The T2K Experiment – *Patrick de Perio*

UNIVERSITY OF TORONTO

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Neutrino Oscillation

- Neutrino flavor content varies as it propagates through space, through mixing of the mass eigenstates

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

Atmospheric & Accelerator — Reactor & Accelerator — Solar & Reactor

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \approx \begin{pmatrix} 0.8 & 0.5 & s_{13}e^{i\delta} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

	Atmospheric & Accelerator	Reactor & Accelerator	Solar & Reactor
Current	$37° < \theta_{23} \le 45°$ $\Delta m_{23}^2 = (2.4\pm0.5)\times10^{-3}$ eV^2	$\theta_{13} < 11°$	$\theta_{12} = (33.9\pm1.4)°$ $\Delta m_{12}^2 = (8.0\pm0.3)\times10^{-5}$ eV^2
T2K Goal	$\delta(\theta_{23}) < 2°$ $\delta(\Delta m_{23}^2) < 0.1 \times 10^{-3}$ eV^2	$\theta_{13} < 2°$ ← Measurement of CP phase δ depends on size of θ_{13}	

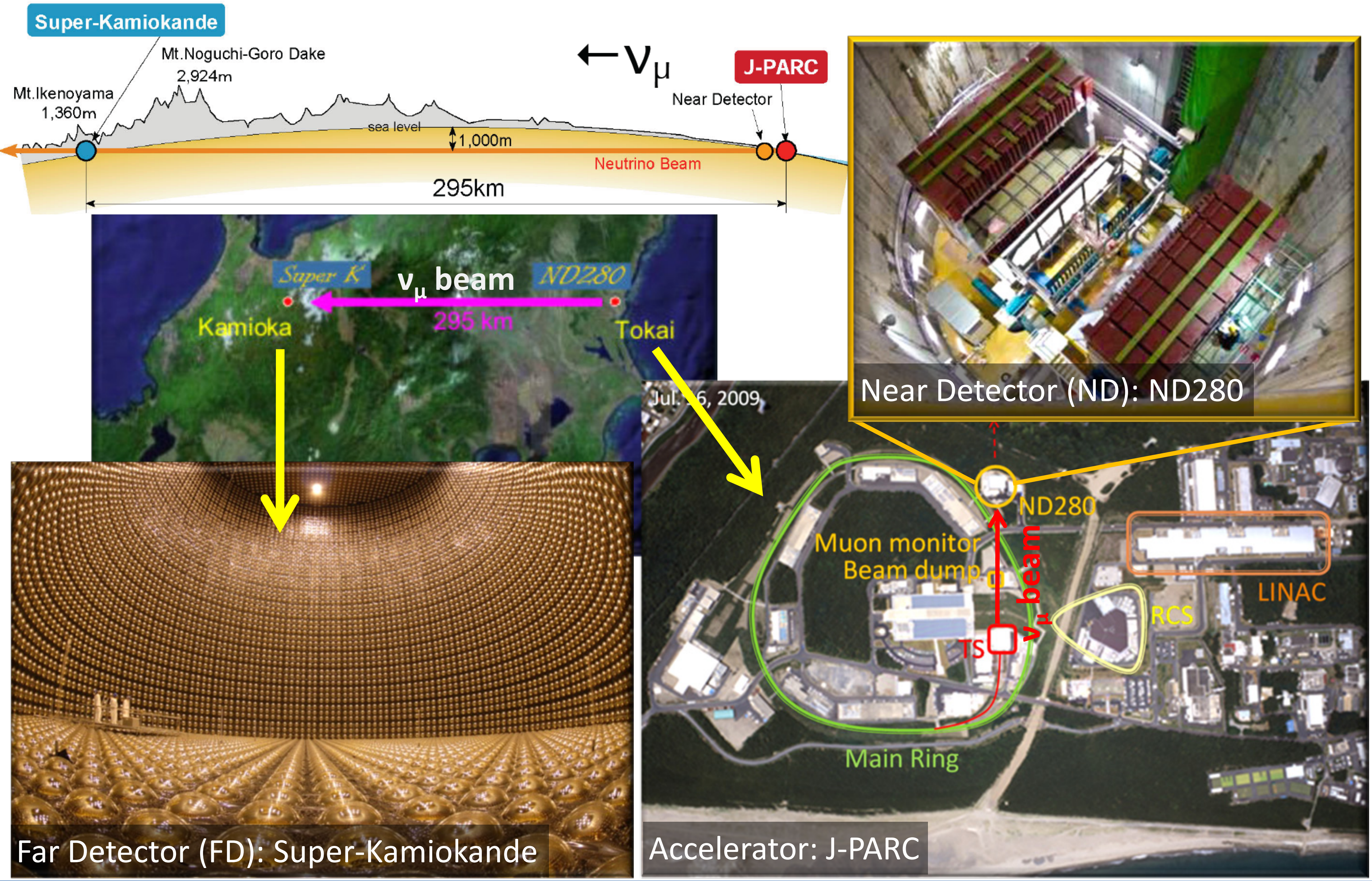
ν_e appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2(\Delta m_{23}^2 L/4E_\nu)$$

ν_μ disappearance

$$P(\nu_\mu \to \nu_x) \approx \sin^2(2\theta_{23})\sin^2(\Delta m_{23}^2 L/4E_\nu)$$

Overview of T2K



Calculating # of Events and Oscillation Parameters

$$N_{FD}^{exp} = \frac{N_{ND}^{data}}{N_{ND}^{MC}} \boxed{N_{FD}^{MC}} \Leftarrow \boxed{\int \phi_{\nu_\mu(\nu_e)}^{FD} \cdot \sigma \cdot \varepsilon_{FD} \cdot P_{osc} \cdot dE_\nu}$$

Number of interactions

Measurements

- N_{ND}^{data} used to normalize prediction at FD
- N_{FD}^{exp} fitted to the number of observed events at the FD, N_{FD}^{data}, to extract the oscillation parameters:

Neutrino Flux

- Prediction from MC simulation
- Understanding of the proton beam and hadron production

Cross Section

- Input from theoretical calculation and previous experiments
- Large uncertainties

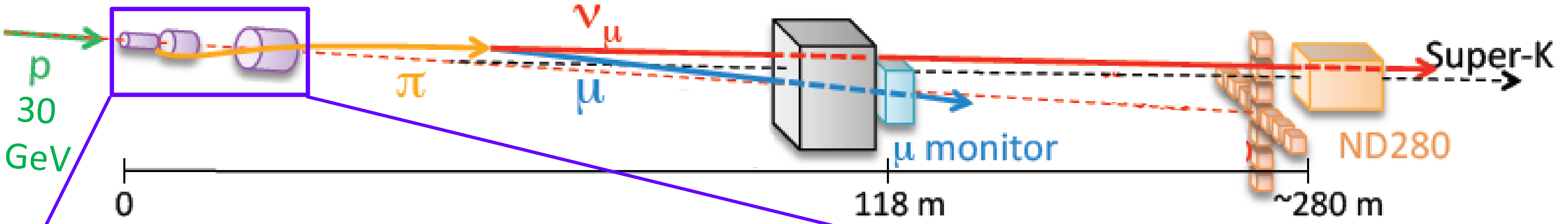
Efficiency

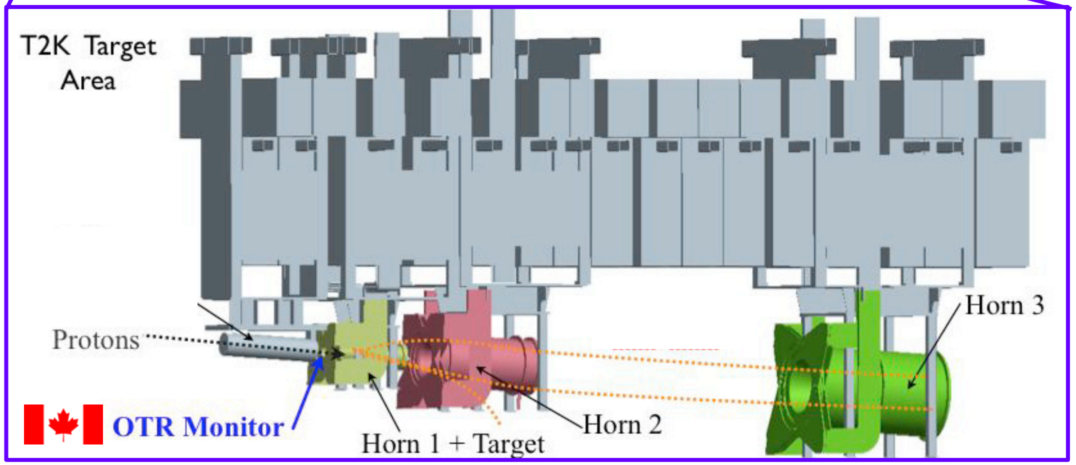
- Detector performance
- Event reconstruction and selection

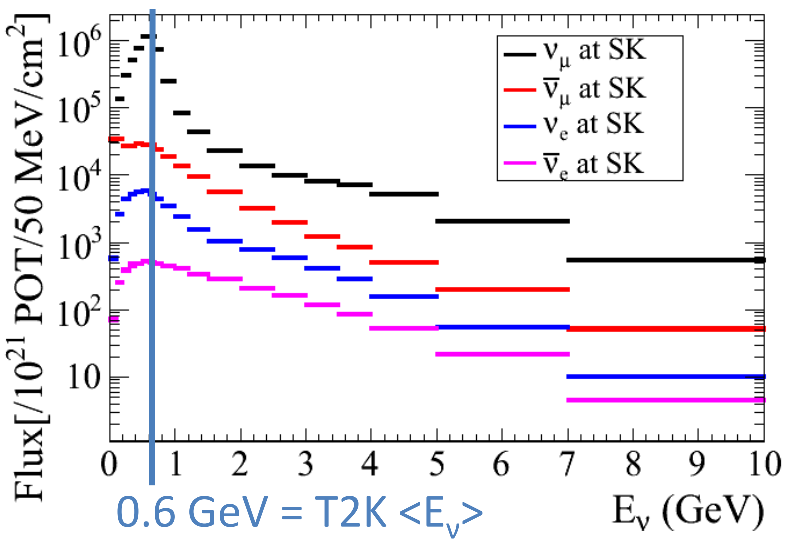
$$P_{osc} = \begin{cases} P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\sin^2(\Delta m_{23}^2 L/4E_\nu), & \nu_\mu \text{ disappearance} \\ P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2(\Delta m_{23}^2 L/4E_\nu), & \nu_e \text{ appearance} \end{cases}$$

Neutrino Beamline

$\phi \cdot \sigma \cdot \varepsilon \cdot P_{osc}$





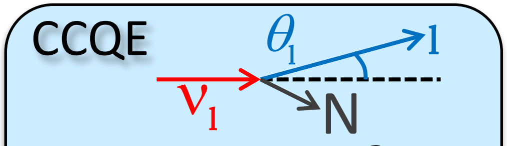


- Geant3/FLUKA MC based flux prediction
- Based on measurements
  - External: Hadron production experiments (NA61 and others)
  - In-situ: Proton beam monitors

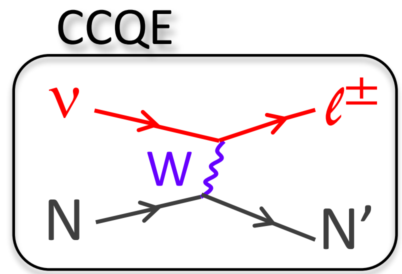
Neutrino Interactions

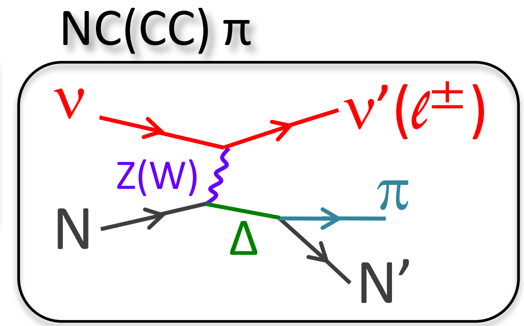
$\phi \cdot \sigma \cdot \varepsilon \cdot P_{osc}$

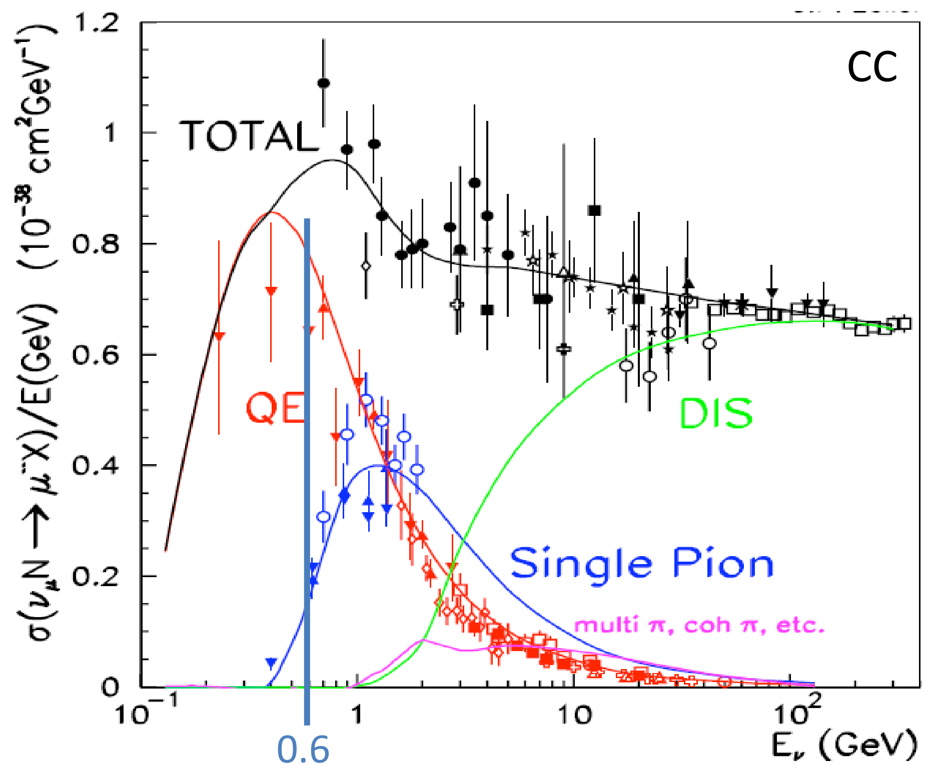
- Event generator MC based on theoretical cross section calculations and tuning from external data
- Reconstruct E_ν and flavour from observed lepton in CCQE interactions



$$E_\nu \approx \frac{m_N E_l - m_l^2/2}{m_N - E_l + p_l \cos\theta_l}$$

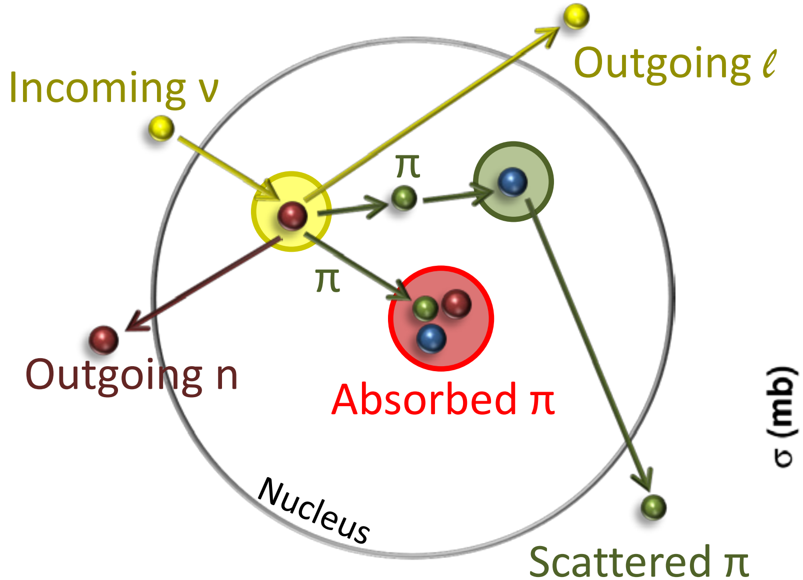




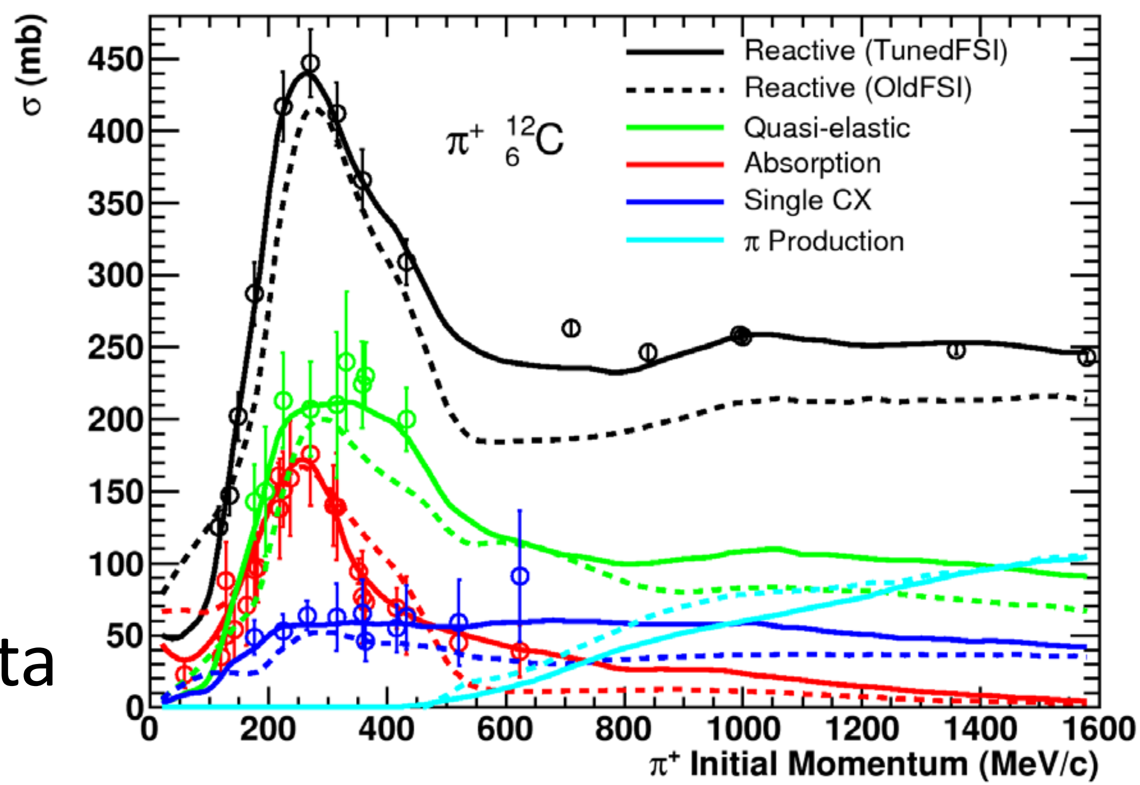


Pion Final State Interactions

$\phi \cdot \sigma \cdot \varepsilon \cdot P_{osc}$



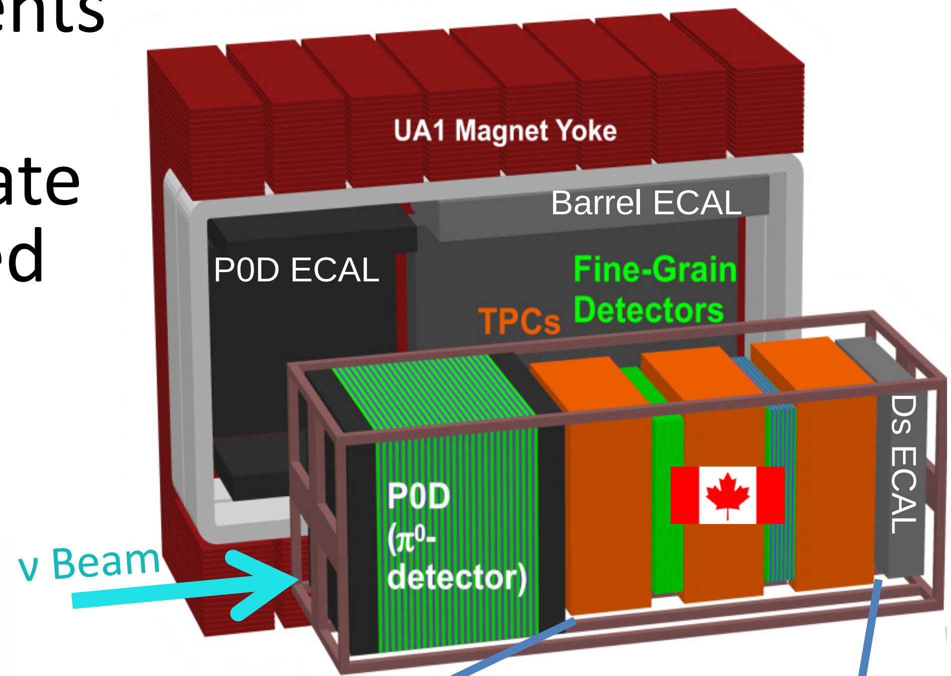
- Affects background contribution to CCQE sample
- Final state interactions (FSI) simulated by microscopic cascade model
- Tuned and constrained with external pion scattering and photoproduction data

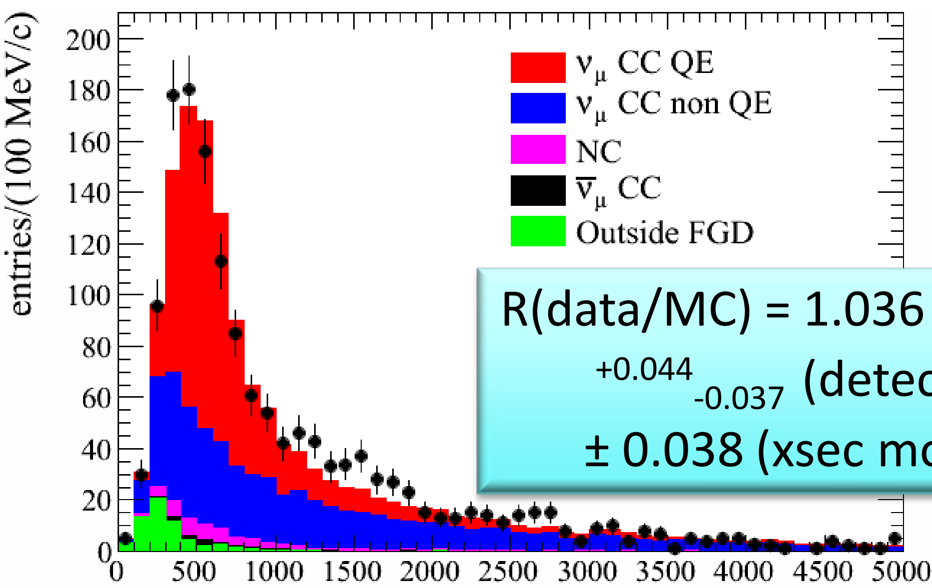


ND280

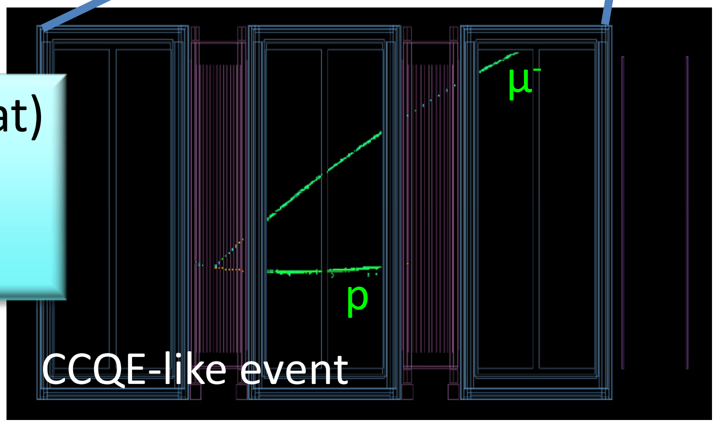
$$N_{FD}^{exp} = \frac{N_{ND}^{data}}{N_{ND}^{MC}} N_{FD}^{MC}, \quad \phi \cdot \sigma \cdot \varepsilon \cdot P_{osc}$$

- Select ν_μ CC candidate events from reconstructed μ^-
- Use data/MC integrated rate ratio to normalize expected number of events at SK
- Future: Neutrino cross section measurements





R(data/MC) = 1.036 ± 0.028 (stat) $^{+0.044}_{-0.037}$ (detector syst.) ± 0.038 (xsec model syst.)

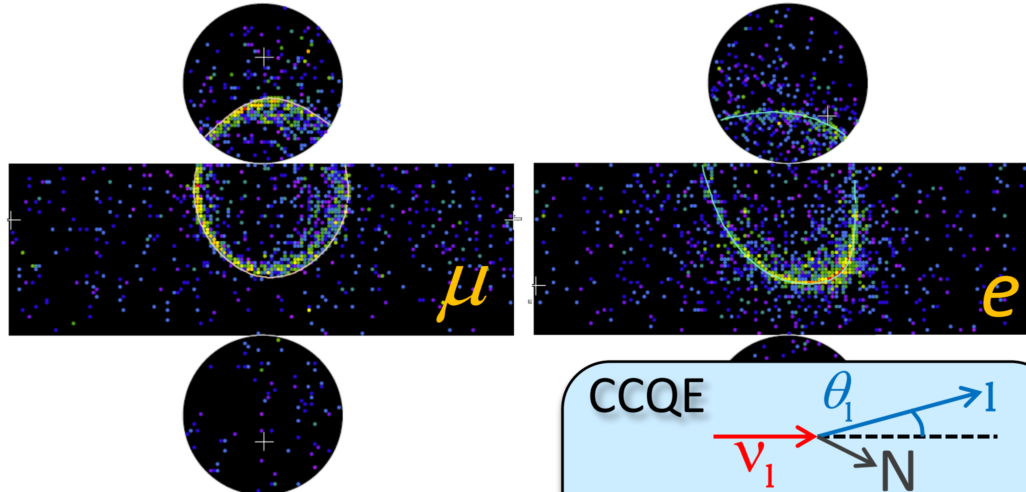


Dataset from 2.88×10^{19} POT

Super-K

$N_{FD}^{\text{data}}, \ \phi\cdot\sigma\cdot\varepsilon\cdot P_{osc}$

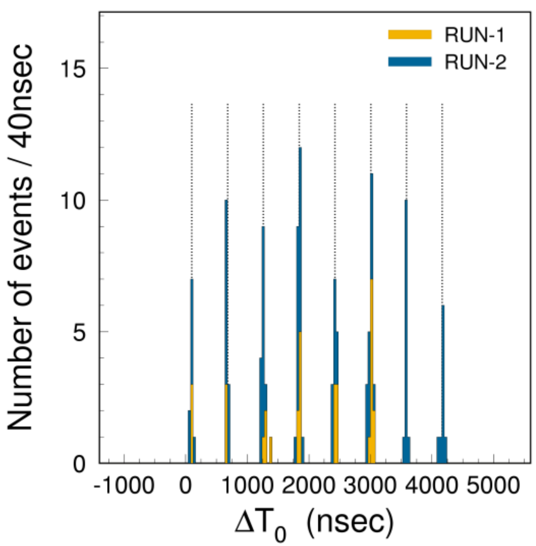
- 50 kton water Čerenkov detector
- 1 km underground
- 11k PMTs in ID
- Event reconstruction: See Shimpei Tobayama's talk tomorrow



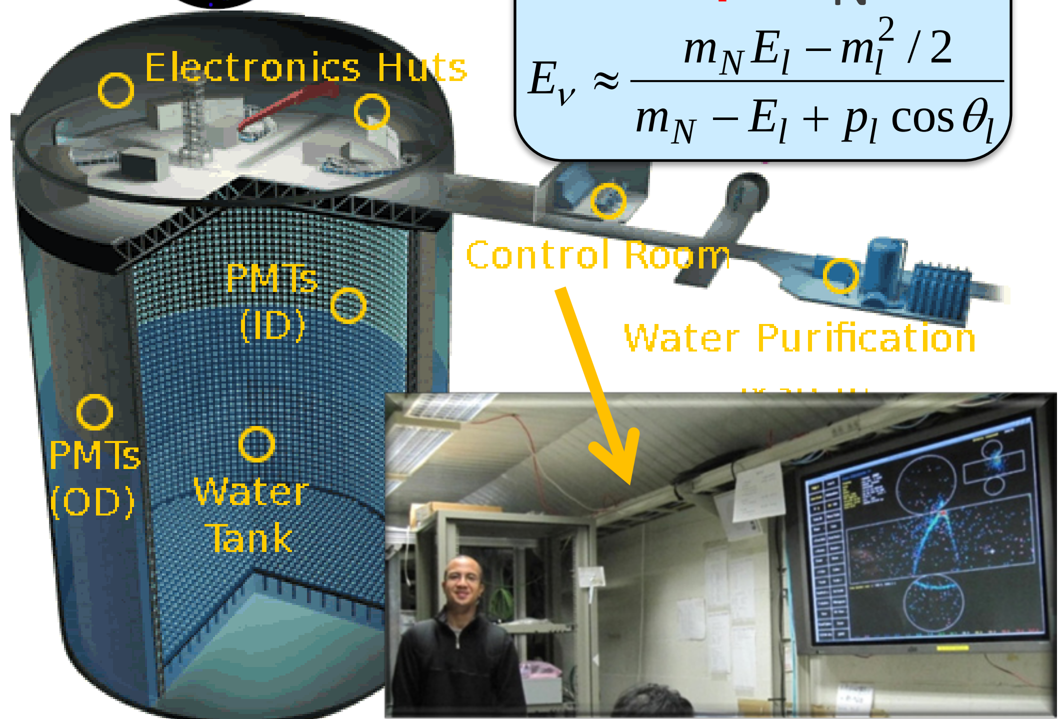
CCQE

ν_l → l, N (θ_l)

$$E_\nu \approx \frac{m_N E_l - m_l^2/2}{m_N - E_l + p_l\cos\theta_l}$$



Timing of events corresponds to beam timing from GPS



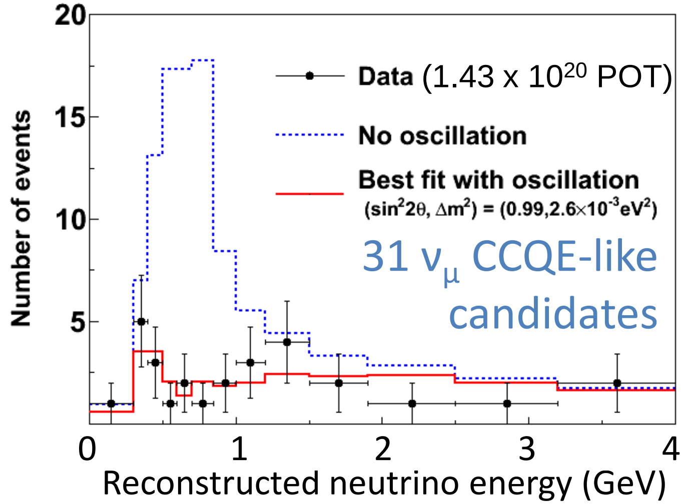
Oscillation Analysis

$$N_{FD}^{data},\ N_{FD}^{exp} = \frac{N_{ND}^{data}}{N_{ND}^{MC}} N_{FD}^{MC},\ \phi\cdot\sigma\cdot\varepsilon\cdot P_{osc}$$

- Select fully contained events in fiducial volume
- 1-ring, μ or e-like
- Perform fit to extract oscillation parameters

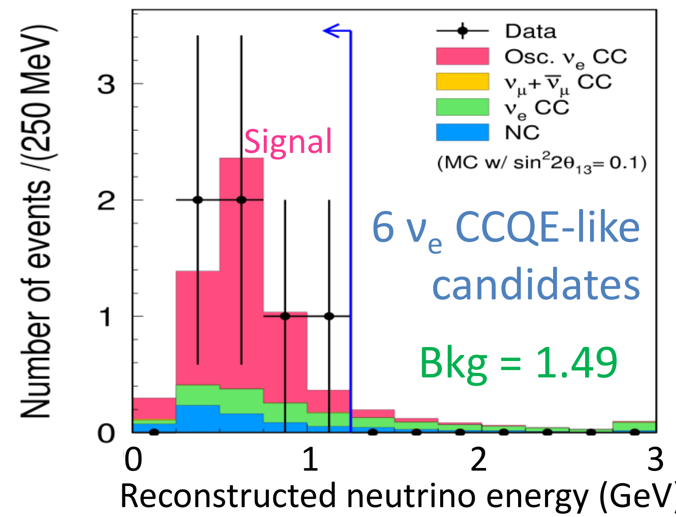
ν_μ disappearance

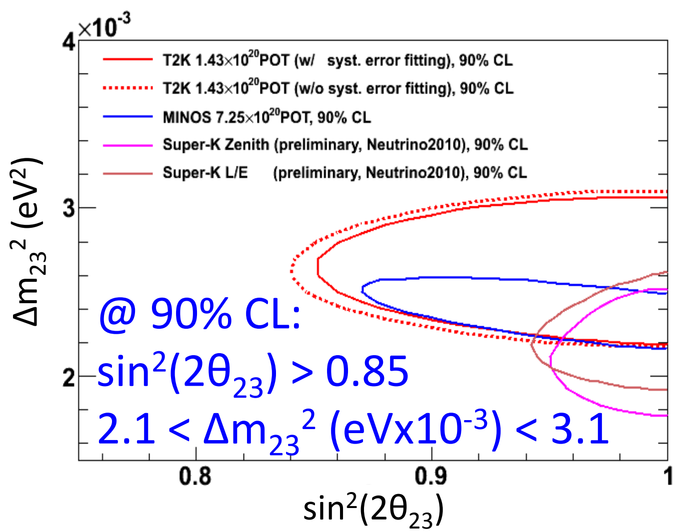
$$P(\nu_\mu \to \nu_x) \approx \sin^2(2\theta_{23})\sin^2(\Delta m_{23}^2 L/4E_\nu)$$

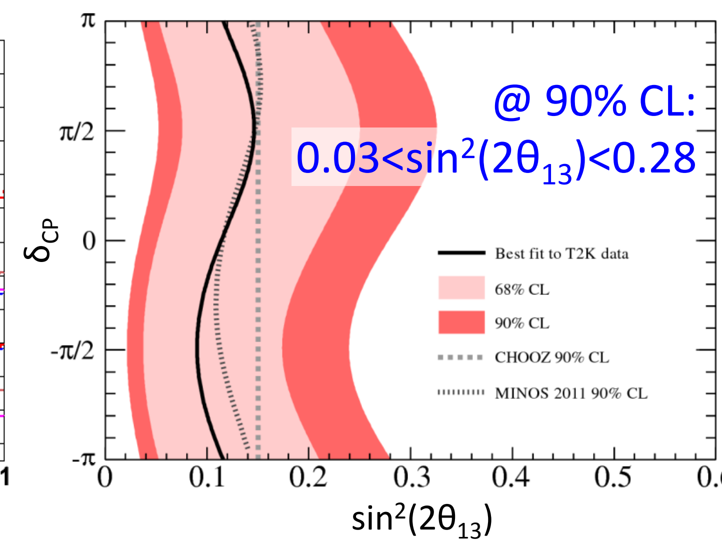


ν_e appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2(\Delta m_{23}^2 L/4E_\nu)$$

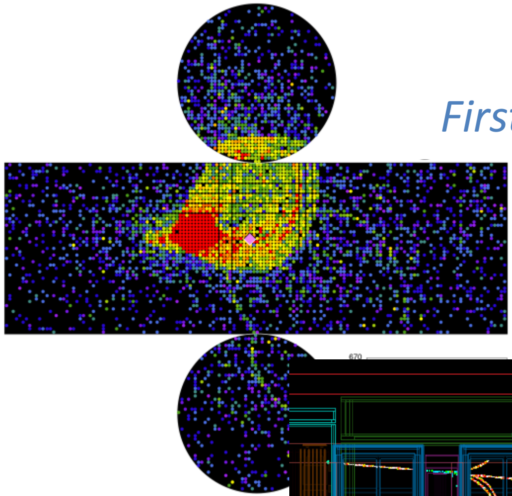


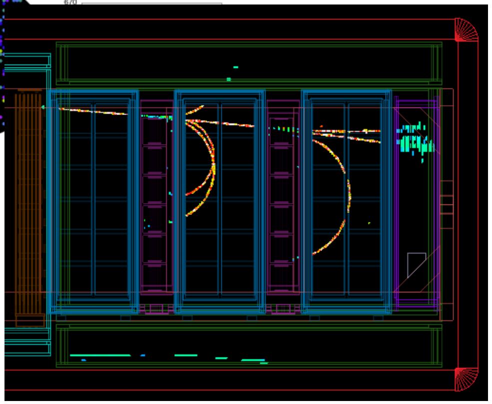




Conclusions and Prospect

- Results with only 2% of design POT:
  - ν_μ disappearance measurement rejects null-oscillation at 4.5σ, consistent with MINOS, SK and K2K
  - ν_e appearance first indication of non-zero θ_{13} at 2.5σ, subsequent results from MINOS and Double Chooz are consistent





First events after earthquake

- Continuous beam running will resume (after the earthquake) in March
- Improvements to analysis and systematics
- Neutrino cross section measurements by ND280

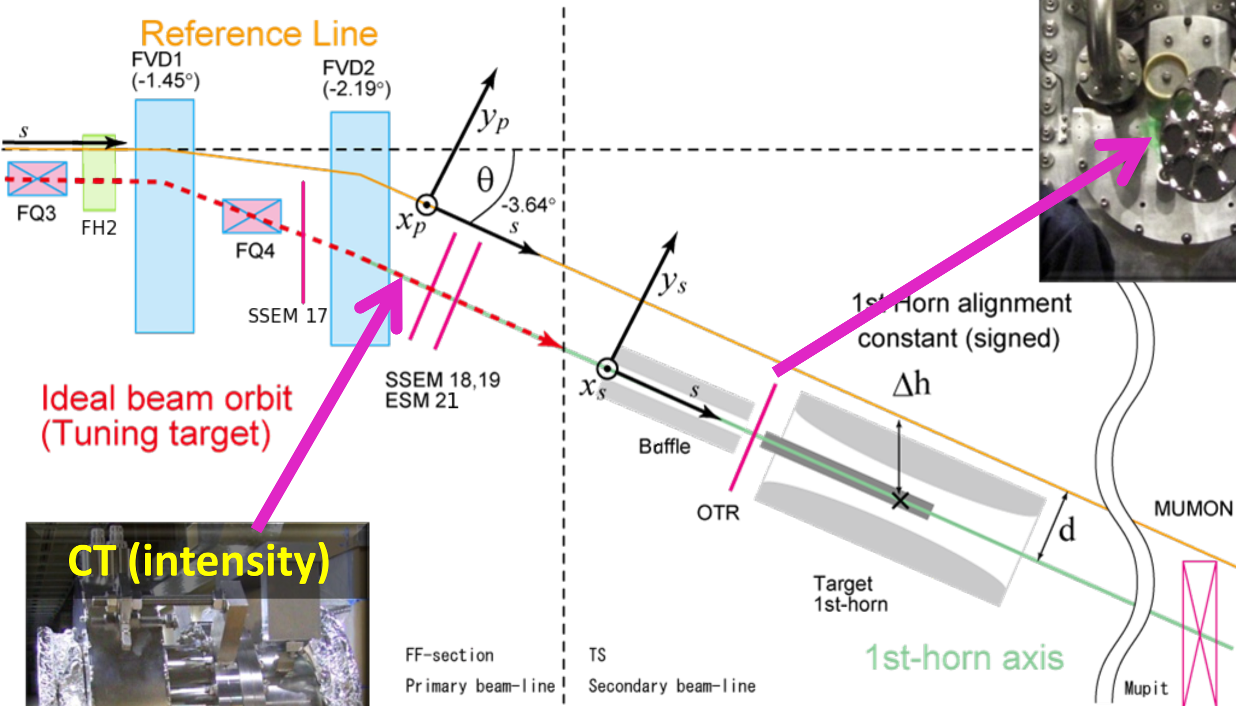

The T2K Collaboration
Thank you and stay tuned...

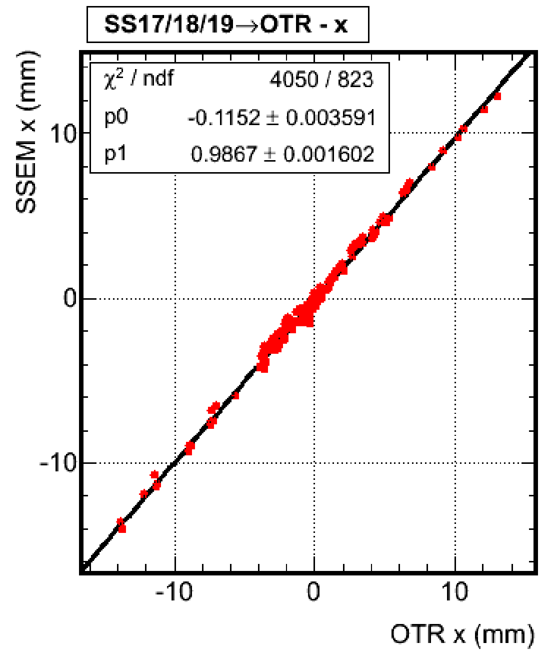
BONUS

Proton Beam Monitors

$\phi \cdot \sigma \cdot \varepsilon \cdot P_{osc}$

$$\phi_{SK}^{MC} \rightarrow \phi[\mathrm{POT}^{-1}] \cdot POT$$

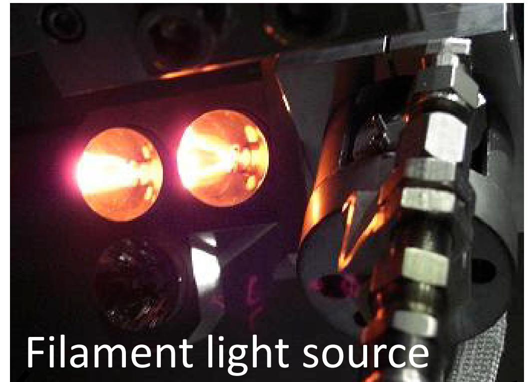


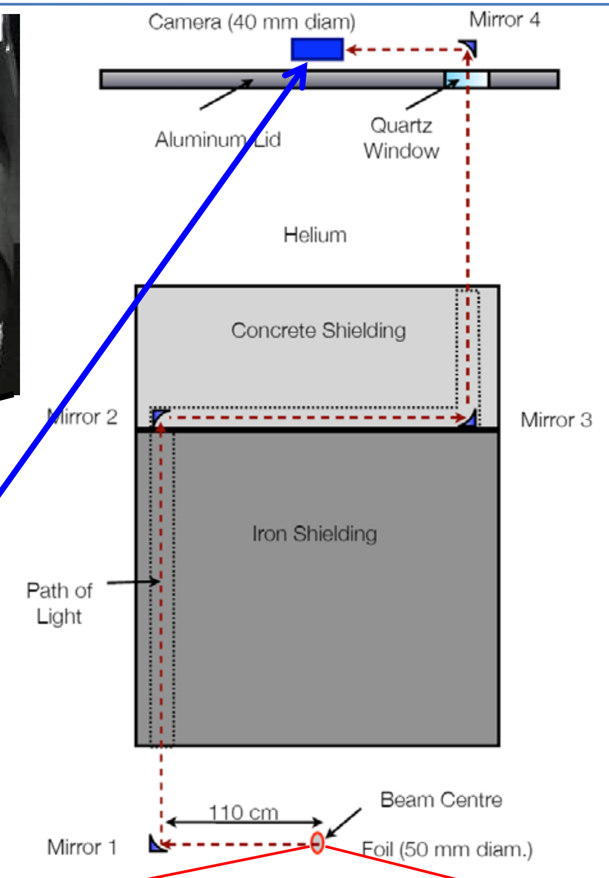


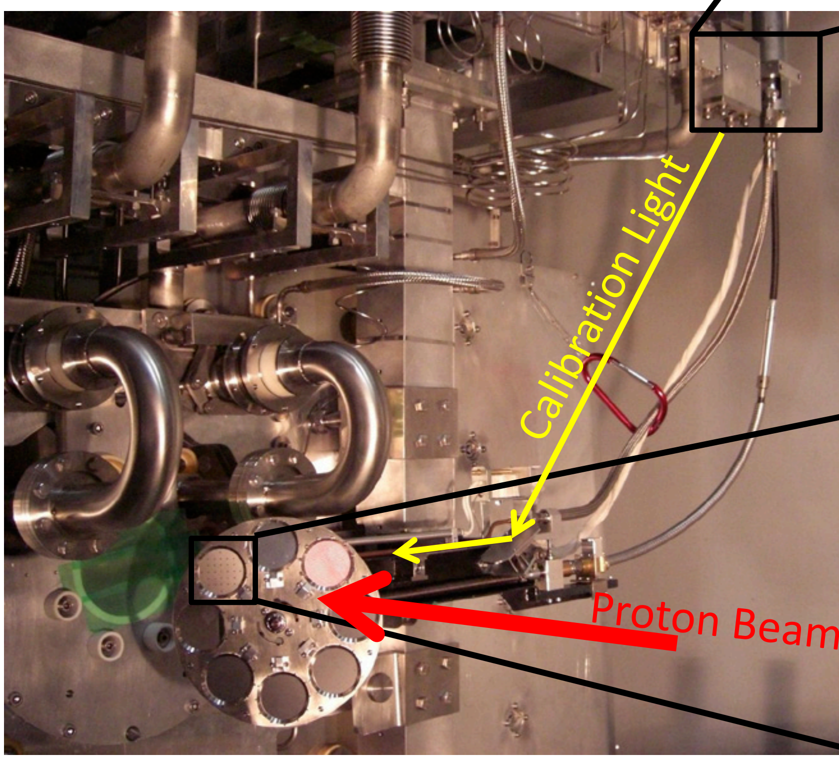
OTR Proton Beam Monitor

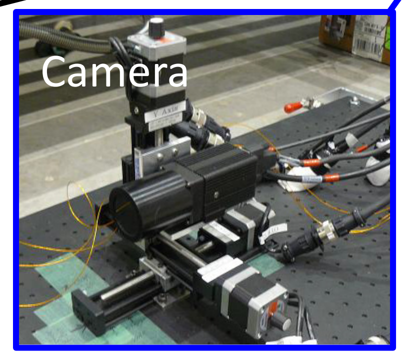
$\phi \cdot \sigma \cdot \varepsilon \cdot P_{osc}$

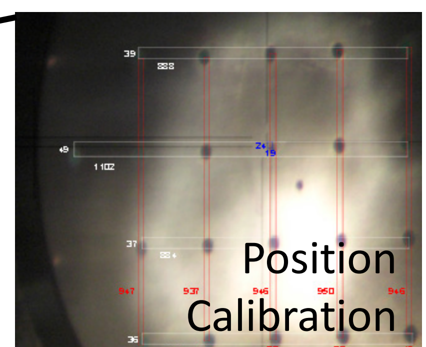
- Measures beam position and width at the target
- Strong constraint on the resulting ν-beam direction

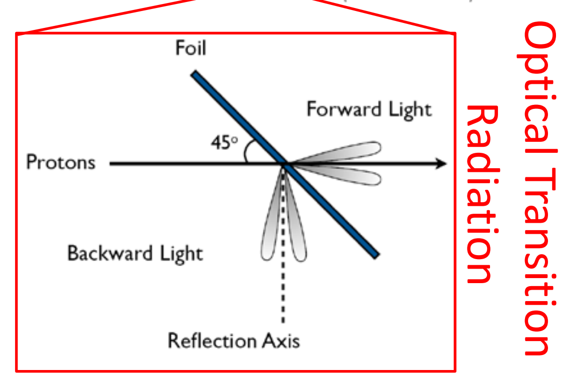










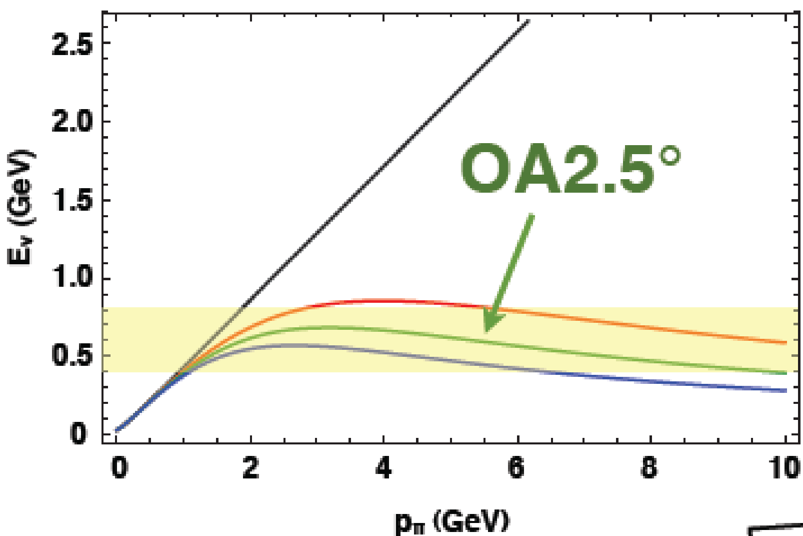


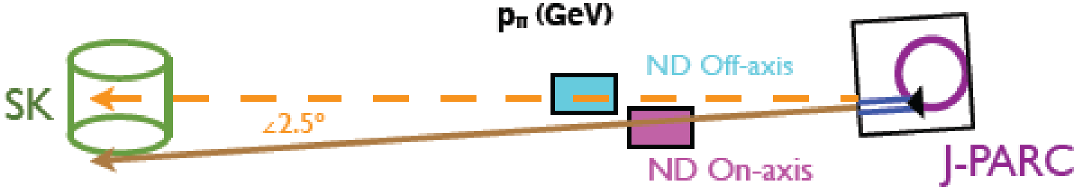
Off-axis Neutrino Beam

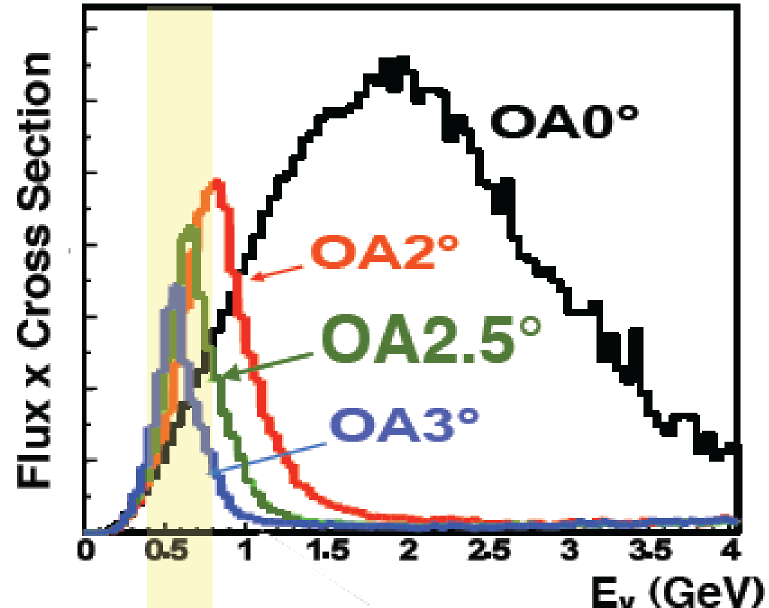
$\phi \cdot \sigma \cdot \varepsilon \cdot P_{osc}$

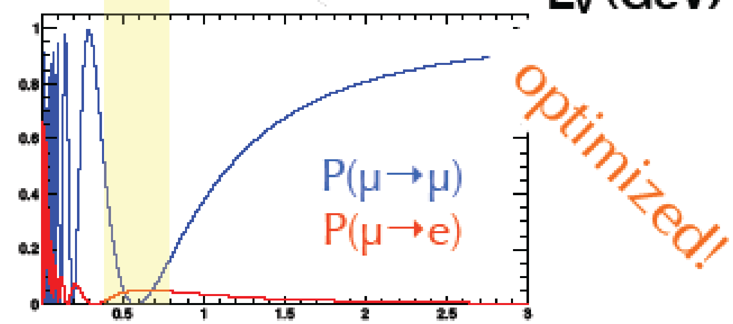
- 2-body decay → exact kinematics

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$



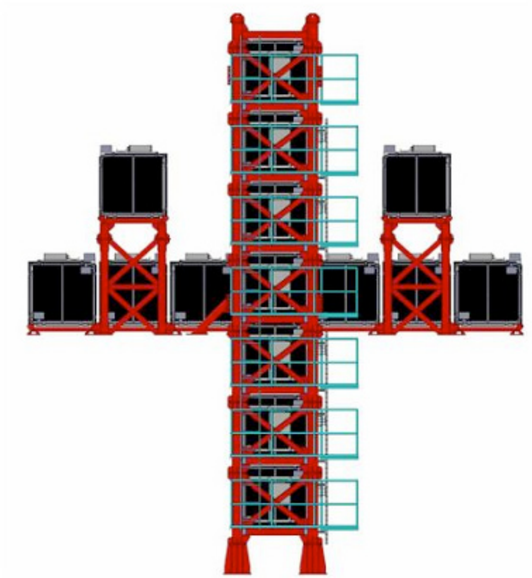




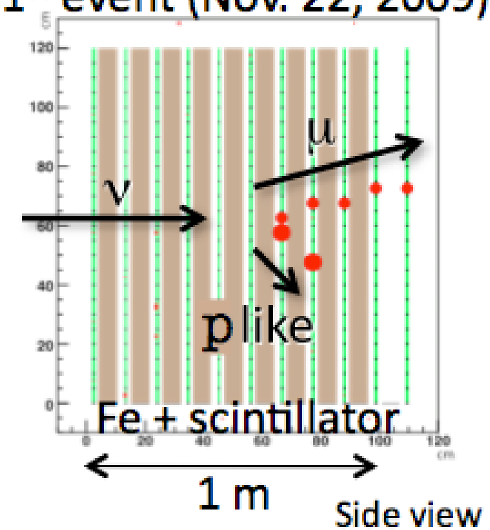


On-Axis Neutrino Detector: INGRID

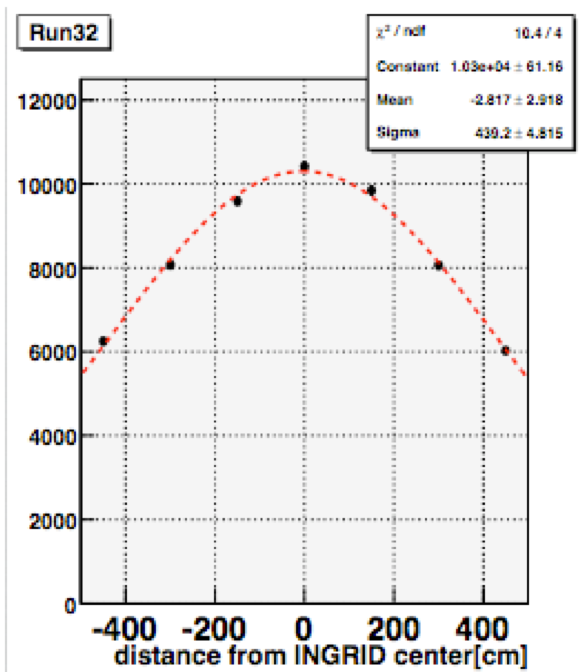
$\phi \cdot \sigma \cdot \varepsilon \cdot P_{osc}$

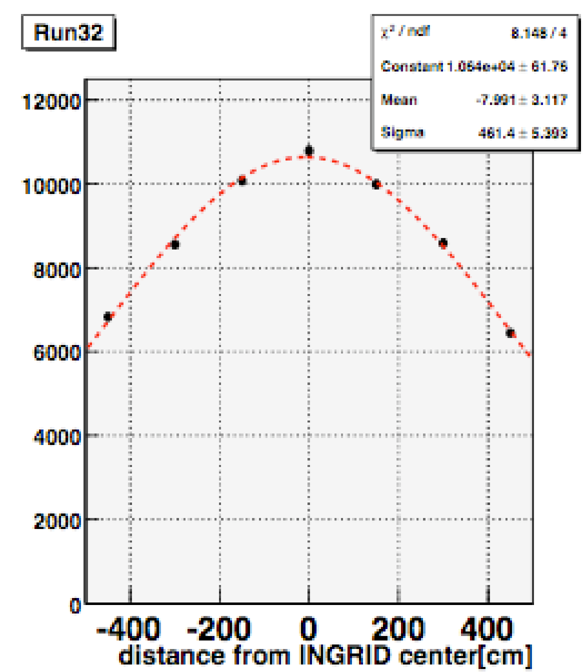


1st event (Nov. 22, 2009)



- 16 modules arranged in a cross
  - X-Y iron-scintillator layers, 7.1 tons each
- Count neutrino interactions in each module to determine neutrino rate vs. position
- Extract beam direction better than 0.5 mrad





ν_e Appearance Backgrounds

$\phi \cdot \sigma \cdot \varepsilon \cdot P_{osc}$

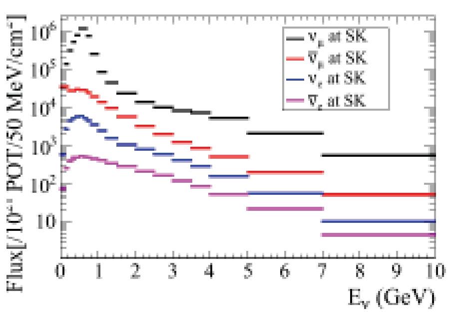
1) Beam ν_e:
ν_μ beam only ~99% pure in signal region

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \overline{\nu_\mu} + \nu_e$$

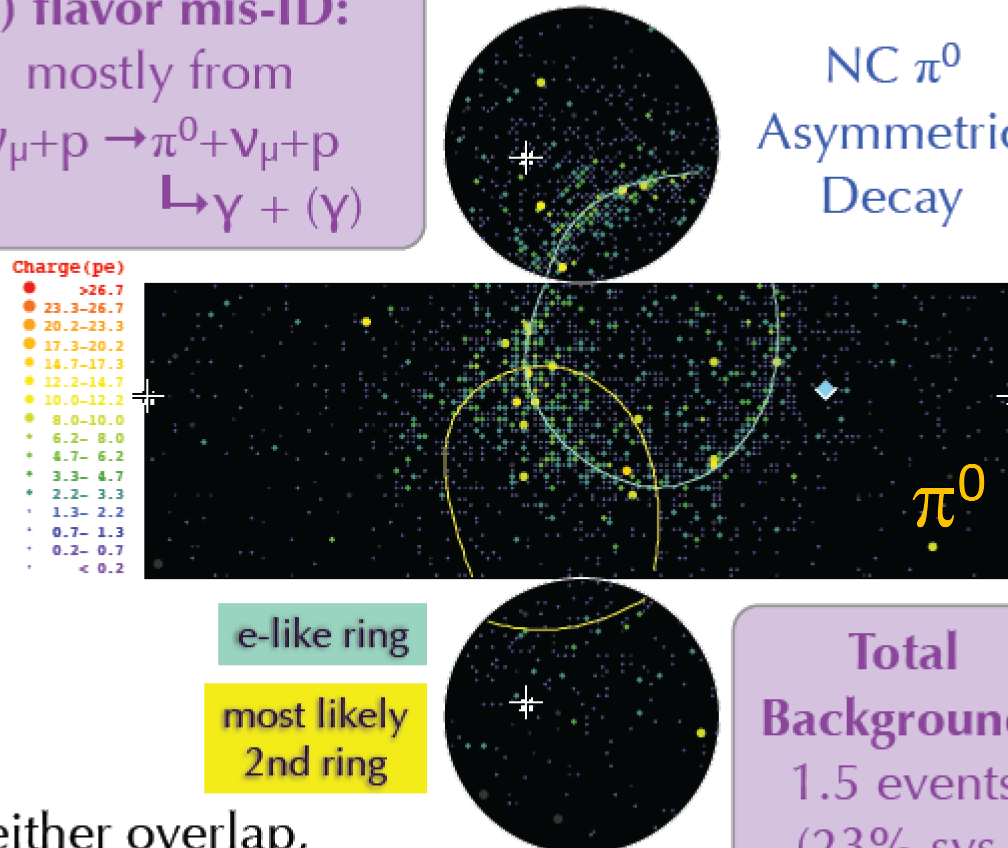
$$K^+ \rightarrow \pi^0 + e^+ + \nu_e$$

$$K_L^0 \rightarrow \pi^+ + e^- + \nu_e$$



2) flavor mis-ID:
mostly from
$\nu_\mu + p \rightarrow \pi^0 + \nu_\mu + p$
$\hookrightarrow \gamma + (\gamma)$

NC π^0 Asymmetric Decay



e-like ring

most likely 2nd ring

SK atmospheric MC

γs either overlap, or one is faint

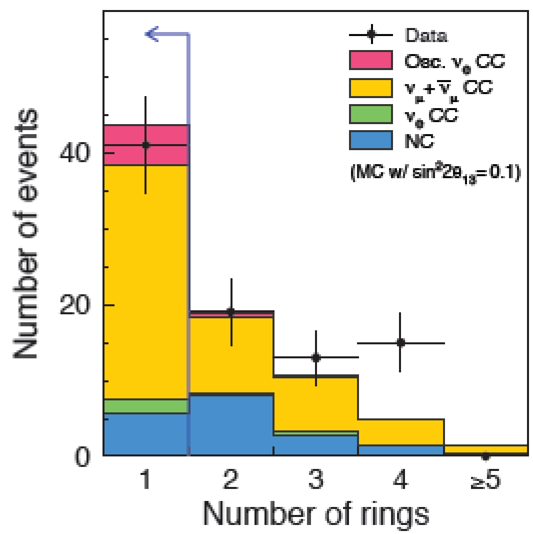
Total Background:
1.5 events
(23% sys. error)

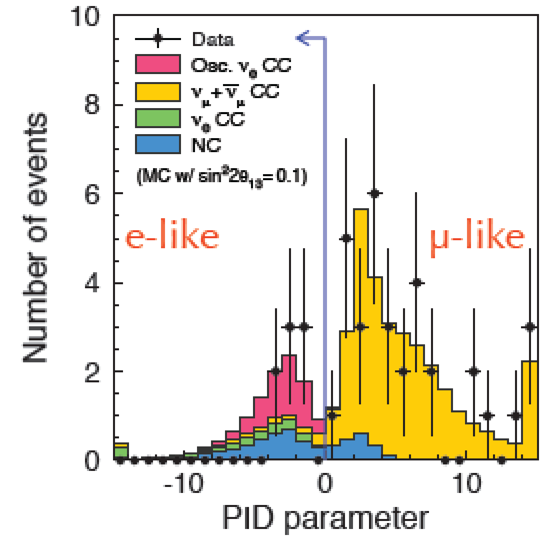
ν_e Event Selection

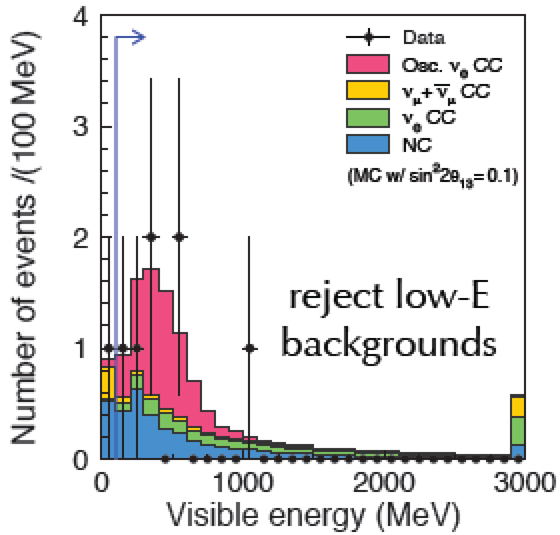
$\phi \cdot \sigma \cdot \varepsilon \cdot P_{osc}$

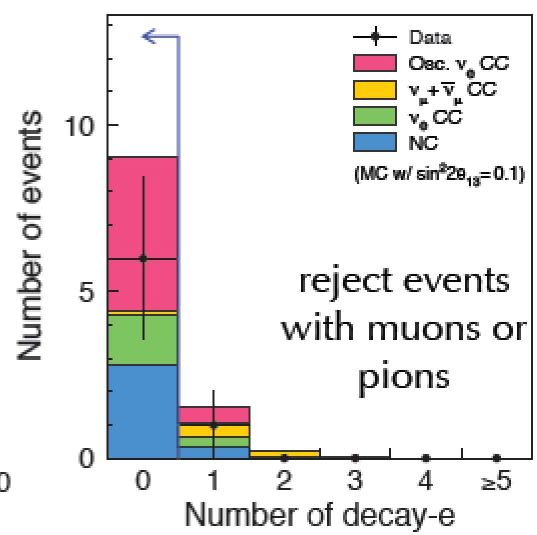
- Fully Contained
- Fiducial Volume
- Single Ring
- e-like
- $E_{visible} > 100$ MeV
- $N_{decay} = 0$
- $m_\pi < 105$ MeV

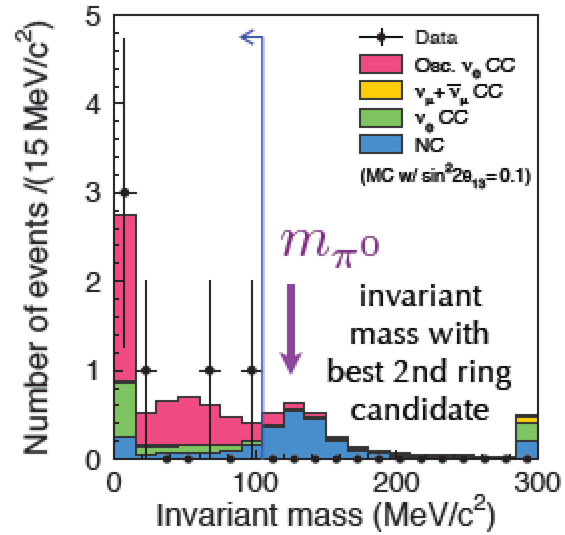
Data: 6 Events...



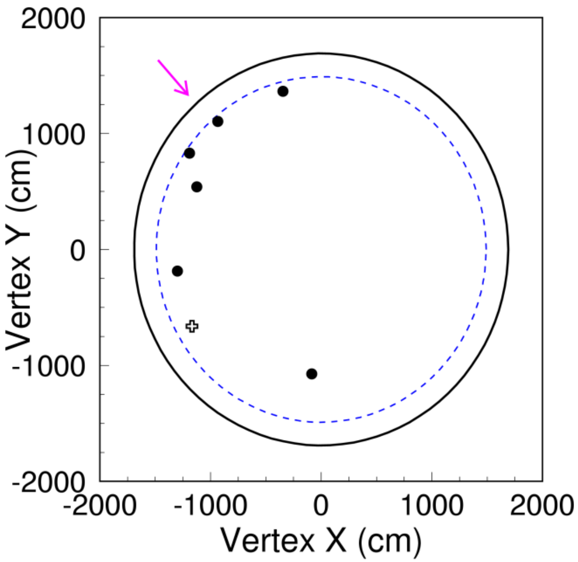


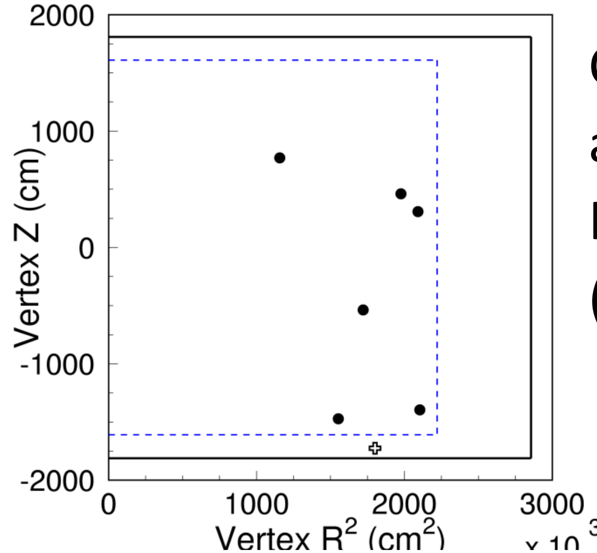






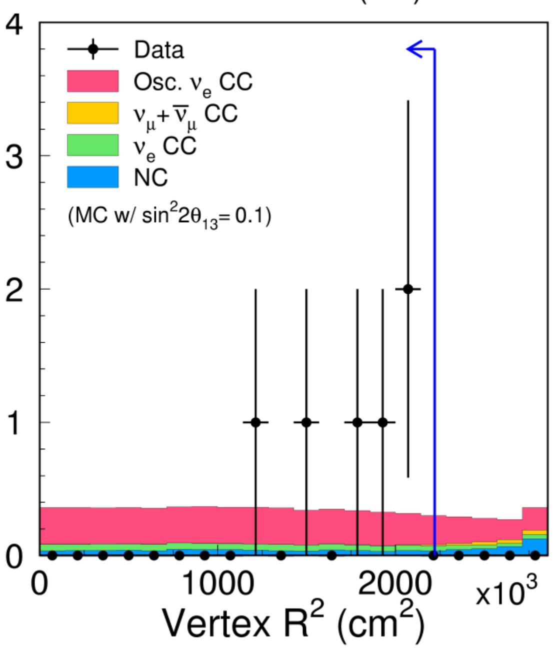
ν_e Event Vertex Distributions

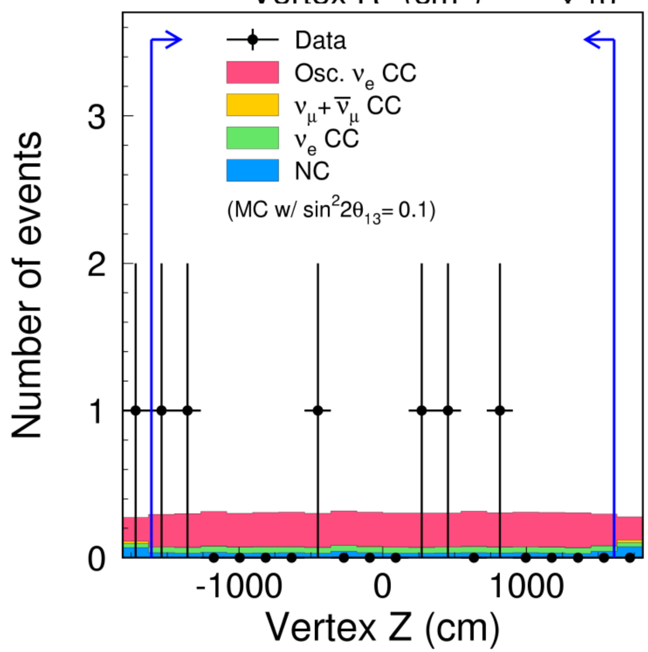




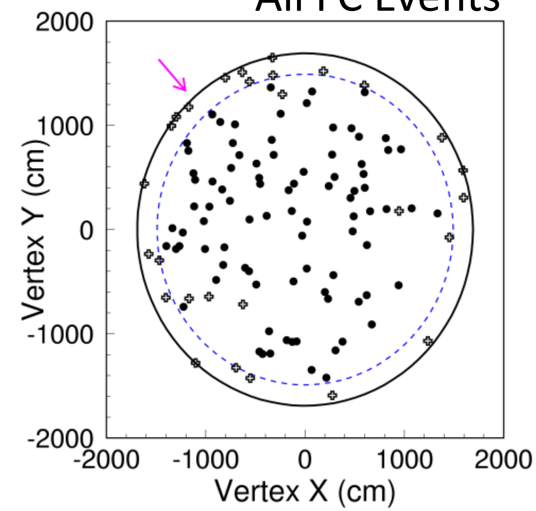
Clustering of candidates at high R in beam direction

KS test of R^2 variable is 3% (does not include beam dir)





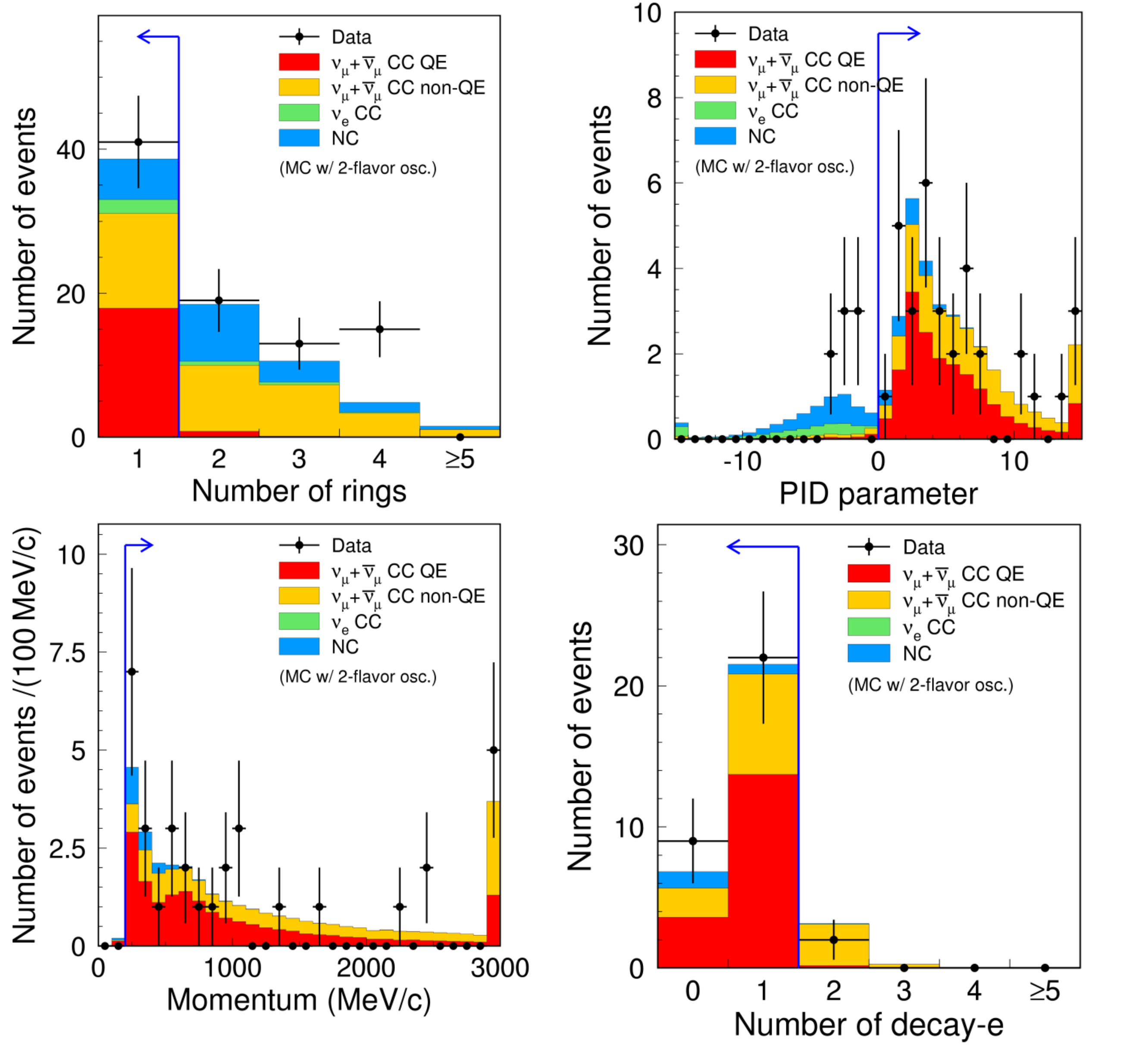
All FC Events



ν_μ Event Selection

$\phi \cdot \sigma \cdot \varepsilon \cdot P_{osc}$

- Single-ring
- μ-like
- $P_\mu > 200$ MeV/c
- [redacted]



Beam and Interaction Uncertainties

$\phi \cdot \sigma \cdot \varepsilon \cdot P_{osc}$

Flux uncertainties	ND	ν_e bkrd	ν_e / ND
Proton beam	2.2%	0.0%	2.2%
Pion production	5.7%	6.2%	2.5%
Kaon production	10.0%	11.1%	7.6%
Other hadronic interactions	9.7%	9.5%	1.5%
Meson focusing, beam direction	2.8%	2.2%	0.8%
Total	15.4%	16.1%	8.5%

Uncertainty (after ND scaling)	ν_μ signal	ν_e bkrd
CCQE nuclear model (@lowE)	2.5%	3.1%
CC1π	+0.4% -0.5%	2.2%
CC coherent π	-	3.1%
CC other	+4.1% -3.6%	4.4%
NC all	0.9%	-
NC1π^0	-	5.3%
NC coherent π	-	2.3%
NC other	-	2.3%
$\sigma(\nu_e)$	N/A	3.4%
Final State Interactions (FSI)	6.7%	10.1%
Total	+8.3%-8.1%	14.0%

ν_e Analysis Summary

$$\phi \cdot \sigma \cdot \varepsilon \cdot P_{osc}$$

Far detector uncertainties (%)	ν_e signal	ν_e bkgd
Ring counting	3.9%	8.3%
Electron PID	3.8%	8.0%
Invariant mass	5.1%	8.7%
π^0 rejection	-	3.6%
Fiducial volume	1.4%	1.4%
Energy scale	0.4%	1.1%
Decay electron eff	0.1%	0.3%
Muon PID	-	1.0%
Total	7.6%	15%

Signal (ν_μ to ν_e osc)	# events
@$\sin^2 2\theta_{13}$=0.1, δcp=0	4.11

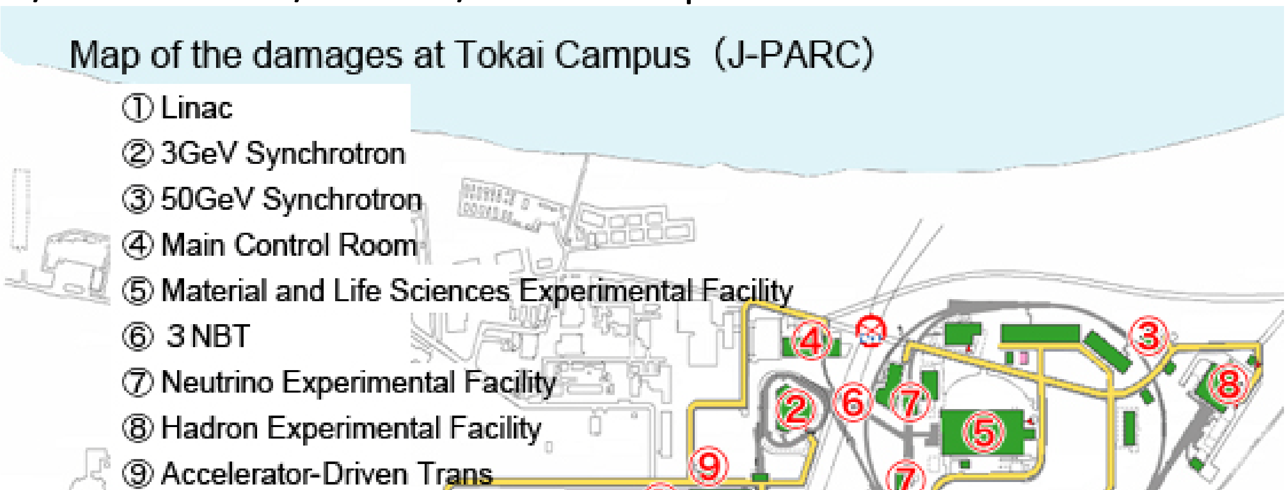
Background	# events
beam ν_e	0.76
ν_μ CC background	0.03
NC background	0.61
osc through θ_{12}	0.09
Total	1.49±0.34(sys)

Uncertainties	ν_e bkrd	ν_e sig+bkrd
ν flux	±8.5%	±8.5%
ν interactions	±14.0%	±10.5%
Near detector	+5.6 -5.2%	+5.6 -5.2%
Far detector	±14.7%	±9.4%
Total	+22.8 -22.7%	+17.6 -17.5%

Earthquake Damage

$\phi \cdot \sigma \cdot \varepsilon \cdot P_{osc}$

http://www.kek.jp/intra-e/Introduction/column/110509map.html

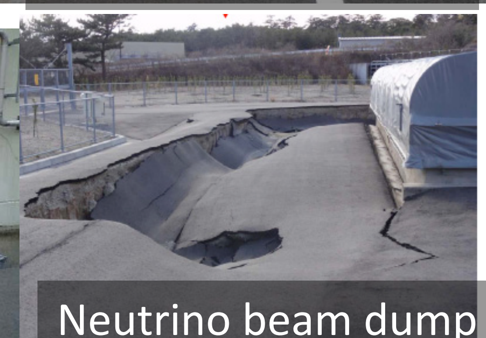



3 GeV synchrotron power station


Road near 3 GeV RCS


LINAC


Neutrino Hall AC


Neutrino beam dump