Recent Neutrino Cross Section Results from T2K

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for the T2K Collaboration

Colorado State University
Outline

• The T2K experiment
• Neutrino Oscillations and Cross sections
• T2K Cross Section Results
• Upcoming Results
• Summary
The T2K Experiment

- Tokai-to-Kamioka (T2K): Neutrino Oscillation experiment
  - Location: Japan
  - Baseline: ~295 km
  - Far Detector: Super-Kamiokande
  - Near Detectors: In J-PARC campus

- **Beam**: J-PARC Lab
  - Beam: 30 GeV proton beam
  - Designed to produce ~0.6 GeV $\nu_\mu$
T2K Beam

- Off-axis experiment
- Beam is aimed 2.5° off the direction to the Super-K (FD)
  - Narrow-band $\nu$ beam
  - Reduce background from high energy tail
T2K Near Detectors

• On-Axis:
  ▪ INGRID
    ○ 16 Modules of Iron and Scintillator
T2K Near Detectors

• On-Axis:
  - INGRID
    - 16 Modules of Iron and Scintillator

• Off-Axis (ND280):
  - Pi-Zero Detector (PØD)
  - Tracker
    - 3 Time Projection Chambers (TPC)
    - 2 Fine Grain Detectors (FGD)
  - Surrounded by Electromagnetic Calorimeters
  - Housed inside the Magnet of the UA1
T2K Far Detector

• Super-Kamiokande (SK)

- 50 kton Water Cherenkov detector
- 41.4 m high, 39.3 m in diameter
- 13k phototubes
- Very efficient in $\mu/e$ separation

Detection of $\nu_\mu + n \rightarrow p + \mu^-$
Detection of $\nu_e + n \rightarrow p + e^-$

Muon track creates “sharp” ring
Electron track creates “fuzzy” ring
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• **Neutrino Oscillations and Cross sections**

• T2K Cross Section Results

• Upcoming Results

• Summary
Neutrino Oscillation

• T2K Oscillation results

\[ \nu_\mu \rightarrow \nu_e \text{ Appearance} \]

\[ \nu_\mu \rightarrow \nu_\mu \text{ Disappearance} \]
Neutrino Oscillation

• T2K Oscillation results

\[ \nu_\mu \rightarrow \nu_e \text{ Appearance} \]

\[ \nu_\mu \rightarrow \nu_\mu \text{ Disappearance} \]

For “Best fit” and background prediction

T2K needs: a Near Detector to constrain

(unoscillated) Beam flux \times \nu \text{ Cross section}
Oscillations and Cross Sections

Cross section model (MC)
  External data tuning
    (Minerva and/or MiniBooNE)

Flux model
  External data from
    NA61 (CERN)

Priors to the
  ND fit(s)
Oscillations and Cross Sections

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Near Detector data fit
  Tune cross section, flux and background parameters to the ND data sets
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Near Detector data fit
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Parameter | Before ND constraint | After ND constraint
--- | --- | ---
$M_A^{QE}$ (GeV/c$^2$) | 1.21±0.45 | 1.24±0.07
$E_B$ ($^{12}$C) (MeV) | 25±9 | 30.9±5.2
$p_F$ ($^{12}$C) (MeV/c) | 217±30.0 | 266.3±10.6
CCQE norm $E_\nu < 1.5$ GeV | 1.00±0.11 | 0.97±0.08
CCQE norm $1.5 < E_\nu < 3.5$ GeV | 1.00±0.30 | 0.93±0.10
CCQE norm $E_\nu > 3.5$ GeV | 1.00±0.30 | 0.93±0.10
$M_A^{RES}$ (GeV/c$^2$) | 1.41±0.11 | 0.96±0.07
$\pi$-less $\Delta$ decay fraction | 0.20±0.20 | 0.21±0.08
CC1$\pi^0$ norm $E_\nu < 2.5$ GeV | 1.15±0.43 | 1.26±0.16
CC1$\pi^0$ norm $E_\nu > 2.5$ GeV | 1.00±0.40 | 1.12±0.17
CC coherent norm | 1.00±1.00 | 0.45±0.16
NC$\pi^0$ norm | 0.96±0.43 | 1.13±0.25
CC other shape | 0.00±0.40 | 0.23±0.29
NC other norm | 1.00±0.30 | 1.41±0.22
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Near Detector data fit
Tune cross section, flux and background parameters to the ND data sets

Priors to the FD fit(s)
Oscillations and Cross Sections

Cross section model (MC)
- External data tuning
  (Minerva and/or MiniBooNE)

Flux model
- External data from
  NA61 (CERN)

Near Detector data fit
Tune cross section, flux and background
parameters to the ND data sets

Constrain FD flux and subset
of cross section parameters
and extracts an event rate
prediction at the FD

Priors to the
FD fit(s)

$\nu_\mu \rightarrow \nu_e$ Appearance

$\nu_\mu \rightarrow \nu_\mu$ Disappearance
Oscillations and Cross Sections

Cross section model (MC)
External data tuning
(Minerva and/or MiniBooNE)

Flux model
External data from
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Near Detector data fit
Tune cross section, flux and background parameters to the ND data sets

Constrain FD flux and subset of cross section parameters and extracts an event rate prediction at the FD

Errors reduced by a factor of ~3-4

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Far Detector data fit
Use the combination of ND and
external errors in oscillation fits at FD

$\nu_\mu \rightarrow \nu_\mu$ Disappearance

Events/0.1 GeV

Reconstructed $\nu$ Energy (GeV)
Oscillations and Cross Sections

Cross section model (MC)
External data tuning
(Minerva and/or MiniBooNE)

Flux model
External data from
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Near Detector data fit
Tune cross section, flux and background
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Constrain FD flux and subset of cross section parameters
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Far Detector data fit
Use the combination of ND and external errors in oscillation fits at FD

ν cross section are key ingredients

νμ → νμ Disappearance

Events/0.10 GeV

Data
MC Unoscillated Spectrum
MC Best Fit Spectrum
NC MC Prediction

Reconstructed ν Energy (GeV)
T2K Cross Sections

- T2K $\nu_\mu$ beam energy peaks $\sim 0.6$ GeV
T2K Cross Sections

• T2K $\nu_\mu$ beam energy peaks $\sim 0.6$ GeV
• Charge Current (CC)

$v$ CC Cross Sections

T2K $v$ beam energy, 0.6 GeV
T2K Cross Sections

- T2K $\nu_\mu$ beam energy peaks $\sim$0.6 GeV
- Charge Current (CC)
  - CC Quasi Elastic (CCQE)

![Diagram of T2K neutrino beam energy, 0.6 GeV]
T2K Cross Sections

- T2K $\nu_\mu$ beam energy peaks ~0.6 GeV
- Charge Current (CC)
  - CC Quasi Elastic (CCQE)
  - CC RESonance or CC $1\pi$

\[ \nu_\mu \rightarrow \mu^- + p + \pi^- + \Delta^{++} \]

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$\gamma$ cross section / $E_\nu$ ($10^{-38}$ cm$^2$/GeV)

T2K $\nu$ beam energy, 0.6 GeV
T2K Cross Sections

- T2K $\nu_\mu$ beam energy peaks ~0.6 GeV
- Charge Current (CC)
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  - CC RESonance or CC $1\pi$
  - $>\text{few GeV}$ DIS processes will dominate
T2K Cross Sections

- T2K $\nu_\mu$ beam energy peaks $\sim 0.6$ GeV
- Charge Current (CC)
  - CC Quasi Elastic (CCQE)
  - CC RESonance or CC $1\pi$
  - $> \text{few GeV}$ DIS processes will dominate
- Neutral Current (NC)
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T2K Cross Section Results

- **On-axis near detector**
  - $\nu_\mu$ CC inclusive on Fe and on CH
- **Off-axis near detector**
  - $\nu_e$ CC inclusive on C
  - $\nu_\mu$ NCE (exclusive) on C and O
- **Far detector**
  - $\nu_\mu$ NCE (exclusive) on O
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• On-axis near detector
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$\nu_\mu$ CC Inclusive on Fe and on CH

- Motivation
  - Very few $\nu$ cross sections on heavy nuclei
  - We have other heavy target material (Pb, Cu-Zn, . . )
$\nu_{\mu}$ CC Inclusive on Fe and on CH

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  - Identify the $\mu^-$ track in an interaction starting within a central module
  - $\mu^-$ candidate: should be in-time with the beam and the longest track.
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• Measurement method
  ▪ Cross section extracted from
    \[ \sigma_{CC} = \frac{N_{sel} - N_{BG}}{\phi T \varepsilon} \]
    $\phi$ = integrated $\nu_\mu$ flux,  
    $T$ = # target nucleons,  
    $\varepsilon$ = detection efficiency
  ▪ Inputs to the calculations (w/ corrections)

<table>
<thead>
<tr>
<th></th>
<th>$N_{sel}$</th>
<th>$N_{BG}$</th>
<th>$\varphi [\times 10^{13}/cm^2]$</th>
<th>$T$</th>
<th>$\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{CC}^{Fe}$</td>
<td>523045</td>
<td>67838</td>
<td>2.999</td>
<td>$2.461 \times 10^{30}$</td>
<td>0.4270</td>
</tr>
<tr>
<td>$\sigma_{CC}^{CH}$</td>
<td>36330</td>
<td>5385.5</td>
<td>3.025</td>
<td>$1.799 \times 10^{29}$</td>
<td>0.4122</td>
</tr>
</tbody>
</table>
\( \nu_\mu \) CC Inclusive on Fe and on CH

- Results
  - Flux average CC inclusive cross section
    \[
    \sigma_{CC}^{Fe} = \left(1.444 \pm 0.002\,\text{(stat)} \pm^{+0.189}_{-0.157}\,\text{(syst)}\right) \times 10^{-38}\,\text{cm}^2/\text{nucleon}
    \]
    \[
    \sigma_{CC}^{CH} = \left(1.379 \pm 0.009\,\text{(stat)} \pm^{+0.178}_{-0.147}\,\text{(syst)}\right) \times 10^{-38}\,\text{cm}^2/\text{nucleon}
    \]
  - Dominated by flux systematic (~11.5%)

Note: NEUT and GENIE = \( \nu \) MC generators

PRD 90 (2014) 052010
\( \nu_\mu \) CC Inclusive on Fe and on CH

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    \]
  - Dominated by flux systematic (~11.5%)
  - Cross section ratio
    \[
    \frac{\sigma_{CC}^{Fe}}{\sigma_{CC}^{CH}} = 1.047 \pm 0.007\text{(stat)} \pm 0.035\text{(syst)}
    \]
    - Flux systematic mostly cancels out

Note: NEUT and GENIE = \( \nu \) MC generators
T2K Cross Section Results

- **On-axis near detector**
  - $\nu_\mu$ CC inclusive on Fe and on CH

- **Off-axis near detector**
  - $\nu_e$ CC inclusive on C
  - $\nu_\mu$ NCE (exclusive) on C and O

- **Far detector**
  - $\nu_\mu$ NCE (exclusive) on O
$\nu_e$ CC Inclusive Cross Section

- Motivation
  - $\nu_e$ contamination is the largest background in $\nu_\mu \rightarrow \nu_e$ Appearance
$\nu_e$ CC Inclusive Cross Section

- **Motivation**
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- **Events selection**
  - Identify the $e^-$ track in an interaction starting within FGD1
  - $e^-$ candidate: Highest momentum, negative charged track that pass electron TPC $dE/dx$ and ECal PID cuts.
  - Main background $\gamma \rightarrow e^+e^-$ treat
    - Veto activity upstream of FGD1
    - $e^+e^-$ invariant mass cut
ν_e CC Inclusive Cross Section

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    ▪ e^+e^- invariant mass cut
  ▪ Selected: 315 ν_e CC events
**ν_e CC Inclusive Cross Section**

- **Measurement method**
  - Cross section extracted from
    \[ \frac{d\langle\sigma\rangle_{\phi}}{dX} \bigg|_k = \frac{N_k}{\Delta X_k T \phi} \]
    - \( X = p_e, \cos\theta_e \) or \( Q^2 \),
    - \( \Delta X = \) bin width,
    - \( N_k = \) # signal events,
    - \( \phi = \) integrated \( \nu_\mu \) flux,
    - \( T = \) # target nucleons
  - Background constrained by a \( \gamma \) sideband

Note: \( \langle \rangle_{\phi} = \text{average on } \phi \)
\( \nu_e \) CC Inclusive Cross Section

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  - Differential distributions: \( p_e, \cos \theta_e \) and \( Q^2 \)
$\nu_e$ CC Inclusive Cross Section

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    - $N_k = \# \text{signal events}$,
    - $\phi = \text{integrated } \nu_\mu \text{ flux}$,
    - $T = \# \text{target nucleons}$
  - Background constrained by a $\gamma$ sideband

- Results
  - Differential distributions: $p_e$, $\cos \theta_e$ and $Q^2$
  - Total $\nu_e$ CC inclusive cross section
    $$\langle \sigma \rangle_\phi = 1.11 \pm 0.10 \text{(stat)} \pm 0.18 \text{(syst)} \times 10^{-38} \text{cm}^2/\text{nucleon}$$
  - Dominant systematics:
    - Flux (12.9%), Statistics (8.7%),
    - Detector (8.6%)

- First total $\nu_e$ cross section measurement since 1978
  (Gargamelle, Nucl. Phys. B 133, 205)
$\nu_\mu$ NCE on C and O
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- **Motivation**
  - The NCE is the analogous process to CCQE
  - A test to the hadronic part of QE scattering
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- Topology
  - Elastic interaction $\nu_\mu + p \rightarrow \nu_\mu + p$
    where only a proton was produced and nothing else (i.e. a proton “appears”)

D.Ruterbories, NuFact2013 Proceeding
$\nu_\mu$ NCE on C and O

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  - The NCE is the analogous process to CCQE
  - A test to the hadronic part of QE scattering

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  - Elastic interaction $\nu_\mu + p \rightarrow \nu_\mu + p$
  - where only a proton was produced and nothing else (i.e. a proton “appears”)

- **Events selection**
  - Identify the proton track in an interaction starting within the PØD
  - Proton candidate: Should pass a Proton dE/dx PID and be the only track in the event.
  - Remove events with a pion or muon decay
  - Main background CCQE (where muon was no reconstructed)
\[ \nu_\mu \text{ NCE on C and O} \]

- **Measurement method**
  - Cross section extracted from
  
  \[ \langle \sigma \rangle_\phi = \frac{N_{\text{select}} - N_{BG}}{\phi T \varepsilon} \]
  
  \( \phi = \) integrated \( \nu_\mu \) flux,
  \( T = \) # target nucleons,
  \( \varepsilon = \) selection efficiency

- **Results**
  - Flux average NCE cross section
  
  \[ \langle \sigma \rangle_\phi = 2.24 \times 10^{-39} \pm 0.07(\text{stat}) \pm 0.53(\text{syst}) \text{ cm}^2/\text{nucleon} \]

  - Dominated systematics:
    - Flux (~17\%-21\%),
    - Physics model parameters (14\%-16\%)

Note: \( \langle \rangle_\phi = \) average on \( \phi \)
T2K Cross Section Results

- **On-axis near detector**
  - $\nu_\mu$ CC inclusive on Fe and on CH
- **Off-axis near detector**
  - $\nu_e$ CC inclusive on C
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- **Far detector**
  - $\nu_\mu$ NCE (exclusive) on O
\( \nu_\mu \) NCE Cross section on O

- Motivation
  - Direct impact on the atmospheric background for low-energy phenomena in neutrino experiments
$\nu_\mu$ NCE Cross section on O

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  - Direct impact on the atmospheric background for low-energy phenomena in neutrino experiments

- **Topology**
  - We look for de-excitation $\gamma$s in SK’s lowest energy sample (4-30 MeV)
  - To be able to isolate $\gamma$s from NCE interactions on oxygen
$\nu_\mu$ NCE Cross section on O

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  - Direct impact on the atmospheric background for low-energy phenomena in neutrino experiments

- **Topology**
  - We look for de-excitation $\gamma$s in SK’s lowest energy sample (4-30 MeV)
  - To be able to isolate $\gamma$s from NCE interactions on oxygen

- **Events selection:**
  - Tight timing cut (around beam bunch time)
  - $4 \text{ MeV} < E_{\text{Reco}} < 30 \text{ MeV}$
  - Remove beam-related background
    - Reject likely decay electron events
    - Cherenkov angle cut $> 34^0$
  - **Observed:** 43 electron-like events
$\nu_\mu$ NCE Cross section on O

- Measurement method
  - Cross section extracted from
  \[
  \langle \sigma_{\text{NCQE}}^{\text{obs}} \rangle = \frac{N_{\text{obs}} - N_{\text{BG}}^{\text{exp}}}{N_{\text{exp}} - N_{\text{BG}}^{\text{exp}}} \langle \sigma_{\text{NCQE}}^{\text{theory}} \rangle
  \]
  - obs = observed in data
  - exp = expected by MC
  - BG = background
  \[
  \langle \sigma_{\text{NCQE}}^{\text{theory}} \rangle = 2.01 \times 10^{-38} \text{cm}^2 \ [\text{PRL 108 (2012) 052505}]$

\[ \langle \sigma_{NCQE}^{obs} \rangle = \frac{N_{obs} - N_{BG}^{exp}}{N_{exp} - N_{BG}^{exp}} \langle \sigma_{NCQE}^{theory} \rangle \]

- Measurement method
  - Cross section extracted from
    \[ \langle \sigma_{NCQE}^{theory} \rangle = 2.01 \times 10^{-38} \text{cm}^2 \] [PRL 108 (2012) 052505]

- Results
  - Flux-average $\nu$-Oxygen NCE
    \[ \langle \sigma_{NCQE}^{obs} \rangle = 1.55^{+0.71}_{-0.35} \times 10^{-38} \text{cm}^2/\text{nucleus} \]
  - Dominant systematics
    - Primary (15%) and secondary (13%) $\gamma$ productions
    - Flux uncertainty (10%)

- First measured $\nu$-Oxygen NCE cross section!
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Upcoming Results

• T2K $\nu$ run measurements
  ▪ $\nu_\mu$ CC-0$\pi$ (CCQE) cross section on C
  ▪ $\nu_\mu$ CC-1$\pi$ (CCRes) cross sections on C
  ▪ $\nu_\mu$ NCE differential cross section on O
  ▪ $\nu_\mu$-Pb cross section
Upcoming Results

• T2K $\nu$ run measurements
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• T2K Anti-$\nu_\mu$ runs (Started May 2014)
  T2K Far Detector
Upcoming Results

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  - $\nu_\mu$-Pb cross section

• T2K Anti-$\nu_\mu$ runs (Started May 2014)
  - Anti-$\nu_\mu$ Oscillation results
  - Anti-$\nu_\mu$ CC inclusive cross section
  - Anti-$\nu_\mu$/$\nu_\mu$ cross sections ratio

• ...
Summary

- Neutrino Physics has entered its precision measurement era
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• $\nu$-nucleus cross section knowledge – key ingredient
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• $\nu$-nucleus cross section knowledge – key ingredient
• T2K is making unique measurements with
  ▪ $\nu_\mu$, $\nu_e$ (and anti-$\nu$ coming soon)
  ▪ Off-axis, on-axis detectors and Far-Detector
  ▪ C, O, Fe and other materials (coming soon)
Summary

• Neutrino Physics has entered its precision measurement era
• $\nu$-nucleus cross section knowledge – key ingredient
• T2K is making unique measurements with
  - $\nu_\mu$, $\nu_e$ (and anti-$\nu$ coming soon)
  - Off-axis, on-axis detectors and Far-Detector
  - C, O, Fe and other materials (coming soon)
• More
  T2K measurements with better precision are on the horizon

For more information see http://t2k-experiment.org/results/
Recent Neutrino Cross Section Results from T2K

Erez Reinherz-Aronis
for the T2K Collaboration

Colorado State University
Additional material
T2K Collaboration

~500 members (337 authors), 59 institutes, 11 counters

Canada
U. Alberta
U. B. Columbia
U. Regina
U. Toronto
TRIUMF
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
U. Aachen

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tokyo Metro U.
U. Tokyo

Poland
NCBJ, Warsaw
IFJ PAN, Cracow
T. U. Warsaw
U. Silesia, Katowice
Duke U.

USA
Boston U.
Colorado S. U.
U. Colorado
U. C. Irvine
Louisiana S. U.
U. Pittsburgh
U. Rochester
Stony Brook U.
U. Washington

UK
Imperial C. L.
Lancaster U.
Liverpool U.
Queen Mary U. L.
Oxford U.
Sheffield U.
STFC/RAL

Switzerland
ETH Zurich
U. Bern
U. Geneva

Spain
IFIC, Valencia
IFAE, Barcelona

Russia
INR

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

UK
Imperial C. L.
Lancaster U.
Liverpool U.
Queen Mary U. L.
Oxford U.
Sheffield U.
STFC/RAL
Neutrino Oscillations

• In general, a state can be written

\[ |\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle \quad \text{i = mass state; } \alpha = \text{flavor state} \]

• From LEP: At least three neutrino types

• The mixing of flavor and mass eigenstates can be written as

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{bmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{bmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

• The PMNS (Pontecorvo–Maki–Nakagawa–Sakata) matrix
The PMNS Matrix

• A unitary 3x3 matrix → 4 degrees of freedom [assume the 3-flavor paradigm]
• Commonly parameterized by 3 mixing angles ($\theta_{12}$, $\theta_{23}$, $\theta_{13}$) and 1 phase ($\delta$)

$$U_{PMNS} = \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix}$$

“Solar ν’s”
Solar, Reactor
$\theta_{12} \approx 34^0$

“Reactor, Accelerator”
$\theta_{13} \approx 9^0$

“Atmospheric ν’s”
Atmospheric, Accelerator
$\theta_{23} \approx 45^0$

• Note:
Large mixing angles compare to the quark section (CKM)
$\theta_{12} \approx 13^0$
$\theta_{13} \approx 0.5^0$
$\theta_{23} \approx 2.3^0$
Oscillation Measurement

- Neutrino production and detection is determined by their flavor ($\nu_e, \nu_\mu, \nu_\tau$) eigenstates.
- But propagation through space is determined by their mass ($\nu_1, \nu_2, \nu_3$) eigenstates.
- How do we measure?

In general the techniques are similar.
T2K Results: J-PARC/Beam

- Protons-On-Target (POT) for T2K Runs 1-5

- Integrated nu beam mode: $\sim 6.9 \times 10^{20}$ POT
- Integrated anti-nu beam mode: $\sim 0.5 \times 10^{20}$ POT