First Neutrino Oscillation Results from the T2K Experiment

Mark Hartz

(University of Toronto, York University)

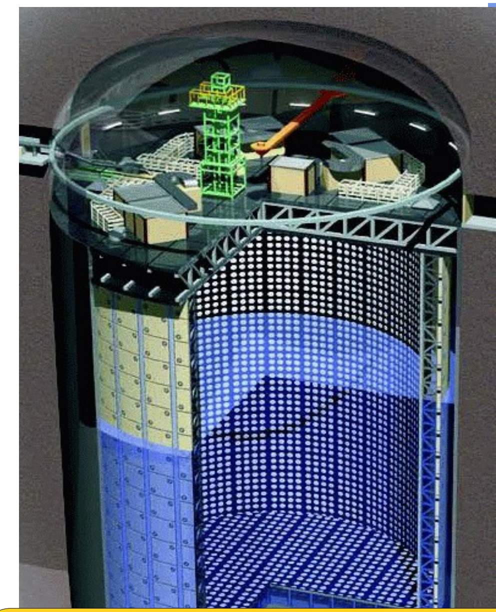
for the T2K Collaboration

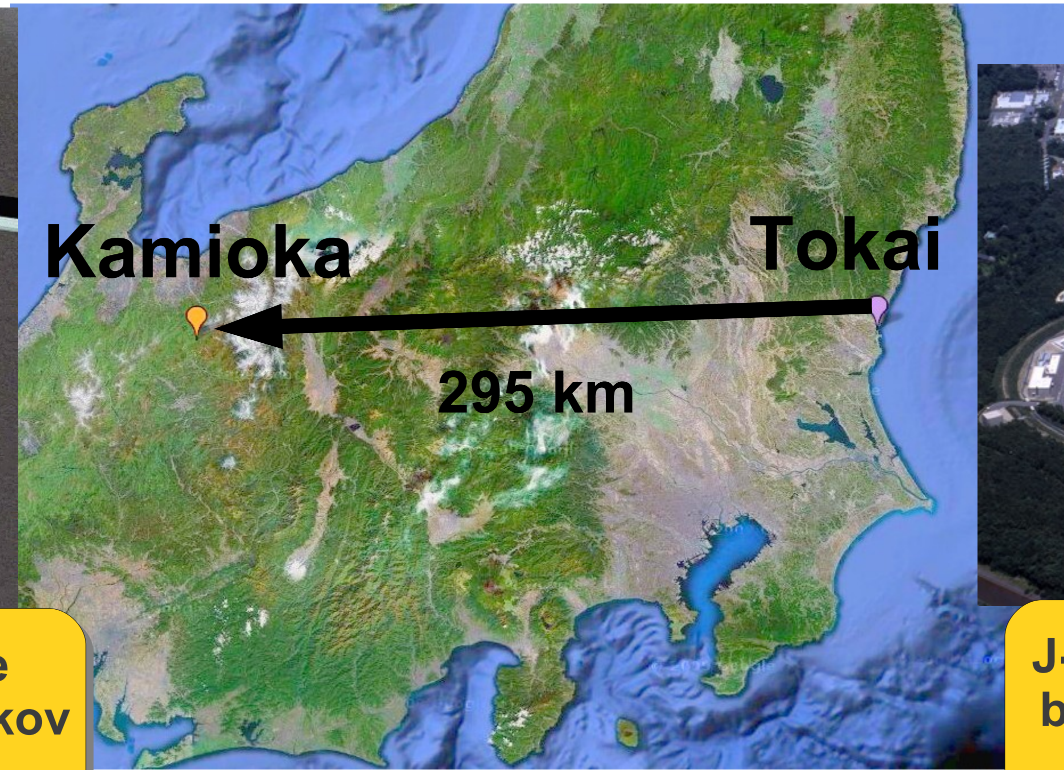
Results officially released at NEUTEL11:

http://neutel11.wordpress.com/2011/03/16/a-rubbia-results-from-t2k/

Rencontres de Moriond Electroweak Session March 13-20, 2011

T2K (Tokai to Kamioka) Experiment





Super-Kamiokande 50 kton water cherenkov detector at 295 km

J-PARC: 30 GeV proton beam, design power of 750 kW

- ~500 collaborators from 59 institutions in 12 countries
- Experiment's goals:
  - Search for ν_e appearance in a ν_μ beam
  - Precise measurement of parameters governing ν_μ disappearance

Aftermath of Earthquake

- The J-PARC facility and surrounding area was affected by the recent earthquake, but avoided the tsunami
- No T2K collaborators or J-PARC associated employees were injured in the quake
- The reactors at the JAEA site in Tokai are ok
- A preliminary inspection of the T2K facilities has been carried out, but a more detailed investigation must wait until power is completely restored (some time next week)
- To this end, restoration of power, water and gas systems at J-PARC is the highest priority
- We will know more about how T2K will be affected in the ensuing weeks

Oscillation & Interactions at T2K

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

SK, K2K, MINOS:

$\sin^2(2\theta_{23}) > 0.92$ (90% C.L.)

$\Delta m_{23}^2 = 2.43\pm0.13 \times10^{-3}\ \mathrm{eV}^2$

Still unknown

CHOOZ limit:

$\sin^2(2\theta_{13}) < 0.15$ (90% C.L.)

KAMLAND, SNO:

$\sin^2(2\theta_{12}) = 0.87\pm0.03$

$\Delta m_{12}^2 = 7.59\pm0.20 \times10^{-5}\ \mathrm{eV}^2$

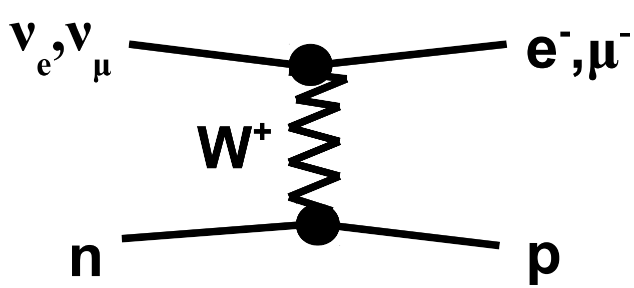
Oscillation Probabilities of Interest:

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

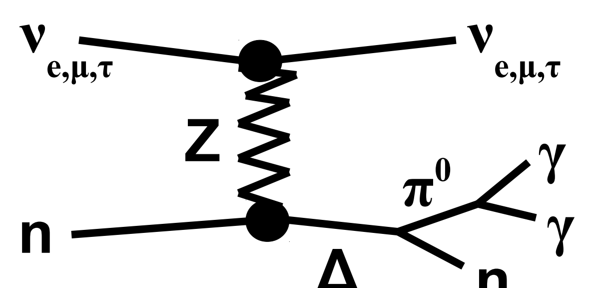
$$P(\nu_\mu\rightarrow\nu_\mu)\approx1-\sin^2 2\theta_{23}\sin^2\frac{\Delta m_{23}^2 L}{4E_\nu}$$

Important neutrino interactions for T2K:

Charge Current Quasi-elastic (CCQE)



Neutral Current π^0 (NCπ^0)



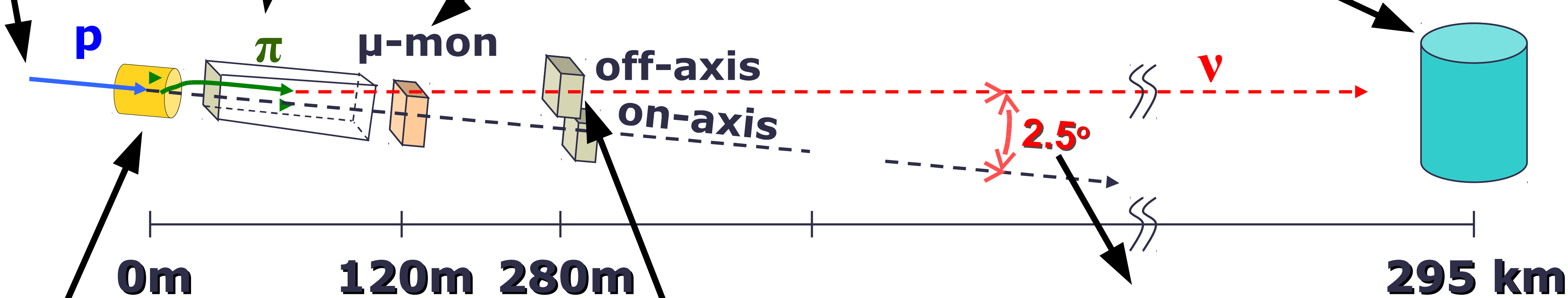
T2K Overview

30 GeV proton beam from J-PARC

Pions decay in 100 m decay volume

MUMON monitor measures muons from pion decay

Off-axis **far detector** at 295 km: Super-Kamiokande (SK) water cherenkov detector measures oscillated flux

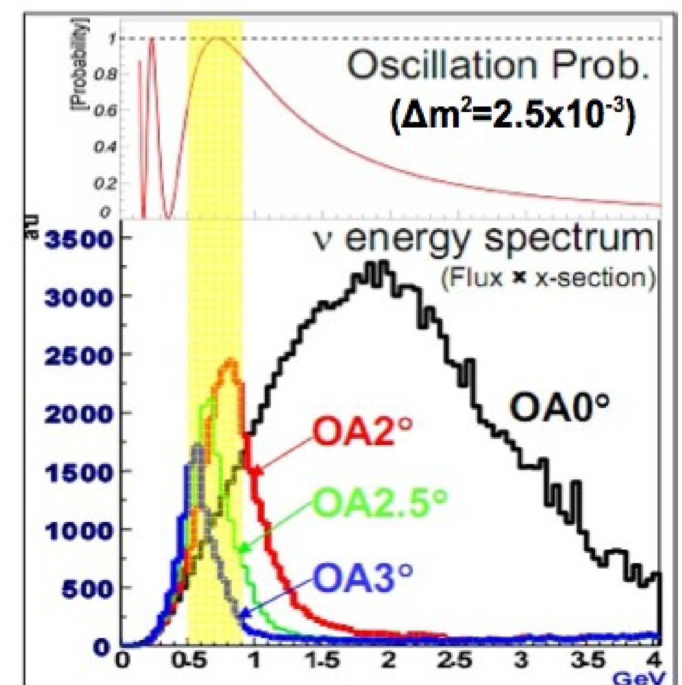


Beam on 90 cm graphite target

3 magnetic horns focus positively charged hadrons

At 280 m, on-axis INGRID detector measures neutrino rate, beam profile

Off-axis **near detector**: ND280 detector measures spectra for various neutrino interactions

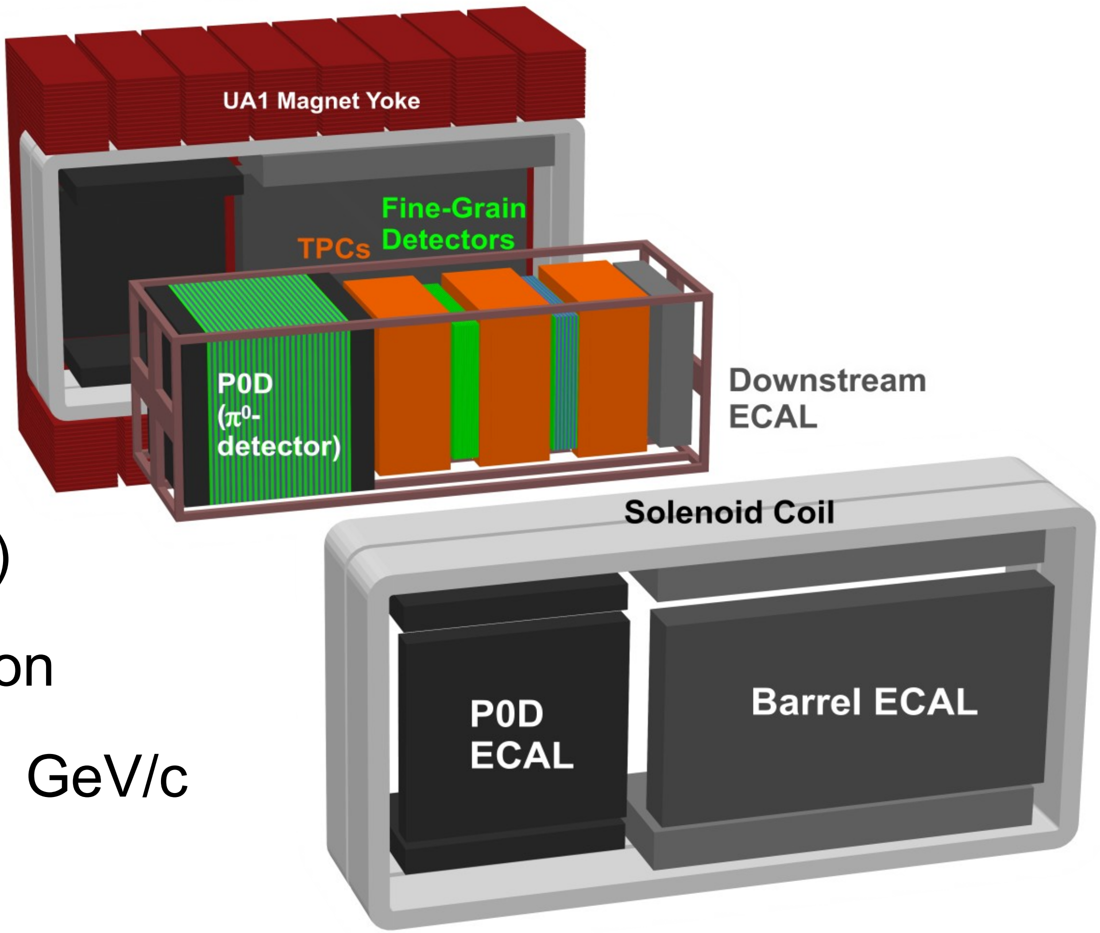


ND280 (Near) Detector

- 0.2 T UA1 magnet

Used in current analysis

- Fine Grain Detectors (FGD)
  - Scintillator bars (+ water target in FGD2) 2.2 tons ν target
- Time Projection Chambers (TPC)
  - Better than 10% dE/dx resolution
  - 10% momentum resolution at 1 GeV/c

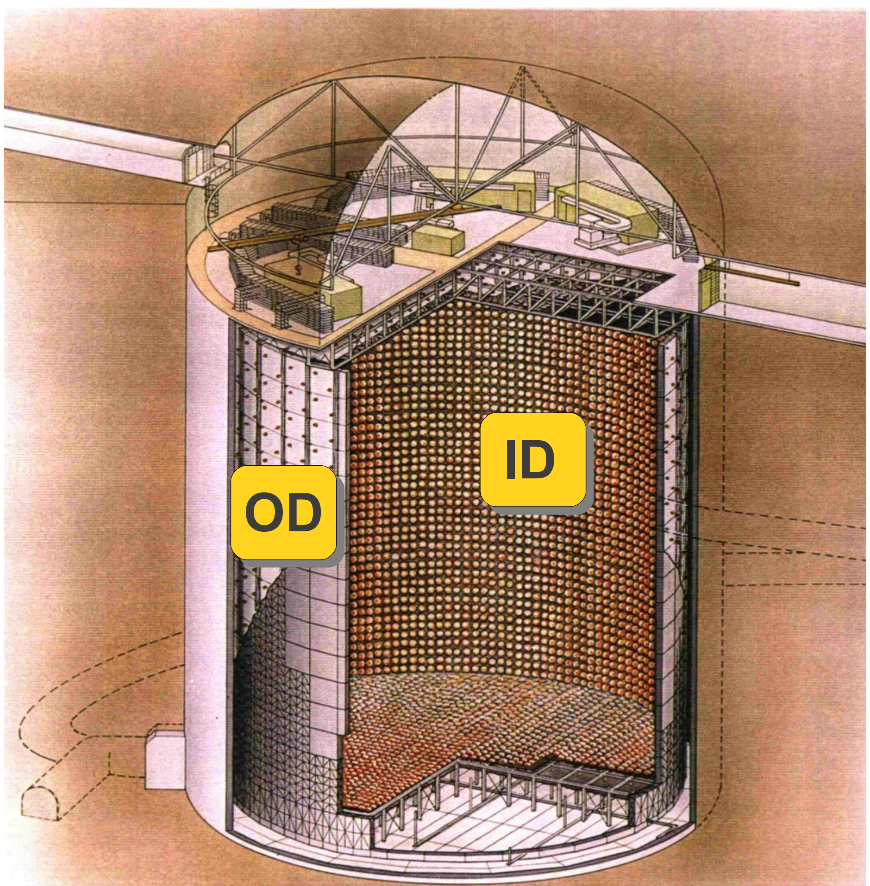


Important for future analyses

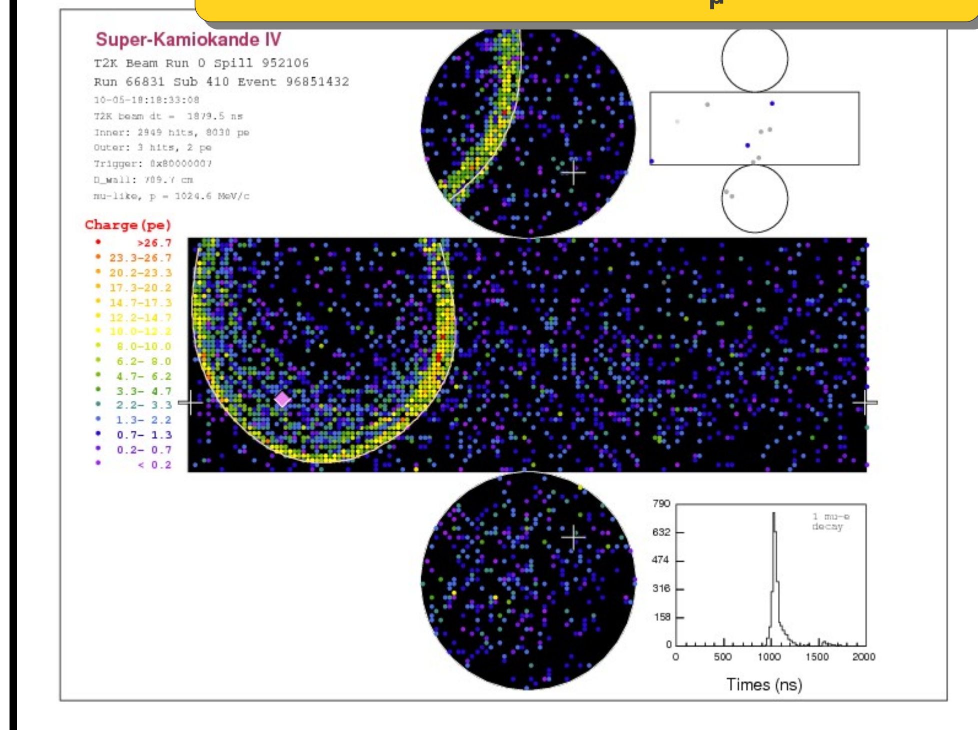
- POD π^0 detector
- Barrel and Downstream Electromagnetic Calorimeters
- SMRD muon detector installed in magnet yoke

SK (Far) Detector

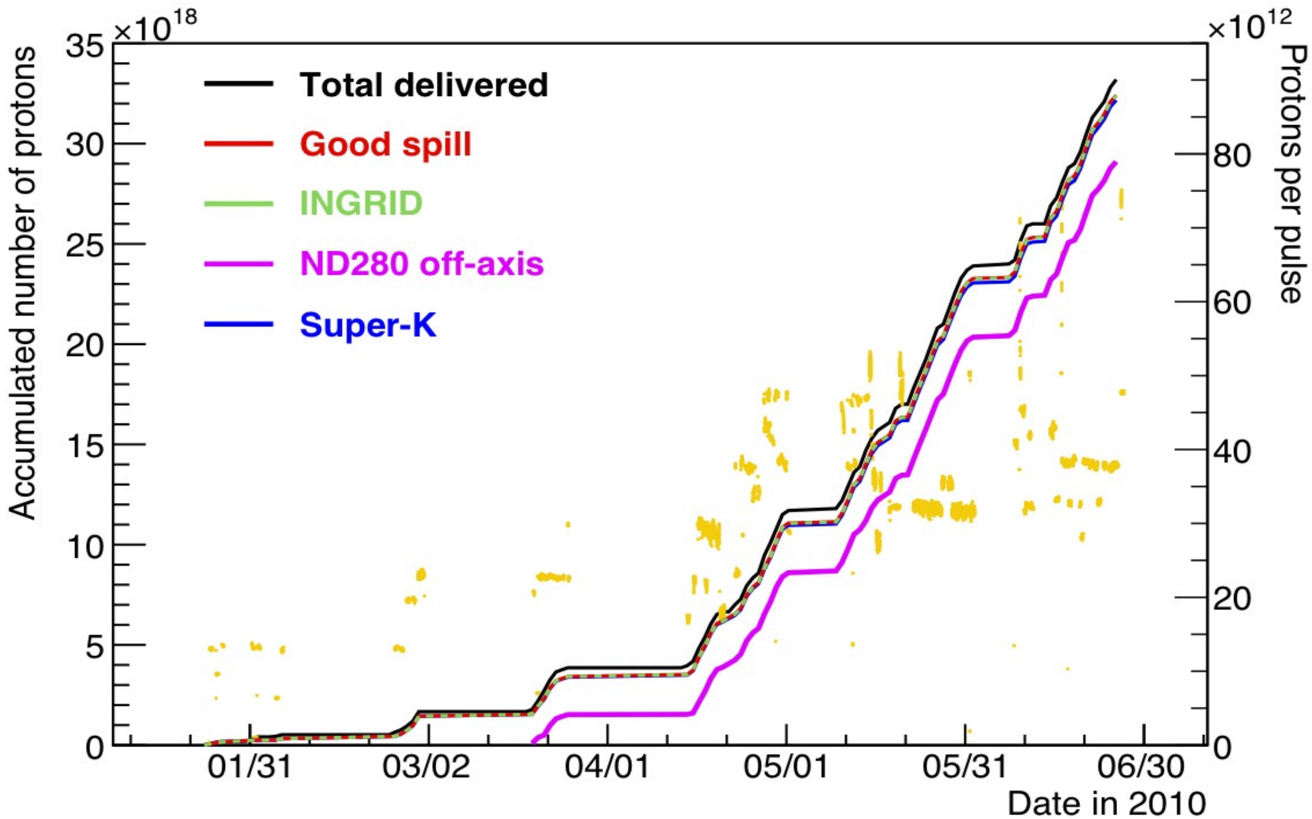
- 50 kton (22.5 kton fiducial volume) water cherenkov detector
- ~11,000 20" PMT for inner detector (ID) (40% photo coverage)
- ~2,000 outward facing 8" PMT for outer detector (OD): veto cosmics, radioactivity
- Good reconstruction of <GeV events: ΔE/E ~ 10% for two-body kinematics



Example single ring ν_μ candidate



Data Collected and Sensitivity



- 2010a dataset: collected from Jan. 2010-June 2010
- Data available for SK analysis: **3.23×10^{19} POT** = **15.5 kWx10^7 sec**
- Stable running at 3.8×10^{13} protons/pulse at 3.52 sec rep. rate = 54 kW
- 90% C.L. sensitivity for **$\sin^2(2\theta_{13}) \sim 0.35$**

SK Data Collection & Reduction

From ±500 μs window around beam spills	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
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	-

Clear indication of oscillation in the 1-ring muon like sample

Single Ring Samples (similar to samples used in the analyses):

- Event is fully containted inner detector
- In fiducial volume and visible energy is >30 MeV
- Event contains only 1 ring
- PID identifies ring as muon or electron

Analysis Flow for 2010a Data

Flux Prediction

- Proton beam measurements
- Hadron production data

ND280 Measurement

- Inclusive ν_μ CC measurement
- Output: $R_{data/MC} = N^{data}_{ND280} / N^{MC}_{ND280}$

Neutrino Cross Sections

- Interaction models
- External cross section data

SK Measurement

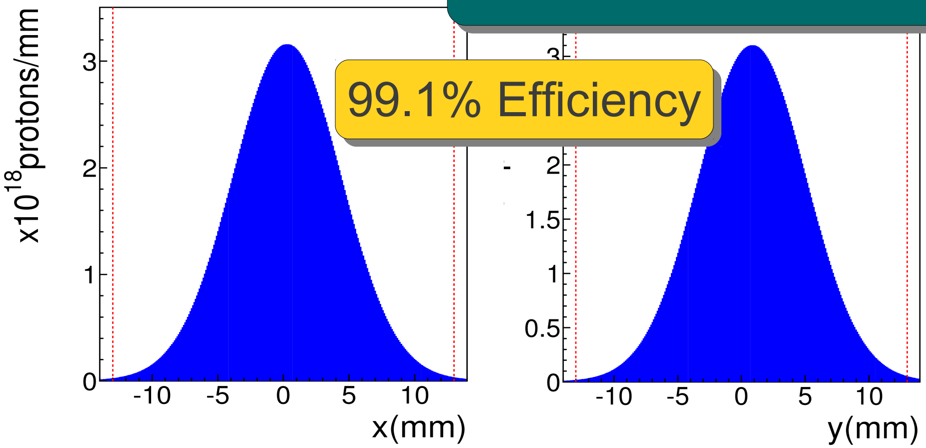
- Select ν_μ and ν_e CC candidate samples
- Simulate expected samples
- Adjust normalization using ND280 measurement:

$$N^{\exp}_{SK} = R_{data/MC} \times N^{MC}_{SK}$$

- Evaluate systematics
- Evaluate convidence intervals (will only show ν_e today)

Simulation of Neutrino Flux

Proton Beam Profile at the Target



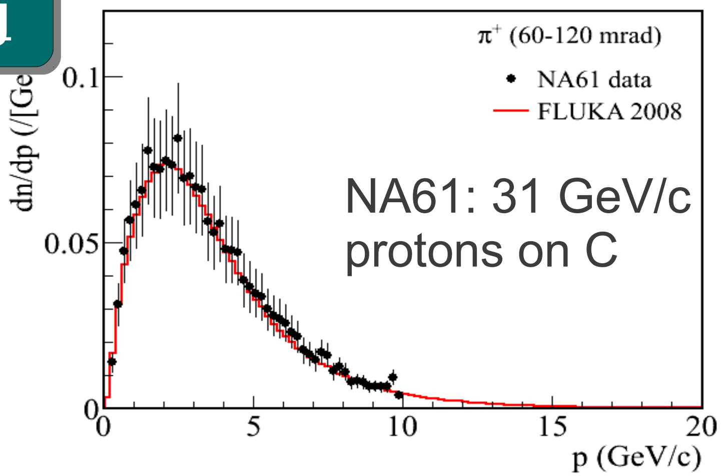
- # of Protons: CT monitors with 2% uncertainty
- Beam Shape: SSEM and OTR with 0.5-1.0 mm uncertainty

Neutrino Flux Simulation

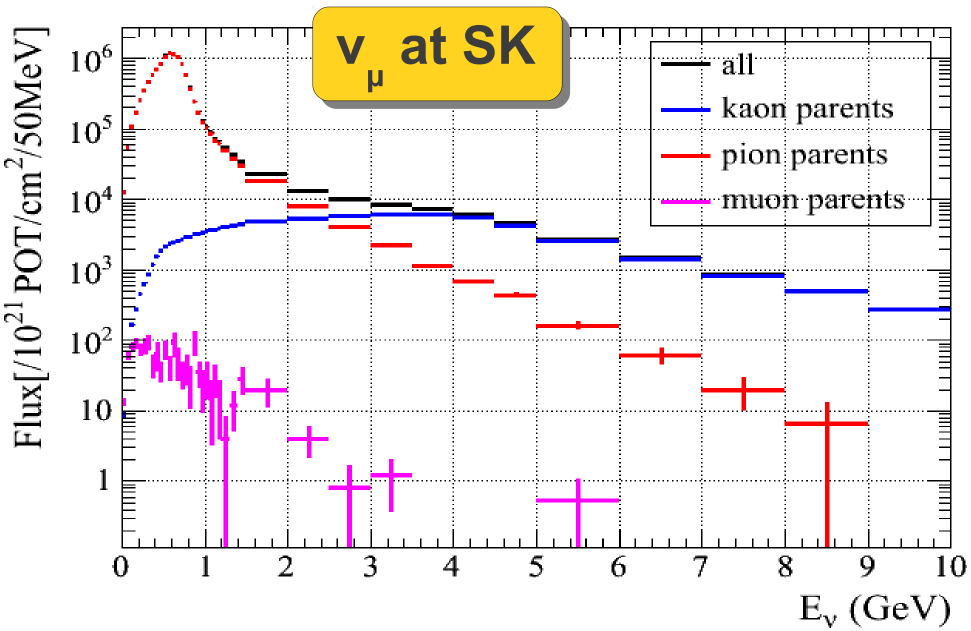
- **In target hadron production: FLUKA2008**
- **Out of target simulation: GEANT3 (GCALOR)**

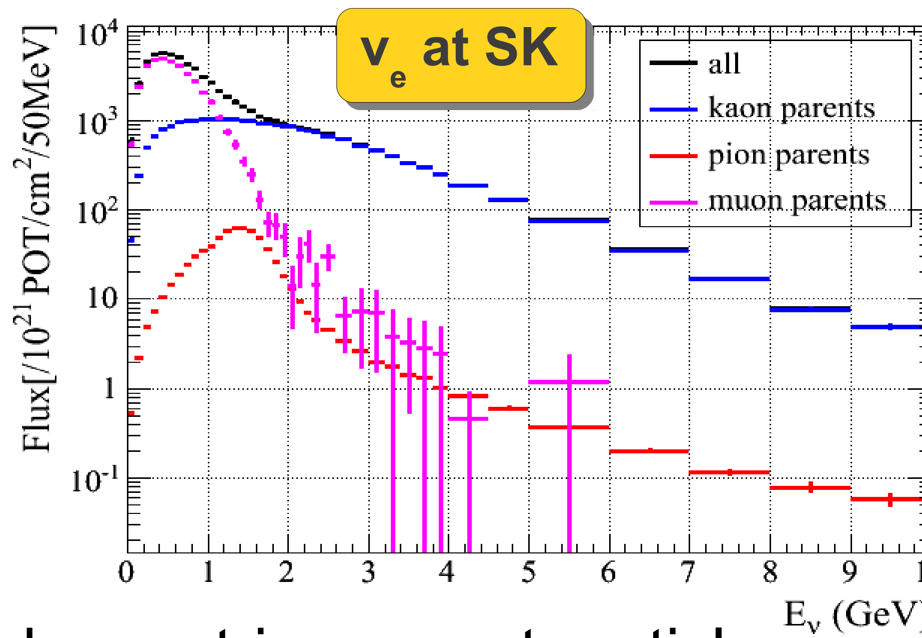
Hadron Production Tuning

- Tune hadron production with data
- NA61/Shine: preliminary π^+ and π^- data with 20% uncertainty **S. Murphy at YSF3**
- Other external data used for kaons



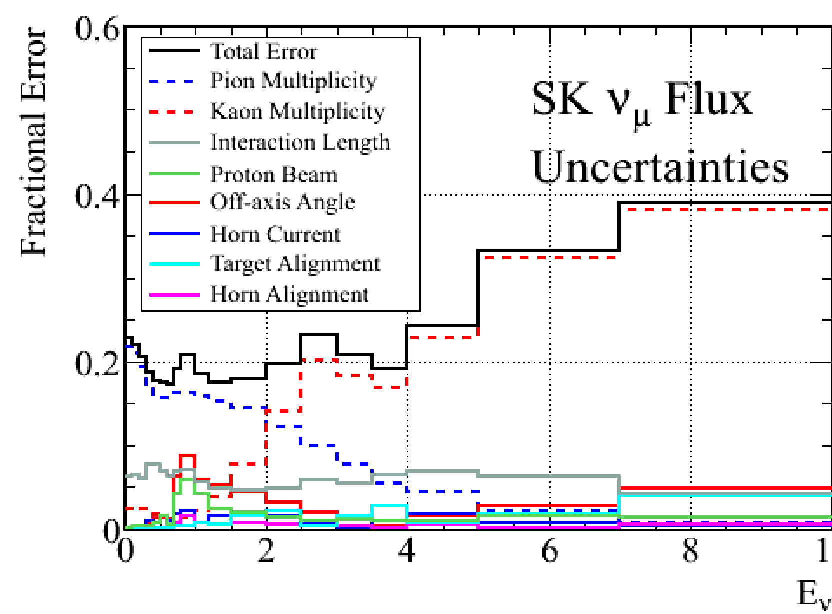
Neutrino Flux and Uncertainty





Neutrino flux at SK broken down by neutrino parent particle

- Dominant uncertainties: pion and kaon production data (~20-40%)
- Other sources: proton beam profile, neutrino beam direction measurement (INGRID), hadron interaction lengths

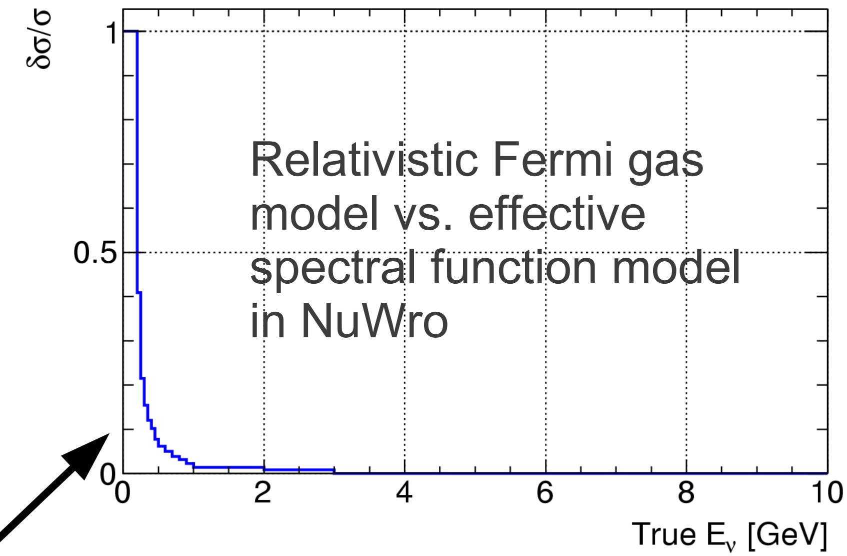


Neutrino Interactions

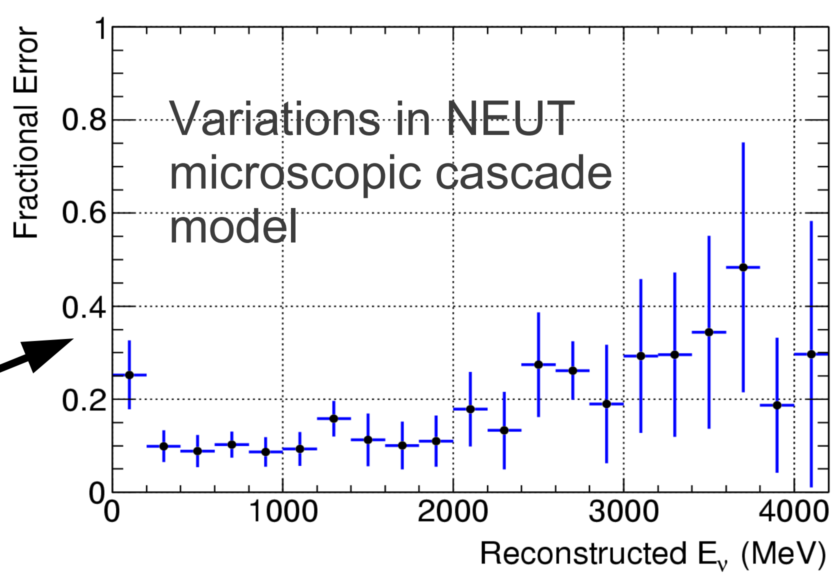
- NEUT and GENIE used to model neutrino interactions
- Uncertainties from:
  - Parameter variations in models, comparisons between models
  - Model comparisons to MiniBooNE, SciBooNE and SK atmospheric data

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	

Low energy CCQE Uncertianty



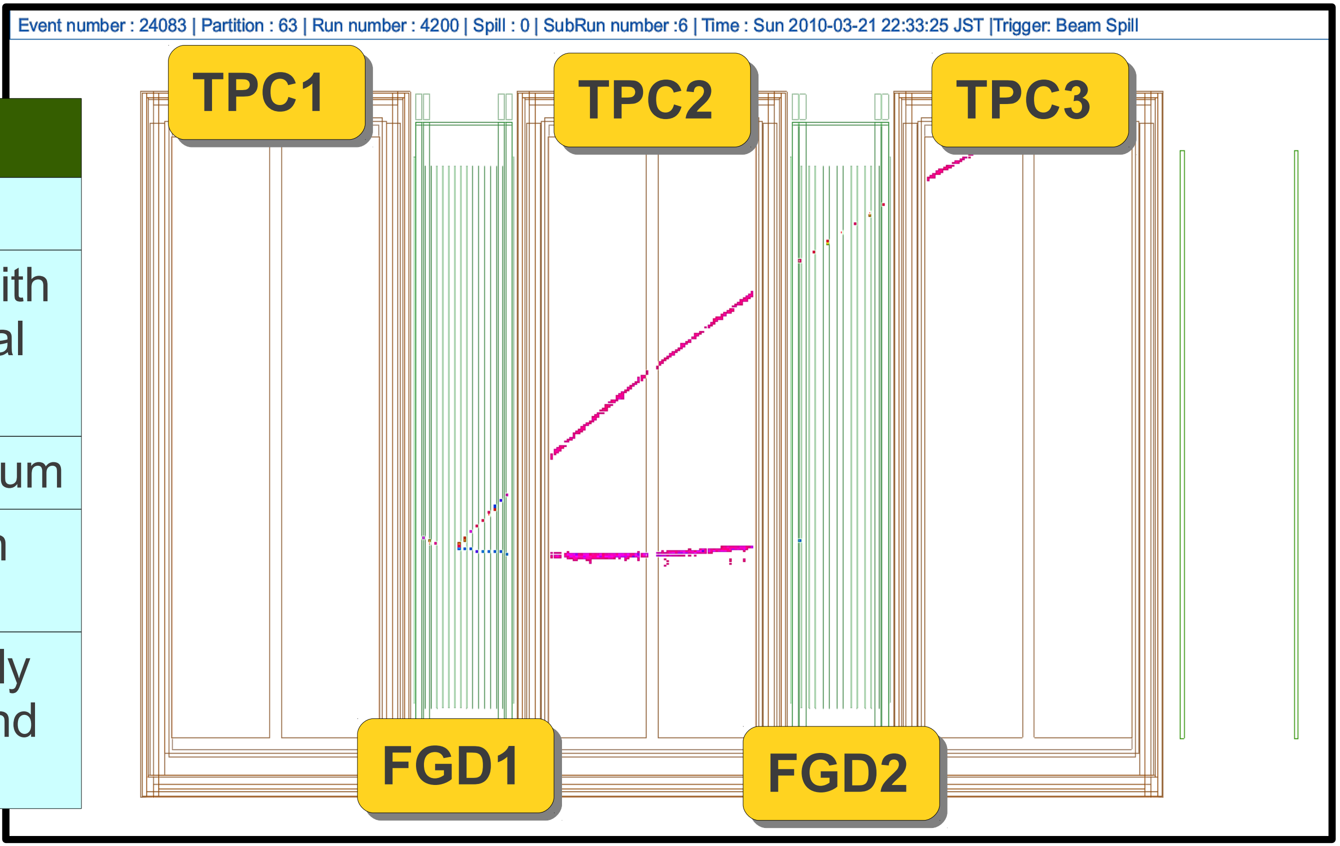
SK NUCEFF ν_e Background - Oscillated ($\sin^2(2\theta_{13}) = 0.1$)



Near Detector (ND280) Analysis

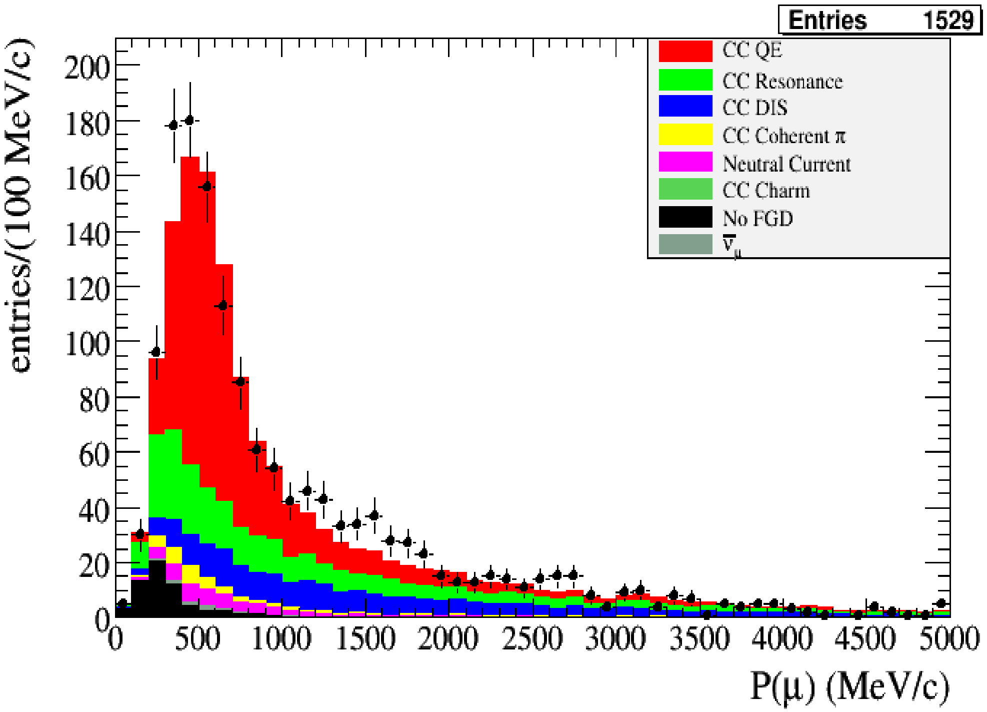
- Analysis using low level reconstructed objects
  - Use FGD hits and and tracks reconstructed in single TPC
  - High Purity: 90% ν_μ CC and 50% CCQE
  - 1529 events

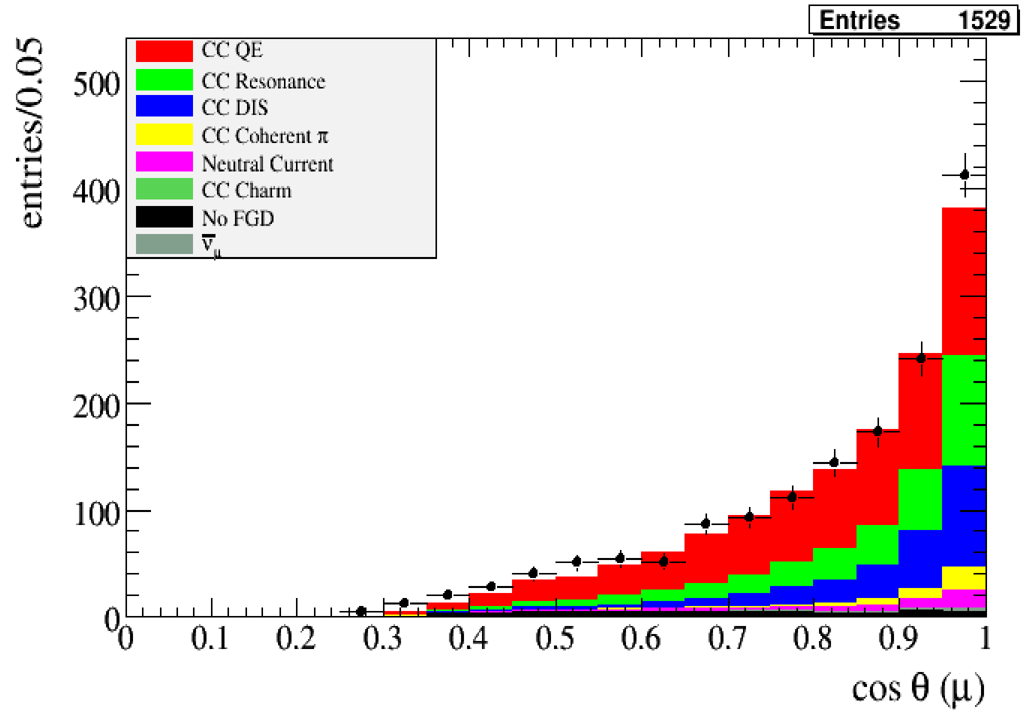
Event Selection
No tracks in first TPC
At least 1 track in second TPC with starting point in first FGD fiducial volume, p>50 MeV/c
Select track with highest momentum
TPC dE/dx cuts to select muon candidates, exclude electrons
If no tracks in second TPC, apply selection to third TPC and second FGD



ND280 Data vs. Prediction

Data vs. MC prediction for 2.88×10^{19} POT (not fitted: flux pred.+NEUT)





$$R_{data/MC}=1.061\pm0.028(stat.)^{+0.044}_{-0.038}(det.\,sys.)\pm0.039(phys.\,model)$$

Includes:
TPC-FGD matching, dE/dx pull distributions, TPC tracking efficiency

SK Event Selection

- Event selection criteria frozen before data collection to avoid bias

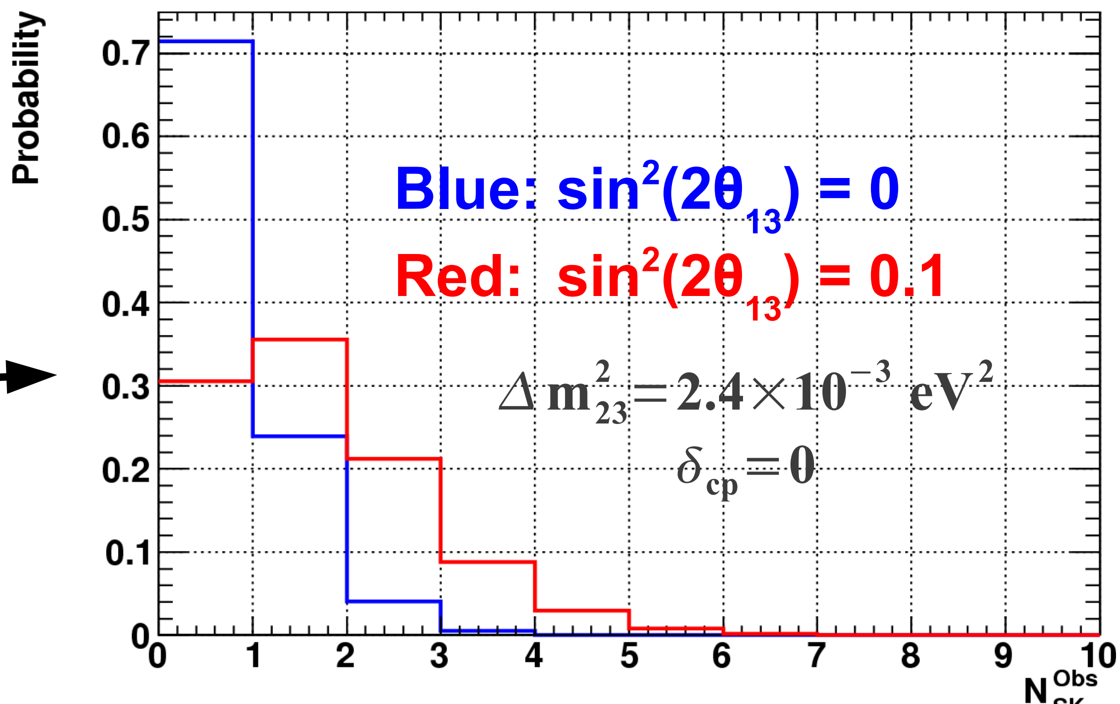
ν_e Event Selection	ν_μ Event Selection
Fully containted in inner detector fiducial volume	
Visible energy > 100 MeV	Visible energy > 30 MeV
Number of rings = 1	
PID identifies ring as electron like	PID identifies ring as muon like
No decay electrons detected	-
π^0 reconstructed mass < 105 MeV/c^2	-
Reconstructed ν energy < 1250 MeV	-
-	Reconstructed μ momentum > 200 MeV/c

- ν_e: Light pattern fit of π^0 mass assuming 2 γ rings, cut removes 75% NC bgnd.
- ν_e efficiency: 66% for signal, 1% for background (after interaction)
- ν_e efficiency error: 7.6% for signal, 15.8% for background

SK ν_e Expectation

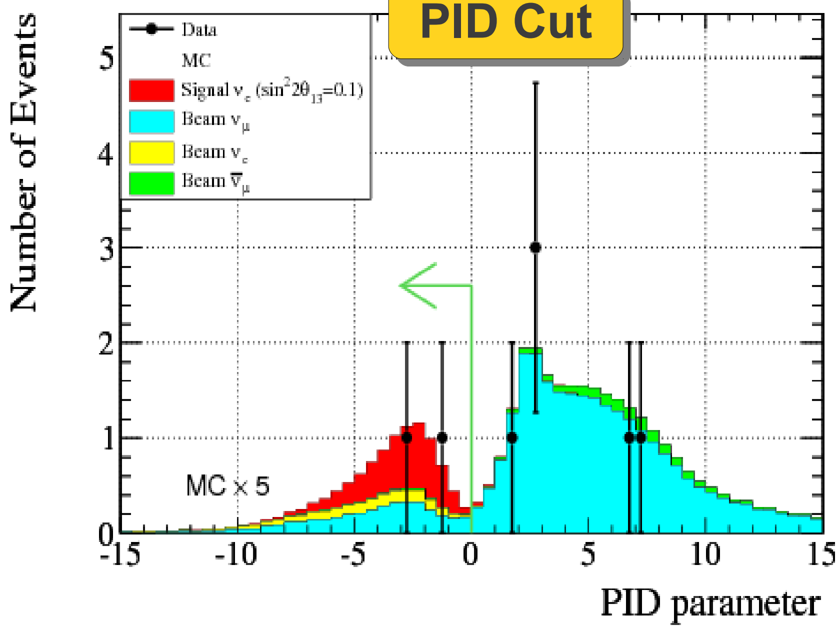
Source	Expected Events	Systematic Error
Beam ν_e Bgnd. (85% CCQE)	0.16	23.9%
ν_μ Bgnd. (95% NC)	0.13	
ν_μ-bar Bgnd.	0.01	
Signal ν_e at $\sin^2(2\theta_{13})$=0.1 + Total Bgnd.	1.20	19.5%

PDFs for expected number of SK ν_e events including statistical and systematic errors

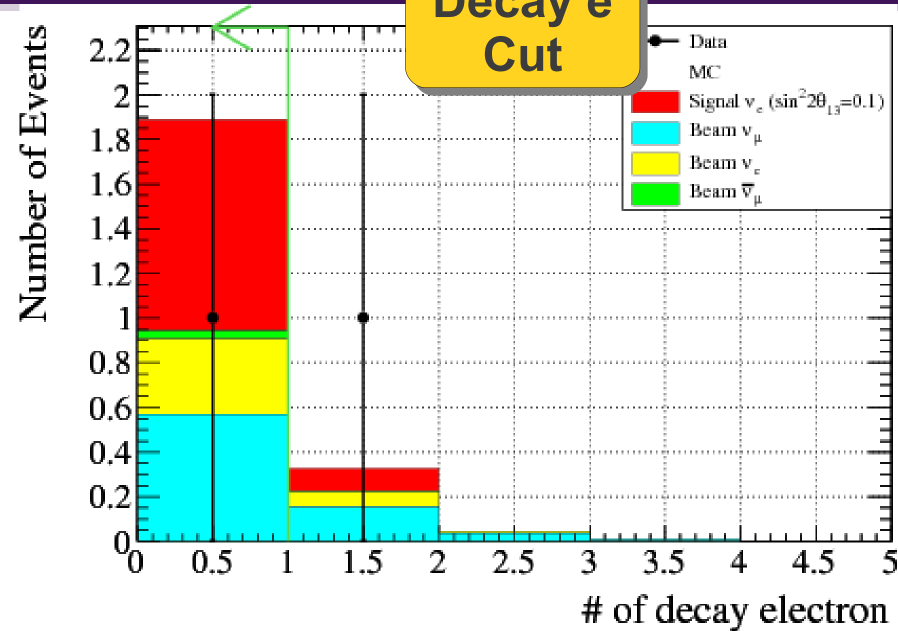


SK ν_e Candiate Sample

PID Cut

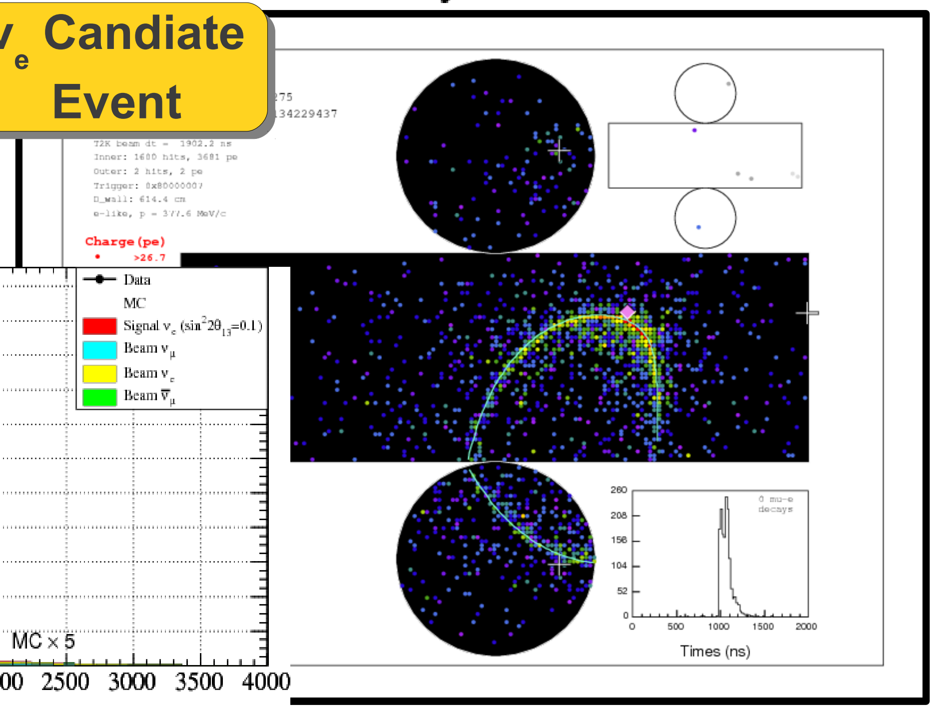


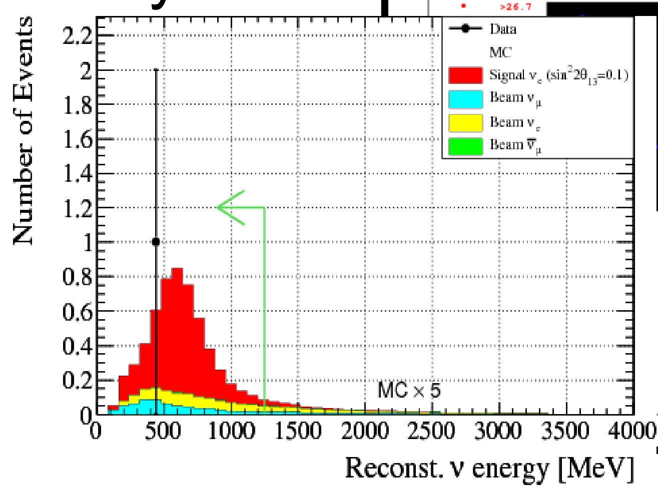
Decay e Cut



- Two candiates survive PID cut
- 1 candidate removed by decay electron cut

ν_e Candiate Event





After all cuts, 1 signal candidate!

T2K ν_e Result

- Two independent analyses give consistent results
- Difference from confidence interval method:

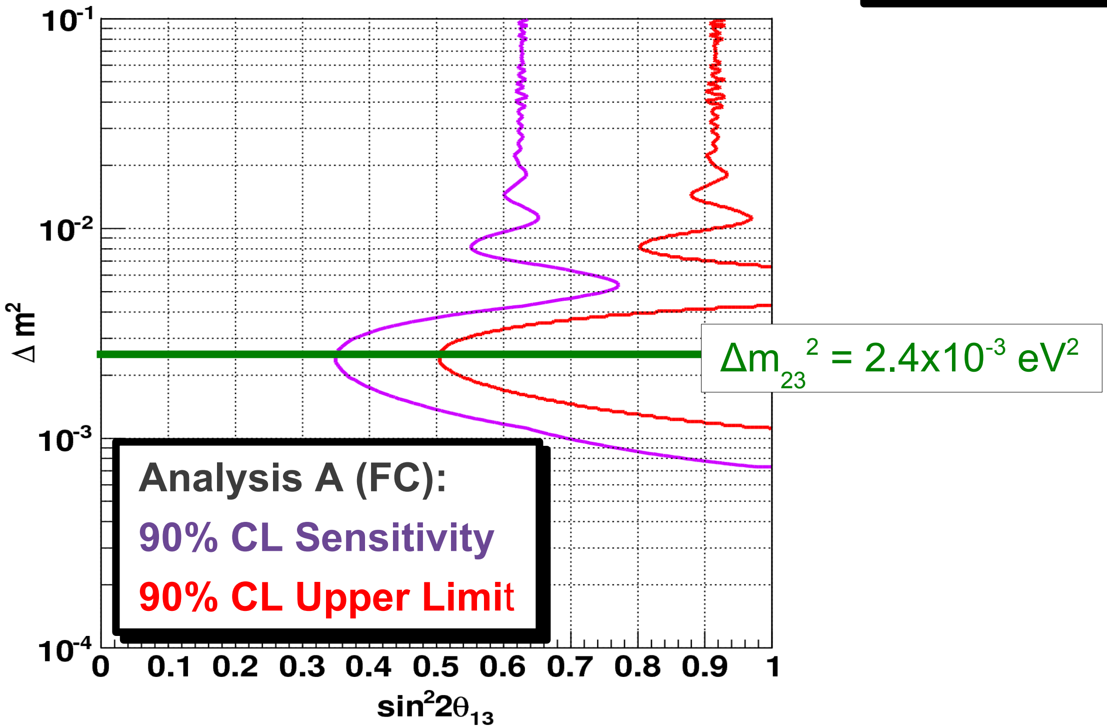
A) Feldman-Cousins:

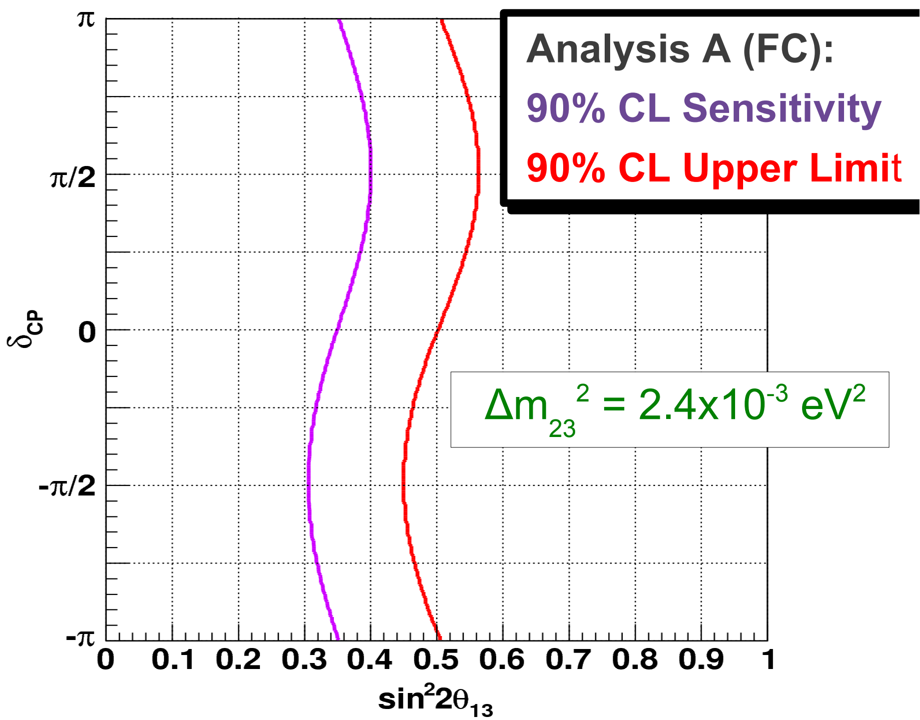
$$\Delta m^2_{23} = 2.4 \times 10^{-3}\ \mathrm{eV}^2, \quad \delta_{cp} = 0$$

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

B) Classical 1-sided limit:

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





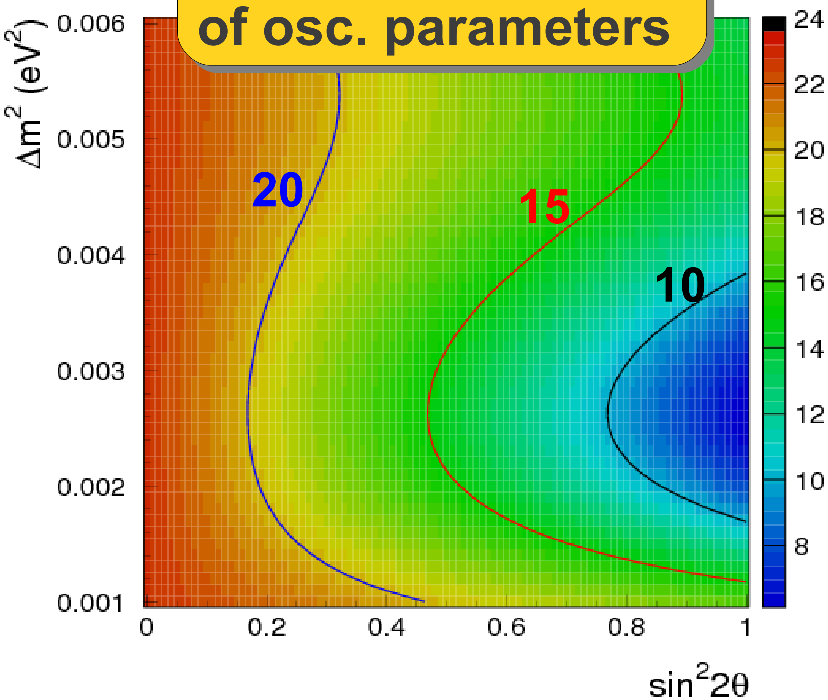
T2K ν_μ Result

- 8 ν_μ candidate events observed at SK
- Expectation:

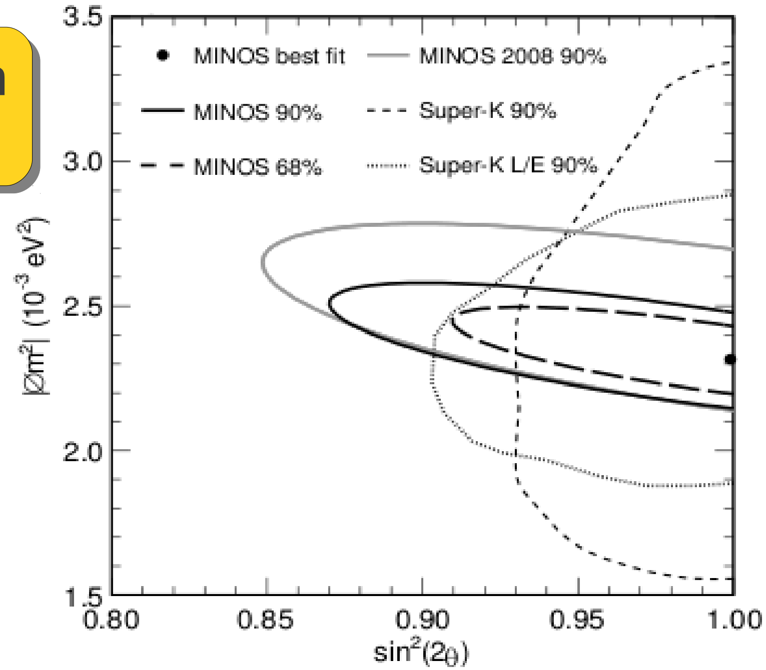
Osc. Hypothesis	Expected Events	Syst. Error
No oscillation	22.81	3.19
$\Delta m_{23}^2 = 2.4\text{x}10^{-3}\ \text{eV}^2$ $\sin^2(2\theta_{23})=1.0$	6.34	1.04

- Parameter fitting is underway, plan to release results in near future

Expected observed events as function of osc. parameters

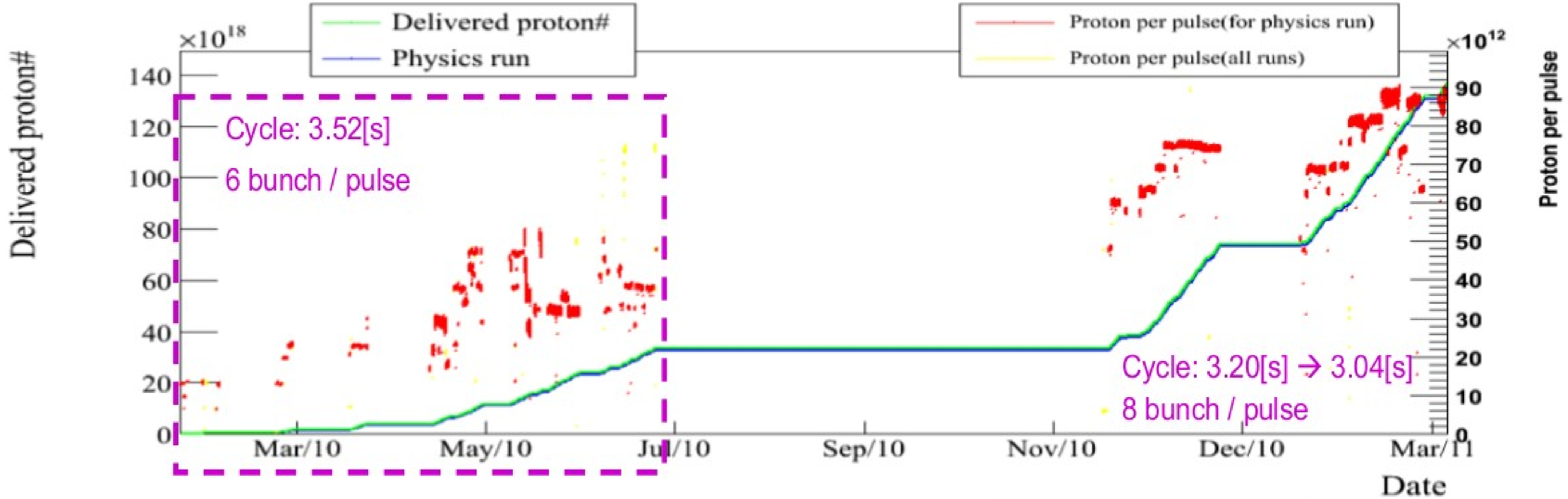


Consistent with MINOS, SK

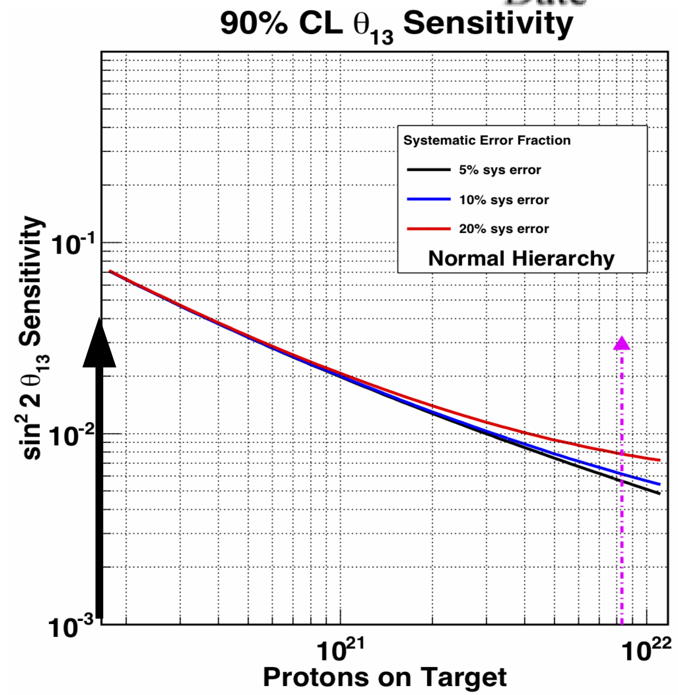


MINOS: arXiv:1103.0340

Future Prospects



- Data collection since Nov. 2010 has quadrupled data set
  - Now 1.45×10^{20} POT
  - Achieved 145 kW continuous running
- Sensitivity already ~0.1
- Given earthquake, data taking schedule is uncertain



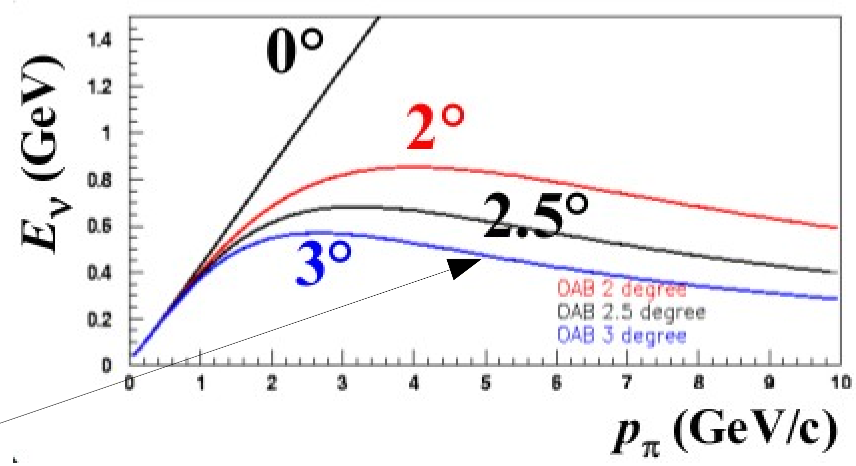
Summary

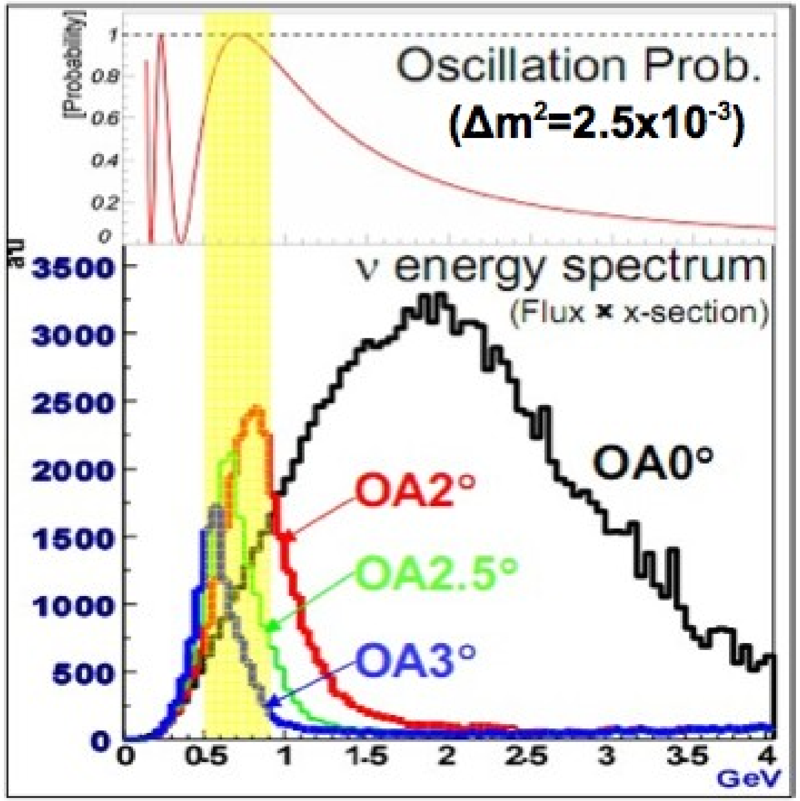
- T2K collected 3.23×10^{19} POT for physics analysis during the 2010a physics run
- Have analyzed both ν_μ and ν_e data samples
- The ν_μ sample at SK is consistent with previous ν_μ disappearance measurements
- From ν_e data, we exclude $\sin^2(2\theta_{13})>0.5$ (normal hierarchy) at 90% C.L.
- We now have x4 the data on disk, moving $\sin^2(2\theta_{13})$ sensitivity to ~0.1 at 90% C.L.
- Earthquake has made near term data taking uncertain, but T2K is committed to bring the experiment back as soon as possible

Backup Slides

Why Off-axis?

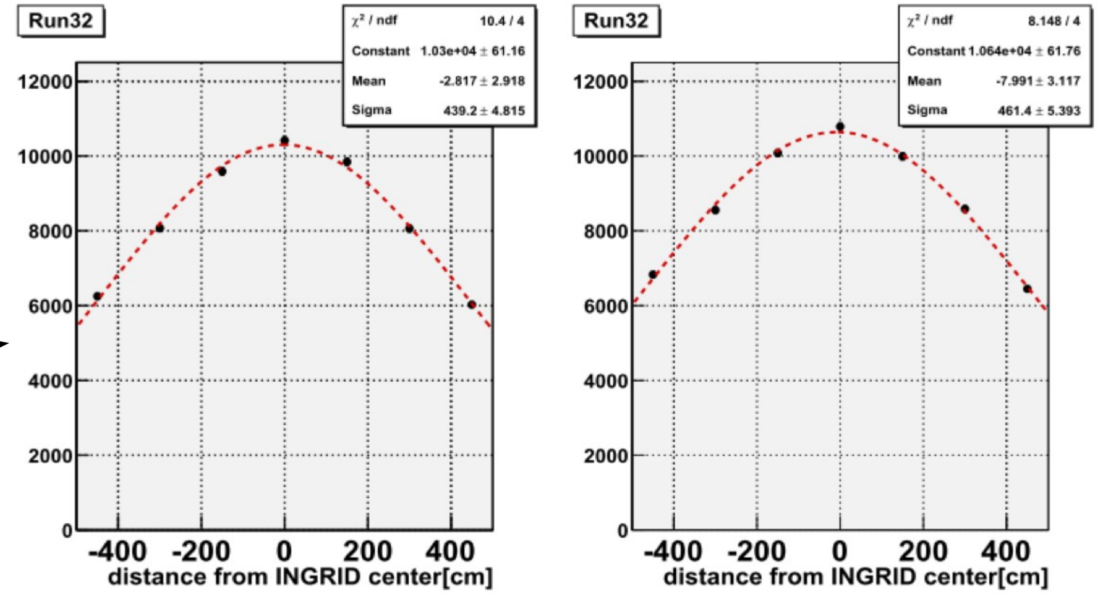
- Pion decay kinematics:
  - Along beam direction, neutrino energy proportional to pion momentum
  - At finite angles, weak dependence on pion momentum
- 2.5° off-axis angle gives neutrino spectrum peaked at the oscillation maximum
  - More statistics in the oscillation region
  - Less feed-down from backgrounds at higher energy

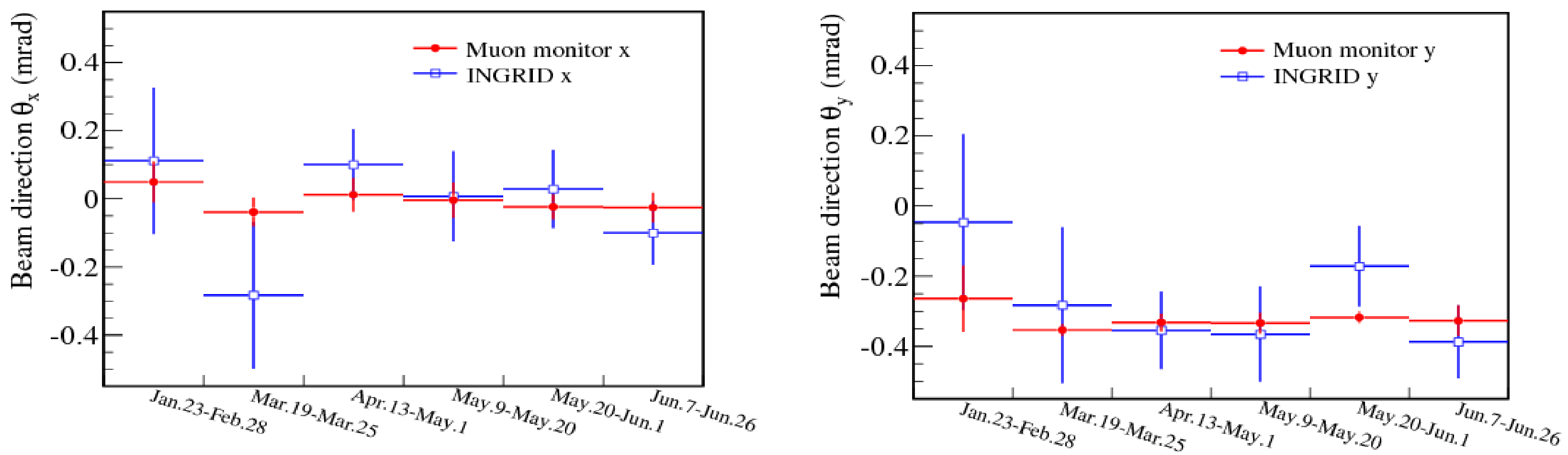




Beam Direction Measurements

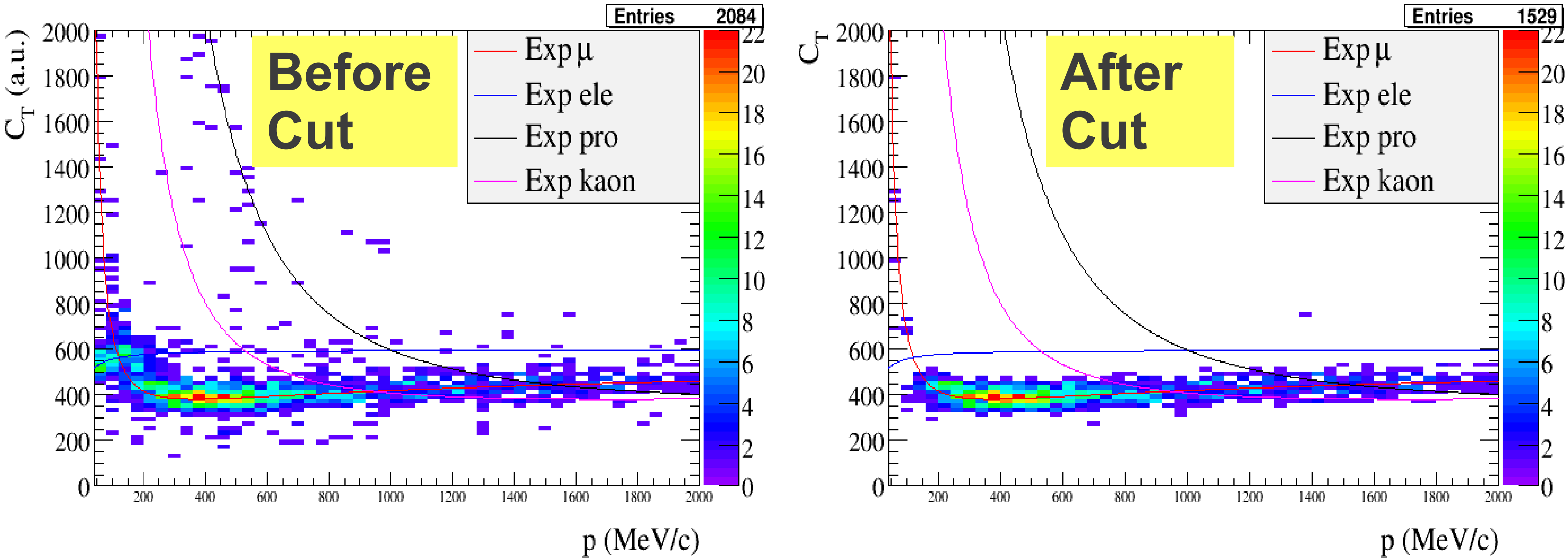
- MUMON: 2D profile of muons from pion decays
- INGRID: neutrino beam profiles in x and y





- MUMON and INGRID measurements in good agreement
- Beam direction is stable and within 1 mrad tuning goal

Particle ID with TPC dE/dx

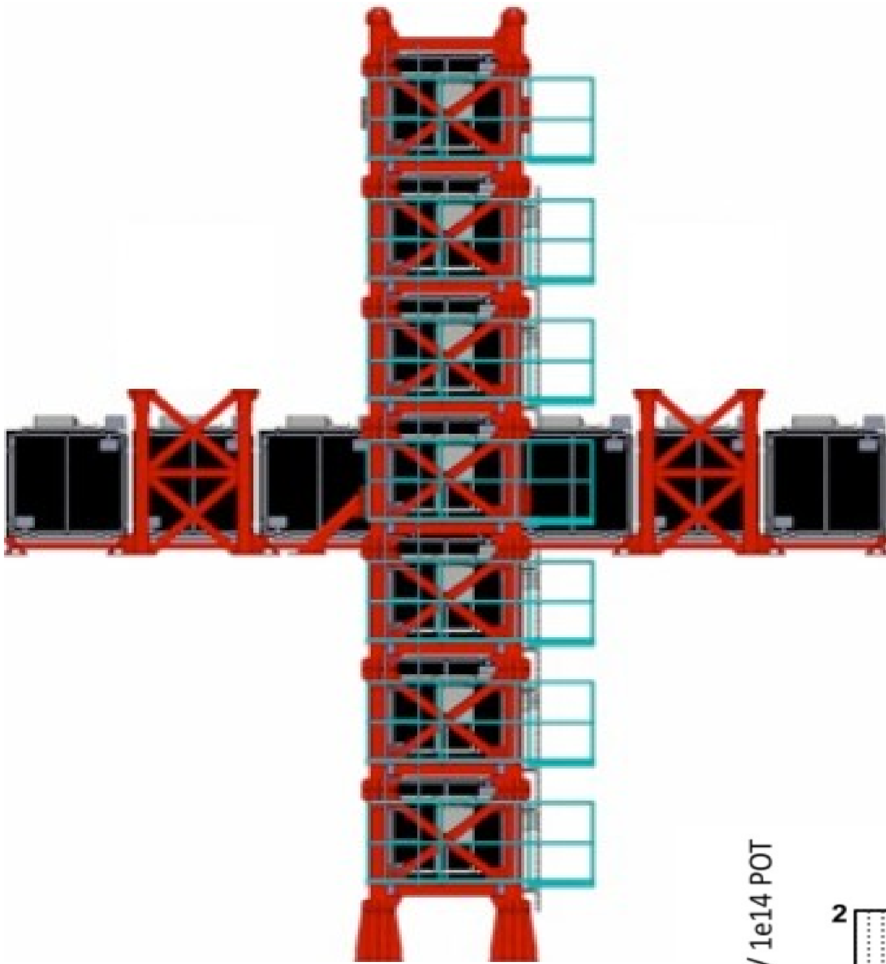


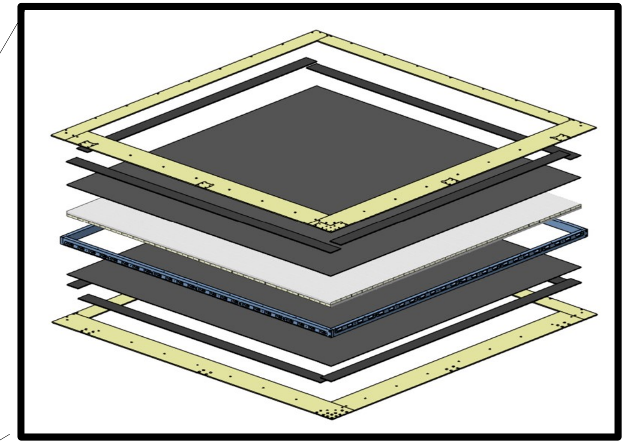
Two dE/dx Cuts:

$$|\delta_E(\mu)| < 2.5, \quad |\delta_E(e)| > 2.0 \qquad \delta_E = dE/dx\ Pull$$

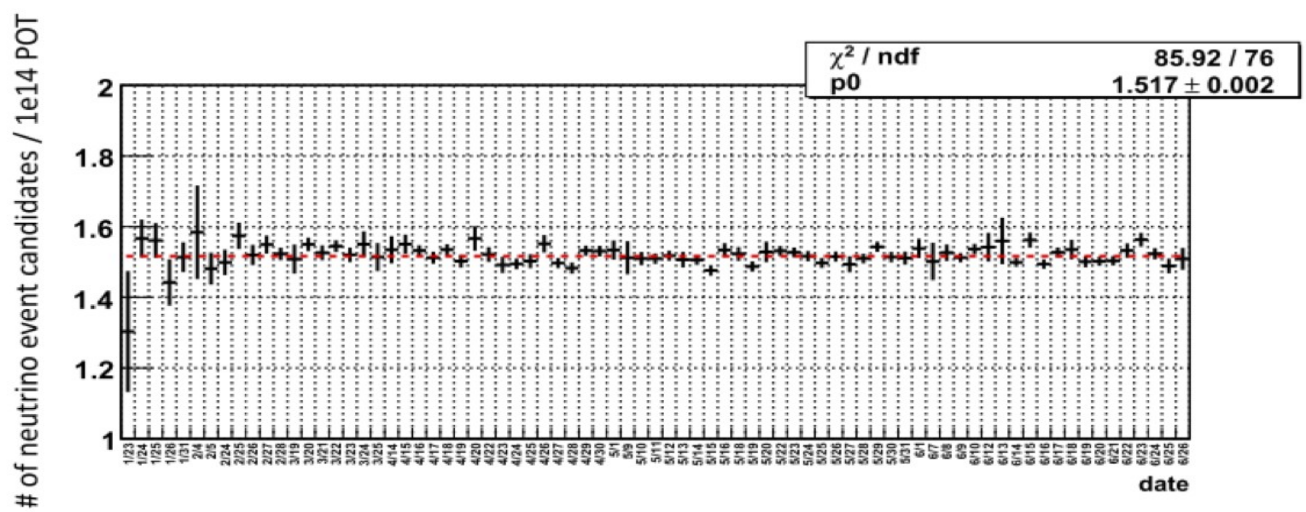
- Cut on TPC dE/dx with muon hypothesis to select muons
- Cut on TPC dE/dx with electron hypothesis to exclude electrons

INGRID On-axis Detector



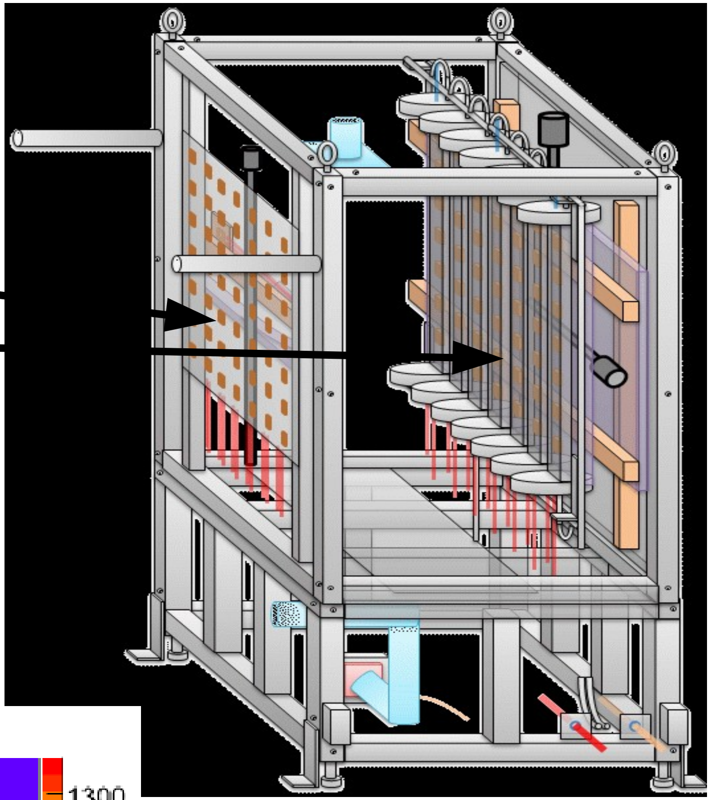


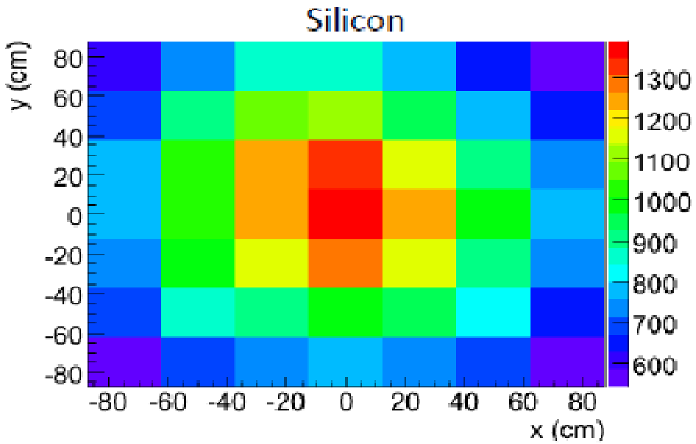
- 16 modules (14 in cross configuration)
- Modules consist of iron and scintillator layers
- Measures neutrino beam profile and rate



MUMON Detector

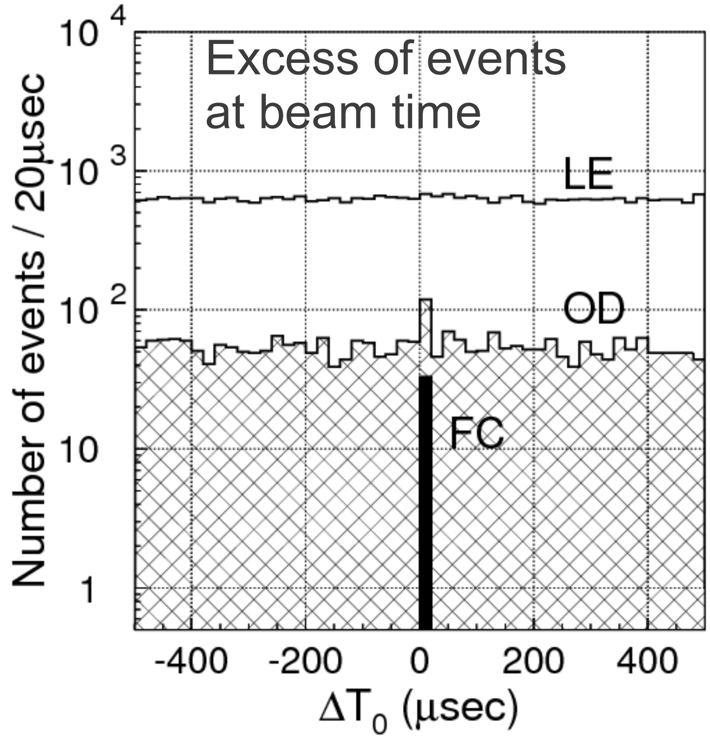
- Located downstream of beam dump (117 m from target)
- Silicon PIN photodiodes
- Ionization chamber
- Measures secondary muons from pion decays
- >5 GeV muons make it through beam dump (tail of distribution):

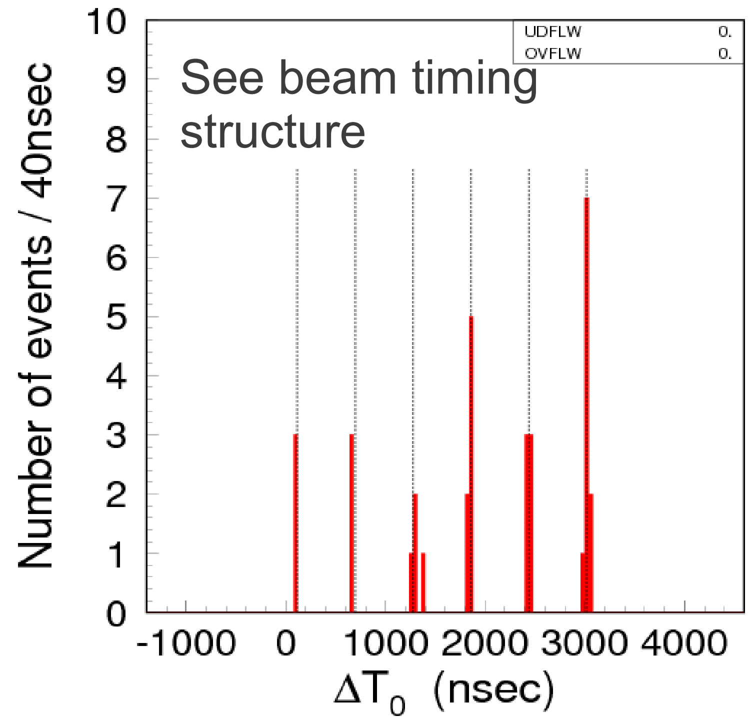




2-D Gaussian fit result

SK Event Sample

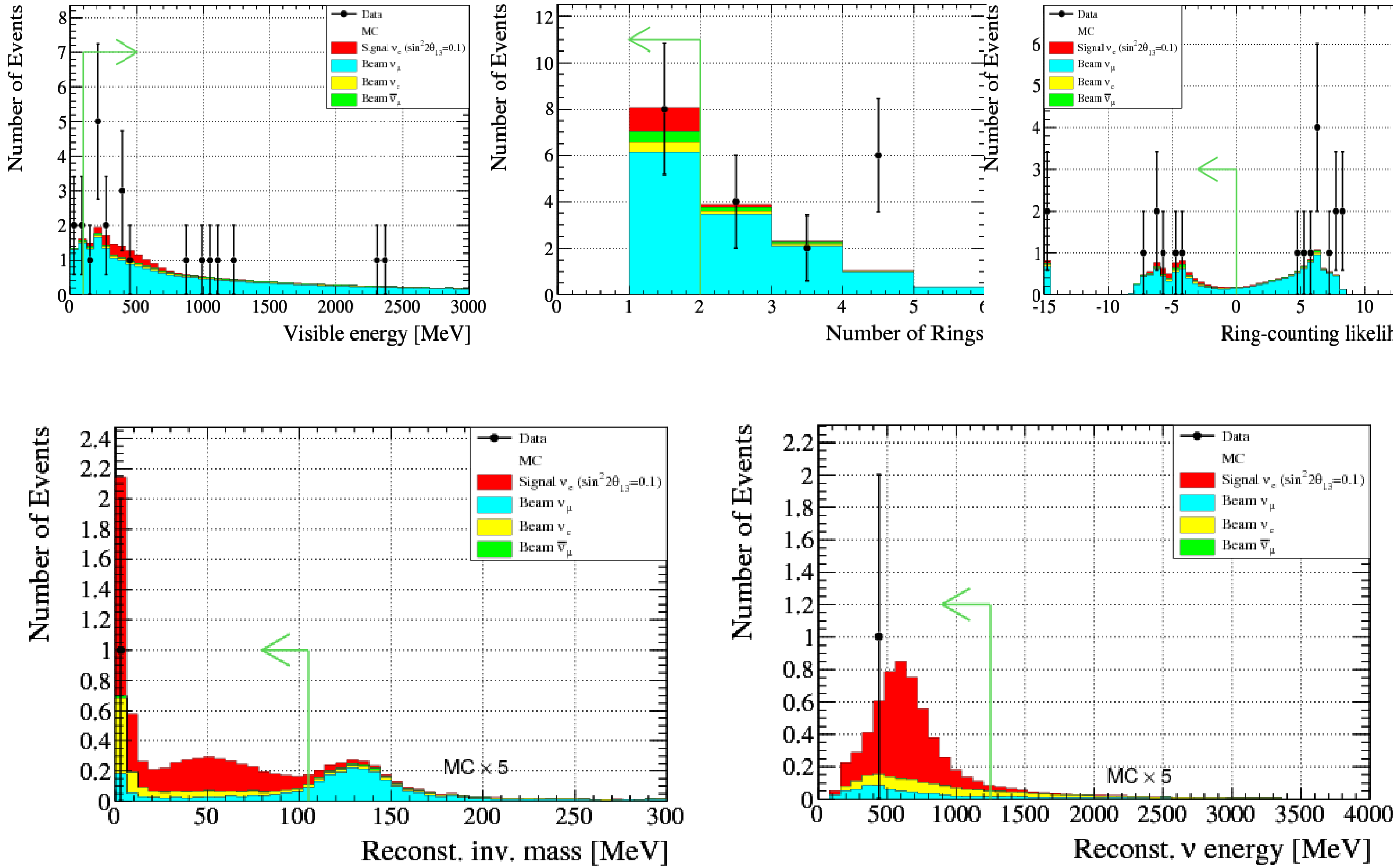




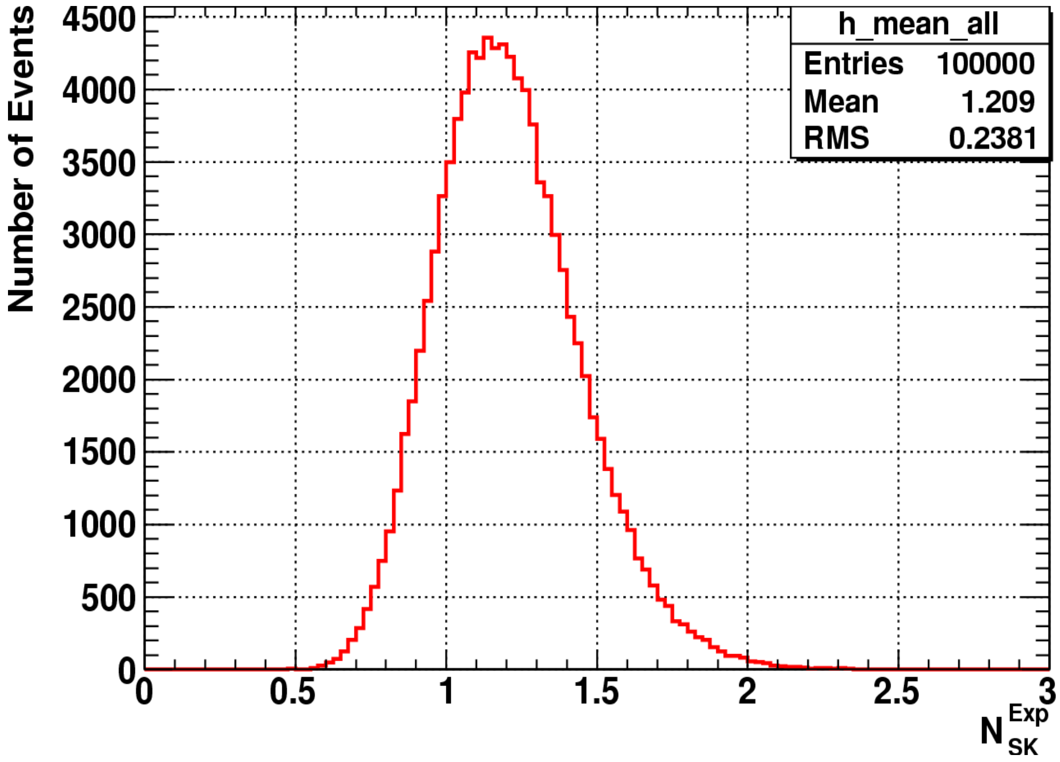
Systematic Errors:

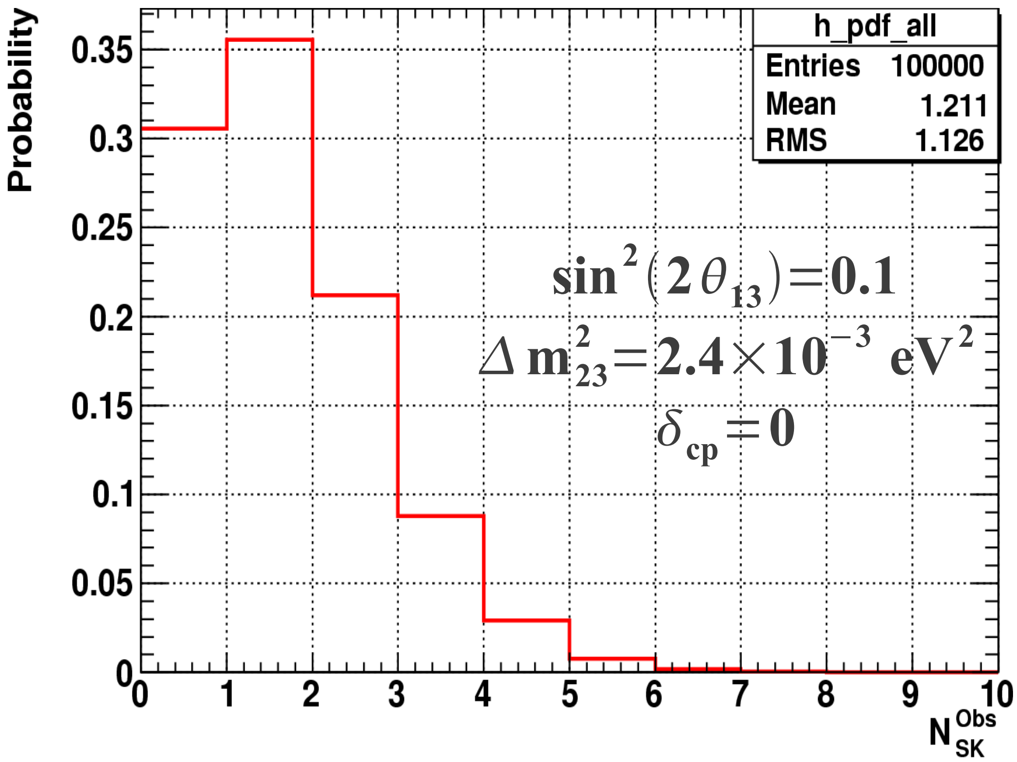
	FCFV single-ring μ-like $P_\mu > 200MeV/c$		FCFV single-ring e-like $P_e > 100MeV/c$	
	No osc.	Osc.	No osc.	Osc.
SK recon.	8.4 %	12.8 %	41.2 %	38.8 %
Flux	10.0 %	6.6 %	5.7 %	8.0 %
Interaction	8.8 %	10.2 %	14.3 %	14.8 %
Total	15.7 %	17.6 %	44.0 %	42.3 %

SK ν_e Reduction



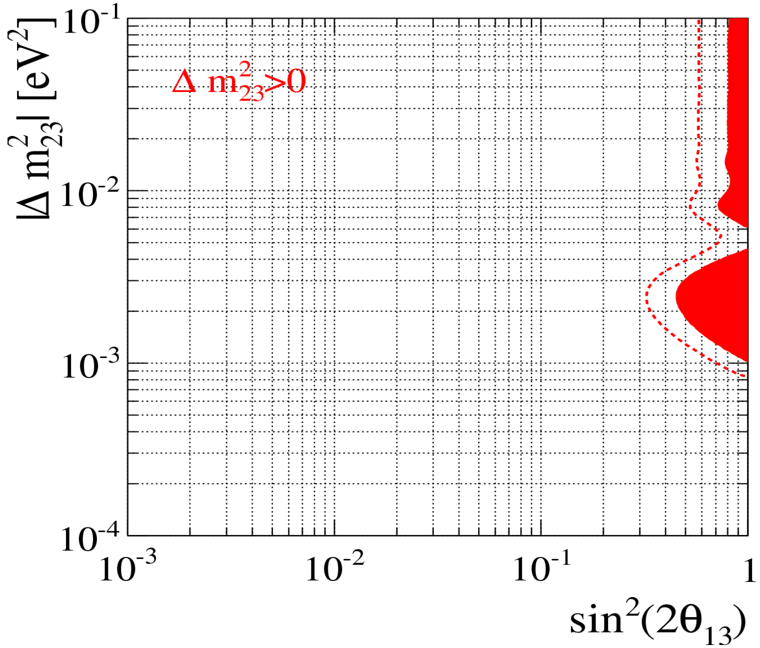
SK ν_e Event PDF Example

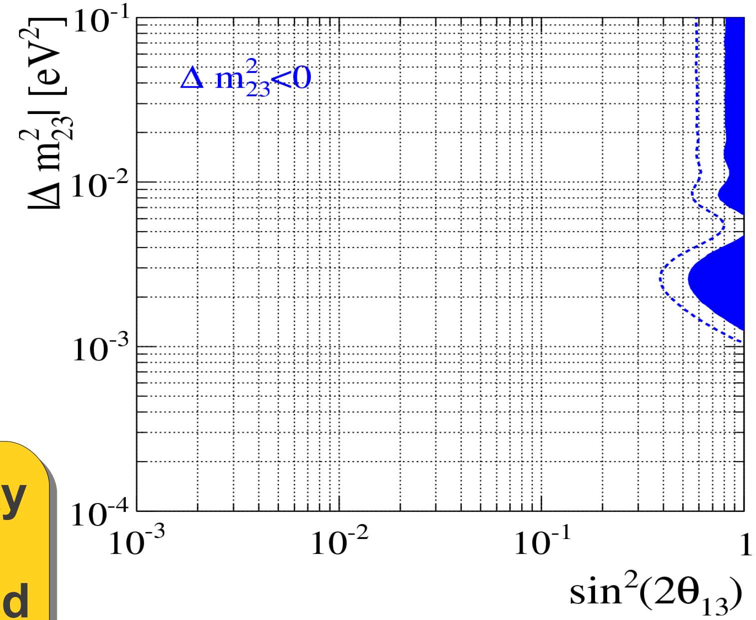




- Left: distribution of expected number of SK events with systematic errors applied
- Right: distribution after applying statistical error

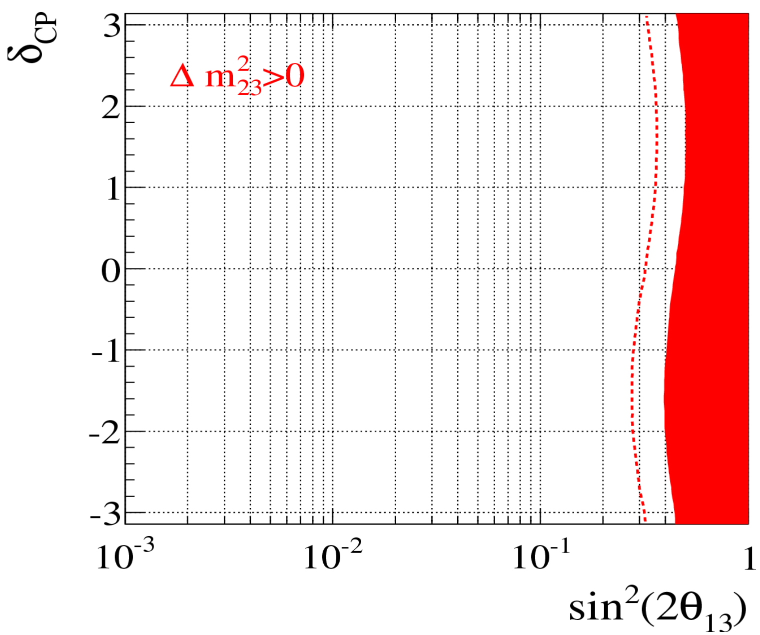
SK ν_e Analysis B Exlcuded Regions

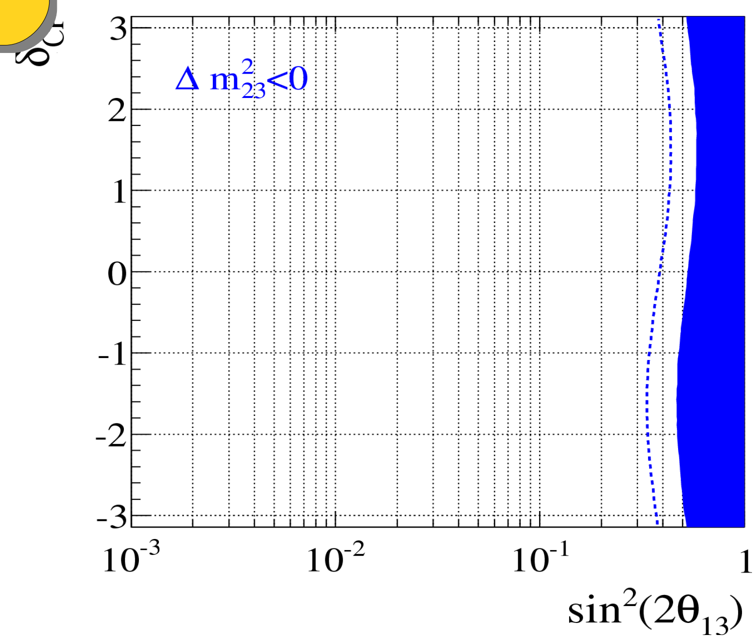




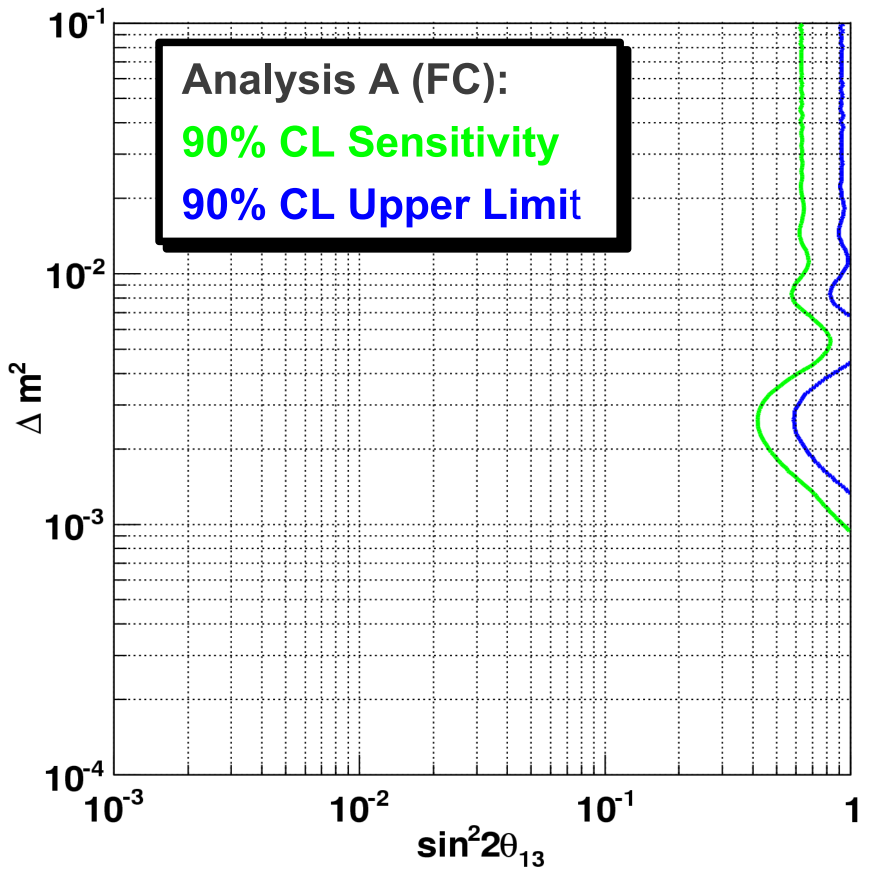
Dotted line: sensitivity

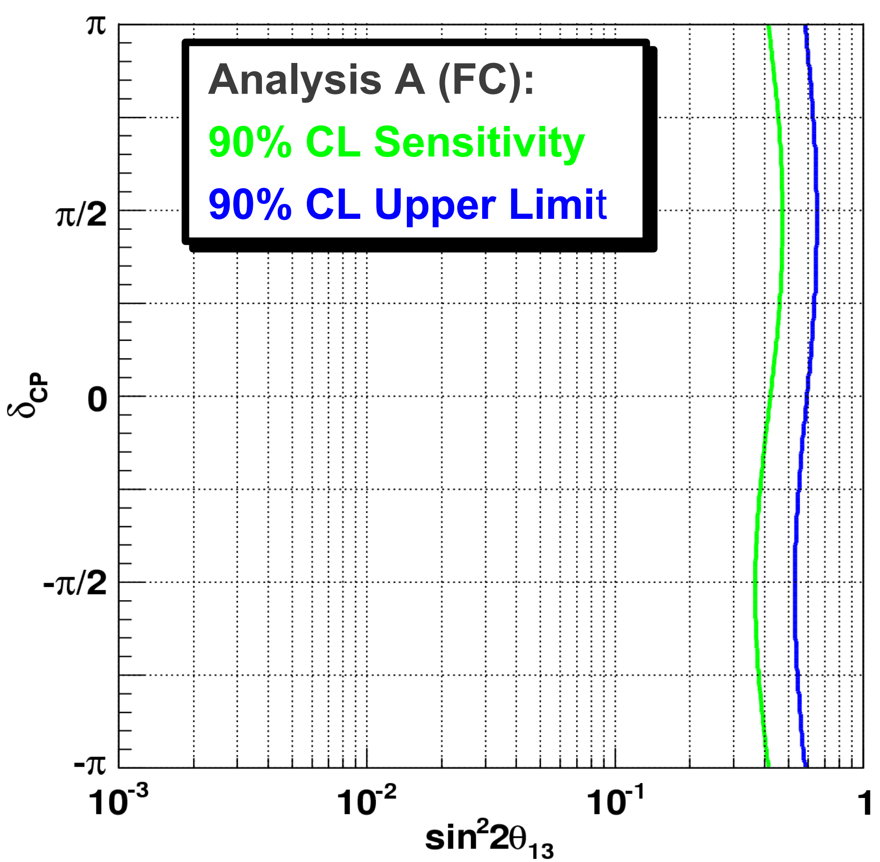
Solid region: excluded at 90% C.L.



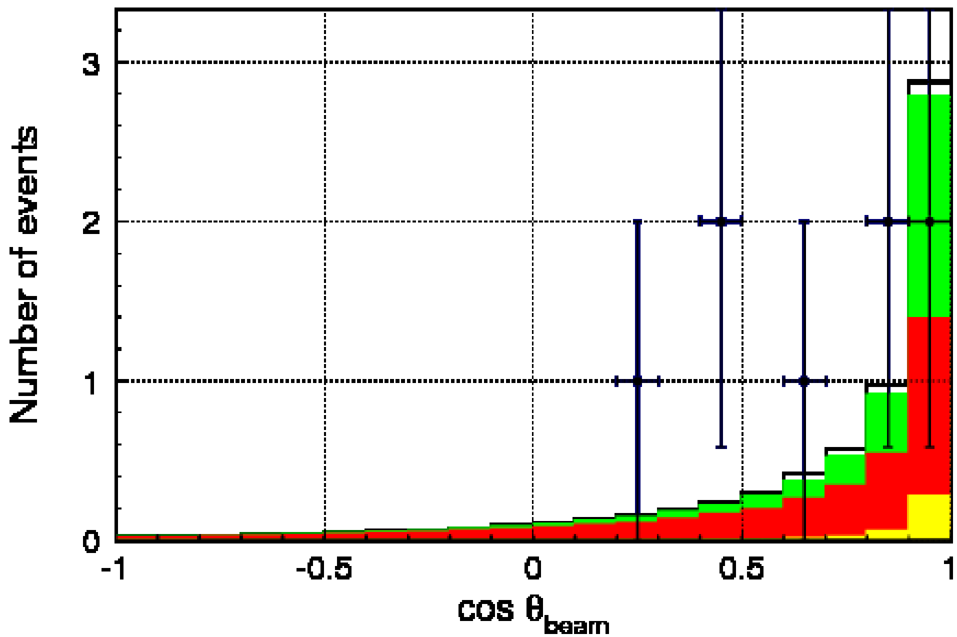


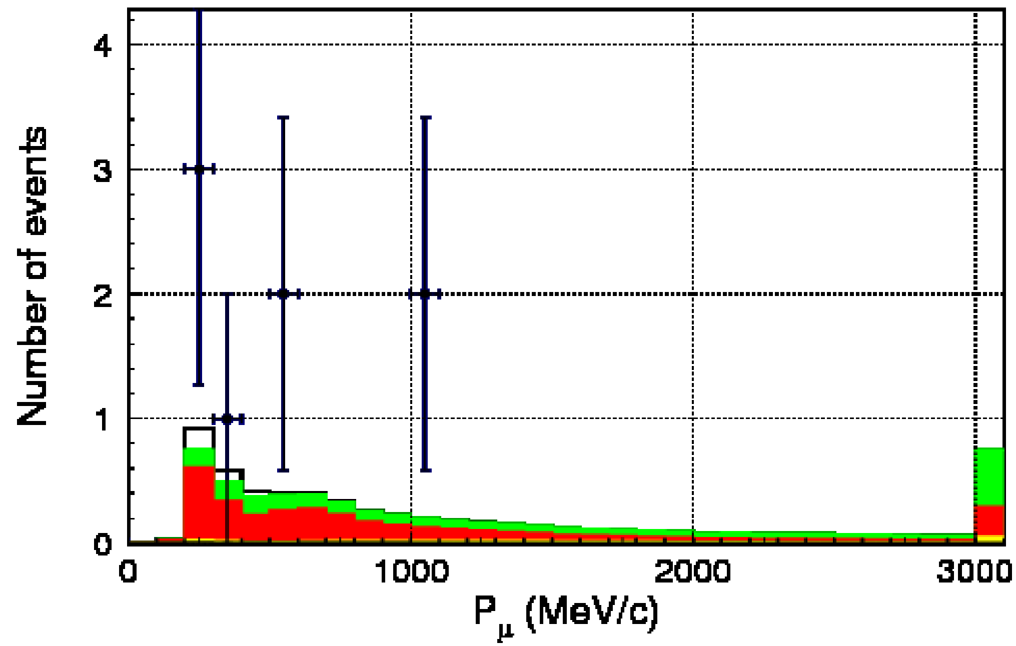
ν_e Analysis A Inverted Hierarchy





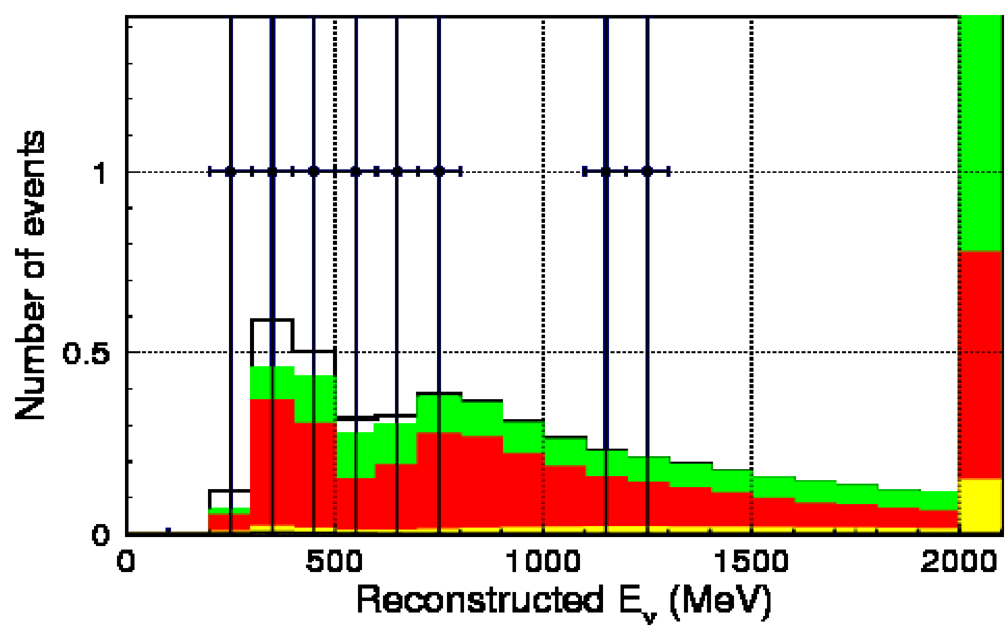
SK ν_μ Distributions





Breakdown:
Red: CCQE
Green: CC non QE
Yellow: anti-muon neutrino
Black: electron neutrino
White: NC

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



SK ν_e Systematic Uncertainties

Systematic uncertainties by source for the ν_e analysis

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	$\pm$ 7.6	$\pm$ 15.8	$\pm$ 9.5	$\pm$ 0.0	$\pm$ 15.8	$\pm$ 9.5
Cross section	$\pm$ 9.7	$\pm$ 13.9	$\pm$ 9.9	$\pm$ 8.4	$\pm$ 14.3	$\pm$ 10.6
Beam Flux	$\pm$ 22.0	$\pm$ 18.1	$\pm$ 20.5	$\pm$ 19.8	$\pm$ 8.9	$\pm$ 11.9
ND Efficiency	$\pm$ 0.00	$\pm$ 0.00	$\pm$ 0.00	$^{+5.6}_{-5.2}$	$^{+5.6}_{-5.2}$	$^{+5.6}_{-5.2}$
Overall Norm.	$\pm$ 0.00	$\pm$ 0.00	$\pm$ 0.00	$\pm$ 0.00	$\pm$ 2.7	$\pm$ 2.7
Total	$\pm$ 25.2	$\pm$ 27.8	$\pm$ 24.7	$^{+22.2}_{-22.1}$	$^{+23.9}_{-23.8}$	$^{+19.5}_{-19.4}$

Some cancellation of errors is seen due to near detector neutrino rate constraint

SK ν_e Systematic Uncertainties

Detailed systematic uncertainties by source for the ν_e analysis

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 Norm.	f^{SKnorm}	$\pm$ 1.41	$\pm$ 1.41	$\pm$ 1.41	$\pm$ 0.0	$\pm$ 1.41	$\pm$ 1.41
SK Energy Scale	f^{Energy}	$\pm$ 0.30	$\pm$ 0.50	$\pm$ 0.35	$\pm$ 0.0	$\pm$ 0.50	$\pm$ 0.35
SK Ring Counting	$f^{N_{ring}}$	$\pm$ 3.90	$\pm$ 8.40	$\pm$ 5.03	$\pm$ 0.0	$\pm$ 8.40	$\pm$ 5.03
SK PID Muon	$f^{PID\mu}$	$\pm$ 0.0	$\pm$ 1.00	$\pm$ 0.25	$\pm$ 0.0	$\pm$ 1.00	$\pm$ 0.25
SK PID Electron	f^{PIDe}	$\pm$ 3.80	$\pm$ 8.10	$\pm$ 4.88	$\pm$ 0.0	$\pm$ 8.10	$\pm$ 4.88
SK POLfit Mass	f^{POLfit}	$\pm$ 5.10	$\pm$ 8.70	$\pm$ 6.01	$\pm$ 0.0	$\pm$ 7.70	$\pm$ 6.01
SK Decay Electron	$f^{N_{dcy}}$	$\pm$ 0.10	$\pm$ 0.30	$\pm$ 0.15	$\pm$ 0.0	$\pm$ 0.30	$\pm$ 0.15
SK π^0 Efficiency	$f^{\pi^0 eff}$	$\pm$ 0.00	$\pm$ 5.90	$\pm$ 1.49	$\pm$ 0.0	$\pm$ 5.90	$\pm$ 1.49
CC QE shape	$f^{CCQEshape}$	$\pm$ 4.91	$\pm$ 2.62	$\pm$ 4.33	$\pm$ 0.0	$\pm$ 2.72	$\pm$ 4.33
CC 1π	$f^{CC1\pi}$	$\pm$ 4.28	$\pm$ 3.76	$\pm$ 4.15	$\pm$ 5.93	$\pm$ 2.10	$\pm$ 1.78
CC Coherentπ	f^{CCcoh}	$\pm$ 0.32	$\pm$ 0.23	$\pm$ 0.30	$\pm$ 3.29	$\pm$ 3.06	$\pm$ 2.99
CC Other	$f^{CCother}$	$\pm$ 0.07	$\pm$ 0.35	$\pm$ 0.14	$\pm$ 4.77	$\pm$ 4.43	$\pm$ 4.63
NC $1\pi^0$	$f^{NC1\pi^0}$	$\pm$ 0.00	$\pm$ 5.86	$\pm$ 1.48	$\pm$ 0.05	$\pm$ 5.56	$\pm$ 1.43
NC Coherentπ	f^{NCcoh}	$\pm$ 0.00	$\pm$ 2.48	$\pm$ 0.63	$\pm$ 0.00	$\pm$ 2.37	$\pm$ 0.62
NC Other	$f^{NCother}$	$\pm$ 0.00	$\pm$ 3.83	$\pm$ 0.97	$\pm$ 1.14	$\pm$ 2.53	$\pm$ 0.17
$\sigma(\nu_e)$	$f^{\sigma(\nu_e)}$	$\pm$ 6.00	$\pm$ 3.17	$\pm$ 5.29	$\pm$ 0.01	$\pm$ 3.28	$\pm$ 5.28
FSI	f^{FSI}	$\pm$ 3.83	$\pm$ 10.34	$\pm$ 5.47	$\pm$ 0.00	$\pm$ 10.32	$\pm$ 5.47
Beam Norm.	$f^{\phi}_{SK/ND}$	$\pm$ 21.97	$\pm$ 18.12	$\pm$ 20.49	$\pm$ 19.83	$\pm$ 9.17	$\pm$ 11.88
ND Efficiency	$f^{\epsilon ND}$	$\pm$ 0.00	$\pm$ 0.00	$\pm$ 0.00	$^{+5.60}_{-5.16}$	$^{+5.60}_{-5.16}$	$^{+5.60}_{-5.16}$
Overall Norm.	f^{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	$^{+22.23}_{-22.13}$	$^{+23.95}_{-23.85}$	$^{+19.55}_{-19.43}$

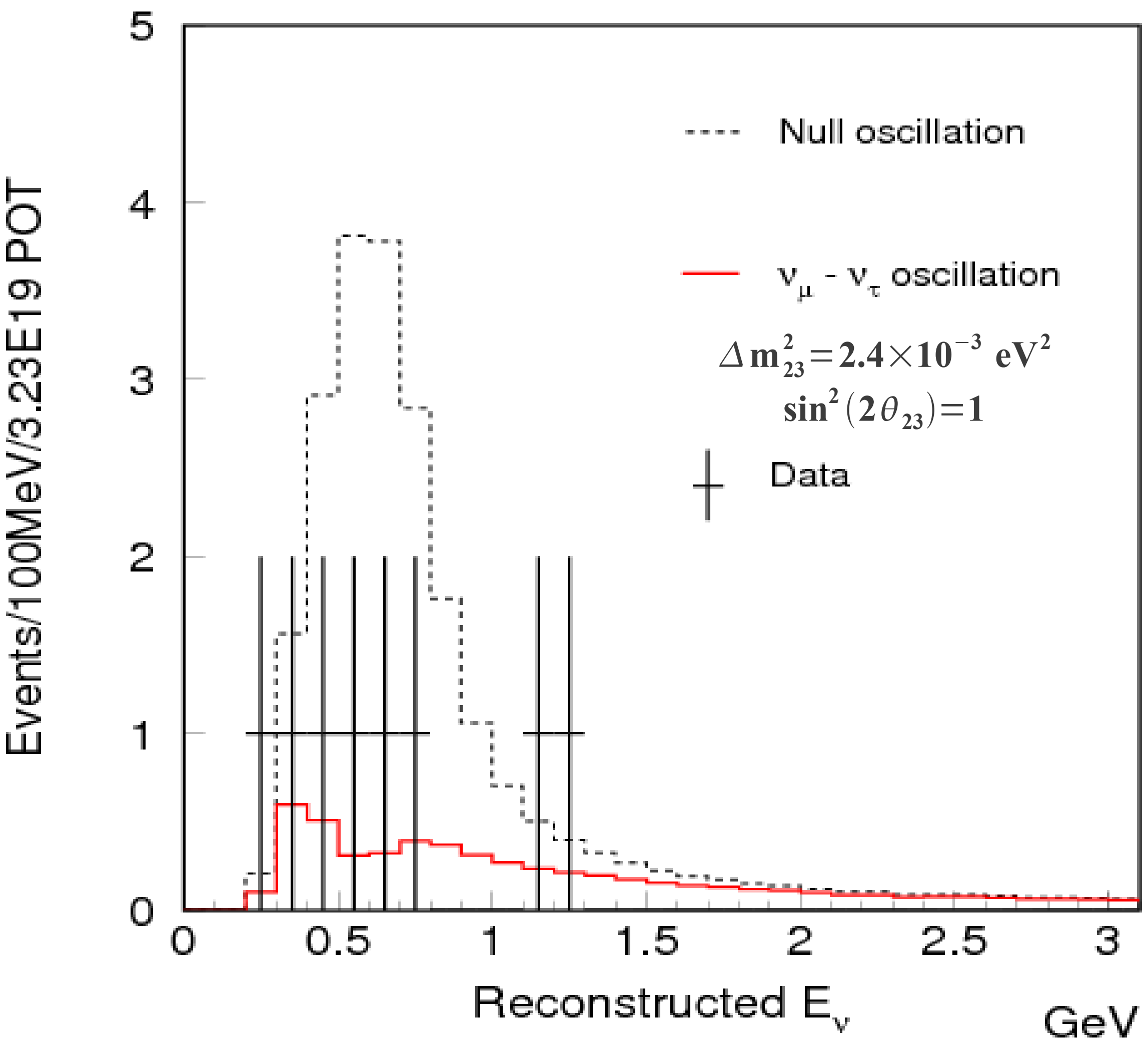
SK ν_μ Systematic Uncertainties

Systematic uncertainties by source for the ν_μ analysis

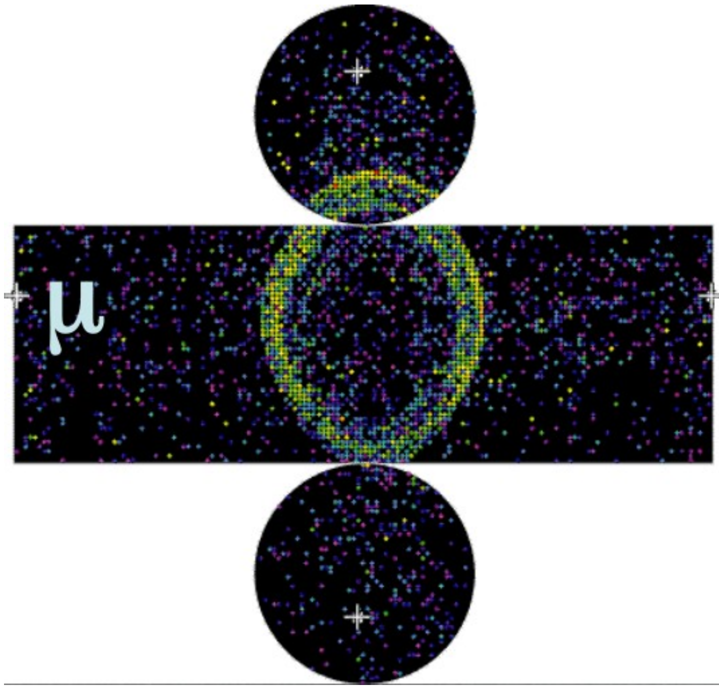
Source of error	% error in N_SK (GENIE)	% error in N_SK (NEUT)
SuperK CCQE efficiency	± 6.4	± 6.4
SuperK CCnonQE efficiency	± 3.9	± 4.3
SuperK NC efficiency	± 2.6	± 2.1
SuperK nue CC efficiency	± 0.0	± 0.0
ND280 efficiency	+5.3 -4.8	+5.3 -4.8
Flux normalisation	± 9.6	± 9.7
CCQE cross section	± 4.3	± 4.1
CC1π/CCQE cross section ratio	+2.7 -2.4	+2.2 -2.0
CC other/CCQE cross section ratio	+5.9 -5.2	+5.4 -4.8
NC/CCQE cross section ratio	± 0.7	± 0.8
FSI	± 3.3	± 3.3
Total	+16.0 -15.5	+15.7 -15.3

T2K ν_μ Spectrum

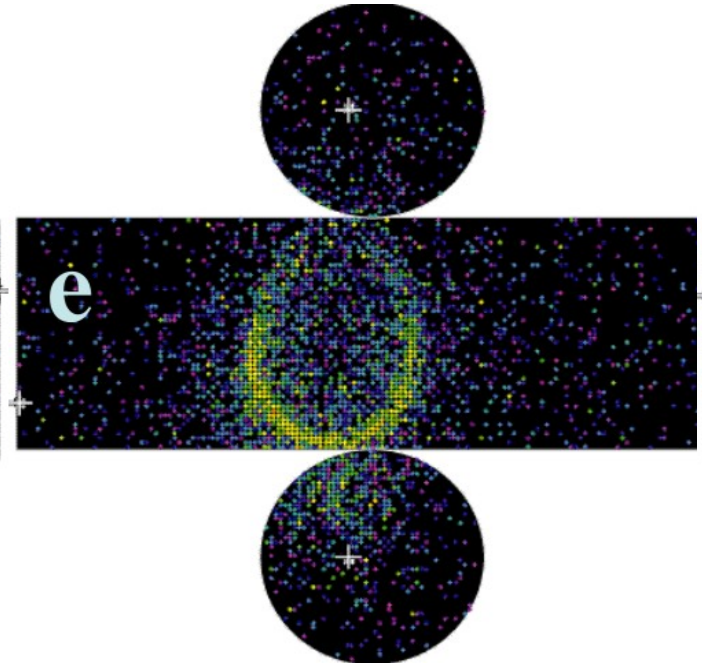
Spectrum of the 8 ν_μ candidate events compared to the expected oscillated and unoscillated spectra



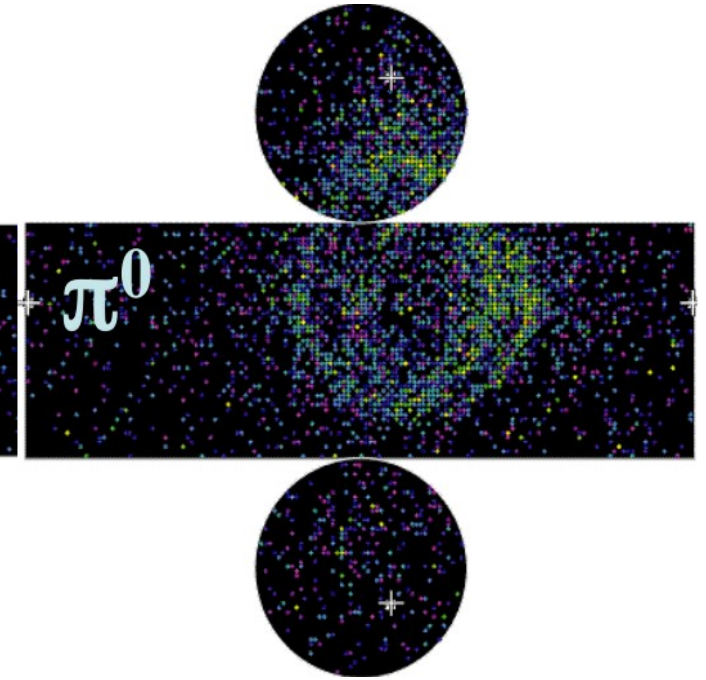
Ring PID at SK



Ring with sharp edges



”Fuzzy” ring due to scattering, EM showering



Two e-like rings from photons