ν_e Cross Section Measurements at the T2K Off-Axis Near Detector

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16 June 2015

Overview

Neutrino Oscillation

- Neutrino oscillation arises from a mixture between the flavour and mass eigenstates of neutrinos, linked by the Maki-Nakagawa-Sakata (MNS) matrix U: $|\nu_\alpha\rangle = \sum_{k=1}^{3} U^*_{\alpha k}|\nu_k\rangle$.

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

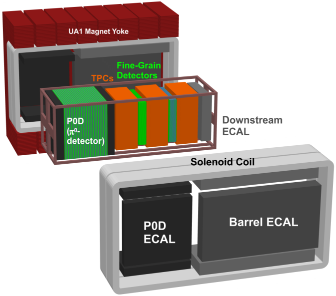
- As a neutrino propagates, the quantum mechanical phases of the three different mass states advance at slightly different rates. This results in a changing mixture of mass states as the neutrino travels.

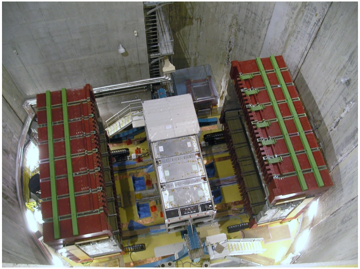
T2K Experiment

- T2K is a long baseline neutrino oscillation experiment in Japan, that targets the measurement of the mixing angle (θ_{13}), as well as a precision measurement for the mass difference (Δm^2_{23}) and their mixing angle (θ_{23}).

ND280 Overview

- The experiment uses two detectors; a near detector at 280 m from the neutrino production (in Tokai), and the far detector at 295 km Super-Kamiokande (SK).
- The near detector complex consists of an on-axis beam profile monitor INGRID, and an off-axis detector ND280.

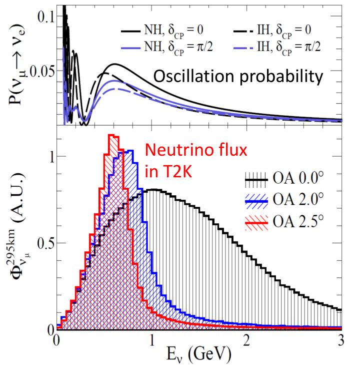




Neutrino Cross Section

- Neutrino cross section is a very important quantity in itself.
- Cross section measurement plays a vital role in the oscillation analysis, as the oscillation probability "$P(E_\nu)$" is inferred from the number of event (oscillated neutrinos at the far detector) "N", efficiency "ϵ", cross section "σ" and the flux "ϕ".

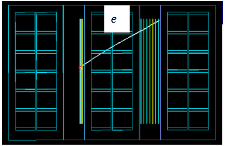
$$N = \int \epsilon\sigma(E_\nu)\phi(E_\nu)P(E_\nu)dE_\nu$$

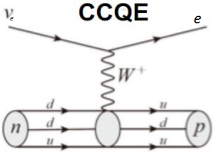


[T.Dorigo]

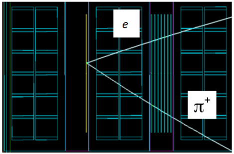
ν_e CC-Inclusive interaction example

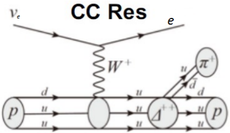
$CC0\pi$



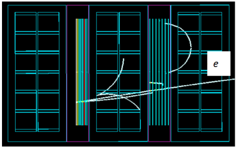


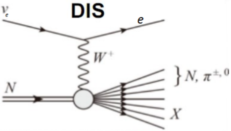
$CC1\pi+$





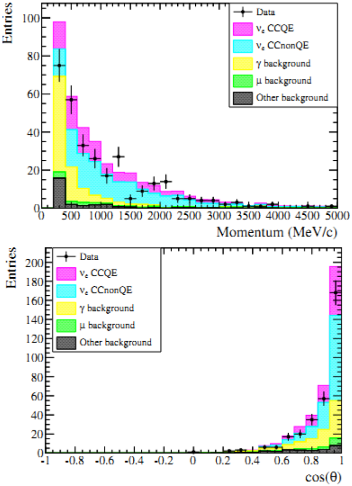
$CCother$





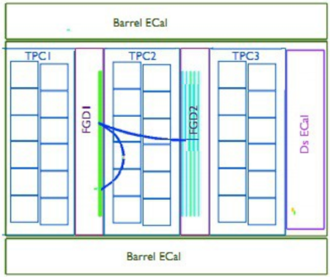
Differential Cross Section

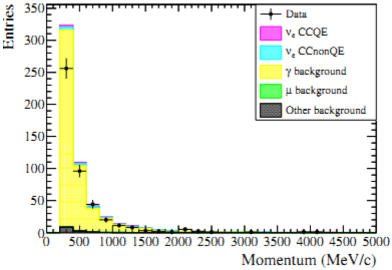
- select ν_e events, e.g: highest momentum negative track, starts at FGD1, TPC and ECAL PIDs
- We measure the Differential Cross Section w.r.t electron momentum "P(e)", electron angle "cos(Θ_e)" or the four momentum transfer "Q_e^2".
- $N_{t_k} = T\phi \int \langle \frac{\partial\sigma}{\partial X} dX \rangle_\phi$
  with:
  N_{t_k} : nb of true interaction at bin k
  T : nb of target nucleons
  ϕ : total flux
  X : refers to P(e), cos(Θ_e) or Q_e^2
- Total Cross Section $\langle \sigma_\phi \rangle = \frac{N_{total}}{T\phi}$
  with N_{total} : total sum of bins t_k



Gamma Background

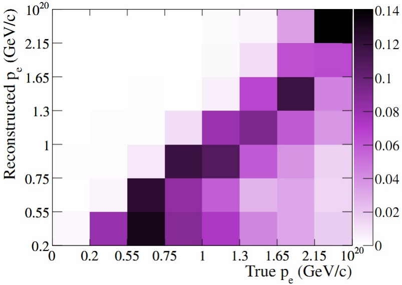
- The main background is photon conversion into e^+ e^- pair $\gamma \longrightarrow e^+e^-$
- Background could be suppressed by rejecting events having tracks with start position not in FGD, or if a particle with mass <100 MeV was found beside the track.





Bayesian Unfolding (Correction for detectors inefficiencies and mis-reconstruction.)

- $N_{t_K}^{m+1} = \frac{1}{\epsilon}\sum_j P_m(t_k|r_j)(N_{r_j}^{meas} - B_{r_j})$



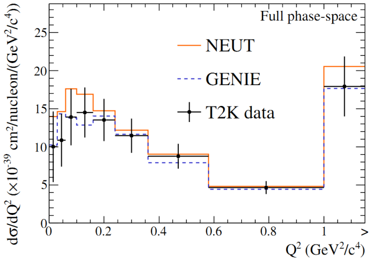
[Smearing Matrix $P(r_j|t_k)$]

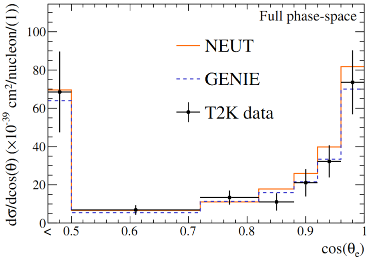
with :

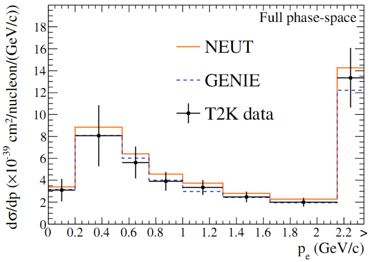
- N_{t_k} : Estimator for true signal event in bin k
- ϵ_{t_k} : Reconstruction efficiency
- $P_m(t_k|r_j)$: Probability at iteration m to have a true event at bin k given a reconstructed event at bin j
- B_{r_j} : Background

T2K ν_e CC-Inclusive XSec results

- Q_e^2 Represent the main results as it is the most interesting kinematic variable and has the smallest systematic error.

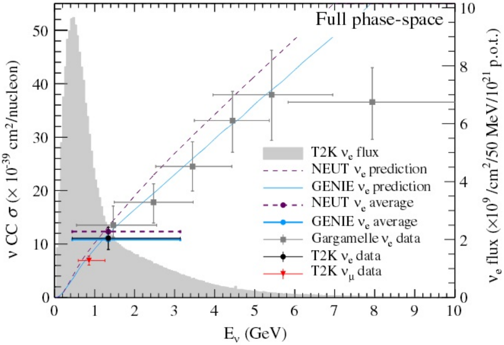






T2K ν_e CC-Inclusive XSec results II

The measured cross section flux average:
$1.11 \pm 0.20x10^{-38} cm^2/nucleon$
is in agreement with:
NEUT ($1.23x10^{-38} cm^2/nucleon$)
and GENIE ($1.07x10^{-38} cm^2/nucleon$)

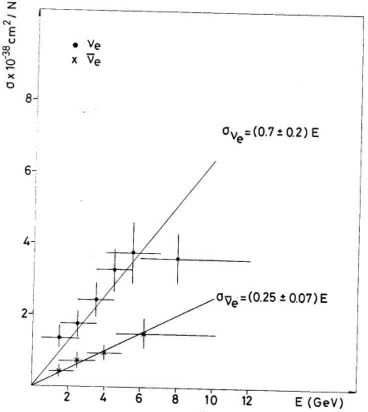


[K.Abe2014]

$\overline{\nu_e}$ Cross Section Measurement

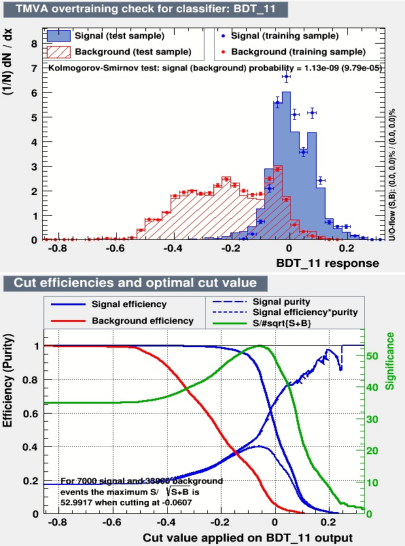
Measurement of the $\overline{\nu_e}$ Charged Current Inclusive Cross Section using Bayesian Unfolding Technique.

- First time to be measured at T2K.
- Latest published results are from the Gargamelle experiment (1970's).
- Use of machine learning algorithms to classify event and eliminate backgrounds.



[J.Blietschau1978]

MVA PID



Developed a Multivariate (Boosted Decision Tree) tool for track identification.

Motivation:

- Look for ways of better identifying gamma and proton background events.
- Use information from FGDs, TPCs, and ECALs.
- Boosted Decision Tree (Root TMVA).
- May help in increasing the selection efficiency and signal purity (not tested on our case yet).
- May help in finding hidden pattern in our data.

Conclusion

- Neutrino cross section is an important and interesting quantity to be measured.
- T2K ν_e CC-Inclusive measured cross section ($1.11 \pm 0.20x10^{-38} cm^2/nucleon$) is in agreement with that predicated by neutrino event generators like NEUT and GENIE.
- Next step is to measure the $\overline{\nu_e}$ cross section.
- The use of a machine learning algorithm in particle identification looks promising.

References

[PDG2010] Review of Particle Physics, Particle Data Group, Journal of Physics G, Nuclear and Particle Physics, Volume 37 Number 7A Article 075021 [July 2010]

[L.Southwell2014] Selecting ν_e charged-current events in the near detector at T2K, Luke Southwell

[B.Jamieson2014] T2K Results Blair Jamieson for the T2K Collaboration HSQCD2014

[J.Blietschau1978] Total cross sections for ν_e and $\overline{\nu_e}$ interactions and search for neutrino oscillations and decay, Nuclear Physics B, Elsevier, 1978, 133, pp.205-219 J. Blietschau et al.

[PDG2013] Particle Data Group, Neutrino Cross Section Measurements [2013]

[B.Smith2014] Measurement of the ν_e CC Inclusive Cross-section on Carbon Using Data From Runs 1 - 4 , B. Smith [August 30, 2014]

[IntrinsicNueT2K2014] Measurement of the intrinsic electron neutrino component in the T2K neutrino beam with the ND280 detector, the T2K Collaboration [March 11, 2014]

[T.Dorigo] Electron Neutrino In T2K, T.Dorigo [Apr 4, 2013]

Measurement of the Inclusive Electron Neutrino Charged Current Cross Section on Carbon with the T2K Near Detector, K. Abe et al. (T2K Collaboration) Phys. Rev. Lett. 113, 241803 [December 2014]

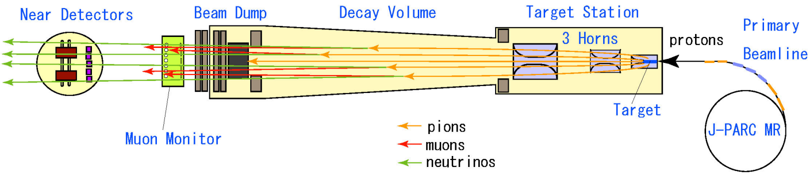
T2K Collaboration

The T2K collaboration includes about 500 physicists from 11 countries (Canada, France, Germany, Italy, Japan, Poland, Russia, Spain, Switzerland, UK, USA).

Thank You

Backup Slides

Beam Production



- Produced by(J-PARC), protons are accelerated up to 31 GeV/c, extracted in 5 μs long spills with a repetition rate that of 2.6 s.
- The protons strike a 91.4 cm long graphite target, producing hadrons, mainly pions and kaons.
- To produce mainly ν_μ, the charged particles can then be focused by a series of three magnetic horns operating at 250 kA before entering a 96 m long decay volume.
- Most of the surviving charged particles are stopped by the beam dump at the end of the decay volume.
- A muon monitor (MUMON) measures the profile of high energy muons not stopped by the beam dump, monitoring the stability of the beam intensity and the direction of the beam.

Beam Production II

Different decay modes with their corresponding branching ratios are given below.

$$\pi^- \longrightarrow \mu^- + \overline{\nu_\mu} \qquad (\sim 99.98\%). \tag{1}$$

$$K^- \longrightarrow \mu^- + \overline{\nu_\mu} \qquad (\sim 63.55\%). \tag{2}$$

$$K^- \longrightarrow \pi^- + \pi^0 \qquad (\sim 20.66\%). \tag{3}$$

$$K^- \longrightarrow \pi^- + \pi^- + \pi^+ \qquad (\sim 5.59\%). \tag{4}$$

$$K^- \longrightarrow e^- + \overline{\nu_e} + \pi^0 \qquad (\sim 5.07\%). \tag{5}$$

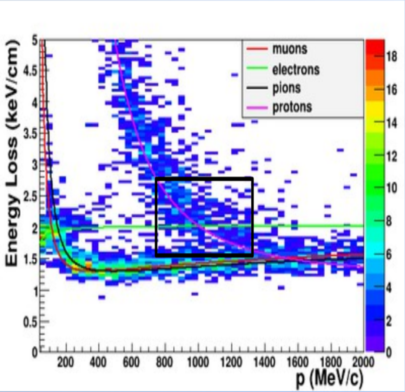
$$K^- \longrightarrow \mu^- + \overline{\nu_\mu} + \pi^0 \qquad (\sim 3.35\%). \tag{6}$$

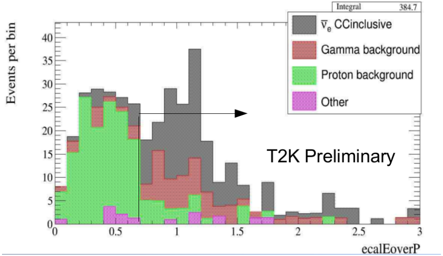
$$K^- \longrightarrow \pi^- + \pi^0 + \pi^0 \qquad (\sim 1.76\%). \tag{7}$$

$$\mu^- \longrightarrow e^- + \overline{\nu_e} + \nu_\mu \qquad (\sim 100\%). \tag{8}$$

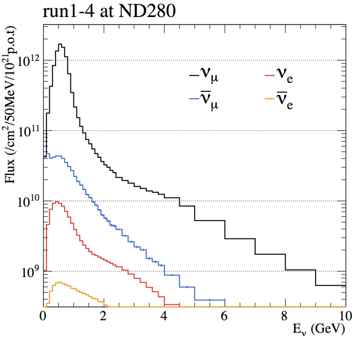
[PDG2010]

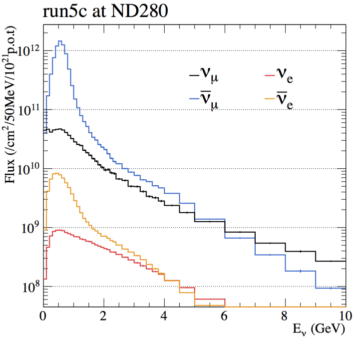
Proton Background



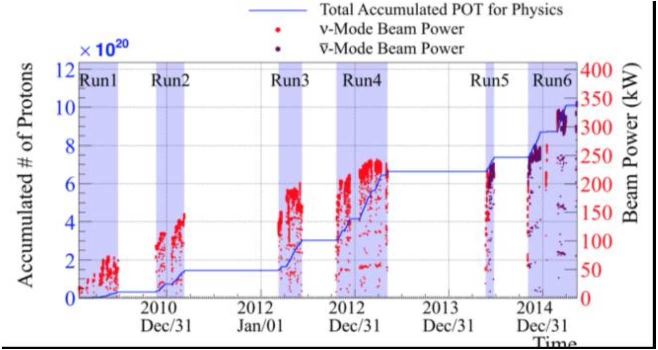


Flux Prediction





$\overline{\nu_e}$ available POT data



- Stable operation at 345kW
- $10.3x10^{20}$ (total) $= 7.0x10^{20}(\nu) + 3.3x10^{20}(\overline{\nu})$ accumulated (Jan 23, 2010 to May 13, 2015)

Expected $\overline{\nu_e}$ CCinclusive events

- expected to have: $4.5x10^{20}$ POT by the end of May 2015 run
- expected to have: 6 (Run 5 CC inclusive events Ref.[B.Smith2014]) x $\frac{4.5x10^{20}(expected\ \ accumulated\ \ POT)}{2.5x10^{19}(Run\ \ 5\ \ POT)} \sim 108 events$

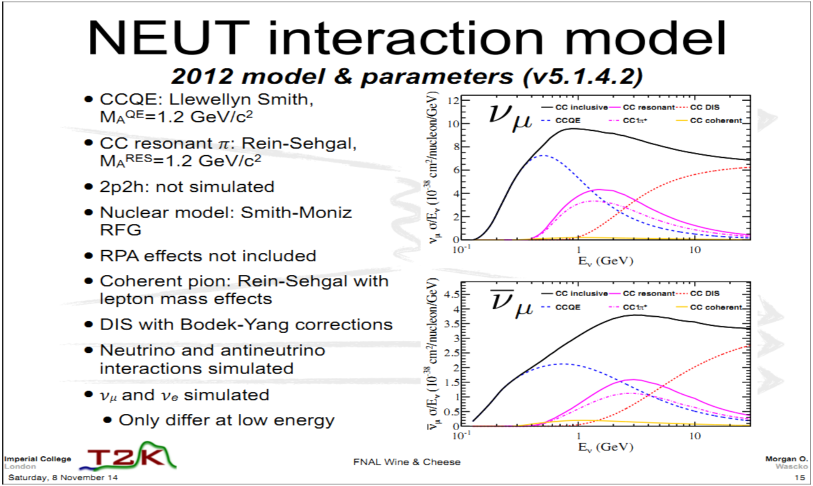
Neutrino Interaction Model (slides from Morgan Waskow, Imperial College)

ν-nucleus interaction models

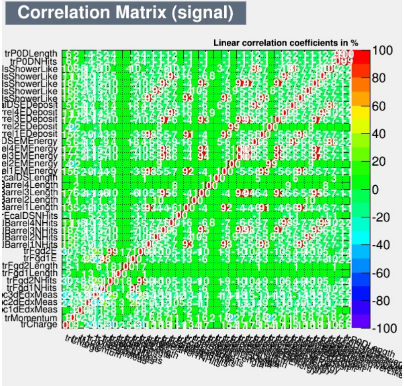
- T2K's primary neutrino generator MC is NEUT
  - Used by SK, SciBooNE, K2K
  - Tuned with fits to external data sets
  - 2012: mainly MiniBooNE CCQE, CC1π^+, CC1π^0, NC1π^0
    - Fits used to tune model parameters for prior inputs to oscillation analysis
    - Constrained and cross-checked with SciBooNE and K2K data
  - 2014: MiniBooNE and MINERvA ν and $\bar{\nu}$ data sets
    - Fits used to down select default interaction model and tune parameters for prior inputs to oscillation analysis
  - Working on a publication to describe the model and the fit procedure
- Also use GENIE and NuWro for cross-check analyses, systematic errors studies, and deeper inquiries into neutrino interactions

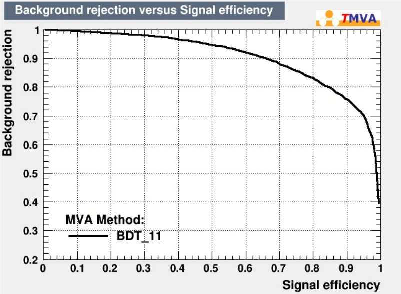
Imperial College London T2K   FNAL Wine & Cheese   Morgan O. Wascko
Saturday, 8 November 14   14

Neutrino Interaction Model (slides from Morgan Waskow, Imperial College)

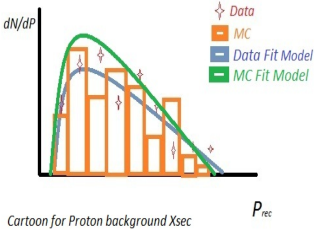


Example of MVA training to select electron like tracks

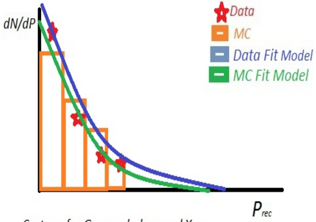




$\overline{\nu_e}$ CC-Inclusive XSec Measurement strategy



Cartoon for Proton background Xsec contribution

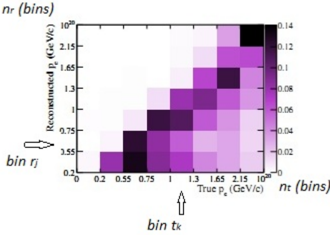


Cartoon for Gamma bakground Xsec contribution

- Get separate sample of γ and protons.
- Compare momentum event spectrum of background sample to simulation.
- Fit a model $N_\gamma(P_{rec}, \vec{a}), N_{proton}(P_{rec}, \vec{b})$.
- From the fit get model uncertainty from difference between data and MC.
- Use a Bayesian unfolding with background subtraction to get cross section as function of E_ν, Q^2.

Bayesian Unfolding Details

- $N_{t_k} = \sum_j S_{r_j t_k} + M_{t_k}$
- $P(r_j|t_k) = \frac{S_{r_j t_k}}{N_{t_k}}$
- $\epsilon_{t_k} = \frac{\sum_j S_{r_j t_k}}{N_{t_k}}$
- $P_m(t_k|r_j) = \frac{P(r_j|t_k)P_{t_k}}{\sum_\alpha P(r_j|t_\alpha)P_{t_\alpha}}$
- $N_{t_K}^{m+1} = \frac{1}{\epsilon} \sum_j P_m(t_k|r_j)(N_{r_j}^{meas} - B_{r_j})$



with :

- N_{t_k} : Estimator for true signal event in bin k
- $S_{r_j t_k}$: Signal matrix,i.e the number of true simulated signal events in true bin t_k that were reconstructed in bin r_j
- M_{t_k}: Missed vector,i.e number of simulated signal events in true bin t_k that were not selected
- ϵ_{t_k} : Reconstruction efficiency
- $P_m(t_k|r_j)$: Probability at iteration m to have a true event at bin k given a reconstructed event at bin j
- B_{r_j} : Background