Simultaneous Analysis of Near and Far Detector Samples of the T2K Experiment to Measure Muon Neutrino Disappearance

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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

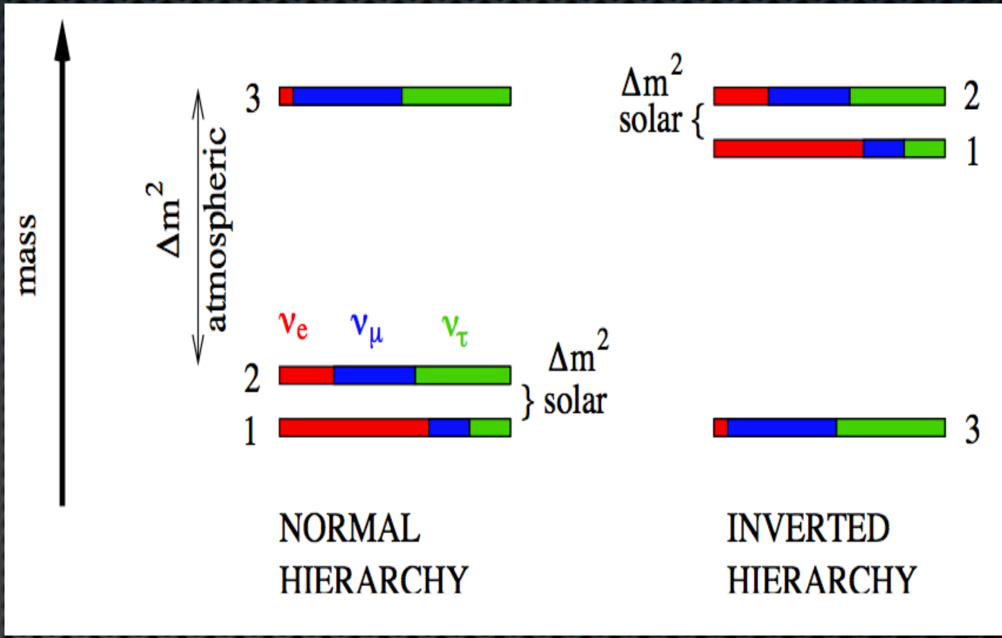
- PMNS matrix often parameterized as

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

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

- 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.

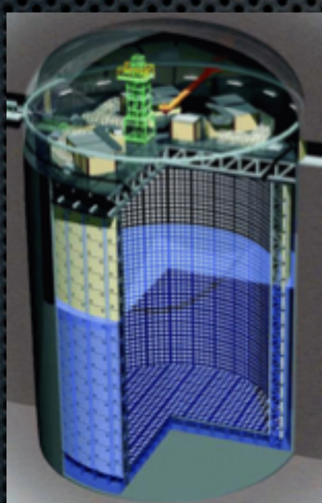
Unknowns

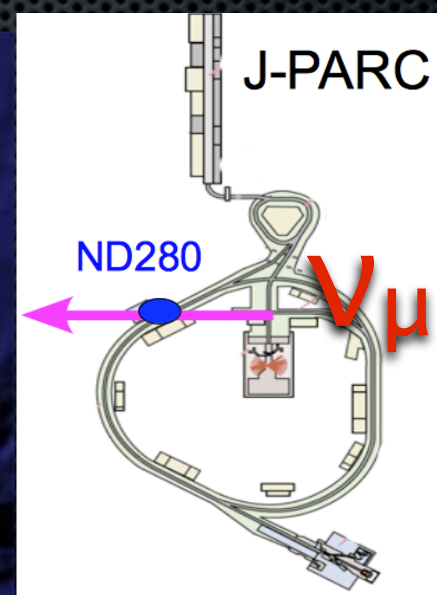


- Mass hierarchy still unknown.
  - $\Delta m_{32}^2 = 2.4 \times 10^{-3}$ eV^2
  - $\Delta m_{21}^2 = 7.6 \times 10^{-5}$ eV^2
- Is θ_{23} maximal, $\theta_{23} = \pi/4$?
- Absolute scale of neutrino masses.
  - Dirac or Majorana neutrinos?
- CP violation in the lepton sector?

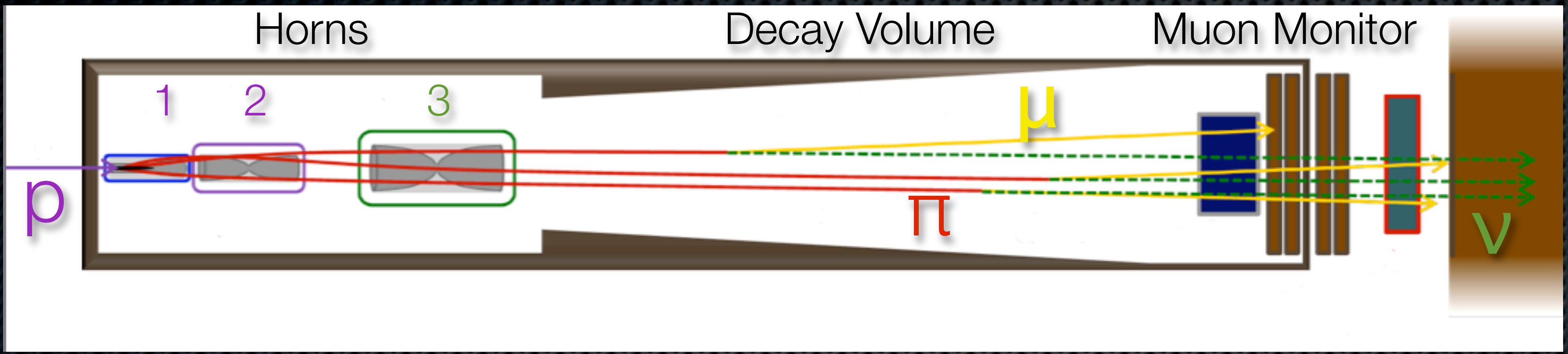
T2K(Tokai to Kamioka)

- Long baseline neutrino oscillation experiment
  - Measurement of neutrino oscillation between near detector (J-PARC) and Super-Kamiokande.
- Main Physics Goals
  - High sensitivity search of θ_{13}. ν_e ***appearance*** $\nu_\mu \rightarrow \nu_e$
  - Precise measurement of Δm^2_{32} θ_{23} . ν_μ ***disappearance*** $\nu_\mu \rightarrow \nu_x$



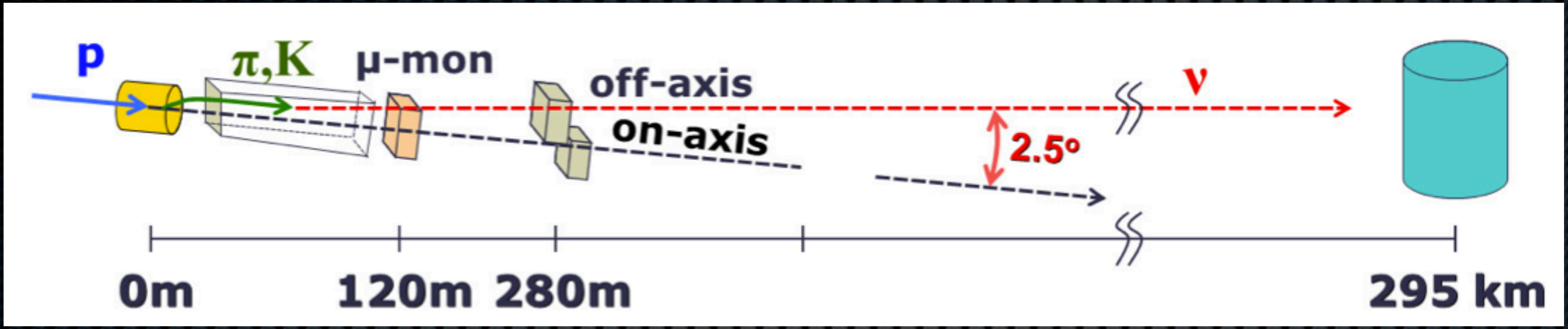


Neutrino Beam

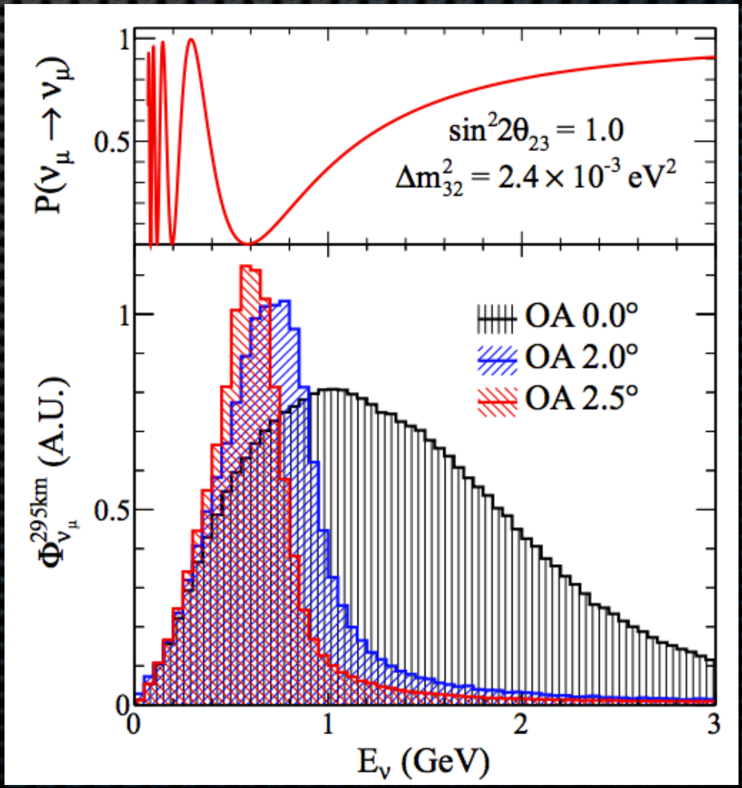


- 30 GeV protons hit graphite target
- Pions produced in proton interactions on a target focused by 3 magnetic horns
  - focus π^+, defocus π^- $$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$
- μ monitor at far end of beam dump
- Creates ν_μ pure beam
  - $\bar{\nu}_\mu$ and ν_e are ~ few percent

Off-Axis Beam

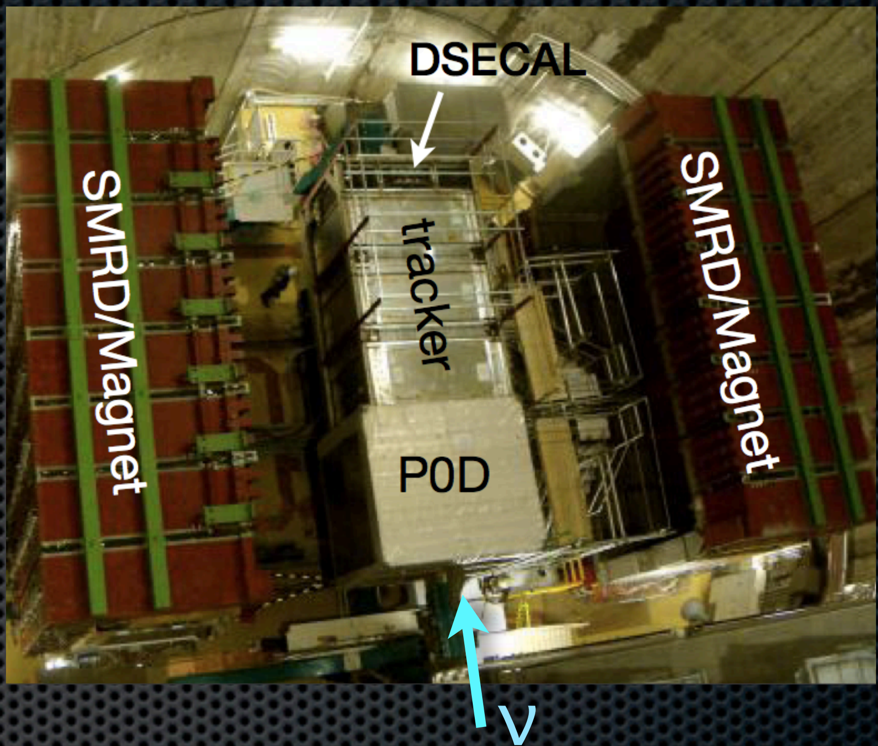


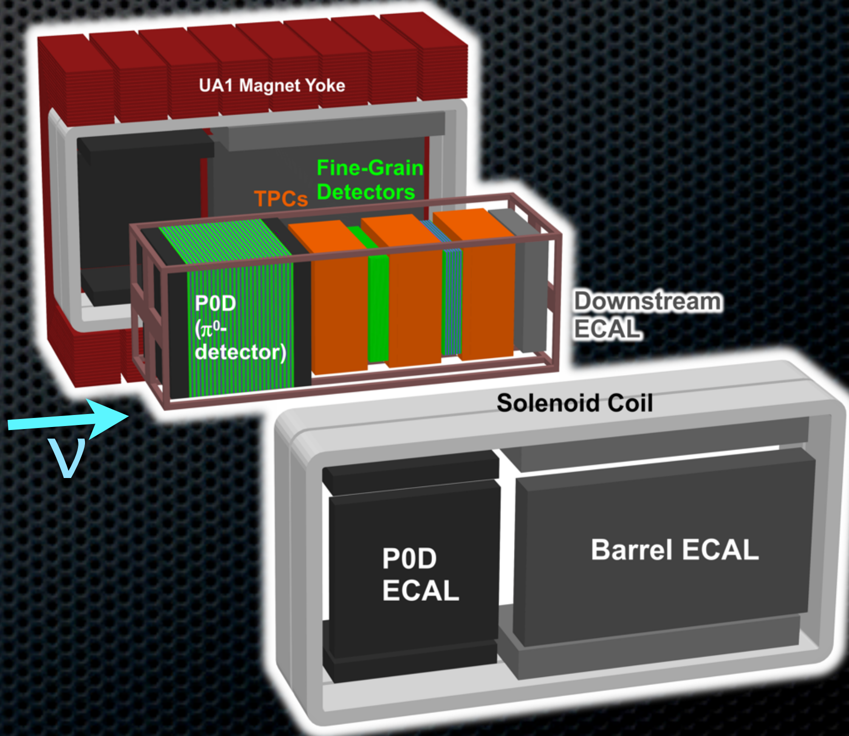
- 2.5^0 off axis. Low energy narrow band beam.
- Peak E_ν tuned for oscillation maximum.
- Reduce background from high energy tail.



Off Axis Near Detector

- ND280 (ND=near detector) is located 280 m from production target.
- Multi-Detector complex installed within UA1 magnet. 0.2 T dipole field
- Current analyses uses tracker, neutrino interactions in Fine Grained Detector FGD that are measured by Time projection chamber TPCs.
- 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.

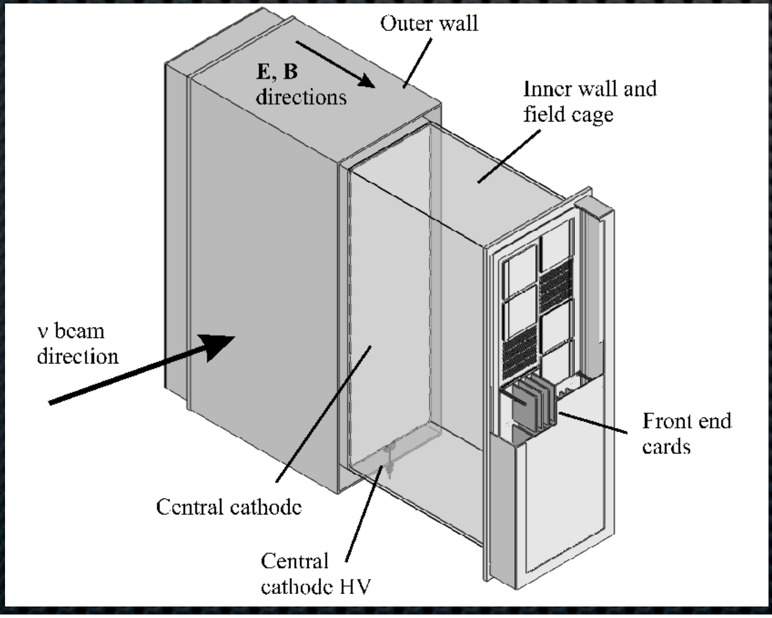


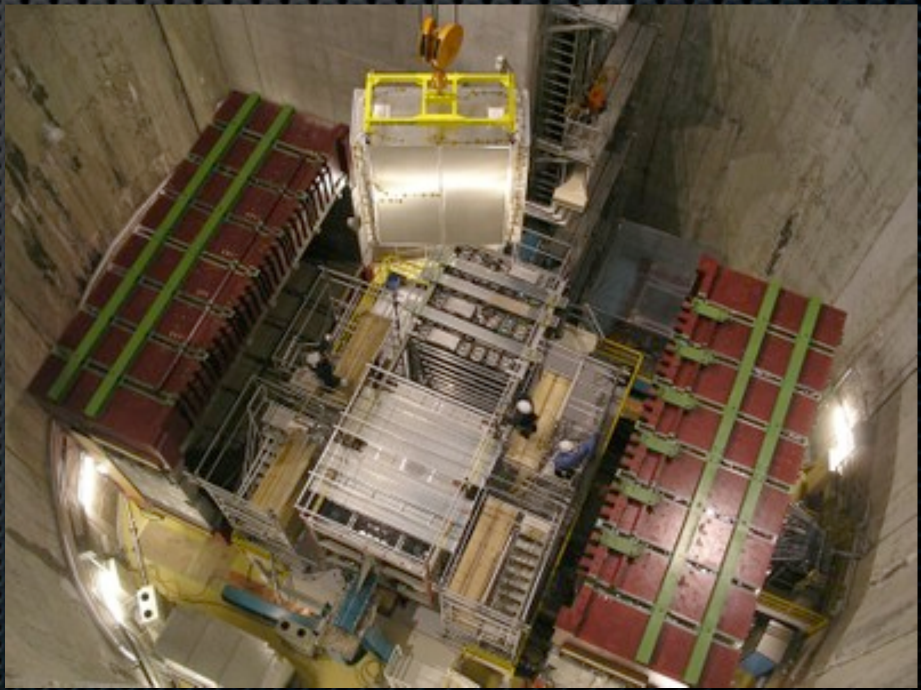


TPCs

- Time Projection Chambers
  - Gaseous ionization detectors
  - Measures momentum of particle from curvature.
  - Energy deposited dE/dx identifies particle type. Good separation between electrons and muons.

Constructing a TPC

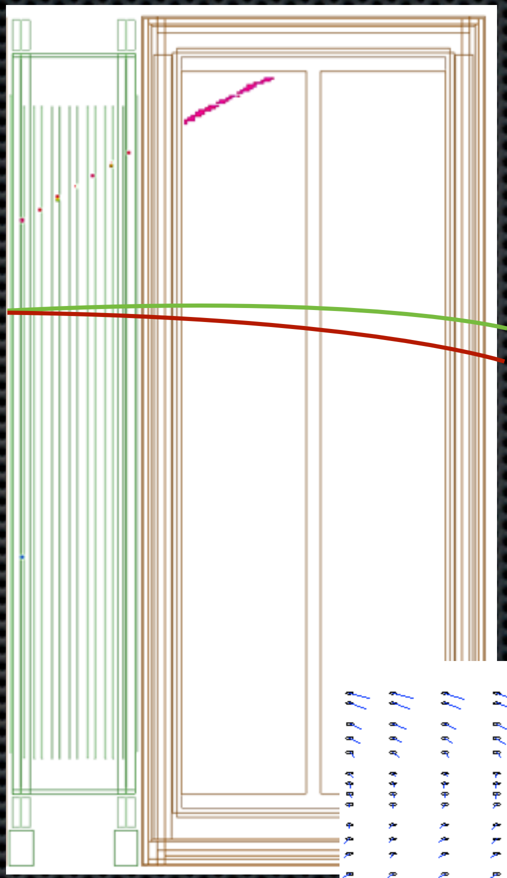




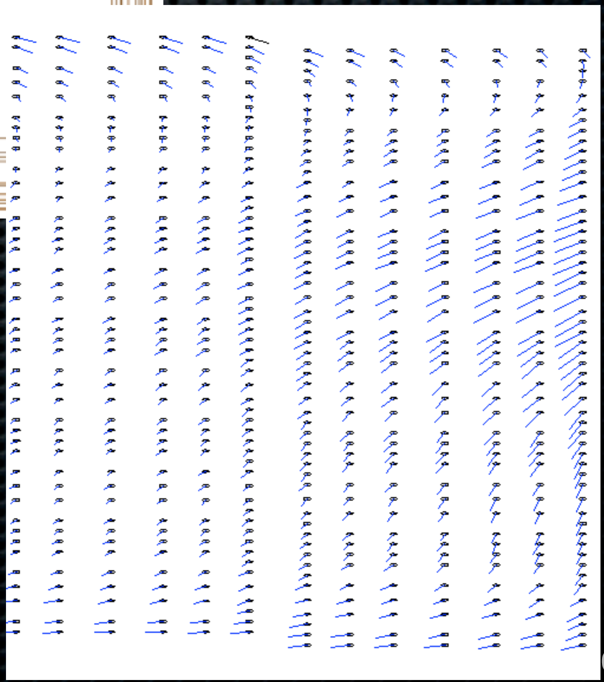
Installing TPC in ND280

Improvements in Spectrum Measurement

- For electrons drifting in TPC, inhomogeneities in magnetic field can distort track shape and distort momentum reconstruction, spectrum.
- Green track before drift, points along primary ionization.
- Red track after drift to readout plane,track shape distorted.
- Photocalibration system in TPC uses laser and targets on central cathode to measure magnetic field distortions.
- Measured distortions corrected for in TPC reconstruction. Bias reduced from ~5%(@ 1GeV) to < 2%.

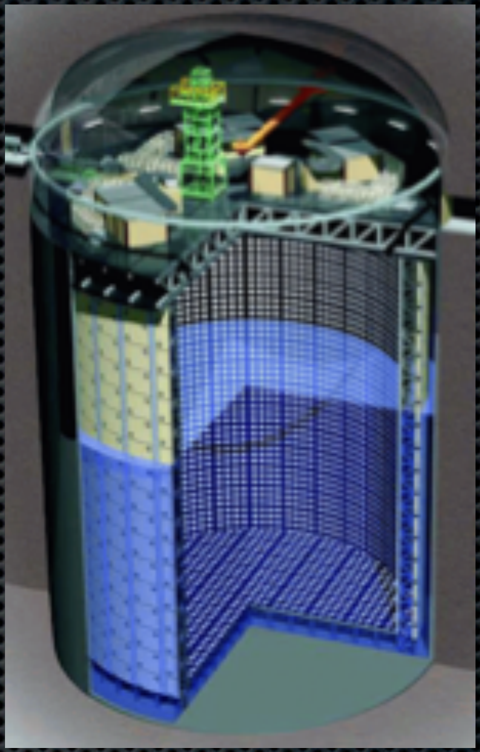


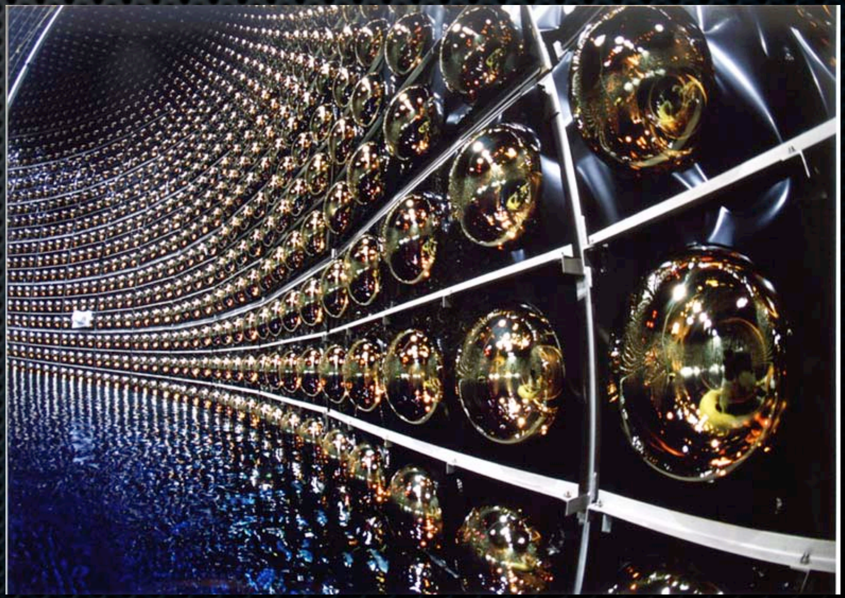
Downstream TPC magnetic field distortions



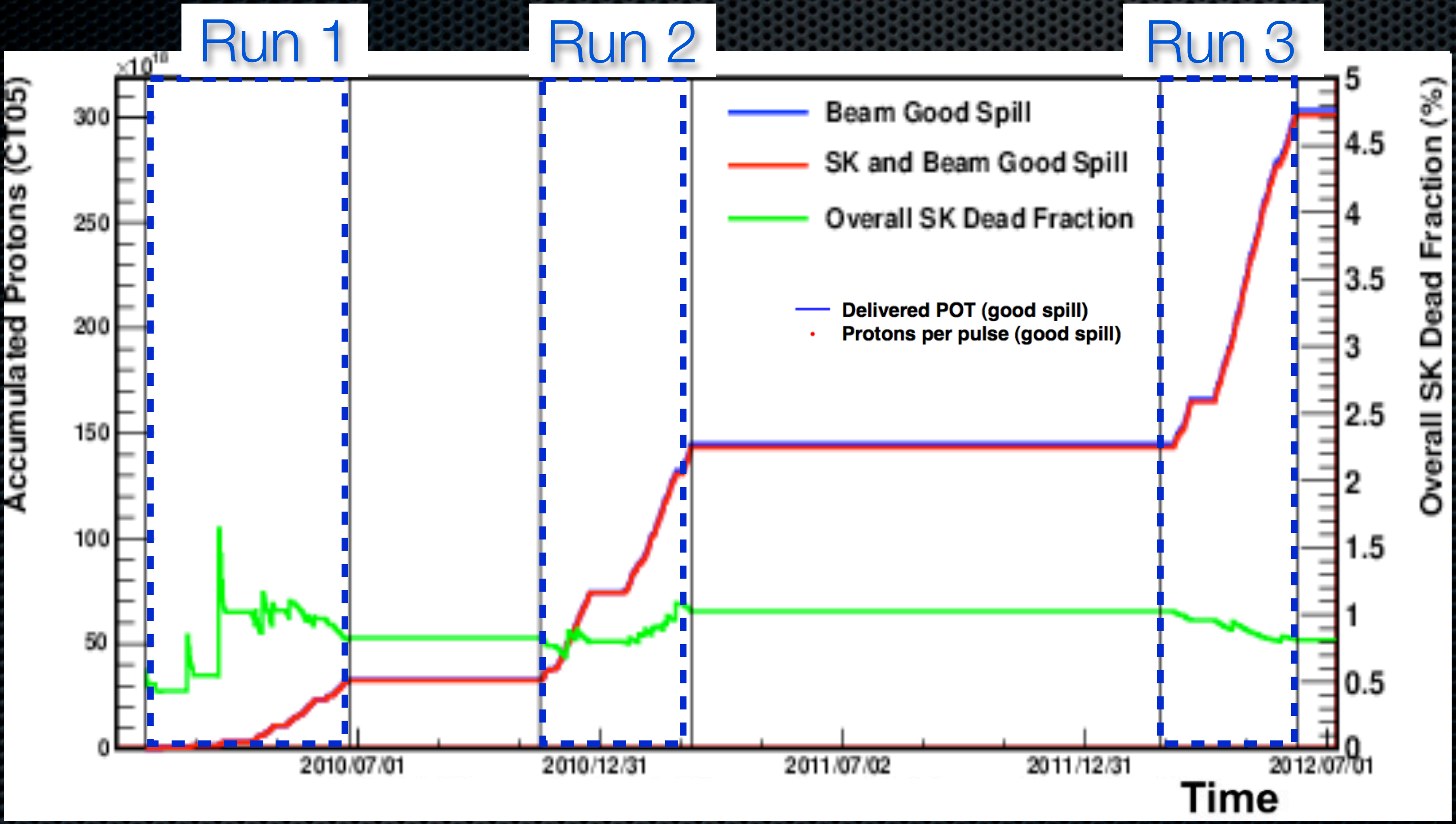
Super-Kamiokande

- 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.



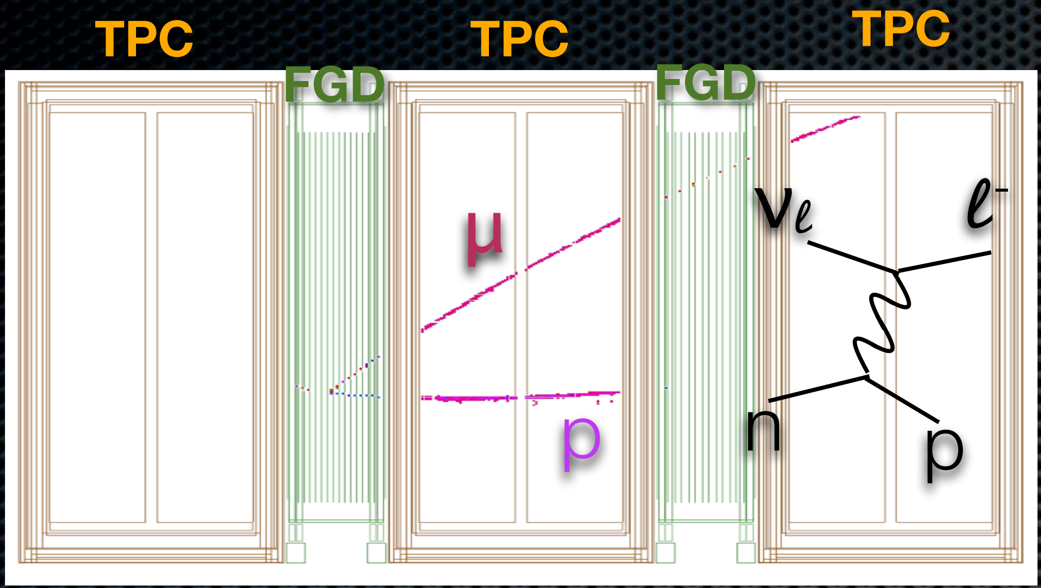


Oscillation Analysis:Data

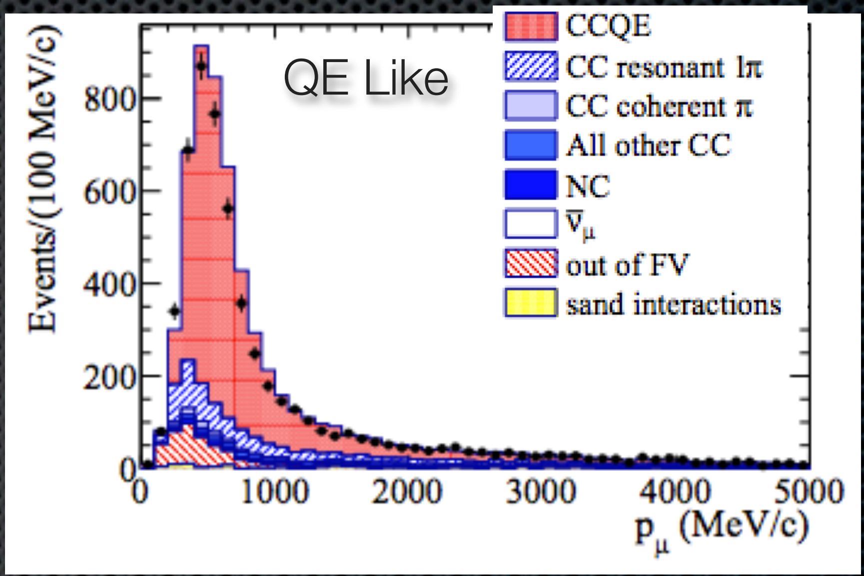


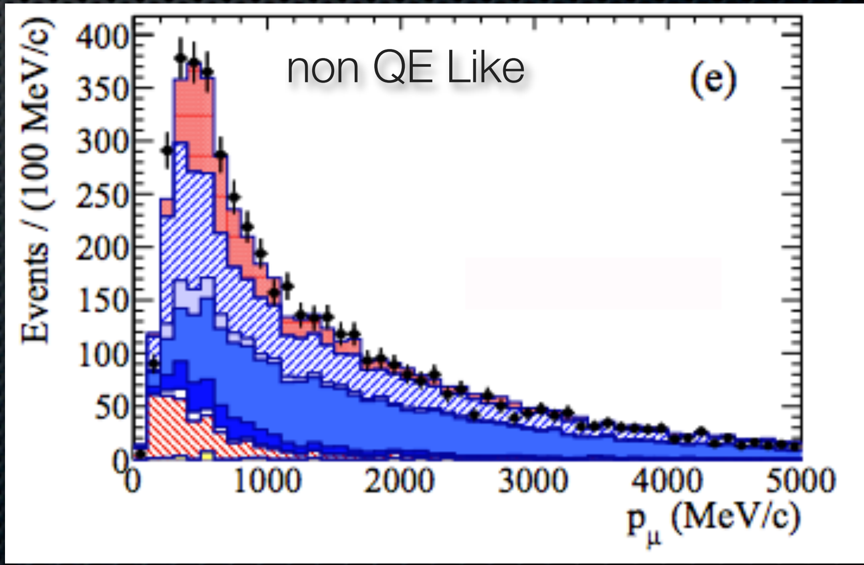
- Data set runs up to June 9th 2012 (End of Run 3)
- Protons on Target (POT) used in this analysis: 3.01 x 10^{20}

ND280 Measurement



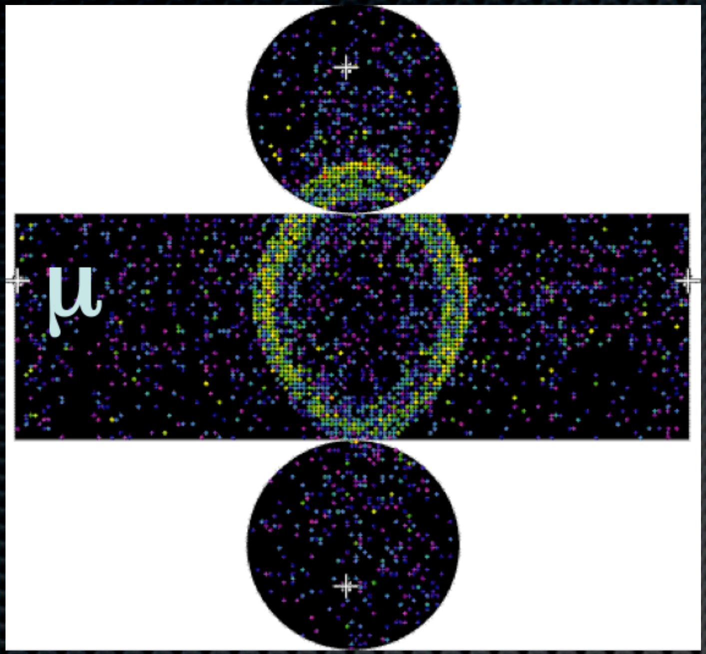
CCQE Candidate

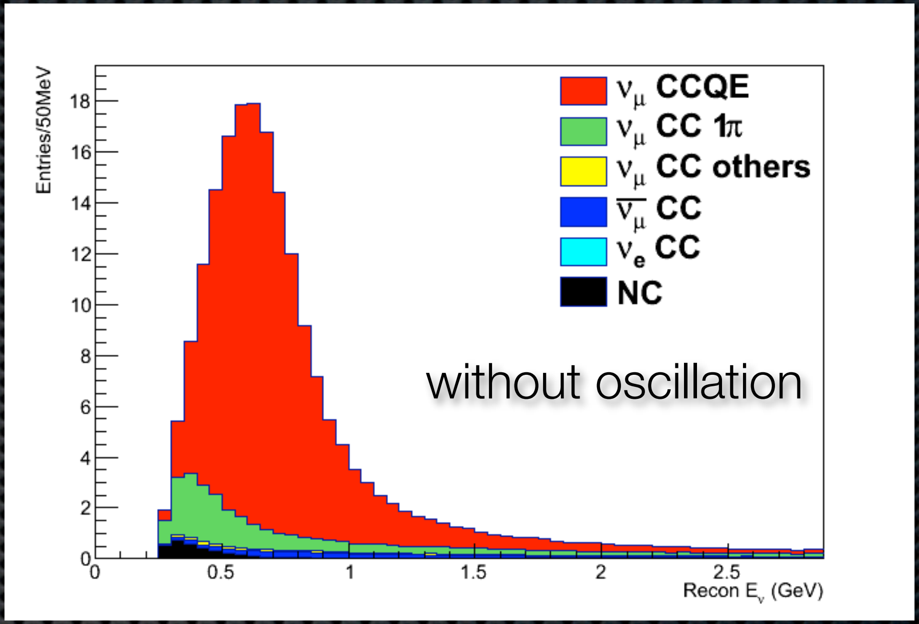




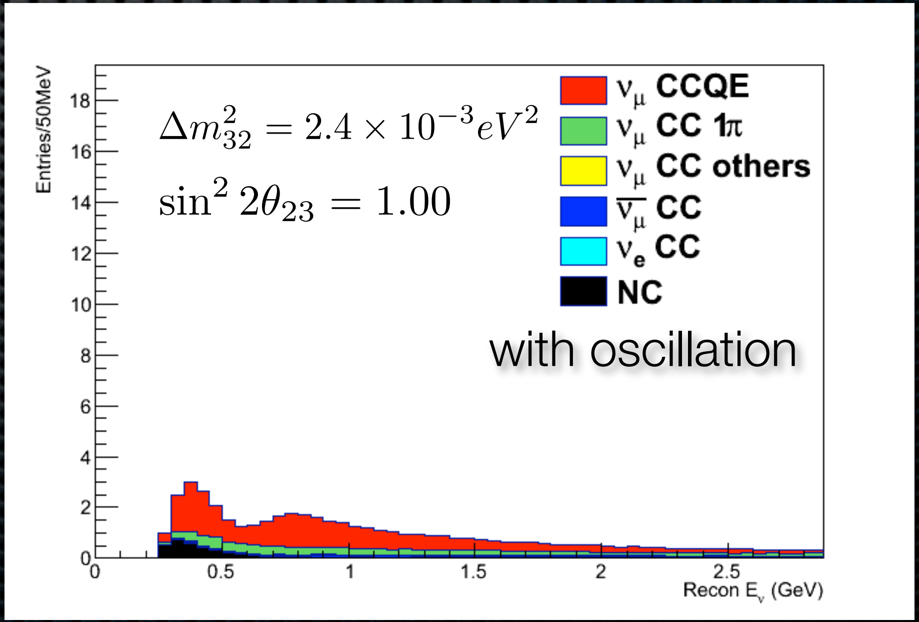
- Select CC events.
  - Lepton originating in FGD.
  - Muon-like dE/dx, negative curvature in TPC.
- Divide into QE-like, non-QE-like based on number of tracks.
- Use CCQE, CCnonQE p-θ distributions in oscillation fit

Expected number of ν_μ Events





- Select muon like rings at SK
- Reconstructed E_ν distribution is used in oscillation fit.
- Expected number of events
  - Without oscillation:210
  - With oscillation:59
- With dip at oscillation maximum



Simultaneous Fit

- Other experiments/T2K do separate near detector fit. Use output from the near detector fit as input to oscillation analyses.
  - Step wise approach makes approximations.
- Simultaneous fitting of near and far detectors avoids such approximations.

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$$L(\theta) = L(\vec{f}|\vec{M}^{ND280})L(\vec{o}, \vec{f}|\vec{M}^{SK})$$

- Likelihood dependent on:
  - M^{ND280}:ND280 CCQE,CCnonQE p-θ sample
  - M^{SK} :SK recon E_ν sample
  - f :Systematic parameters
  - o: Oscillation parameters

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  - M^{SK} :SK recon E_ν sample
  - f:Systematic parameters →
  - o: Oscillation parameters
- Systematic parameters includes:
  - Cross section
  - Flux
  - SK/ND280 detector
  - Other oscillation parameters

Simultaneous Fit

99 Systematic parameters

Very complex fit.

$$L(\theta) = L(\vec{f}|\vec{M}^{ND280})L(\vec{o},\vec{f}|\vec{M}^{SK})$$

- Likelihood dependent on:
  - M^{ND280}:ND280 CCQE,CCnonQE p-θ sample
  - M^{SK} :SK recon E_ν sample
  - f:Systematic parameters →
  - o: Oscillation parameters

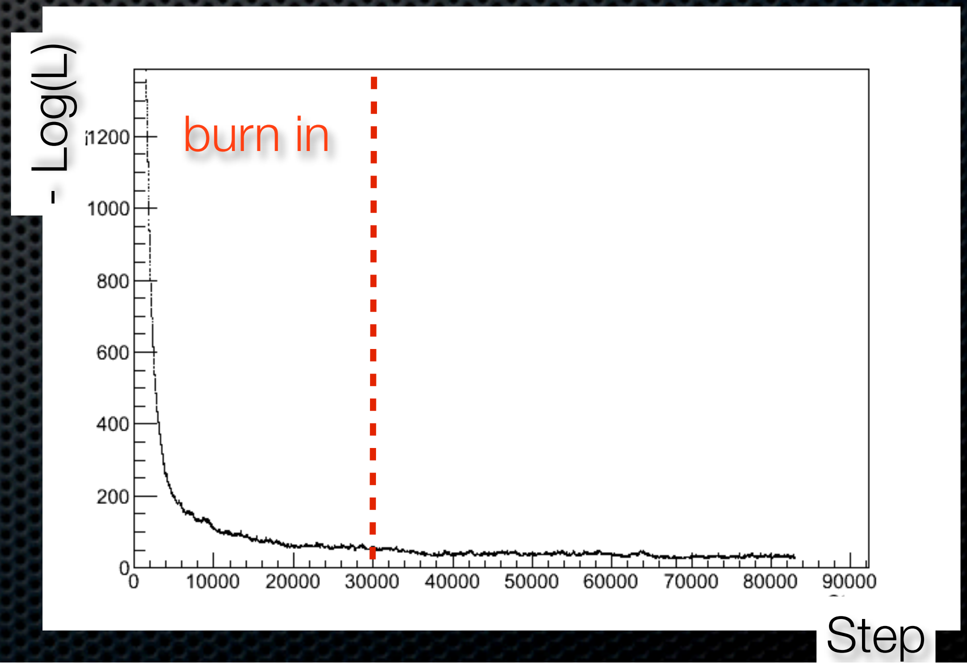
- Systematic parameters includes:
  - Cross section
  - Flux
  - SK/ND280 detector
  - Other oscillation parameters

Markov Chain Monte Carlo

- Most analyses use MINUT to minimize negative likelihood.
  - MINUT has issues converging with a *large number* of parameters.
- Can use Markov Chain Monte Carlo Metropolis Hastings algorithm to sample a likelihood
- Perform a weighted random walk to get the shape, maximum of posterior probability distribution.
  - Posterior probability equivalent to likelihood for flat prior.

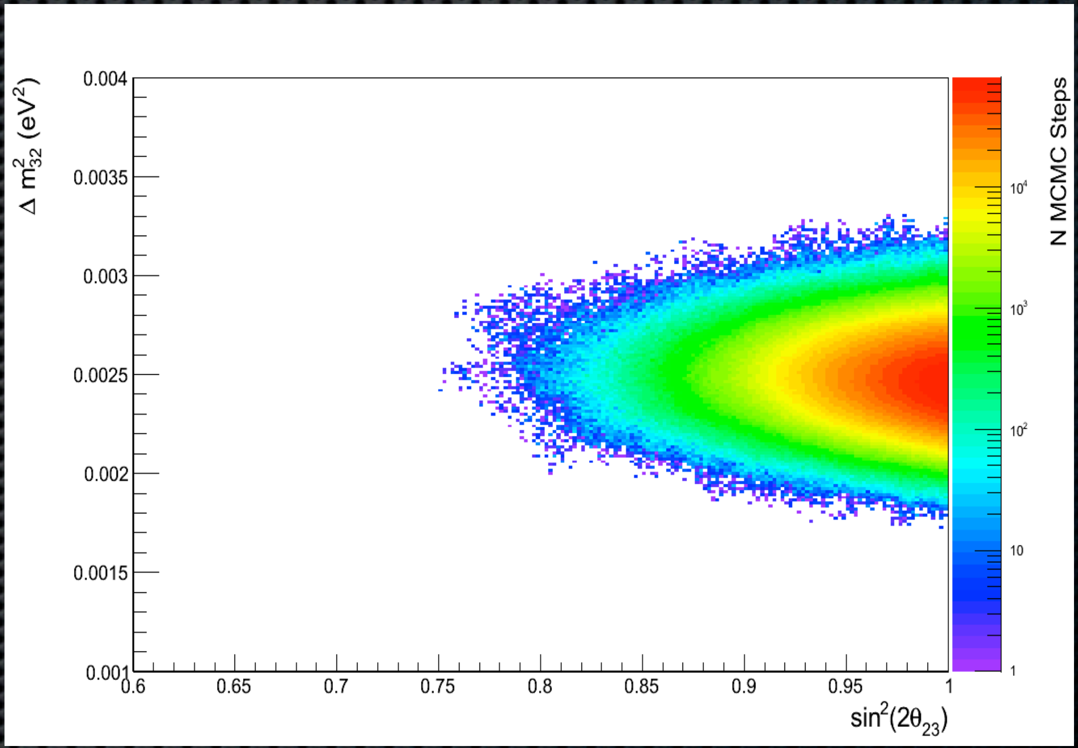
Markov Chain Monte Carlo

- Start Markov chain with arbitrary set of parameters θ_t where the posterior is $L(\theta_t)$.
- At random step to a new state θ_{t+1}
- If $L(\theta_{t+1}) > L(\theta_t)$ accept step.
- Or accept step with a probability $P_{accept} = \dfrac{L(\theta_{t+1})}{L(\theta_t)}$
- Random walk directed to posterior max.
- When starting from arbitrary position throw out first n steps, known as burn in.



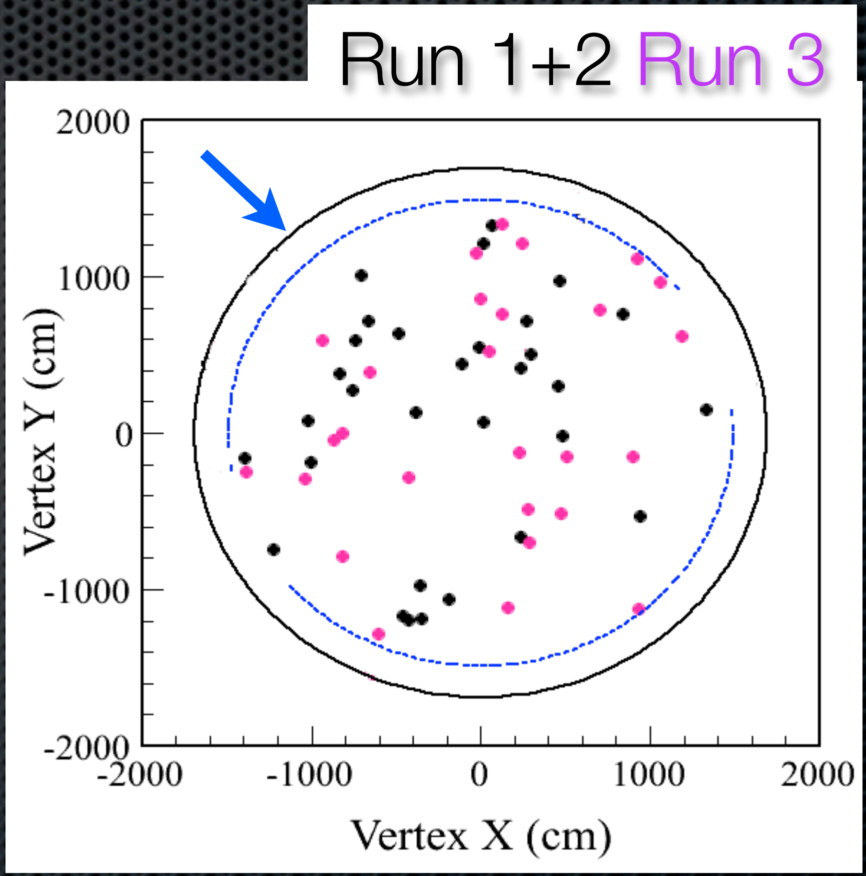
Parameter Estimation

- Monte Carlo Markov Chain explores multidimensional parameter space.
- Project points in parameter space onto axes of oscillation parameters.
- Projection follows posterior distribution marginalized over all other parameters.



ν_μ candidates

- 58 candidate events observed.
- Oscillation probability calculated using 3 neutrino flavours
- Use values from particle data group for oscillation parameters not fit for.



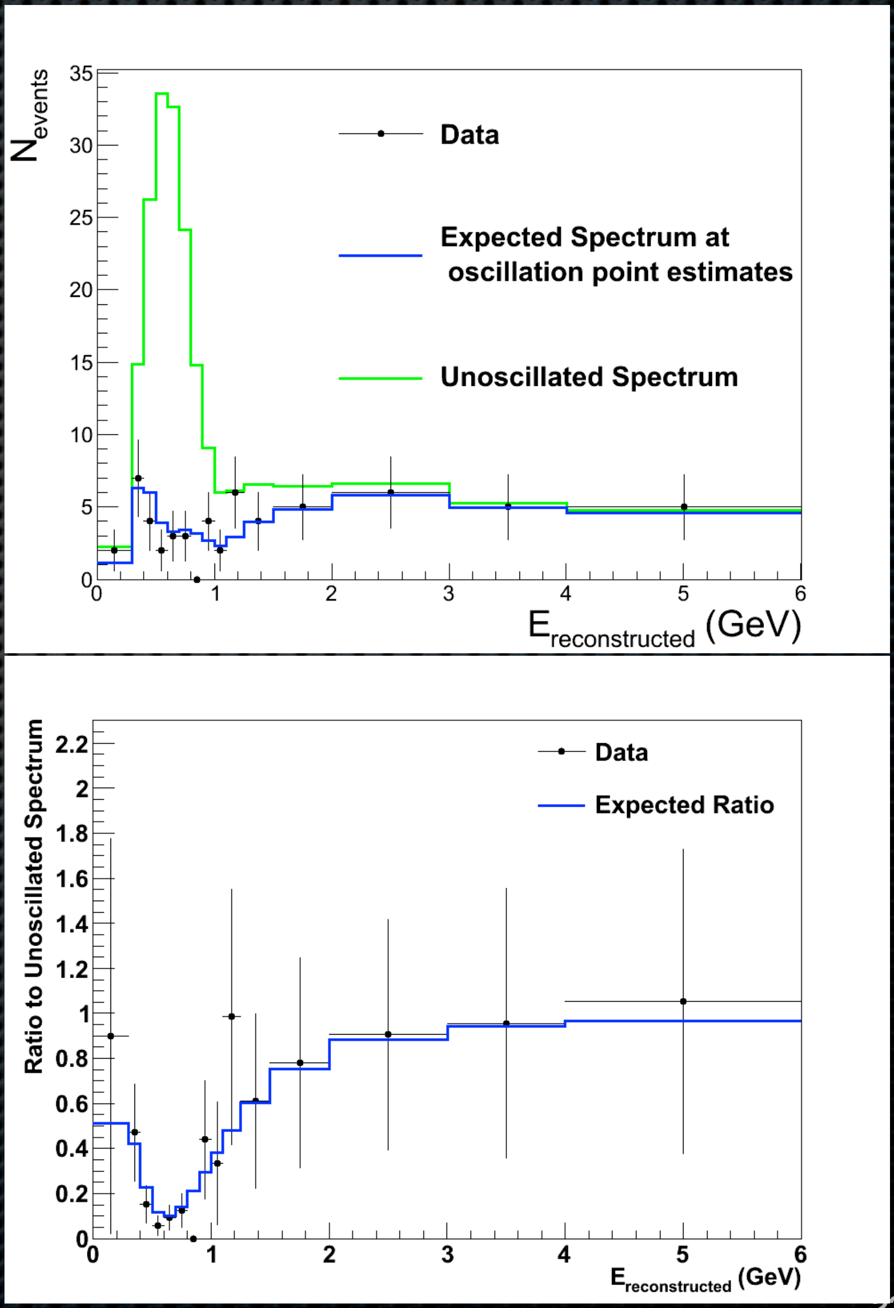
$\sin^2 2\theta_{13}$	0.098
$\sin^2 2\theta_{12}$	0.857
$\Delta m^2_{21}(eV^2)$	7.5×10^{-5}

ν_μ disappearance oscillation fit

- Maximum of posterior

$$\Delta m^2_{32} = 2.45 \times 10^{-3} \mathrm{eV}^2$$
$$\sin^2 2\theta_{23} = 0.999$$

- Oscillation minimum clearly seen in when comparing oscillated to unoscillated reconstructed E spectrum.



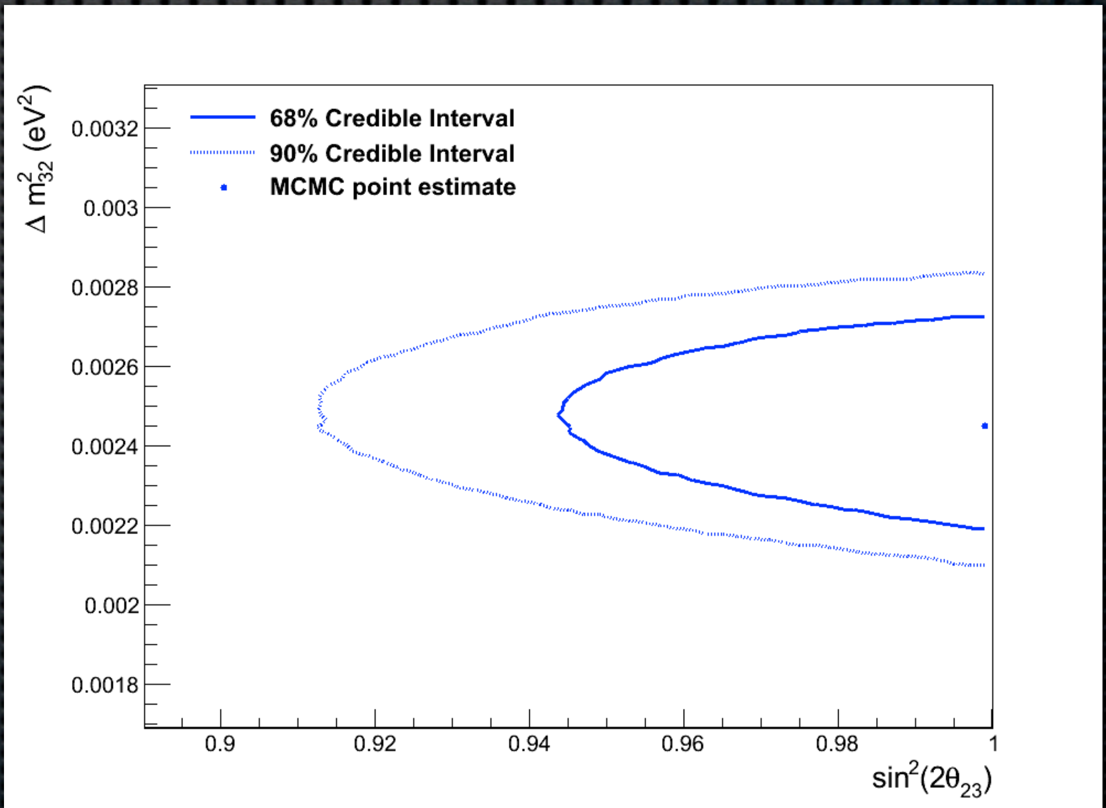
Oscillation parameter limits

- Measures maximal mixing.
- Statistical error dominant
- MCMC point estimate and shape/size of contours comparable to other T2K analyses.
- Precision of $\sin^2 2\theta_{23}$ slightly larger than world best measurement.
- Values different from those quoted in thesis.
    - Analysis done considering only the first octant $\theta_{23} < \pi/4$. Oversight by myself and collaboration.

90% credible intervals

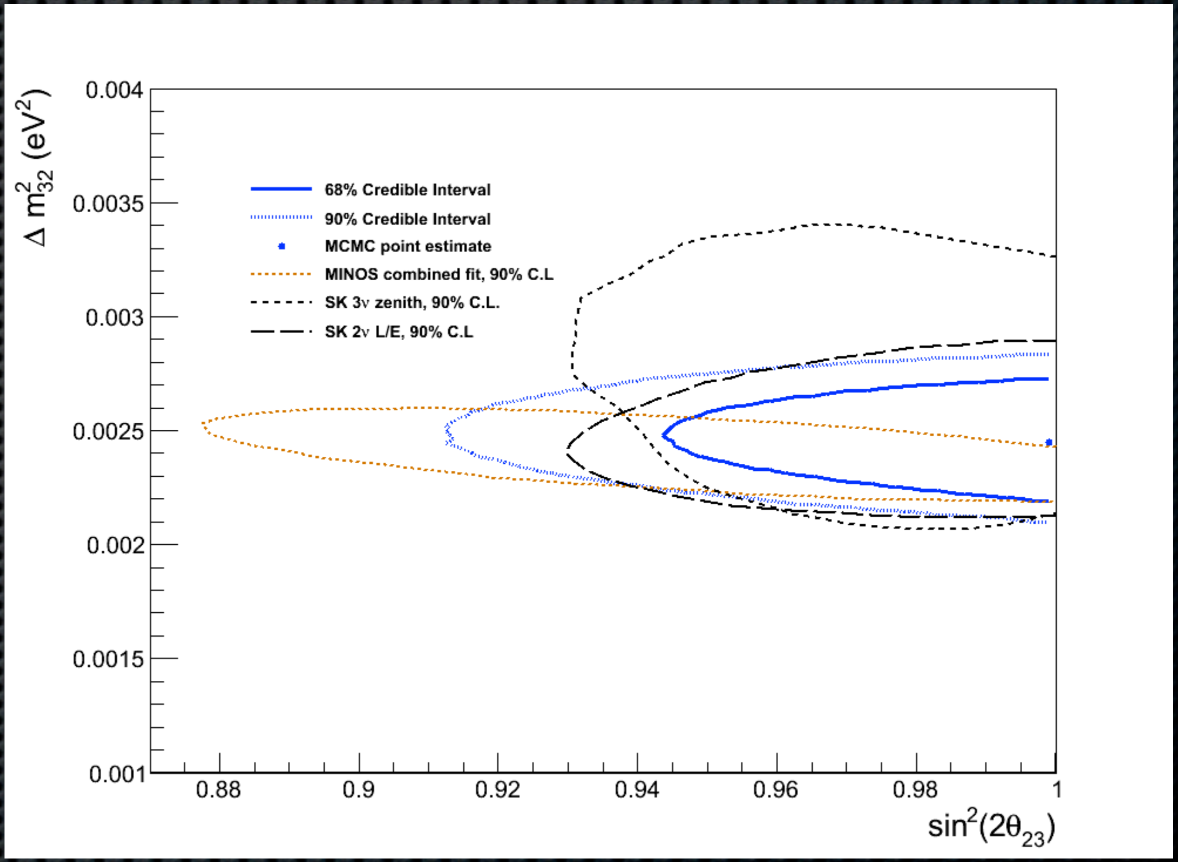
$$2.22 \times 10^{-3} < \Delta m^2_{32} [eV]^2 < 2.74 \times 10^{-3}$$

$$\sin^2(2\theta_{23}) > 0.934$$



Oscillation parameter limits

- Contours for other experiments.
- With credible intervals from MCMC analysis.
- Not directly comparable. All measurements are consistent.

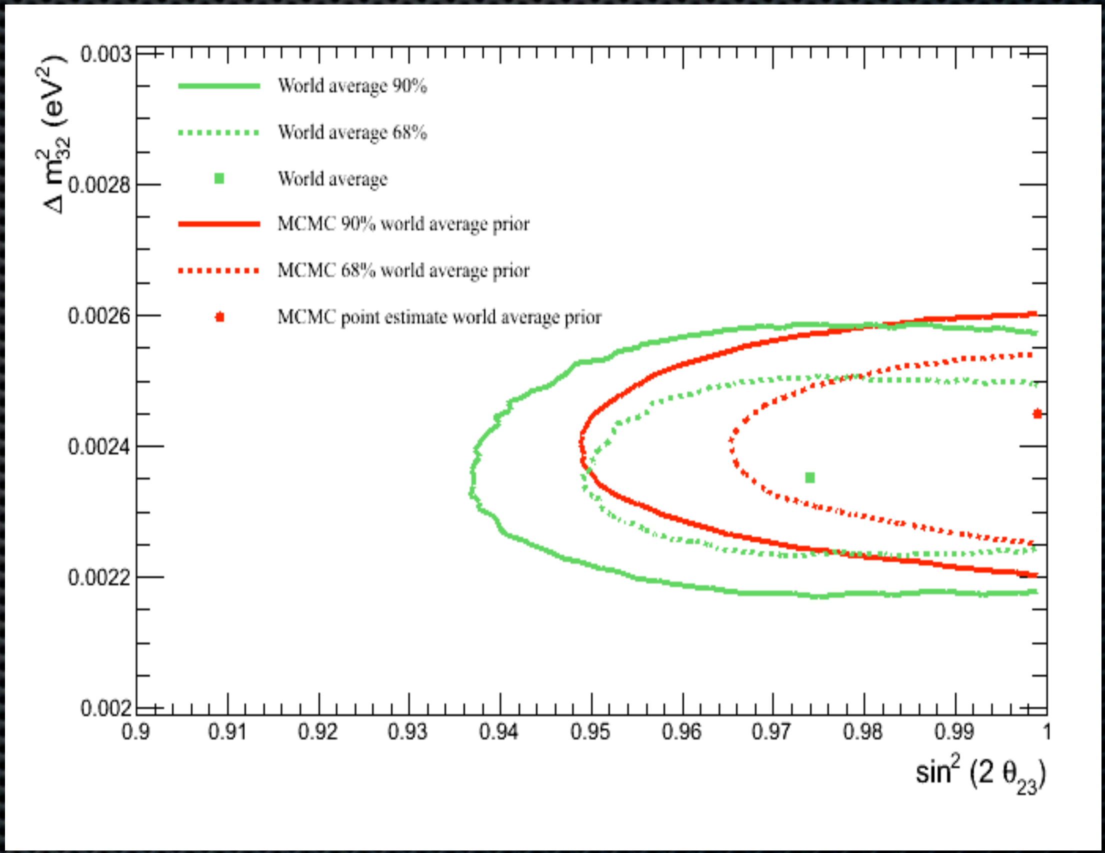


World Average Prior

- Analysis done with world average from PDG used as prior.
- Maximum posterior consistent with world average

$$\Delta m^2_{32} = 2.40 \times 10^{-3} \mathrm{eV}^2$$
$$\sin^2 2\theta_{23} = 0.999$$

- T2K data pulls mixing angle to maximal value, larger value for Δm^2_{32}.



Oscillation/Systematic parameter correlations.

- Monte Carlo studies showed there correlations between oscillation systematic parameters (7.8 x 10^{21} POT at SK).
- For future analyses, reducing the errors on systematic parameters can improve the measurement of Δm^2_{32}.
  - Binding energy on water.
    - Can possibly be reduced with studies in FGD water panels.
  - SK energy scale.
    - Already precisely known.

Summary

- Neutrino oscillation mixing angles have all been measured.
- Mass hierarchy, CP violating phase δ and more precise measurements of mixing angles θ need to be measured.
- Simultaneous fitting near and far detector in the T2K oscillation experiment to measure ν_μ disappearance, $\nu_\mu \rightarrow \nu_x$
  - Use MCMC techniques to sample likelihood.
- Results consistent with other oscillation analyses. For $\sin^2 2\theta_{23}$ precision comparable to world best.

Summary

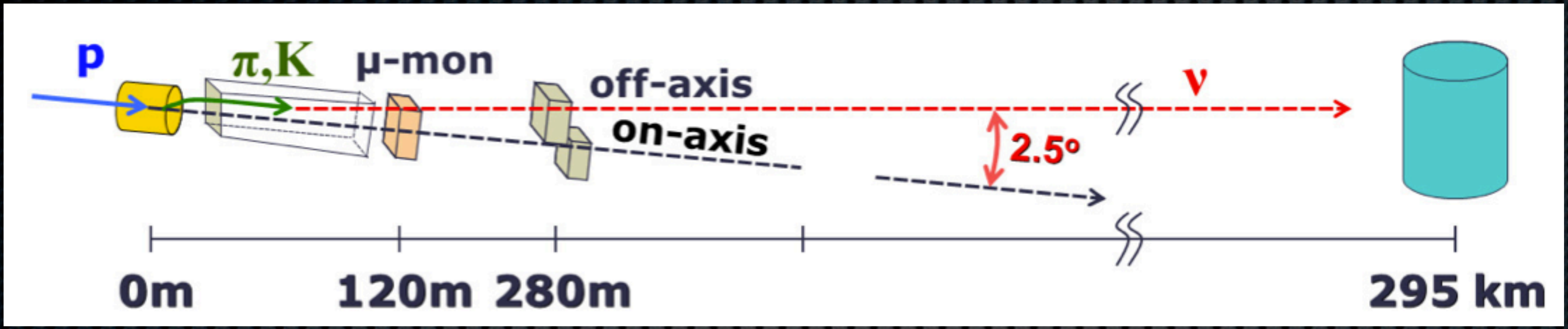
- Analysis done with world average prior, analysis results consistent with world average mixing angle pulled to maximal value.
- With increased statistics MC studies show that the uncertainty on the binding energy of water and SK energy scale will limit the sensitivity on Δm^2_{32}.

T2K Collaboration

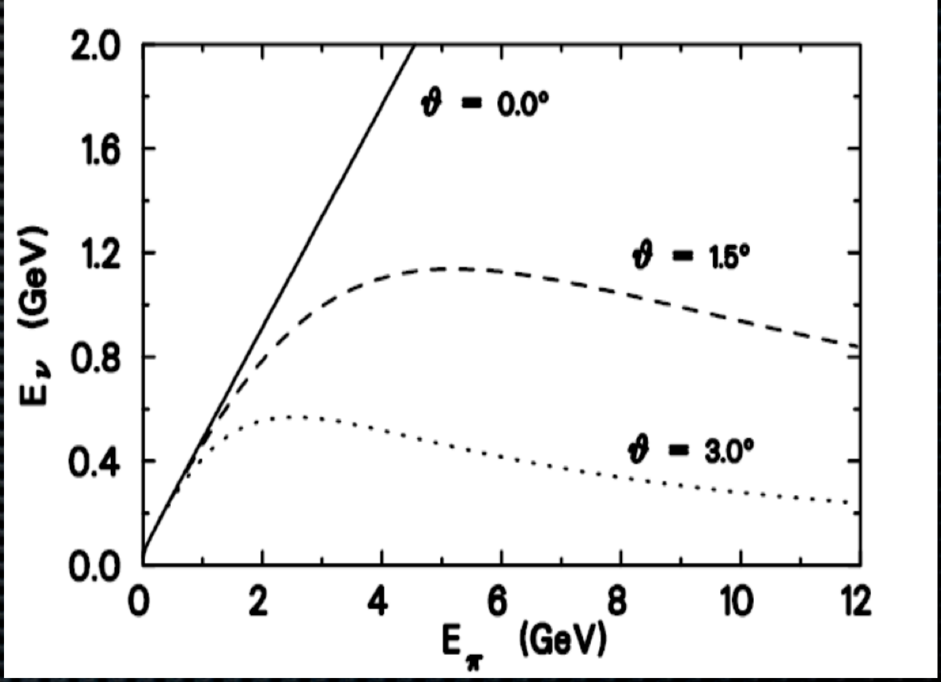
~500 collaborators from 56 institutions, 11 nations

Back up

Off-Axis Beam

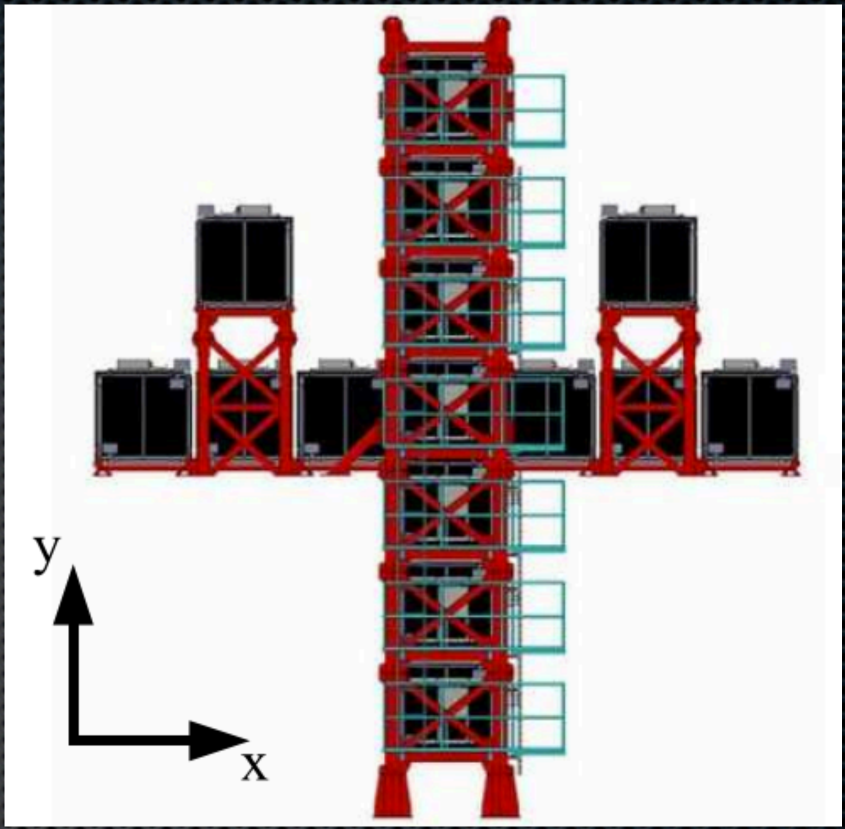


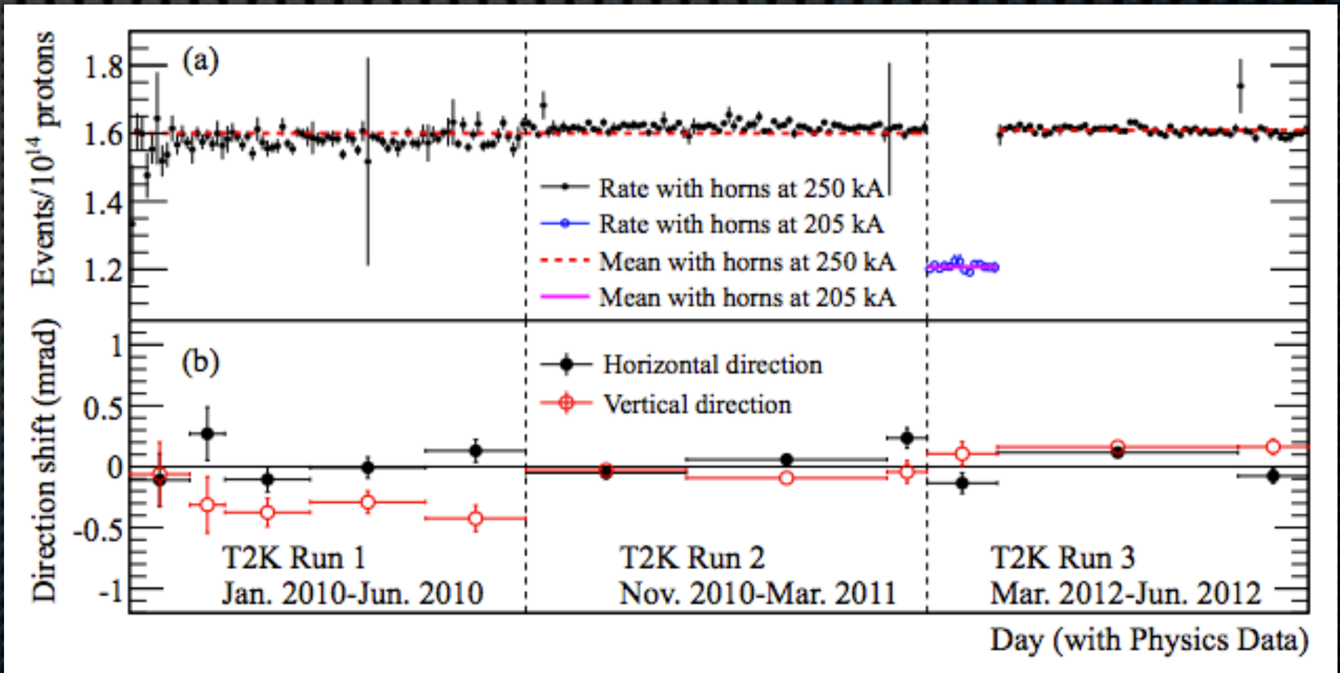
- At small angles to the beam axis, neutrino energy is insensitive to parent pion energy
- 2.5^0 off axis. Low energy narrow band beam.



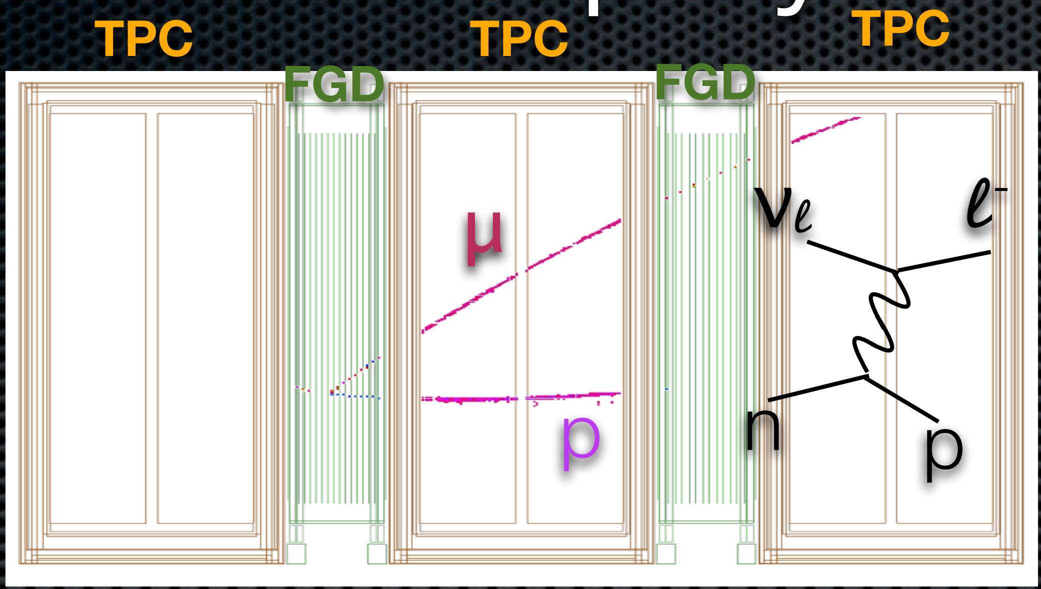
On axis INGRID

- 14 modules consisting of iron and scintillator arranged in a cross pattern
- Measures profile, direction and intensity of neutrino beam.
- Records stability

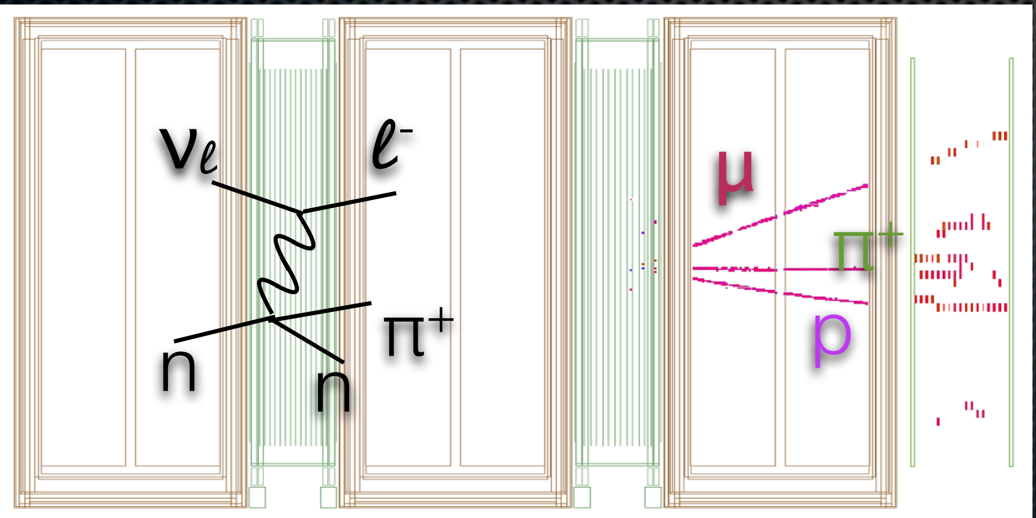




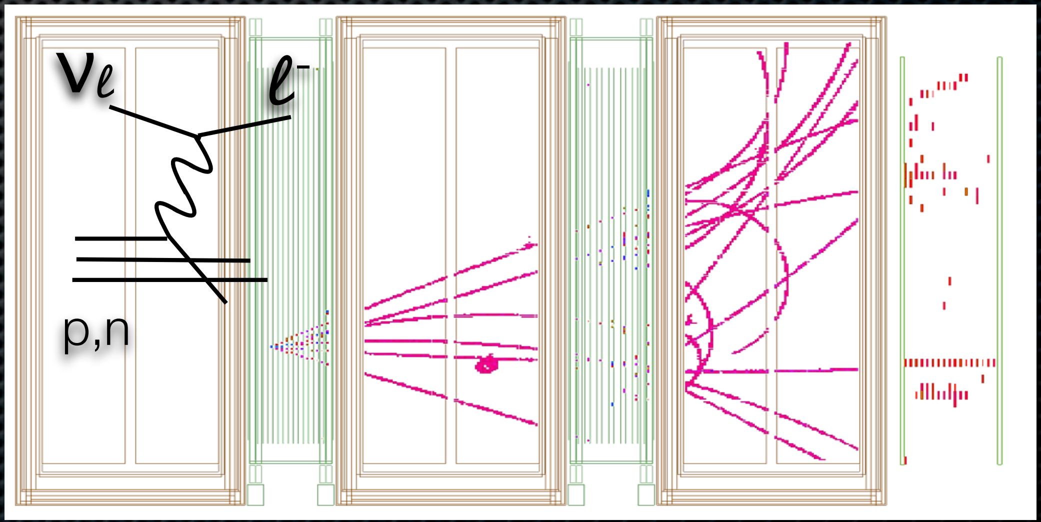
ND280 Event Display



Quasi Elastic candidate



single pion candidate

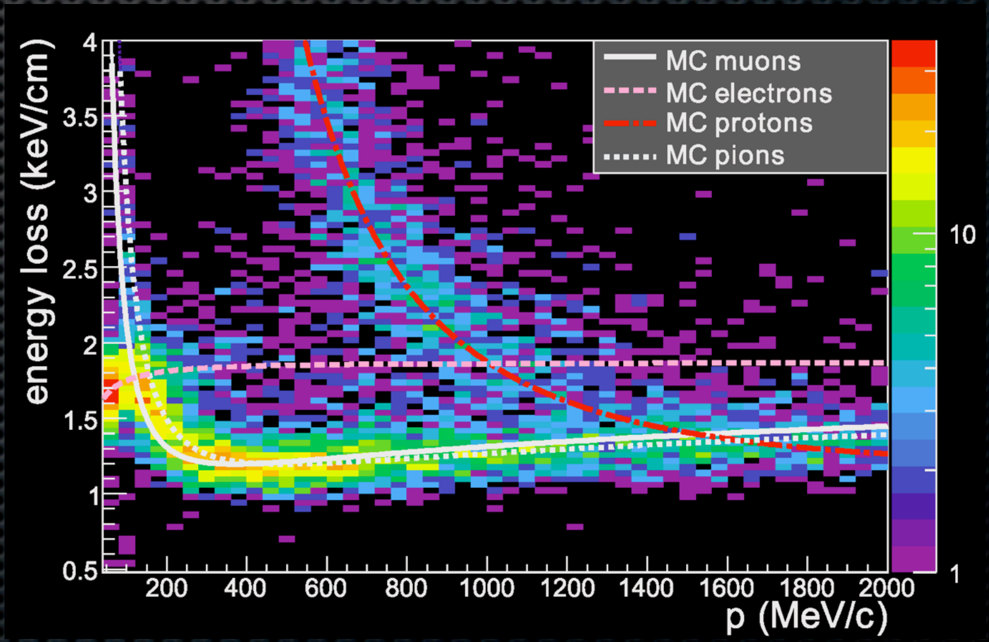


DIS candidate

DIS = deep inelastic scattering.

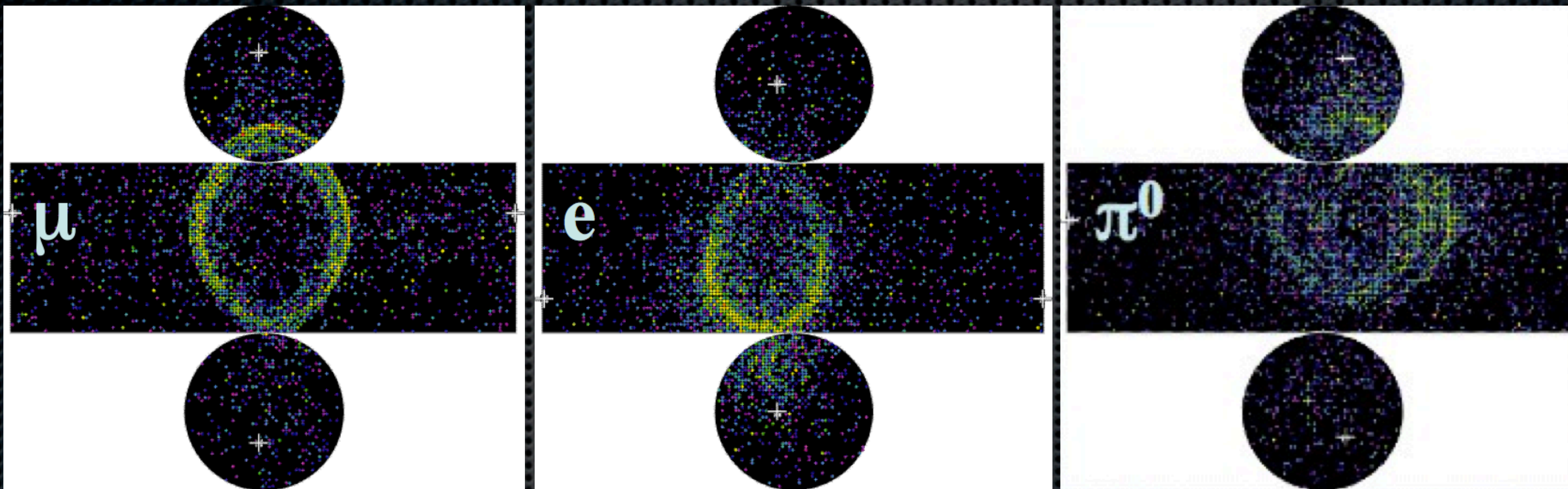
Particle ID With TPC

- For particles traversing TPCs
  - Reconstruct momentum
  - Measure dE/dx
- Compare dE/dx with the expected energy loss of different particles. Select μ like or e like particle.
- Energy resolution in TPCs <10%. Probability of misidentifying μ as e < 0.2% (p < 1 GeV/c).



Sample of positively charged particles produced in neutrino interactions.
Run 1 Data

Super-Kamiokande Event Displays



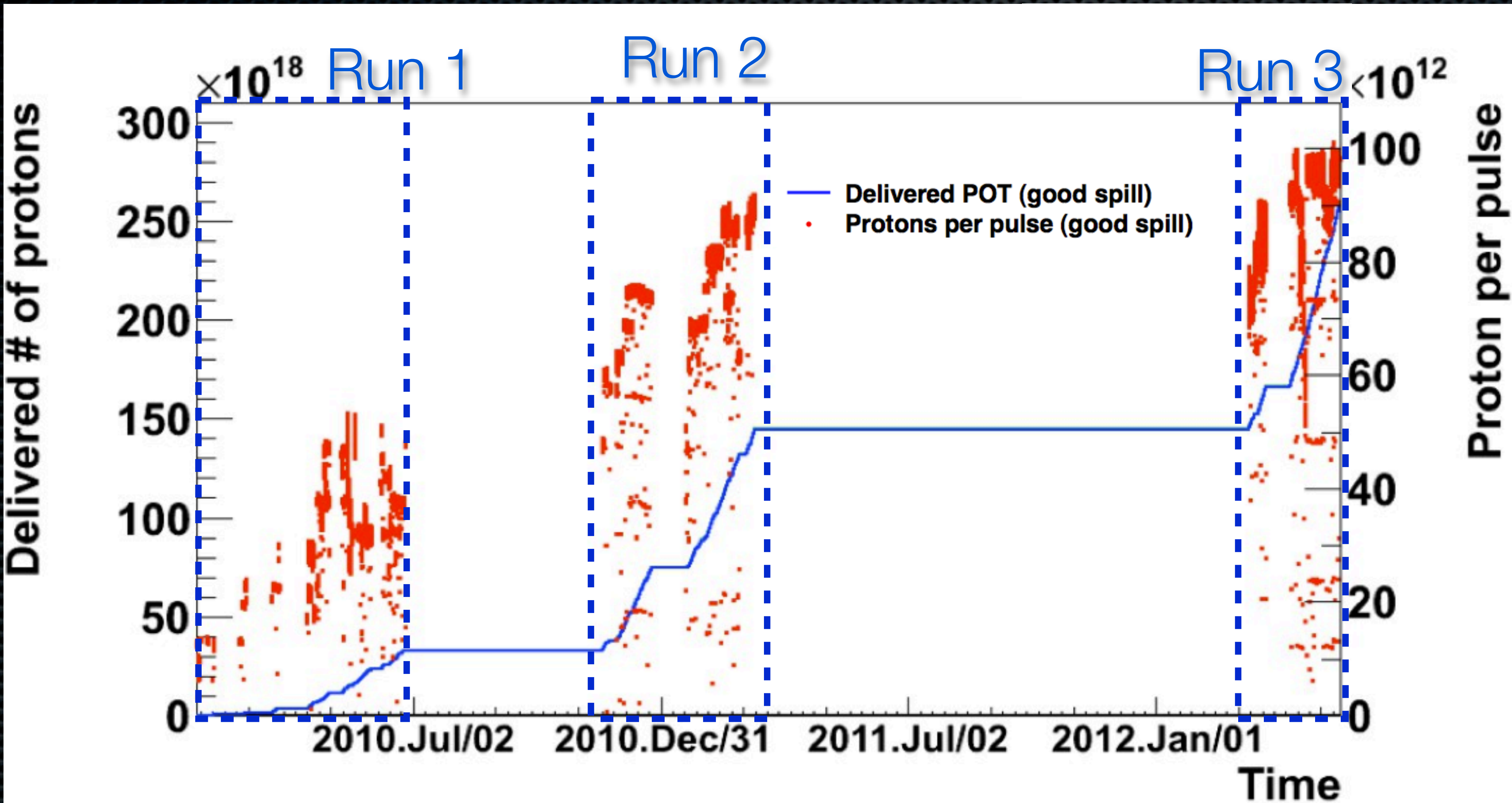
Sharp μ Cherenkov ring

Fuzzy e Cherenkov ring

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

*events displays generated with MC

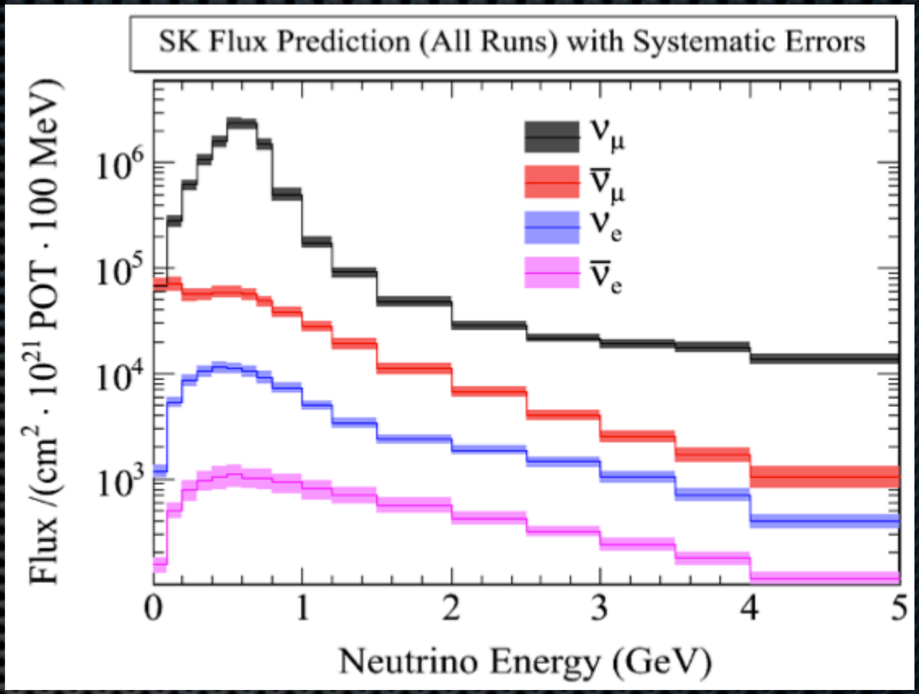
Analyzed Data

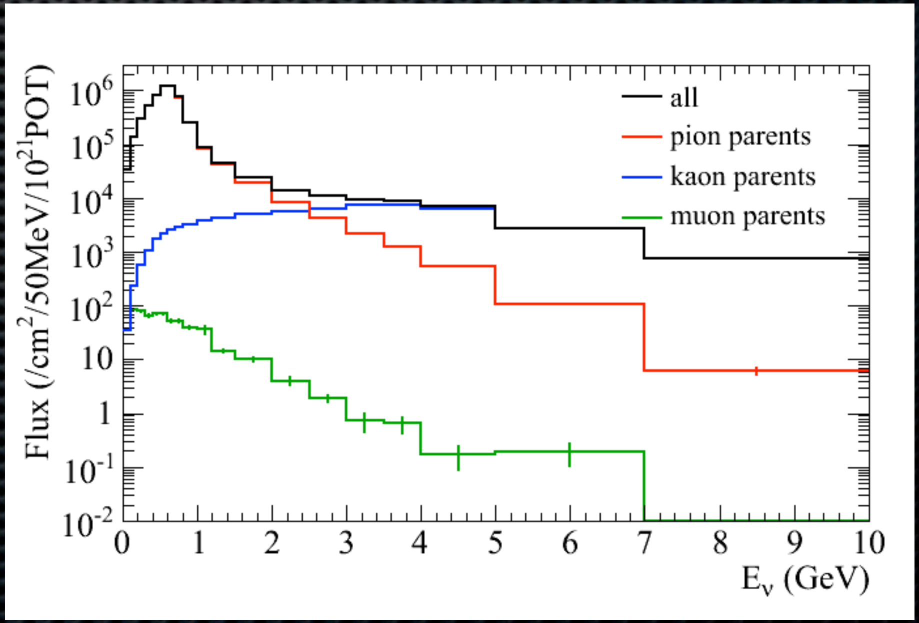


- Data set runs up to 2012/06/09 (End of Run 3)
- POT used in this analysis: 3.01×10^{20}

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.

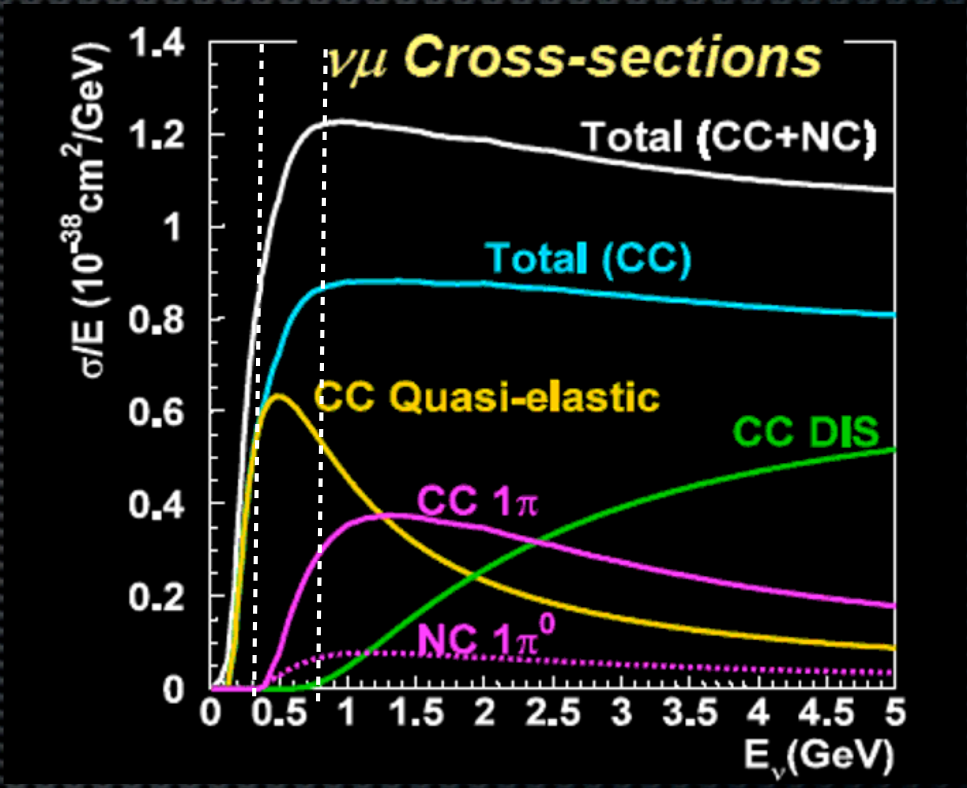




ν_μ flux broken down by parent that produces ν

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...

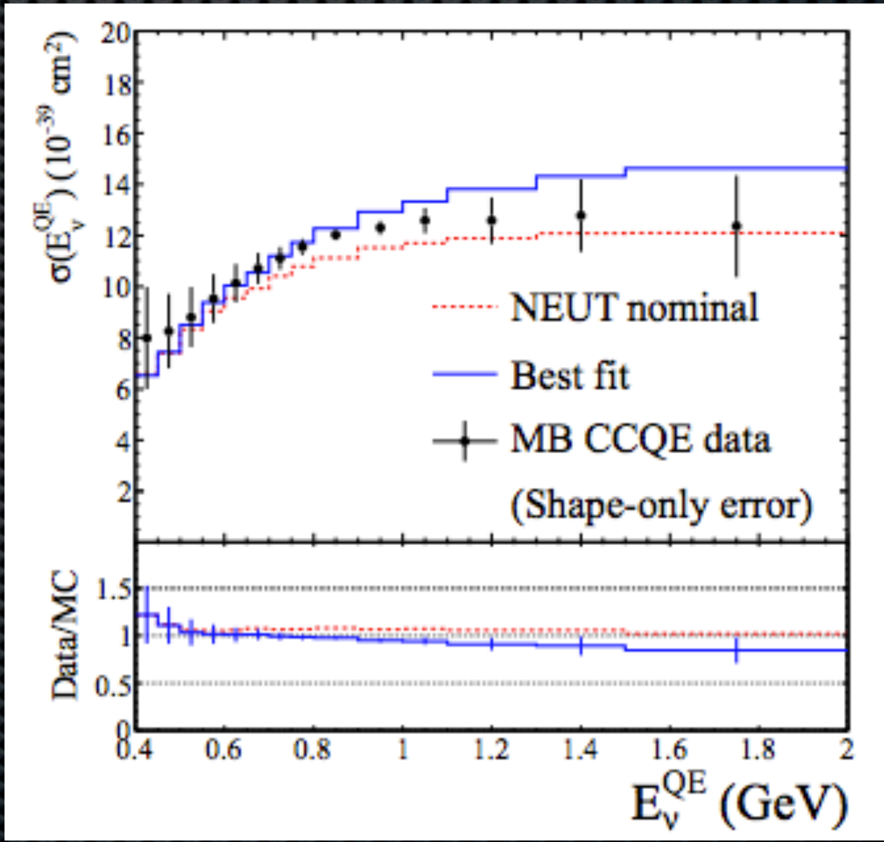


- CCQE Signal Interactions. Initial neutrino can be reconstructed from the energy and direction of final lepton

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

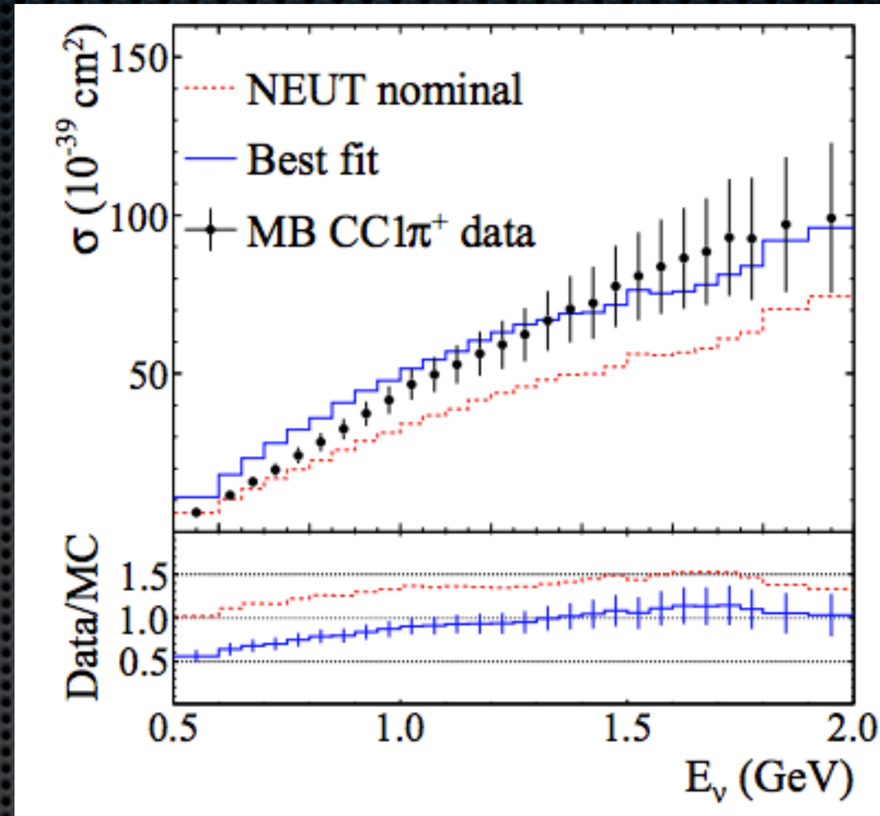
Neutrino Cross Section Uncertainties

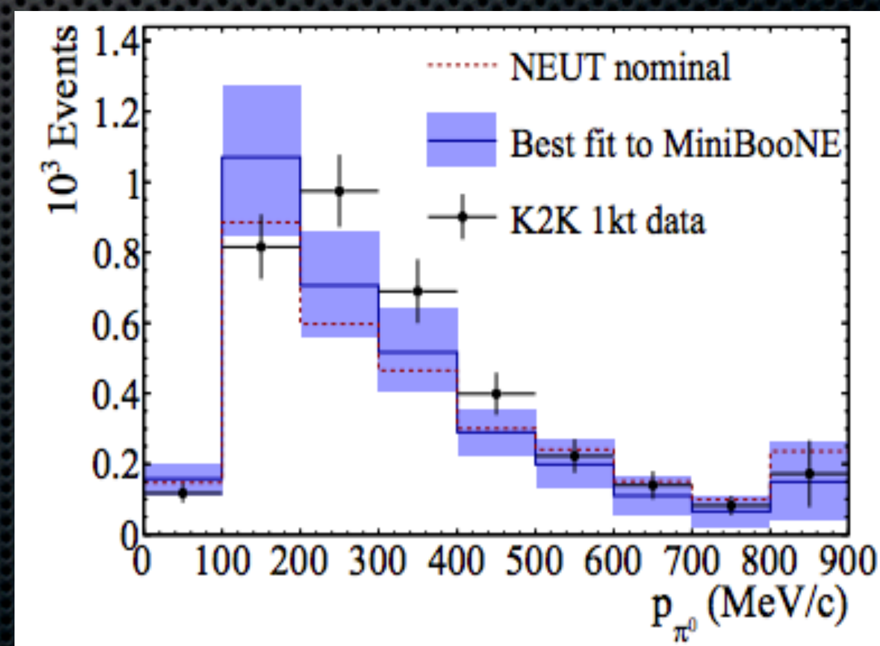
- Cross section uncertainties set by external data at ~1 GeV from Mini-BooNE, other experiments.
- T2K primary neutrino interaction model is NEUT, with GENIE used as a cross-check.
- Signal
  - CCQE interactions use the model of Llewellyn Smith with nuclear effects described by relativistic Fermi gas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



Neutrino Cross Section Uncertainties

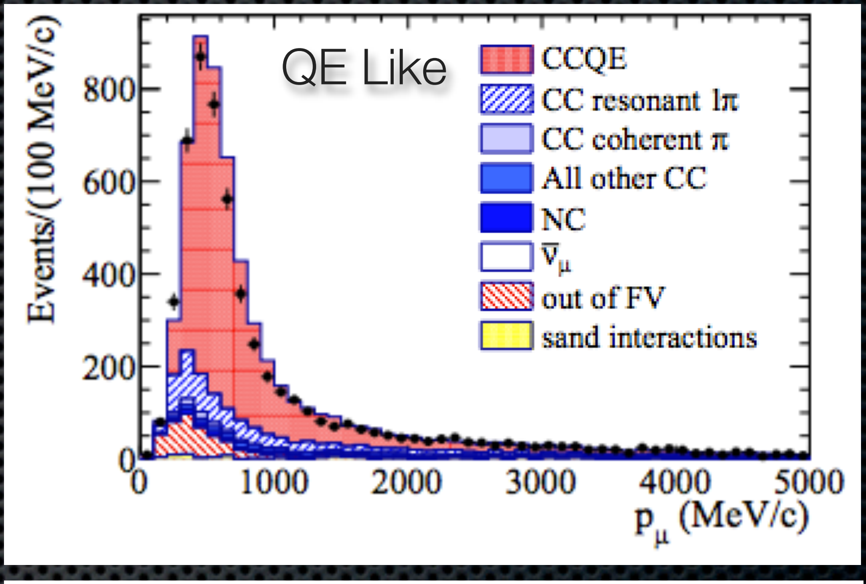
- Backgrounds
  - Single Pion Production CC1π main background for ν_μ disappearance: MisID'd as CCQE if pion is not identified
  - Pion production via hadronic resonances using Rein and Seghal Model
  - NCπ^0 backgrounds main background to ν_e appearance, flux dependant and can mimic a CC ν_e interaction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

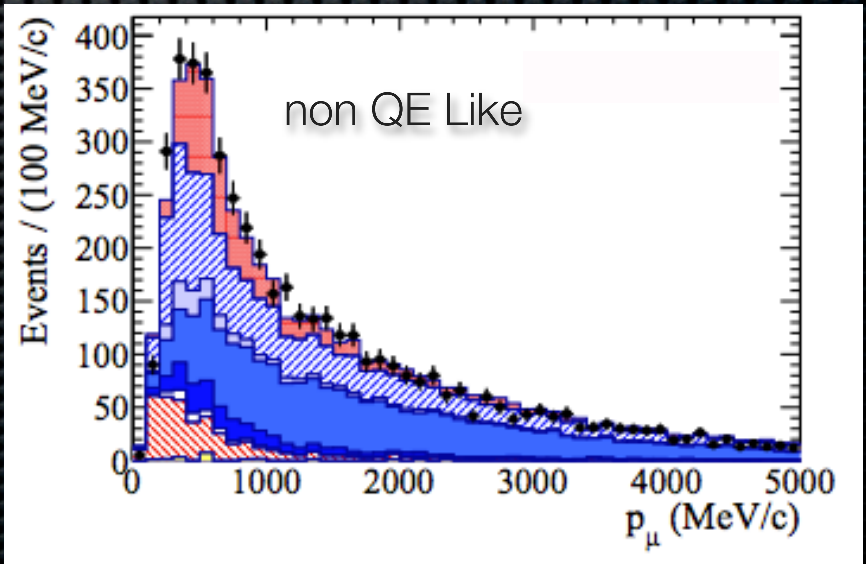




ND280 ν_μ measurements in CCQE and CCnonQE samples

- 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.
- Constrain flux and cross section uncertainties

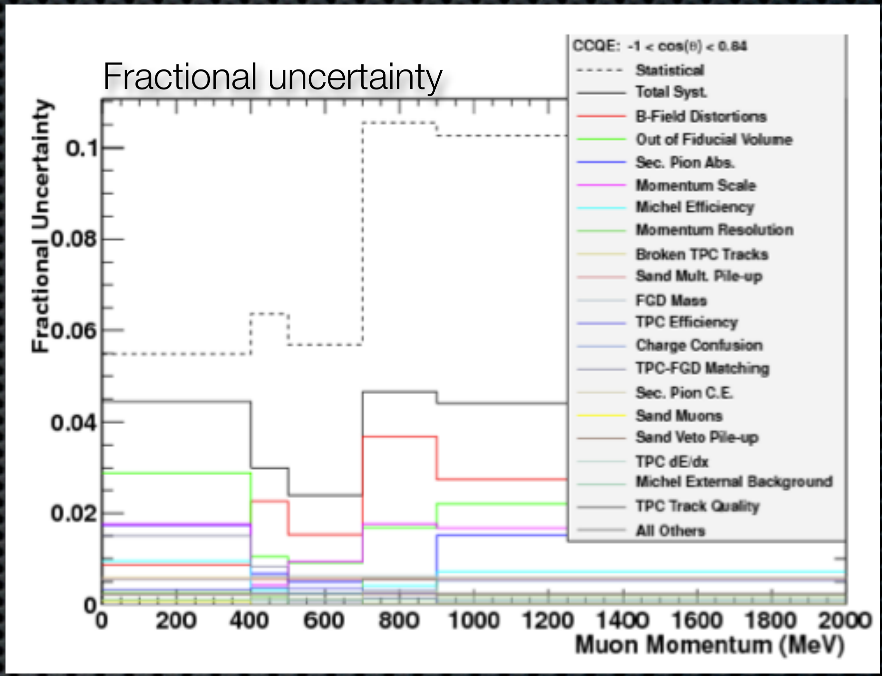




ND280 ν_μ measurements in CCQE and CCnonQE samples

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

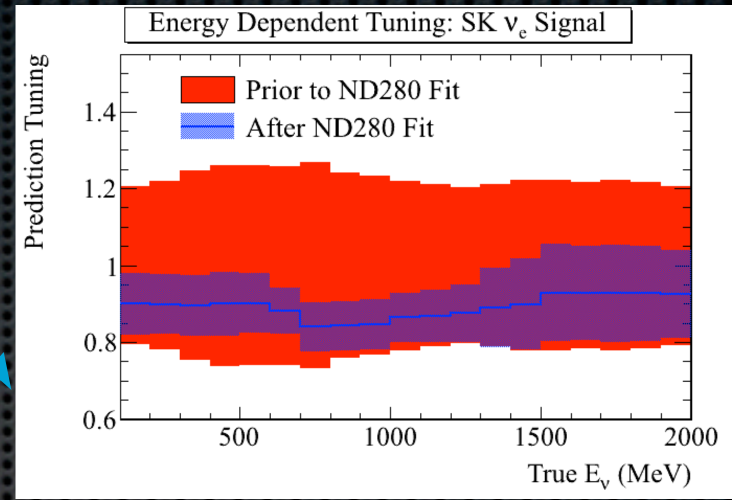


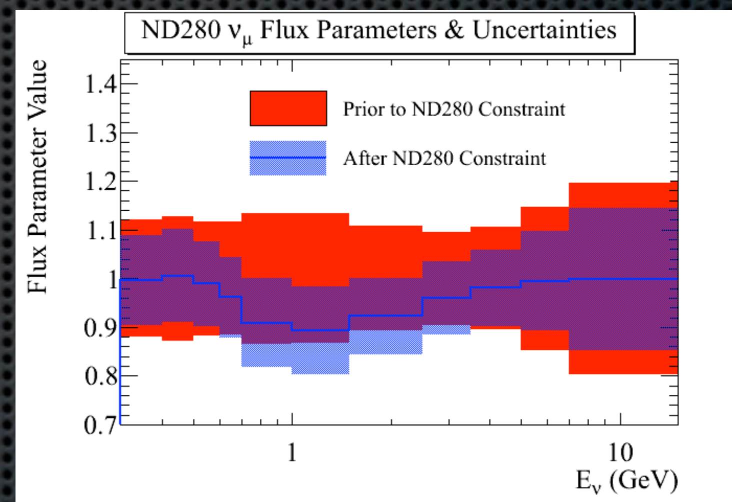
Systematic error	Error Size (%)	
	Minimum and maximum fractional error	Total fractional error
B-Field Distortions	0.3 - 6.9	0.3
Momentum Scale	0.1 - 2.1	0.1
Out of FV	0 - 8.9	1.6
Pion Interactions	0.5 - 4.7	0.5
All Others	1.2 - 3.4	0.4
Total	2.1 - 9.7	2.5

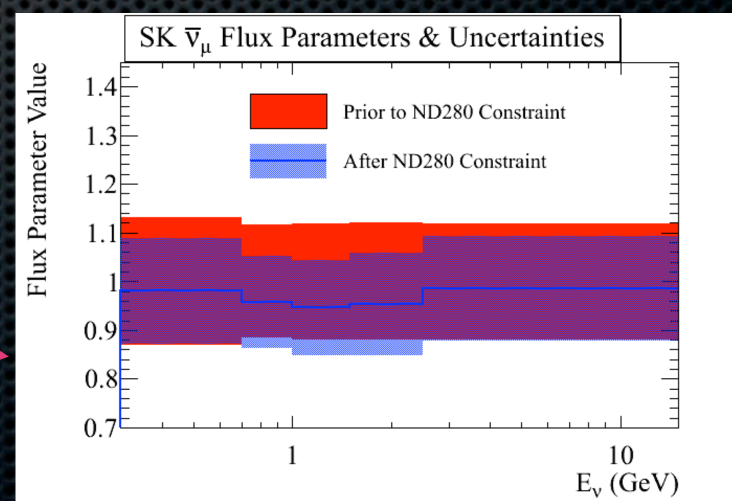
Flux + Cross Section Fit

ND280: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 $\bar{\nu}_\mu$



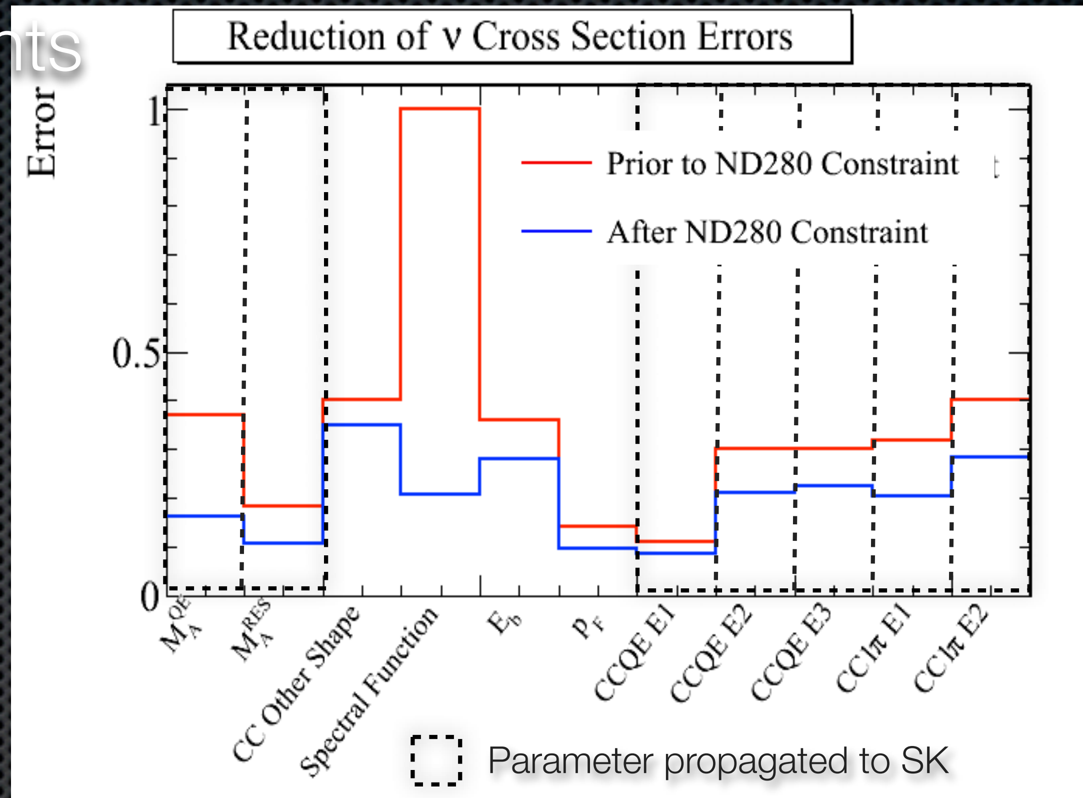




Flux + Cross Section Fit

ND280: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.



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

Error w/o oscillation 6.8%

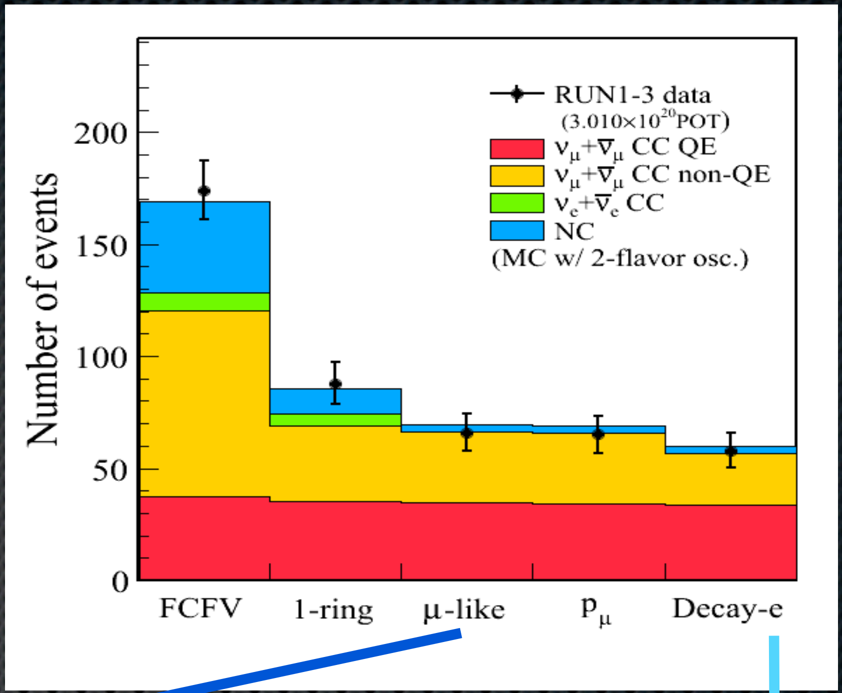
ν_μ Selection

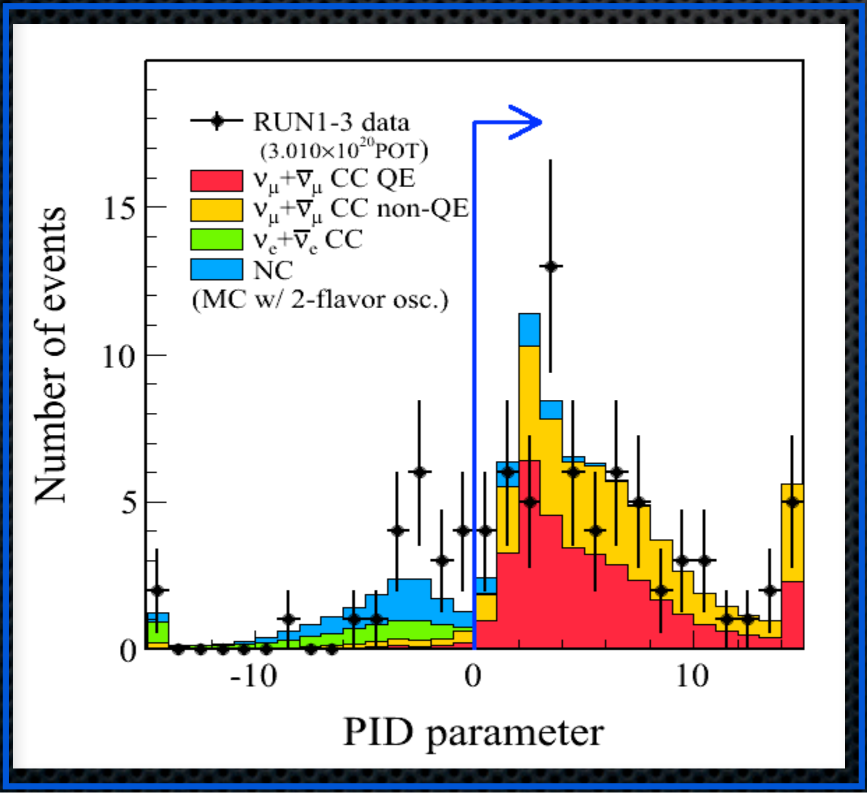
- Ring is muon like
- Reconstructed muon momentum is greater than 200 MeV.
- 1 or less Michel electron

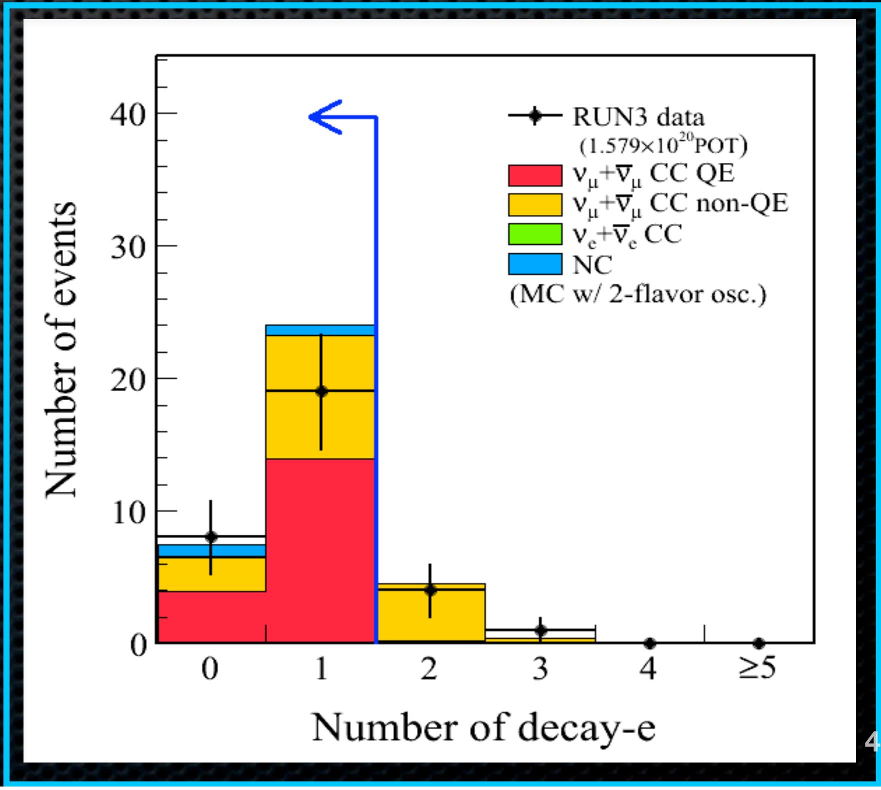
Error w/o oscillation 5.5%

ν_μ Selection

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

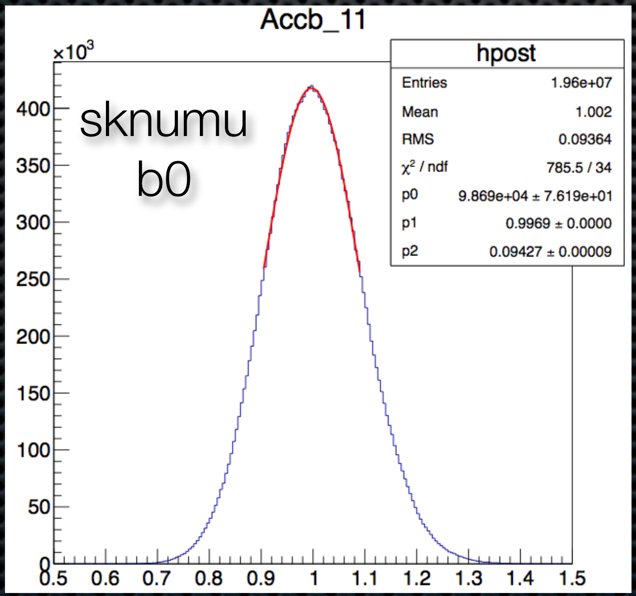


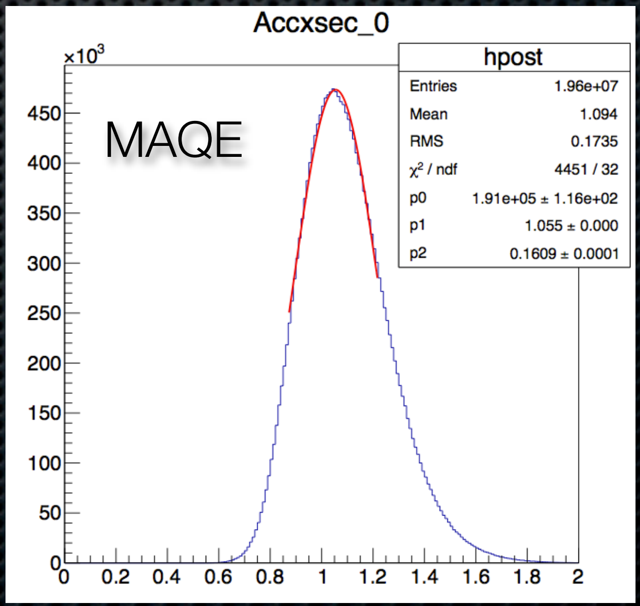




Parameter Estimation

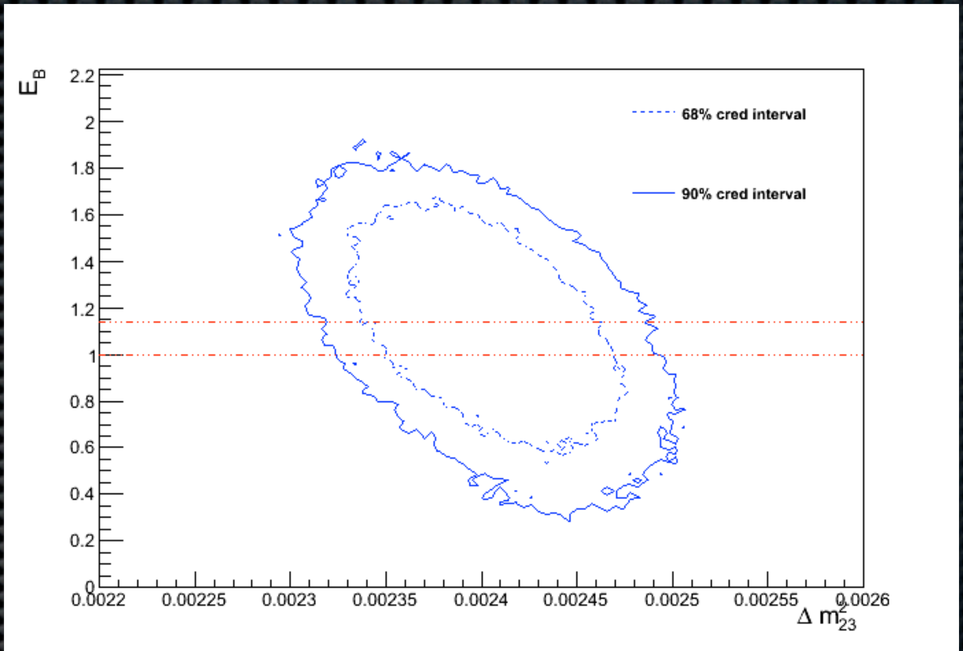
- Monte Carlo Markov Chain explores multidimensional parameter space.
  - Project points in parameter space onto an axis for a given parameter.
  - Projection follows likelihood distribution marginalized over all other parameters.
- Estimate parameter by fitting 1d projection distribution within 1σ of peak.

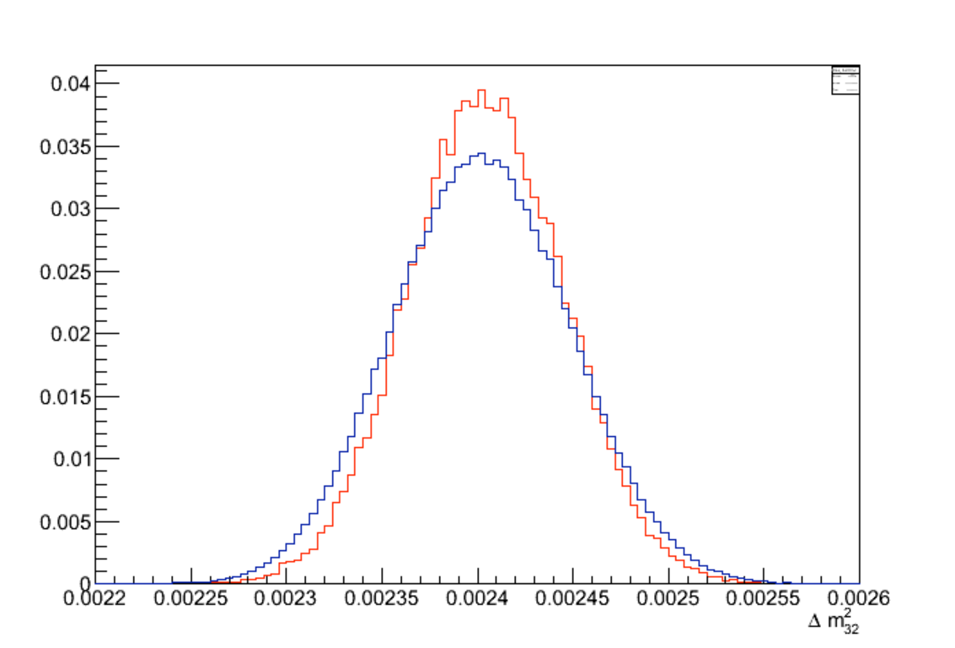




Systematic Oscillation Parameter Correlations

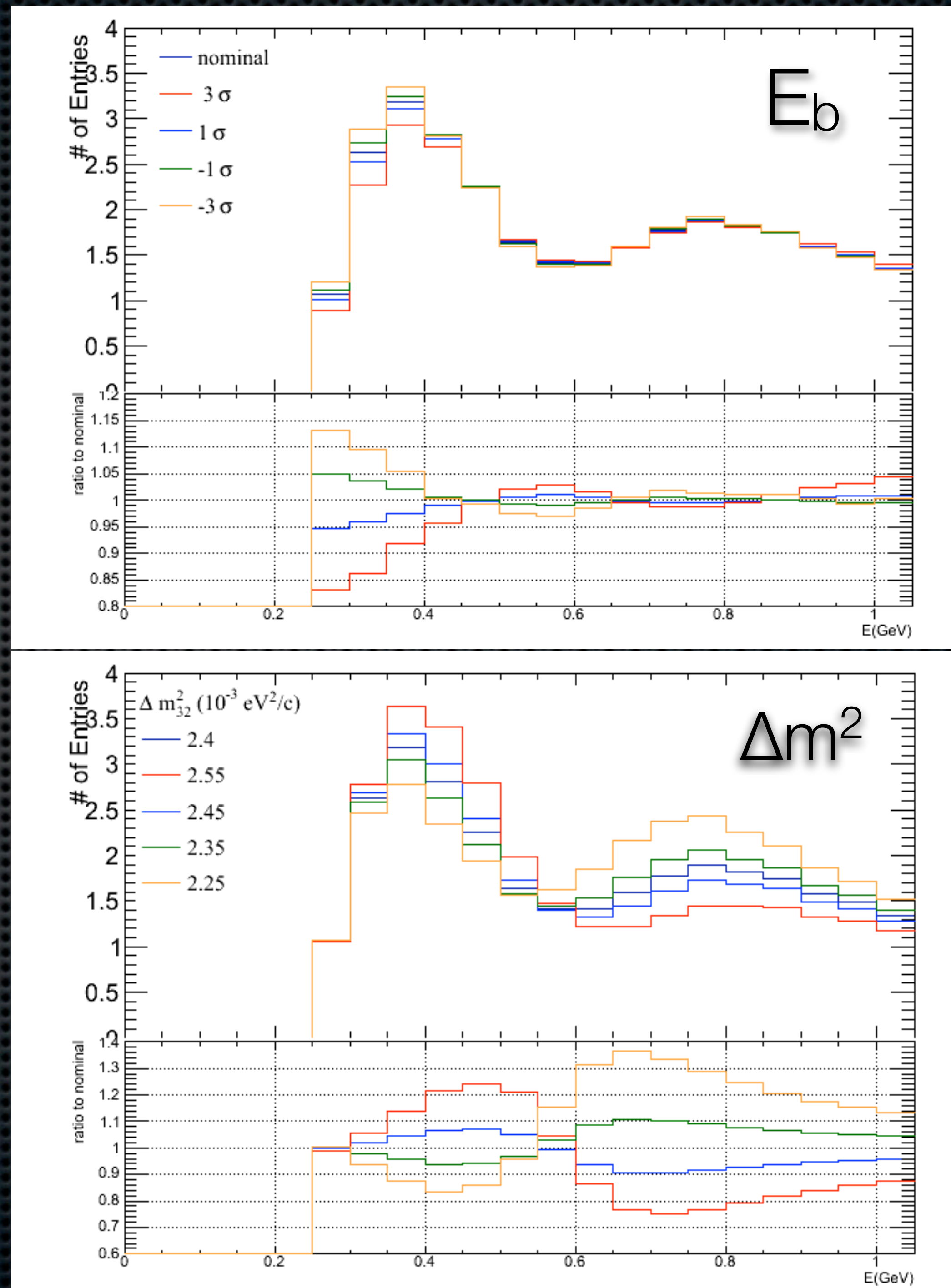
- Projecting onto Δm^2 axis to find the effect the correlation introduces into the error.
- Fit projection with Gaussian.
- Marginalizing over Eb
  - Error: 0.0461 $\times 10^{-3}$ eV^2
- Marginalizing over a thin slice in Eb, near fit value.
  - Error: 0.0407 $\times 10^{-3}$ eV^2
- Difference of ~12%





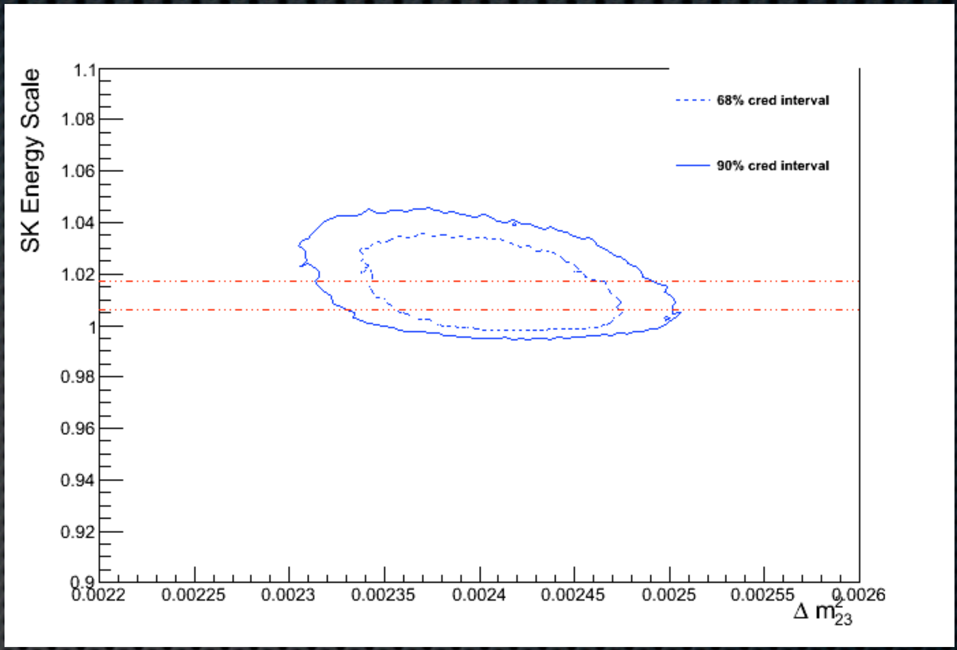
Systematic Oscillation Parameter Correlations

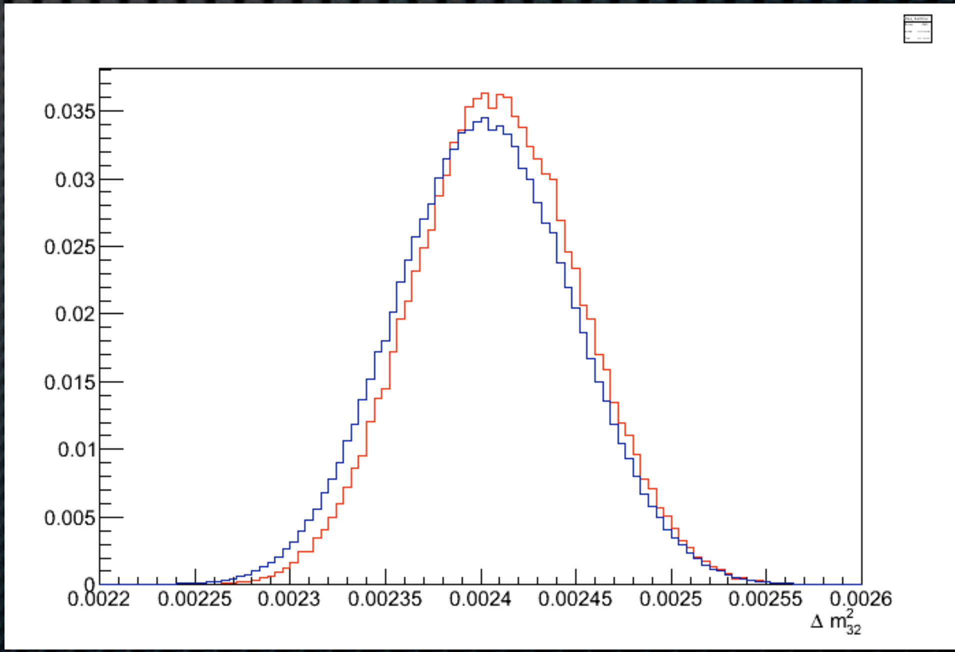
- Definite correlation seen between binding energy at SK and Δm^2
- Nominal value for Eb on ^{16}O
  - 27 +/- 9 MeV.



Systematic Oscillation Parameter Correlations

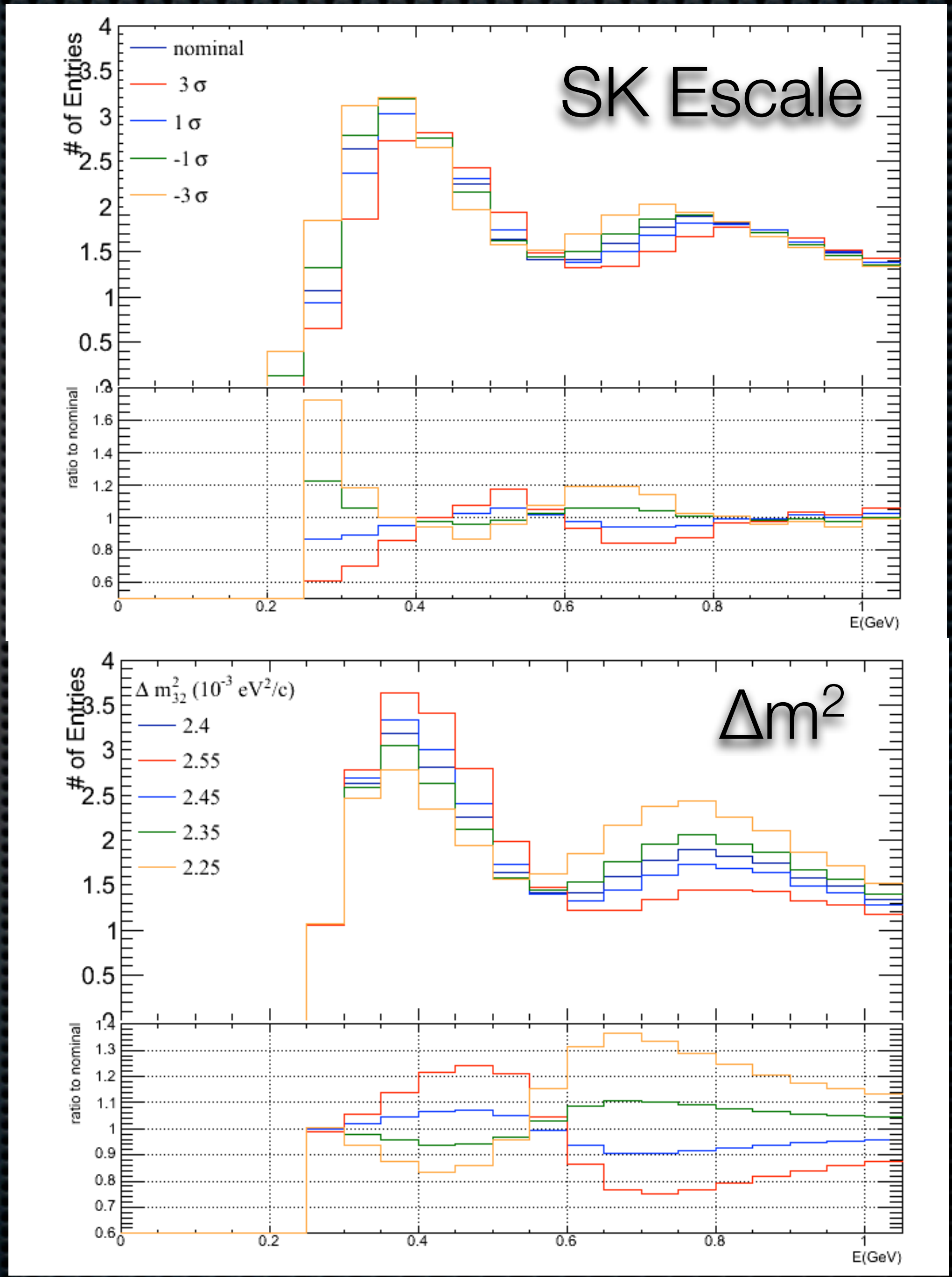
- SK energy scale vs Δm^2
- Marginalizing over energy scale
  - Error: 0.0461 $\times 10^{-3}$ eV^2
- Marginalizing over a thin slice in energy scale, near fit value.
  - Error: 0.0435 $\times 10^{-3}$ eV^2
- Difference of ~ 6%.



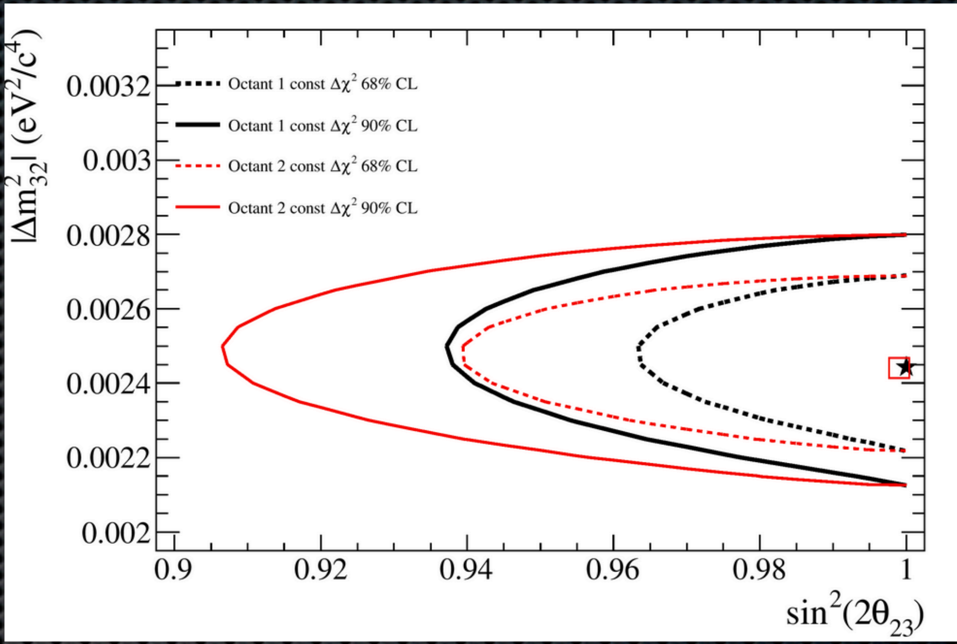


Systematic Oscillation Parameter Correlations

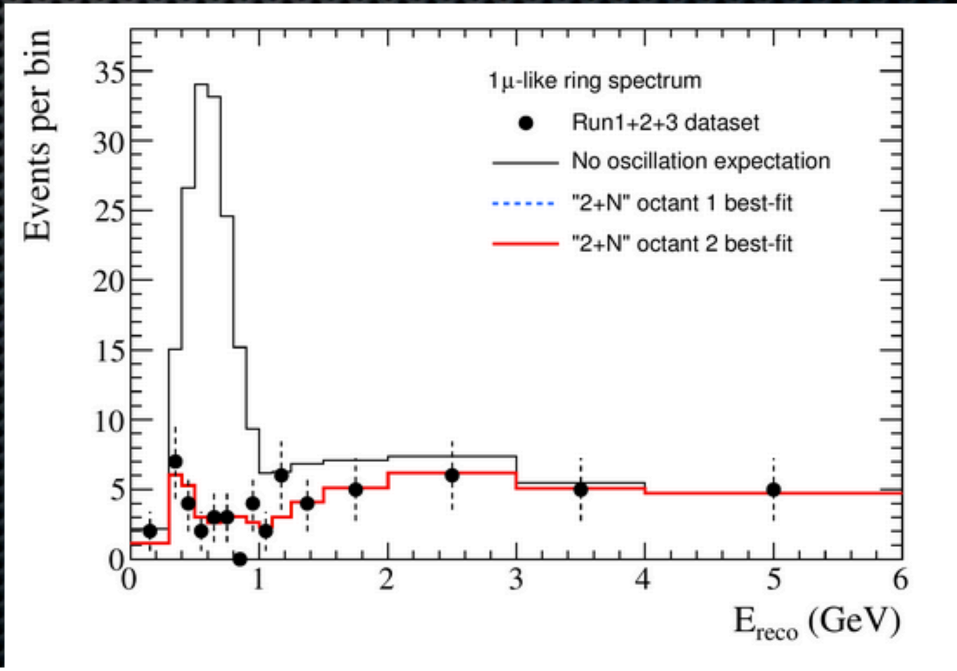
- SK energy scale
  - Nominal value of 1.0
  - Error of 2.3%



Other T2K disappearance analysis.



	$\sin^2 2\theta_{23}$	$\Delta m_{32}{}^2$
$\theta_{23} \leq \pi/4$	1.000	2.44e-3
$\theta_{23} \geq \pi/4$	0.999	2.44e-3



*Plots from T. Dealtry

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 .

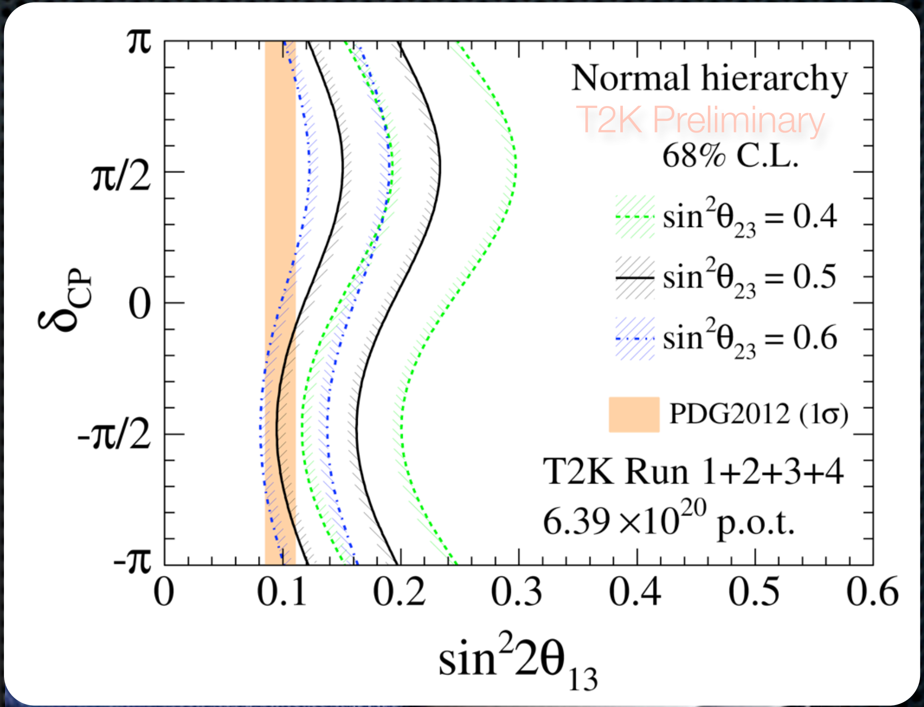
$$P(\nu_\mu \to \nu_e) \sim \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right) +$$
$$(\mathrm{CPV\ term}) + (\mathrm{matter\ term})$$

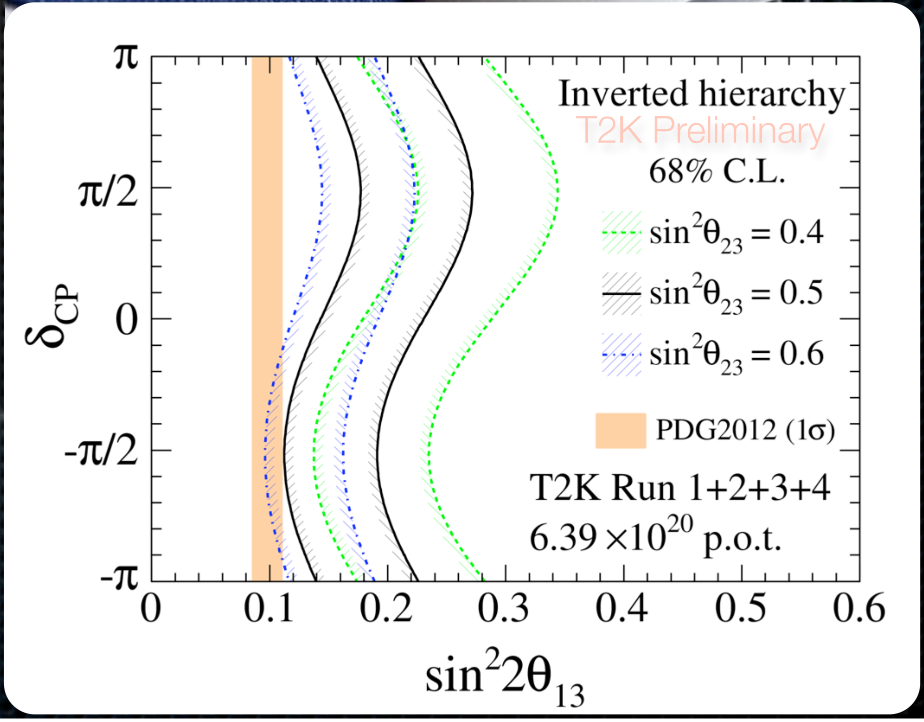
- Up to eight-fold ambiguity in determining θ_{13} and δ from $P(\nu_\mu \to \nu_e)$

Effect of θ_{23} Uncertainty

- ν_e appearance probability also depends on the value of θ_{23}
I
- f θ_{23} is fixed at values near the edge of the current allowed region, the fit contours shift

- Future improved measurements of θ_{23} will be important to extract information about other oscillation parameters (including δ_{CP}) in long-baseline experiments
- A T2K combined ν_e+ν_μ analysis is underway





*Slide from M. Wilking.

Octant Issue

Leading

Next to leading

$$P(\mu \to \mu) \simeq 1 - \left(\cos^4(\theta_{13})\sin^2(2\theta_{23}) + \sin^2(\theta_{23})\sin^2(2\theta_{13})\right)\sin^2\left(\frac{\Delta^2 m_{32} L}{4E_\nu}\right).$$

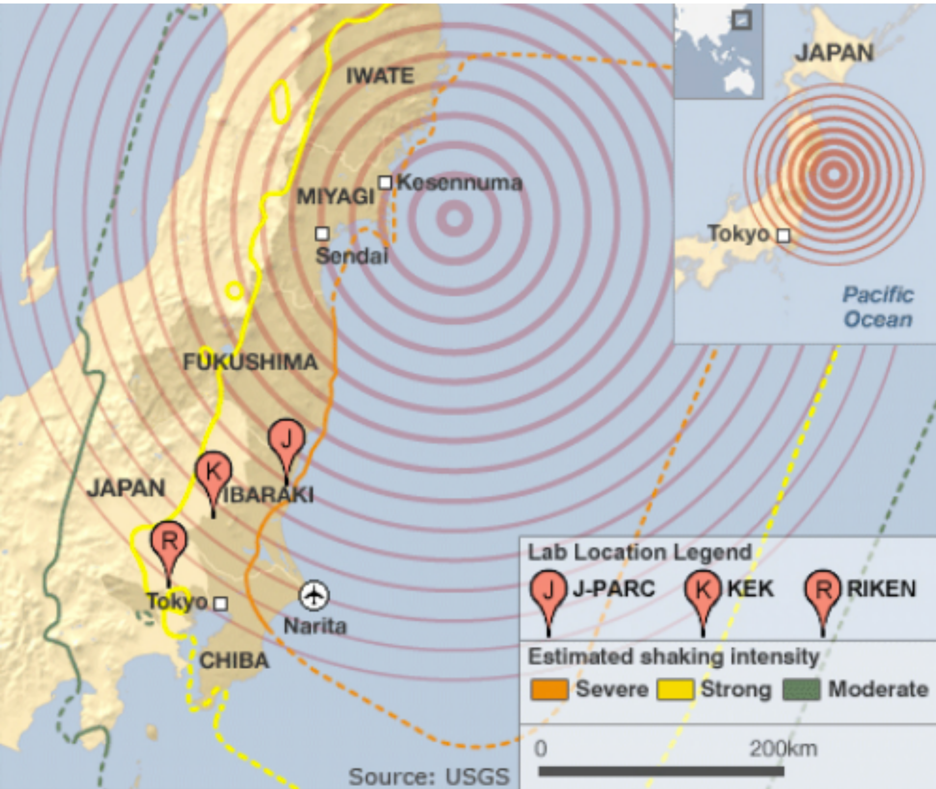
- Previous experiments (MINOS) consider only leading term. 2 flavour fit, no knowledge of θ_{13}.
- T2K oscillation parameters becoming sensitive to octant of θ_{23}.
  - First octant $\theta_{23} < \pi/4$
  - Second octant $\theta_{23} > \pi/4$.

$$\sin^2\theta_{23} = \frac{1}{2}\left(1 \pm \sqrt{1 - \sin^2 2\theta_{23}}\right).$$

- Software for oscillation probability with $\sin^2 2\theta_{23}$ parameterization only considers first octant.
- Credible intervals larger when considering 2nd octant.

Updates

- Numbers in abstract, conclusion changed.
- Figures 5.20,5.21,5.22,5.23, 5.26, 5.29, 5.30
- Limits in Section 5.8.3, 5.10



- 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.