Imperial College London

ν_μ Oscillation

An independent analysis

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T2K

Outline

Introduction

- ν_μ oscillation
- Signal and backgrounds at Super-K

Analysis

- Unbinned Likelihood method
- PDF construction and prediction of expected number of events at Super-K
- Systematic uncertainties

Results

- Monte-Carlo study for first T2K results

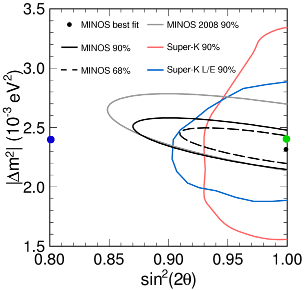
Summary

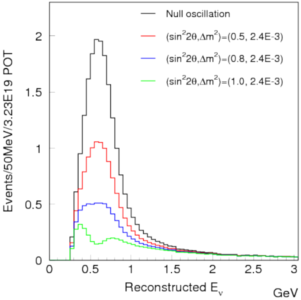
ν_μ oscillation

- $\nu_\mu \rightarrow \nu_\tau$ oscillation probability in two flavour approximation:

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta_{23} \sin^2 \left(\frac{1.27 \Delta m^2_{23}(\mathrm{eV}^2) L(\mathrm{km})}{E_\nu(\mathrm{GeV})} \right)$$

- Oscillation varies with values of oscillation parameters $\sin^2 2\theta_{23}$ and Δm^2_{23}:
- MINOS experiment: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 2.32 \times 10^{-3}$
- Accumulated data corresponding to 22.8 expected events in the Null hypothesis case (0.3% of total requested data)



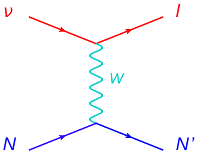


Signal and backgrounds at Super-K

Signal

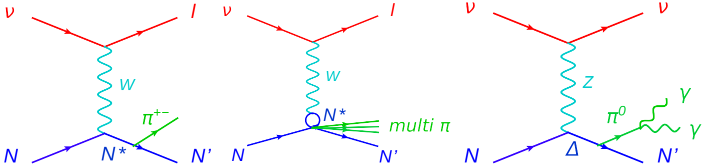
- ν_μ Charged Current Quasi Elastic (CCQE)
  - μ-like ring at Super-K, reconstructed using two body kinematics

$$E_\nu = \frac{m_p^2 - (m_n - V)^2 + 2(m_n - V)E_\mu - m_\mu^2}{2(m_n - V - E_\mu + pcos\theta_\mu)}$$



Backgrounds

- ν_μ:
  - CC1π (Dominant background)
  - CCOther (Multi-π, Charged Current Coherent π...)
  - NCπ^0
- $\bar{\nu}_\mu$ and ν_e:
  - CCQE + same as ν_μ



(a) (b) (c)

Unbinned Likelihood method

The Likelihood function is the product of spectrum shape and normalisation terms and penalty terms to constrain systematic errors:

$$L(\sin^2 2\theta, \Delta m^2, \mathrm{f}) = L_{\mathrm{Norm}}(\sin^2 2\theta, \Delta m^2, \mathrm{f}) \times L_{\mathrm{Shape}}(\sin^2 2\theta, \Delta m^2, \mathrm{f}) \times L_{\mathrm{Pen}}(\mathrm{f})$$

- L_{Norm} assuming Poisson probability:

$$L_{\mathrm{Norm}} = \frac{(N_{\mathrm{SK}}^{\mathrm{exp}}(\sin^2 2\theta, \Delta m^2, \mathrm{f}))^{N_{\mathrm{SK}}^{\mathrm{obs}}}}{N_{\mathrm{SK}}^{\mathrm{obs}}!} e^{-N_{\mathrm{SK}}^{\mathrm{exp}}(\sin^2 2\theta, \Delta m^2, \mathrm{f})}$$

- L_{Shape} calculated from spectrum shape Probability Density Function:

$$L_{\mathrm{Shape}} = \prod_{i=1}^{N_{\mathrm{SK}}^{\mathrm{obs}}} P(E_{\mathrm{Recon}} | \sin^2 2\theta_{23}, \Delta m_{23}^2, \mathrm{f})$$

- L_{Pen} assuming Gaussian systematic errors

$$L_{\mathrm{Pen}} = \prod_{\mathrm{pen}} e^{-\left(\frac{\Delta \mathrm{f}}{\sigma_{\mathrm{f}}}\right)^2}$$

PDF Construction and N_{SK}^{exp} prediction

1. Super-K un-oscillated true MC data (NEUT generator)

PDF Construction and N_{SK}^{exp} prediction

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2. Super-K **cuts** to select muon like particles

PDF Construction and N_{SK}^{exp} prediction

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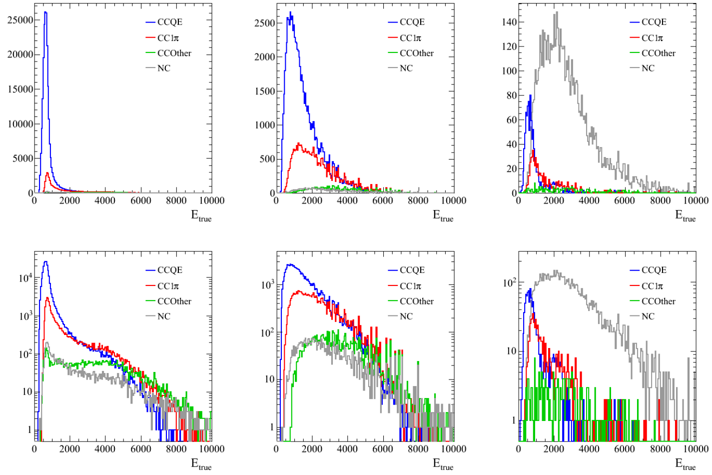
2. Super-K **cuts** to select muon like particles
3. Seperation of signal and backgrounds
    - 12 **Un-oscillated histograms** (1 signal, 11 backgrounds)

True Un-oscillated histograms from Super-K MC

ν_μ $\bar{\nu}_\mu$ ν_e



PDF Construction and N_{SK}^{exp} prediction

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   - Obtain true oscillated energy PDF

PDF Construction and N_{SK}^{exp} prediction

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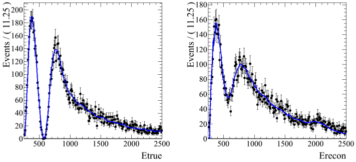
7. Charged Current PDFs multiplied by oscillation probability PDF
   - Obtain true oscillated energy PDF
8. True energy converted to recon energy with **conversion matrices**
   - Obtain **reconstructed oscillated spectra**

True to Reconstructed oscillated spectra

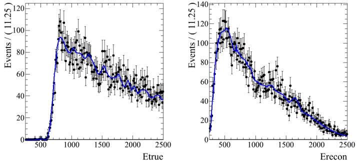
ν_μ spectra

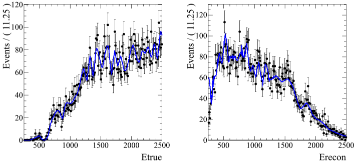
- PDFs built using linear interpolation
- 10000 fake events generate below from the PDFs for each mode
- PDF accuracy for each mode limited by SK MC statistics
- Kernel method should smooth PDF

CCQE

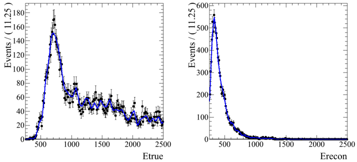


CC1π





CCOther



NC (no oscillation)

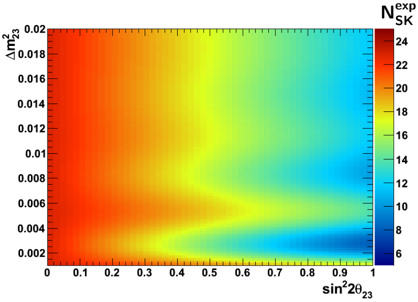
PDF Construction and N_{SK}^{exp} prediction

1. Super-K un-oscillated true MC data (NEUT generator)
2. Super-K **cuts** to select muon like particles
3. Seperation of signal and backgrounds
   - 12 **Un-oscillated histograms** (1 signal, 11 backgrounds)
4. **Flux correction** applied by re-weighting histograms
5. ND280 data driven correction factor on the flux×cross-section product
6. Histograms turned into PDFs with RooFit
7. Charged Current PDFs multiplied by oscillation probability PDF
   - Obtain true oscillated energy PDF
8. True energy converted to recon energy with **conversion matrices**
   - Obtain **reconstructed oscillated spectra**
9. Add signal and background PDFs
   - Obtain final **reconstructed oscillated spectra** (without systematics)

PDF Construction and $N_{\mathrm{SK}}^{\mathrm{exp}}$ prediction

$N_{\mathrm{SK}}^{\mathrm{exp}}$ prediction

	Un-Oscillated	Oscillated
Total	22.8167	6.3332
ν_μ		
$CCQE$	18.0705 (79.199%)	3.5907 (56.697%)
$CC1\pi$	3.0891 (13.538%)	1.5143 (23.911%)
$CCOther$	0.5230 (2.292%)	0.4062 (6.414%)
NC	0.3777 (1.655%)	0.3777 (5.959%)
$\bar{\nu}_\mu$		
$CCQE$	0.5026 (2.203%)	0.2523 (3.983%)
$CC1\pi$	0.1882 (0.825%)	0.1317 (2.079%)
$CCOther$	0.0281 (0.123%)	0.02486 (0.393%)
NC	0.0219 (0.096%)	0.0219 (0.346%)
ν_e		
$CCQE$	0.0017 (0.008%)	0.0006 (0.009%)
$CC1\pi$	0.0010 (0.004%)	0.0005 (0.009%)
$CCOther$	0.0003 (0.001%)	0.0002 (0.004%)
NC	0.0124 (0.055%)	0.0124 (0.196%)



Systematic uncertainties

Uncertainties currently in the model:

- Super-K efficiency uncertainties:
  - CCQE: 7.8%
  - CCnonQE: 25.5%
  - NC: 115.1%
  - ν_e CC: 100%
- Cross section uncertainties:
  - CCQE cross section uncertainty (Shape only effect)
  - fractional uncertainties (Shape+Normalisation effect):
    - CC1π/CCQE: $30\% E_{\mathrm{true}}$ below 2 GeV, 20% above
    - CCOther/CCQE: $30\% E_{\mathrm{true}}$ below 2 GeV, 25% above
    - NC/CCQE: 36%

Other Uncertainties

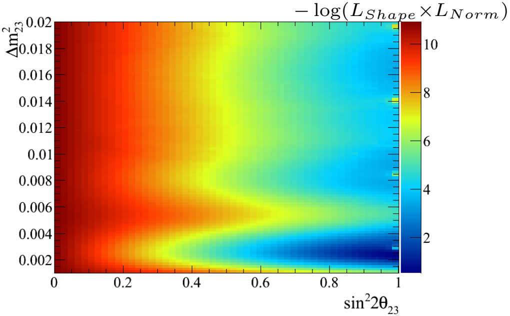
- ND280: efficiency error
- Flux uncertainties: flux shape and normalisation uncertainties
- Neutrino generator model uncertainty: effect of Final State Interaction

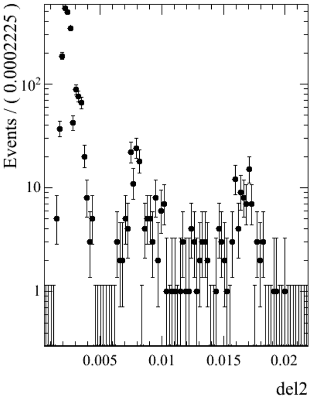
Monte-Carlo study for first T2K results

Shape and Normalisation Likelihoods. No Systematics

Fake Data studies:

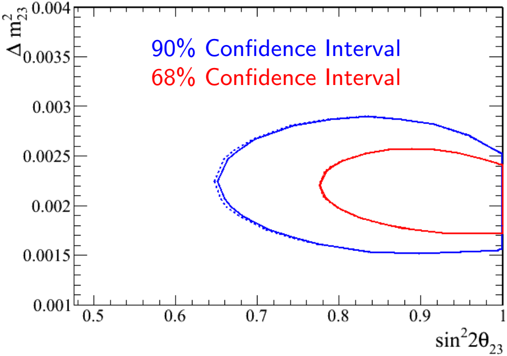
1. Generate Poisson number of expected events from E_{Recon} PDF.
2. Likelihood scan over parameter space
3. Repeat thousands of times.
4. Combine likelihoods from each fake experiment.
5. Combine Norm and Shape results





Monte-Carlo study for first T2K results

Sensitivity with and without systematics

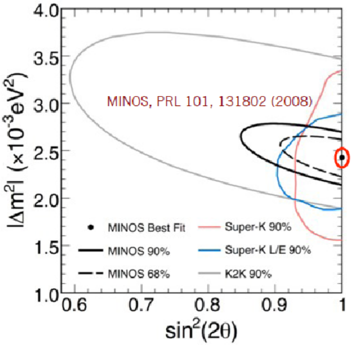


INPUT PARAMETERS	
$\sin^2 2\theta$	1.00
Δm^2	$(2.4).10^{-3}$

FITTED PARAMETERS	
Stats Only	
$\sin^2 2\theta$	1.00 ± 0.04
Δm^2	$(2.14 \pm 0.49).10^{-3}$
Systs + Stats	
SK^{eff}_{CCQE}	$(9.06 \pm 0.77).10^{-1}$
$SK^{eff}_{CC1\pi}$	$(9.97 \pm 2.54).10^{-1}$
$SK^{eff}_{CCOther}$	$(9.74 \pm 2.54).10^{-1}$
SK^{eff}_{NC}	2.45 ± 0.87

Summary

- Presented MC analysis coresponding to data from first T2K run
  - 23 expected events at SK in null oscillation hypothesis
- Currently T2K has collected 5 times more data
- 5 year results will have the best sensitivity for both oscillation parameters



Appendix

PDF construction

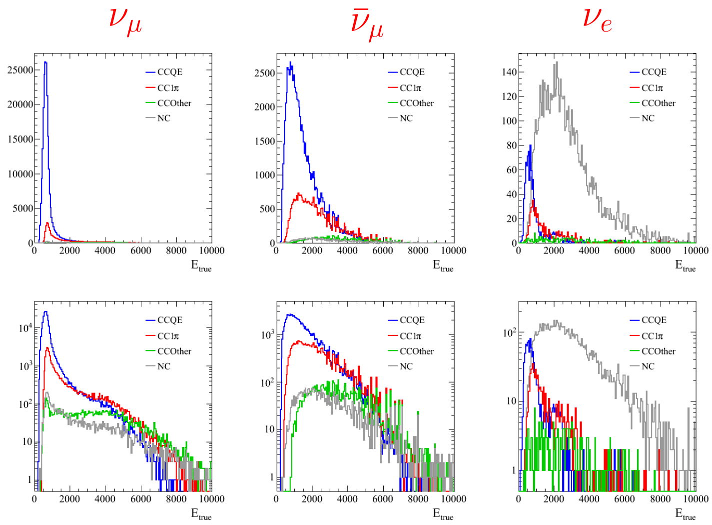
- Super-K selection cuts
- True Un-oscillated histograms from Super-K MC
- Flux Correction
- E_{true} to E_{recon} conversion matrices
- True to Reconstructed oscillated spectra

Super-K selection cuts

Fully Contained Full Volume (FCFV) 1 ring μ-like tight cuts

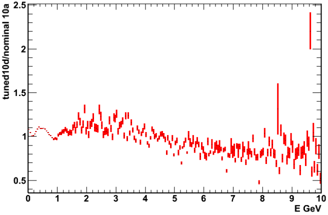
- Number of PMT hits in highest charge Outer Detector cluster $<=$ 15
- Vertex from Inner Detector wall $>$ 2m
- Visible energy $>$ 30MeV
- Exactly 1 ring
- Particle ID of a muon
- Momentum of the muon like ring $>$ 200MeV
- 0 or 1 decay electron

True Un-oscillated histograms from Super-K MC

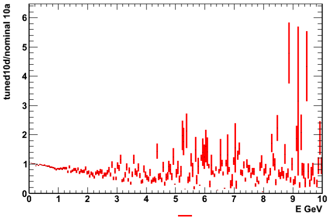


Flux Correction

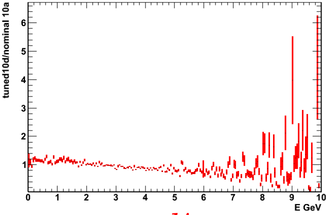
Re-weighting of 10a data with ratio of 2010d_v2/10a Nominal



ν_μ

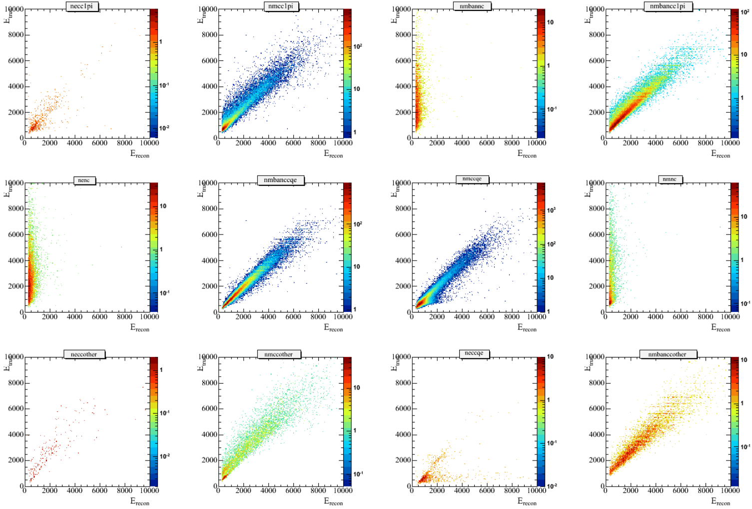


$\bar{\nu}_\mu$



ν_e

E_{true} to E_{recon} conversion matrices



True to Reconstructed oscillated spectra

ν_μ spectra

- PDFs built using linear interpolation
- 10000 fake events generate below from the PDFs for each mode
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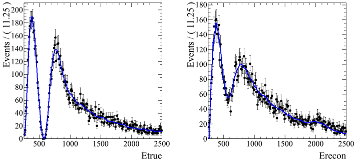
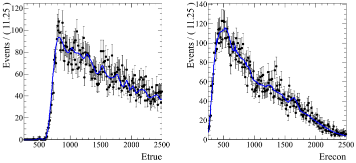
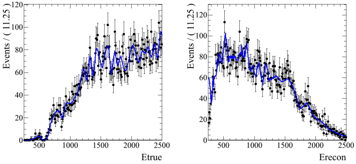
CCQE

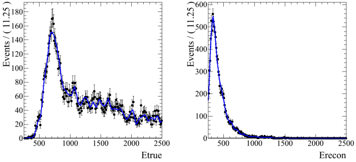


CC1π





CCOther

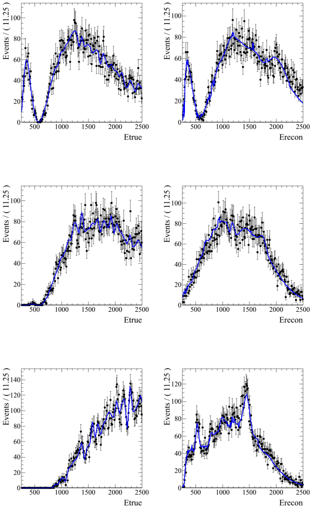


NC (no oscillation)

True to Reconstructed oscillated spectra

$\bar{\nu}_\mu$ and ν_e spectra

$\bar{\nu}_\mu$



CCQE

CC1π

CCOther

ν_e