The T2K Neutrino Flux Predictions

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On behalf of the T2K Collaboration
The T2K Experiment

- T2K (Tokai-to-Kamioka): Long-baseline neutrino oscillation experiment located in Japan
- Measures $\nu_\mu$ ($\bar{\nu}_\mu$) disappearance and $\nu_e$ ($\bar{\nu}_e$) appearance in $\nu$ ($\bar{\nu}$) mode
- Neutrino flux uncertainty affects the oscillation analysis through the far detector flux prediction
- Precise knowledge of the neutrino flux is also vital for T2K $\nu$ cross-section measurements

\[
N_{\nu_e}^{SK} = P_{\nu_\mu \rightarrow \nu_e} \times \Phi_{\nu_\mu}^{SK} \times \sigma_{\nu_e}^{SK}
\]

Observed Number of Events

Far Detector (Super-Kamiokande)
T2K Neutrino Production Beamline

- 30 GeV (kinetic energy) protons striking the 90 cm long T2K graphite target
- Hadronic cascade is created (chain of hadronic interactions inside the target)
- 3 magnetic horns used to focus pions and kaons from the cascade
- In-flight pion and kaon decays inside the decay volume (~96 m)

- Hadronic interactions not only with the graphite target, but also the horns (Al), decay volume walls (Fe), decay volume itself (He) etc.
- Stable beam operation achieved at maximum power of 470 kW
The T2K Off-Axis Neutrino Flux

- SK and ND280 are placed at 2.5° off-axis angle with respect to the primary proton beam direction
- On-axis near detector (INGRID) used to monitor beam stability and direction
- Off-axis beam makes the $\nu_\mu$ flux more narrow and peaked around the energies needed for observing the first oscillation maximum at SK (295 km baseline)
- High energy background gets reduced
The T2K Neutrino Flux Prediction

- Understanding the $\nu_e$ ($\bar{\nu}_e$) background is important for the $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) appearance analysis.
- Wrong sign contamination is greater in $\bar{\nu}$ mode flux.

**Neutrino Mode Flux at SK**

- $\nu_\mu$, $\nu_e$, $\bar{\nu}_\mu$, $\bar{\nu}_e$

2.3% $\bar{\nu}_\mu$ & 0.4% $\nu_e$ (for $E_\nu \sim 0.6$ GeV)

**Antineutrino Mode Flux at SK**

- $\nu_\mu$, $\nu_e$, $\bar{\nu}_\mu$, $\bar{\nu}_e$

3.2% $\nu_\mu$ & 0.4% $\bar{\nu}_e$ (for $E_\nu \sim 0.6$ GeV)
Understanding The T2K Neutrino Flux

- Neutrino production dominated by pion (and muon) decays at low energies, and kaon decays at high energies
- Uncertainty on the hadron production models limits the neutrino flux uncertainty
- Problem: Available models cannot describe the existing data
- Solution: Constrain model predictions with external hadron production data!

Neutrino Ancestry (Parents)

### Main $\nu$-producing channels

<table>
<thead>
<tr>
<th>Decay Products</th>
<th>Branching Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+ \rightarrow \mu^+\nu_\mu$</td>
<td>99.9877</td>
</tr>
<tr>
<td>$\pi^+ \rightarrow e^+\nu_e$</td>
<td>$1.23 \times 10^{-4}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+\nu_\mu$</td>
<td>63.55</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^0\mu^+\nu_\mu$</td>
<td>3.353</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^0\nu_e$</td>
<td>5.07</td>
</tr>
<tr>
<td>$K_L^0 \rightarrow \pi^-\mu^+\nu_\mu$</td>
<td>27.04</td>
</tr>
<tr>
<td>$K_L^0 \rightarrow \pi^-\nu_e$</td>
<td>40.55</td>
</tr>
<tr>
<td>$\mu^+ \rightarrow e^+\bar{\nu}_\mu\nu_e$</td>
<td>100</td>
</tr>
</tbody>
</table>
NA61/SHINE Experimental Setup

- Multi-purpose hadron production experiment based in CERN (effectively a large spectrometer)
- Different targets can be inserted (two target configurations used for T2K, thin-target and replica-target)
- Triggering on incoming particle type and energy
- 5 time projection chambers (TPCs) combined with magnets used for particle tracking
- Time-of-flight (ToF) and energy-loss analysis employed for outgoing PID
Phase Space Coverage Of NA61 Thin-Target Data (2007 & 2009)

- Thin-target: 2 cm thick graphite
- Good coverage of the phase space relevant for the T2K neutrino flux prediction

NA61 2007 thin-target dataset
arXiv:1102.0983
arXiv:1112.0150

NA61 2009 thin-target dataset
arXiv:1510.02703

Proton beam
2 cm

\( \pi^\pm, \ldots \)
NA61 2009 Thin-Target Data Currently Used by T2K

- Part of the NA61 2009 thin-target data ([arXiv:1510.02703](https://arxiv.org/abs/1510.02703))

\[ \pi^+ \text{ multiplicities} \quad \pi^- \text{ multiplicities} \]
The T2K Neutrino Flux Simulation

FLUKA2011.2c ➔ GEANT3+GCALOR ➔ FLUX REWEIGHTING

- Modelling hadronic interactions inside the graphite target
- T2K beam profile measurements used as an input for running FLUKA

- FLUKA output used as an input for this step
- Propagates particles exiting from the target through the horns and the decay volume
- Detailed knowledge of the secondary beamline is needed
- Out-of-target interactions are modelled using GCALOR

- Constraining the hadron production model with available external hadron production data
- Kinematic coverage of external data is extended by using parametrizations obtained from fits to data
- Scaling applied to account for interactions on different target nuclei and to cover a wider range of centre-of-mass energies
Flux Reweighting Procedure

- A weight is applied to the neutrino yield based on its history (hadronic ancestry cascade)
- For every hadronic interaction in the cascade, two distinct (data/simulation) weights are applied

- Interaction Length Weight (corrects the yield based on the length travelled by the hadron through different materials before interacting)

\[
\text{weight}(x) = \frac{\sigma_{\text{data}}}{\sigma_{\text{MC}}} e^{-\rho(\sigma_{\text{data}} - \sigma_{\text{MC}})x}
\]

- Multiplicity Weight (corrects the yield based on the momentum and direction of the outgoing hadron produced in the interaction)

\[
\text{weight}(p, \theta) = \frac{\left[ \frac{d^2n(p, \theta)}{dpd\theta} \right]_{\text{data}}}{\left[ \frac{d^2n(p, \theta)}{dpd\theta} \right]_{\text{MC}}}
\]
Effect Of Flux Reweighting On The Flux Prediction

- The reweighting procedure changes the nominal neutrino flux prediction
- The weight assigned to every neutrino event is given by the product of interaction length and multiplicity weights for every interaction in the hadronic cascade

**νμ at SK (ν-mode)**

- **νμ at SK (ν-mode)**
- **νμ at SK (ν-mode)**

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T2K PRELIMINARY
The total uncertainty on the neutrino flux is still dominated by our limited understanding of hadronic interactions inside the long graphite target.

- Thin-target data directly constrains primary $p + C$ interactions inside the target ($\sim 60\%$).
- Expect a further reduction of uncertainties with NA61 2009 replica-target data: directly constrains both primary ($\sim 60\%$) and secondary ($\sim 30\%$) interactions inside the target.
T2K Flux Prediction Uncertainties Separated Into Different Contributions

**SK: Positive Focussing ($\nu$) Mode, $\nu_\mu$**

- Mult. Error
- Pion Rescatter Error
- Nucl. Error
- Int. Length Error
- Horn Alignment
- Target Alignment

**SK: Negative Focussing ($\bar{\nu}$) Mode, $\bar{\nu}_\mu$**

- Mult. Error
- Pion Rescatter Error
- Nucl. Error
- Int. Length Error
- 13av2 Error

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**Non-Hadronic Contribution**

**Hadronic Interaction Contribution**
NA61 also collected data with an exact replica of the T2K target.

Incorporating the **NA61 2009 replica-target data** (only $\pi^\pm$ multiplicity) into the flux reweighting procedure.

Replica-target data is additionally binned in the longitudinal ($z$) coordinate of the outgoing hadron exiting position, besides the standard ($p, \theta$) bins.

This dataset is expected to constrain up to 90% of hadronic interactions.

**T2K Neutrino Flux Prediction: Where next?**

Part of NA61 2009 Replica Target Data for $\pi^+$

**Exiting z-position**

**Proton beam**

**18 cm**

**90 cm**

**$\pi^\pm$**

**$\bar{p}$**

**$\theta$**

**NA61 Data Taking Periods for T2K**

<table>
<thead>
<tr>
<th>Beam+target</th>
<th>Mom (GeV/c)</th>
<th>year</th>
<th>Data</th>
<th>POT ($\times 10^6$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p+C</td>
<td>31</td>
<td>2007</td>
<td>$\pi^+, \pi^-, K^+$</td>
<td>0.7</td>
</tr>
<tr>
<td>p+C</td>
<td>31</td>
<td>2009</td>
<td>$\pi^+, \pi^-, K^+, K^-, K_S^0, p$</td>
<td>5.4</td>
</tr>
<tr>
<td>p+T2K RT</td>
<td>31</td>
<td>2007</td>
<td>$\pi^+, \pi^-$</td>
<td>0.2</td>
</tr>
<tr>
<td>p+T2K RT</td>
<td>31</td>
<td>2009</td>
<td>$\pi^+, \pi^-$</td>
<td>4</td>
</tr>
<tr>
<td>p+T2K RT</td>
<td>31</td>
<td>2010</td>
<td>still to be released</td>
<td>10</td>
</tr>
</tbody>
</table>

**NA61 2009 replica-target dataset**

arXiv:1603.06774
Replica-target reweighting corrects only the outgoing rate for charged pions exiting the T2K target (no reweighting is applied for interactions inside the target, unless the exiting particle is different from a pion, in which case thin-target reweighting is applied):

\[ \text{total weight} = \text{weight}(p, \theta, z_3) \]

NA61 replica-target data favours a lower value for the proton production cross section compared to the thin-target data.
Conclusion

- Current uncertainty on the T2K neutrino flux prediction is ~9% at peak T2K neutrino energy

- Flux reweighting is based on the NA61 2009 thin-target data

- NA61 replica-target data directly constrains ~30% more hadronic interactions than thin-target data

- Expecting to reduce T2K flux uncertainties at peak neutrino energy to ~5% level with NA61 2009 replica-target data (dataset consists of exiting $\pi^{\pm}$ rates)

- Analysis of NA61 2010 replica-target data is ongoing, NA61 collaboration expects to extract for the first time rates of $K^{\pm}$ exiting from the replica target, in addition to higher statistics $\pi^{\pm}$ rates