BNL Seminar

First T2K Neutrino Oscillation Results

Clark McGrew
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For the T2K Collaboration

- Background
- Experiment
  - Accelerator
  - Near Detectors
  - Far Detector (SK)
- Results
  - ν_μ Disappearance Measurement
  - ν_e Appearance Search

The Earthquake

- As you might expect, the situation after the March 11 quake is changing rapidly
- No T2K collaborators or JPARC staff were injured
  - Most foreign collaborators left Japan following the quake
- Preliminary inspections are being carried out by on-site collaborators
  - No "significant" damage found
- KEK and JPARC are beginning to open for visitors
- Power is still limited
- No official word on when the next T2K run will start

T2K Goals

- Search for $\nu_\mu \rightarrow \nu_e$ (ν_e appearance) consistent with $|\Delta m^2_{13}|$
  - Observation will indicate non-zero θ_{13}
    - But, sensitive to admixture of θ_{13} and δ_{CP}
  - First direct observation of ν_e, ν_μ or ν_τ appearance
- Precision measurement of $\nu_\mu \rightarrow \nu_\mu$ (ν_μ disappearance)
  - Measure $|\Delta m^2_{13}|$ and θ_{23}
- Neutrino properties at $E_\nu \sim 700$ MeV
  - Narrow band off axis neutrino beam.

Neutrino Oscillation Redux

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Solar Mixing: Δm^2_{12}, θ_{12}

Atmospheric Mixing: $|\Delta m^2_{13}|$, θ_{23}

$\nu_\mu \rightarrow \nu_e$ appearance (disappearance) at L/E consistent with $|\Delta m^2_{13}|$

Unknown: θ_{13}, δ_{CP}, sign(Δm^2_{13})

neutrino/anti-neutrino differences

matter effects

T2K

The T2K Collaboration

Canada

U. Alberta
U. B. Columbia
U. Regina
U. Toronto
TRIUMF
U. Victoria
York U.

France

CEA Saclay
IPN Lyon
LLR E. Poly
LPNHE Paris

Germany

RWTH
Aachen U.

Italy

INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan

ICRR Kamioka
ICRR RCCN
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu
Osaka City U.
U. Tokyo

Poland

A. Soltan, Warsaw
H.Niewodniczansk Cracow
U. Silesia, Katowice
T. U. Warsaw
U. Warsaw
U. Wroclaw

Russia

INR

S Korea

N. U. Chonnam
U. Dongshin
N. U. Seoul

Spain

IFIC, Valencia
U. A. Barcelona

Switzerland

ETH Zurich
U. Bern
U. Geneva

UK

Imperial C. L
Lancaster U
Liverpool U.
Queen Mary U. L
Oxford U.
Sheffield U.
STFC/RAL
STFC/Daresbury
Warwick U.

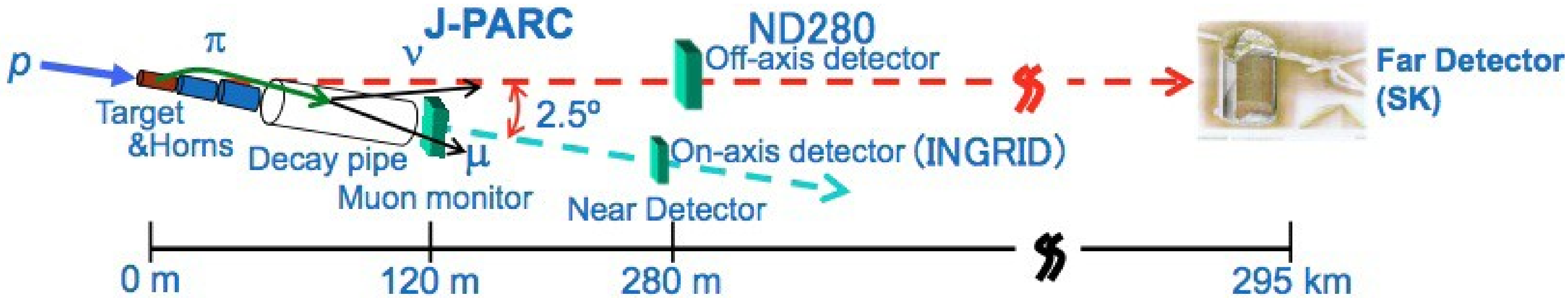
USA

Boston U.
B.N.L.
Colorado S. U.
U. Colorado
Duke U.
U. C. Irvine
Louisiana S. U.
U. Pittsburgh
U. Rochester
Stony Brook U.
U. Washington

Host Institutions: KEK/JAEA (J-PARC), ICRR (Kamioka Observatory)

12	Countries
59	Institutions
~500	Members

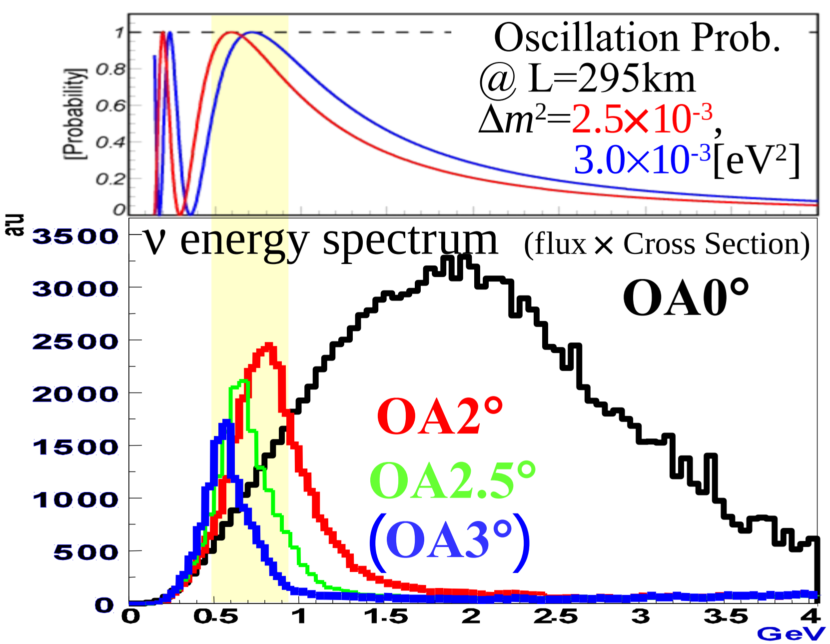
T2K Overview

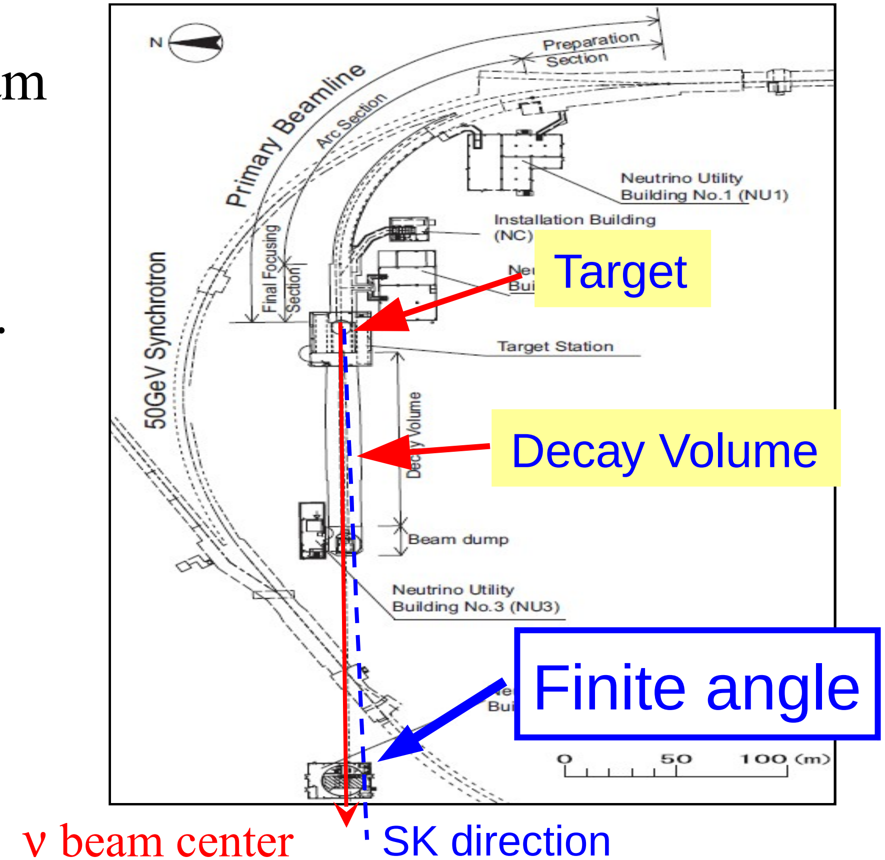


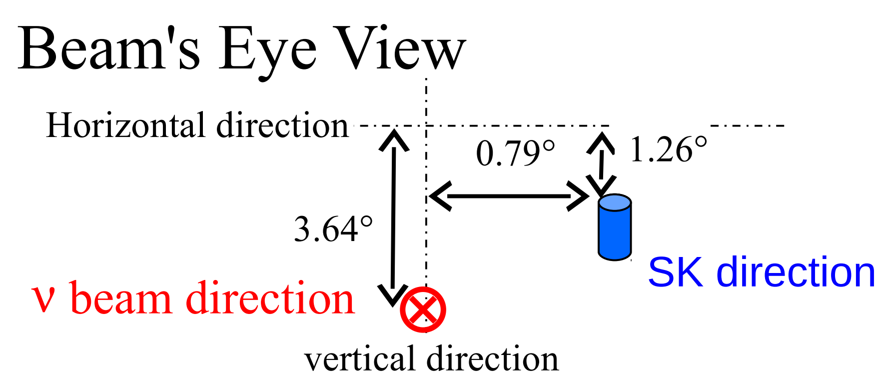
- Beam
  - 30 GeV proton beam on 90 cm graphite target
  - 3 magnetic horns focus positively charged hadrons
- Beam Monitoring
  - Primary proton beam intensity, position, profile
  - Muon monitors after beam dump: secondary beam intensity/direction
- Near Detector at 280 m
  - INGRID on-axis: ν beam direction/intensity
  - ND280 off-axis: ν beam flavor/flux/spectrum and cross-section
- Far Detector at 295 km @ 2.5 degree off-axis
  - Super-Kamiokande: ν flavor/flux/spectrum

T2K Off Axis Neutrino Beam

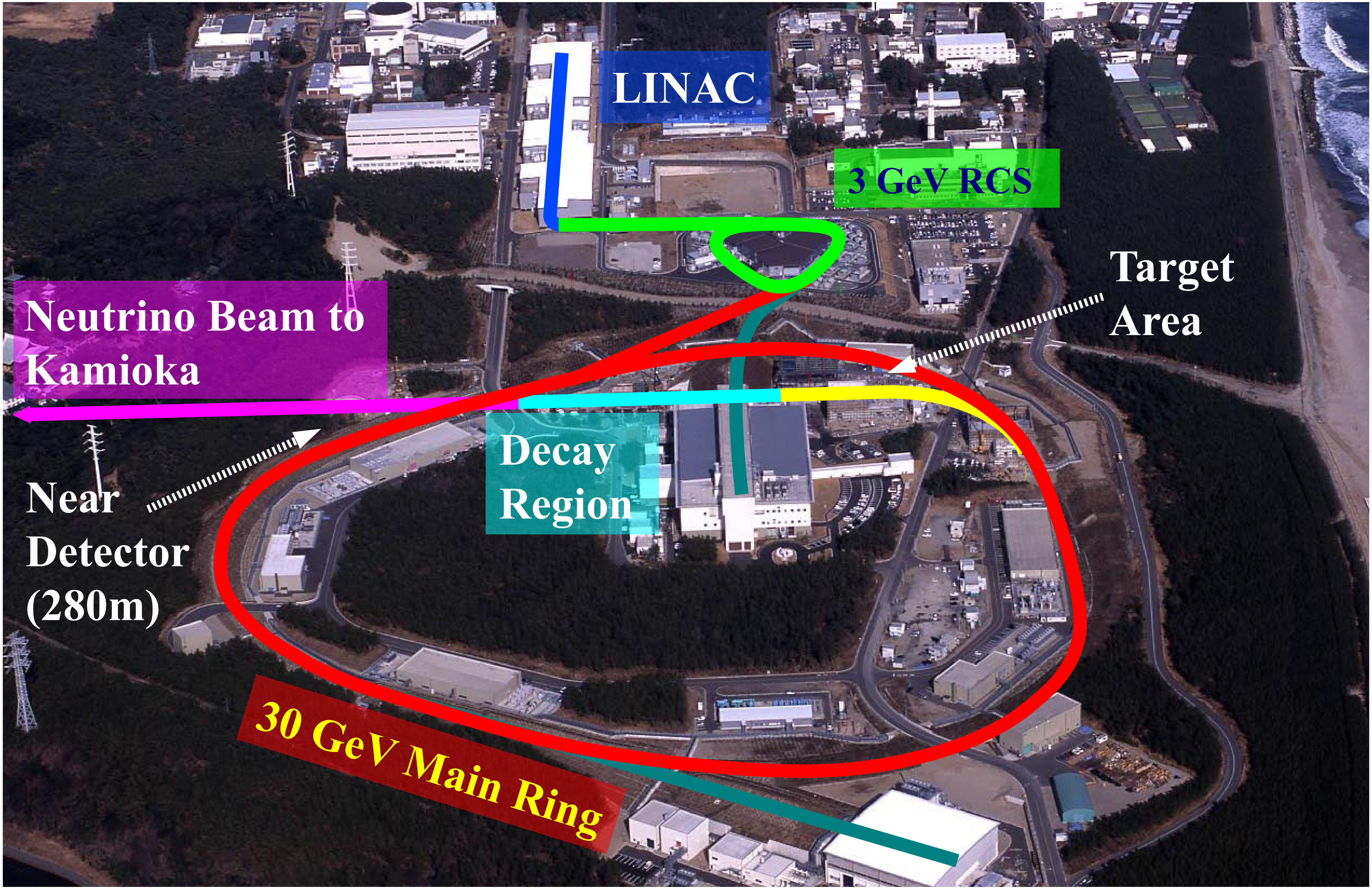
- Pseudo-monochromatic off axis neutrino beam (ref. BNL E899)
  - ν_μ beam doesn't go directly toward far detector.
  - T2K off axis angle is **2.504°**
- Set peak of (flux x σ_{CC}) near oscillation max.
  - Minimize the high energy neutrino flux to reduce the background events.





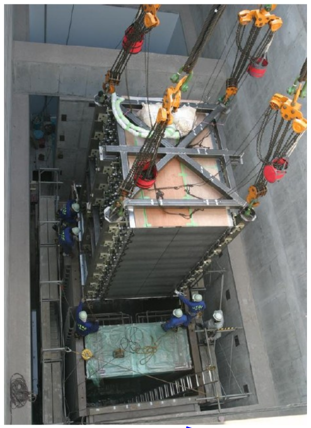


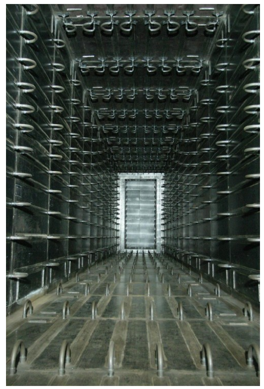
J-PARC facility (KEK/JAEA)



J-PARC ν Beam Line

Beam Dump

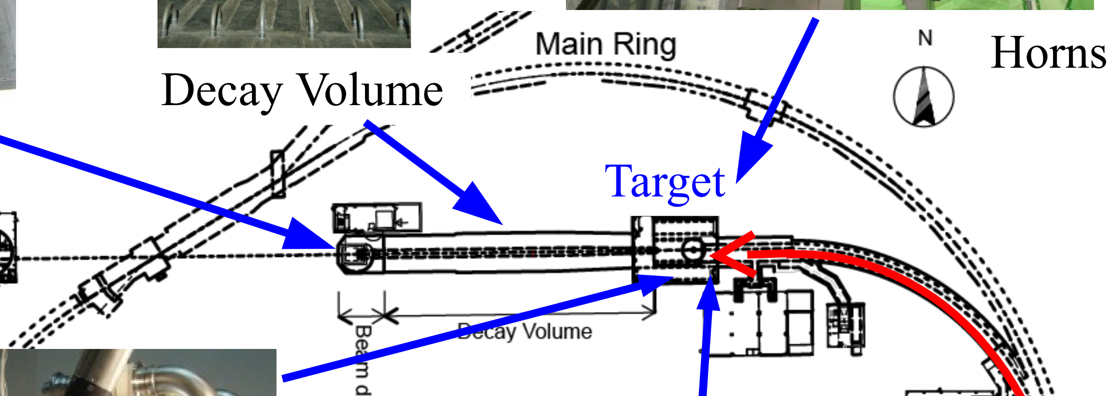




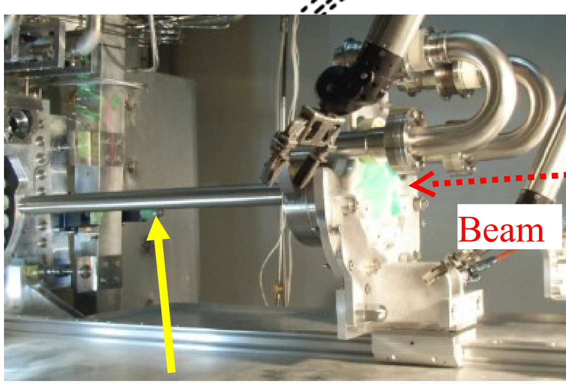
Decay Volume

Horns

Super-conducting combined-function magnets



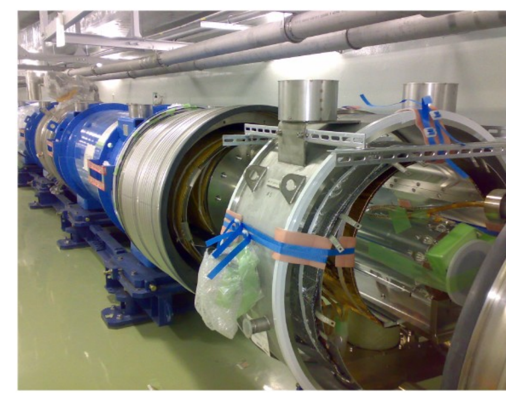
Target



Target: graphite rod
ϕ26mm,L=900mm

Optical Transition Radiation (OTR)
Profile monitor

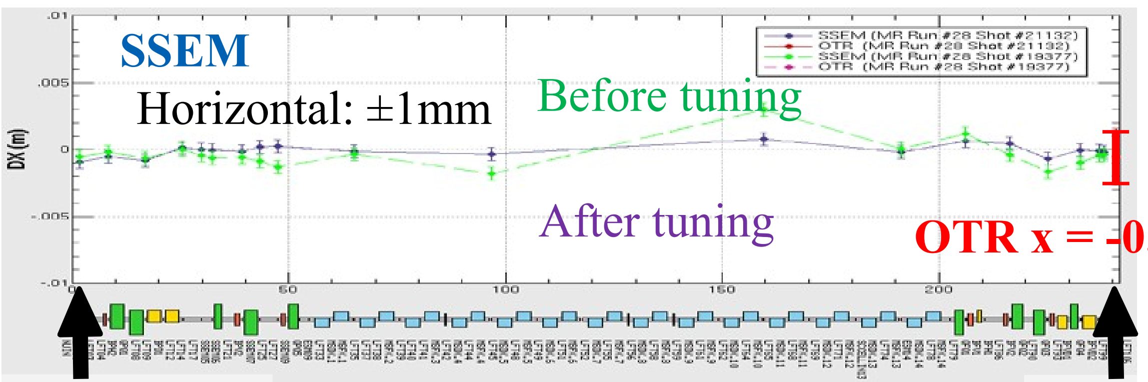
Extraction point



Corrector coils installed
in beam line

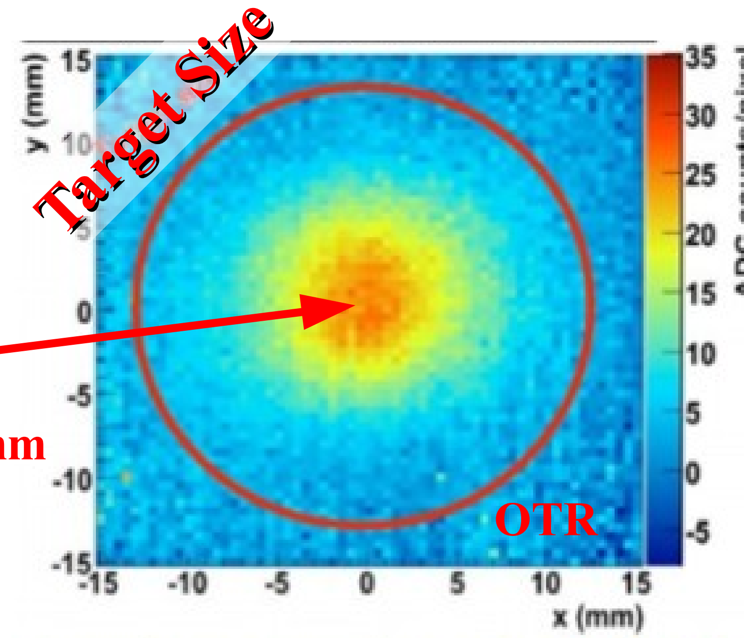
Beam Monitoring

Proton beam tuned to minimize beam loss and control neutrino beam direction



MR Extraction

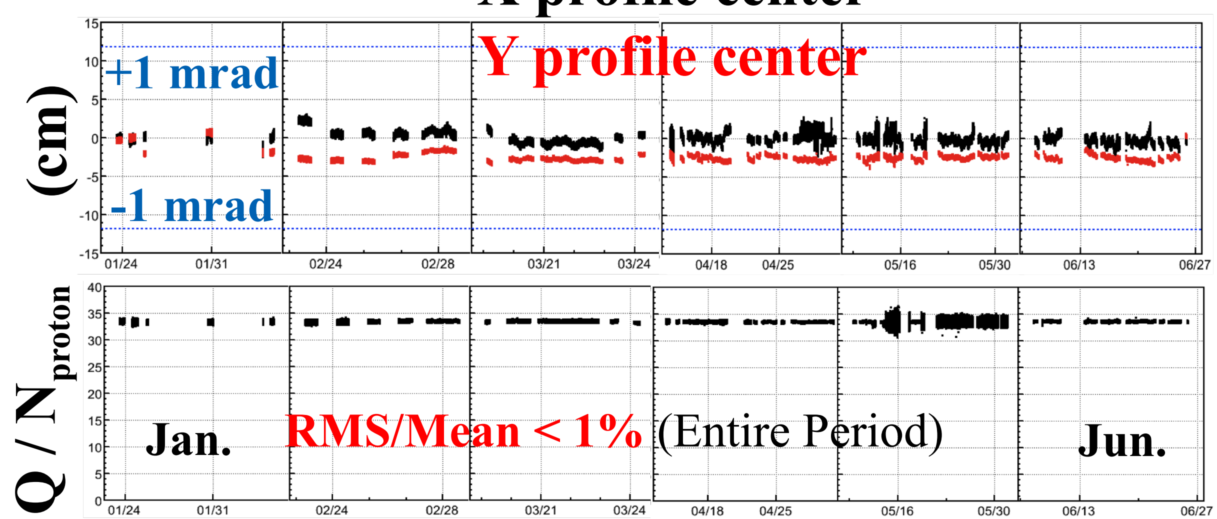
Target



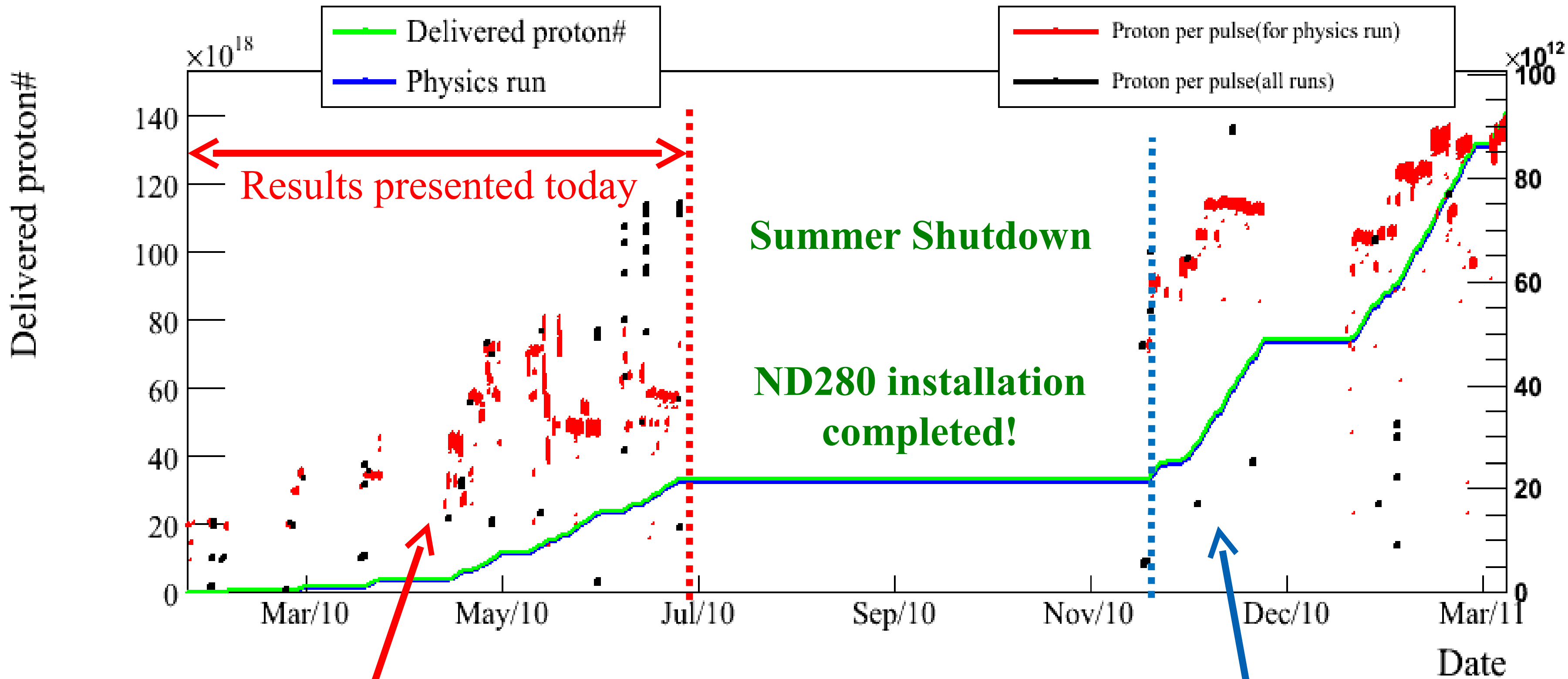
Muon Monitors

Measure secondary beam direction and intensity for every spill

Direction controlled to better than 1 mrad during the entire period



Delivered Protons



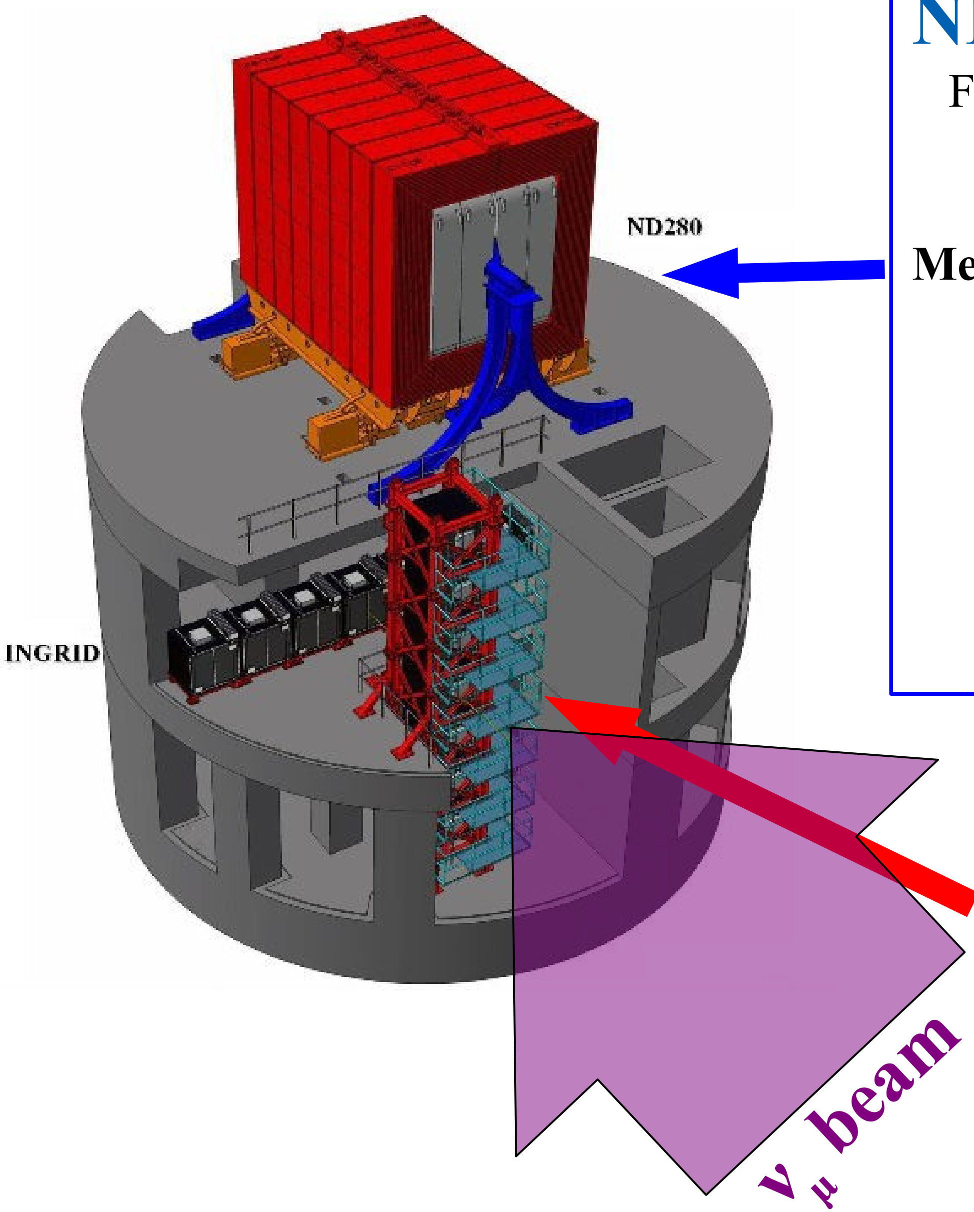
T2K run 1 (Jan. to Jun. 2010)

- **6 bunches/spill, 3.5 s spill**
- **3.23 x 10^{19} POT for T2K analysis**
- **~50 kW operation**

T2K run 2 (from Nov. 2010)

- **8 bunches/spill, 3.2 s → 3.04 s period**
- **Run 1 & 2 POT ~1.45 x 10^{20}**
- **Up to ~145 kW operation**

Near Detector @ 280 m From Target



ND280 Off-axis Detector

Fine grain detectors in the UA1/NOMAD magnet (0.2 T) at ~2.5° off-axis

Measures

- Normalization for ν_μ disappearance
  - CC ν_μ (Spectrum and normalization)
- Background prediction for ν_e appearance
  - Beam related CC ν_e
  - NC π^o production
- General neutrino interaction properties.

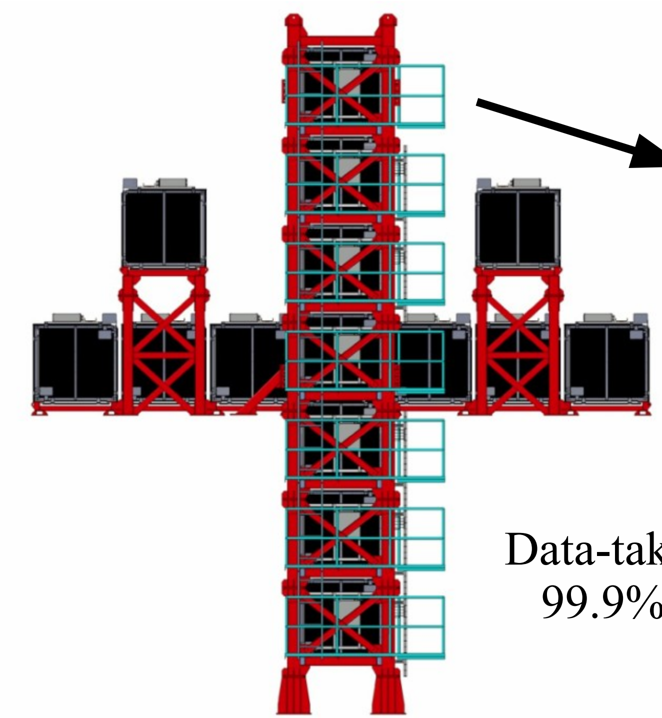
ND280 On-axis (INGRID)

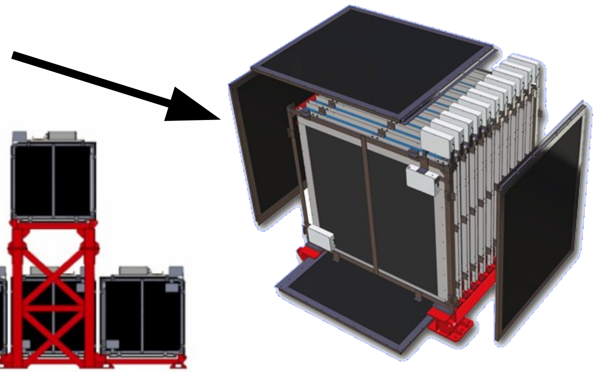
Iron-Scintillator tracking detectors

Measures

- Beam profile
- Neutrino beam normalization (on axis)

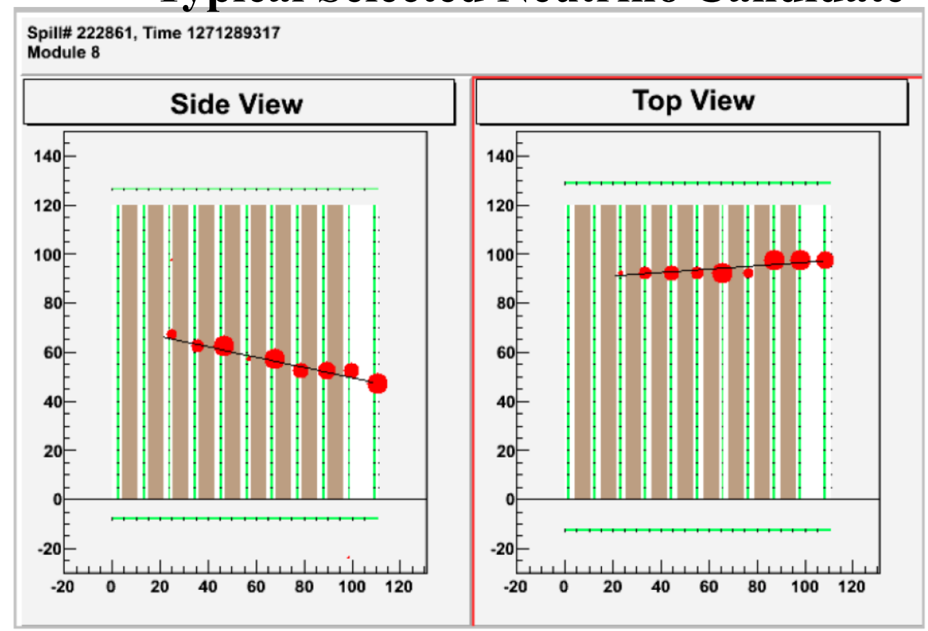
ND280 On-axis ν Beam Monitor
(INGRID)

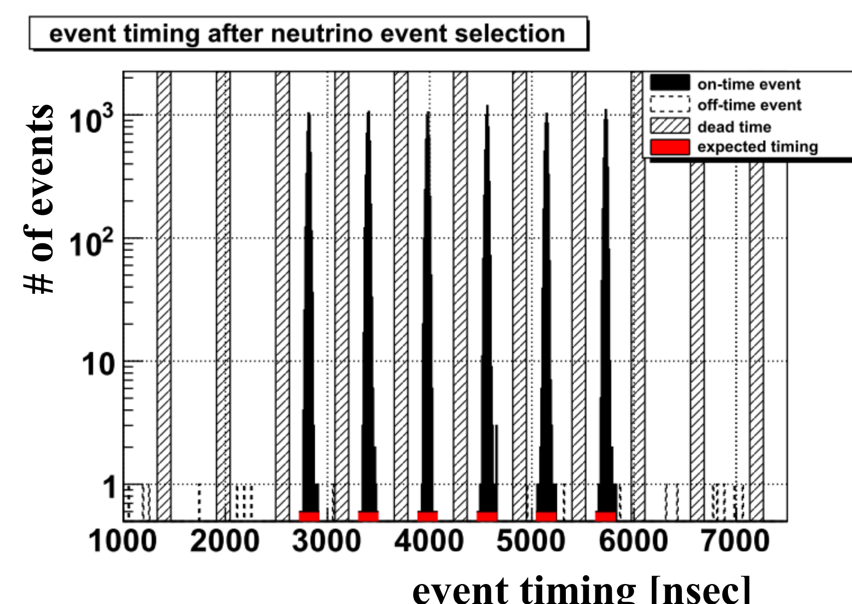




Data-taking efficiency was 99.9% during T2K Run 1

Typical Selected Neutrino Candidate

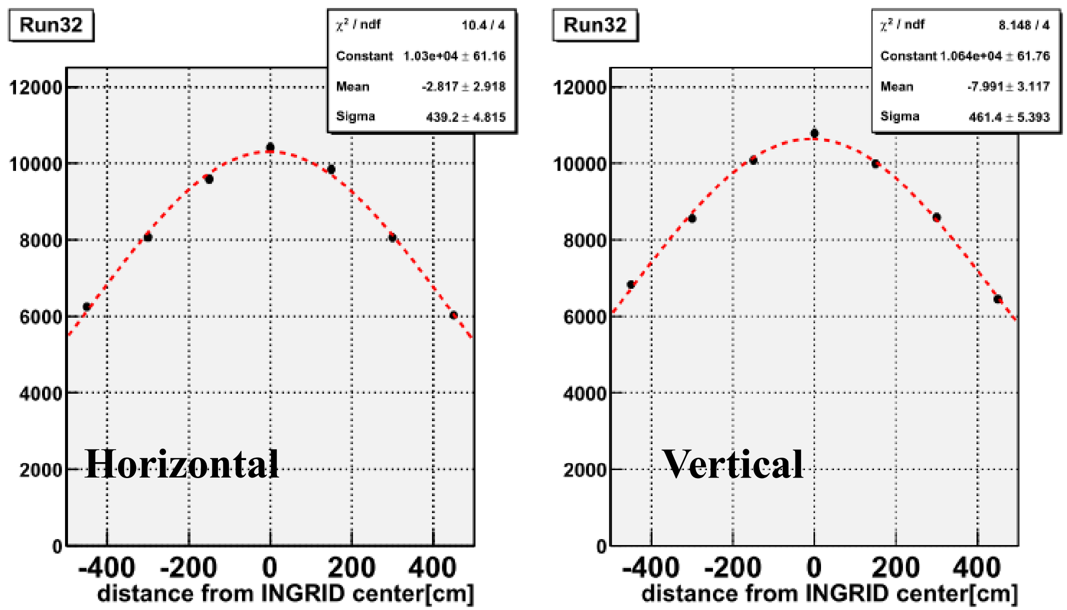




- 7 by 7 cross + 2 off-cross + 1 proton modules
  - Alternating scintillator & iron layers
    - 7 ton per module
    - Scintillator + WLS + MPPC
  - Surrounding veto
  - 10 x 10 m^2 coverage
  - 1400 interactions/day/100 kW

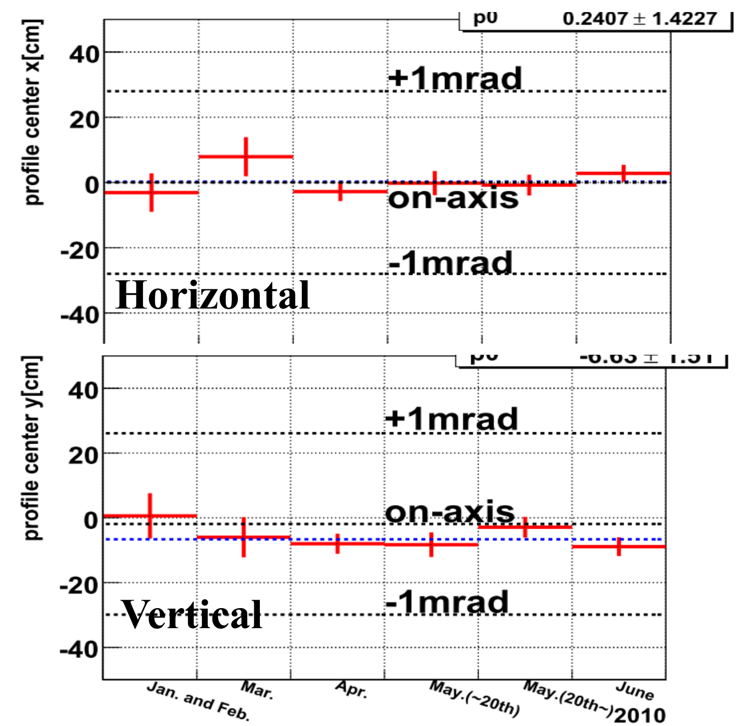
INGRID ν Beam Measurements

ν Beam Profile

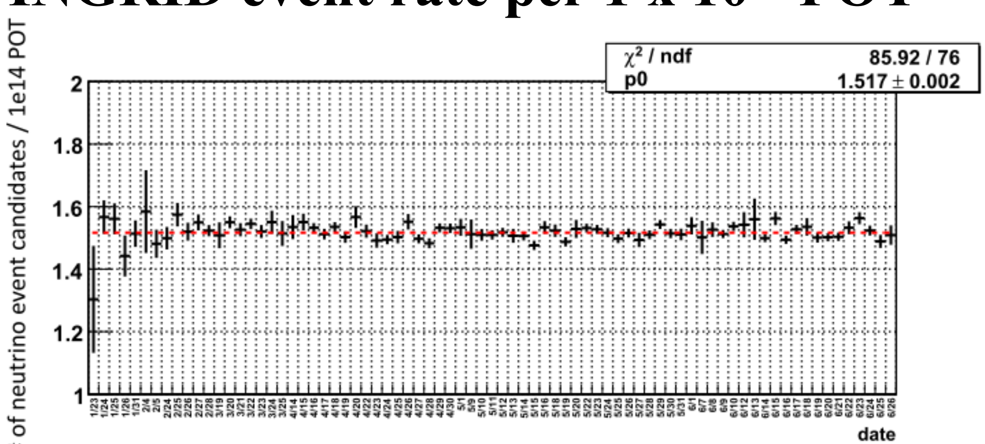


(0.1 degree = 49cm @ INGRID)

Profile center



INGRID event rate per 1 x 10[14] POT



- Beam Center
  - Horiz: +0.2 ± 1.4 (stat) ± 9.2 (sys) cm
  - Vert: -6.6 ± 1.5 (stat) ± 10.4 (sys) cm
  - Off-axis angle: 2.519 ± 0.021°
    - i.e. ± 0.37 mrad
- Event Rate
  - Data/MC: 1.073 ± 0.001 (stat) ± 0.040 (sys)

ND280 Off-axis Detector

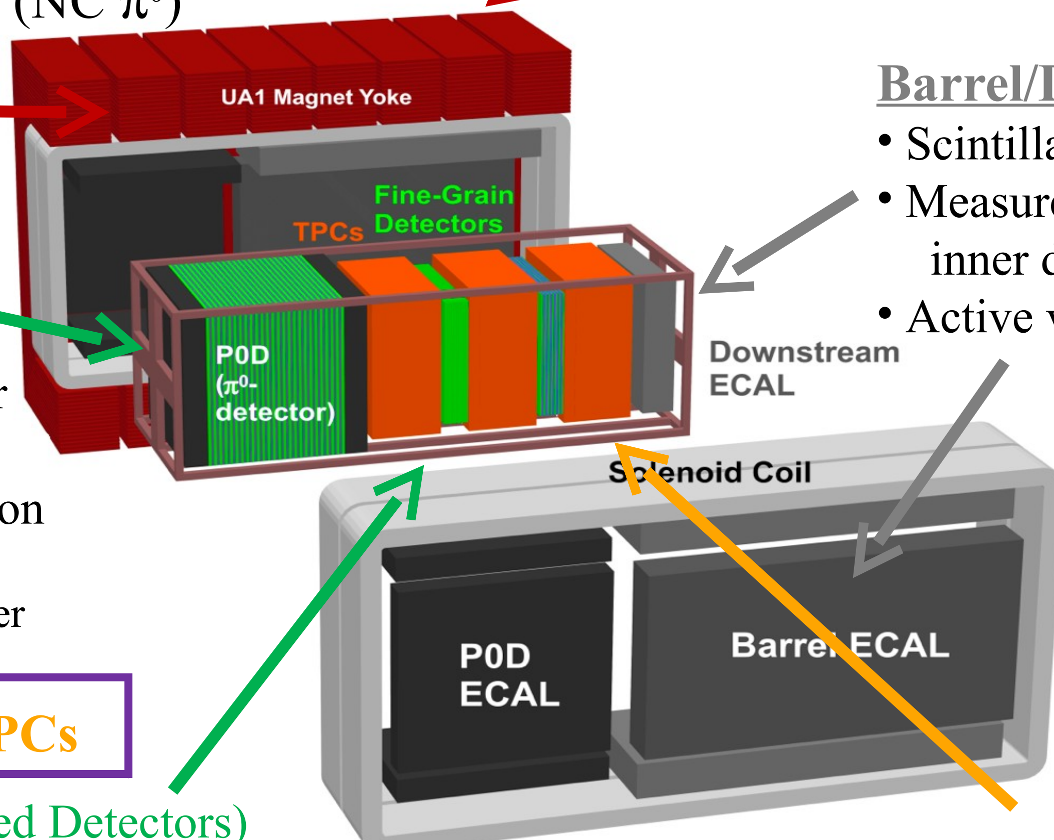
Designed for measurement of
- Off-axis spectrum using CCQE
- Beam ν_e contamination
- Super-K background (NC π^0)

SMRD (Side Muon Range Detector)
- Scintillator planes in magnet yoke
- Detect muons from inner detector
- Momentum measurement

UA1 Magnet
- **0.2 T**

Barrel/DownStream ECAL
- Scintillator planes with radiator
- Measure EM showers from inner detector (γ for NC π^0 etc)
- Active veto

P0D (π^0 Detector)
- Scintillator planes interleaved with water
- & lead/brass layers
- Optimized for γ detection
- Mass: 16.1 tons w/ water
  13.3 tons w/o water

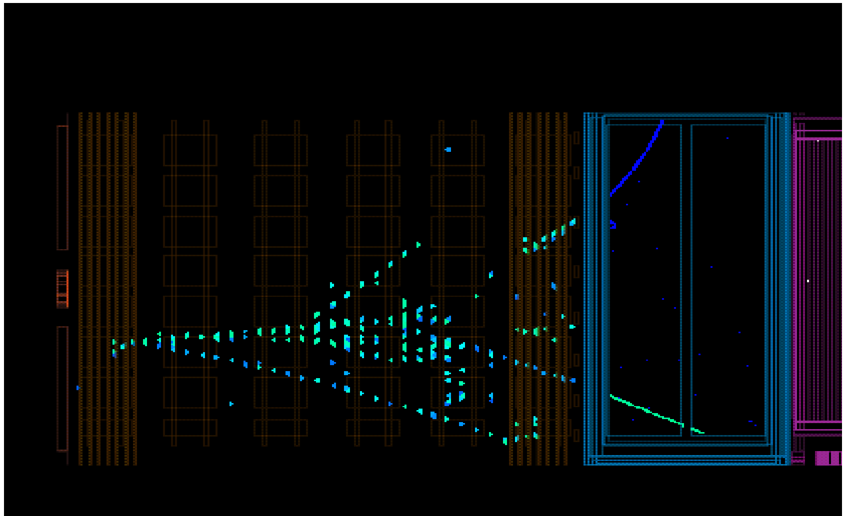


Tracker: FGDs+TPCs

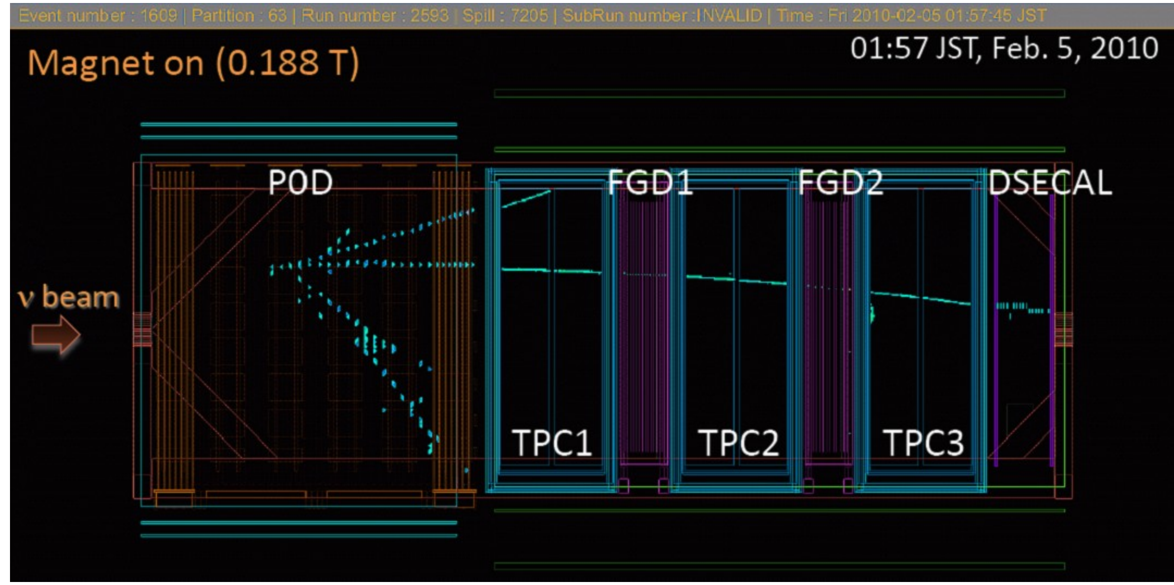
FGDs (x2) (Fine Grained Detectors)
- Provide full active target mass
- FGD1: Scintillator planes ~ 1 ton
  FGD2: Scinti. & water planes ~ 0.5 & 0.5 ton

TPCs (x3) (Time Projection Chambers)
- Measure charged particles from FGD/P0D
- Good PID via dE/dx measurement

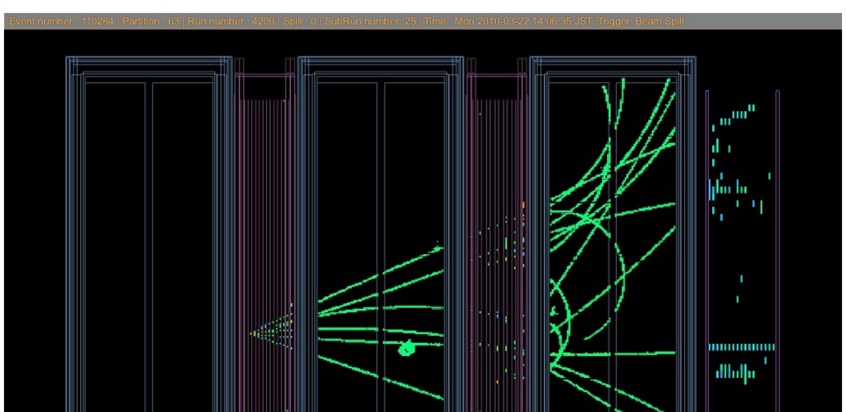
ND280 Off-axis Event Gallery



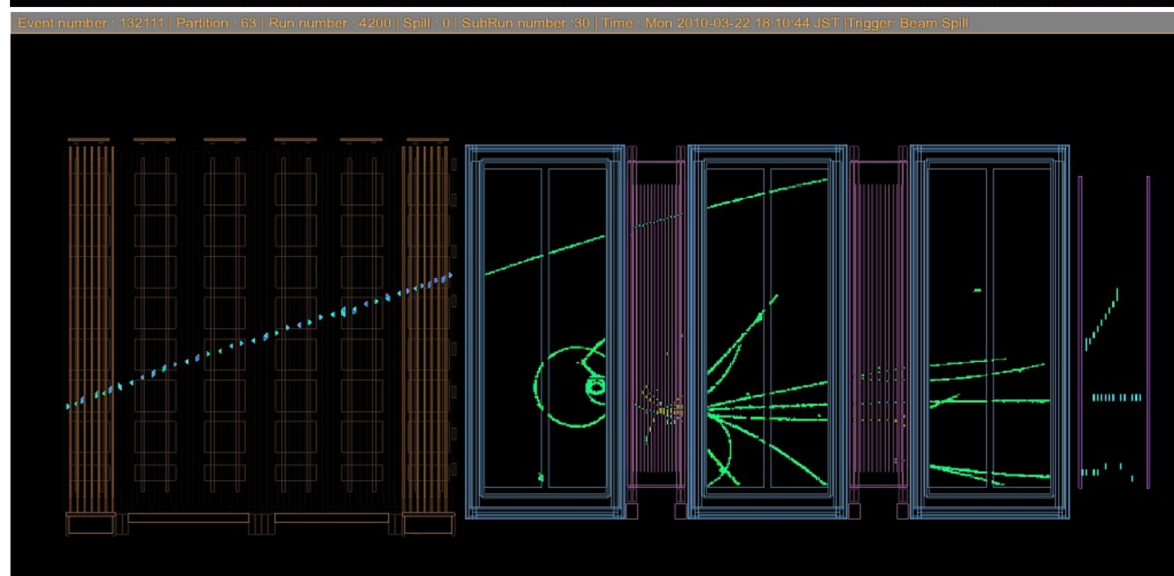
P0D/TPC event with shower



Fine grained scintillation detectors with TPC for momentum measurement

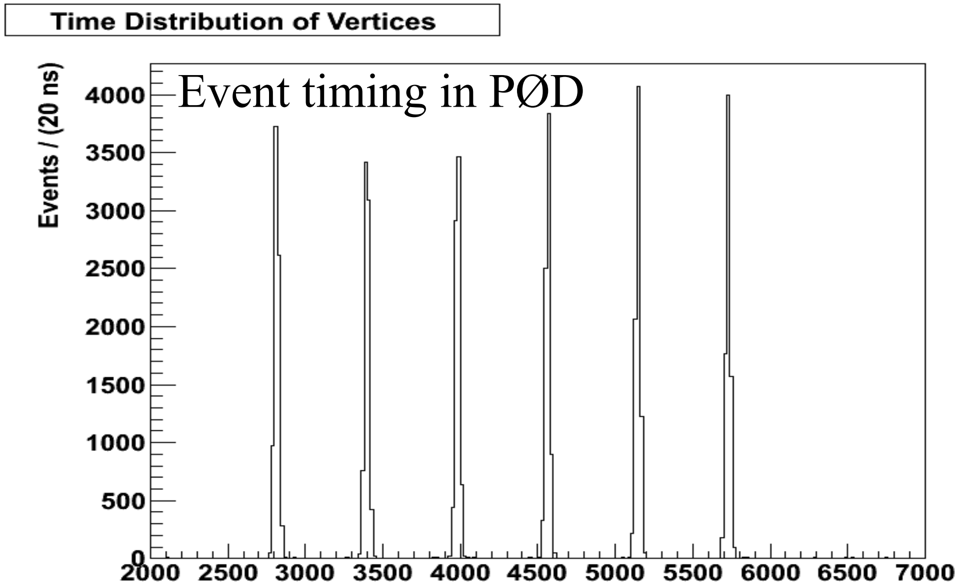


FGD1 Interaction

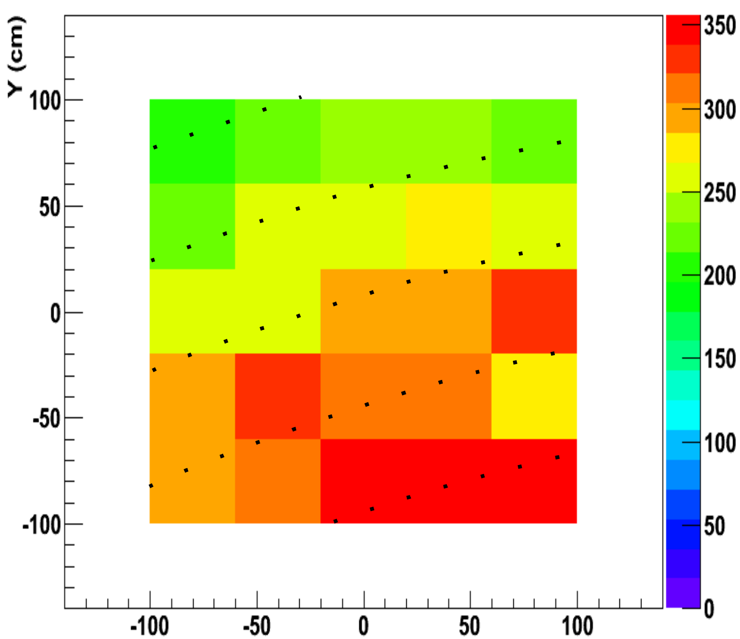


Sand Muon & FGD interaction

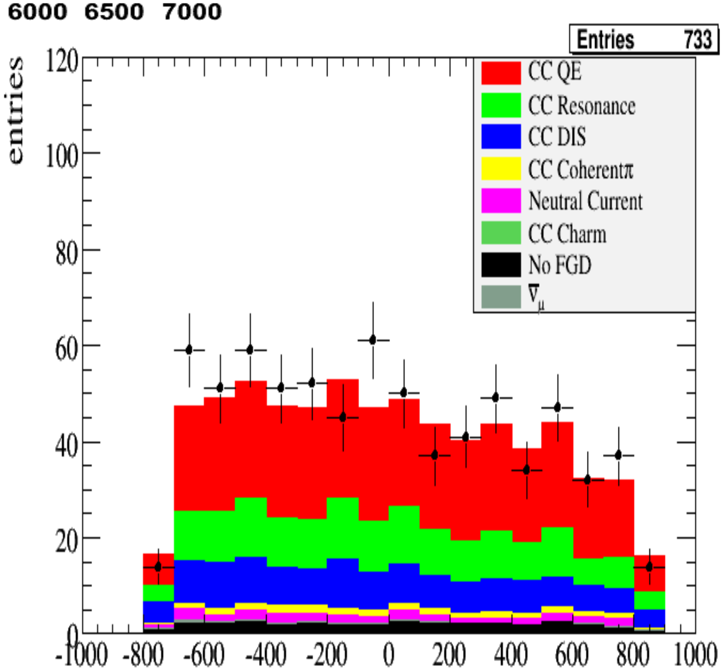
ND280 Off-axis Performance



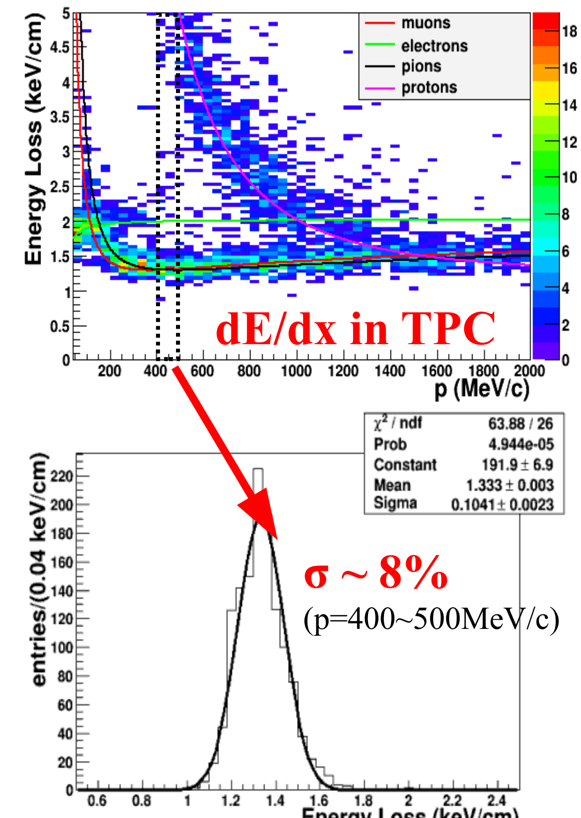
Detector	Channels	Bad ch.	Bad fraction
ECAL (DSECAL)	22,336 (3,400)	35 (11)	0.16% (0.32%)
SMRD	4,016	7	0.17%
PØD	10,400	7	0.07%
FGD	8,448	20	0.24 %
INGRID	10,796	18	0.17 %
TPC	124,416	160	0.13 %



PØD event rate vs X and Y



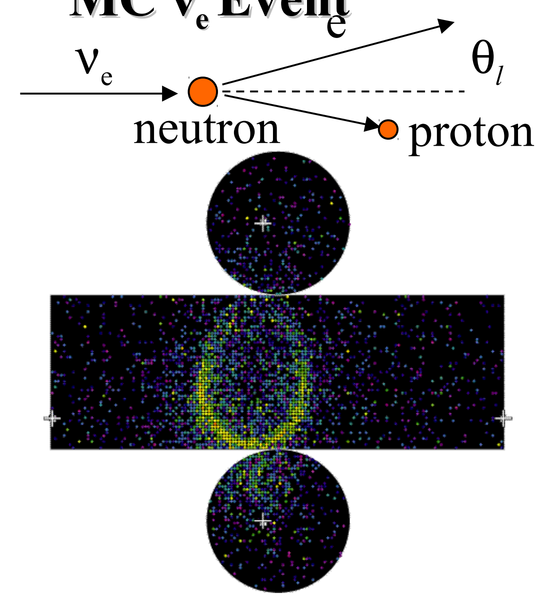
FGD event rate vs Y



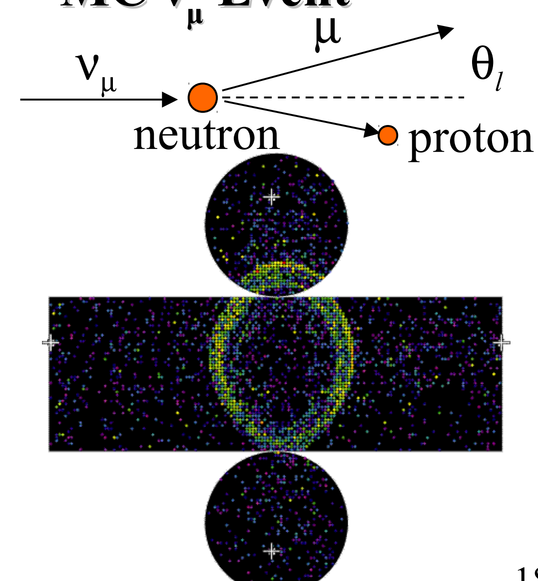
Far Detector @ 295 km
Super-Kamiokande

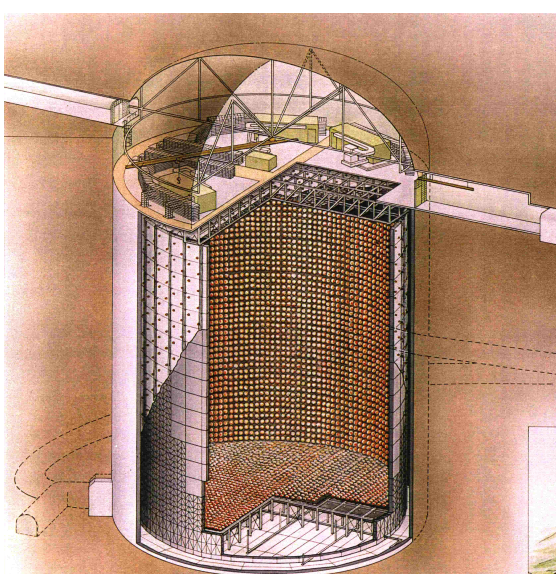
- 50kt Water Cherenkov detector (Fiducial 22.5kt)
- 11,129 20' ID PMTs: 40% photo coverage and 1885 8' OD PMT
- New readout electronics and deadtime free DAQ
  - Improved decay electron tagging
- 1st oscillation maximum near Eν ~ 600 MeV
- Good performance for sub-GeV ν detection
  - Very efficient e / μ separation (~99% at 600 MeV)
  - Energy reconstruction: ΔE/E ~10% (← 2-body kinematics)

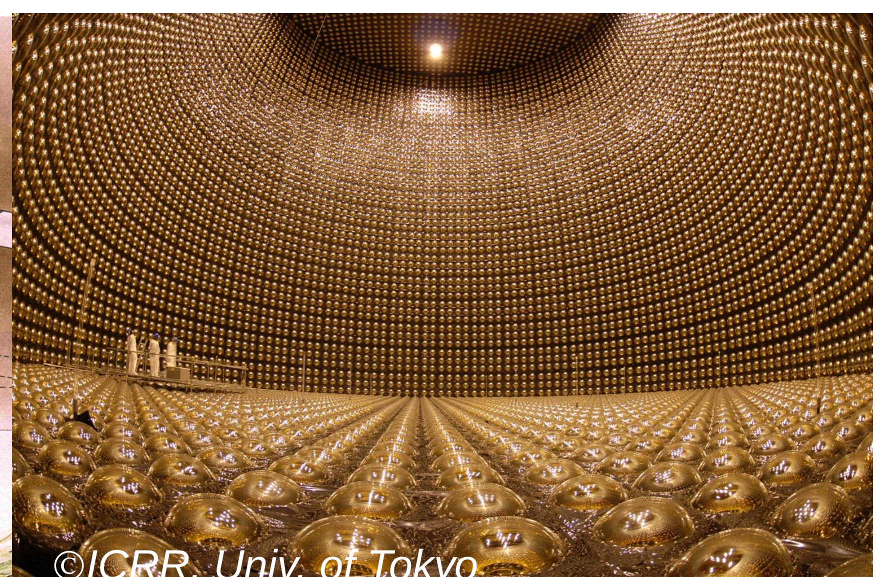
MC ν_e Event



MC ν_μ Event







2010 Analysis Strategy

- Neutrino Flux Prediction
  - Proton Beam Data
  - Hadron Production Data

- SK Detector Measurements
  - Data reduction and classification

- ND280 Detector Measurements
  - ν_μ CC Inclusive Rate
  - Measure ratio of Data to MC
    - $R_{data/mc} = N^{Data}_{cc} / N^{MC}_{cc}$

- Neutrino Cross-Sections
  - External Data
  - Interaction Models
    - Parameter variation over allowed ranges

- Extract Oscillation Parameters
  - Evaluation of Systematic Errors
  - Signal and Background Expectation

$$N^{MC}_{sig} = \int dE_\nu \Phi(E_\nu) \times \sigma(E_\nu) \times \varepsilon(E_\nu) \times P(\nu_\mu \rightarrow \nu_e; E_\nu; \theta_{13}, \Delta m^2_{13})$$

  - Normalization to ND280

$$N^{exp}_{SK} = R_{Data/MC} \times (N^{MC}_{signal} + N^{MC}_{bkg})$$

In the current analysis, we don't use the measured near detector spectrum, or the far/near ratio

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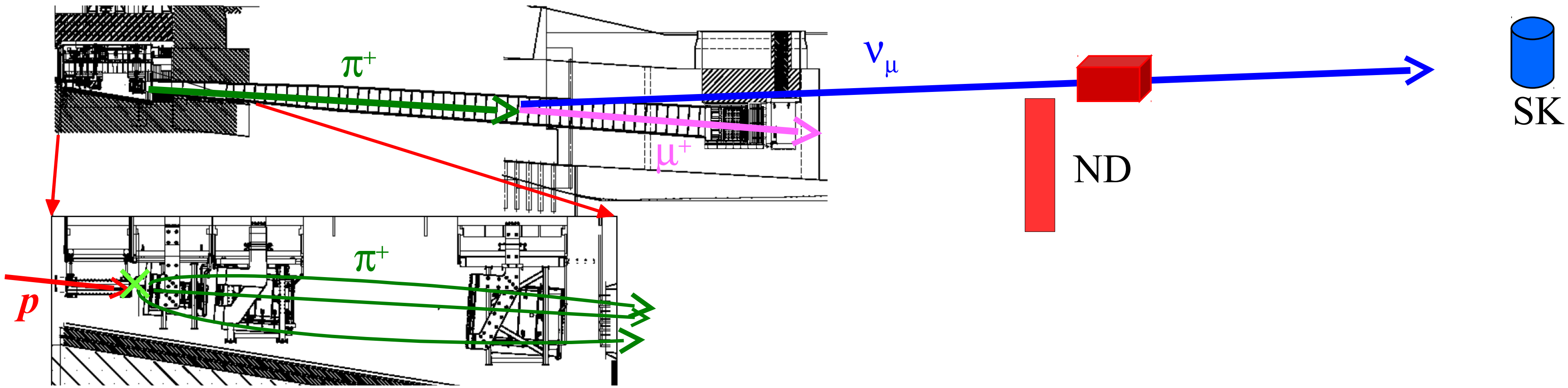
Beam MC Flux Prediction



(1) Hadron production by p+C interaction and secondary interaction in target is simulated using FULKA framework.

* Pion production cross section is corrected using NA61 data → next page.

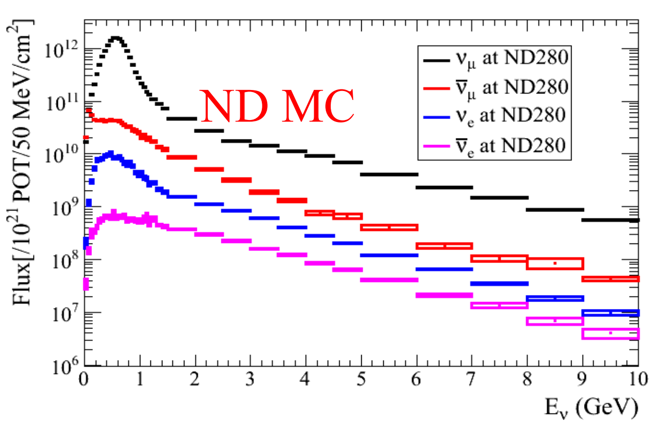
* Measured proton parameters is assumed.

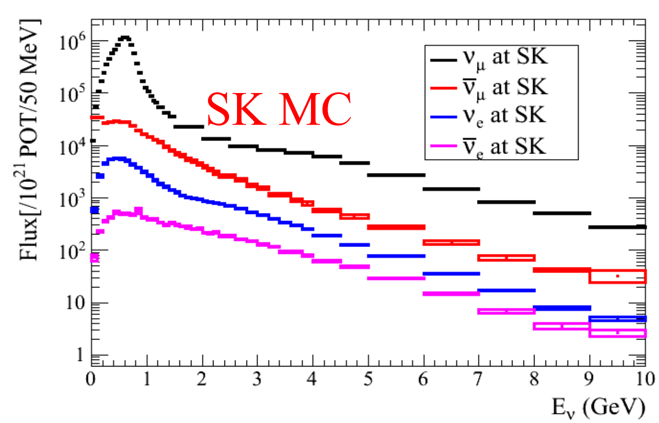
(2) Propagation of produces hadrons (π, K, etc) including Horn focusing is simulated using GEANT3 framework.

* Secondary interaction cross section is corrected using existing data by other experiments.

(3) ν producing decay is simulated. Geometrical acceptance is calculated.

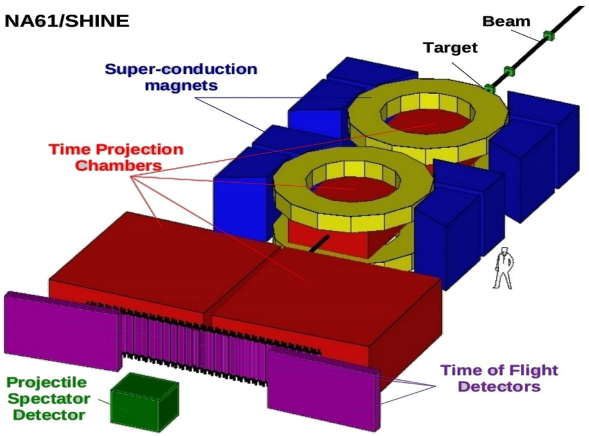
→ ν flux obtained at ND & SK, respectively



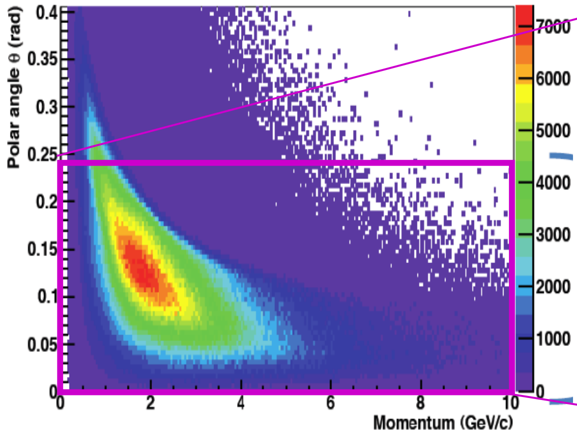


SHINE/NA61

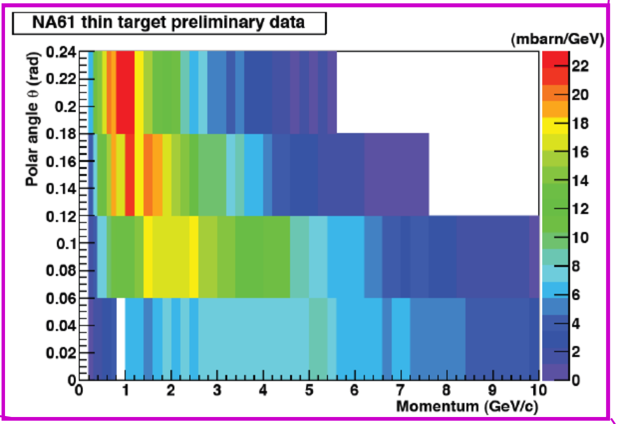
- The SHINE experiment (CERN NA61)
  - Data was taken in 2007 and 2009.
    - p (30GeV) + C (target thin:2cm / thick: 90cm)
  - $\pi^{\pm}$ production model in T2K-MC is corrected by the NA61 preliminary results released in Dec. 2009.
  - Systematic uncertainty
    - 10% : Inelastic p + C cross section
    - 20%: Pion multiplicity

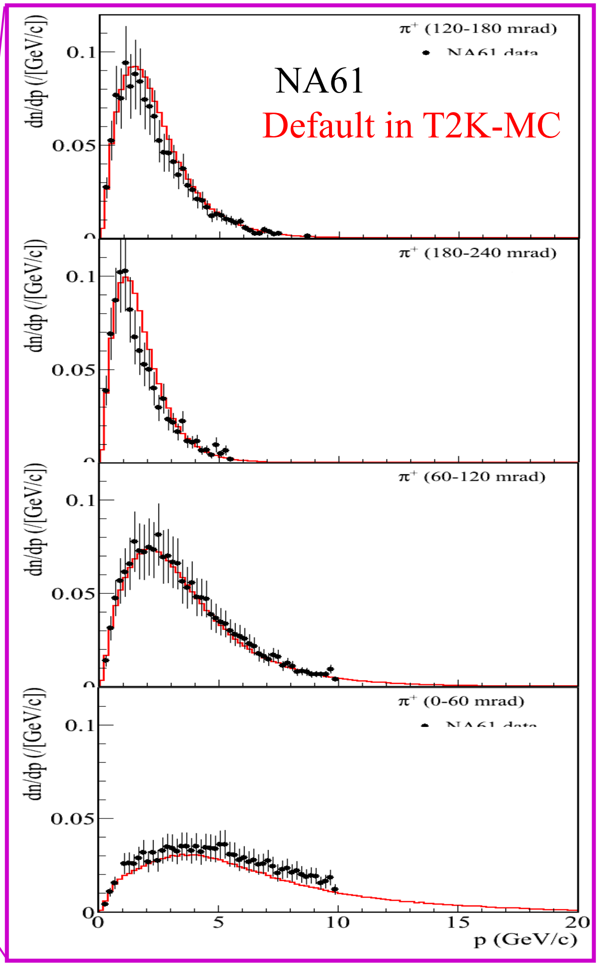


MC(T2K):π^+ produce ν_μ @ SK



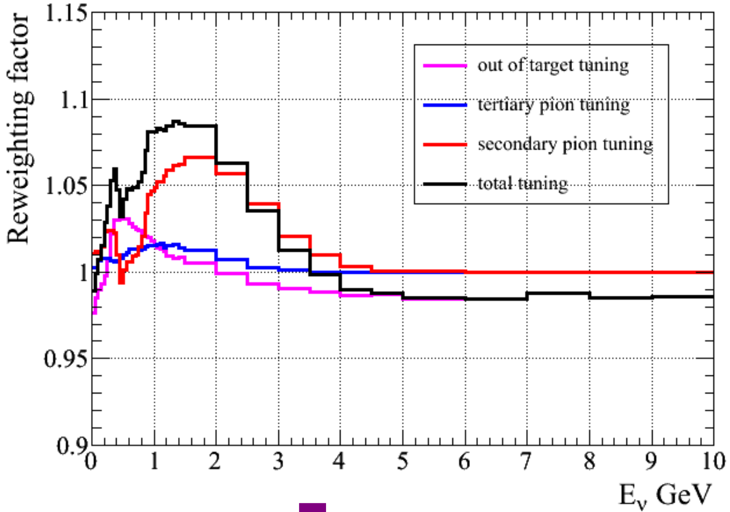
NA61 2007 data: π^+

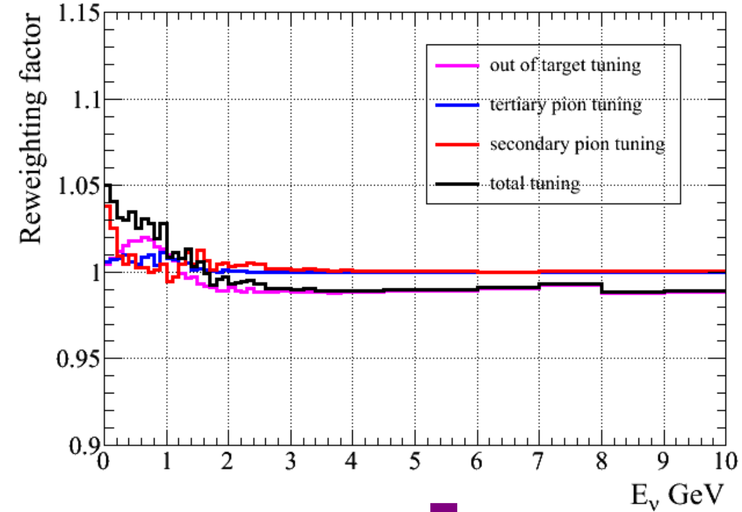




Tuned Neutrino Fluxes

Hadron Production Weighting Factors Applied to Beam MC (FLUKA)

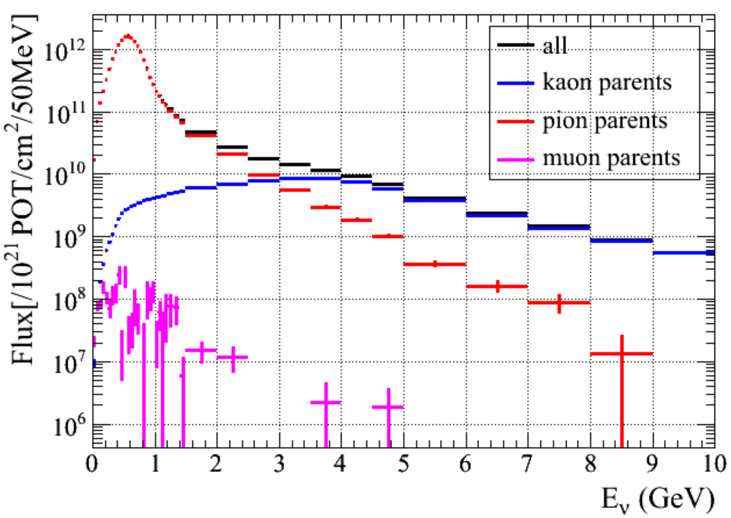


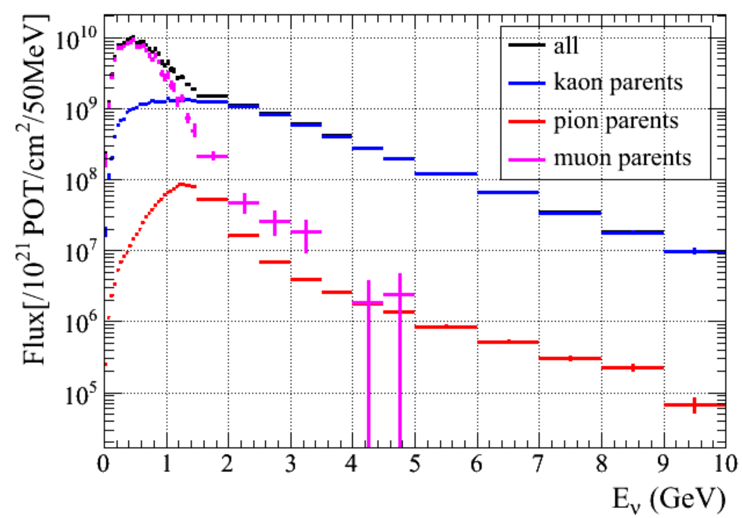


ν_μ

Tuned Neutrino Fluxes

ν_e





SK/ND Neutrino Flux Uncertainty

of events at SK (MC) / # of events at ND280 (MC)

$$N_{SK}^{expected} = (N_{ND}^{DATA} / N_{ND}^{MC}) \times (N_{SK}^{MC} + N_{bkg}^{MC})$$

Source	(νe Sig.)/ND	(νe Bkg.)/ND	(νe Tot.)/ND
Pion Multiplicity	10.7%	5.6%	9.1%
Kaon Multiplicity	9.6%	7.2%	7.9%
Prod. Cross Sections	4.0%	0.7%	2.8%
Proton Beam	1.1%	2.1%	1.4%
ν Beam Direction	0.6%	0.6%	0.6%
Target Alignment	0.3%	0.2%	0.3%
Horn Alignment	0.2%	0.1%	0.2%
Horn Current	0.8%	0.2%	0.6%
Total	**15.0%**	**9.4%**	**12.5%**

@ Δm_{23}^2=2.4x10^{-3} eV^2, $\sin^2 2\theta_{23}$ = 1.0, $\sin^2 2\theta_{13}$=0 for 1 ν_μ signal, $\sin^2 2\theta_{13}$=0.1 for ν_e signal

2010 Analysis Strategy

- Neutrino Flux Prediction
  - Proton Beam Data
  - Hadron Production Data

- SK Detector Measurements
  - Data reduction and classification

- ND280 Detector Measurements
  - ν_μ CC Inclusive Rate
  - Measure ratio of Data to MC
    - $R_{data/mc} = N^{Data}_{cc} / N^{MC}_{cc}$

- Neutrino Cross-Sections
  - External Data
  - Interaction Models
    - Parameter variation over allowed ranges

- Extract Oscillation Parameters
  - Evaluation of Systematic Errors
  - Signal and Background Expectation

$$N^{MC}_{sig} = \int dE_\nu \Phi(E_\nu) \times \sigma(E_\nu) \times \varepsilon(E_\nu) \times P(\nu_\mu \rightarrow \nu_e; E_\nu; \theta_{13}, \Delta m^2_{13})$$

  - Normalization to ND280

$$N^{exp}_{SK} = R_{Data/MC} \times \left(N^{MC}_{signal} + N^{MC}_{bkg} \right)$$

In the current analysis, we don't use the measured near detector spectrum, or the far/near ratio

Uncertainties from ν Interactions

$$N_{SK}^{expected} = (N_{ND}^{DATA} / N_{ND}^{MC}) \times (N_{SK}^{MC} + N_{bkg}^{MC})$$

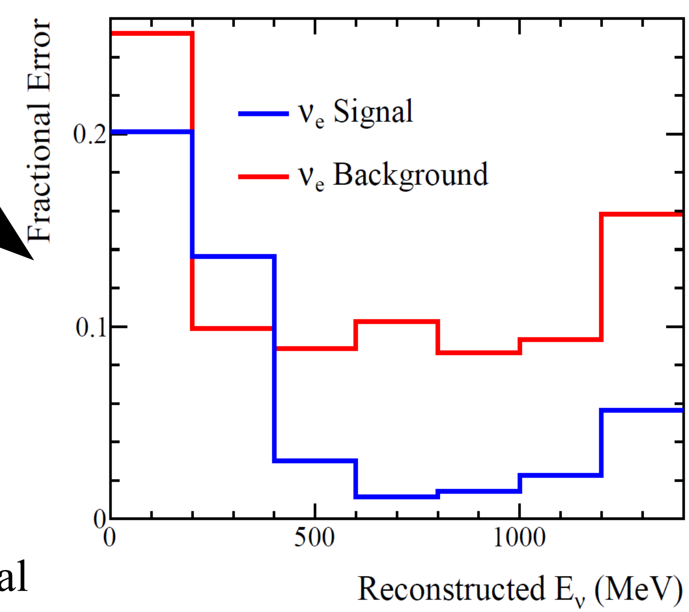
Comparison of NEUT/GENIE to external data to determine effect of cross section parameter and FSI variations on event rate and efficiencies.

Category	Error [%]	
CC QE	Depends on true neutrino energy	
CC 1π	30 (E_ν<2 GeV)	20 (E_ν>2 GeV)
CC coherent π	100	
CC other	30 (E_ν<2 GeV)	25 (E_ν>2 GeV)
NC $1\pi^0$	30 (E_ν<1 GeV)	20 (E_ν>1 GeV)
NC coherent	30	
NC other	30	
FSI error	Depends on reconst. neutrino energy	

~20% @ 400 MeV
~15% @ 600 MeV

Uncertainty of the ratio to CCQE

Uncertainty of σ(νe) / σ(νμ) = 0.06



Total uncertainty for N_{SK}/N_{ND}: ±14.2% for background
±10.2% for (signal + bkg)

@ Δm_{23}^2 = 2.4×10^{-3} eV^2, $\sin^2 2\theta_{23}$ = 1.0, δ_{CP}=0, $\sin^2 2\theta_{13}$ = 0.1 for ν_e signal

2010 Analysis Strategy

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  - Hadron Production Data

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  - Data reduction and classification

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  - ν_μ CC Inclusive Rate
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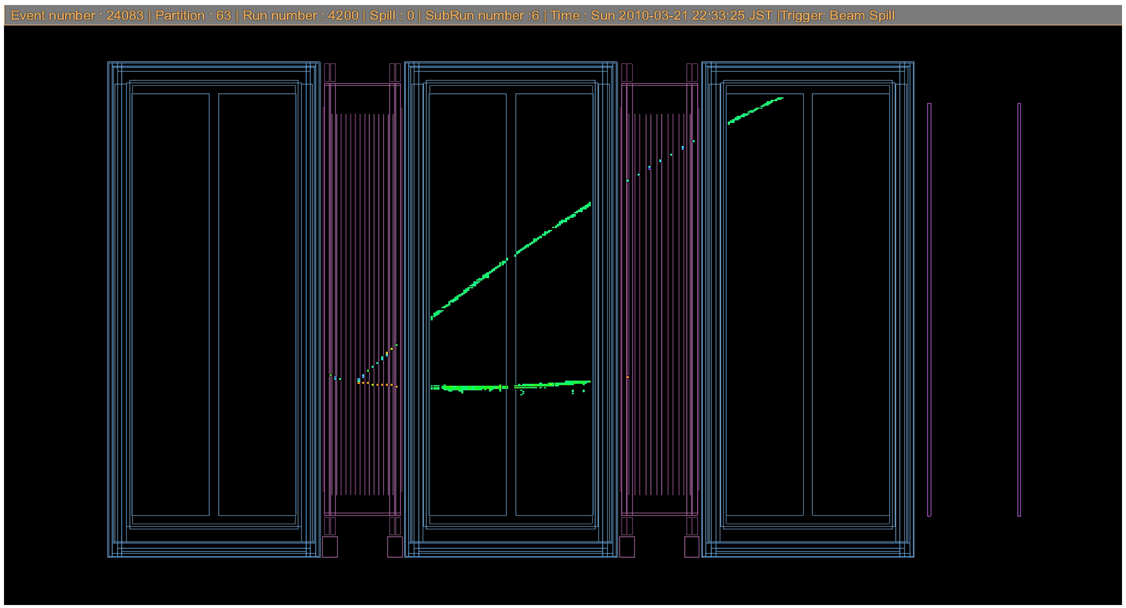
$$N_{sig}^{MC} = \int dE_\nu \Phi(E_\nu) \times \sigma(E_\nu) \times \varepsilon(E_\nu) \times P(\nu_\mu \to \nu_e; E_\nu; \theta_{13}, \Delta m_{13}^2)$$

  - Normalization to ND280

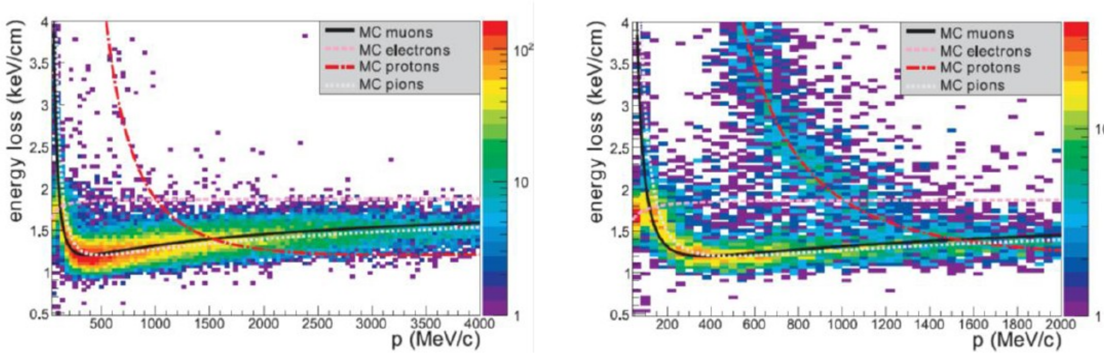
$$N_{SK}^{exp} = R_{Data/MC} \times \left(N_{signal}^{MC} + N_{bkg}^{MC}\right)$$

In the current analysis, we don't use the measured near detector spectrum, or the far/near ratio

ND280 Inclusive CC ν_μ Sample



TPC PID for particles from neutrino interactions



negative

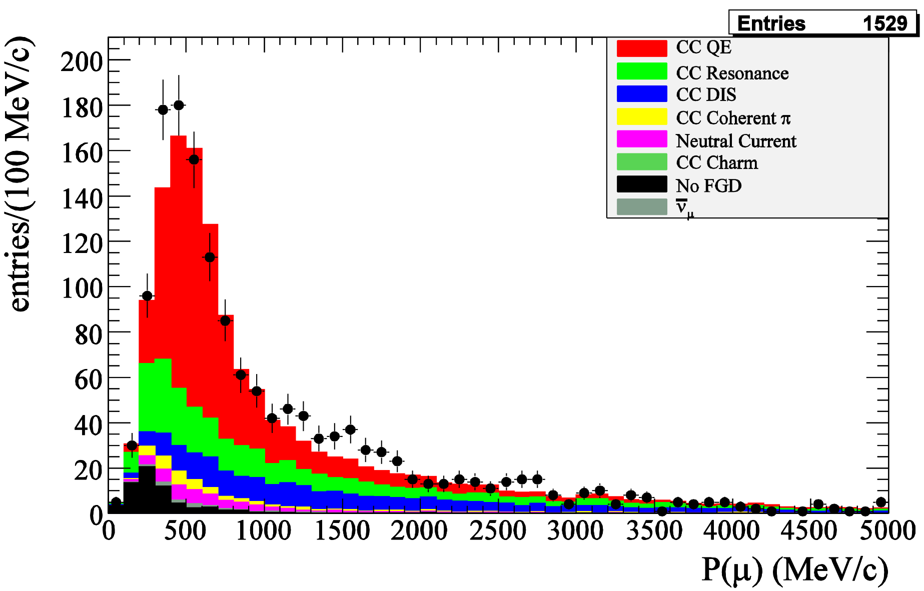
positive

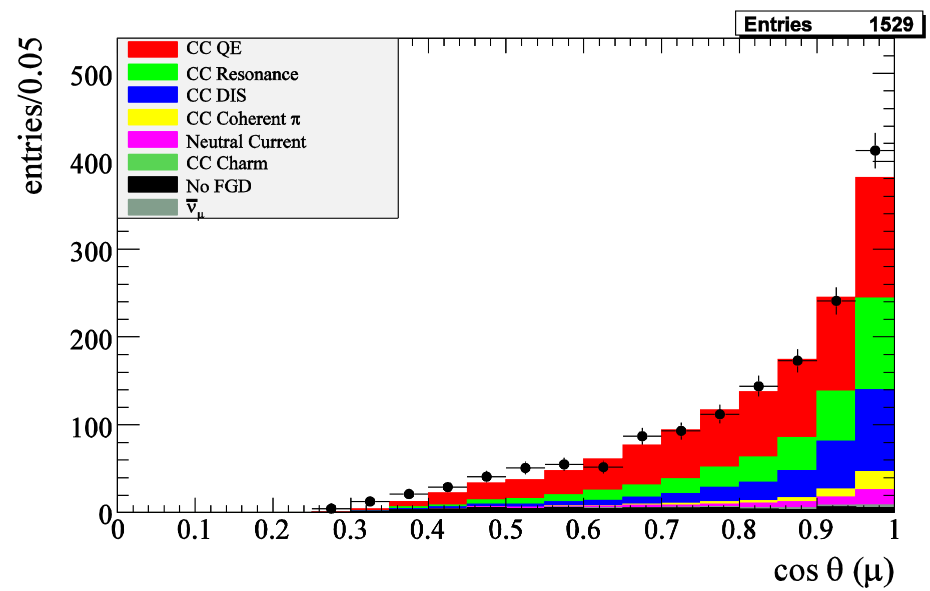
- Selection
  - If no tracks in the first TPC
    - At least one track in second TPC starting in first FGD fiducial volume
      - p>50 MeV/c
    - For highest momentum track
      - Require muon-like TPC dE/dx
  - If no tracks in second TPC
    - Apply selection to third TPC and second FGD fiducial volume
- Analysis only uses low level reconstruction objects
- Sample Purity
  - 90% CC ν_μ
  - 50% CC QE

ND280 CC ν_μ Normalization ($R_{data/mc}$)

$$N_{SK}^{expected} = \underline{(N_{ND}^{DATA} / N_{ND}^{MC})} \times (N_{SK}^{MC} + N_{bkg}^{MC})$$

Kinematic Properties





$$R_{Data/MC} = 1.061 \pm 0.028(\text{stat.})^{+0.044}_{-0.038}(\text{det. sys.}) \pm 0.039(\text{phys. model})$$

2010 Analysis Strategy

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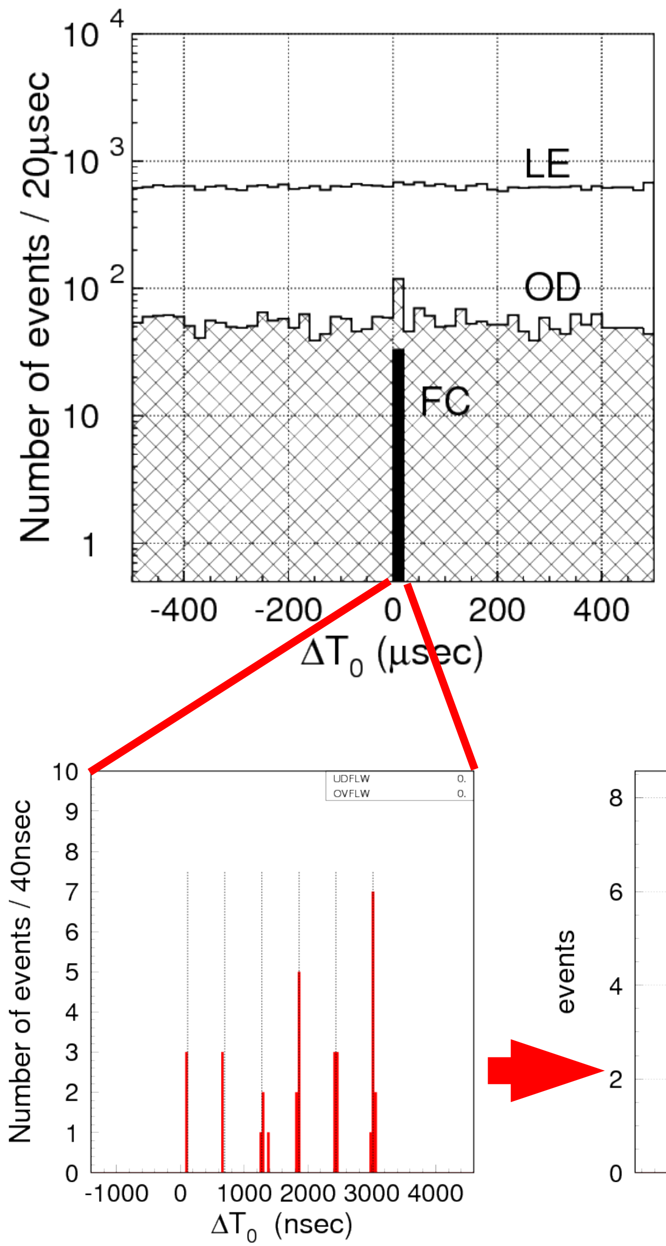
  - Normalization to ND280

$$N^{\exp}_{SK} = R_{Data/MC} \times \left(N^{MC}_{signal} + N^{MC}_{bkg}\right)$$

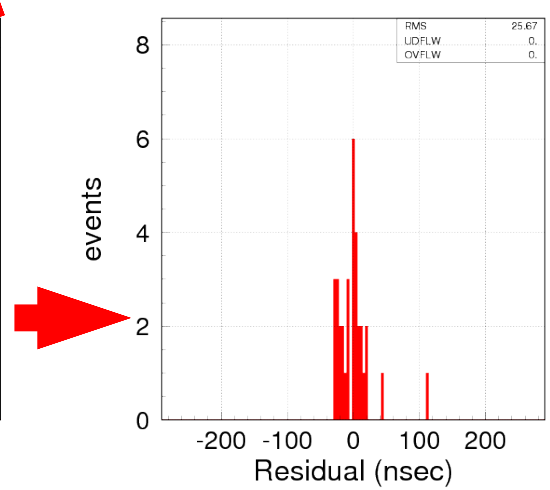
In the current analysis, we don't use the measured near detector spectrum, or the far/near ratio

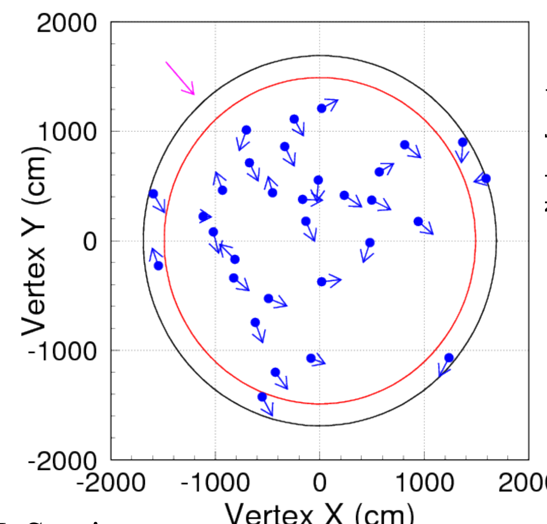
Super-K Fully Contained Events

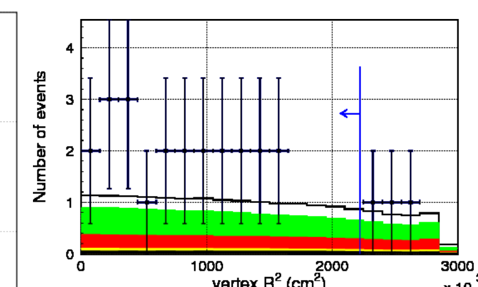


- Select events within ± 500μs of spill arrival time.
  - Time synchronized with GPS
- Select events with no outer-detector signal.

	Data	MC		BG (12μs window)
		No oscillation	Oscillation $\Delta m^2 = 2.4 \times 10^{-3}$ (eV^2) $\sin^2 2\theta_{23} = 1.0$	
Fully-Contained	**33**	54.5	24.6	0.0094
Fiducial Volume, $E_{vis} > 30$MeV	**23**	36.8	16.7	0.0011



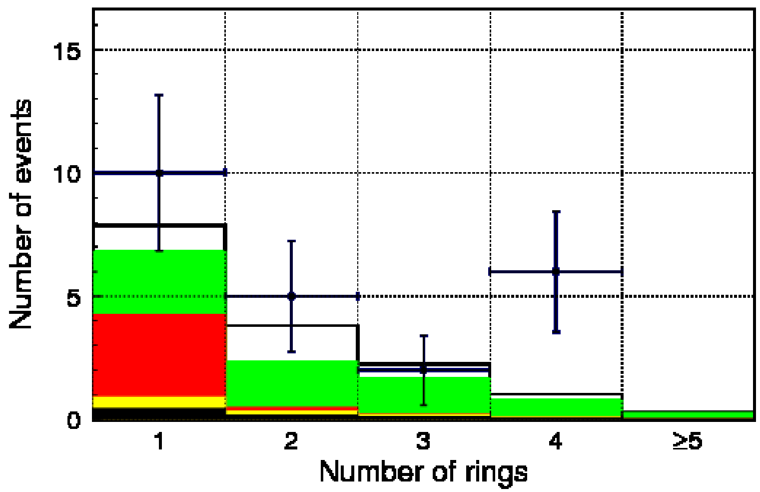


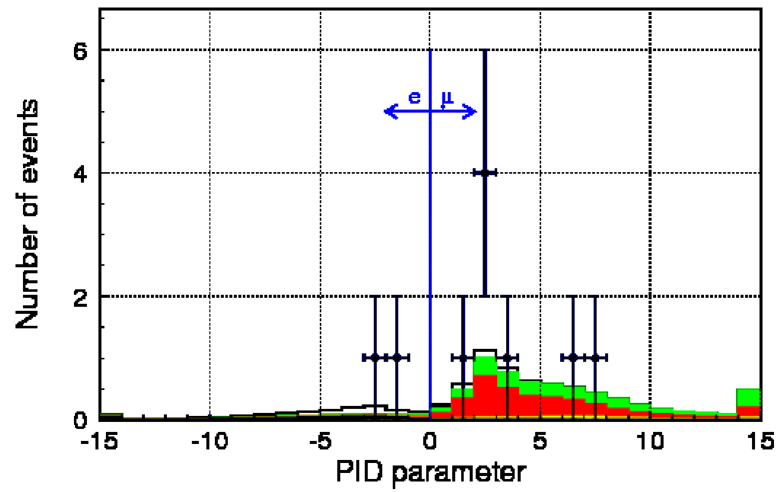


$E_{vis} > 30$ MeV

T2K

Super-K Ring Counting and PID

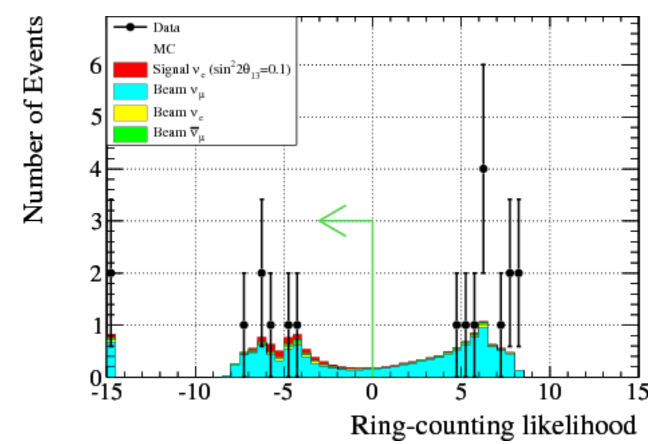




Oscillated Expectation

Neutral Current (white)
ν_μ CC non-QE (green)
ν_μ CC QE (red)
anti-ν_μ (yellow)
beam ν_e (black)

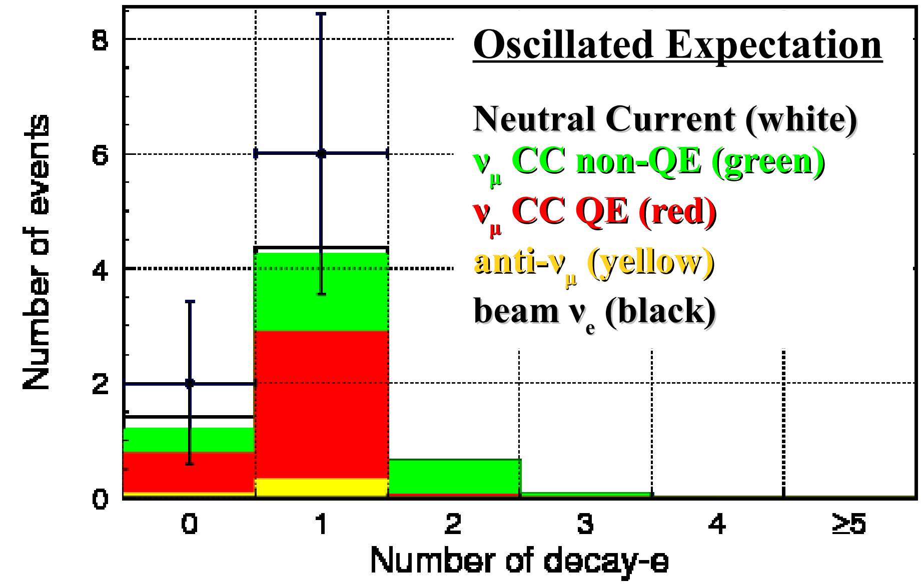
	Data	MC	
		No oscillation	Oscillation $\Delta m^2 = 2.4 \times 10^{-3}$ (eV^2) $\sin^2 2\theta_{23} = 1.0$
Fully-Contained	33	54.5	24.6
Fiducial Volume, E_{vis} > 30MeV	23	36.8	16.7
Single-ring μ-like (P_μ>200MeV/c)	8 (8)	24.6 (24.5 ±3.9)	7.2 (7.1 ±1.3)
Single-ring e-like (P_e>100MeV/c)	2 (2)	1.9 (1.5 ±0.7)	1.5 (1.3 ±0.6)
Multi-ring	13	10.2	8.0



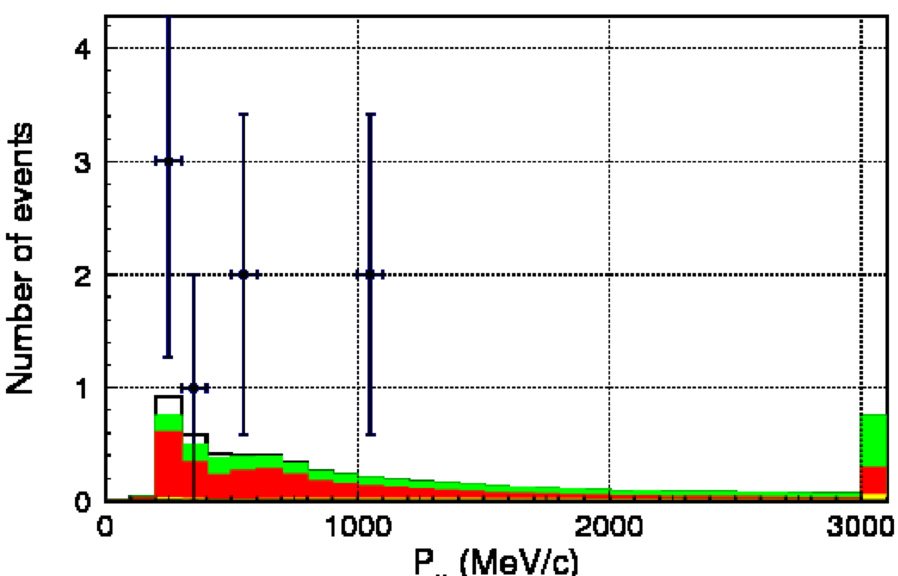
Not the final cuts used in the oscillation analysis.

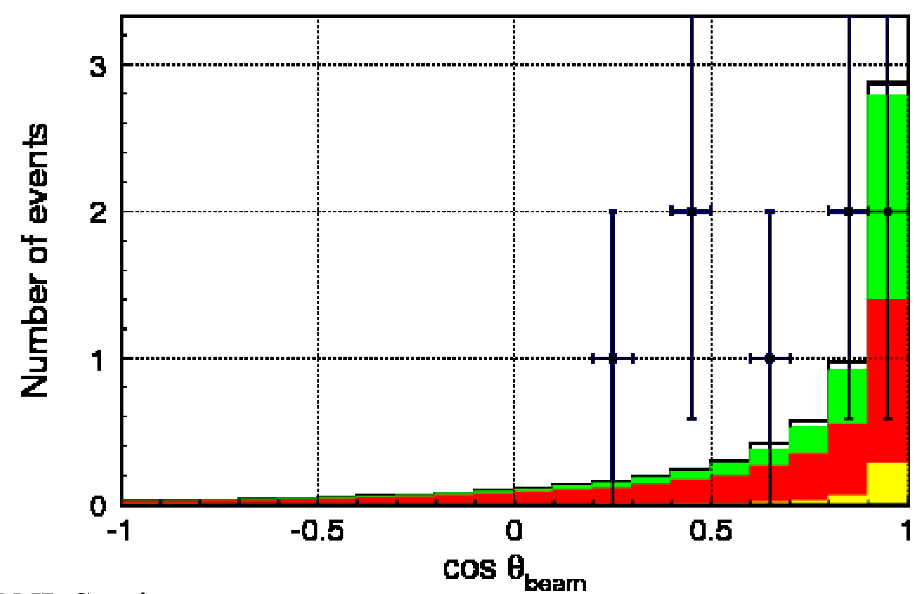
Final ν_μ Selection

T2K-SK events	Data	MC No oscillation	MC W/ oscillation
Fully-Contained	33	54.5	24.6
Fiducial Volume, E_{vis} > 30MeV	23	36.8	16.7
Single-ring μ-like P_μ>200MeV/c	8	24.5±3.9	7.1±1.3
+ number decay-e <=1 & Erec<10 GeV	8	22.8±3.2	6.3±1.0



Final ν_μ Event Selection

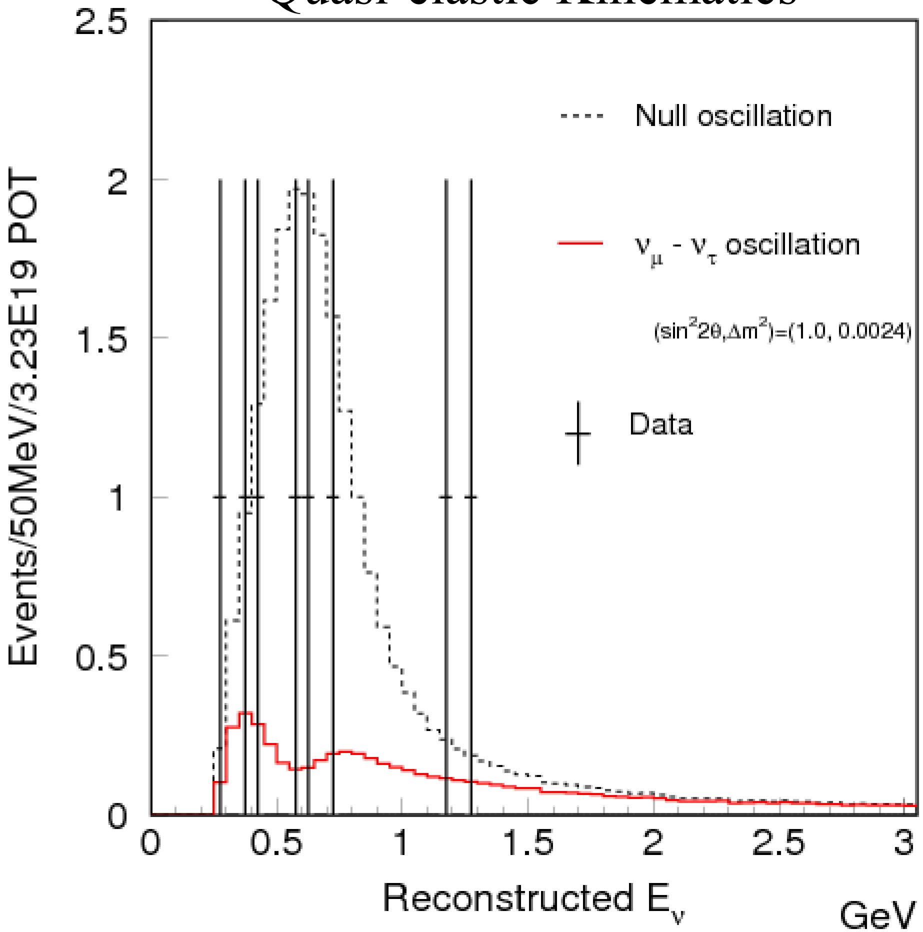




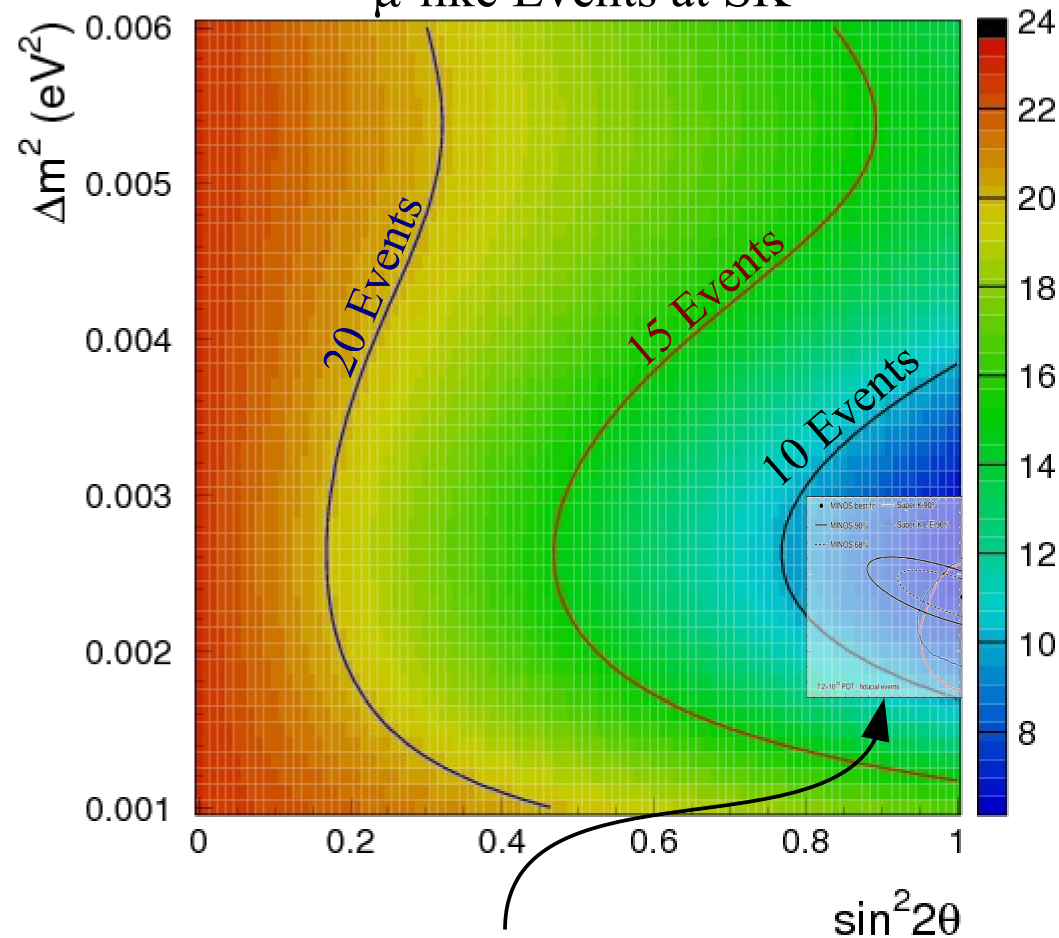
ν_μ Oscillation Expectation

8 Single Ring μ-Like Events Selected

Reconstructed E_ν Assuming Quasi-elastic Kinematics



Expected Number of Single-ring μ-like Events at SK

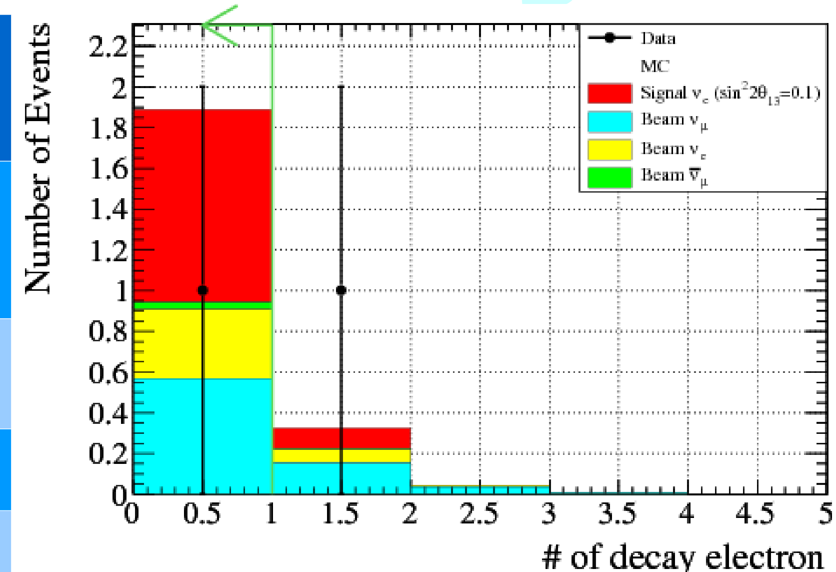


Current MINOS and SK Allowed Regions (Neutrino 2010)

Consistent with SK, K2K and MINOS

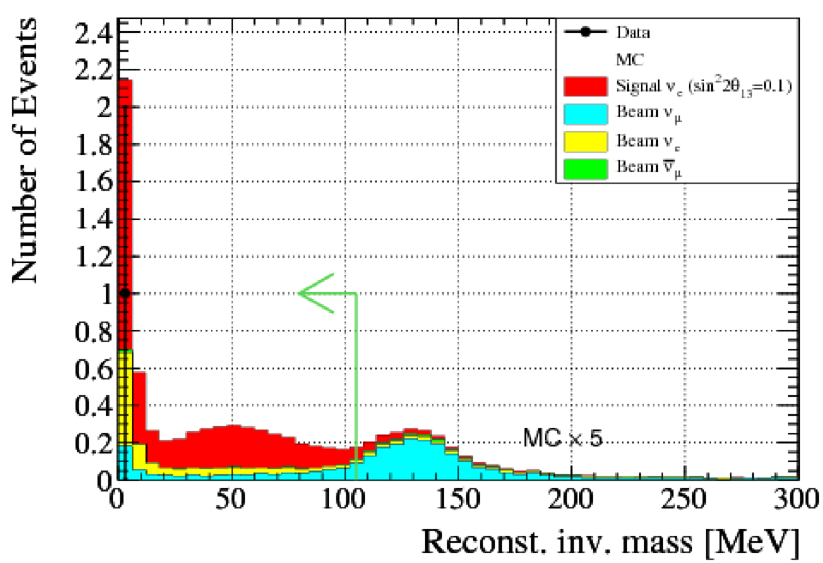
Final ν_e Appearance Selection

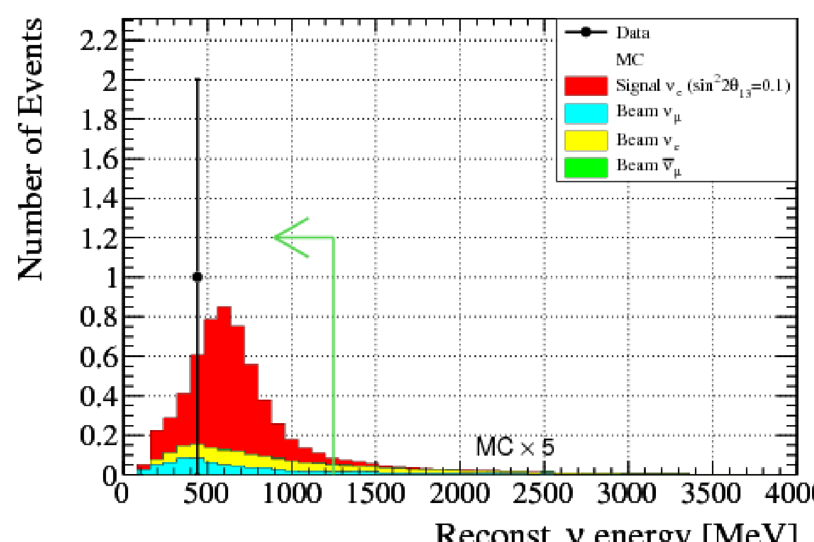
T2K-SK Events	Data	Background (Δm2=0.0024)	Signal (sin2θ13 = 0.1)
FC, Fiducial Volume Evis > 30 MeV	23	15.6	1.24
Single Ring e-like Pe > 100 MeV/c	2	1.22	1.1
No Decay Electron	1	0.94	0.95
Mγγ < 105 MeV/c2	1	0.39	0.87
Reconstructed Ev < 1250 MeV	1	0.28	0.85



Final ν_μ Event Selection

Signal selection efficiency: 65.9%





T2K Preliminary

Super-K Reconstruction Systematics

Parameter	Error source	Signal	Background
f^{SKnorm}	Normalization	1.4	1.4
f^{Energy}	Energy scale	0.3	0.5
$f^{N_{ring}}$	Ring counting	3.9	8.4
$f^{PID\mu}$	Muon PID	0.0	1.0
f^{PIDe}	Electron PID	3.8	8.1
f^{POLfit}	POLfit mass cut	5.1	8.7
$f^{N_{dcy}}$	Decay electron finding	0.1	0.3
$f^{\pi^0 eff}$	π^0 rejection	0.0	5.9

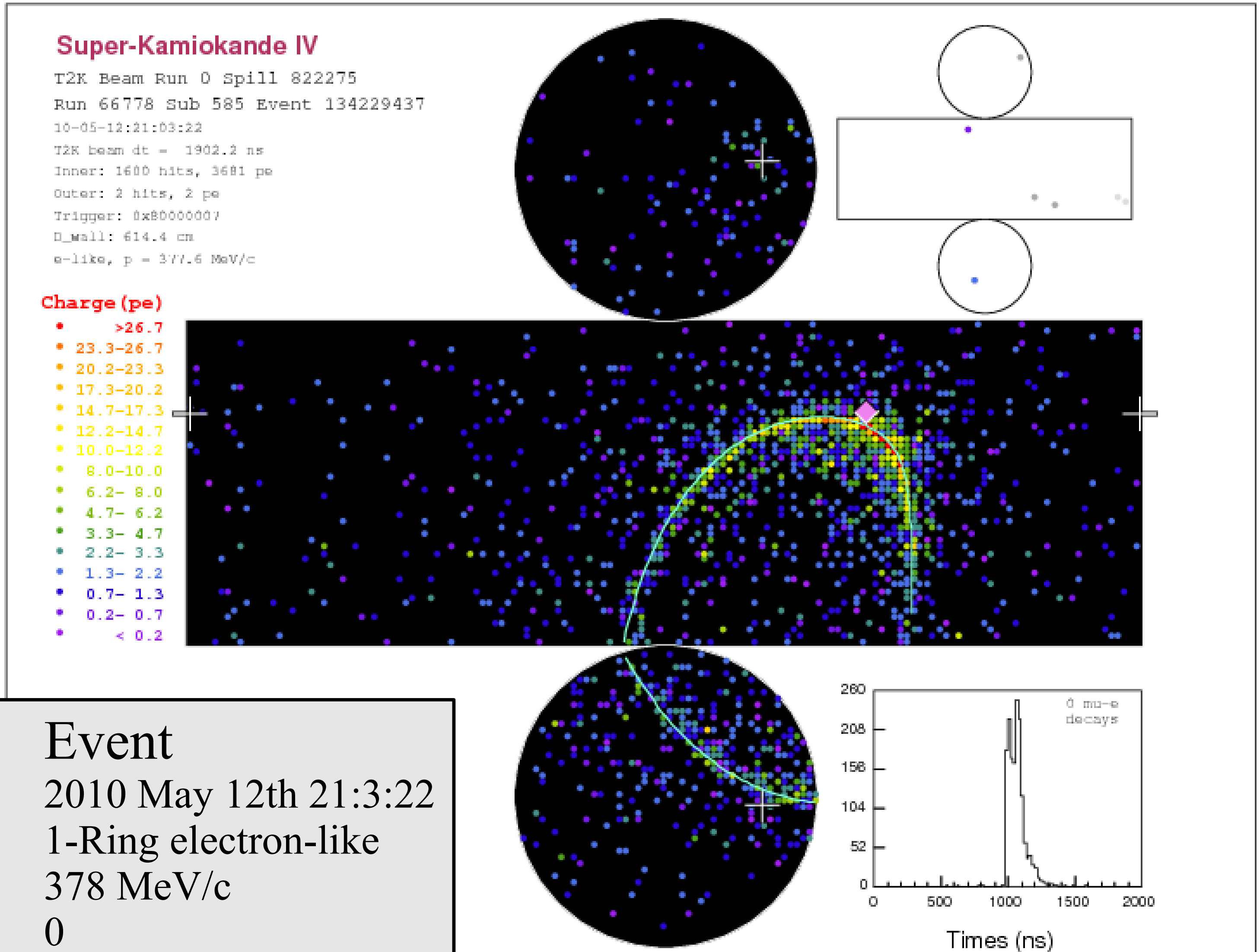
Total Uncertainty
Signal: 7.6%
Background: 15.8%

Super-Kamiokande atmospheric neutrinos and "hybrid π^o events" used as control samples.
Systematic error estimates benefit from SK atmospheric neutrino experience.

@ $\Delta m_{23}^2 = 2.4\text{x}10^{-3}\ \text{eV}^2$, $\sin^2 2\theta_{23} = 1.0$, $\delta_{CP}=0$, $\sin^2 2\theta_{13} = 0.1$ for ν_e signal

T2K Preliminary

The ν_e Candidate



Item	Event
Date (JST)	2010 May 12th 21:3:22
Ring & PID	1-Ring electron-like
Momentum	378 MeV/c
Decay Elec.	0
Inv. Mass	0.13 MeV/c^2
E_ν	496 MeV

2010 Analysis Strategy

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  - Normalization to ND280

$$N^{exp}_{SK} = R_{Data/MC} \times (N^{MC}_{signal} + N^{MC}_{bkg})$$

In the current analysis, we don't use the measured near detector spectrum, or the far/near ratio

T2K Preliminary

T2K ν_e Appearance Analysis Systematic Uncertainty

Error source	N_{SK}^{sig}	N_{SK}^{bkg}	N_{SK}^{s+b}	N_{ND}	N_{SK}^{bkg}/N_{ND}	N_{SK}^{s+b}/N_{ND}
SK Efficiency	$\pm$ 7.60	$\pm$ 15.81	$\pm$ 9.47	$\pm$ 0.0	$\pm$ 15.81	$\pm$ 9.47
Cross section	$\pm$ 9.66	$\pm$ 13.90	$\pm$ 9.88	$\pm$ 8.37	$\pm$ 14.17	$\pm$ 10.61
Beam Flux	$\pm$ 21.97	$\pm$ 18.12	$\pm$ 20.49	$\pm$ 19.83	$\pm$ 9.17	$\pm$ 11.88
ND Efficiency	$\pm$ 0.00	$\pm$ 0.00	$\pm$ 0.00	$^{+5.60}_{-5.16}$	$^{+5.60}_{-5.16}$	$^{+5.60}_{-5.16}$
Overall Norm.	$\pm$ 0.00	$\pm$ 0.00	$\pm$ 0.00	$\pm$ 0.00	$\pm$ 2.70	$\pm$ 2.70
Total	$\pm$ 25.17	$\pm$ 27.77	$\pm$ 24.64	$^{+22.23}_{-22.13}$	$^{+23.95}_{-23.85}$	$^{+19.55}_{-19.43}$

@ Δm_{23}^2 = 2.4x10^{-3} eV^2, $\sin^2 2\theta_{23}$ = 1.0, δ_{CP}=0, $\sin^2 2\theta_{13}$ = 0.1 for ν_e signal

Constrained by ND280 Normalization

Total Systematic Error (Approximate)
Background Only: ~24%
Signal and Background ~20%

Effect of input systematic errors re-estimated for each set of oscillation parameters.

Expected Background

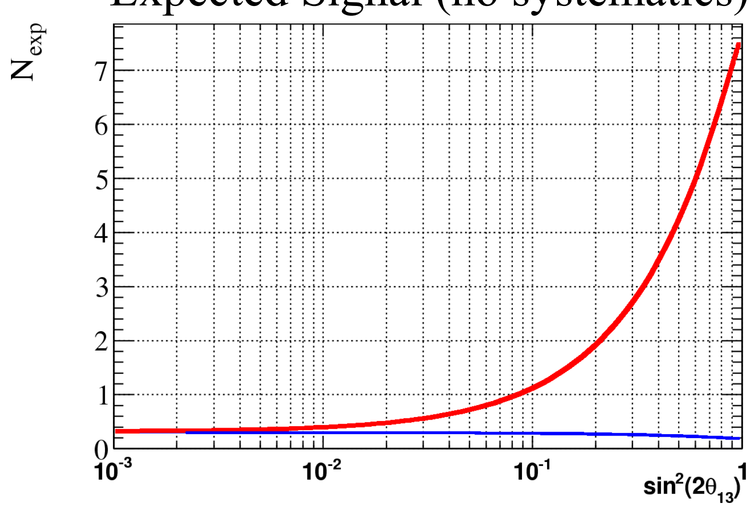
Source	Estimated Background
Beam ν_μ (CC + NC)	0.13
Beam $\bar{\nu}_\mu$ (CC + NC)	0.01
Beam ν_e (CC)	0.16
Total	**0.30 ± 0.07**

Probability of observing more than zero background events is about 29%

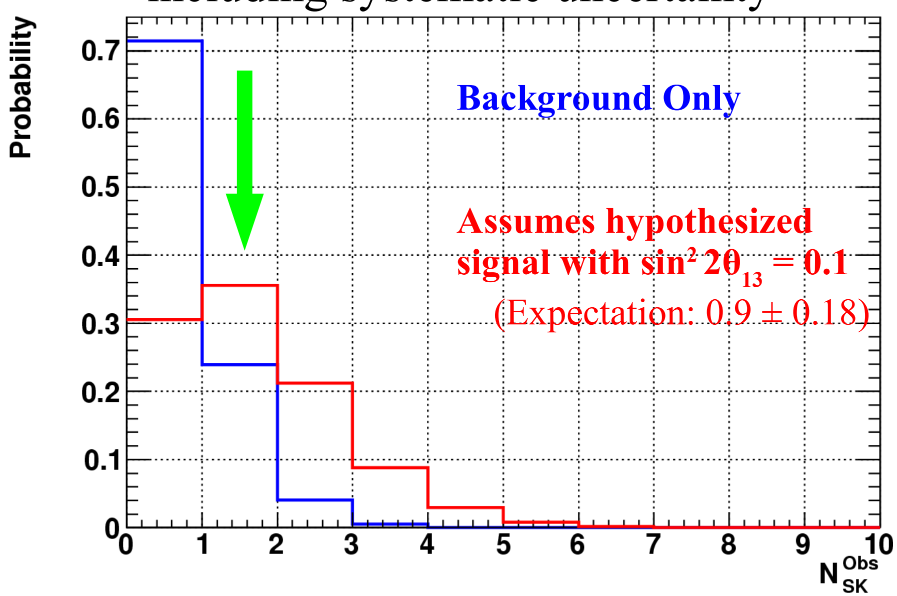
- Poisson statistics plus systematic uncertainty

@ Δm_{23}^2 = 2.4×10^{-3} eV^2, $\sin^2 2\theta_{23} = 1.0$, $\delta_{CP}=0$

Expected Signal (no systematics)



Probability of observing N_{SK} including systematic uncertainty



$\nu_\mu \rightarrow \nu_e$ Oscillation Limits

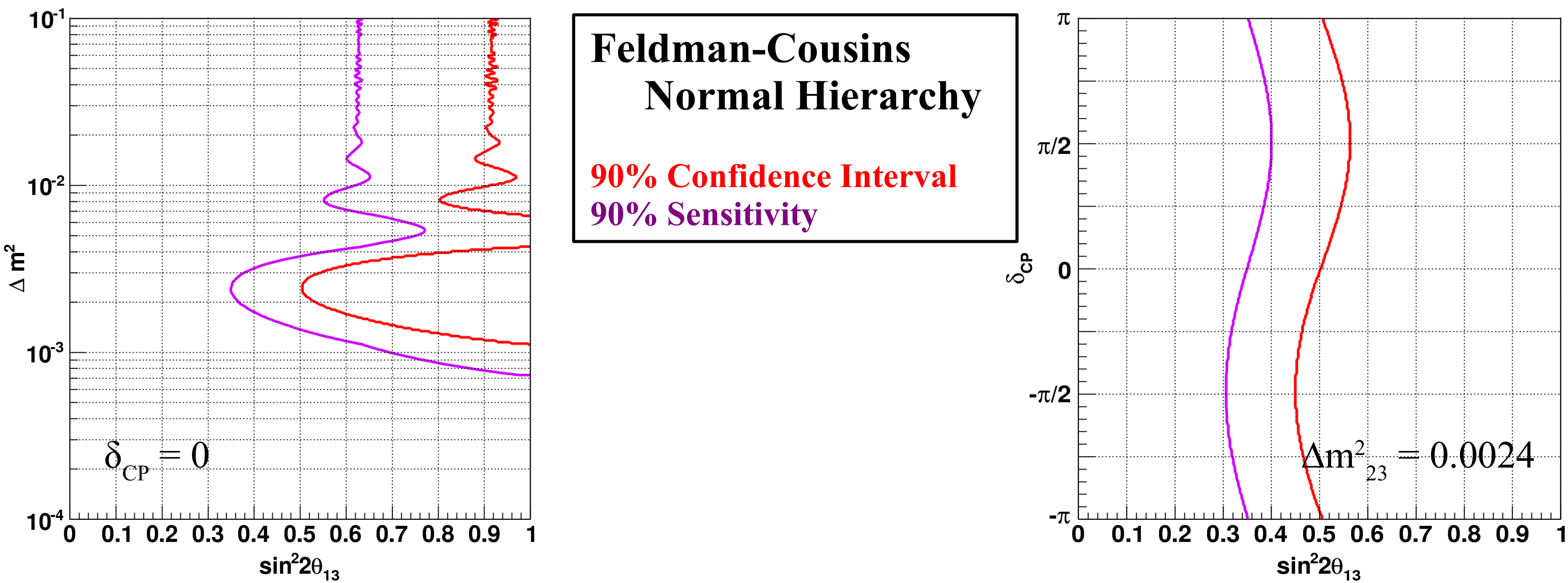
- Neyman confidence intervals are calculated in two ways
  - Feldman-Cousins
  - Single-sided Poissonian

Feldman-Cousins

Hierarchy	Upper Limit	Sensitivity
Normal ($\Delta m^2_{23} > 0$)	0.50	0.35
Inverted ($\Delta m^2_{23} < 0$)	0.59	0.42

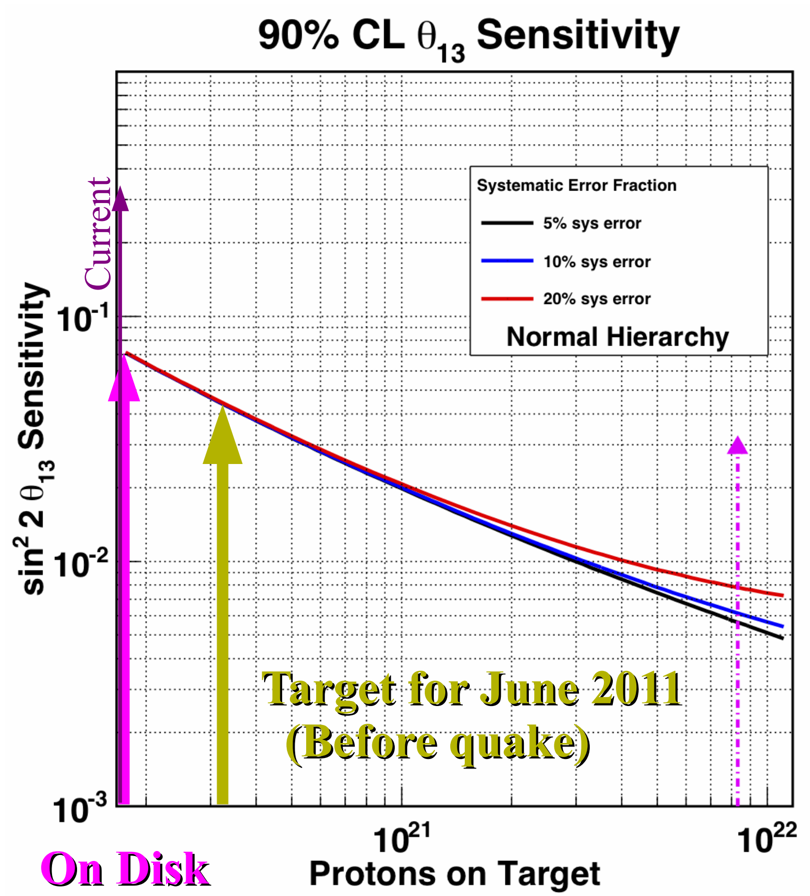
Single-sided Poissonian

Hierarchy	Upper Limit	Sensitivity
Normal ($\Delta m^2_{23} > 0$)	0.44	0.32
Inverted ($\Delta m^2_{23} < 0$)	0.53	0.39



Prospects for Updated Results

- Exposure collected this year:
  - 1.45 x 10^{20} P.O.T.
    - (includes 2010a)
  - 4½ times 2010a analysis
  - This is 73kW x 10^7s
    - Original goal: 150kW x 10^7s
  - Will likely be first reported using 2010a analysis technique
    - Still statistics limited.
- Planned Analysis improvements
  - New NA61 results
  - Spectral information from ND280 and near/far ratio to reduce model dependence
  - NC π^o and beam-ν_e measurements from ND280



Conclusions

- T2K is the first off-axis long baseline neutrino oscillation experiment
  - Searching for ν_e appearance (θ_{13})
  - Precision measurement of $\nu_\mu \rightarrow \nu_x$ (atmospheric oscillation) parameters
  - Data collected from January 2010
- First oscillation results reported based on 3.23×10^{19} protons on target
  - Observed 1 ν_e candidate
    - Expected background is 0.3 ± 0.07 events ($\theta_{13} = 0$)
    - Upper limit of $\sin^2 2\theta_{13} < 0.50$ for normal hierarchy (< 0.59 inverted).
  - Observed 8 ν_μ candidates
    - Consistent with SK, K2K and MINOS oscillation parameters.
- Total integrated proton intensity collected is 1.45×10^{20} p.o.t.
  - Analysis method is being improved
  - Expect improve on current CHOOZ limit
- Full impact of the earthquake on T2K is unknown

Backup Slides

Current Global Best Fit

- hepex-1103.0743v1: Thomas Schwetz, Miriam Tortola, J.W.F.Valle
  - Dated: 3 March 2011
- Parameters important for T2K
  - $\Delta m^2_{31} = 0.00245 \pm 0.00009$ (NH) or -0.00234 ± 0.0001 (IH)
  - $\sin^2 2\theta_{23} > 0.98$ (at 1σ)
  - $\sin^2 2\theta_{13}$
    - Best fit: **$\sin^2 2\theta_{13} = 0.07$**
    - 3σ upper limit: **$\sin^2 2\theta_{13} < 0.17$**

parameter	best fit $\pm 1\sigma$	2σ	3σ
Δm^2_{21} [10^{-5}eV^2]	$7.64^{+0.19}_{-0.18}$	7.27–8.03	7.12–8.23
Δm^2_{31} [10^{-3}eV^2]	2.45 ± 0.09 $-(2.34^{+0.10}_{-0.09})$	$2.28 - 2.64$ $-(2.17 - 2.54)$	$2.18 - 2.73$ $-(2.08 - 2.64)$
$\sin^2\theta_{12}$	0.316 ± 0.016	0.29–0.35	0.27–0.37
$\sin^2\theta_{23}$	0.51 ± 0.06 0.52 ± 0.06	0.41–0.61 0.42–0.61	0.39–0.64
$\sin^2\theta_{13}$	$0.017^{+0.007}_{-0.009}$ $0.020^{+0.008}_{-0.009}$	≤ 0.031 ≤ 0.036	≤ 0.040 ≤ 0.044

Neutrino Oscillations

Interaction Eigenstates

Mass Eigenstates

$$|\nu_\alpha\rangle = \sum_{i=1}^{n} U_{\alpha i} |\nu_i\rangle \,\Big|_{\alpha \in e,\mu,\tau}$$

Mixing Matrix

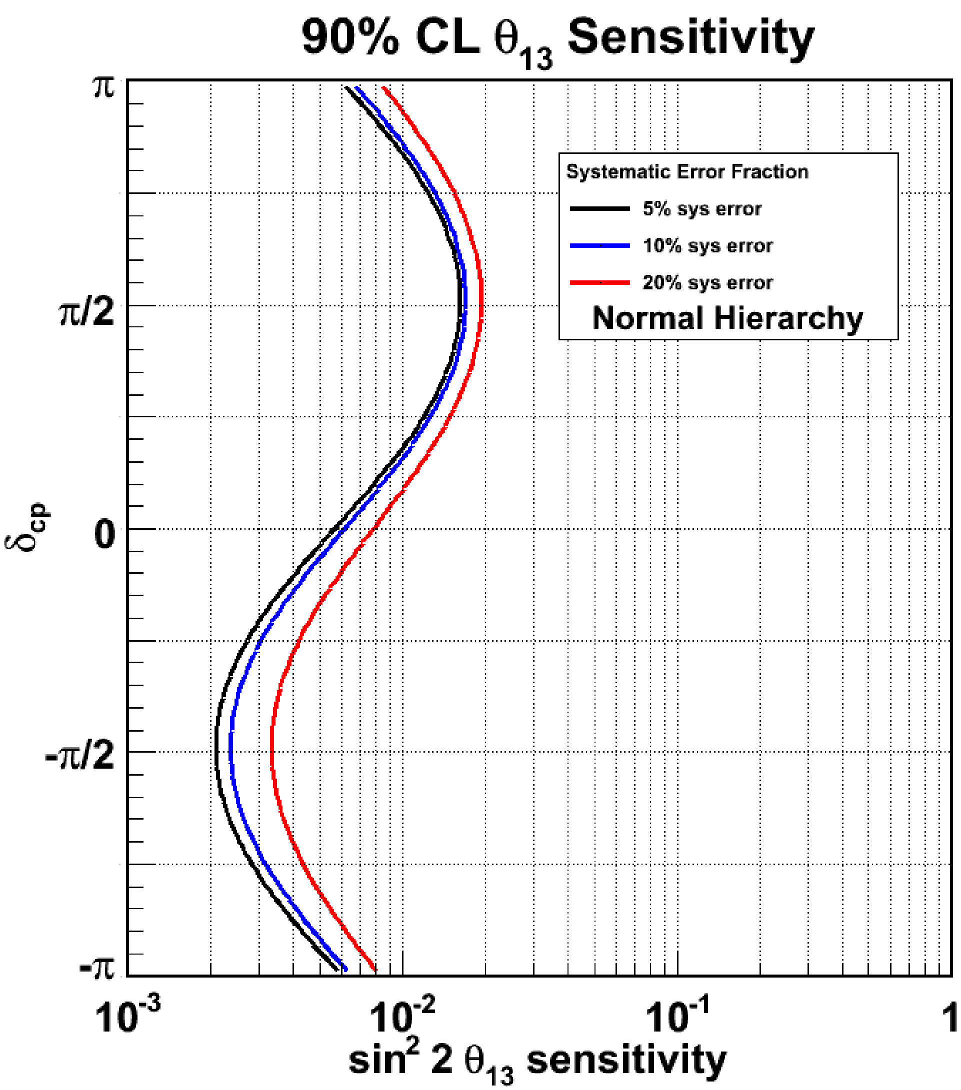
$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{cp}} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta_{cp}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Atmospheric Oscillations

Unknown

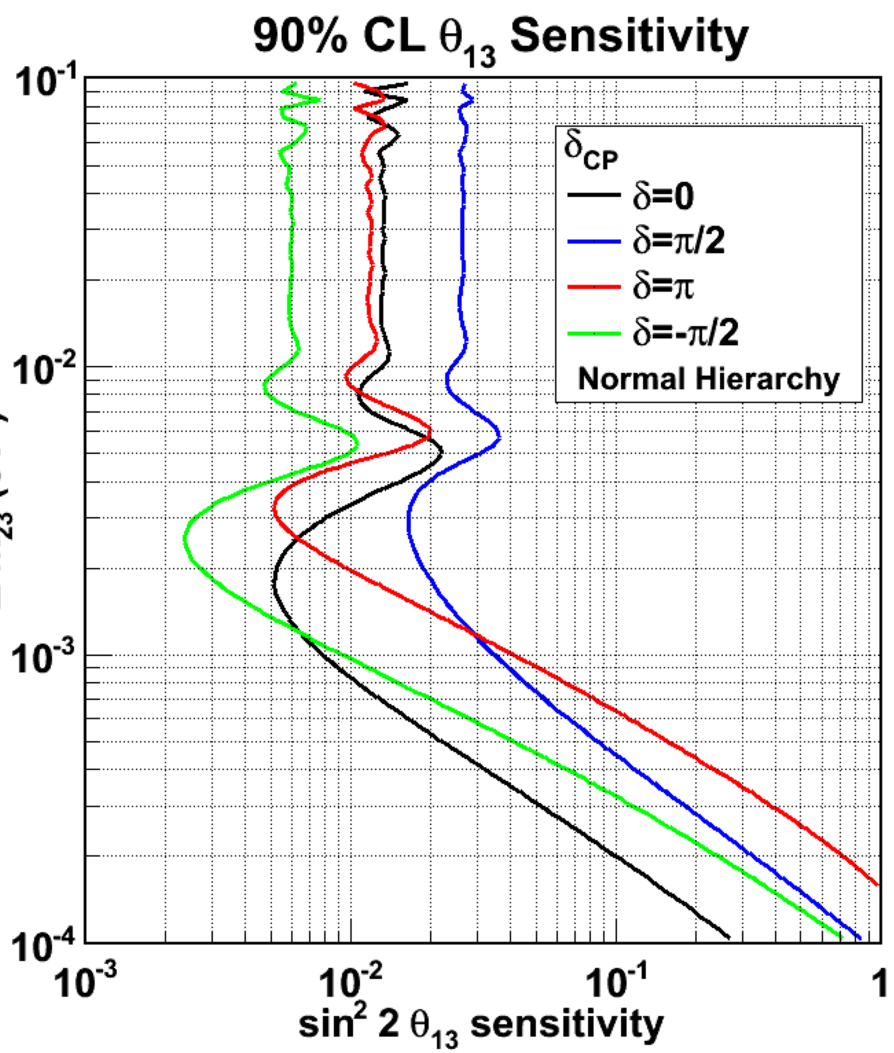
Solar Oscillations

T2K Sensitivity vs δ_{CP}



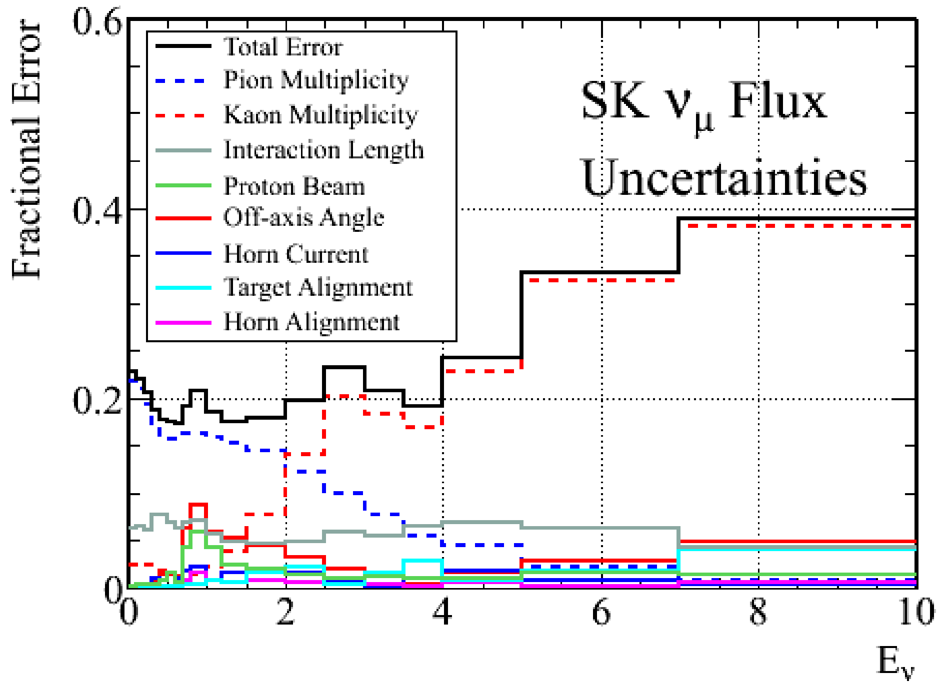
- T2K sensitivity to θ_{13} at the 90% confidence level as a function of δ_{CP}.
- Beam is assumed to be running at 750kW for 5 years, using the 22.5 kton SK fiducial volume.
- The following oscillation parameters are assumed:
  - $\sin^2 2\,\theta_{12} = 0.8704$,
  - $\sin^2 2\,\theta_{23} = 1.0$,
  - $\Delta m^2_{12} = 7.6 \times 10^{-5}\ eV^2$,
  - $\Delta m^2_{13} = 2.4 \times 10^{-3}\ eV^2$,
  - Normal hierarchy.

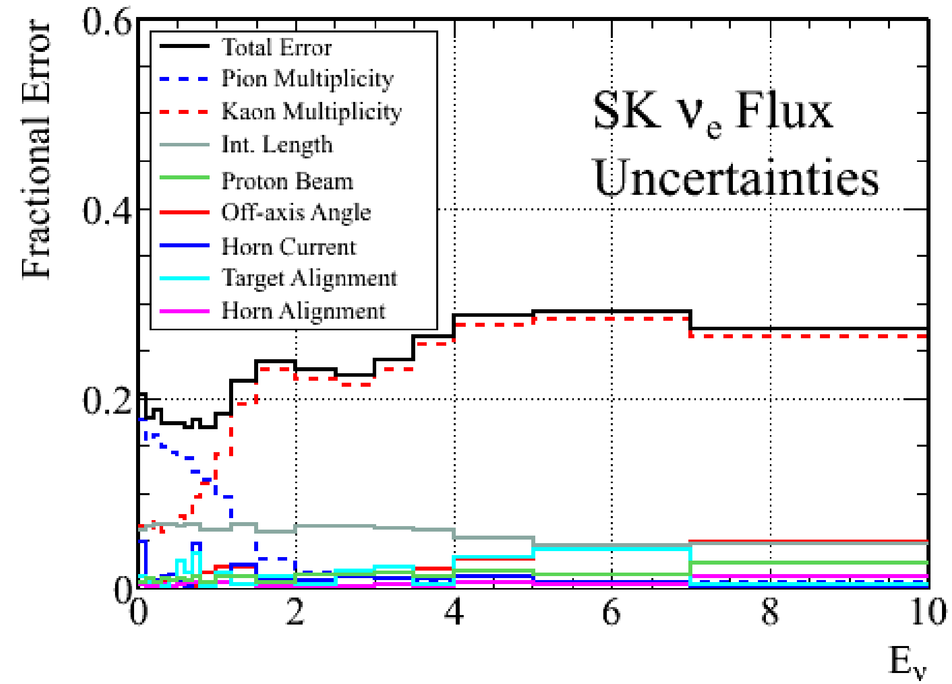
T2K Sensitivity vs Δm^2_{13}



- T2K sensitivity to θ_{13} at the 90% confidence level as a function of Δm^2_{13}.
- Beam is assumed to be running at 750kW for 5 years, using the 22.5 kton SK fiducial volume.
- The following oscillation parameters are assumed:
  - $\sin^2 2\,\theta_{12} = 0.8704$,
  - $\sin^2 2\,\theta_{23} = 1.0$,
  - $\Delta m^2_{12} = 7.6 \times 10^{-5}\ eV^2$,
  - Normal hierarchy.

Neutrino Flux Uncertainty





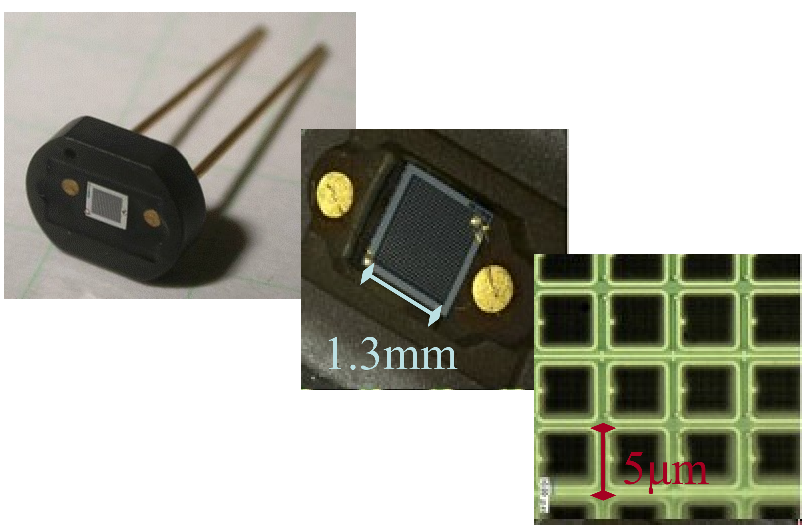
- Dominant Uncertainties
  - Pion Multiplicity at low E_ν
  - Kaon Multiplicity at high E_ν
- Expect improvement with final SHINE/NA61 Data

T2K Scintillator Det. Technology
(ECAL, FGD, INGRID, P0D, SMRD)

Active material of detector is plastic scintillator bars with WLS fibres in central channels to photosensors.

✓ Well proven & economical: Similar technology used by K2K, MINOS, MINERvA, SciBooNE…

T2K uses an innovative readout: **M**ulti-**P**ixel **P**hoton **C**ounters:



667 pixels, each acts as an avalanche photodiode in Gieger mode. Impervious to magnetic field. Operating voltage is ~70 V.

Pixels are read out by a single anode. Charge is proportional to number of photons observed

T2K uses about 60,000 MPPCs in the ND280 scintillator detectors.

The ND280 Hall (Hole)