T2K NEUTRINO EXPERIMENT
RECENT RESULTS AND PLANS

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on behalf of the T2K Collaboration

H2020 Oscillation physics Workshop, Valencia
NEUTRINO OSCILLATIONS

Neutrino mixing: Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
0 & s_{13} e^{-i\delta_{CP}} \\
1 & 0 \\
0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\[c_{ij} = \cos \theta_{ij}\]
\[s_{ij} = \sin \theta_{ij}\]
\[\Delta m^2_{ij} = m_i^2 - m_j^2\]

Oscillations governed by *PDG 2016*

- three mixing angles:
  - \(\theta_{12} \approx 34^\circ, \theta_{13} \approx 9^\circ, \theta_{23} \approx 45^\circ\)
- two mass squared differences:
  - \(\Delta m^2_{21} \approx 7.6 \times 10^{-5} \text{ eV}^2\) and \(|\Delta m^2_{32}| \approx 2.4 \times 10^{-3} \text{ eV}^2\)
- source-detector baseline and neutrino energy

Open questions:
- CP-violation in lepton sector? \(\delta_{CP}\) value?
- Mass hierarchy (MH), “normal” (NH) or “inverted” (IH):
  - \(m_1 < m_2 \ll m_3\) or \(m_3 \ll m_1 < m_2\)?
- Octant of \(\theta_{23}\): <, > or \(\leq 45^\circ\)?
- Dirac/Majorana, steriles, CPT…
T2K (TOKAI-TO-KAMIOKA) EXPERIMENT

- World-leading neutrino oscillations physics project
- T2K — long-baseline neutrino oscillation accelerator experiment in Japan
- International collaboration:
  - ~500 members, 67 institutes, 12 countries
### T2K Experiment International Collaboration

#### ~ 500 members, 67 institutes, 12 countries

<table>
<thead>
<tr>
<th>Country</th>
<th>Organizations</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>CEA Saclay, IPN Lyon, LLR E. Poly., LPNHE Paris</td>
</tr>
<tr>
<td>Germany</td>
<td>Aachen</td>
</tr>
<tr>
<td>Japan</td>
<td>ICRR Kamioka, ICRR RCCN, Kavli IPMU, KEK</td>
</tr>
<tr>
<td>Switzerland</td>
<td>U. Bern, U. Geneva</td>
</tr>
<tr>
<td>Vietnam</td>
<td>IFIRS, IOP, VAST</td>
</tr>
<tr>
<td>Russia</td>
<td>INR RAS</td>
</tr>
<tr>
<td>Spain</td>
<td>IFAE, Barcelona, IFIC, Valencia, U. Autonoma Madrid</td>
</tr>
<tr>
<td>Switzerland</td>
<td>U. Liverpool, U. Sheffield, U. Warwick</td>
</tr>
<tr>
<td>Vietnam</td>
<td>IFIRS, IOP, VAST</td>
</tr>
</tbody>
</table>
T2K DESIGN

- Near and Far detectors
- Off-axis (anti)muon-neutrino beam
- Energy peaked at oscillation maximum (E~0.6 GeV)
- Neutrino and antineutrino enhanced modes via horn polarity switching
- Dominant process for $\nu$ detection: charged-current quasi-elastic interactions (CCQE)
- Reduced intrinsic $\nu_e$ contamination ($\leq 1\%$)
- Reduced backgrounds from high-energy tail
NEUTRINO OSCILLATIONS IN T2K

\[ P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - (\cos^4 \theta_{13} \sin^2 2\theta_{23}) \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right) \]

"Disappearance" channel
- Precise measurement of "atmospheric" parameters \( \theta_{23} \) and \( \Delta m_{32}^2 \) and CPT test via \( \nu \) vs anti-\( \nu \) analysis

\[ P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \times \frac{\sin^2[(1 - x)\Delta]}{(1 - x)^2} \]

- Leading term
- CP-violating: \( -\alpha \sin \delta_{CP} \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin \Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1 - x)\Delta]}{(1 - x)} \]
- CP-conserving: \( +\alpha \cos \delta_{CP} \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \cos \Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1 - x)\Delta]}{(1 - x)} \]
- \( +O(\alpha^2) \)

\[ \alpha = \left| \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \right| \sim \frac{1}{30} \quad \Delta = \frac{\Delta m_{31}^2 L}{4E} \quad x = \frac{2\sqrt{2}G_F N_e E}{\Delta m_{31}^2} \]

"Appearance" channel: measuring \( \theta_{13} \) and probing CP-violation (CPV)
- Leading term defines the octant of \( \theta_{23} \): <, > or = 45
- Sub-leading term accounts for CPV: enhanced effect when comparing neutrino and antineutrino data

* T2K leading efforts
T2K DATA TAKING

- POT (Protons on Target) for present results (Jan 2010 - May 2018):
  - $1.51 \times 10^{21}$ (ν mode) + $1.65 \times 10^{21}$ (anti-ν mode) POT (47.8% : 52.2%)

2010:
- start operation

2018:
- stable operation at ~480 kW
- 50/50 for FHC/RHC

23 Jan. 2010 – 31 May 2018
- POT total: $3.16 \times 10^{21}$

T2K results release:
- $\nu_e$ app 2.5σ
- $\nu_\mu$ 1st release
- $\nu_e$ app 7.3σ
- 1st constraint on $\delta_{CP}$
- $\nu_\mu$ highest precision on $\theta_{23}$

2018 results
- FHC: $1.49 \times 10^{21}$ POT
- RHC: $1.12 \times 10^{21}$ POT
FITTED FLUX PARAMETERS

Fitted flux parameters are generally near their nominal value of 1.0. Most of the fitted flux parameters fall within their assigned 1 sigma prior uncertainty.

Super-K Neutrino Mode Flux

Super-K Antineutrino Mode Flux

Neutrino Energy (GeV)

NEAR DETECTOR MEASUREMENTS

- On-axis detector INGRID
- Iron-scintillator layers
- Day-by-day monitoring of the \( \nu \) beam position and rate
- Off-axis detector ND280
- Detectors in 0.2 T B field
- Tracker:
  - Time projection chambers
  - Scintillator fine-grained detectors

Super-K flux parameters

Example: neutrino candidate in antineutrino mode
ND280 ANALYSIS

Example samples

- Fit to ND280 samples constrains neutrino flux and cross-section model
- Reduce systematic uncertainty for oscillation analysis: $\approx 12\% \rightarrow \approx 6\%$
- Many cross-section results with ND280 data
FAR DETECTOR MEASUREMENTS
SUPER-KAMIOKANDE (SUPER-K)

- 50 kton water-Cherenkov tank
- Separate e/μ-like rings:
  - <1% misidentified μ as e
- π⁰ rejection
- No magnetic field

- 5 Super-K samples used for analysis
- l-ring μ and e-like events in ν and anti-ν modes + CC1π e-like for ν mode
**T2K ANALYSIS STRATEGY**

*Two approaches: frequentist and Bayesian (MCMC) to obtain/present final results*
T2K FAR DETECTOR SAMPLES

Energy distribution

ν-mode

anti-ν-mode

* T2K Preliminary
ANALYSIS RESULTS: ATMOSPHERIC PARAMETERS $\theta_{23}$ AND $\Delta m^2_{32}$

- T2K continues to favour maximal mixing
- Interesting tensions with NOVA
- More data needed to improve the results

<table>
<thead>
<tr>
<th>$\sin^2 \theta_{23}$</th>
<th>Normal</th>
<th>Inverted</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$0.536^{+0.031}_{-0.046}$</td>
<td>$0.536^{+0.031}_{-0.041}$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m^2</td>
<td>_{(10^{-3} \text{ eV}^2)}$</td>
</tr>
</tbody>
</table>
ANALYSIS RESULTS: $\theta_{13}$ and $\delta_{CP}$ MEASUREMENTS

- Good agreement with reactor experiments
  - T2K best fit (NH): $\sin^2 \theta_{13} = 0.0277^{+0.0054}_{-0.0047}$
  - PDG 2016: $\sin^2 \theta_{13} = 0.0210 \pm 0.0011$

- 2$\sigma$ exclusion for CP-conservation independent of OA

- Large CPV favoured

2-sigma exclusion with reactors
### ANALYSIS RESULTS: DISCUSSION

<table>
<thead>
<tr>
<th>Sample</th>
<th>Predicted rates</th>
<th>Observed rates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>δ=0</td>
<td>δ=π/2</td>
</tr>
<tr>
<td>v-mode CCQE 1-ring μ-like</td>
<td>268.2</td>
<td>268.5</td>
</tr>
<tr>
<td>v-mode CCQE 1-ring e-like</td>
<td>61.6</td>
<td>50.1</td>
</tr>
<tr>
<td>v-mode CC1π 1-ring e-like</td>
<td>6.0</td>
<td>4.9</td>
</tr>
<tr>
<td>ĭ-mode CCQE 1-ring μ-like</td>
<td>95.3</td>
<td>95.5</td>
</tr>
<tr>
<td>ĭ-mode CCQE 1-ring e-like</td>
<td>13.4</td>
<td>14.9</td>
</tr>
</tbody>
</table>

- Preference for $\delta_{cp} = -\pi/2$ → maximize $\nu_e$ appearance probability, minimize $\bar{\nu}_e$ appearance
- Larger effect in e-like+1π (2.5% probability of observing 15 events when 6.9 are expected)
- For $\bar{\nu}_e$ appearance background level is $\sim 6.3$ events → No strong statistical conclusion
- In ν-mode deficit of μ-like events → compatible with our systematic uncertainties model
ANALYSIS RESULTS: DISCUSSION
T2K FUTURE PROSPECTS

- $7.8 \times 10^{21}$ POT approved (expected by ~2021)
- Gain “effective” statistics: new CC-nonQE, multi-ring samples: already ~30% with new SK reconstruction
- Decrease systematic uncertainties: new ND280 samples + analysis improvements
- T2K phase-II proposal to start in ~2021 and run till 2026 (Hyper-Kamiokande time?):
  - Collect ~$20 \times 10^{21}$ POT
  - Beam power: $450 \text{ kW} \rightarrow 750 \text{ kW} \rightarrow 1.3 \text{ MW}$
  - Near detector upgrade

![Current data taking](chart.png)

![T2K-II Protons-On-Target Request](chart2.png)
SUPER-KAMIOKANDE REFURBISHMENT

• For the first time in a decade, the Super-K tank is open.
• There are ongoing repairs and maintenance to the tank.
• This will be followed by two phases of gadolinium-doping for the water target.
  • First 0.02% Gd, offering 50% neutron capture rate.
  • Later 0.2% Gd, offering 90% neutron capture rate.

$^{157}$Gd has a very high neutron capture cross-section.

• Allows charge discrimination:
  • Greater CP-violation sensitivity.
  • And improvements to many other SK targets.

T2K to continue data-taking in spring 2019

IFIC members made valuable contributions in SK work
SUPER-KAMIOKANDE REFURBISHMENT

Just looks great!
T2K FUTURE PROSPECTS: SENSITIVITY

- Exclude CP conservation at more than $3\sigma$ level for $\delta_{CP} = -\pi/2$ and NH
- Significant improvement in the precision for atmospheric parameters
T2K FUTURE PROSPECTS: NEAR DETECTOR UPGRADE

- Reduction of systematic uncertainties is crucial
  - 18% (2011) → 9% (2014) → 6% (2016) → 4% (2021)?
- ND280 measurements are important

Upgrade of T2K near detector: target date ~2021
- New design (work on-going):
  - improve acceptance + reduce threshold for low momentum particles (e.g. protons)

+ TOF detectors

*Spain: IFAE
SUMMARY

- **T2K is working steadily on its quest on filling neutrino puzzle**
- With $\approx 31.6 \times 10^{20}$ POT (\approx 40\% of expected POT): \~50/50 neutrino/antineutrino modes
  - Measurement of $\sin^2 \theta_{13}$ in agreement with reactor data
  - **T2K data agrees with max $\theta_{23}$ mixing and some preference for NO**
  - **Exclusion of CP-conservation at 2$\sigma$ level**
- Short term plans:
  - Work with NOvA to understand/confirm/improve the differences
  - Continuous data-taking with beam power increase to 750 kW
  - New analysis samples to increase statistics and improve systematics
- **T2K Phase-II proposed**, extended run for \~2020-2026. Smooth transition to Hyper-Kamiokande time
  - With $20 \times 10^{21}$ POT reach 3$\sigma$ exclusion of CP conservation for certain $\delta_{CP}$ and MH
  - Near detector upgrade to further reduce systematic uncertainties
- **Stay tuned for the new results on neutrino physics from T2K!**
Thank You
RECENT ANALYSIS IMPROVEMENTS

• Neutrino interactions modelling is rapidly developing → changes may affect the results
  • Huge efforts in recent years to improve NEUT (Acta Phys. Polon. B42477 (2009)) neutrino generator used in T2K
    • Improved model for CCQE with inclusion of long-range correlations in nucleus (Random Phase Approximation, RPA calculation)
  • 2017 analysis: new parametrisation of uncertainties for multi-nucleon and RPA
  • On-going checks of results robustness: preliminary systematics parameters used!
    • Small effect on $\delta_{CP}$ but larger for “atmospheric” parameters

• Super-Kamiokande event reconstruction
  • New algorithm (fitQun) applied for all analysis samples
  • (Re-)optimised the fiducial volume cuts
  • $\sim$30% increase in “effective” statistics
NEUTRINO OSCILLATIONS IN T2K

\( \delta_{\text{CP}} \) and mass hierarchy (MH) both cause differences in \( \nu \) and anti-\( \nu \) oscillations

At T2K baseline (L~295km, E~0.6GeV):

- CPV: \( \approx \pm 30\% \) effect
- Mass hierarchy: \( \approx \pm 10\% \) effect
ANALYSIS RESULTS: ATMOSPHERIC PARAMETERS \( \theta_{23} \) AND \( \Delta m_{32}^2 \)

- 2016 analysis (joint fit of 5 samples with reactor constraint for \( \theta_{13} \)):
  - Compatible and consistent results with other experiments
  - Consistent results for \( P(\nu_\mu \rightarrow \nu_\mu) \) and \( P(\nu_\mu \rightarrow \nu_\mu) \): CPT conserved
T2K NEUTRINO FLUX PREDICTION

- Simulation: FLUKA, GCALOR and GEANT3
- Tuned to external data: NA61/SHINE (CERN)
  - Measurement of pion/kaon production of 31 GeV/c proton beam with carbon target
  - Thin target (4%λ) and T2K replica target
  - Reduction of uncertainties: ~30% to ~10%
- Intrinsic $\nu_e$ background at ~0.5% level

Replica target results are being incorporated into analysis.
T2K NEUTRINO INTERACTIONS MODEL

- NEUT neutrino generator
- Model tuned to external data: MiniBooNE, MINERνA, bubble chambers
- CCQE: Relativistic Fermi Gas (weighted from Spectral Function) + relativistic Random Phase Approximation for nuclear system
- Pre-(ND280)fit uncertainty for Super-K: ~7.5%
ON-AXIS NEAR DETECTOR INGRID

- T2K utilises off-axis neutrino beam:
  - Important to monitor beam intensity and direction
- Iron/scintillator detector to measure beam profile and rate
- Day-by-day monitoring
- Direction stable within 1 mrad (~2% shift in peak energy)
ND280 ANALYSIS: $\nu$-MODE

- ND280 samples in FGD1 and FGD2: $\nu_\mu$ interactions in $\nu$ mode running
  - CC-0$\pi$: muon and no pions in the final state
  - CC-1$\pi$: muon and $\pi^+$ in the final state
  - CC-Other: all other CC interactions (DIS dominated)
ND280 ANALYSIS: ANTI-$\nu$-MODE

- ND280 samples in FGD1 and FGD2
- CC-Itracks and CC-Ntrack samples
- $\mu^+$ samples and $\mu^-$ to constrain “wrong-sign” background
Two hypotheses:

Standard PMNS $\bar{\nu}_e$ appearance ($\beta=1$) and no $\bar{\nu}_e$ appearance ($\beta=0$)

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>Hypothesis</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta=0$</td>
<td>No $\bar{\nu}_e$ Appearance</td>
<td>P=0.233</td>
</tr>
<tr>
<td>$\beta=1$</td>
<td>PMNS $\bar{\nu}_e$ Appearance</td>
<td>P=0.0867</td>
</tr>
</tbody>
</table>

No evidence yet!

Event distribution is also consistent with background
ND280 INPUTS TO OSCILLATION ANALYSIS (2016)

- Each model parameter (flux + neutrino interactions) has its uncertainty
- Fit to ND280 data constrains flux and cross-section model, uncertainties propagated to SK as covariance
  - Significant reduction of systematic uncertainties

<table>
<thead>
<tr>
<th>Total NSK Fraction Uncertainty, %</th>
<th>$_{\mu}$</th>
<th>$\nu_e$</th>
<th>anti-$\nu_{\mu}$</th>
<th>anti-$\nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux</td>
<td>W/O ND280</td>
<td>7.6</td>
<td>8.9</td>
<td>7.1</td>
</tr>
<tr>
<td>Cross section</td>
<td>W/O ND280</td>
<td>7.7</td>
<td>7.2</td>
<td>9.3</td>
</tr>
<tr>
<td>Flux and cross section</td>
<td>W/ ND280</td>
<td>2.9</td>
<td>4.2</td>
<td>3.4</td>
</tr>
<tr>
<td>Final/sec. hadronic interactions</td>
<td></td>
<td>1.5</td>
<td>2.5</td>
<td>2.1</td>
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<tr>
<td>Far detector</td>
<td></td>
<td>3.9</td>
<td>2.4</td>
<td>3.3</td>
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<tr>
<td>Total</td>
<td>W/O ND280</td>
<td>12.0</td>
<td>11.9</td>
<td>12.5</td>
</tr>
<tr>
<td>Total</td>
<td>W/ ND280</td>
<td>5.0</td>
<td>5.4</td>
<td>5.2</td>
</tr>
</tbody>
</table>

* T2K Preliminary
2016 ANALYSIS RESULTS: $\theta_{23}$ AND $\Delta m^2_{32}$

- Joint analysis with reactor constraint: $\sin^2 2\theta_{13} = 0.085 \pm 0.05$
- T2K data consistent with maximal mixing
- Compatible with other experiments (intervals for fixed mass hierarchy)

<table>
<thead>
<tr>
<th>PARAMETER/MASS HIERARCHY</th>
<th>NORMAL MASS HIERARCHY</th>
<th>INVERTED MASS HIERARCHY</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 2\theta_{32}$</td>
<td>$0.532^{+0.046}_{-0.068}$</td>
<td>$0.534^{+0.043}_{-0.07}$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m^2_{32}</td>
<td>$</td>
</tr>
</tbody>
</table>
CPT INVARIANCE TEST: $\nu_\mu$ AND anti-$\nu_\mu$ DISAPPEARANCE

• Strategy
  • Assign independent oscillation parameters for antineutrinos
  • Neutrino samples constrain “wrong-sign” background
  • Test CPT: $\theta_{23} \neq \bar{\theta}_{23}$ and $\Delta m^2_{32} \neq \Delta m^2_{32}$

• Consistent results for $P(\nu_\mu \rightarrow \nu_\mu)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$: CPT conserved
2016 COMPARISON WITH NOVA BEST-FIT

$\nu_\mu$ μ-like

$\bar{\nu}_e$ e-like

$\nu_e$ e-like

$\bar{\nu}_\mu$ μ-like

ν-mode

anti-ν-mode
NEW SAMPLE: CC1 π

- $\nu_e$ e-like single ring events
- Require additional ring from Michel electron
- Energy with 2-body kinematics with $\Delta$ baryon
- Applied only for $\nu$-mode running
  - Gain $\sim$10% more statistics (MC)
  - 15 events observed
- Total 5 samples available for T2K analysis
EVENT RATES

- Largely in line with the prediction for $\delta_{\text{CP}} = -\pi/2$

<table>
<thead>
<tr>
<th>Sample</th>
<th>Predicted Rates</th>
<th>Observed Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\delta_{\text{CP}}=-\pi/2$</td>
<td>$\delta_{\text{CP}}=0$</td>
</tr>
<tr>
<td>CCQE 1-Ring e-like FHC</td>
<td>73.5</td>
<td>61.5</td>
</tr>
<tr>
<td>CC1$\pi$ 1-Ring e-like FHC</td>
<td>6.92</td>
<td>6.01</td>
</tr>
<tr>
<td>CCQE 1-Ring e-like RHC</td>
<td>7.93</td>
<td>9.04</td>
</tr>
<tr>
<td>CCQE 1-Ring $\mu$-like FHC</td>
<td>267.8</td>
<td>267.4</td>
</tr>
<tr>
<td>CCQE 1-Ring $\mu$-like RHC</td>
<td>63.1</td>
<td>62.9</td>
</tr>
</tbody>
</table>

- Generally within statistical and systematic uncertainties
  - p-value: $\sim 0.42$
  - More observed e-like CC1$\pi$ events than maximum expectation 6.92
TOTAL SYSTEMATICS UNCERTAINTIES

- Total systematics uncertainties (%) used in 2017 analysis

<table>
<thead>
<tr>
<th>Error Source</th>
<th>1Rmu</th>
<th>1Re</th>
<th>1Re 1 d. e.</th>
<th>FHC/RHC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FHC</td>
<td>RHC</td>
<td>FHC</td>
<td>RHC</td>
</tr>
<tr>
<td>SK Detector</td>
<td>1.9</td>
<td>1.6</td>
<td>3.0</td>
<td>4.2</td>
</tr>
<tr>
<td>SK FSI+SI+PN</td>
<td>2.2</td>
<td>2.0</td>
<td>2.9</td>
<td>2.5</td>
</tr>
<tr>
<td>SK Detector+FSI+SI+PN</td>
<td>2.9</td>
<td>2.5</td>
<td>4.2</td>
<td>4.8</td>
</tr>
<tr>
<td>ND280 const. flux &amp; xsec</td>
<td>3.3</td>
<td>2.7</td>
<td>3.2</td>
<td>2.9</td>
</tr>
<tr>
<td>$\sigma(\nu_e)/\sigma(\nu_{\mu})$, $\sigma(\bar{\nu}<em>e)/\sigma(\bar{\nu}</em>{\mu})$</td>
<td>0.0</td>
<td>0.0</td>
<td>2.6</td>
<td>1.5</td>
</tr>
<tr>
<td>NC1$\gamma$</td>
<td>0.0</td>
<td>0.0</td>
<td>1.1</td>
<td>2.6</td>
</tr>
<tr>
<td>NC Other</td>
<td>0.3</td>
<td>0.3</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Syst. Total</td>
<td>4.4</td>
<td>3.8</td>
<td>6.3</td>
<td>6.4</td>
</tr>
</tbody>
</table>
HEAVY NEUTRAL LEPTONS

How to explain neutrino masses (and consequently oscillations)?

A natural extension is one with 3 new right-handed neutrinos (sterile):

\[
\begin{pmatrix}
\bar{\nu}_L & \nu_R^c \\
0 & m_D & m_R
\end{pmatrix}
\begin{pmatrix}
\nu^c_L \\
\nu_R
\end{pmatrix}
\]

\[M = \begin{pmatrix}
\frac{m_D}{m_R} & m_R
\end{pmatrix}
\]

Light neutrinos

\[m_\nu \sim \frac{m_D^2}{m_R} \lesssim 0.1 \text{ eV}\]

Heavy neutrinos

\[M_N \sim m_R\]

Three new heavy neutrinos at an unknown scale (eV → GUT)!

How to detect heavy neutrinos?

- \(N_1\) couple to \(W\) and \(Z\) with a strength

\[U_{\alpha 1}^2 \equiv |\Theta_{\alpha 1}|^2 \sim \mathcal{O} \left( \frac{m_\nu}{M_N} \right)\]

- Can be produced e.g. in colliders or in meson decays (arXiv:1502.00477).
- For \(0.1 < M_N < 100 \text{ GeV/c}^2\), we have

\[U_{\alpha 1}^2 \sim 10^{-10} - 10^{-8}\]

90% limits from current experiments on the mixing of heavy neutrinos to electron and muon.
HEAVY NEUTRAL LEPTONS

Detection in T2K:
Heavy neutrinos are produced alongside standard neutrino beam. They propagate and can decay in T2K near detector ND280 → detection of 2 particles with opposite charges.

\[ K^+ \rightarrow \ell^+N \]
\[ N \rightarrow \ell^\pm \pi^\mp, \ell^\pm \ell^\mp \nu \]

Analysis and results:
- Remaining background after selection: less than 2 evts (from active $\nu$ int.)
- Bayesian approach, marginalization with a Markov Chain Monte Carlo.

90% C.L.

T2K put the most stringent limits in the high mass region.
T2K: SPANISH GROUPS IMPACT

• Spanish groups provide important and in many ways crucial contributions to the T2K experiment

• Near Detector:
  • Magnet operations (IFAE), TPCs (IFAE and IFIC), near detector calibration, reconstruction and analysis
  • Conveners of the groups responsible of the data-taking coordination, neutrino interactions modelling, tracking, analysis framework development, “exotics” physics searches

• UAM actively participates in the Super-Kamiokande calibrations + work on Gd addition

• Further work beyond current activities:
  • T2K+SK+reactors global fit (IFIC+UAM with T2K-UK/Japan groups)
  • T2K ND280 analysis software for DUNE(-SP) analyses