Neutrino Interaction Cross-Section Measurements from the T2K Collaboration

David Payne on behalf of the T2K Collaboration
The T2K Experiment

Super-Kamiokande looks at neutrinos after 295km journey

Super-K looks at neutrinos after 295km journey

Near detectors look at ~initial state of neutrinos

Neutrinos produced

J-PARC
The Beam

- Off-axis beam
- Direction of horn current used to focus neutrinos or anti neutrinos
Protons On Target

Total Accumulated POT for Physics

ν-Mode Beam Power

¯ν-Mode Beam Power

Accumulated POT

× $10^{20}$

Run1  Run2  Run3  Run4  Run5  Run6  Run7


Dec/31 Jan/01 Dec/31 Dec/31 Dec/31 Jan/01

Beam Power (kW)

0 100 200 300 400 500

0 2 4 6 8 10 12 14 16 18
At 280m, off Axis: ND280
At 280 m, on Axis: INGRID
Neutrino interactions

Quasi-elastic (CCQE)

Resonance

Deep Inelastic Scattering (DIS)

Coherent $\pi$ Production

Intra-nuclear Effects
Neutrino Interactions

- Low energy: nucleus interaction
- High energy: nucleon interaction
- Intermediate energy: “a complex combination of quasi-elastic (QE) scattering, resonance production, and deep inelastic scattering processes, each of which has its own model and associated uncertainties”
  - SNOWMASS (arXiv:1310.4340v1 [hep-ex])

T2K energy range
Cross Section of $\nu_\mu$ CCQE on Carbon at INGRID

- (CCQE – Charged Current Quasi Elastic)
- Uses special proton module as target
- Events split into low energy (<1.5GeV) and high energy (>1 GeV) by penetration of muon

$\sigma_{\text{CCQE}}(1.94\text{GeV}) = 11.95 \pm 0.19^{+1.82}_{-1.47} \times 10^{-39} \text{ cm}^2/\text{neutron}$

$\sigma_{\text{CCQE}}(0.93\text{GeV}) = 10.64 \pm 0.37^{+2.03}_{-1.65} \times 10^{-39} \text{ cm}^2/\text{neutron}$

Phys. Rev. D 91,112002
Measurement of $\nu_\mu$ CC-Inclusive Cross Section on Iron at INGRID

- Doesn’t use proton module
- Events split into energy categories by predicted energy profile of module and contained/non-contained event
- Phys. Rev. D 93, 072002 (2016)

$\sigma_{CC}(1.1 \text{ GeV}) = 1.10 \pm 0.15 \times 10^{-38} \text{ cm}^2/\text{nucleon}$

$\sigma_{CC}(2.0 \text{ GeV}) = 2.07 \pm 0.27 \times 10^{-38} \text{ cm}^2/\text{nucleon}$

$\sigma_{CC}(3.3 \text{ GeV}) = 2.29 \pm 0.45 \times 10^{-38} \text{ cm}^2/\text{nucleon}$
Measurement of $\nu_\mu$ CCQE Cross Section on Carbon at ND280

- ND280 lets us measure energy, direction
- $\sigma^{\text{CCQE}}(\text{FI}) = 0.83 \pm 0.12 \times 10^{-38} \text{ cm}^2$
- Axial mass $M^{\text{QE}}_A$ parameter was measured* to be $1.26^{+0.21}_{-0.18} \text{ GeV/c}^2$
  - (Shape only $1.43^{+0.28}_{-0.22} \text{ GeV/c}^2$)

*Assumptions: Smith-Moniz CCQE model with a relativistic Fermi gas nuclear model

Phys. Rev. D 92, 112003
$\nu_\mu$ Charged Current Interactions on Carbon; Double Differential Cross Section

• Flux-integrated cross section in terms of $(\cos\theta_\mu, p_\mu)$ of outgoing $\mu$ for model independence

• Two separate analyses with different selections, backgrounds and cross section extraction methods used to demonstrate robustness of result

• Analysis 1: Binned likelihood fit

• Analysis 2: Bayesian unfolding
Double Differential Cross Section continued

• Good agreement between methods
• Compares favourably with recent models (nucleon-nucleon correlations)
• Cannot distinguish between models with current precision
• Good agreement with MC tuned to external data to describe nuclear effects

\[ \sigma_{CCQE}(\text{Full phase space}) = 0.417 \pm 0.047 \pm 0.005 \ (10^{-38}\text{cm}^2/\text{nucleon}) \]

\[ \sigma_{CCQE}(\text{Best S/B}) = 0.202 \pm 0.036 \pm 0.003 \ (10^{-38}\text{cm}^2/\text{nucleon}) \]
# Summary of Published Results

<table>
<thead>
<tr>
<th>Result</th>
<th>Beam</th>
<th>Target</th>
<th>Published</th>
<th>Summary</th>
</tr>
</thead>
</table>
| CCQE                        | On Axis    | Carbon | Phys. Rev. D 91,112002 | $\sigma_{\text{CCQE}}(1.94\text{GeV}) = 11.95 \pm 0.19^{+1.82}_{-1.47} \times 10^{-39} \text{cm}^2/\text{neutron}$  
$\sigma_{\text{CCQE}}(0.93\text{GeV}) = 10.64 \pm 0.37^{+2.03}_{-1.65} \times 10^{-39} \text{cm}^2/\text{neutron}$ |
| Inclusive CC                | On Axis    | Iron   | Phys. Rev. D 93, 072002 | $\sigma_{\text{CC}}(1.1 \text{GeV}) = 1.10 \pm 0.15 \times 10^{-38} \text{cm}^2/\text{nucleon}$  
$\sigma_{\text{CC}}(2.0 \text{GeV}) = 2.07 \pm 0.27 \times 10^{-38} \text{cm}^2/\text{nucleon}$  
$\sigma_{\text{CC}}(3.3 \text{GeV}) = 2.29 \pm 0.45 \times 10^{-38} \text{cm}^2/\text{nucleon}$ |
| CCQE                        | Off Axis   | Carbon | Phys. Rev. D 92, 112003 | $\sigma_{\text{CCQE(FI)}} = 0.83 \pm 0.12 \times 10^{-38} \text{cm}^2$  
$\text{MAQE}=1.26^{+0.21}_{-0.18} \text{GeV}^2/\text{c}^2$ (Absolute)  
$\text{MAQE}=1.43^{+0.28}_{-0.22} \text{GeV}^2/\text{c}^2$ (Shape) |
| CCQE double differential    | Off Axis   | Carbon | Accepted by PRD | $\sigma_{\text{CCQE(Full phase space)}} = 0.417 \pm 0.047 \pm 0.005 \times 10^{-38} \text{cm}^2/\text{nucleon}$  
$\sigma_{\text{CCQE(Best S/B)}} = 0.202 \pm 0.036 \pm 0.003 \times 10^{-38} \text{cm}^2/\text{nucleon}$ |
ND280 CC1π+ Cross Section on Water (preliminary)

- Selects for events interacting in water.

\[ <\sigma>_\phi = 4.25\pm0.48({\text{stat}})\pm1.56({\text{syst}}) \times 10^{-40}\, \text{cm}^2/\text{nucleon} \]
In Conclusion

• Cross-section results vital for understanding neutrino interactions
  • Vital for all other neutrino results

• T2K has many cross-section results already published

• And many on the way
  • Bigger datasets
  • Anti-neutrinos
  • Multivariate technique for $\nu_\mu$ charged-current coherent pion production
  • Double-differential CCQE-like on water (unfolding and subtraction)

• Thanks!
The T2K Collaboration
Backup Slide: Double Differential vs models

Backup Slide: Double Differential vs models — with and without correlations