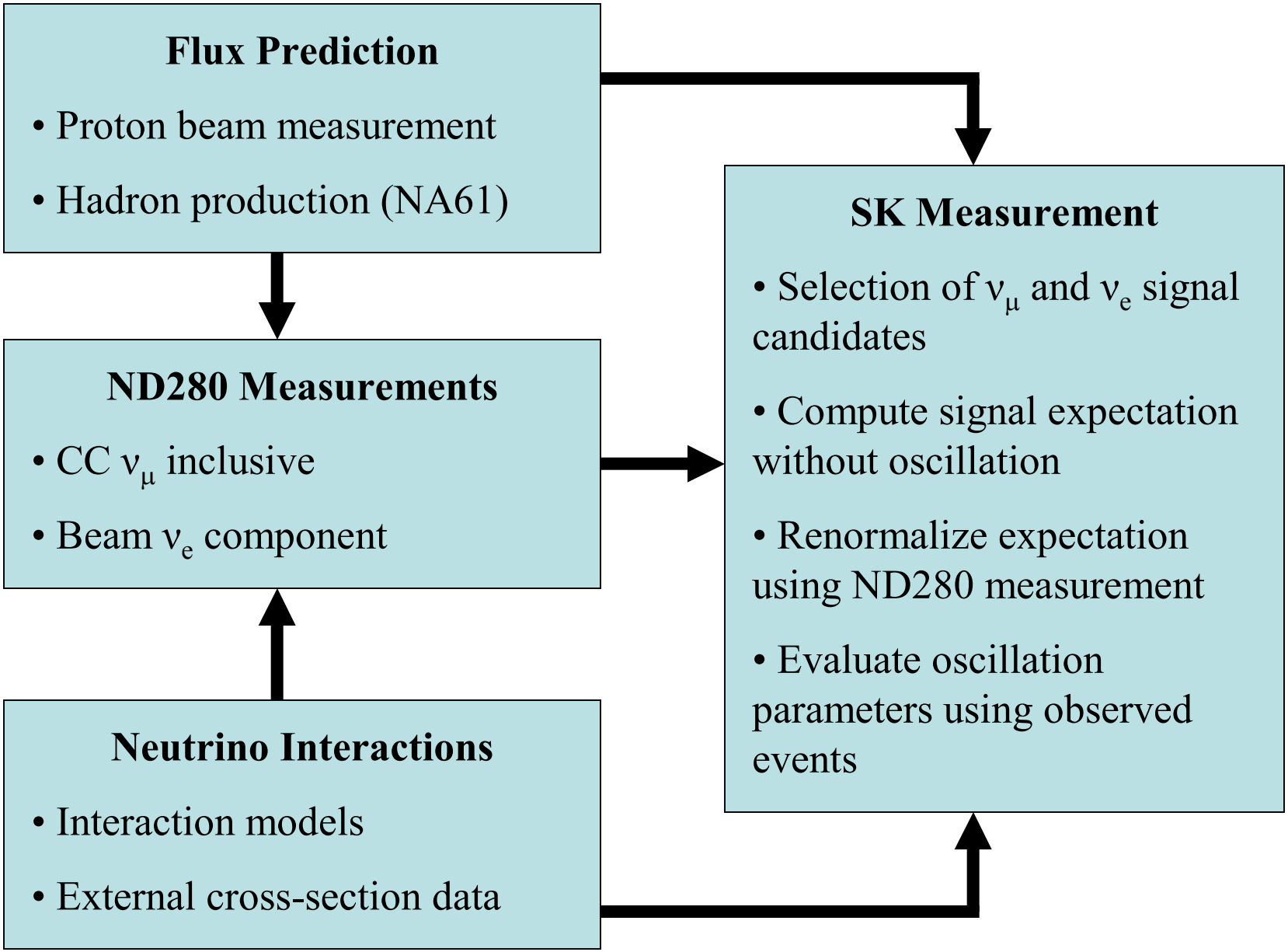
Beam ν_e Component

- Select ν_e interactions in the FGD with tracks indentified as e-like using TPC dE/dx
- Largest source of background to ν_e oscillation analysis

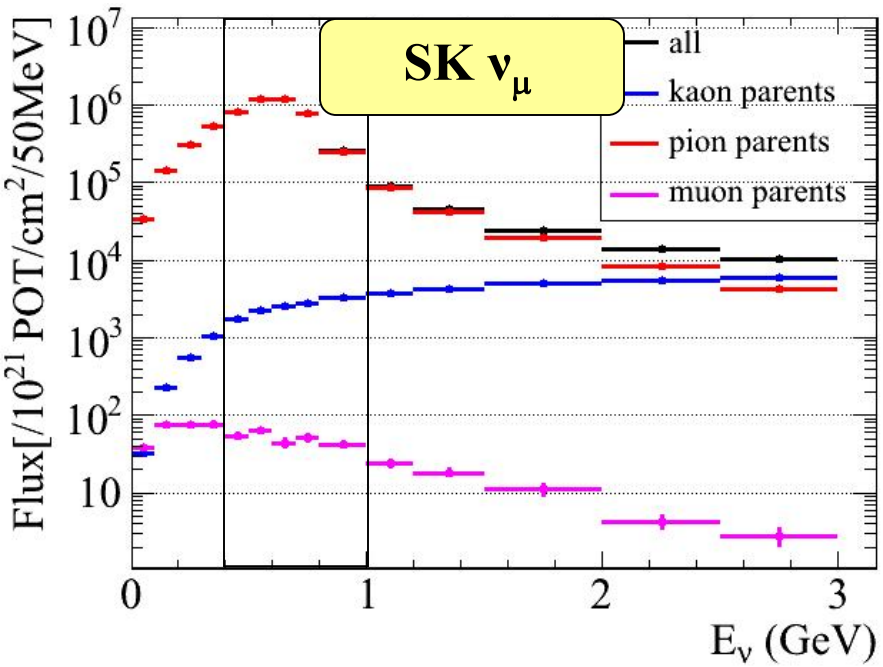
$$R(\nu_e/\nu_\mu) = (1.0 \pm 0.7(stat) \pm 0.3(syst))\%$$

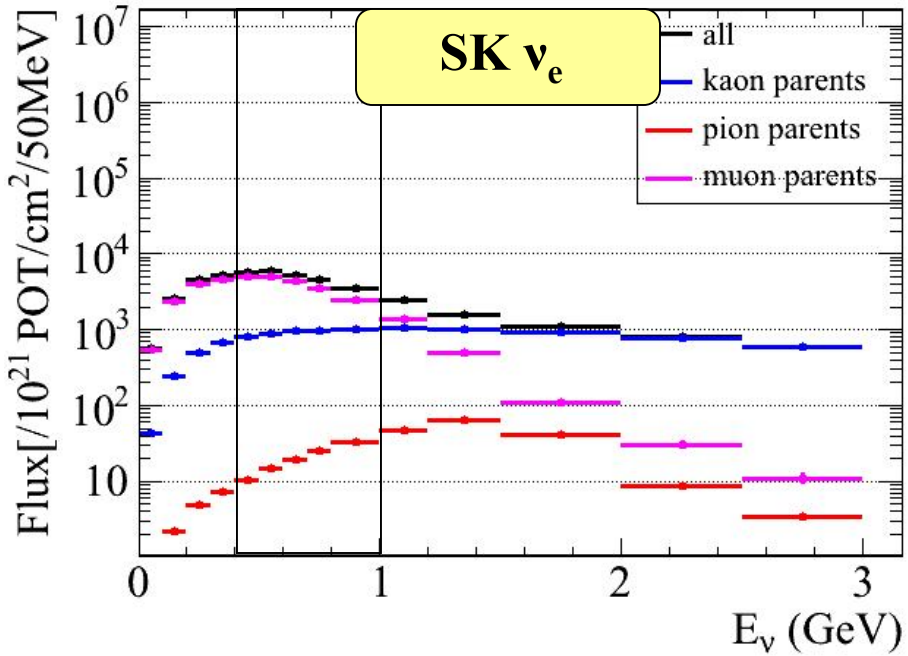
Oscillation Analysis

Oscillation Analysis Overview



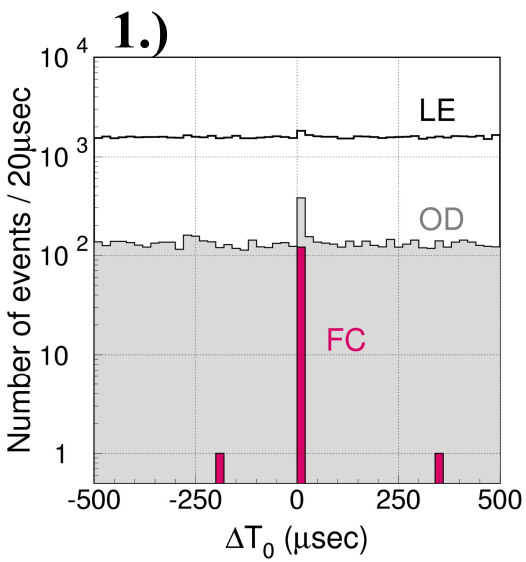
Flux Prediction

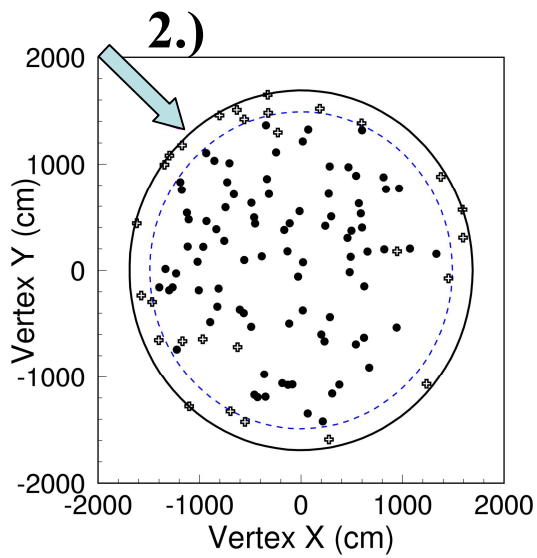


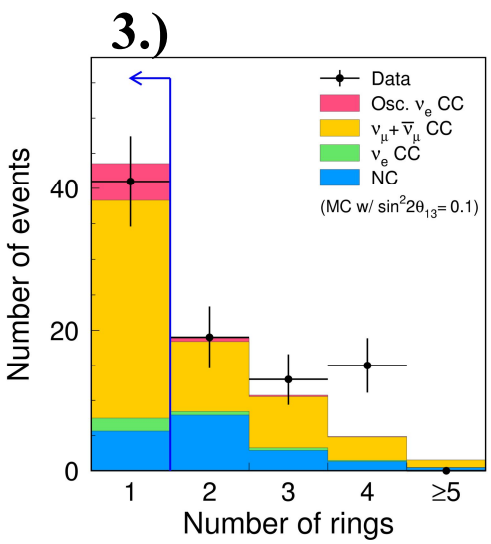


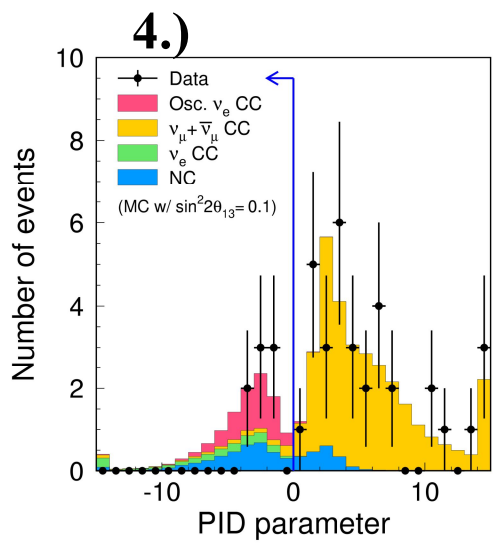
- T2K proton beam monitor measurements provide inputs to flux simulation
- Data from NA61 Experiment at CERN used to model pion production in target
- Kaon production modeled with FLUKA
- Out of target interactions, horn focusing, particle decays
  - GEANT3 simulation
  - Interaction cross sections tuned to existing data

Super Kamiokande Event Selection









Predefined event selection criteria for ν_μ and ν_e

1. Event time coincident with beam (±500μs)
2. Event fully contained in ID, vertex reconstructed in fiducial volume (> 200 cm from wall in r and z)
3. Single ring event
4. PID parameter of ring consistent with electron or muon

Further event selection for specific analyses

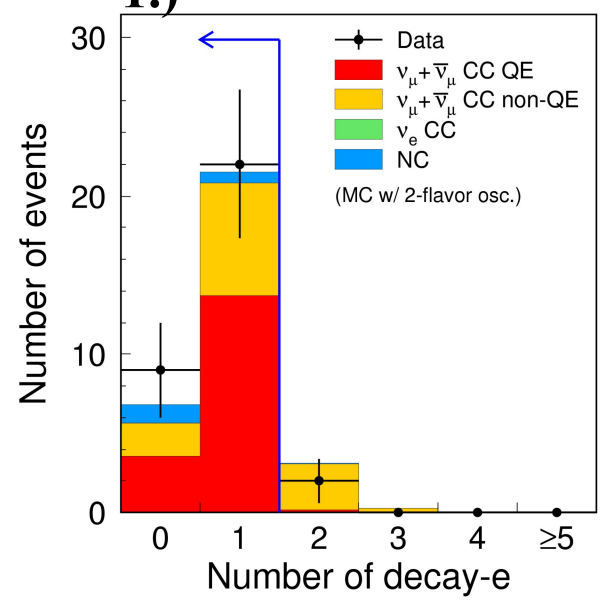
ν_μ disappearance analysis

SK ν_μ Event Selection

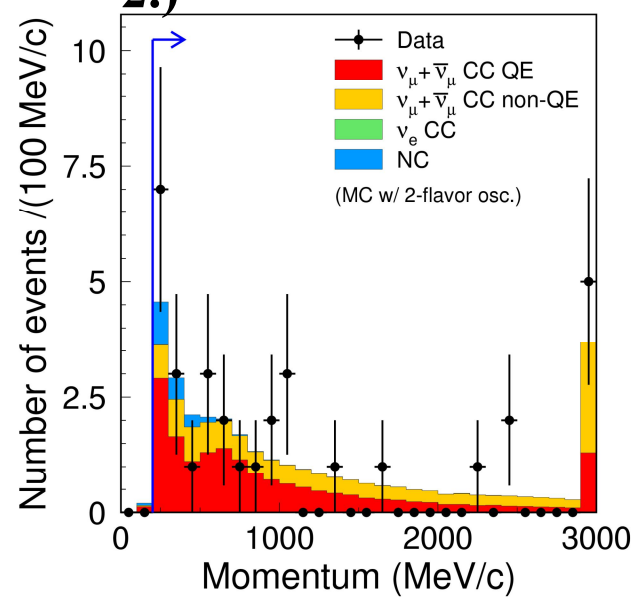
- 33 single ring μ-like events remain
- Additional cuts
  1. Less than 2 reconstructed decay electrons
  2. Reconstructed muon momentum larger than 200 MeV
- 31 events pass all selection cuts

	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 %

1.)



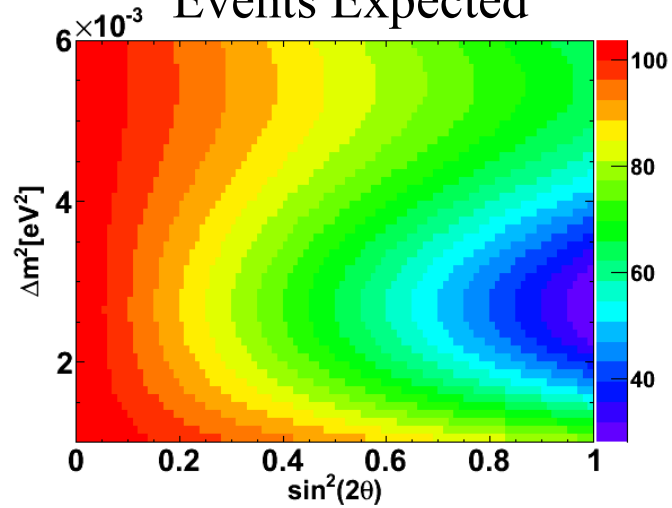
2.)



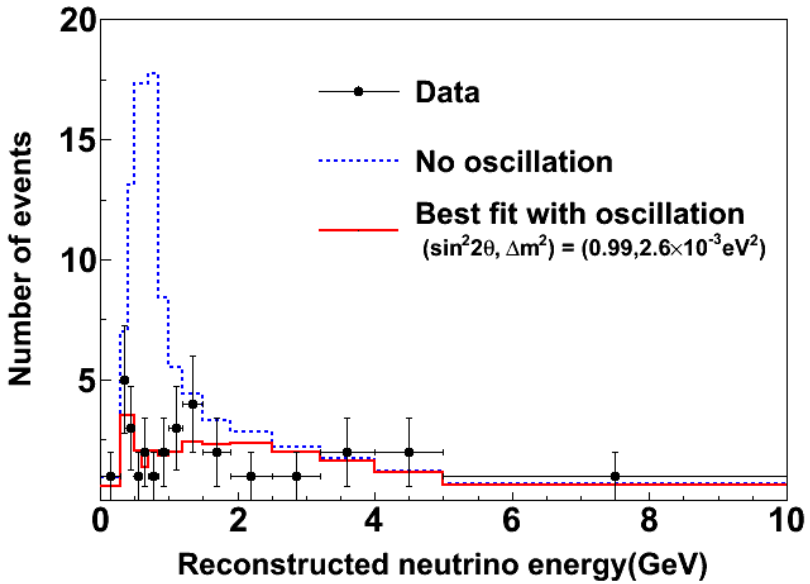
Remaining ν_μ Events

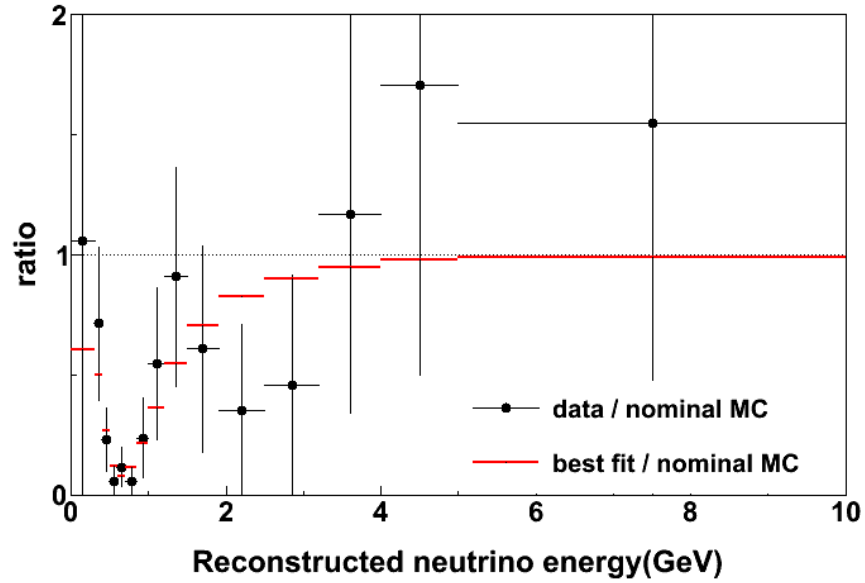
- We observe 31 events after all selection cuts
  - Expect **103.7** assuming no oscillation
  - Expect **28.3** w/$\sin^2(2\theta_{23}) = 1, \Delta m^2_{23} = 2.4\times10^{-3}$
- Null-oscillation hypothesis excluded at 4.5σ

Events Expected



Data/MC ratio assuming no oscillation



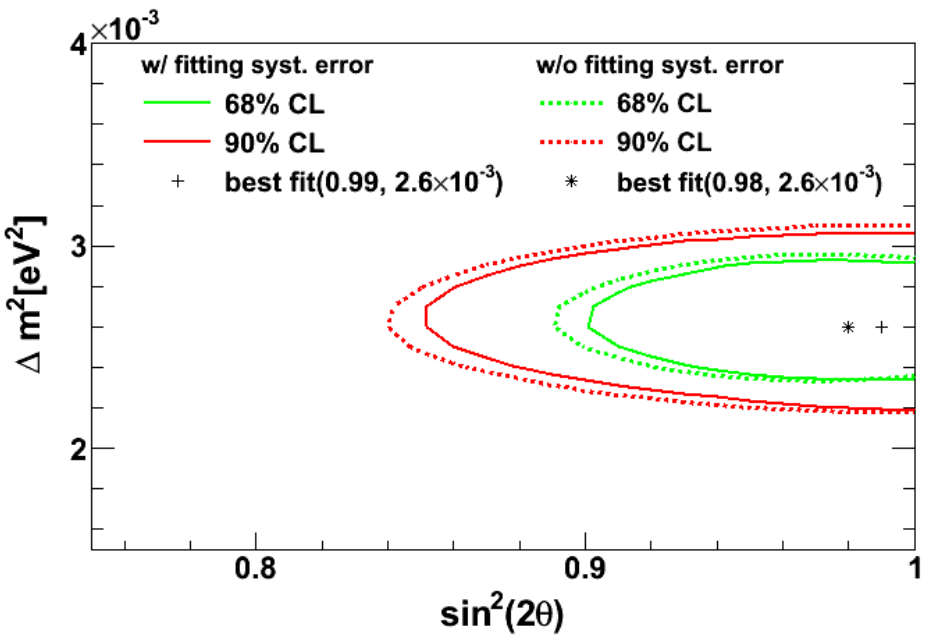


ν_μ Analysis Results

- 2 flavor neutrino oscillation fit

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{23} L/E)$$

- 2 different fits performed
  - One allows varying systematic errors, the other fixes them
- Feldman-Cousins method used to construct confidence intervals



Analysis Results:

Best fit 1: $\sin^2(2\theta_{23}) = 0.99, \left|\Delta m^2_{23}\right| = 2.6\times10^{-3}\ \mathrm{eV}^2$

Best fit 2: $\sin^2(2\theta_{23}) = 0.98, \left|\Delta m^2_{23}\right| = 2.6\times10^{-3}\ \mathrm{eV}^2$

Confidence intervals (90% C.L.)

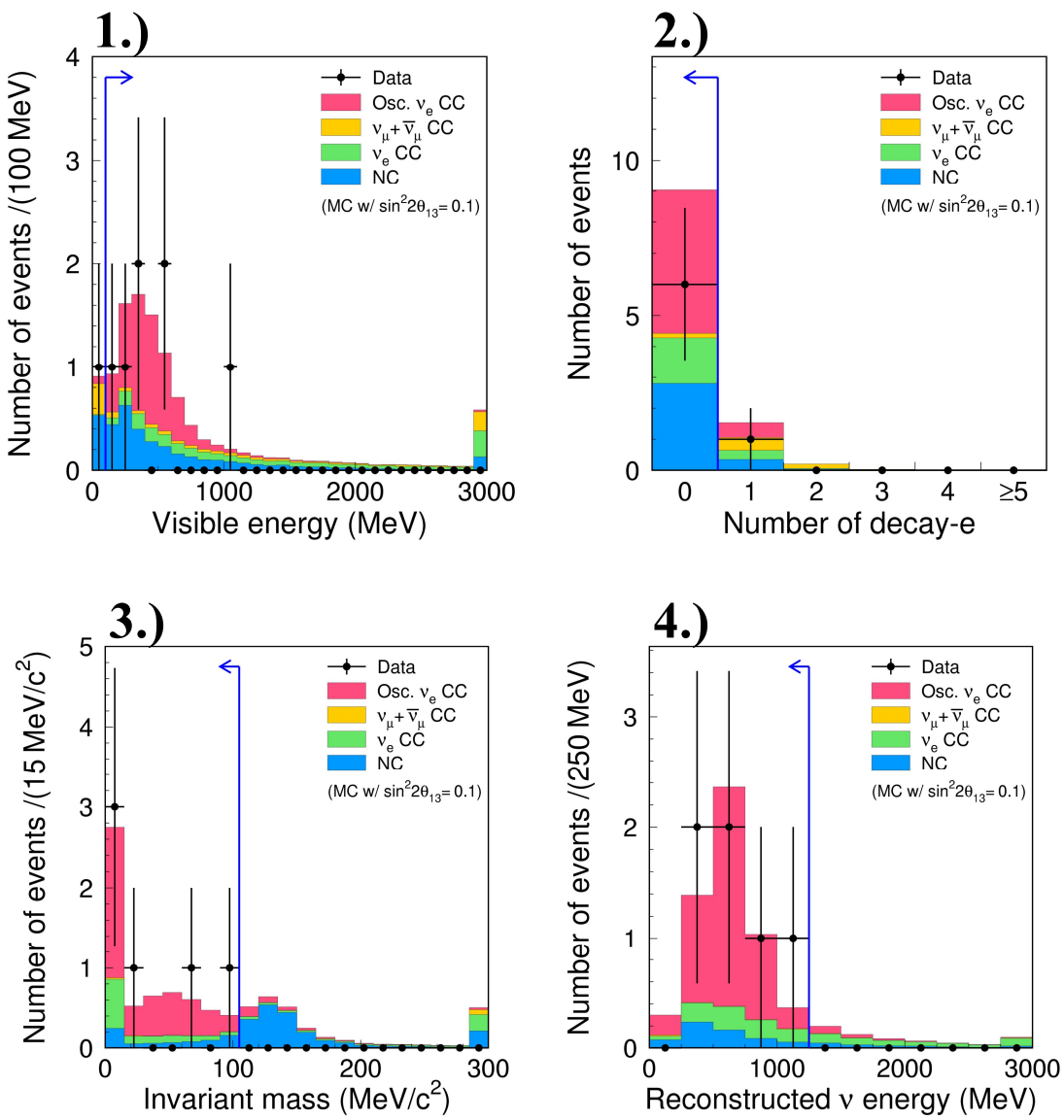
$\sin^2(2\theta_{23}) > 0.85,\quad 2.1\times10^{-3} < \left|\Delta m^2_{23}\right| < 3.1\times10^{-3}\ \mathrm{eV}^2$

$\sin^2(2\theta_{23}) > 0.84,\quad 2.1\times10^{-3} < \left|\Delta m^2_{23}\right| < 3.2\times10^{-3}\ \mathrm{eV}^2$

Good agreement between the analyses

ν_e appearance analysis

SK ν_e Event Selection



8 single-ring e-like events remain

Further cuts are applied to reduce backgrounds

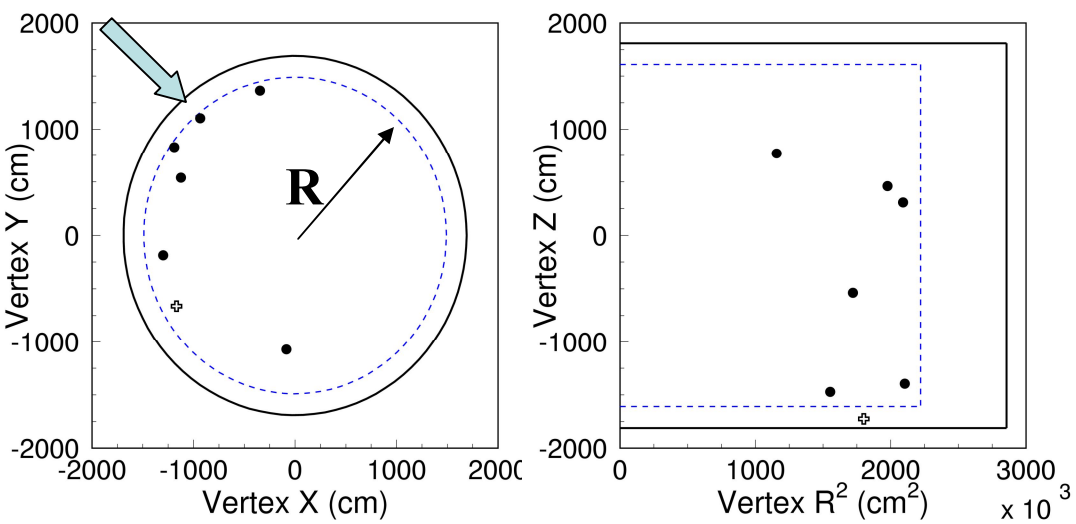
1. Visible energy > 100 MeV
2. No decay electrons
3. M_{inv} with forced second ring < 105 MeV
4. Reconstructed neutrino energy < 1250 MeV

6 events remain after all selection cuts

Remaining ν_e Events

Source	N_{exp}
Beam ν_e	0.76
ν_μ Neutral Current	0.61
$\nu_\mu \rightarrow \nu_e$ (solar)	0.09
ν_μ Charged Current	0.03
Total	**1.49±0.34**

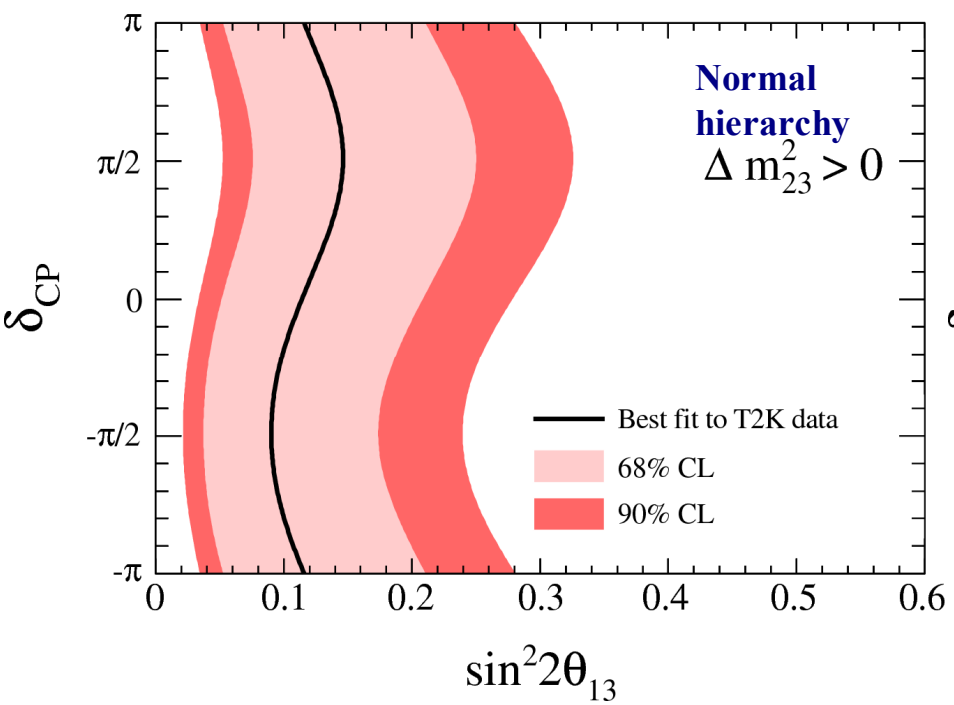
- We observe 6 events remaining after all selection cuts
  - Expect only 1.5 events from background ($\sin^2(2\theta_{13})=0$)
  - Expect 5.5 events assuming $\sin^2(2\theta_{13}) = 0.1$

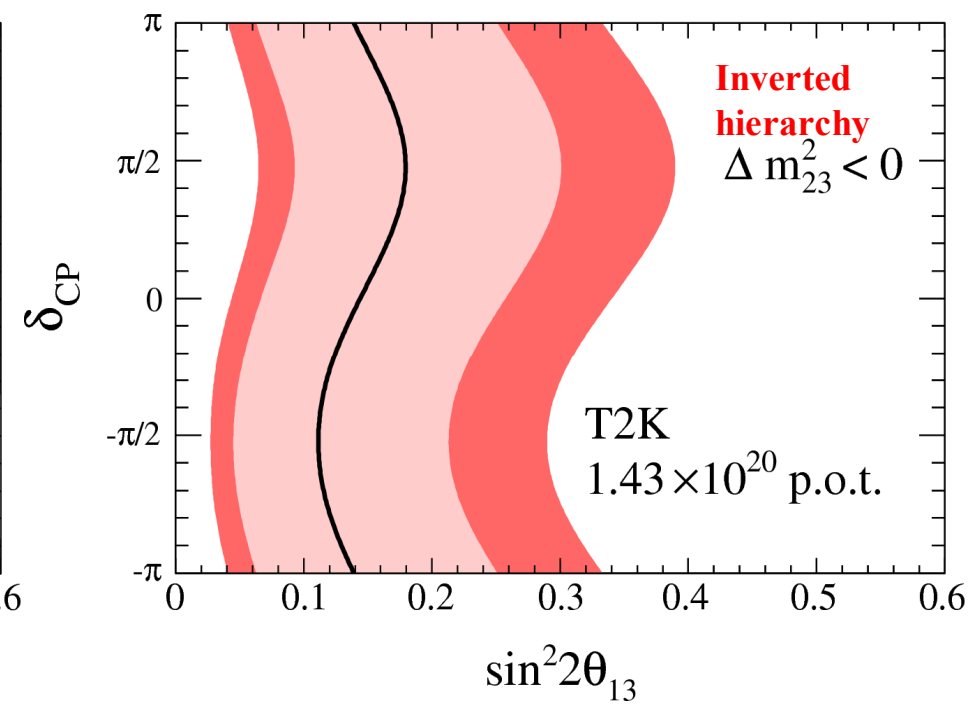


- Vertex distribution of these events show clustering at large R
- KS test of R^2 distribution gives p-value of 0.03
- Do not observe accumulation of events outside the FV or in the OD

ν_e Analysis Results

- Confidence intervals produced using the Feldman-Cousins method
- Probability of observing 6 events if $\sin^2(2\theta_{13}) = 0$ → **0.7% (2.5σ)**
- Normal hierarchy, $\delta = 0$ **$0.03 < \sin^2(2\theta_{13}) < 0.28$** at 90% C.L.
  - Best fit: **$\sin^2(2\theta_{13}) = 0.11$**
- Inverted hierarchy, $\delta = 0$ **$0.04 < \sin^2(2\theta_{13}) < 0.34$** at 90% C.L.
  - Best fit: **$\sin^2(2\theta_{13}) = 0.14$**





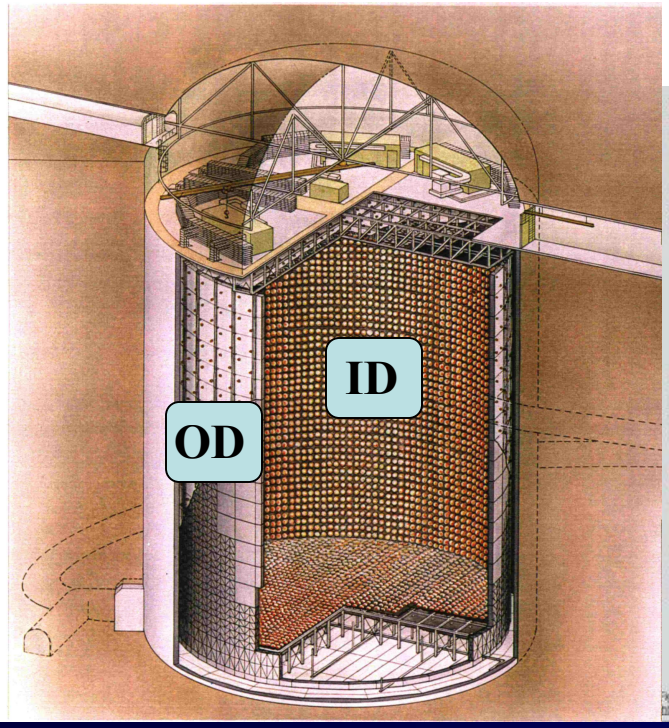
Summary

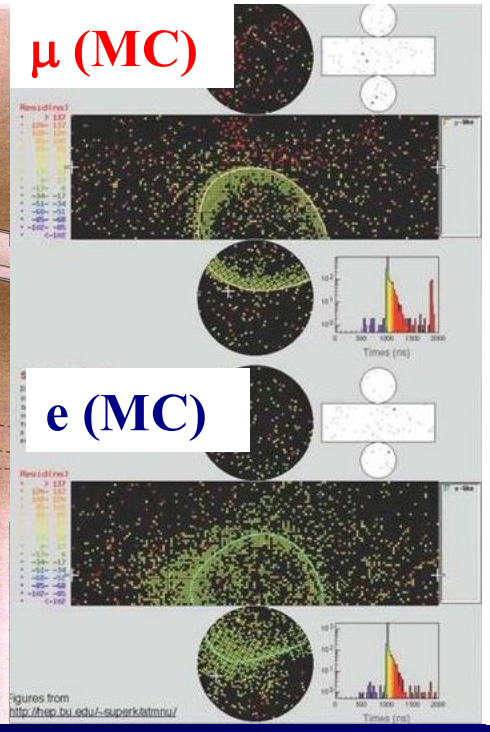
- The ν_μ disappearance and ν_e appearance analyses have been performed on a dataset corresponding to 1.43×10^{20} p.o.t. (2% of T2K goal)
- ν_e appearance analysis:
  - 6 events observed (expect 1.5±0.03)
  - Probability of observing 6 events with $\theta_{13}=0$ is **0.7% (2.5σ)**
  - 90% confidence interval of **0.03(0.04) < $\sin^2(2\theta_{13})$ < 0.28(0.34)** for normal (inverted) hierarchy and $\delta = 0$
- ν_μ disappearance analysis:
  - Null oscillation hypothesis excluded at 4.5σ
  - **$\sin^2(2\theta_{23}) > 0.85$** and **$2.1 \times 10^{-3} < \Delta m^2_{23} < 3.1 \times 10^{-3}$** (90% CL)
- Recovery from earthquake:
  - Plan to restart accelerator by end of 2011
  - T2K will resume data taking soon after

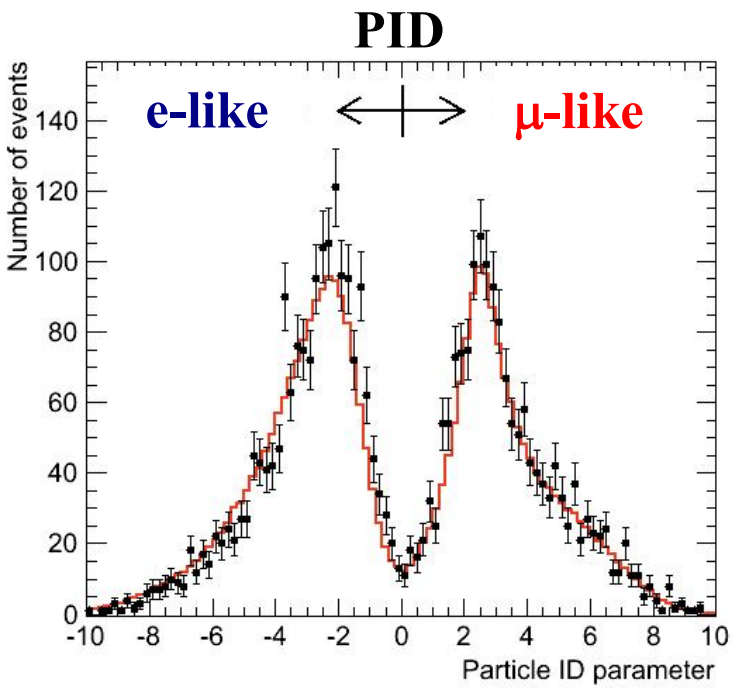
Backup

Far Detector – Super Kamiokande

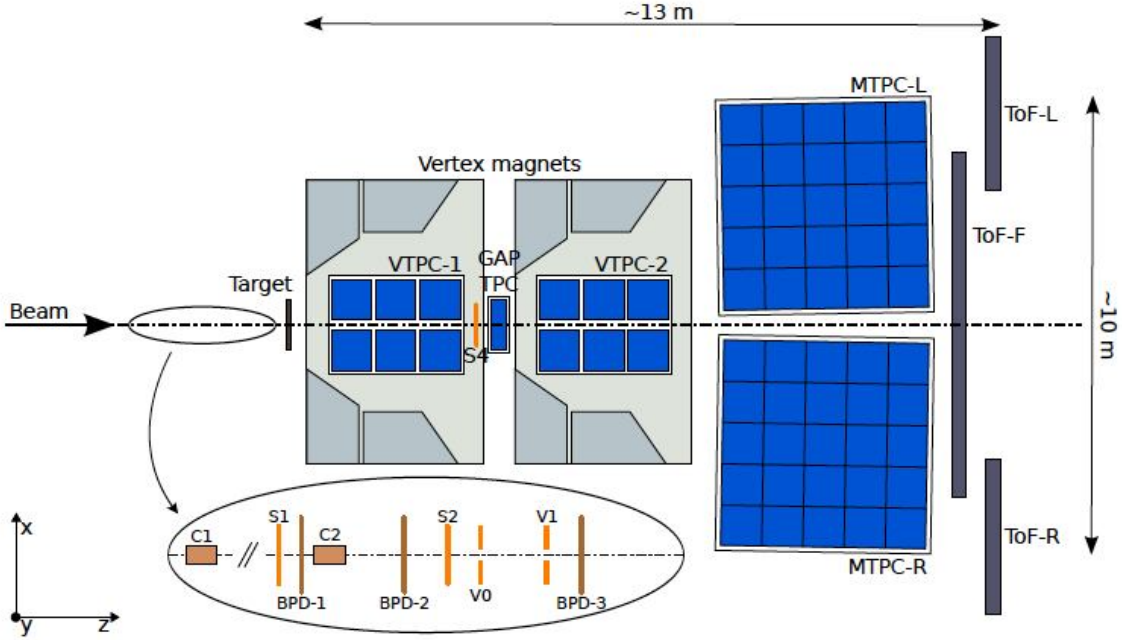
- 50 kton (22.5 fiducial) water Cherenkov detector
- Inner detector: ~11,000 20” PMTs
- Outer detector: ~8,000 8” PMTs
- Good e/μ identification using Cherenkov light pattern
  - Muons produce clean Cherenkov rings
  - Electrons produce “fuzzy” rings due to electromagnetic showers







NA61 Experiment



Large acceptance spectrometer and TOF detectors

30 GeV proton beam

Two types of targets used

- 0.04 λ "thin target"
- T2K replica "long target"

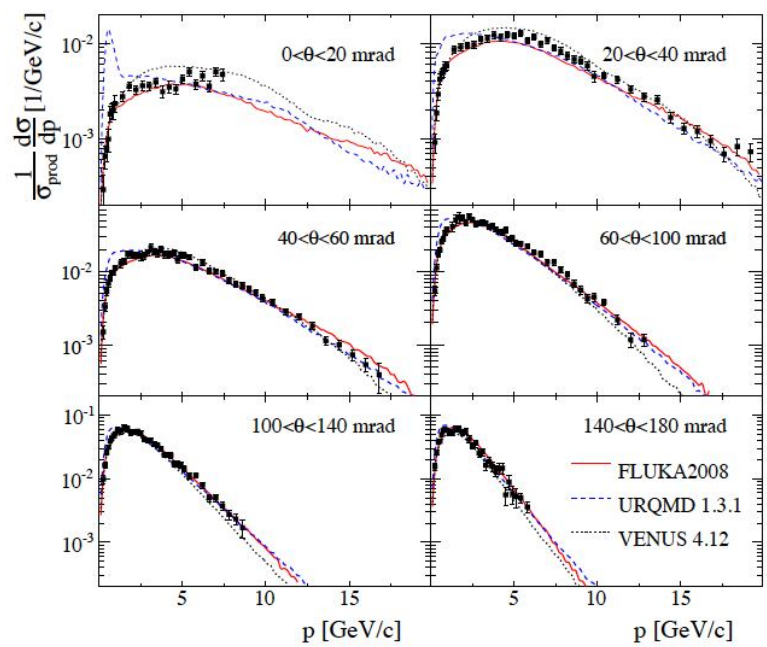
Measure differential pion production multiplicity

5-10% systematic uncertainties for each point in p-θ space

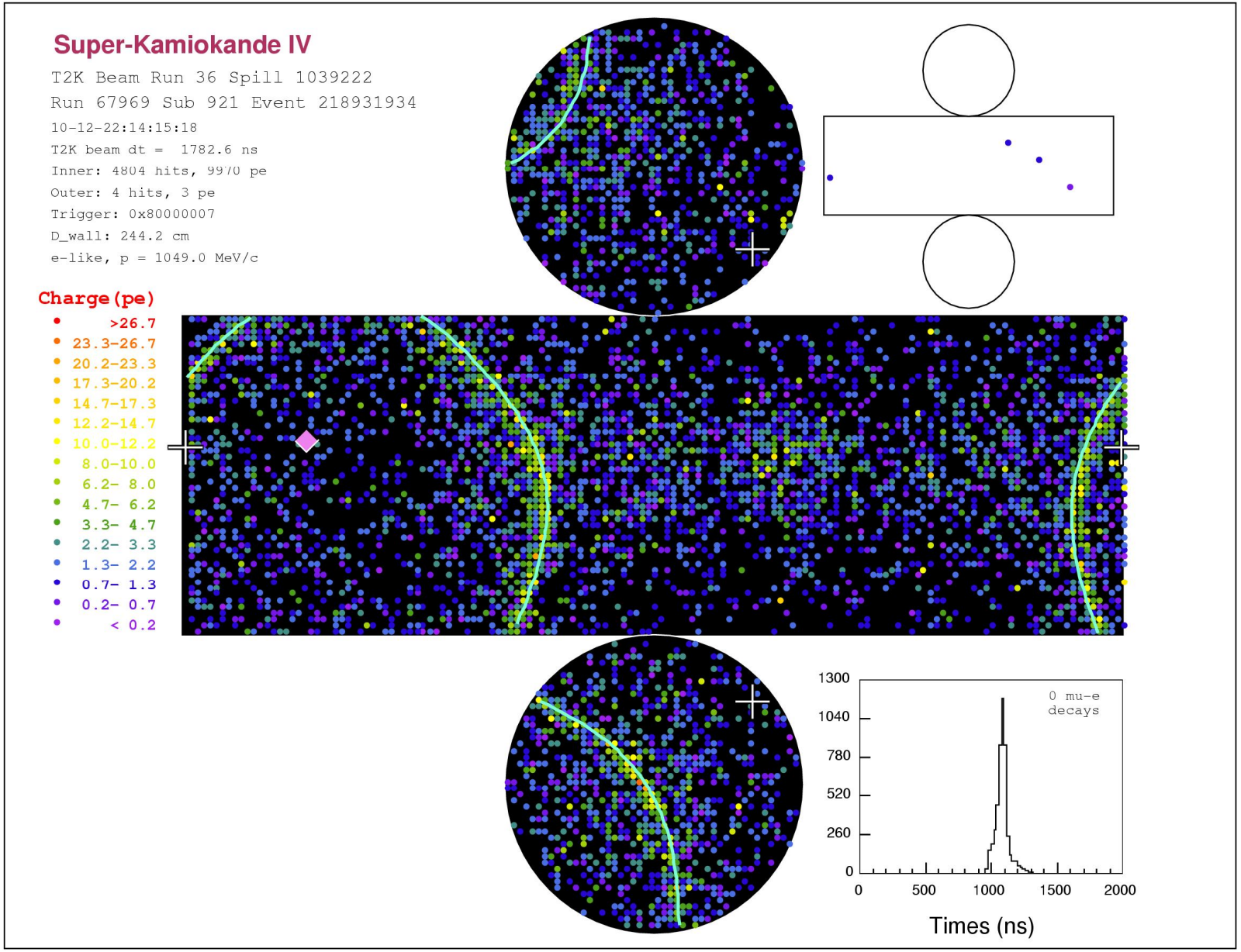
2.3% normalization uncertainty

Uncertainties propagated into oscillation analysis

NA61 data reproduced by FLUKA



Event Display of ν_e Candidate



Comparison of ν_μ Analysis Results