Recent Results from T2K on Neutrino Oscillations and Interactions

Tianlu Yuan for the T2K Collaboration
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Neutrino Oscillation

- Possible if neutrinos have non-degenerate masses but are measured in non-mass (flavor) eigenstates $|\nu_i> = \sum_{\alpha} U_{\alpha i} |\nu_\alpha>$

- Mixing can be described by unitary transformation:

**Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix**

$$U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix} \begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\
0 & 1 & 0 \\
-s_{13} e^{i\delta_{CP}} & 0 & c_{13}
\end{pmatrix} \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 0
\end{pmatrix} \begin{pmatrix}
1 \\
e^{i\alpha_1/2} \\
e^{i\alpha_2/2}
\end{pmatrix}$$

**Dirac Mixing**

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

$$P_{\nu_\alpha \rightarrow \nu_\beta} (L, E) = \sum_{k,j} U^\ast_{k\alpha} U_{\beta k} U_{\alpha j} U^\ast_{\beta j} \exp \left( -i \frac{\Delta m^2_{kj} L}{2E} \right)$$

Experiments control $L/E$
4 Remaining Questions

\[ U = \begin{pmatrix}
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    0 & c_{23} & s_{23} \\
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\end{pmatrix} \begin{pmatrix}
    c_{12} & s_{12} & 0 \\
    -s_{12} & c_{12} & 0 \\
    0 & 0 & 0
\end{pmatrix} \begin{pmatrix} 1 \\ e^{i\alpha_1/2} \\ e^{i\alpha_2/2} \end{pmatrix} \]

1. \( \delta_{CP} \) (T2K + NOvA, DUNE, HyperK)

2. Dirac vs Majorana (EXO, Majorana, etc)

3. Mass Hierarchy (NOvA, DUNE, PINGU)

4. Absolute Mass (cosmology, tritium \( \beta \)-decay)

Matter effects can split degeneracy
1. Neutrinos produced here. Primarily $\nu_\mu$s.

2. Near detector at 280m provides on-axis and off-axis constraints on flux and background.

3. Off-axis (2.5°) beam travels 295km through earth to SK.
**Off-axis Effect**

- First exploited by T2K
- Energy of neutrinos from two-body π-decay, at angles relative to π momentum, is capped due to Lorentz boost
  - T2K has **narrowband** spectrum peaking at \(\sim 0.6\) GeV at 2.5° off-axis
- Maximizes oscillation probability at far detector and reduces high-E backgrounds

![Diagram of Off-axis Effect](image-url)
1. J-PARC accelerator produces 30GeV protons
2. T2K extracts protons after each acceleration cycle in 8 bunches
3. Protons impinge on graphite target \(\rightarrow\) secondary hadrons (mostly \(\pi^0\s\))
4. \(\pi^0s\) focused by magnetic horns
5. \(\pi^0s\) decay to (anti)neutrinos in 96m decay volume
On-axis Near Detector (INGRID)

- 16 identical cubic modules arranged vertically and horizontally
  - Each standard module a sandwich of 10 iron and 11 scintillator planes
- 1 “Proton Module” at center of cross
  - Finer scintillator planes and no iron
- Centered on beam
- Primary purpose beam monitoring
- Carbon and iron cross sections
Off-axis Near Detector (ND280)

- 2.5° off-axis
- Constrains off-axis flux and background rates
- Carbon and oxygen cross sections

- Scintillator-based Pi-zero detector (PØD) sits upstream of tracker
- Tracker consists time projection chambers interspaced with scintillator-based detectors for momentum reconstruction
- Surrounded by calorimeter, side muon detectors, and 0.2 T magnet
Far Detector – Super-Kamiokande

- 50 kton water Cherenkov detector
- 295 km away from beam source and 2.5° off-axis
- Inner detector (ID): ~11k PMTs
- Outer detector (OD): ~2k PMTs (Veto)

- Capable of distinguishing between e and μ based on shape distribution of Cherenkov radiation rings
General Steps for T2K’s Oscillation Analyses

- Simulate **neutrino flux** using hadron production models and constraints from NA61/SHINE
- Use **near detector** data to improve predictions at far detector
- Select $\nu_\mu$ ($\nu_e$) **candidate events** at far detector for disappearance (appearance) analysis
- Predict **expected number of events** after oscillation with oscillation model
- Construct **likelihood function** based on predicted and measured event rates while incorporating covariance matrices from various systematic sources and fit

![Image of T2K detector]

**General Steps for T2K’s**

**Oscillation Analyses**

- **Simulate** neutrino flux using hadron production models and constraints from NA61/SHINE
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- **Select** $\nu_\mu$ ($\nu_e$) candidate events at far detector for disappearance (appearance) analysis
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![Image of T2K detector]
Neutrino Flux

- Primarily $\nu_\mu$s in neutrino mode
- Other flavors mainly from decays of muons, kaons, and wrong-sign pions
- Wrong-sign contribution $\sim$3%
- Intrinsic beam $\nu_e$ a source of background in appearance analysis
  - $\sim$1.2% $\nu_e$ contamination

![T2K unoscillated flux prediction at SK for neutrino-mode running. Bands indicate the systematic uncertainty.](image-url)

**TABLE III. Contributions to the systematic uncertainties for the**

<table>
<thead>
<tr>
<th>Error source</th>
<th>Fractional Error</th>
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<tbody>
<tr>
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<tr>
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<td>Pion multiplicities</td>
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<td>Horn misalignment</td>
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<tr>
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<td>Proton beam, alignment and off-axis angle</td>
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</tr>
</tbody>
</table>
Neutrino Flux Uncertainties

- Sources include:
  - Hadron production model (largest)
  - Beam profile
  - Horn current, alignment
  - Other factors

- Vary underlying parameters and evaluate effect on flux prediction in $E_\nu$ bins

- Hadron production constraints from NA61/SHINE experiment

- Covariance between ND and SK flux allows for ND data constraint

Fractional systematic on $\nu_\mu$ flux at SK prior to ND constraints
Neutrino Interactions

- Rely on final state lepton from **charged-current** interactions to distinguish the neutrino flavor; final state topology to distinguish interaction channel.
- Important not just for oscillation analyses but also cross section measurements.

**Free nucleon**

- Quasielastic
- Resonance
- DIS

**Atomic Nucleus**

- Coherent \( \pi \)-Production
- Intranuclear Effects

Nuclear effects can alter final state kinematics and topologies.
Events in ND280

- Different interaction channels are governed by different models
- Need to select pure samples from each channel to provide better data constraints on models for both oscillation analyses and cross sections
- Event classification based on reconstructed kinematics and particle ID (PID)

**CC-inclusive** selection uses highest momentum negatively charged particle as $\mu^-$ candidate

For oscillation analysis, further subdivide based on final state after emerging from nucleus

- $0\ \pi^-$
- $1\ \pi^+$
- Other
Constraints from ND280

Binned likelihood fit of predicted $N^p$ to ND280 data $N^d$. $N^p$ (MC) dependent on flux, interaction, and detector parameters.

Effect of ND280 constraints on oscillated SK flux predicted with typical oscillation parameter values.
SK Event Selection

Out of all single-ring fully-contained fiducial volume events

**e-like**
- Electron-like ring
- $E_{\text{vis}} > 100$ MeV
- $N_{\text{michels}} = 0$
- $E_{v, \text{rec}} < 1250$ MeV
- Not $\pi^0$-like

**$\mu$-like**
- Muon-like ring
- $P_\mu > 200$ MeV/c
- $N_{\text{Michels}} < 2$

28 $\nu_e$ events
120 $\nu_\mu$ events
**\(v_e\) Appearance Analysis**

- 28 electron neutrino signal events detected compared to 4.92±0.55 expected background
- 7.3\(\sigma\) significance
- Oscillation parameters evaluated using binned maximum-likelihood fit

<table>
<thead>
<tr>
<th>Reconstructed neutrino energy (MeV)</th>
<th>Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>Best fit</td>
</tr>
</tbody>
</table>

**Best-fit value** of \(\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032} (0.170^{+0.045}_{-0.037})\)

for the normal (inverted) hierarchy and assuming \(|\Delta m^2_{32}| = 2.4 \times 10^{-3} \text{eV}^2\), \(\sin^2 \theta_{23} = 0.5\), \(\delta_{CP} = 0\).
\( \nu_e \) Appearance Constraints on \( \delta_{CP} \)

- Constrain \( \delta_{CP} \) using combined reactor \( \theta_{13} \) constraint term
- Combined T2K and reactor data prefers \( \delta_{CP} = -\pi/2 \)
- Excludes \( \delta_{CP} \) between \([0.19, 0.80]\pi\) for normal hierarchy at 90% C.L.

Marginalized likelihood as function of \( \delta_{CP} \) with 90% C.L. evaluated using Feldman-Cousins method

Phys.Rev.Lett. 112, 061802
v_\mu \text{ Disappearance Analysis}

Top: observed spectrum compared to unoscillated and best-fit prediction. Bottom: ratio of observed and best-fit to unoscillated prediction.

Best-fit $\sin^2 \theta_{23} = 0.514^{+0.055}_{-0.056} (0.511 \pm 0.055)$ and $\Delta m^2_{32} = (2.51 \pm 0.10) \times 10^{-3} \text{eV}^2 / c^4$ ($\Delta m^2_{13} = (2.48 \pm 0.10) \times 10^{-3} \text{eV}^2 / c^4$) for the normal (inverted) hierarchy.
Joint Analysis w/o Reactor Constraints

- Use both $\nu_\mu$ and $\nu_e$ data hence “joint analysis”
- Simultaneous fit to $|\Delta m^2|$, $\sin^2 \theta_{23}$, $\sin^2 \theta_{13}$, and $\delta_{\text{CP}}$

**NH best-fit:**

\[
\begin{align*}
\sin^2 \theta_{23} &= 0.524^{+0.057}_{-0.059}, \\
\sin^2 \theta_{13} &= 0.042^{+0.013}_{-0.021}, \\
\Delta m_{32}^2 &= 2.51^{+0.11}_{-0.12} \times 10^{-3} \text{eV}^2 / c^4
\end{align*}
\]

$\sin^2 \theta_{13}$ larger than reactor results of $0.0243 \pm 0.0026$
Joint Analysis with Reactor Constraints

- Additional $\chi^2_{\text{reactor}}$ term added to likelihood function
- External constraints from Daya Bay, RENO, and Double Chooz
- $(\sin^2 \theta_{13})_{\text{reactor}} = 0.0243 \pm 0.0026$

**Figure 33 (color online)**: Profiled parameter $\delta_{\text{CP}}(\pi)$ as a function of $\Delta m^2_{\text{sol}}$ (left) and $\Delta m^2_{\text{atm}}$ (right) for the joint three-flavor oscillation analysis combined with the results from reactor experiments.

**Equation 1**: The parameter $\delta_{\text{CP}}(\pi)$ represents $\delta_{\text{CP}}$, where $\delta_{\text{CP}}$ is the CP-violating phase and $\pi$ is the oscillation parameter.

**Equation 2**: The profiled parameter $\delta_{\text{CP}}(\pi)$ is excluded at 90% C.L. for NH with F-C method.

**Equation 3**: The profiled parameter $\delta_{\text{CP}}(\pi)$ is excluded at 90% C.L. for NH with F-C method.

**Equation 4**: The profiled parameter $\delta_{\text{CP}}(\pi)$ is excluded at 90% C.L. for NH with F-C method.

**Equation 5**: The profiled parameter $\delta_{\text{CP}}(\pi)$ is excluded at 90% C.L. for NH with F-C method.

**Equation 6**: The profiled parameter $\delta_{\text{CP}}(\pi)$ is excluded at 90% C.L. for NH with F-C method.

**Equation 7**: The profiled parameter $\delta_{\text{CP}}(\pi)$ is excluded at 90% C.L. for NH with F-C method.

**Equation 8**: The profiled parameter $\delta_{\text{CP}}(\pi)$ is excluded at 90% C.L. for NH with F-C method.

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**Equation 10**: The profiled parameter $\delta_{\text{CP}}(\pi)$ is excluded at 90% C.L. for NH with F-C method.

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**Equation 12**: The profiled parameter $\delta_{\text{CP}}(\pi)$ is excluded at 90% C.L. for NH with F-C method.

**Equation 13**: The profiled parameter $\delta_{\text{CP}}(\pi)$ is excluded at 90% C.L. for NH with F-C method.

**Equation 14**: The profiled parameter $\delta_{\text{CP}}(\pi)$ is excluded at 90% C.L. for NH with F-C method.

**Equation 15**: The profiled parameter $\delta_{\text{CP}}(\pi)$ is excluded at 90% C.L. for NH with F-C method.

**Equation 16**: The profiled parameter $\delta_{\text{CP}}(\pi)$ is excluded at 90% C.L. for NH with F-C method.

**Equation 17**: The profiled parameter $\delta_{\text{CP}}(\pi)$ is excluded at 90% C.L. for NH with F-C method.

**Equation 18**: The profiled parameter $\delta_{\text{CP}}(\pi)$ is excluded at 90% C.L. for NH with F-C method.

**Equation 19**: The profiled parameter $\delta_{\text{CP}}(\pi)$ is excluded at 90% C.L. for NH with F-C method.

**Equation 20**: The profiled parameter $\delta_{\text{CP}}(\pi)$ is excluded at 90% C.L. for NH with F-C method.

**Equation 21**: The profiled parameter $\delta_{\text{CP}}(\pi)$ is excluded at 90% C.L. for NH with F-C method.
Antineutrino Analyses

- 4.01E20 PoT in antineutrino mode
- Several now public appearance and disappearance analyses
- Ongoing effort for full $\nu$-$\bar{\nu}$ joint analysis

Comparison of best-fit and CLs from T2K $\nu$ and $\bar{\nu}$ disappearance analyses, as well as external results.

34 $\mu$-like events observed at SK.
Top: comparison of data to best-fit.
Bottom: ratio of data and best-fit to unoscillated prediction.

3 $e$-like events observed (~3.7 predicted. Currently not enough sensitivity to favor $\bar{\nu}_e$ appearance over non-oscillation.
Cross section at the Near Detector

- Cross section measurements are important for better interaction model constraints
- INGRID
  - Centered on beam (on-axis)
  - Carbon and iron targets
- ND280
  - 2.5° off-axis
  - Carbon and oxygen targets
- On-axis INGRID sees higher energy neutrinos
Recent Cross Section Measurements at T2K

- **INGRID**
  - $\nu_\mu$ charged-current quasielastic (CCQE) on carbon
  - $\nu_\mu$ inclusive charged-current on carbon
  - $\nu_\mu$ charged-current coherent pion production on carbon (preliminary)

- **ND280**
  - $\nu_\mu$ CCQE on carbon
  - Double differential CCQE on carbon (preliminary)

\[ \nu_\mu \rightarrow n + p + W^+ \]
\[ \nu_\mu \rightarrow p + p + \Delta^{++} + W^+ \]
\[ \nu_\mu \rightarrow d + u + p + W^+ \]
\[ \nu_\mu \rightarrow \pi, K, p \ldots \]

\[ \text{Nuclear} \]
\[ \text{Coherent } \pi\text{-Production} \]
\[ \text{Intranuclear Effects} \]
Measurement of $\nu_\mu$ CCQE at INGRID

Energy classification based on track topology in standard module

Low and high energy cross sections extracted for one track and two track samples.

Good agreement with predictions from models
Measurement of $\nu_\mu$ CCQE at ND280

- Binned likelihood fit to observed $p_\mu$-$\cos \theta_\mu$
- Parameterized in $E_\nu$
- Energy dependent cross section extracted

Flux integrated CCQE cross section:
$\sigma = (0.83 \pm 0.12)E^{-38}$ cm$^2$/neutron
Future Work

- Oscillation analyses in progress to perform joint neutrino-antineutrino analyses using full Runs 1-6 dataset
- Several ongoing cross section measurements
  - Multivariate technique for $\nu_\mu$ charged-current coherent pion production
  - Double differential CCQE-like on water using unfolding and subtraction
  - Antineutrino inclusive charged-current cross section on carbon
- Plan to keep taking antineutrino beam in 2016
- A lot of good progress in 2015! More work to be done for 2016!
Thank you

The presenter would like to acknowledge support from the US DoE
Backups
Comparison of Neutrino Flux in Neutrino and Antineutrino modes

T2K unoscillated flux prediction at SK for each neutrino type under neutrino-mode and antineutrino-mode running. Bands indicate the systematic uncertainty.
Neutrino Interaction Modeling

- Necessary to evaluate signal and background selection efficiencies
  - Needed for cross section measurements and accurate predicted spectra
  - NEUT is primary model with energies from ~100 MeV to ~100 TeV

- Elastic and quasi-elastic scattering: Llewellyn Smith model
  - Target nucleon is nucleus so rely on relativistic Fermi gas (RFG) model by Smith and Moniz
  - Spectral function (SF) for interactions on C and O

- Single pion production: Rein and Sehgal
  - Two steps: $\nu + N \rightarrow l + N^*$, $N^* \rightarrow \pi + N'$

- Deep inelastic scattering (DIS): Parton distribution function with Bodek-Yang corrections

- Final state interactions (FSI) due to intranuclear hadronic interactions
  - Cascade model steps hadron through nucleus and calculates interaction probabilities at each step
  - Examples: charge exchange, pion absorption/production
## Interaction Uncertainty Parameterization

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$E_\nu$/GeV Range</th>
<th>Units</th>
<th>Nominal</th>
<th>Error</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{QE}^A$</td>
<td>all</td>
<td>GeV/c$^2$</td>
<td>1.21</td>
<td>0.45</td>
<td>1</td>
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<td>$x_1^{QE}$</td>
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<td>0.11</td>
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<tr>
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<tr>
<td>$x_3^{QE}$</td>
<td>$E_\nu &gt; 3.5$</td>
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<tr>
<td>$p_F^{12C}$</td>
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<td>0.40</td>
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</table>

- Interaction uncertainties, $x$, parameterized as shown
- Category definitions
  1. Common between ND280 and SK and constrained by ND280 data
  2. Independent between ND280 and SK
  3. Common between ND280 and SK but negligible ND280 sensitivity
- Constrained by external data
  - $x^{FSI}$ constrained by pion-nucleus scattering data
  - MiniBooNE CCQE, inclusive single-$\pi$
INGRID Beam Monitoring and Constraints

Updated INGRID analysis with improved track reconstruction and better pileup handling.

Beam direction stability as measured by INGRID and the muon monitor. Stat errors shown.

Fractional uncertainties of SK $\nu_\mu$ flux due to beam direction uncertainty (w/o ND280 constraints).
ND280 Fits and Binning

Detector systematics

Observed events
π^0 Background Rejection

- Dominant background to ν_e signal: NCπ^0
- If one of two γs is missed or their rings overlap → misreconstructed as e-like
- Calculate maximum likelihoods for signal and π^0 hypotheses
  - Dependent on track parameters fitted to PMT q, t
- Impose cut dependent on likelihood ratio and reconstructed m_{γγ}

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**FIG. 23.** Efficiencies for rejecting NC photon conversion points. The common vertex and the directions and momenta of the two which point back to a common vertex. In addition to the charge and time contributions from two electron tracks, each track has an additional free parameter which allows one to reconstruct the rest of the decay products. The plots show the distribution of the likelihood ratio ln(L) for signal (ν,CCQE) and background (NCπ^0) events. The size of each box is proportional to the number of events the bin. The two figures use the same scale for representing the number of events and are normalized to the same POT.

**FIG. 22 (color online).** Two-dimensional distributions of the logarithm of the likelihood ratio ln(L) as a function of the energy of the less energetic γ and the reconstructed invariant mass of the electron hypothesis. Figure shows the improvement in rejection efficiency for rejecting NCπ^0 events from what is described above introducing the new method, which is different from the previous method. The new method reduces the background by roughly a factor of nine, as indicated by the diagonal line in the plot. The improvement in the selection efficiency for the appearance signal is also shown.

**Improved NCπ^0 rejection efficiency**
T2K-only:
Inverted, $|\Delta m^2_{32}| = 2.571 \times 10^{-3} \text{eV}^2 / c^4$, $\sin^2 \theta_{23} = 0.520$, $\sin^2 \theta_{13} = 0.0454$, $\delta_{CP} = 0$ (fixed)

Posterior probabilities for T2K-only analysis in the inverted hierarchy
Joint Bayesian Analysis

- ND280 $\nu_\mu$ and SK $\nu_\mu$, $\nu_e$ samples simultaneously fitted
  - No use of ND280 constraints

- Include priors on oscillation parameters
  - Uniform except when external constraints used (e.g. solar, reactor) then gaussian
  - 0.5 each for NH, IH

- Posterior numerically calculated using Markov Chain Monte Carlo (MCMC)

Most probable values T2K+reactor:

Normal, $|\Delta m^2_{32}| = 2.509 \times 10^{-3} \text{eV}^2 / c^4$,

$\sin^2 \theta_{23} = 0.528$, $\sin^2 \theta_{13} = 0.0250$, $\delta_{CP} = -1.601$
Measurement of $\nu_\mu$ CC-Inclusive at INGRID

- $\chi^2$ minimization fit to cross section normalization parameters
- Binned in $E_\nu$

Energy dependence from module where interaction occurred and topology

![Graph showing energy dependence and selected events](Image)

$\sigma^{CC}(1.1\,\text{GeV}) = 1.10\pm0.15\, (10^{-38}\,\text{cm}^2/\text{nucleon})$

$\sigma^{CC}(2.0\,\text{GeV}) = 2.07\pm0.27\, (10^{-38}\,\text{cm}^2/\text{nucleon})$

$\sigma^{CC}(3.3\,\text{GeV}) = 2.29\pm0.45\, (10^{-38}\,\text{cm}^2/\text{nucleon})$

Good agreement with models.
Measurement of $\nu_\mu$ CC-coherent at INGRID

- Flux-averaged cross section as calculated by:

$$\sigma_{CCcoh.\pi} = \frac{N_{sel} - N_{BG}}{\phi T \varepsilon},$$

Distribution of pion angle for selected events

90% CL upper limit:
$$\sigma_{CCcoh,\pi} < 1.9761 \times 10^{-39} \text{ cm}^2/\text{nucleus}$$
Double Differential $\nu_\mu$ CCQE-like at ND280

- Two independent analyses
  1. Binned likelihood fit
  2. Bayesian unfolding
- First double differential measurement in $p_\mu$-$\cos\theta_\mu$

In regions of equal binning, the two analyses agree within errors.