Results from the T2K long baseline neutrino oscillation experiment

IceCube Particle Astrophysics Symposium

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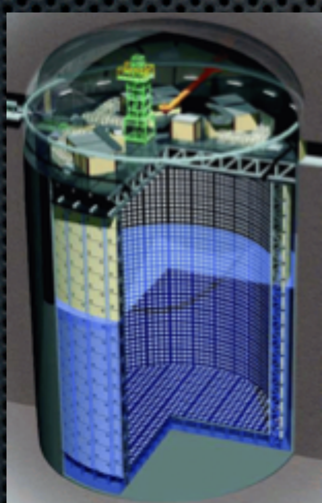
University of Victoria

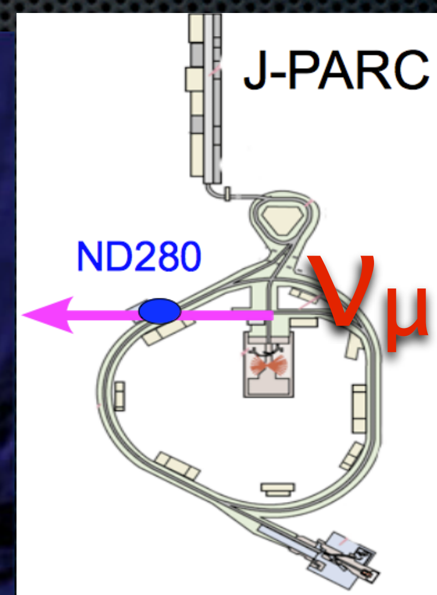
Outline

- T2K Experiment: Elements and physics goals.
- Oscillation Analyses
  - ν_e appearance
  - ν_μ disappearance
- Future prospects

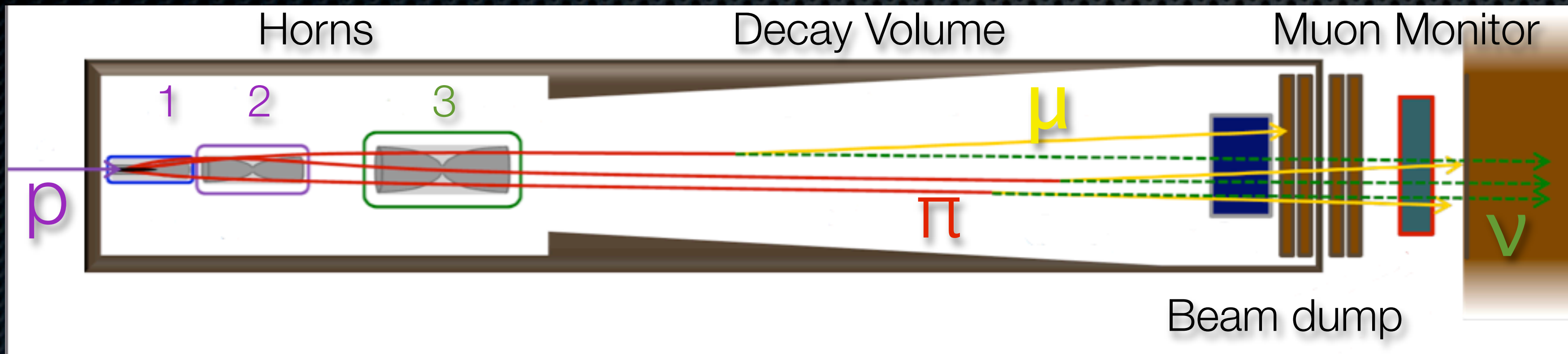
T2K(Tokai to Kamioka)

- Long baseline neutrino oscillation experiment
  - Measurement of neutrino oscillation between near detector (J-PARC) and Super-Kamiokande.
- Main Physics Goals
  - Search for ν_e ***appearance*** $\nu_\mu \rightarrow \nu_e$
  - Precise measurement of Δm^2_{32}, θ_{23} . ν_μ ***disappearance*** $\nu_\mu \rightarrow \nu_x$





Neutrino Beam

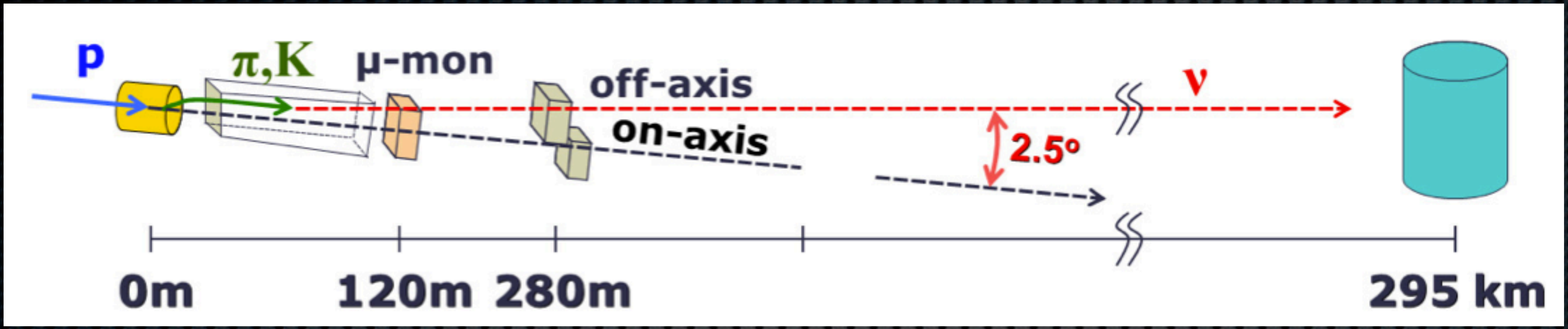


- 30 GeV protons hit graphite target
- Pions produced in proton interactions on a target focused by 3 magnetic horns
  - focus π^+, defocus π^-

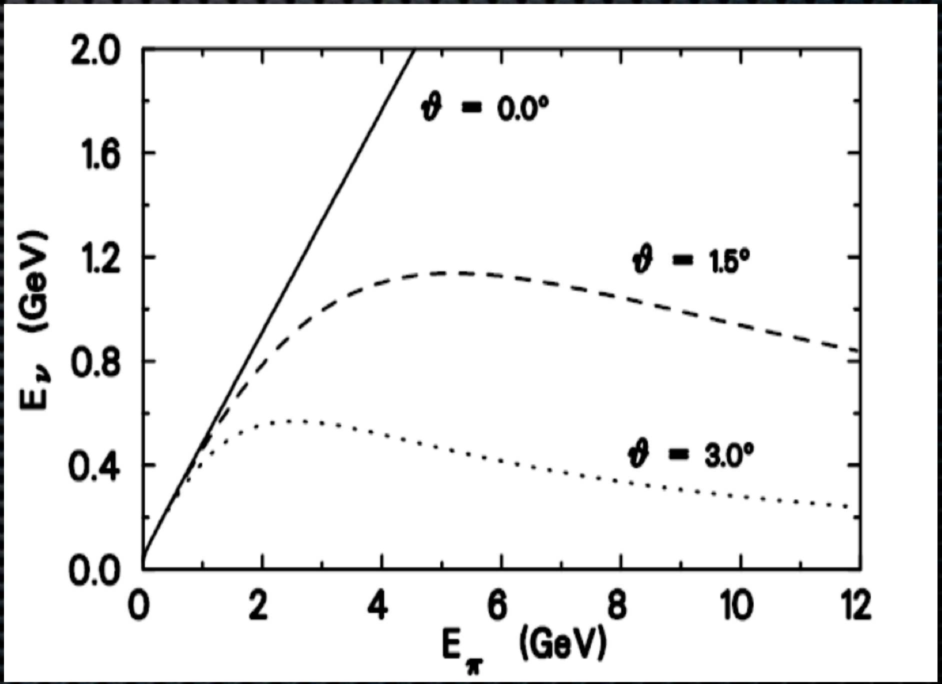
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

- μ monitor at far end of beam dump
- Creates ν_μ pure beam
  - $\bar{\nu}_\mu$ and ν_e are ~ few percent

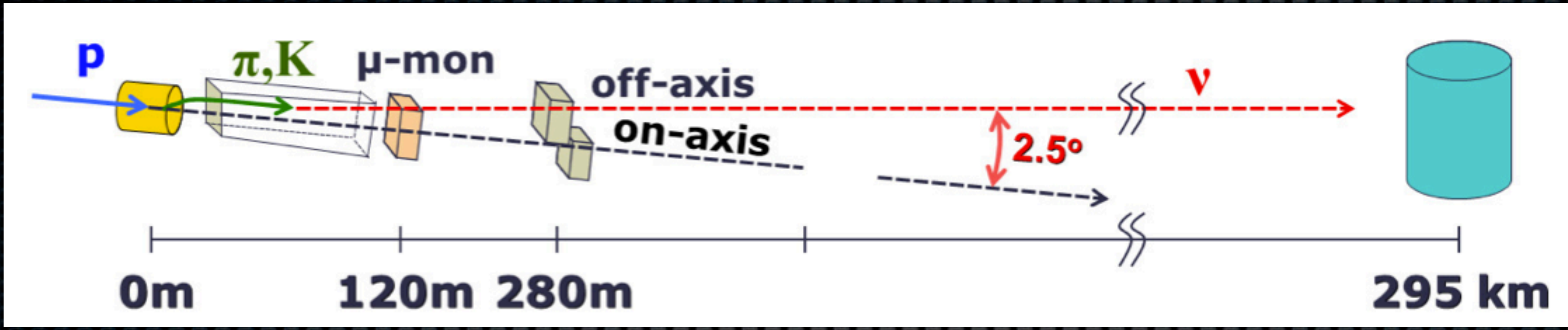
Off-Axis Beam



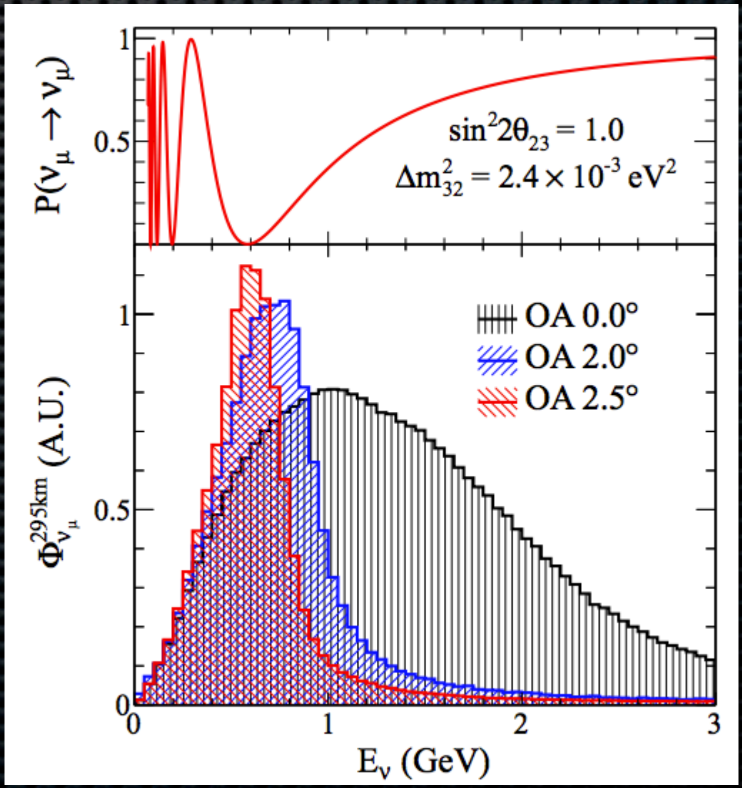
- At small angles to the beam axis, neutrino energy is insensitive to parent pion energy



Off-Axis Beam

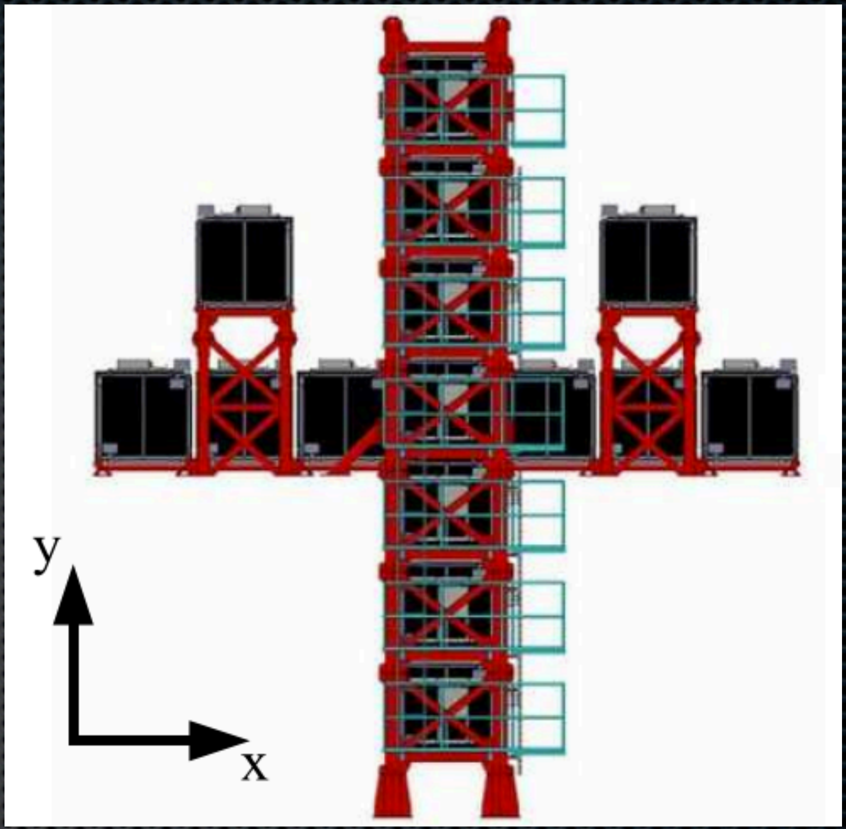


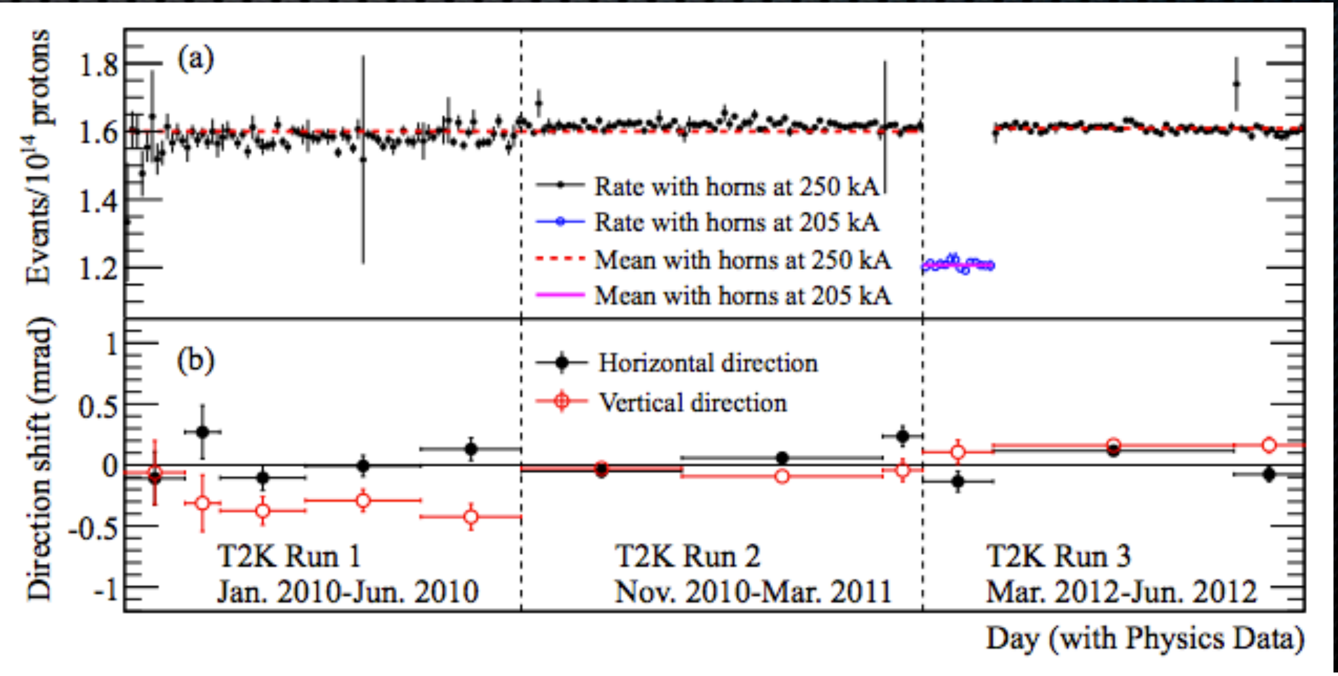
- Peak E_ν tuned for oscillation maximum.
- 2.5^0 off axis. Low energy narrow band beam.
- Reduce background from higher energy neutrinos



On axis INGRID

- 14 modules consisting of iron and scintillator arranged in a cross pattern
- Measures profile, direction and intensity of neutrino beam.
- Rate and beam direction stable over running period.

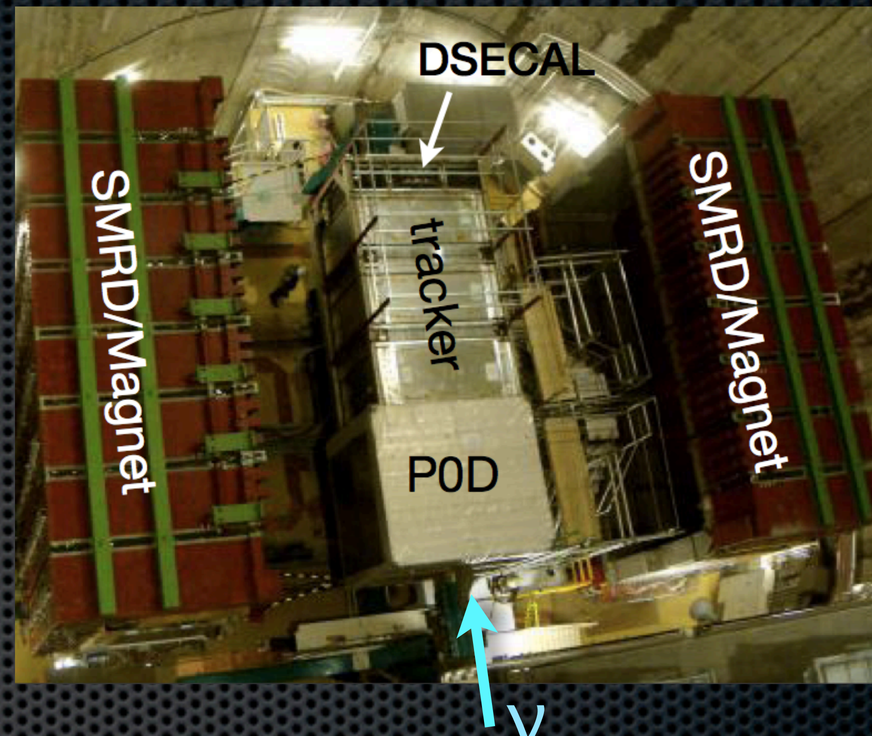


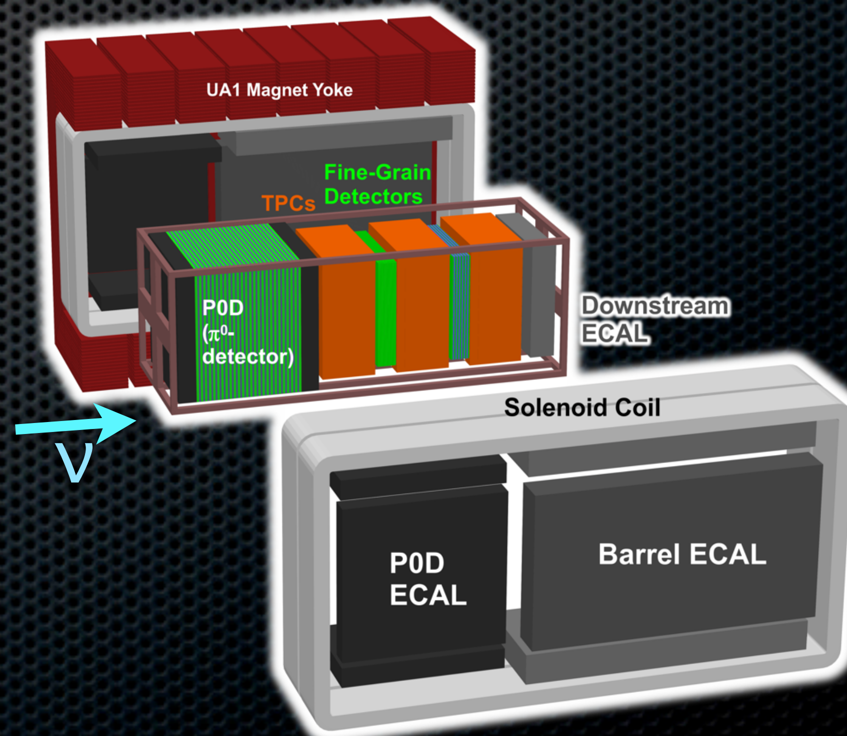


1mrad → 2% shift in E

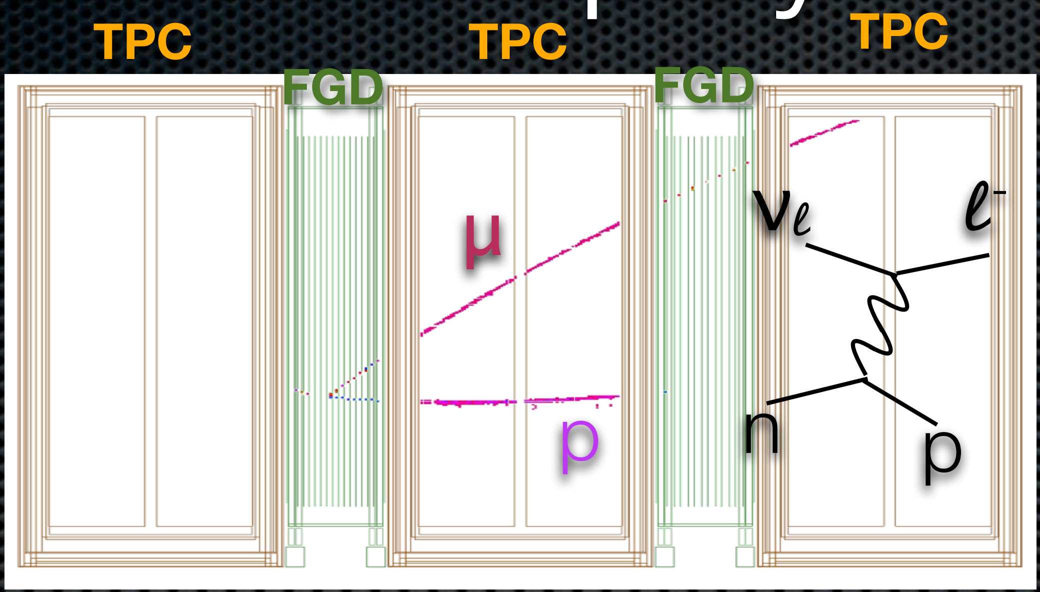
Off Axis Near Detector

- ND280 (ND=near detector) is located 280 m from production target.
- Multi-Detector complex installed within UA1 magnet.
- Current analyses uses tracker, neutrino interactions in Fine Grained Detectors that are measured by Time Projection Chambers.
- FGDs provide fiducial mass, particle tracking.
- TPCs measure momenta, particle type.
- Makes measurement of unoscillated beam. ν_μ charged current interactions.
- Crucial in reducing systematic errors for precision oscillation measurements.

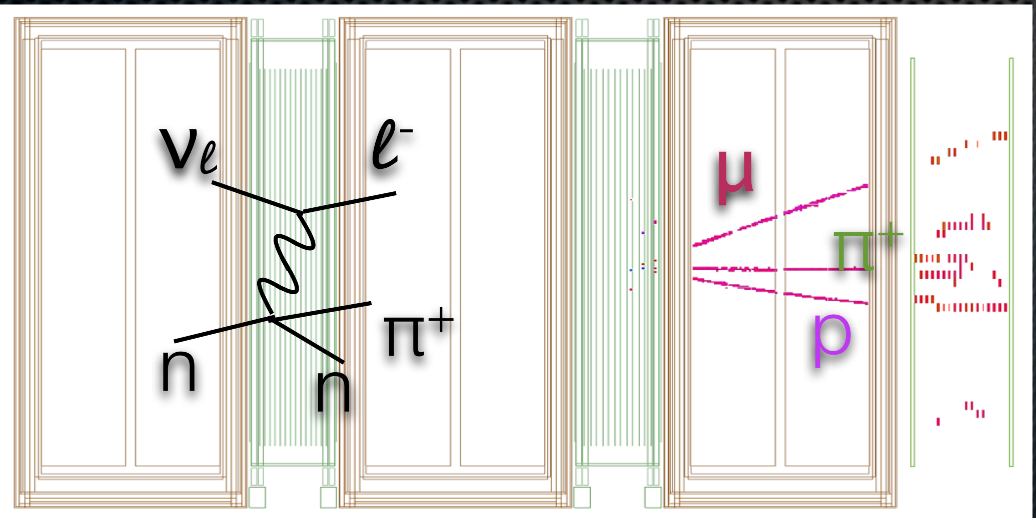




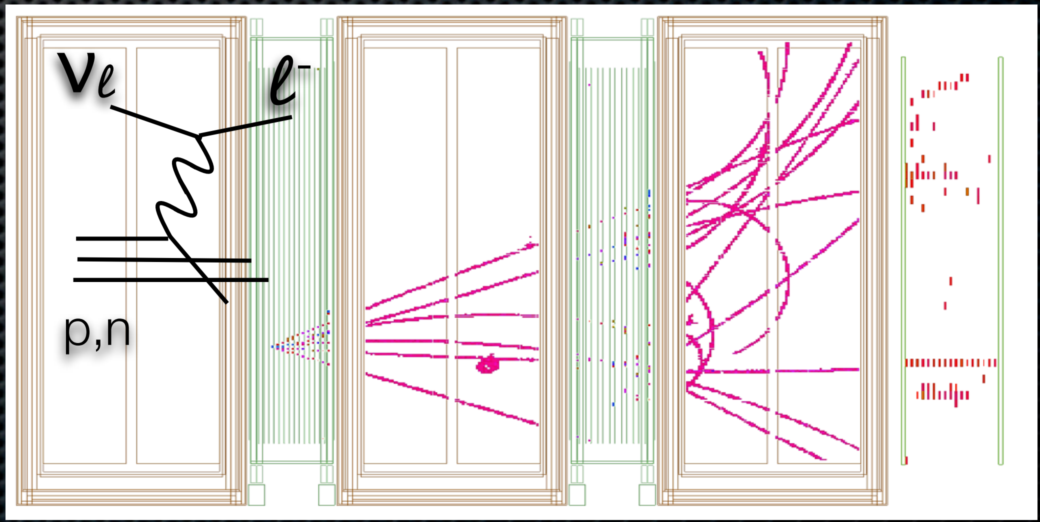
ND280 Event Display



Quasi Elastic candidate



single pion candidate

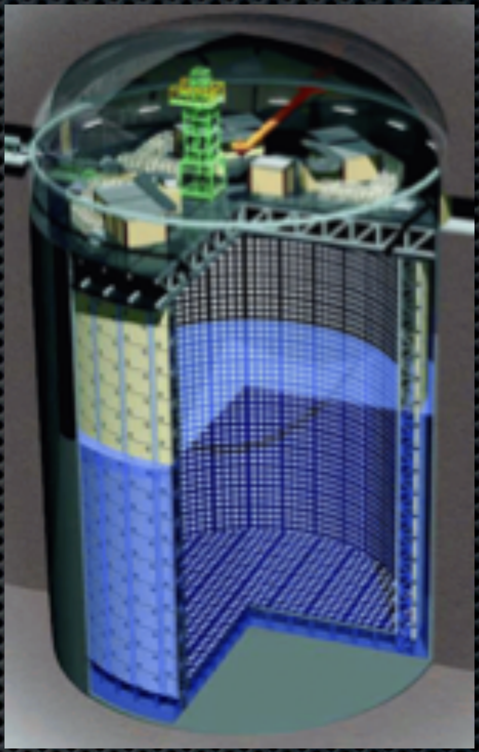


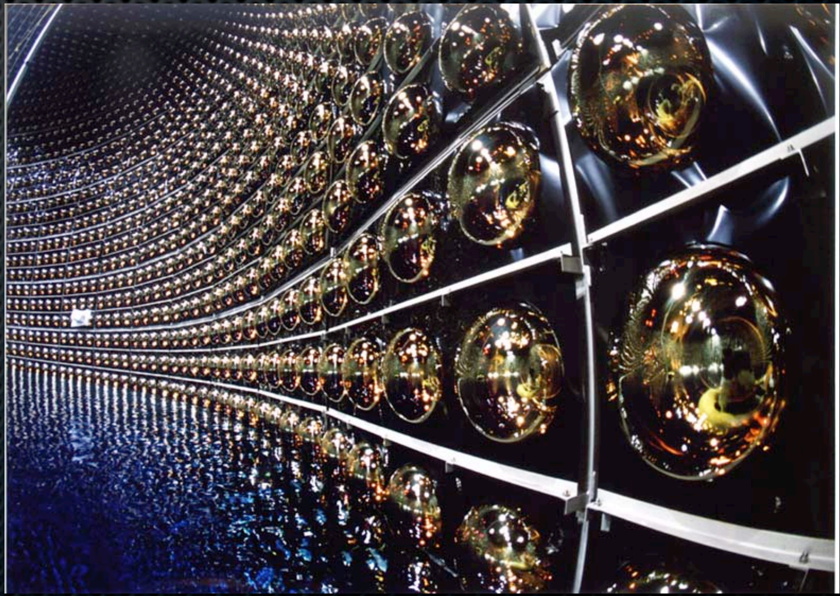
DIS candidate

DIS = deep inelastic scattering.

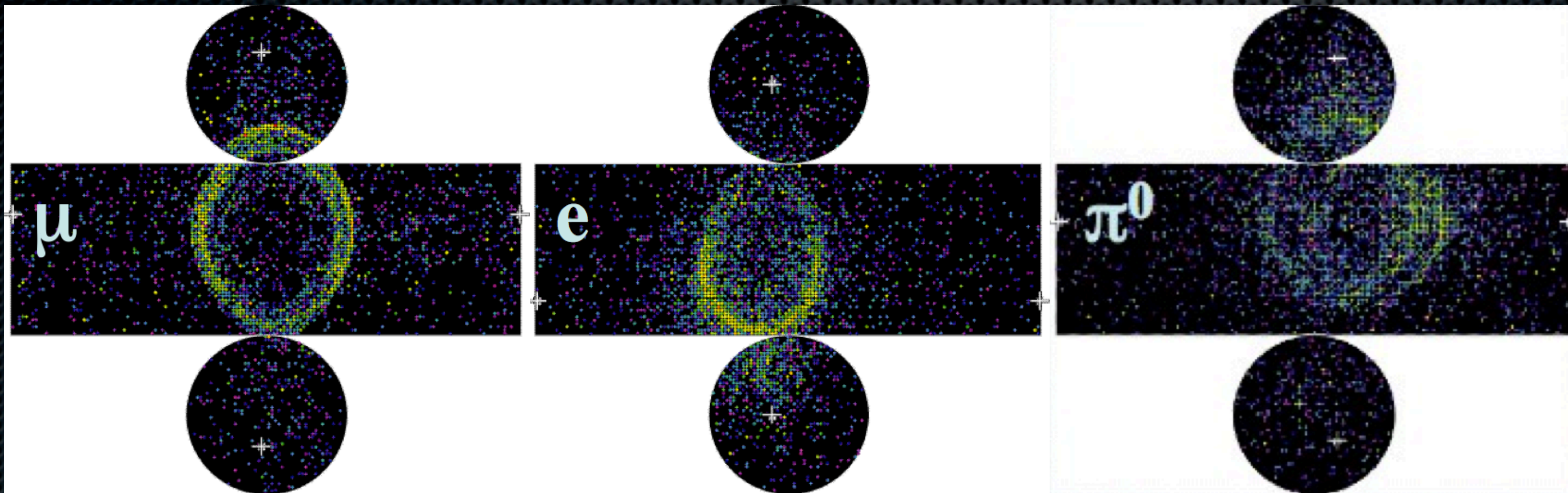
Super-Kamiokande

- 50 kton water Cherenkov detector. 22.5 kTon fiducial volume.
- PMTs line the inner and outer volumes of detector.
- Charged particles from neutrino interactions produce Cherenkov light. Ring recorded by PMTs.
- Detector measures direction of recoil particle, momenta, particle type.





Super-Kamiokande Event Displays



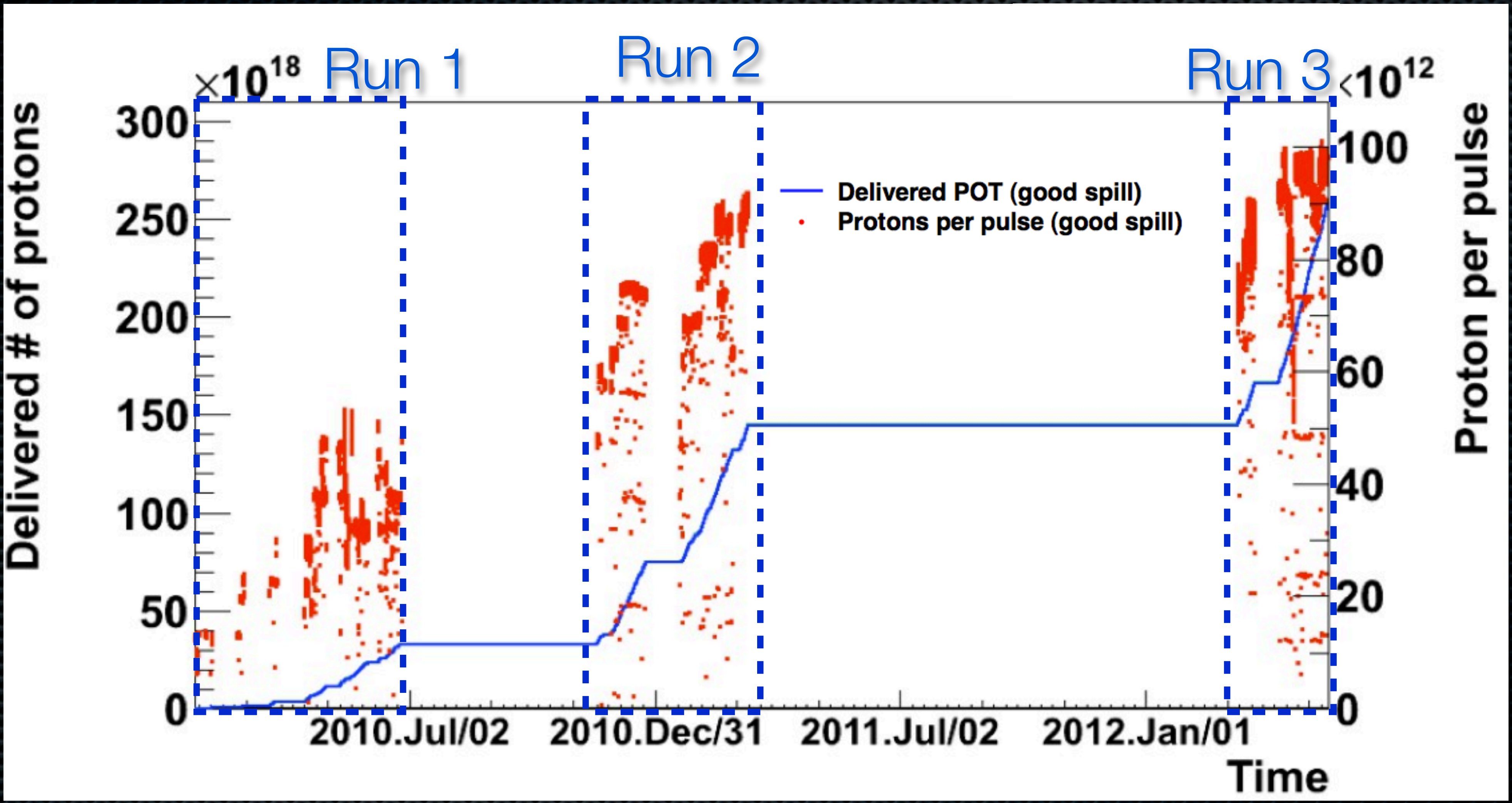
Sharp μ Cherenkov ring

Fuzzy e Cherenkov ring

NC π^0 event: can mimic e if one ring is missed.

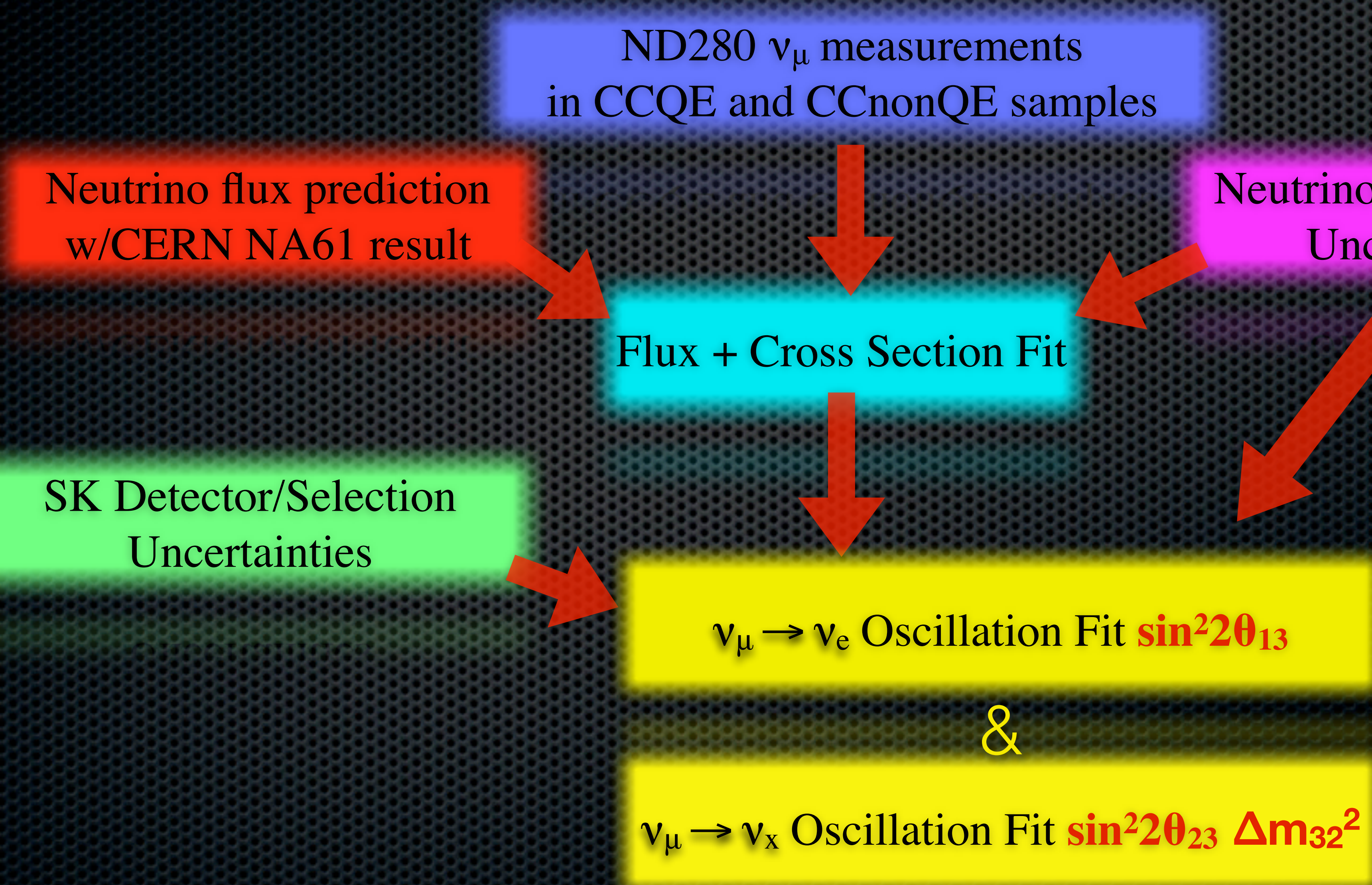
*events displays generated with MC

Analyzed Data



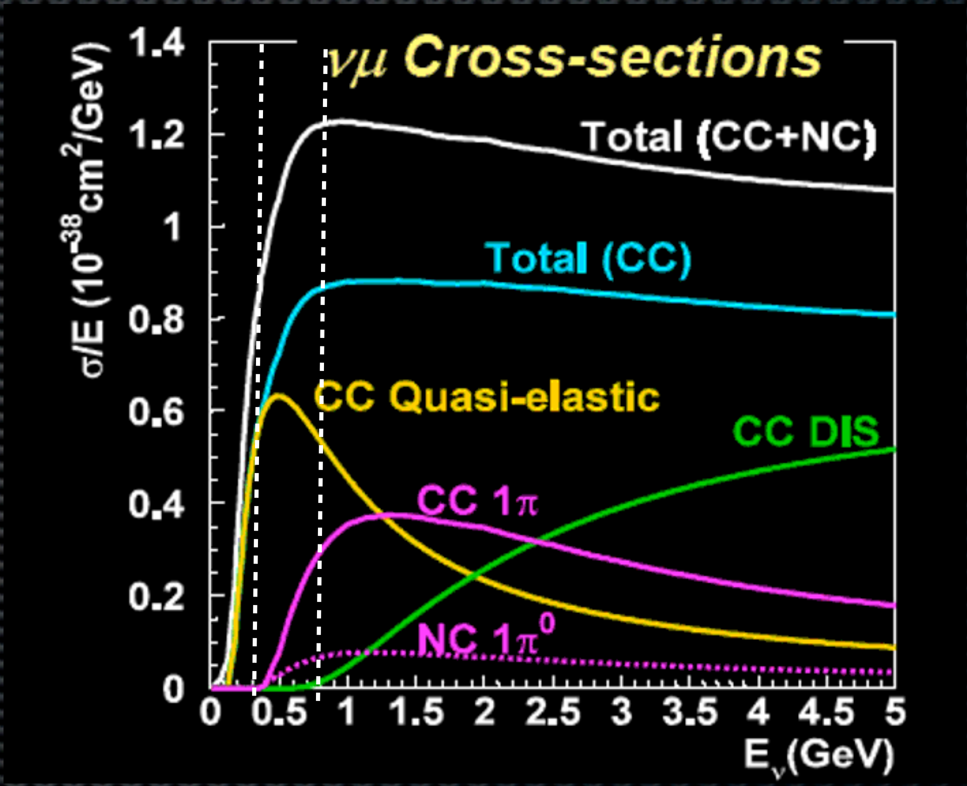
- Data set runs up to 2012/06/09 (End of Run 3)
- POT used in this analysis: 3.01×10^{20}

Oscillation Analyses



ν Interactions

- CC (Charged-Current) quasi elastic (CCQE).
  - ν + n → μ⁻ + p (n in ^{12}C or ^{16}O)
- CC (resonance) single π(CC-1π)
  - ν + n(p) → μ⁻ + π⁺ + n(p)
- DIS (Deep Inelastic Scattering)
  - ν + q → μ⁻ + mπ$^{+/-/0}$ + X
- CC coherent π (ν + A → μ⁻ + π⁺ + A)
- NC (Neutral-Current) NC-1π^0, etc...

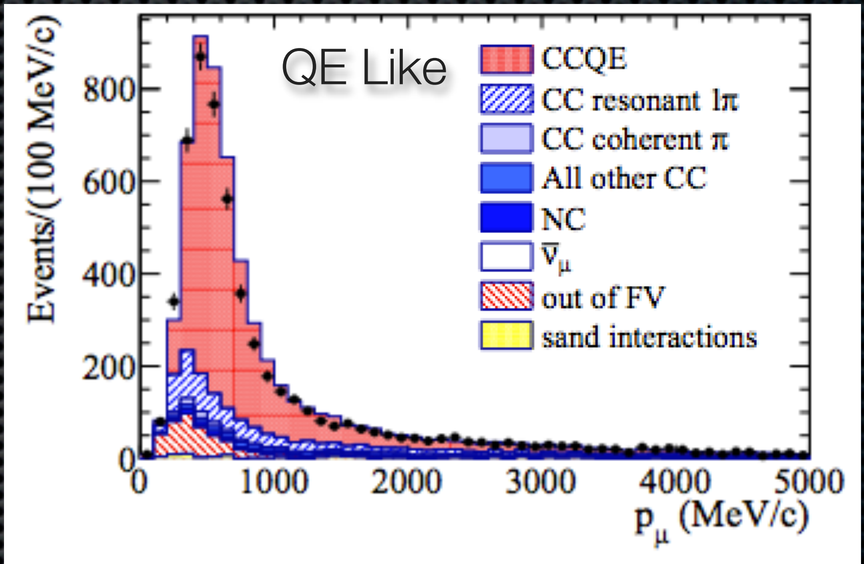


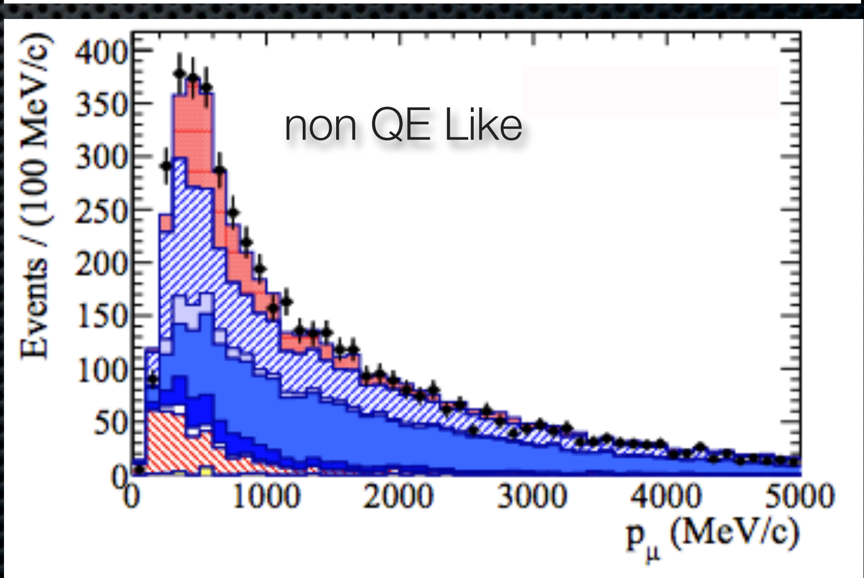
- CCQE Signal Interactions. Initial neutrino can be reconstructed from the energy and direction of final lepton

$$E_\nu^{QE} = \frac{m_p^2 - (m_n - E_b)^2 - m_l^2 + 2(m_n - E_b)E_l}{2(m_n - E_b - E_l + p_l \cos(\theta_l))}$$

ND280 Measurement

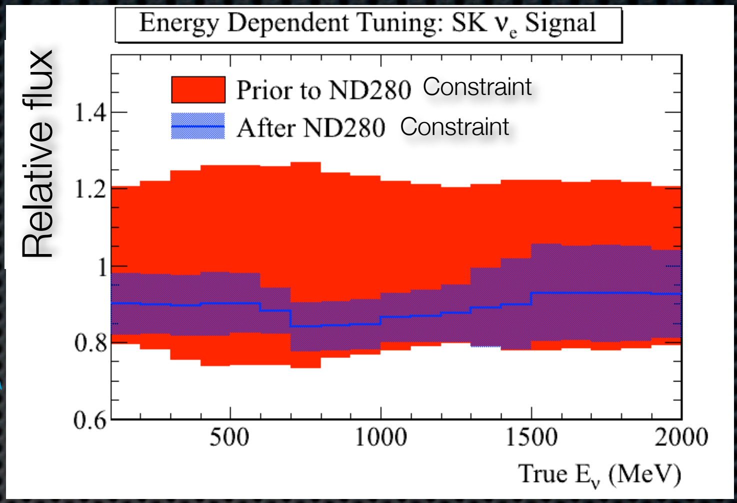
- Select CC events.
  - Lepton originating in FGD.
  - Muon-like dE/dx, negative curvature in TPC.
- Divide into QE-like, non-QE-like based on number of tracks.
- Likelihood fit to CCQE, CCnonQE p-θ distributions.
- Reduce flux and cross section uncertainties

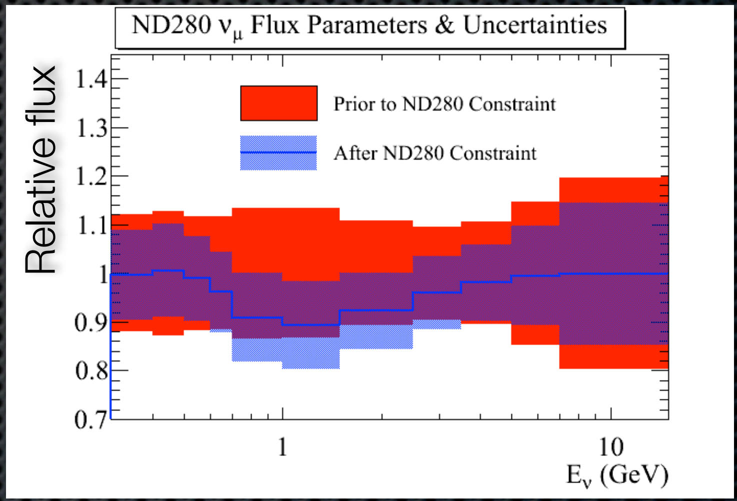


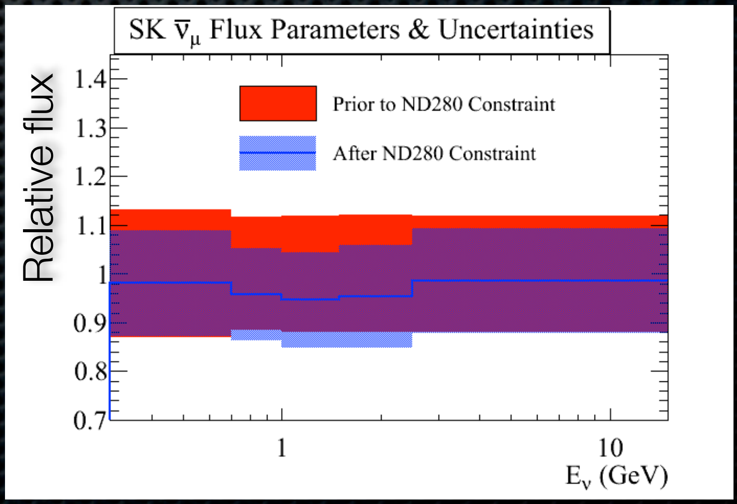


Flux Constraints

- Common systematic parameters for ND280 and SK. ND280 used to tune flux and constrain error at SK
- Fits done with 2 different flux parameterizations.
  - ν_e
  - ν_μ and $\bar{\nu}_\mu$

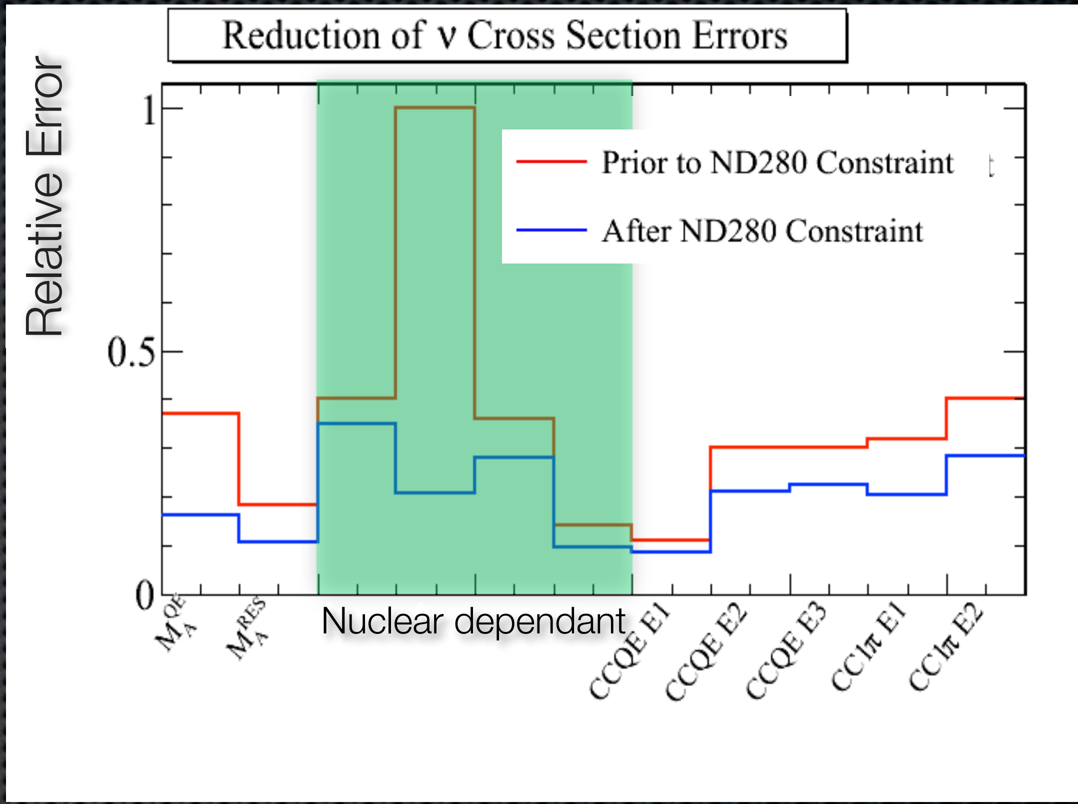






Cross Section Constraints

- Parameters with prior uncertainties from Mini-BooNE and other experiments are further constrained at ND280.
- Parameters that do not depend on nuclear target
  - Axial mass for CCQE, CC1π
  - Normalization parameters.

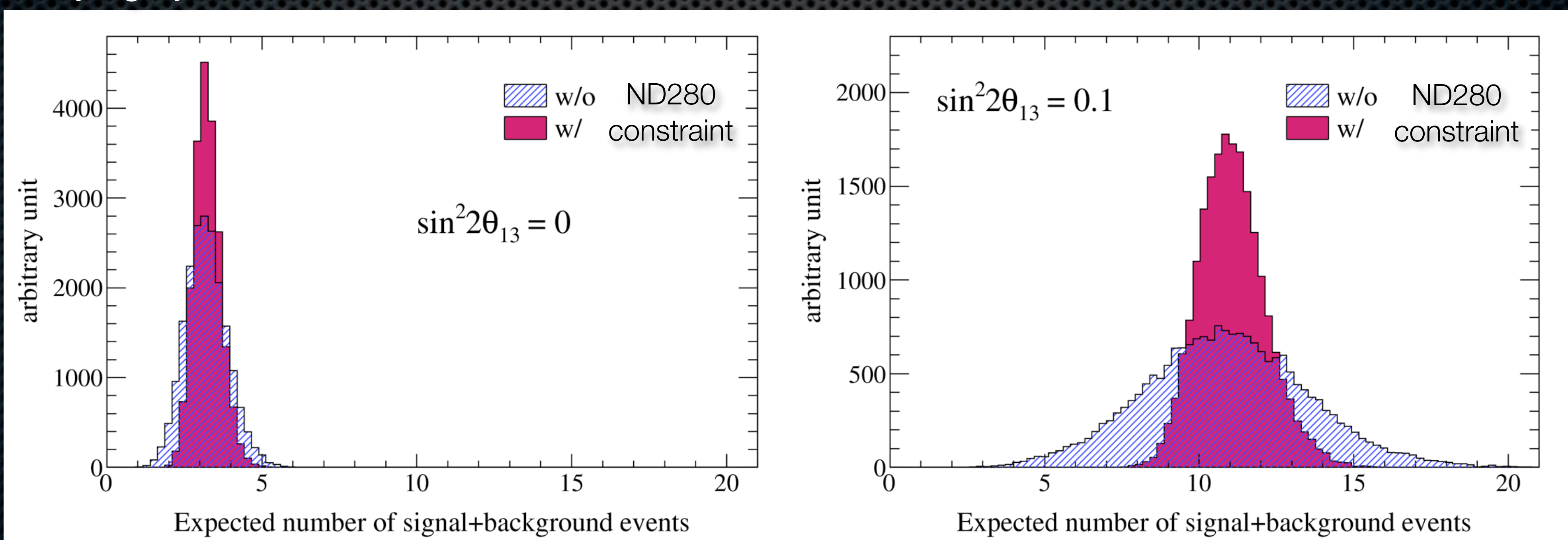


ν_e appearance

Expected number of ν_e Events

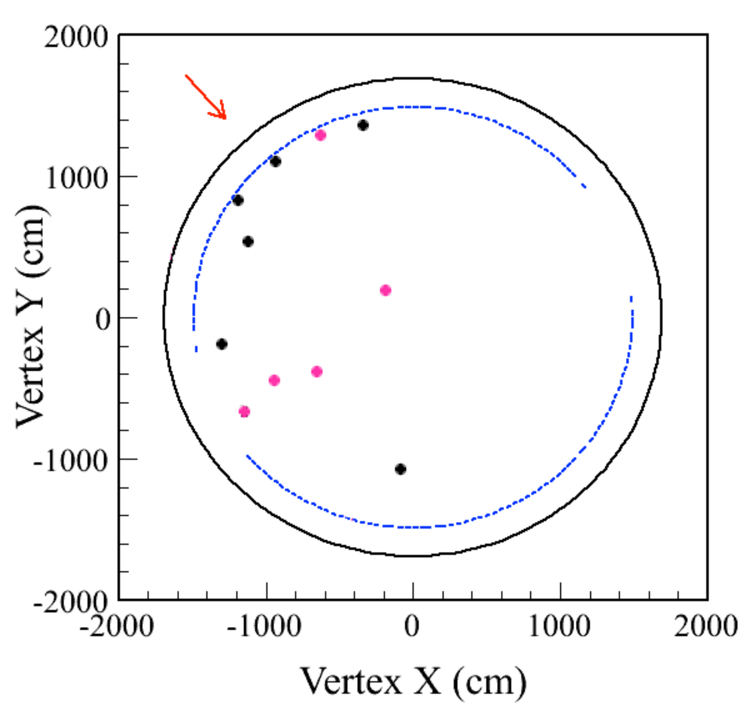
	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
total	3.3	11.2
CC $\nu_\mu \rightarrow \nu_e$	0.2	8.2
CC ν_μ	0.06	0.06
CC ν_e	1.8	1.7
NC	1.2	1.2

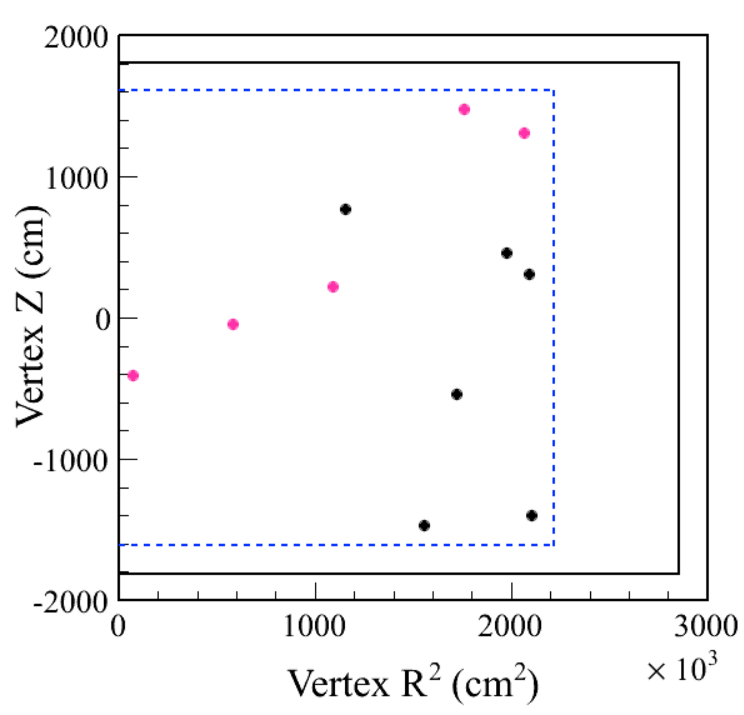
*varying systematics



ν_e candidates

- 11 candidate events observed.
- Probability to observe 11 or more events based on the predicted background of 3.3 +/- 0.4 (syst.) events is 9 x10^{-4}, (3.1 σ)
- Perform analysis using (p,θ) spectrum.



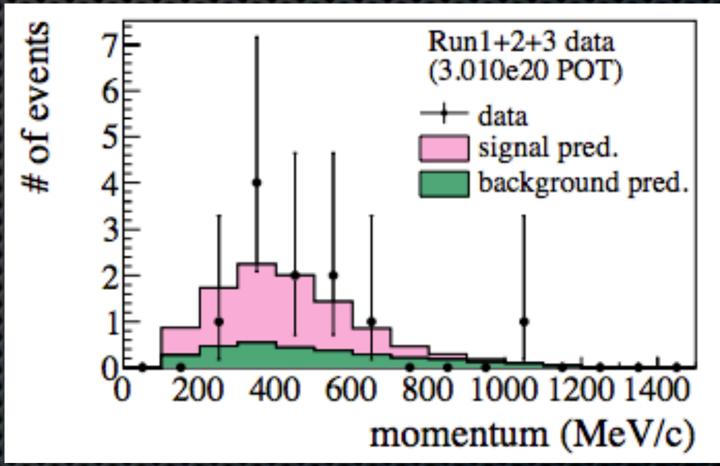


ν_e appearance oscillation fit

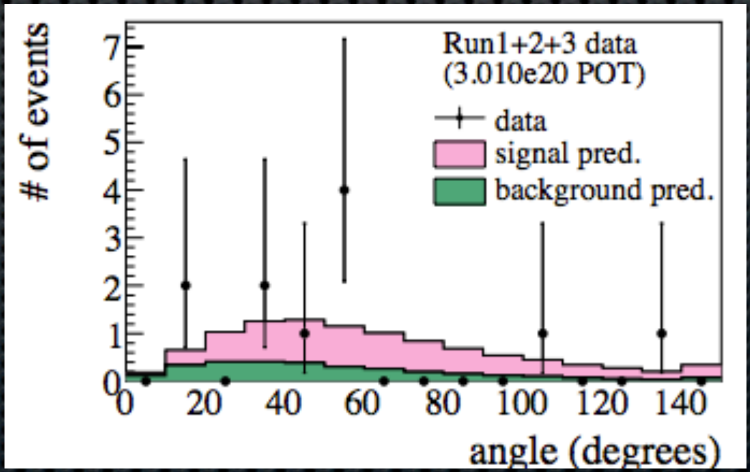
$\delta_{CP} = 0 \qquad \sin^2 2\theta_{23} = 1.0 \qquad \Delta m^2_{32} = 2.4 \times 10^{-3} eV^2$

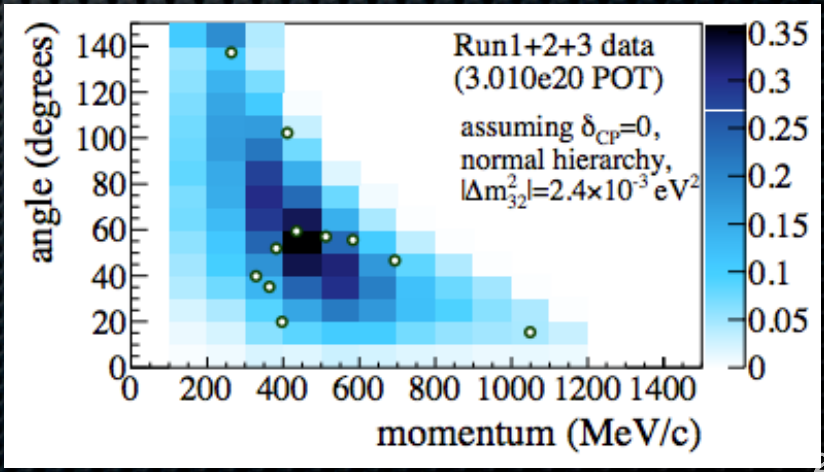
$$\sin^2 2\theta_{13} = 0.088^{+0.049}_{-0.039} (\text{normal hierarchy})$$

$$\sin^2 2\theta_{13} = 0.108^{+0.059}_{-0.046} (\text{inverted hierarchy})$$



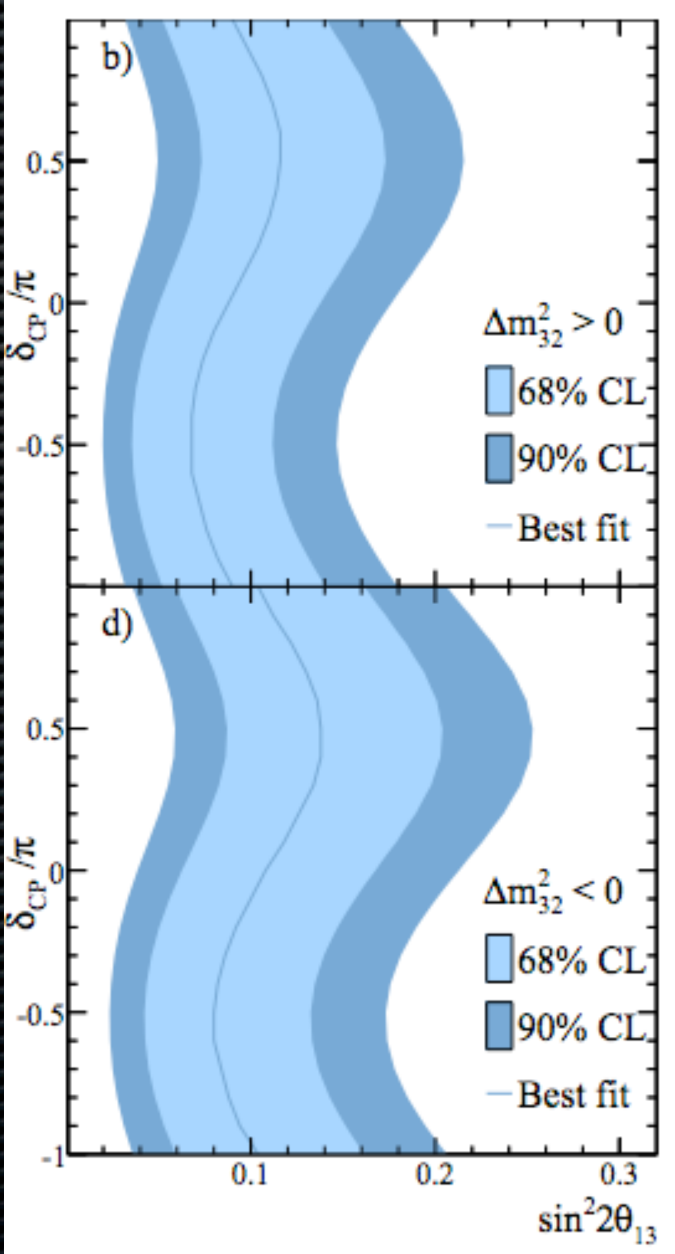
p-value off 1x 10^{-3}
θ_{13} =0 hypothesis





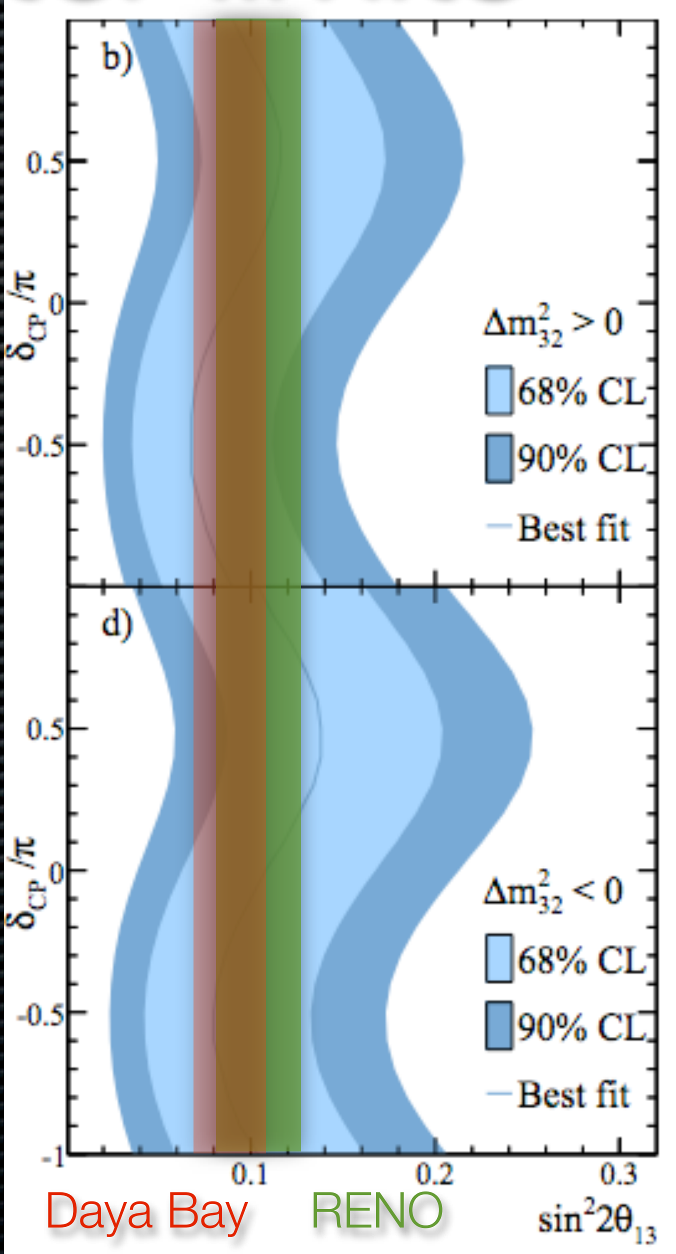
Oscillation parameter limits

- 68% and 90% confidence intervals scanning over δ
  - Top: Normal hierarchy
  - Bottom: Inverted hierarchy
- Analysis done with 2 other methods
  - Rate + Reconstructed Ev
  - Rate only.
- All 3 methods give consistent results.



Oscillation parameter limits

- Reactor experimental results (Daya Bay,RENO) consistent with T2K.
- Reactor experiments non sensitive to δ complementary to accelerator experiments.



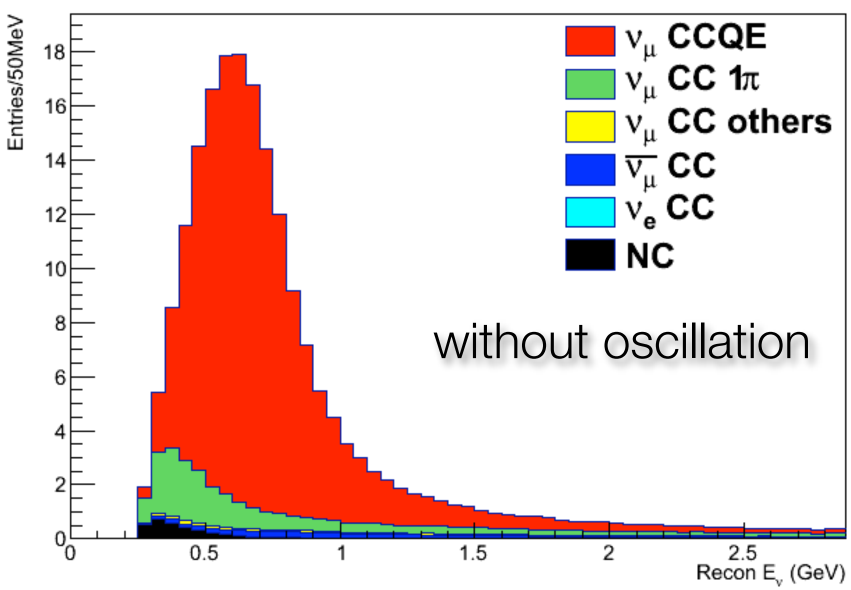
ν_μ disappearance

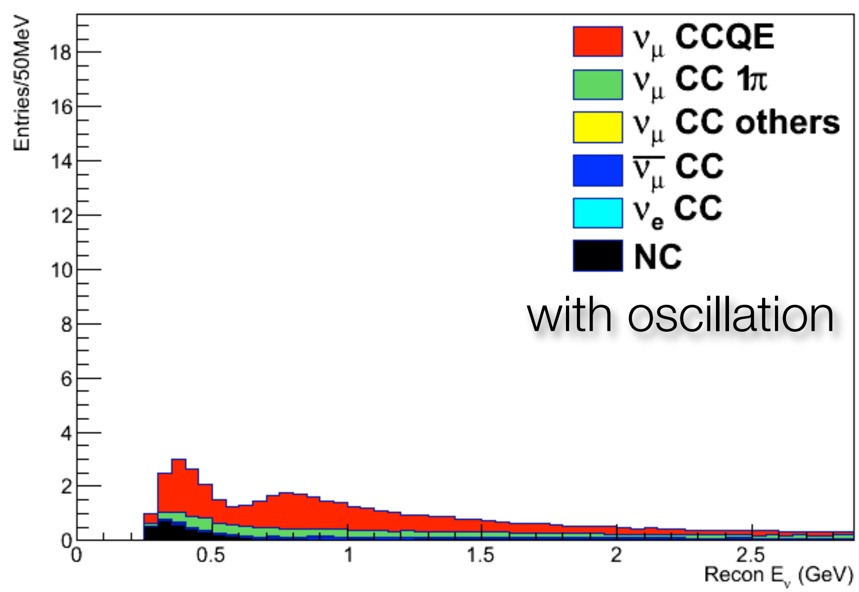
Expected number of ν_μ Events.

	# of pre-calculated events	
Event category	without oscillation	with oscillation
Total	210.46	59.39
CC ν_μ signal	200.55	52.17
CC $\bar{\nu}_\mu$ background	6.37	3.56
CC ν_e background	0.03	0.03
CC $\bar{\nu}_e$ background	0.00	0.00
Appearance ν_e background	0.00	0.12
NC background	3.51	3.51

	w/o ND280 constraint	w ND280 constraint
Total Error(%)	24.7	8.3

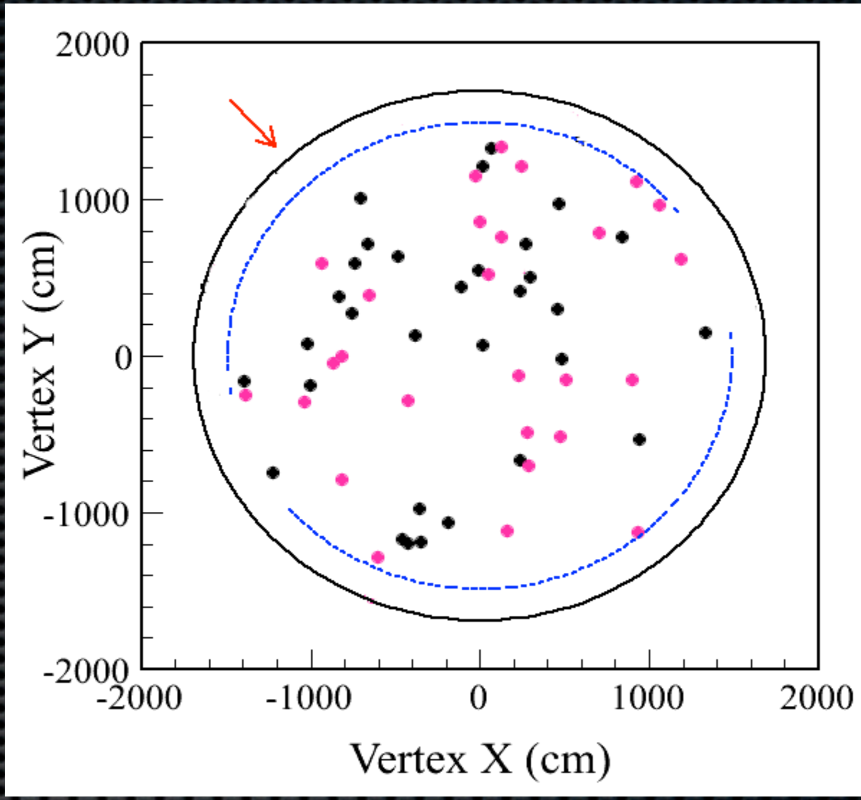
without oscillation





ν_μ candidates

- 58 candidate events observed
- Likelihood ratio fit binned in reconstructed energy. Compare the observed to expected in 73 variable width bins, concentrated in oscillation region.

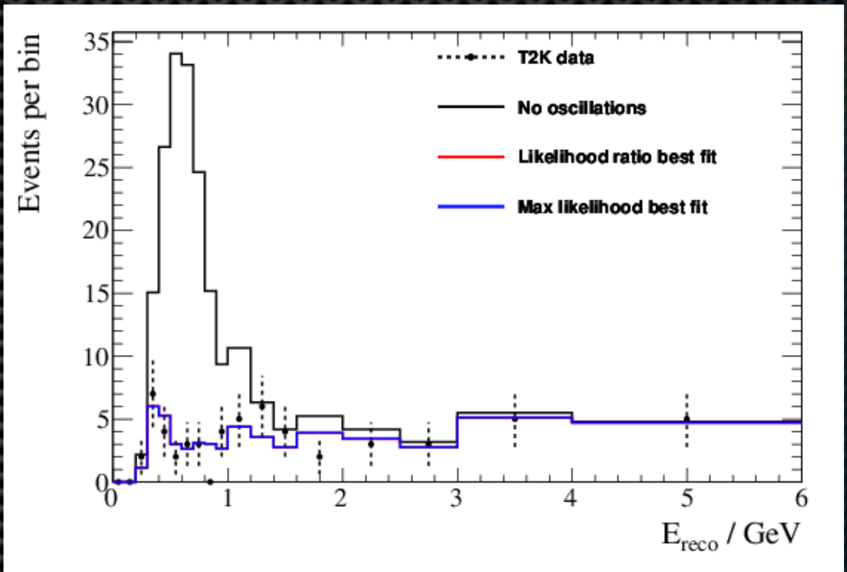


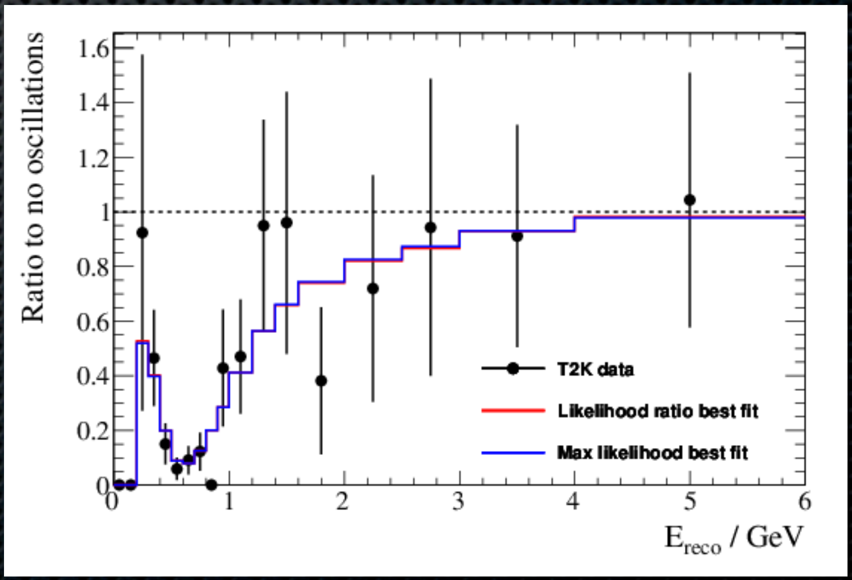
- Oscillation probability calculated using 3 neutrino flavours, θ_{13} using average of reactor experiments
- Using normal hierarchy, earth density 2.6 g/cm^3, δ =0

$\sin^2 2\theta_{13}$	0.098
$\sin^2 2\theta_{12}$	0.857
$\Delta m^2_{21}(eV^2)$	7.5×10^{-5}

ν_μ disappearance oscillation fit

- Deficit at survival probability minimum.
- Analysis done with likelihood ratio fit and Alternative method using unbinned maximum likelihood consistent





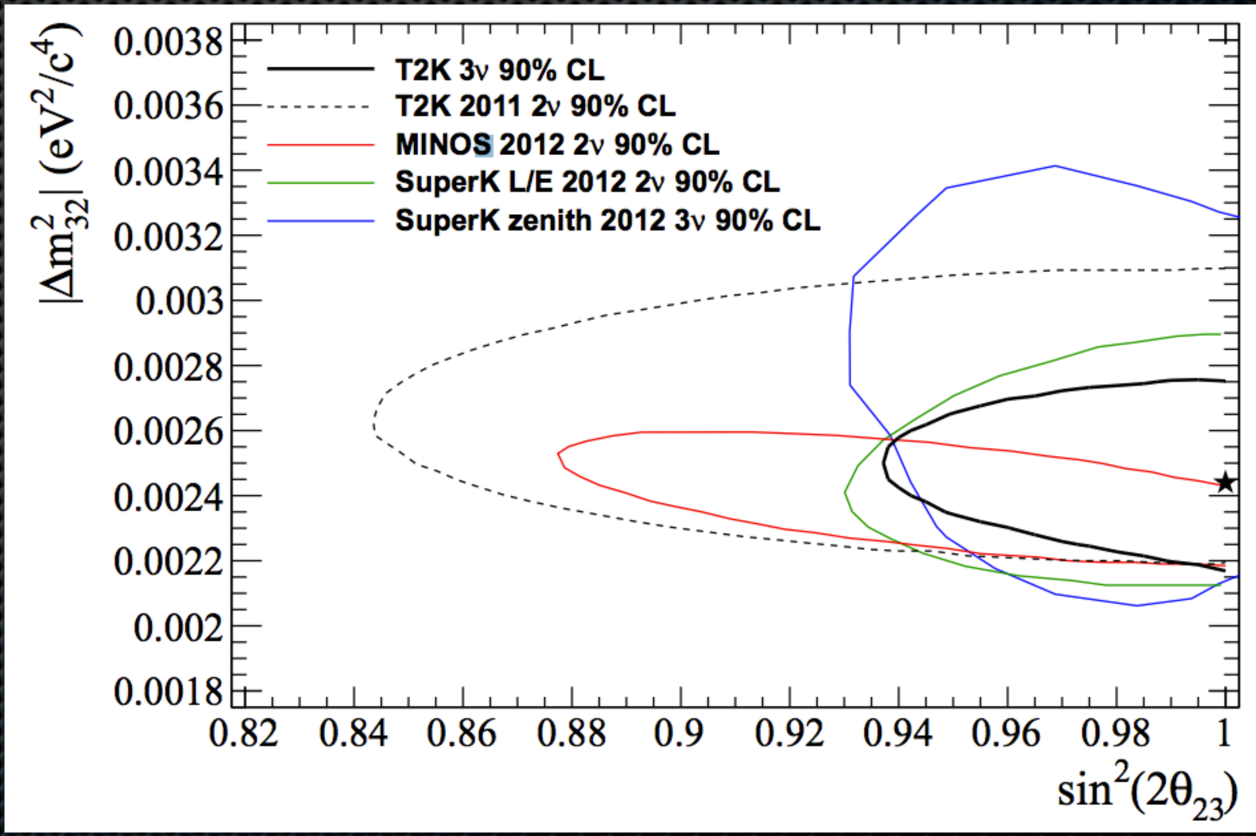
Oscillation parameter limits

90% CL

$$2.14 \times 10^{-3}\mathrm{eV}^2 < |\Delta m^2_{32}| < 2.76 \times 10^{-3}\mathrm{eV}^2$$

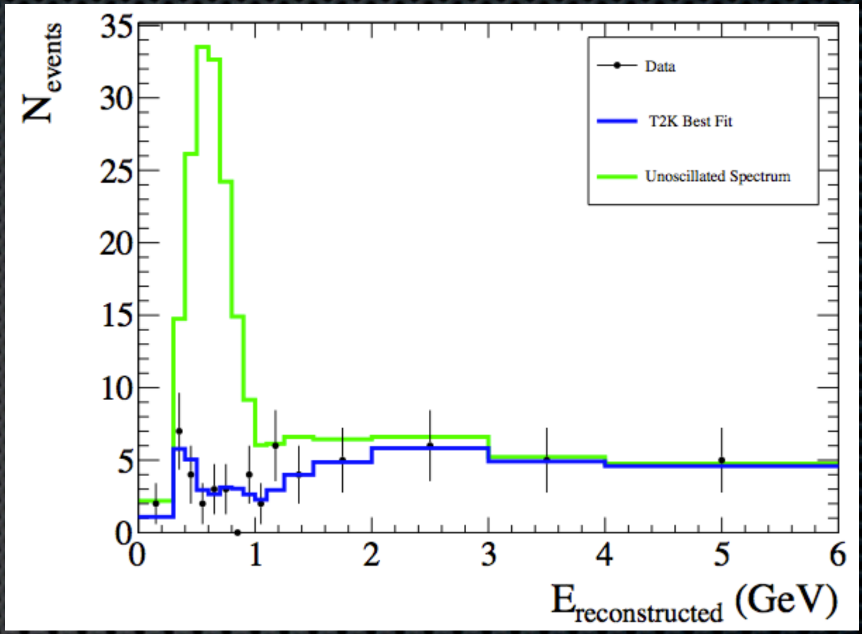
$$\sin^2 2\theta_{23} > 0.957$$

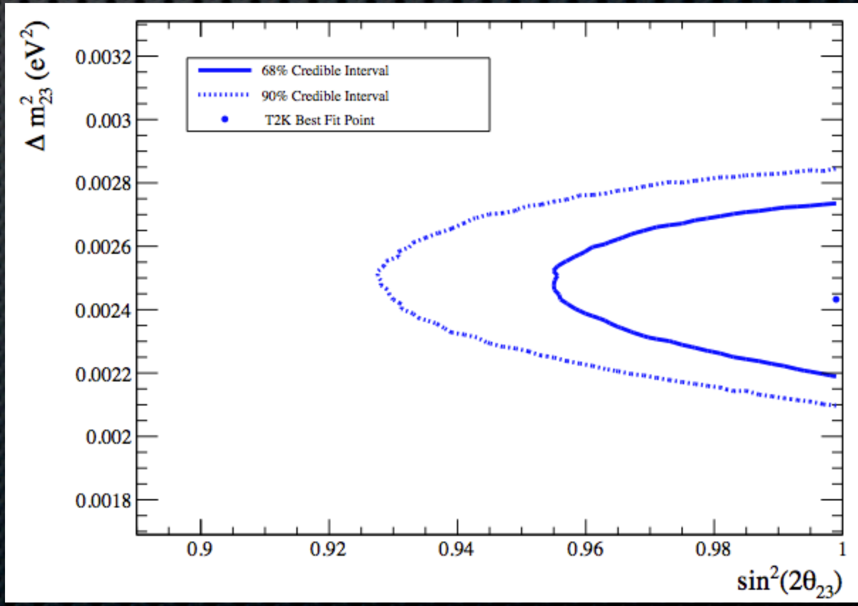
- Measures maximal mixing.
- Statistical error dominant



Simultaneous Fit

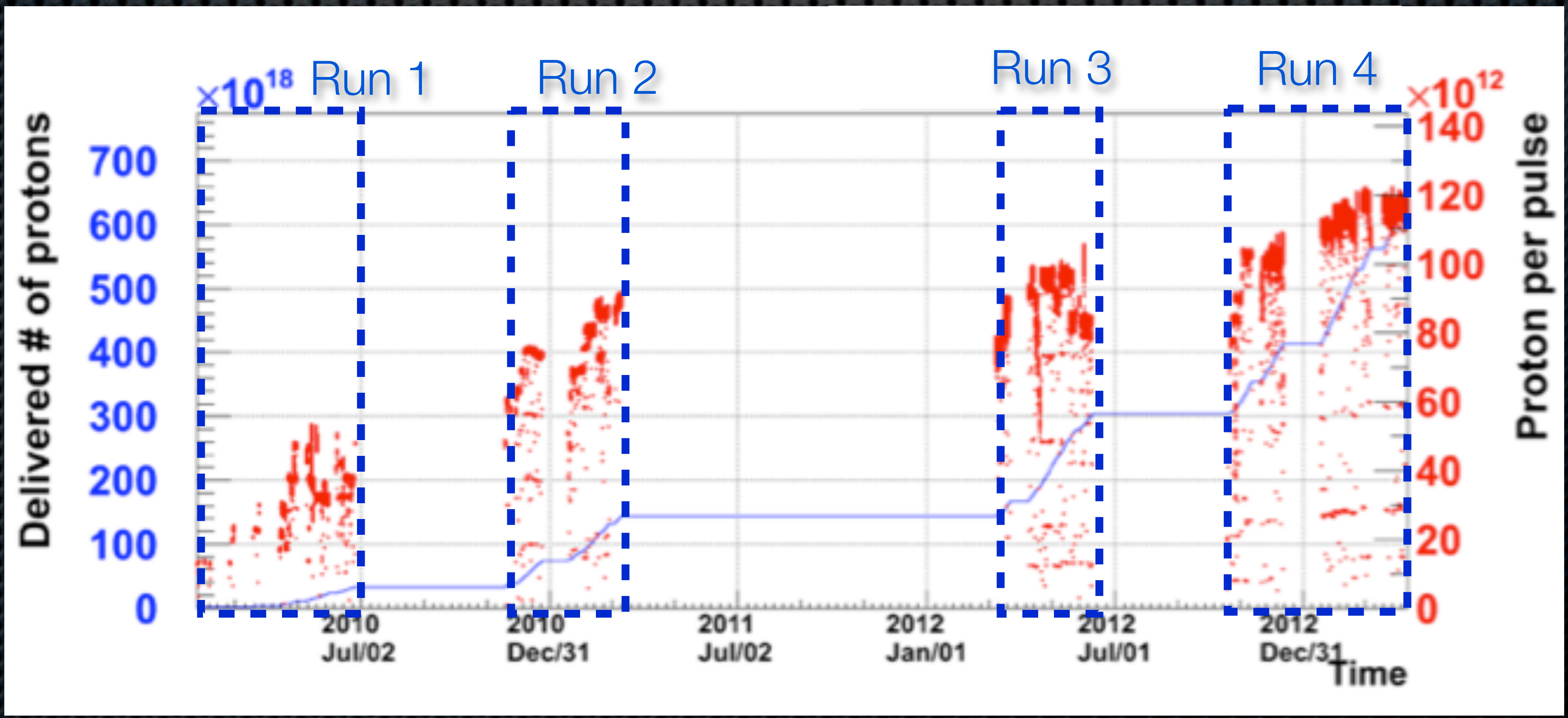
- Complementary study was done doing a simultaneous fit of ND280 and SK.
- Monte Carlo Markov Chain (MCMC) to find posterior distribution
- MCMC analysis produced Bayesian credible intervals.
- Credible/confidence intervals similar shape and size.





Future Prospects

- 3.01 x 10^{20} POT is 4% of T2K goal, measurements are still statistics limited.
- Data collection ongoing 6.39 x 10^{20} POT as of April 12th



Future Prospects

- Analysis upgrades
  - Upgraded SK fitting algorithm. Upgraded SK cuts, error evaluation. New samples used at ND280.
- Move to simultaneous fitting of ν_e & ν_μ samples
- Task force formed to study future sensitivity of T2K, best combination of ν $\bar{\nu}$ running. Combining T2K with other experiments to search for the θ_{23} octant, mass hierarchy and CP violation.

T2K Collaboration

~500 collaborators from 56 institutions, 11 nations

Back up

ν Oscillations

- The flavour state of the neutrino, ν_α can be expressed as a superposition of mass states ν_i.

$$|\nu_\alpha\rangle = \sum U_{\alpha i}|\nu_i\rangle$$

- Three neutrino flavours, neutrino mixings are described by the 3x3 PMNS matrix.

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

ν Oscillations

- PMNS matrix often parameterized as

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

- Measured with atmospheric and long baseline ν. $\theta_{23} \approx \pi/4$
- Measured with solar, reactor ν. $\theta_{12} \approx \pi/6$
- Measured with reactor, long baseline ν. $\theta_{13} \approx \pi/20$
- Very different than the CKM matrix!
- CP violating phase δ has not yet been measured.

CP Violation in Lepton Sector

- CPV in quarks (CKM matrix) does not explain the matter antimatter asymmetry in the Universe.
- What about the leptons?
- CPV in neutrinos could give hints towards matter antimatter asymmetry.
- The CP asymmetry of neutrinos in terms of ν_e appearance.

$$\frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu_\mu} \to \bar{\nu_e})}{P(\nu_\mu \to \nu_e) + P(\bar{\nu_\mu} \to \bar{\nu_e})} \simeq \frac{\Delta m^2_{21} \sin 2\theta_{12}}{4E_\nu \sin \theta_{13}} \sin \delta.$$

- Measurements of θ_{13} made in the past few years.

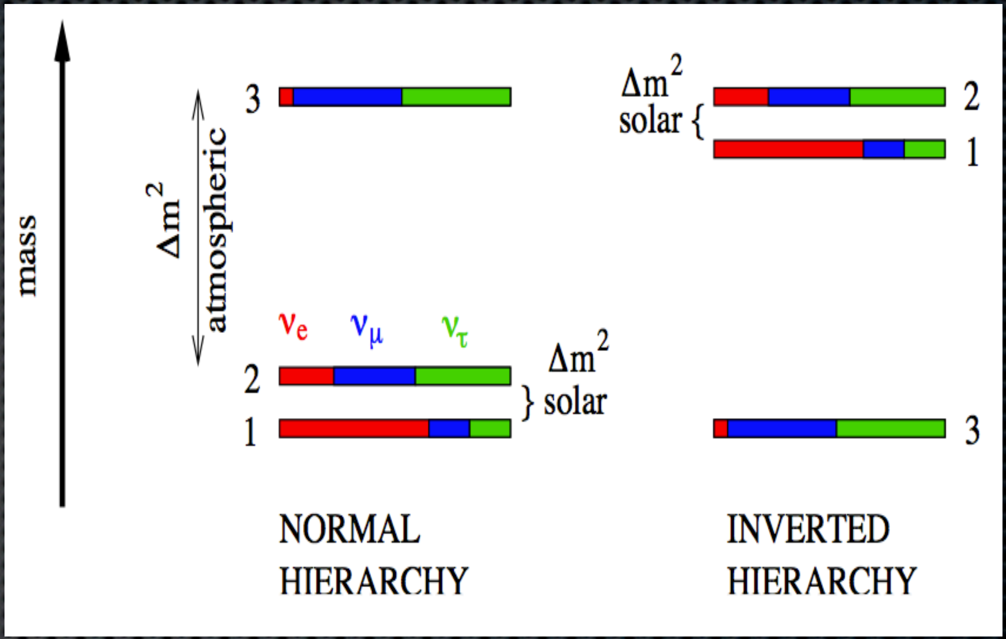
θ_{13} at T2K

- T2K measures θ_{13} via ν_e appearing in a ν_μ beam.
- Appearance dependant θ_{13} as well as CPV term, mass hierarchy, θ_{23} octant .

$$P(\nu_\mu \to \nu_e) \sim \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right) +$$
$$(\text{CPV term}) + (\text{matter term})$$

- Up to eight-fold ambiguity in determining θ_{13} and δ from $P(\nu_\mu \to \nu_e)$

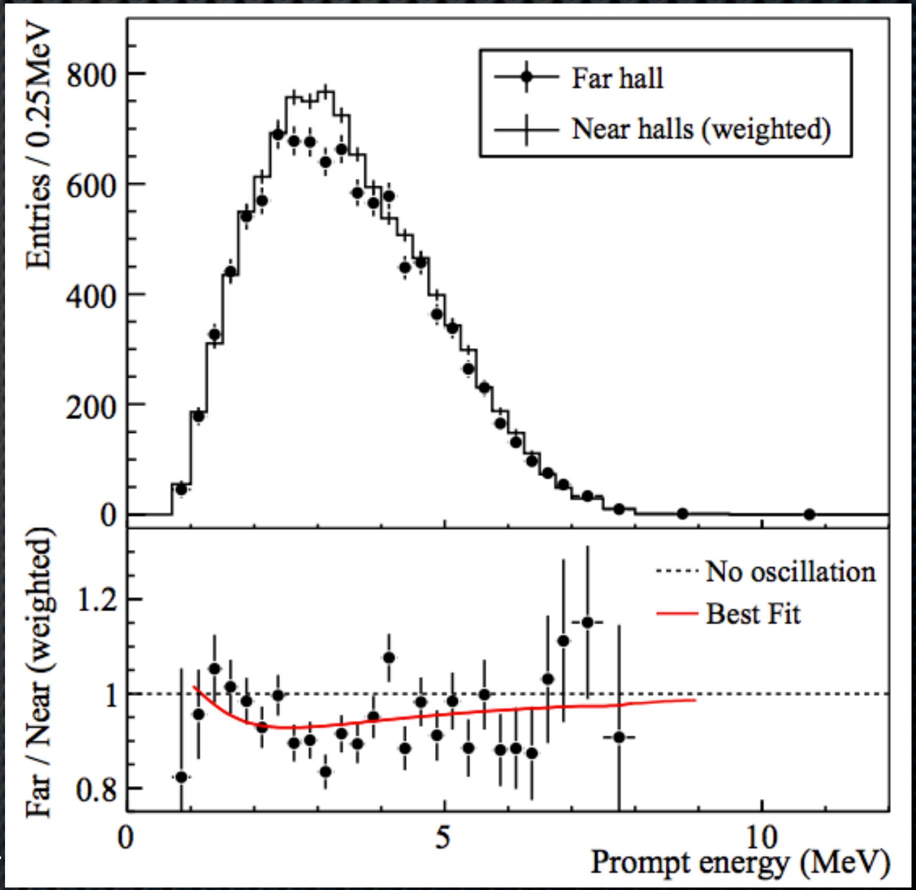
Unknowns



- Mass hierarchy still unknown.
  - $\Delta m_{32}^2 = 2.4 \times 10^{-3}$ eV^2
  - $\Delta m_{21}^2 = 7.6 \times 10^{-5}$ eV^2
- θ_{23} is still consistent will maximal mixing $\pi/4$
- Deviation of θ_{23} from maximal mixing? Lower or higher octant?

The past few years.

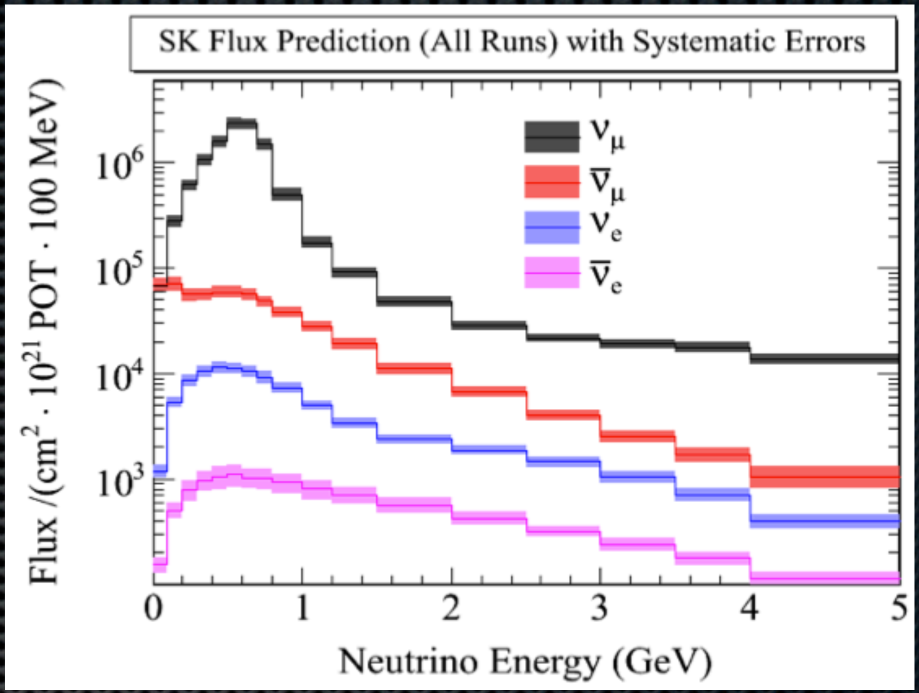
- June 2011: T2K. Electron neutrino *appearance*
- $\sin^2 2\theta_{13} = 0.11 \pm 0.044$ (2.5 σ) (at $\delta_{cp} = 0$, NH).
  - PRL 107, 041801
- March 2012: Daya Bay. Electron neutrino *disappearance*
  - $\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{sys})$ (5.2 σ)
  - PRL 108, 171803
- April 2012: RENO. Electron neutrino *disappearance*
  - $\sin^2 2\theta_{13} = 0.113 \pm 0.013(\text{stat}) \pm 0.019(\text{sys})$ (4.9 σ)
  - arXiv:1204.0626

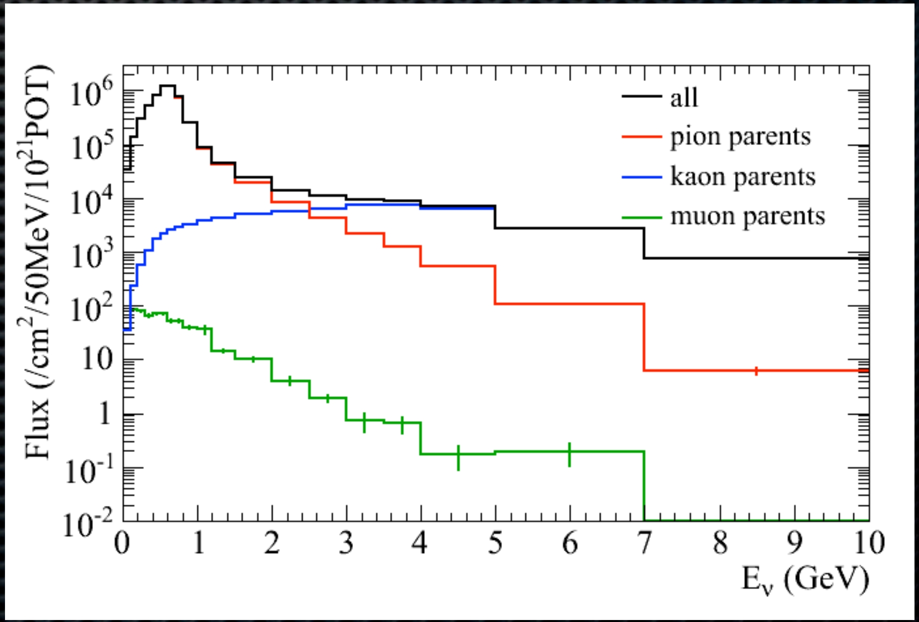


Daya Bay reactor neutrino disappearance

Neutrino flux prediction w/CERN NA61 result

- Uncertainty in flux found from proton beam profile, hadron production uncertainties.
- Kaon, pion production measured from NA61 experiment with same target material, beam energy as T2K.
- Tuned FLUKA + GEANT3 simulation used to estimate fluxes at ND280 and SK
- Beam flux uncertainty at Super Kamiokande ~15% before ND280 constraint.

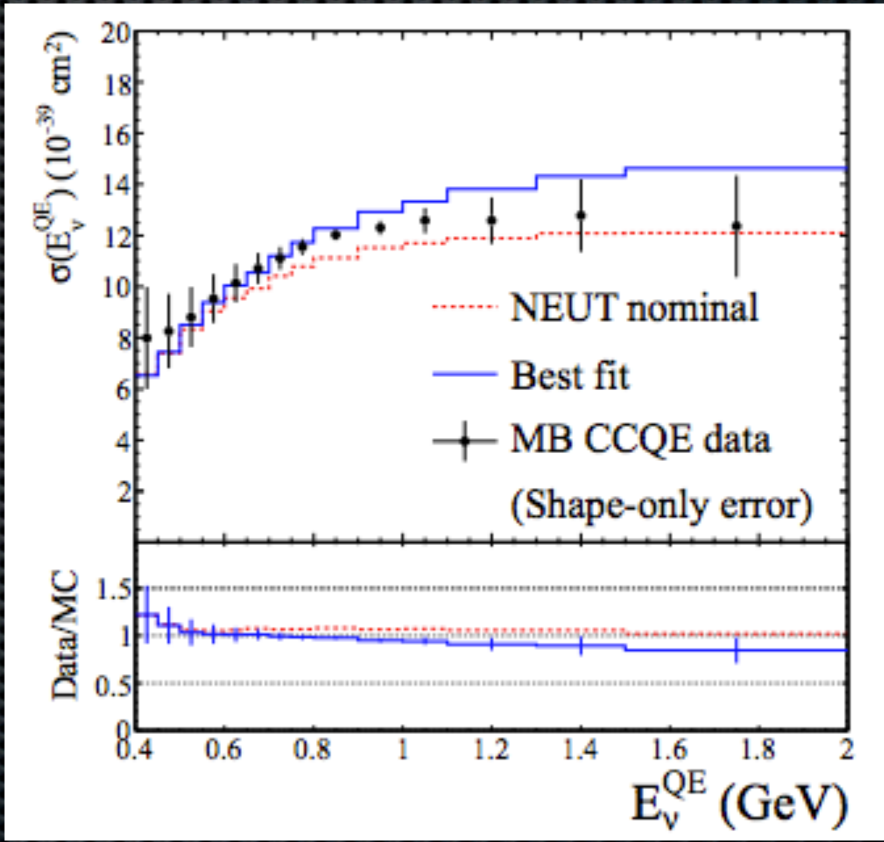




ν_μ flux broken down by parent that produces ν

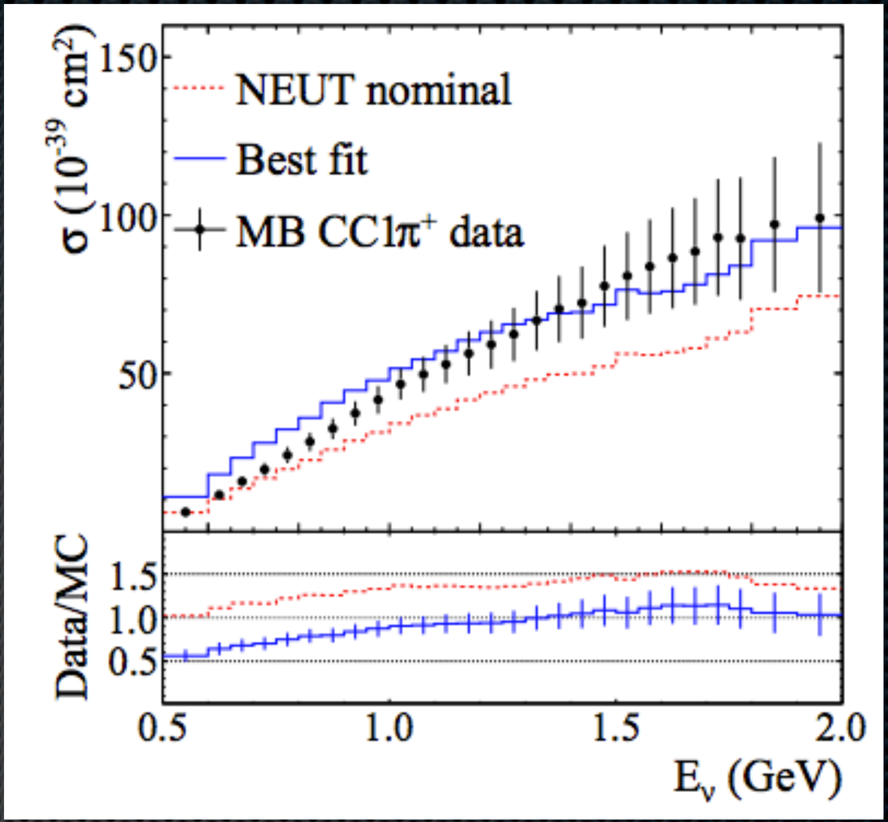
Neutrino Cross Section Uncertainties

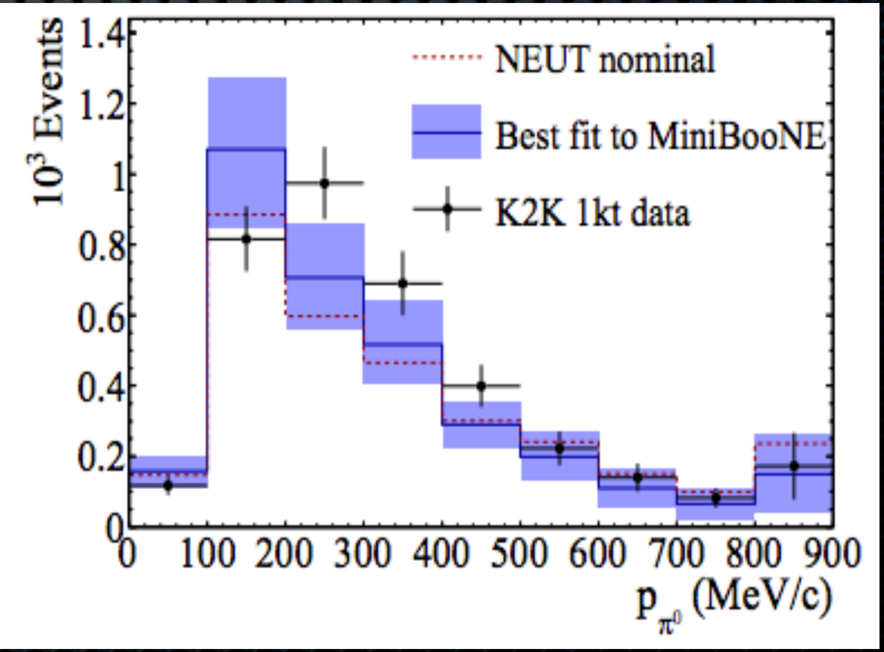
- Cross section uncertainties set by external data at ~1 GeV from Mini-BooNE, other experiments.
- T2K primary neutrino interaction model is NEUT, with GENIE used as a cross-check.
- Signal
  - CCQE interactions use the model of Llewellyn Smith with nuclear effects described by relativistic Fermi gas model.
- Differences between NEUT and Mini-BooNE best fit used as prior uncertainty. ND280 further constrains models.



Neutrino Cross Section Uncertainties

- Backgrounds
  - Single Pion Production CC1π main background for ν_μ disappearance: MisID'd as CCQE if pion is not identified
  - Pion production via hadronic resonances using Rein and Seghal Model
  - NCπ^0 backgrounds main background to ν_e appearance, flux dependant and can mimic a CC ν_e interaction
  - Results from Mini-BooNE NCπ^0 fit compared with K2K data (same target material as SK)

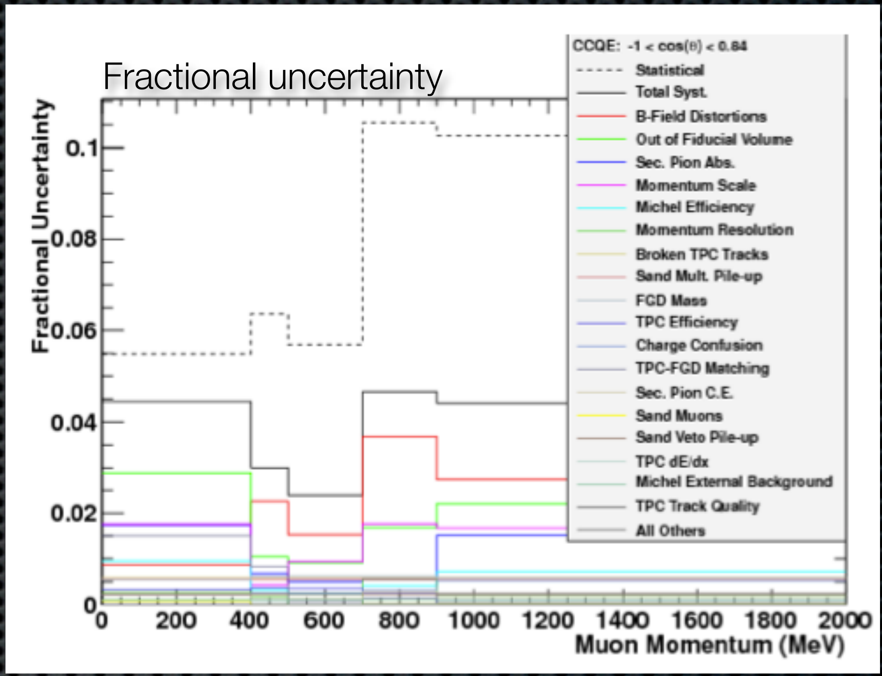




ND280 ν_μ measurements
in CCQE and CCnonQE samples

Systematics

- Statistics limited analysis
- Major Systematics
  - Magnetic field distortions in TPCs
  - background from interaction outside the FGD
  - Secondary pion interactions
- Uncertainty given in terms of p-θ bins 40x40 covariance for each systematic



Systematic error	Error Size (%)	
	Minimum and maximum fractional error	Total fractional error
B-Field Distortions	0.3 - 6.9	0.3
Momentum Scale	0.1 - 2.1	0.1
Out of FV	0 - 8.9	1.6
Pion Interactions	0.5 - 4.7	0.5
All Others	1.2 - 3.4	0.4
Total	2.1 - 9.7	2.5

SK Detector/Selection Uncertainties

- SK DAQ timing cuts.
- Event is fully contained in inner detector Reconstructed vertex is within fiducial volume
- Only one reconstructed ring.

ν_e Selection

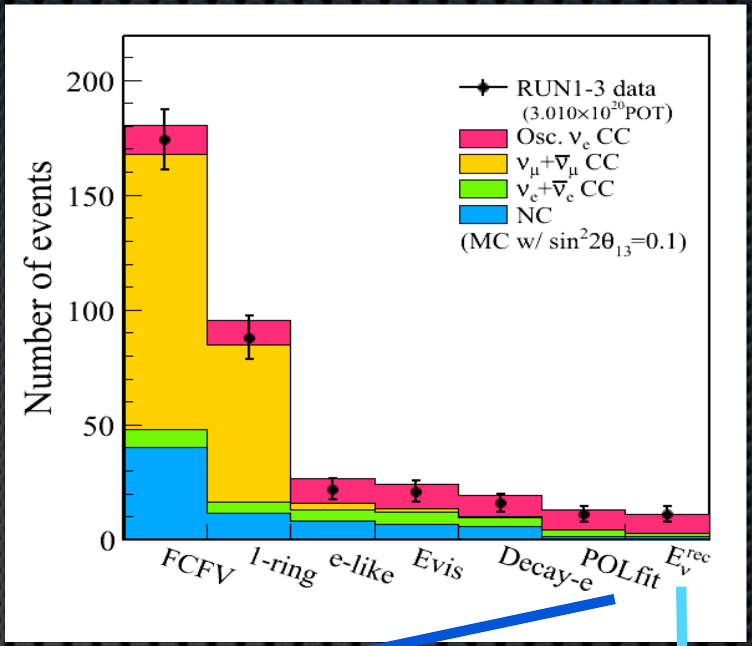
- Ring is electron like
- Visible energy is greater than 100 MeV
- No Michel electron
- Invariant mass is not consistent with π^0 mass
- Reconstructed energy is less than 1250 MeV

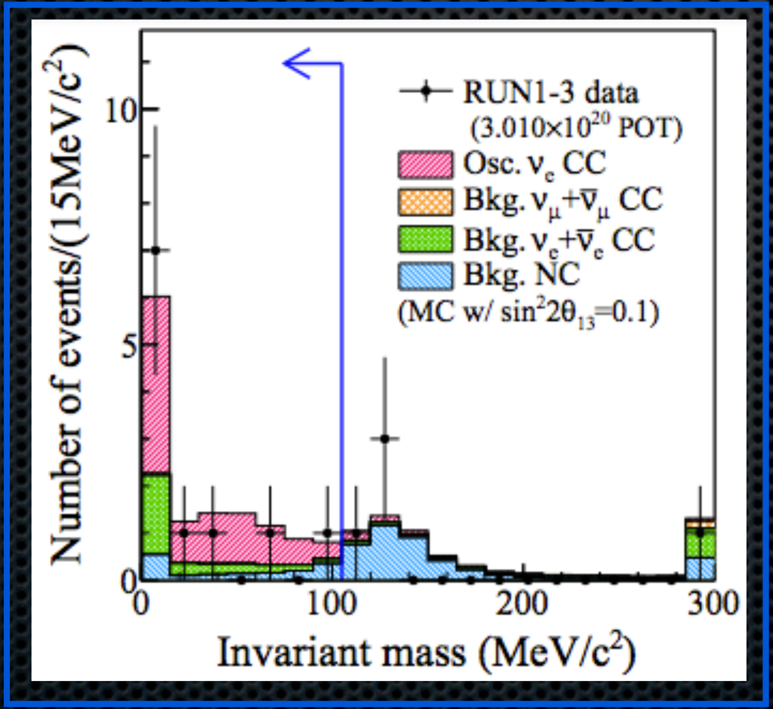
ν_μ Selection

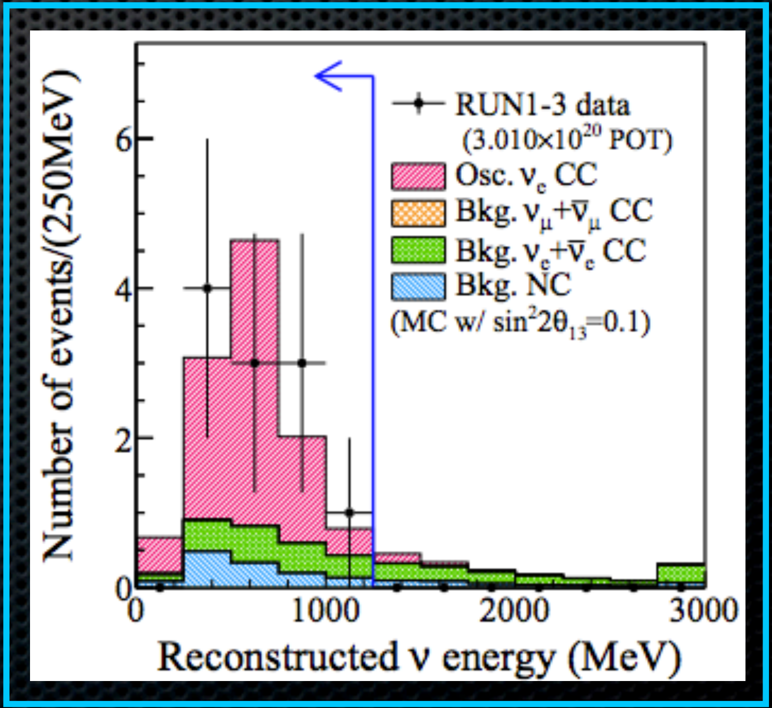
- Ring is muon like
- Reconstructed muon momentum is greater than 200 MeV.
- 1 or less Michel electron

ν_e Selection

- Ring is electron like
- Visible energy is greater than 100 MeV
- No Michel electron
- Invariant mass is not consistent with π^0 mass
- Reconstructed energy is less than 1250 MeV

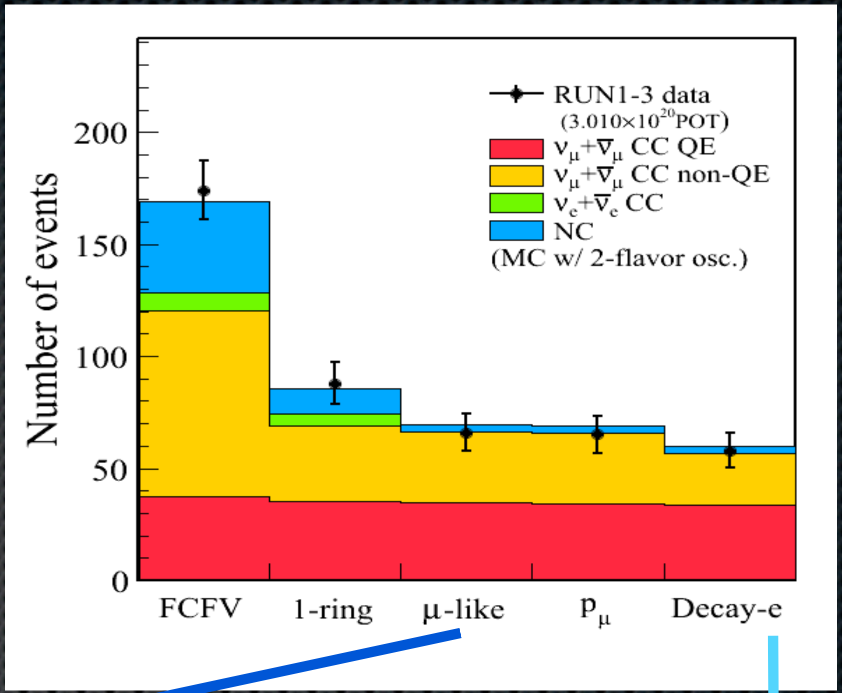


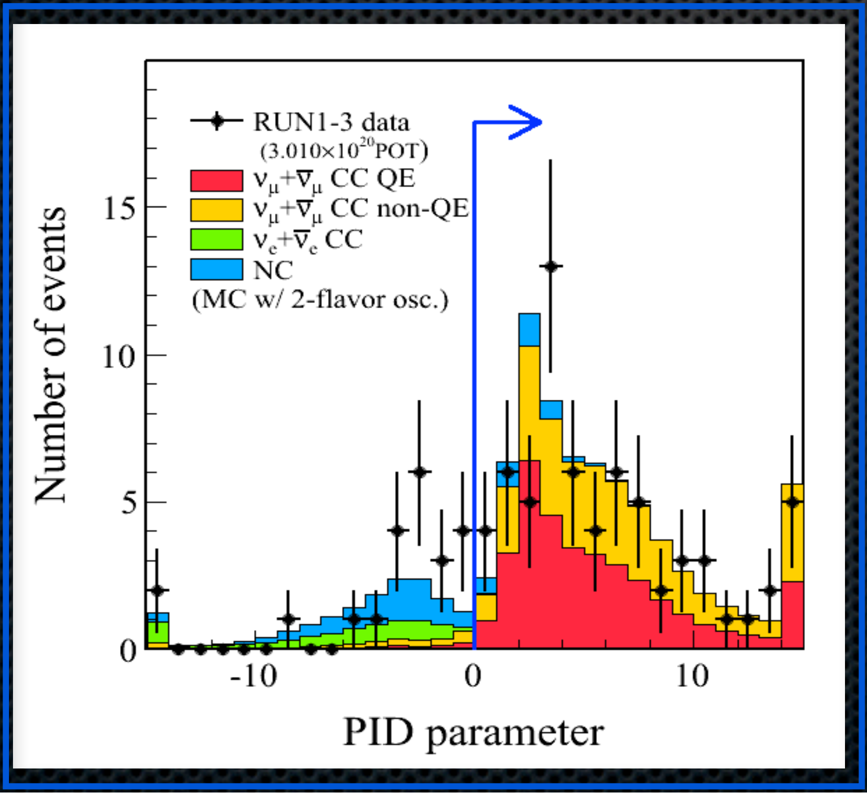


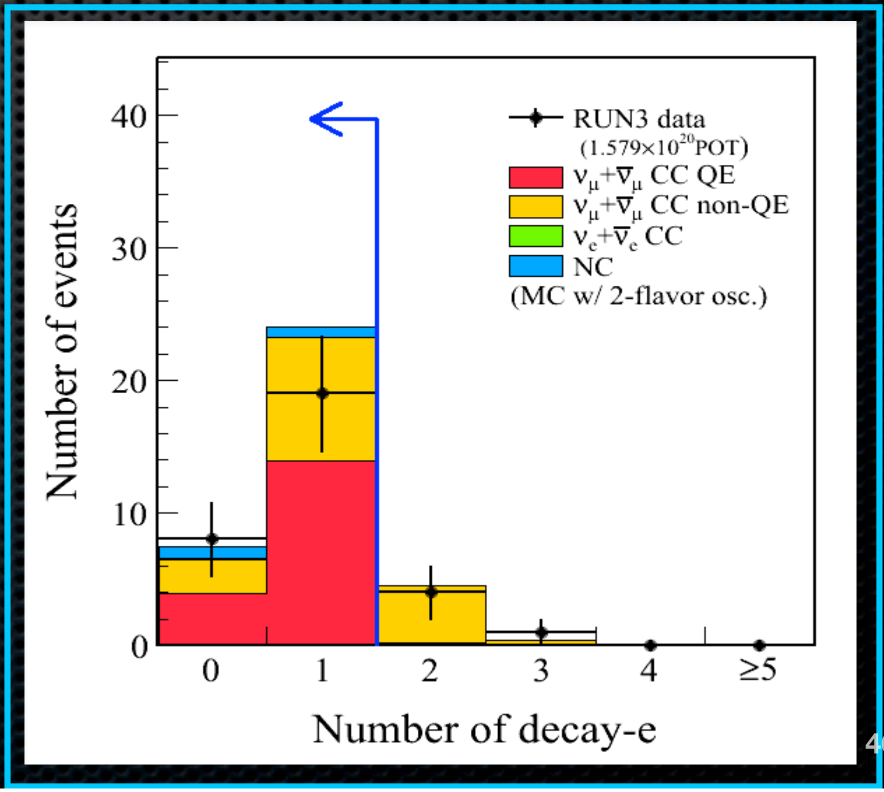


ν_μ Selection

- Ring is muon like
- Reconstructed muon momentum is greater than 200 MeV.
- 1 or less Michel electron



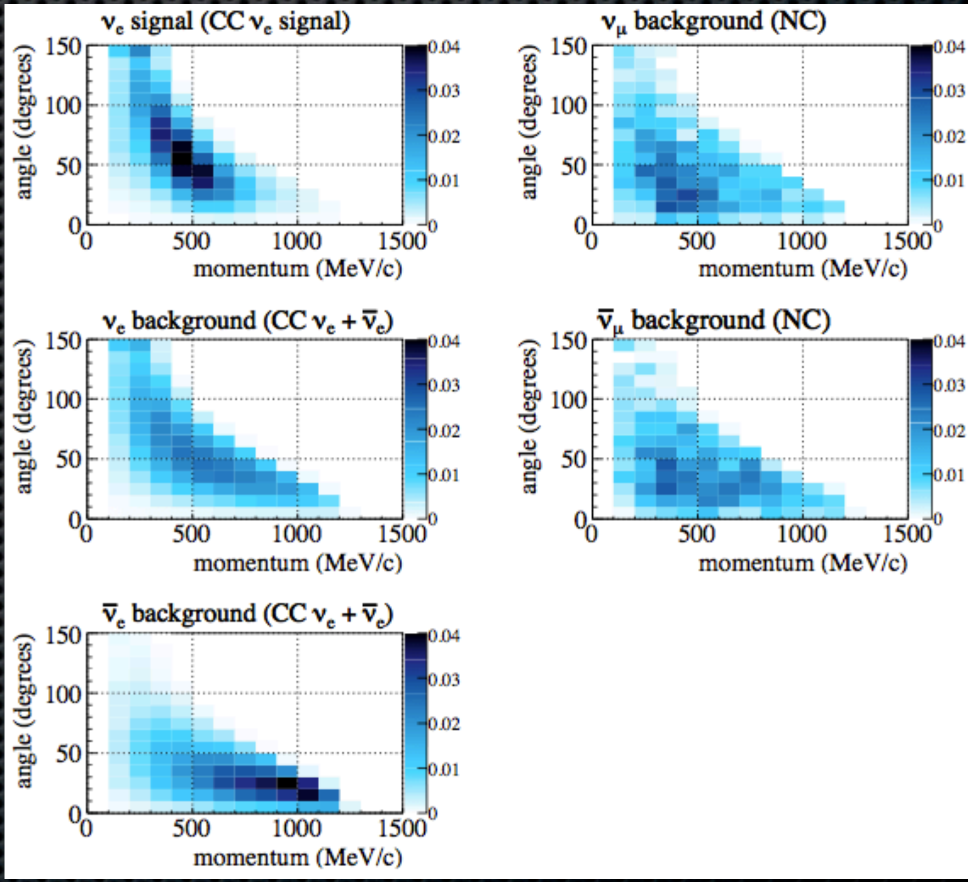




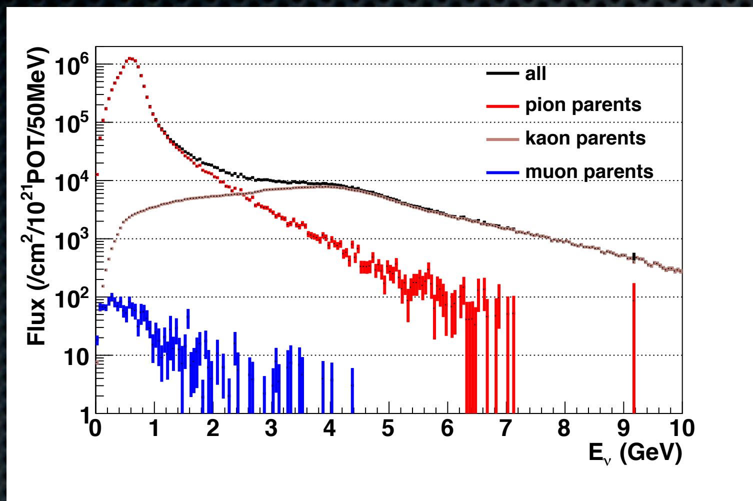
ν_e appearance oscillation fit

$$\mathcal{L}(N_{obs}, x; o, f) = \mathcal{L}_{norm}(N_{obs}; o, f) \times \mathcal{L}_{shape}(x; o, f) \times \mathcal{L}_{sys}(f)$$

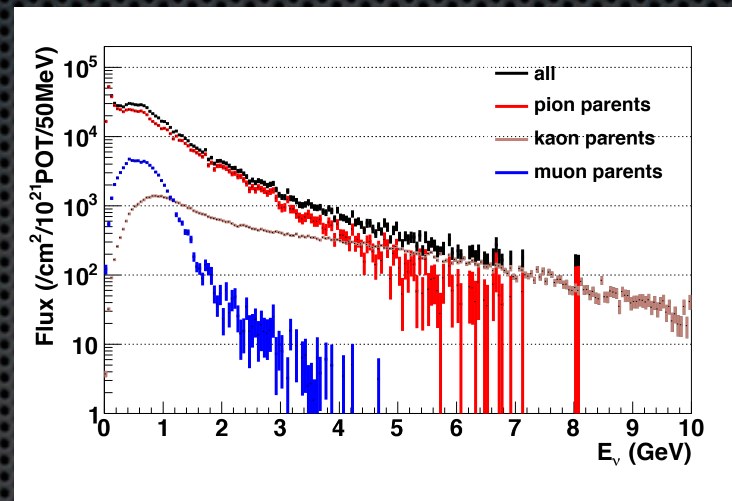
- Extended likelihood fit of the reconstructed electron momentum and angle spectrum
  - x: measurements in (p_e,θ_e)
  - o: oscillation parameters
  - f: systematic parameters
- Fit templates of ν_e signal and background.
  - Backgrounds have a wider range in kinematic space.



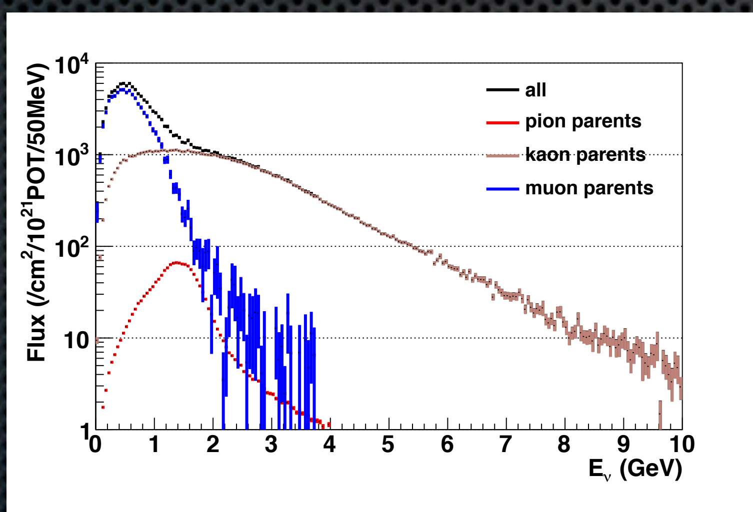
SK Flux



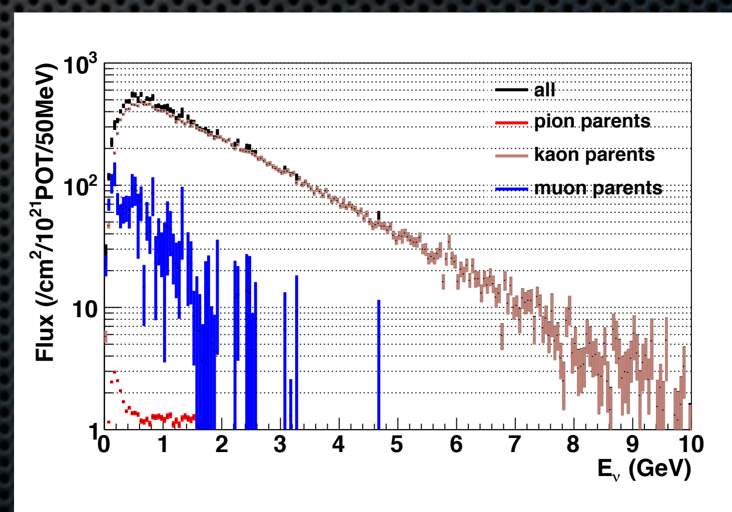
(a) ν_μ flux



(b) $\bar{\nu}_\mu$ flux

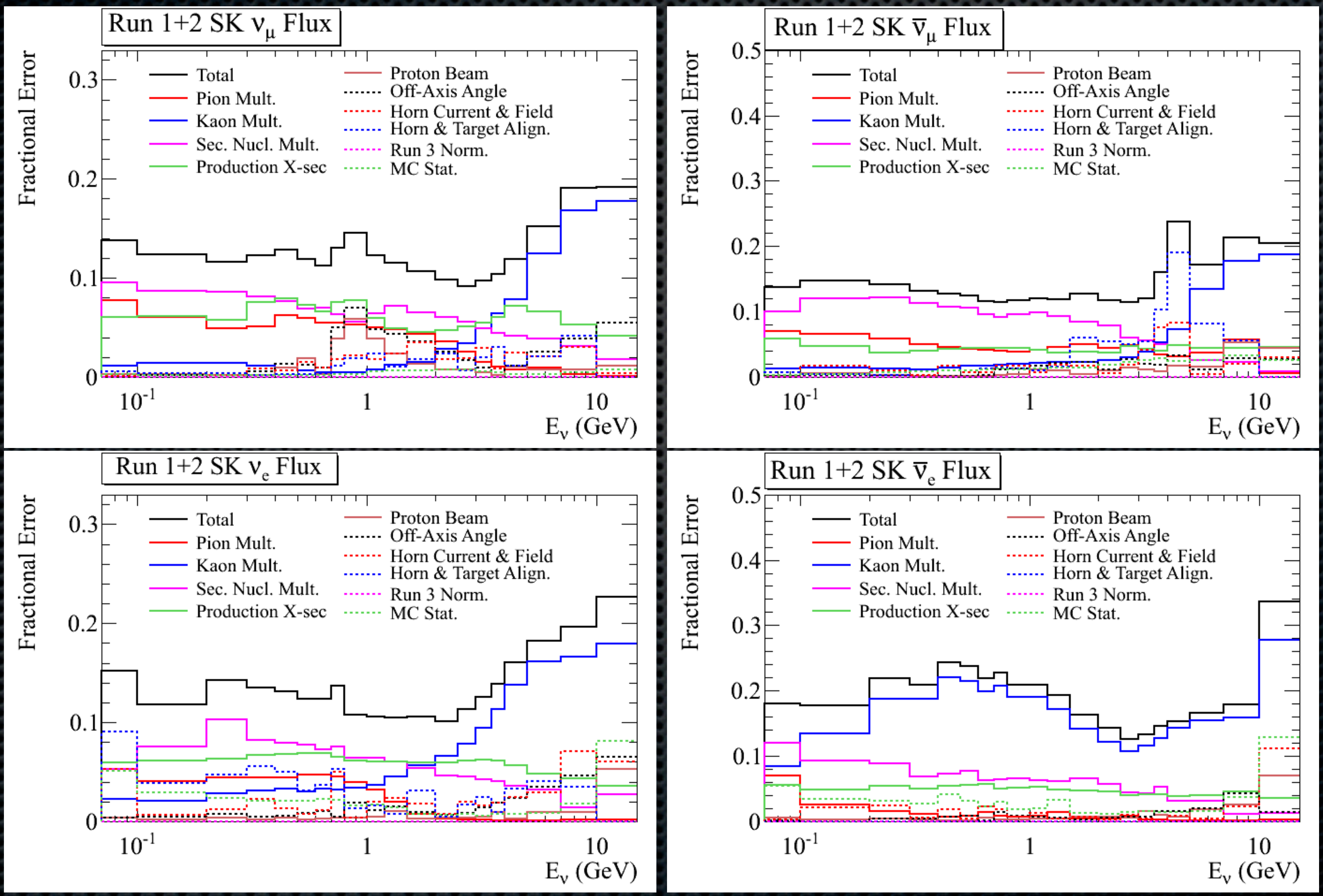


(c) ν_e flux



(d) $\bar{\nu}_e$ flux

SK Flux Uncertainties.



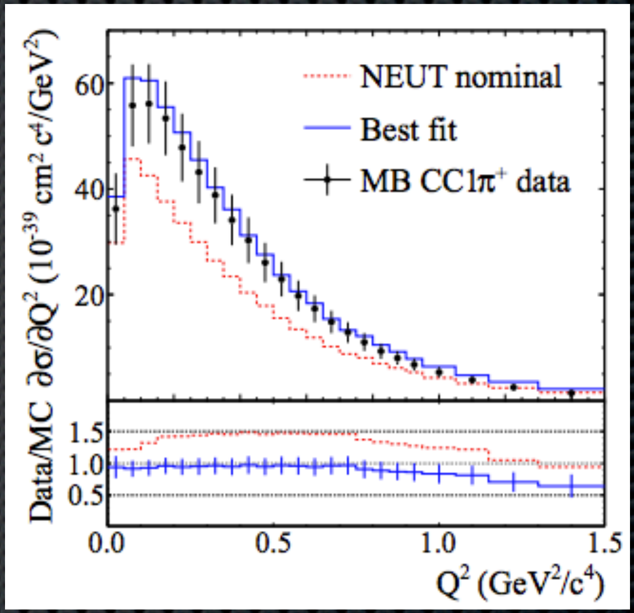
Beam Uncertainties

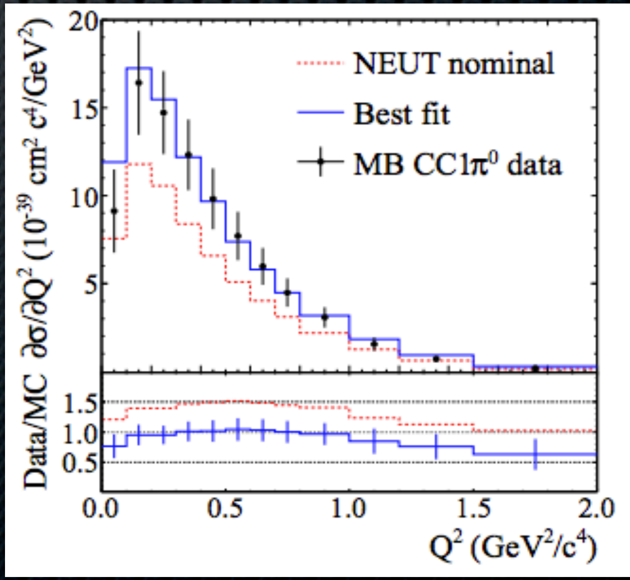
$\sin^2(2\theta_{13})=0.1$ $\Delta m^2_{32}=2.4\times10^{-3}\ eV^2$ $\sin^2(2\theta_{23})=1.0$

	% Errors on Sample Predictions		
	N_{ND}	N_{SK}	N_{SK}/N_{ND}
Pion Production	3.41	4.97	1.88
Kaon Production	3.48	1.17	2.99
Secondary Nucleon Production	5.46	6.61	1.34
Hadronic Interaction Length	5.78	6.56	1.90
Proton Beam, Alignment & Off-axis Angle	3.45	2.08	1.75
Horn Current and Magnetic Field	1.40	1.16	1.39
Total	10.04	10.94	4.78

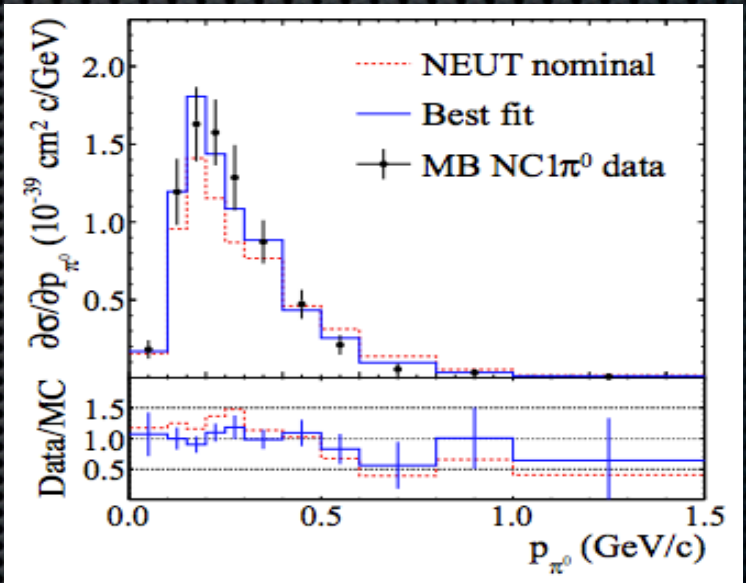
CCQE backgrounds

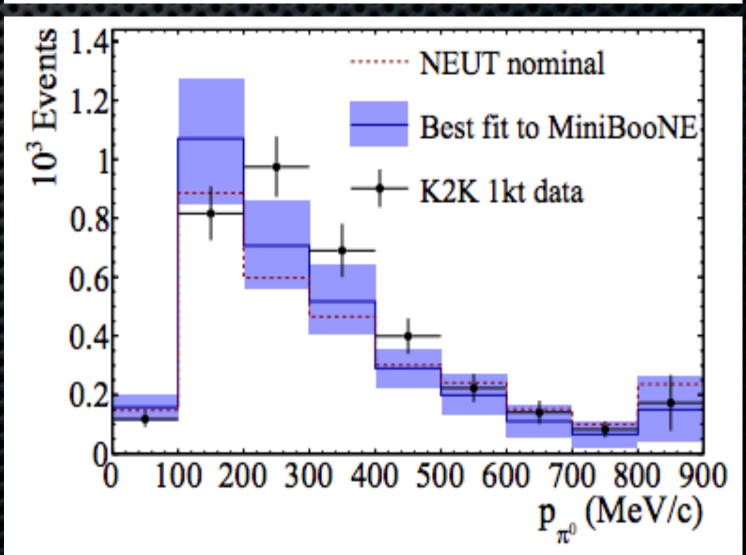
- Joint Fit is done on Mini-BooNE CC1π+ CC1π0 and NC1π0 data.
- CC1π Single Pion Production CC1π
- Main Background for **νμ** disappearance: Same as CCQE if pion is not identified
- Pion production via hadronic resonances using Rein and Seghal Model. Uses axial mass MARES and several normalization parameters.
- Parameters MARES, CC1π and NC1π0 are propagated to ND280.





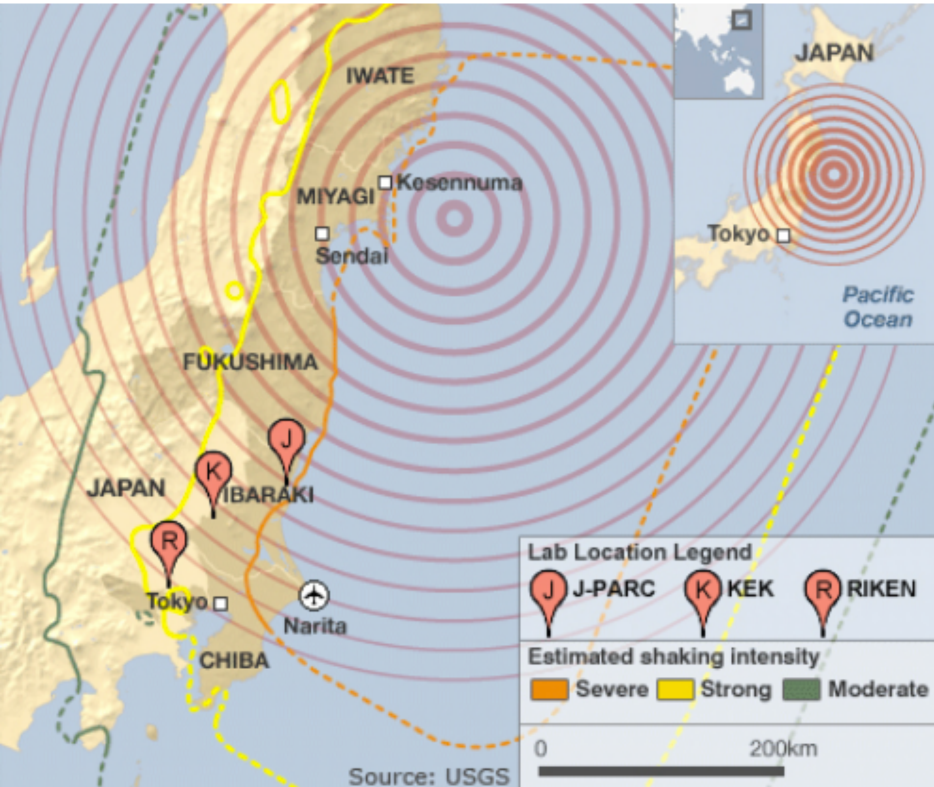
- νe appearance: NC backgrounds are flux dependant and can mimic a CC νe interaction
- Results from Mini-BooNE NC fit compared with K2K data.
- K2K same nuclear target as SK.





Systematic error contribution to the predicted number of events in oscillation analysis (%)

	$\sin^2 2\theta_{13} = 0$		$\sin^2 2\theta_{13} = 0.1$	
Error source	w/o ND280 fit	w/ ND280 fit	w/o ND280 fit	w/ ND280 fit
Beam only	10.8	7.9	11.8	8.5
M_A^{QE}	10.6	4.5	18.7	7.9
M_A^{RES}	4.7	4.3	2.3	2.0
CCQE norm. ($E_\nu < 1.5$ GeV)	4.6	3.7	7.8	6.2
CC1π norm. ($E_\nu < 2.5$ GeV)	5.3	3.7	5.5	3.9
NC1π^0 norm.	8.1	7.7	2.4	2.3
CC other shape	0.2	0.2	0.1	0.1
Spectral Function	3.1	3.1	5.4	5.4
p_F	0.3	0.3	0.1	0.1
CC coh. norm.	0.2	0.2	0.2	0.2
NC coh. norm.	2.1	2.1	0.6	0.6
NC other norm.	2.6	2.6	0.8	0.8
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$	1.8	1.8	2.6	2.6
W shape	2.0	2.0	0.9	0.9
pion-less Δ decay	0.5	0.5	3.5	3.5
CC1π, NC1π^0 energy shape	2.5	2.5	2.2	2.2
SK detector eff.	7.1	7.1	3.1	3.1
FSI	3.1	3.1	2.4	2.4
SK momentum scale	0.0	0.0	0.0	0.0
Total	21.5	13.4	25.9	10.3



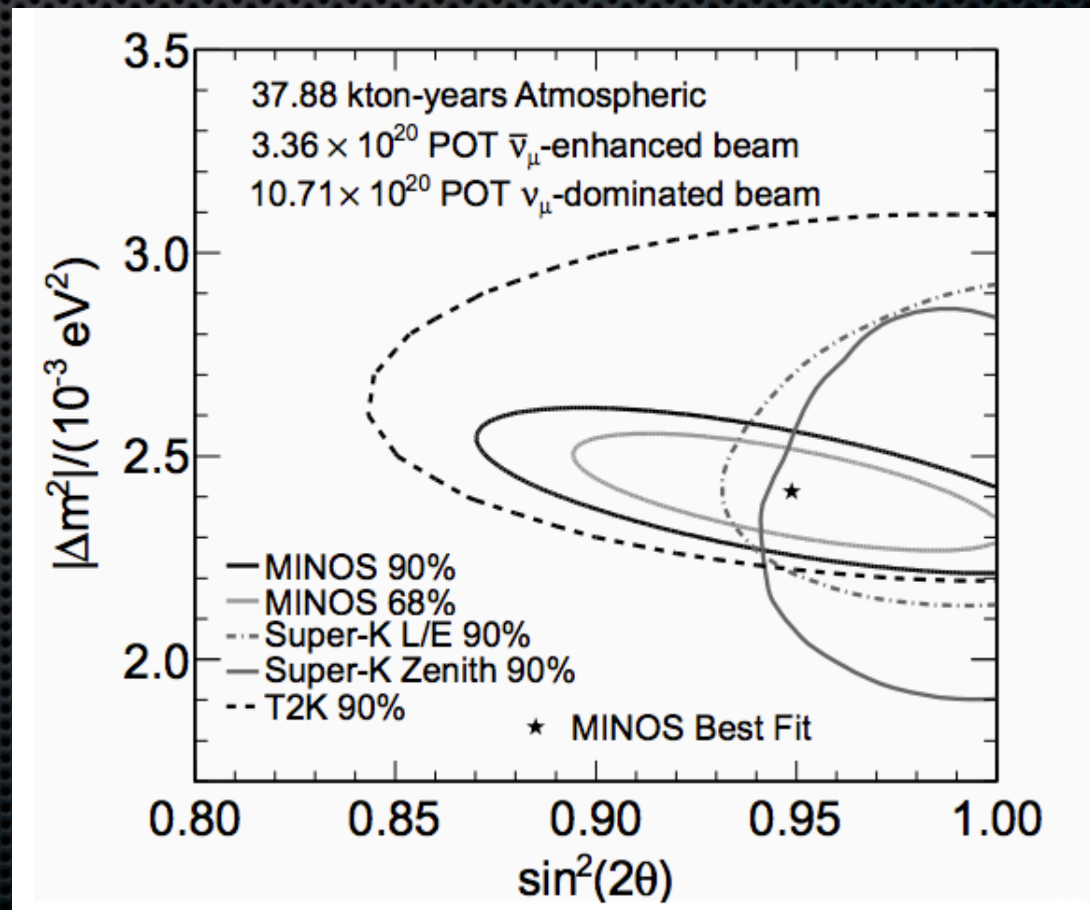
- T2K/J-PARC has recovered from the "Great East Japan Earthquake" March 2011.
- Dec 9th LINAC operation restarted.
- Dec 24th. Neutrino events observed in T2K-ND80.

Markov Chain Monte Carlo

- Sample from a multidimensional probability distribution is a with a directed random walk.
  - Randomly move from one point to another in your multidimensional space.
  - If the probability density is higher the second point, step to that point, if it is lower accept with a probablitly P = P(current)/P(proposed)

MINOS

- Latest results measure non maximal θ_{23}
- arXiv:1304.6335

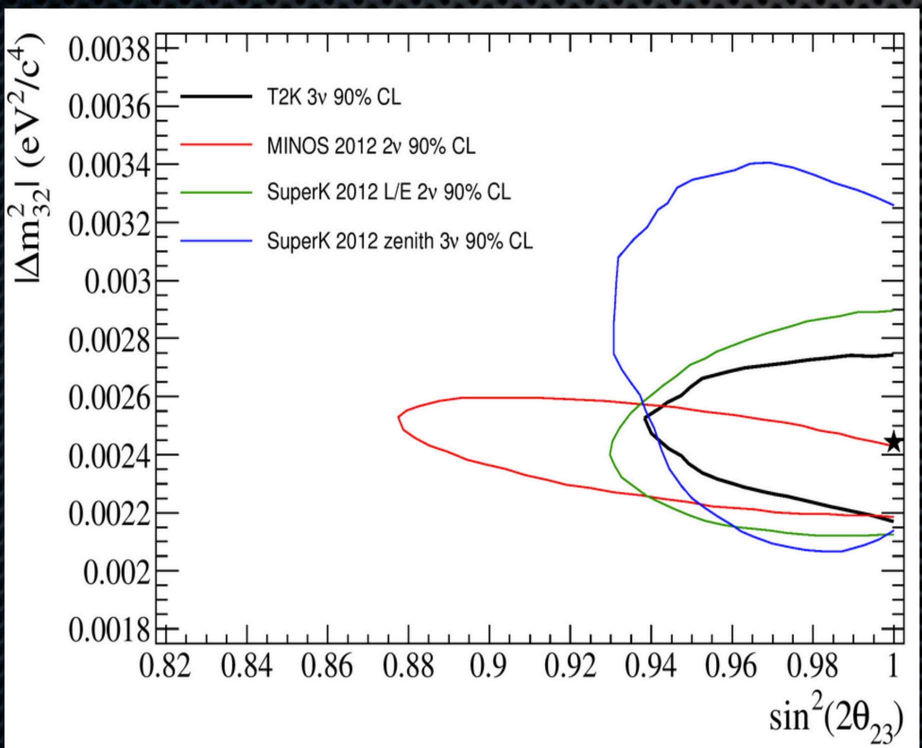


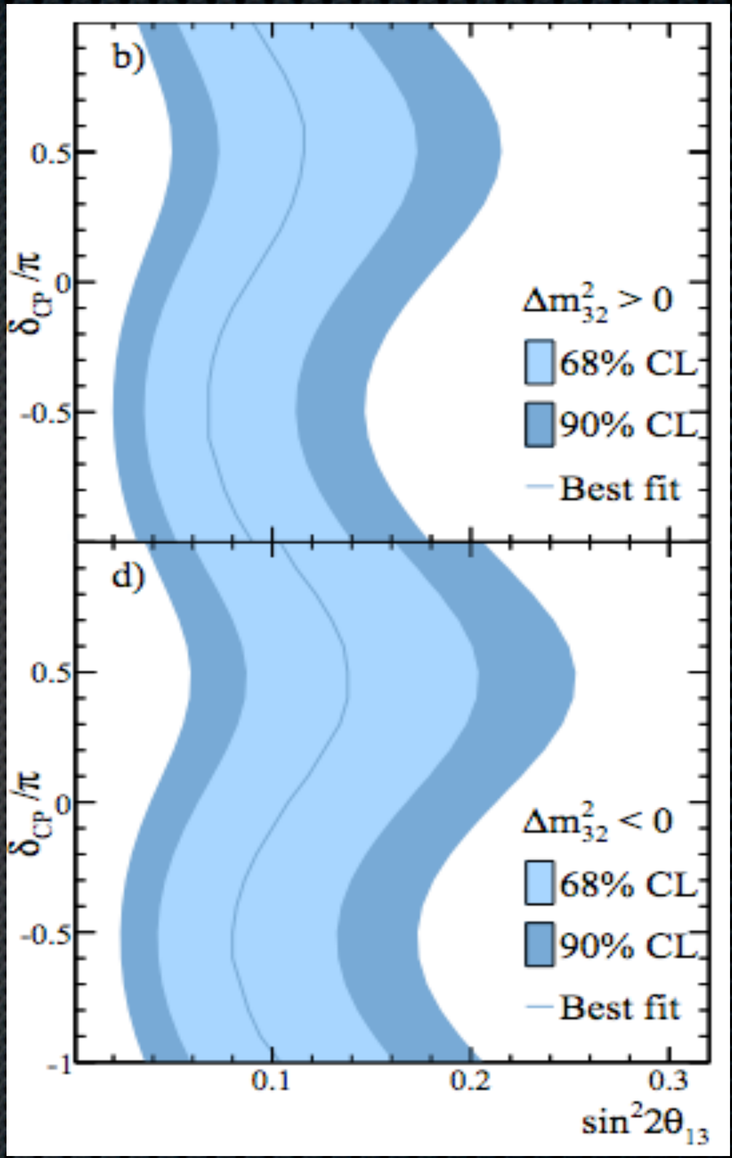
Measurements

90% CL

$$2.14 \times 10^{-3}\mathrm{eV}^2 < |\Delta m^2_{32}| < 2.76 \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2 2\theta_{23} > 0.957$$





$$\sin^2 2\theta_{13} = 0.088^{+0.049}_{-0.039}(\text{normal hierarchy})$$

$$\sin^2 2\theta_{13} = 0.108^{+0.059}_{-0.046}(\text{inverted hierarchy})$$