Constraints on T2K neutrino flux predictions with NA61/SHINE experimental data

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on behalf of the NA61/SHINE collaboration

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Rencontres de Moriond - QCD session

Outline:
- The T2K experiment and its need for flux constraints
- The NA61/SHINE experiment
  - Charged hadron analysis
  - Neutral strange particle analysis
- Tools for neutrino flux prediction
- Conclusions & Perspectives
The T2K experiment in Japan

Primary goals:

- $\theta_{13}$ measurement by $\nu_\mu \rightarrow \nu_e$ oscillation
  T2K discovery
  $\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032} \ (N.H.)$ at 68% C.L.

- $\theta_{23}$ measurement by $\nu_\mu \rightarrow \nu_x$ oscillation
  T2K world leading measurement
  $\sin^2 \theta_{23} = 0.514 \pm 0.082 \ (N.H.)$ at 90% C.L.

Neutrino flux predictions at far detector [SK]

Summary of the contributions to the total uncertainty for the $\nu_e$ appearance analysis:

<table>
<thead>
<tr>
<th>Error source [%]</th>
<th>$\sin^2 2\theta_{13} = 0.1$</th>
<th>$\sin^2 2\theta_{13} = 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam flux and near detector (w/o ND280 constraint)</td>
<td>2.9</td>
<td>4.8</td>
</tr>
<tr>
<td>$\nu$ interaction (external data)</td>
<td>7.5</td>
<td>6.8</td>
</tr>
<tr>
<td>Far detector and FSI+SI+PN</td>
<td>3.5</td>
<td>7.3</td>
</tr>
<tr>
<td>Total</td>
<td>8.8</td>
<td>11.1</td>
</tr>
</tbody>
</table>
T2K Neutrino flux prediction


Major source of neutrinos:

\[ \pi \rightarrow \mu \nu_\mu \ \Gamma = 99.9\% \]
\[ K_0 \rightarrow \pi e \nu_e \ \Gamma = 40.5\% \]
\[ \rightarrow e \nu_e \ \Gamma = 10^{-4}\% \]
\[ \rightarrow \pi \nu_\mu \ \Gamma = 27.0\% \]

K \[ \rightarrow \mu \nu_\mu \ \Gamma = 63.5\% \]
\[ \rightarrow \pi^0 e \nu_e \ \Gamma = 5.1\% \]
\[ \rightarrow \pi^0 \mu \nu_\mu \ \Gamma = 3.3\% \]

+ contributions from not well-defocused hadrons

T2K requirements is a **5% precision** on neutrino flux in each detectors

The major source of uncertainties of the beam are due to the poorly known hadron production leading to neutrinos. Previously available data were not accurate enough to fulfill the requirements of T2K.

We thus need an auxiliary experiment which will reproduce the conditions of creation of the neutrino beam \( \rightarrow \text{NA61/SHINE} \)
The NA61/SHINE experiment at CERN

Large acceptance
Good tracking resolution
5 TPCs
3 ToFs
Mag. Field of 1.14 Tm

2 types of measurements for T2K: 31 GeV/c proton on
- Thin target (4% $\lambda_{\text{int}}$): Primary interaction studies
- Replica target (1.9 $\lambda_{\text{int}}$): Hadronic production along the target

<table>
<thead>
<tr>
<th>Year</th>
<th>Thin Target</th>
<th>Replica Target</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>630 k</td>
<td>230 k</td>
<td>Published</td>
</tr>
<tr>
<td>2009</td>
<td>4.4 M</td>
<td>2.4 M</td>
<td>Being Analyzed</td>
</tr>
<tr>
<td>2010</td>
<td>-</td>
<td>10 M</td>
<td>Under calibration</td>
</tr>
</tbody>
</table>

Charged hadron measurements from thin target data

**ToF+dE/dx analysis:** Combined informations from Time of Flight \([m^2]\) and energy loss \([dE/dx]\) to identify \(\pi^\pm, p, K^\pm\) for \(p>1\ \text{GeV/c}\)
(2007 data: only \(\pi^\pm\) and \(K^+\))

Spectra are normalized to the production cross section:

\[
\sigma_{prod}^{2009} = 233.5 \pm 2.8(\text{stat.}) \pm 4.2(\text{model}) \pm 1.0(\text{trigger})\ \text{mb}
\]

Spectra are compared to Monte Carlo predictions:
- Fluka2011
- Geant4 FTF_BIC physics list, with 3 different releases of Geant4:
  - Geant4.9.5 [Oct. 12]
  - Geant4.9.6 [May 13]
  - Geant4.10 [Dec 13]
Charged hadron measurements from thin target data

**π⁺ multiplicity in p+C at 31 GeV/c**

<table>
<thead>
<tr>
<th>Angle Range</th>
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<th>Data - 2007</th>
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<tbody>
<tr>
<td>0 &lt; θ &lt; 10 mrad</td>
<td>+ + +</td>
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<td>10 &lt; θ &lt; 20 mrad</td>
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**K⁺ multiplicity in p+C at 31 GeV/c**

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Charged hadron measurements from thin target data

**π⁺ multiplicity in p+C at 31 GeV/c**

**K⁺ multiplicity in p+C at 31 GeV/c**

Data - 2009

Data - 2007

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Charged hadron measurements from thin target data

- Statistical uncertainty lowered by a factor of 2-3
- Systematic uncertainty improved by a factor of 2

Largest contributions:
- PID
- Feed-down: decay of neutral strange particles ‘V^0’

π^+ multiplicity in p+C at 31 GeV/c

- Statistical uncertainty lowered by a factor of 2-3
- Systematic uncertainty improved by a factor of 2

Largest contributions:
- PID
- Feed-down: decay of neutral strange particles ‘V^0’
**V^0 measurements from thin target data**

Goals of the measurement:
- Main source of systematic uncertainty in \( \pi^\pm \) and \( p \) measurement comes from \( V^0 \) decay: \( K^0_S \rightarrow \pi^+\pi^- \), \( \Lambda \rightarrow p\pi^- \)
- Main source of \( \nu_e \) at high energy in T2K comes from \( K^0_L \rightarrow \pi\nu\nu_e \)

Analysis strategy:
Yields of \( V^0 \) candidates are extracted from invariant mass fits. Same normalization as for charged particle spectra.

2007 results recently published. 2009 data are released and are being prepared for publication.

**Podolanski-Armenteros plots**

- \( p_T \): transverse momentum of daughters w.r.t. \( V^0 \)
- \( \alpha \): longitudinal momentum asymmetry

---

No Selections

\( K^0_S \rightarrow \pi\pi \)

\( \Lambda \rightarrow p\pi^- \)

\( \alpha = (p_T^\pi - p_T^\pi)/(p_T^\pi + p_T^\pi) \)

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\( \alpha = (p_T^\pi - p_T^\pi)/(p_T^\pi + p_T^\pi) \)
$V^0$ measurement from thin target data

$K^0_s$ multiplicity in p+C at 31 GeV/c

- Large statistical error due to electronic noise in the dataset.
- Major sources of systematic uncertainties:
  - Fitting procedure
  - Cuts
- $K^0_s$ yields can be predicted from $K^\pm$ measurement:
  - using the isospin symmetry assumption:
    $$N(K^0_s) = \frac{1}{2}(N(K^+) + N(K^-))$$
  - using a quark-counting argument:
    $$N(K^0_s) = \frac{1}{8}(3 \cdot N(K^+) + 5 \cdot N(K^-))$$
  where $pp$ and $pn$ interactions in the Carbon nucleus have been taken into account.
$V^0$ measurement from thin target data

**$K^0_s$ multiplicity in p+C at 31 GeV/c**

- $20 < \theta < 60$ mrad
- $60 < \theta < 100$ mrad
- $100 < \theta < 140$ mrad
- $140 < \theta < 180$ mrad
- $180 < \theta < 240$ mrad

**$\Lambda$ multiplicity in p+C at 31 GeV/c**

- $0 < \theta < 50$ mrad
- $50 < \theta < 100$ mrad
- $100 < \theta < 150$ mrad
- $150 < \theta < 200$ mrad
- $200 < \theta < 250$ mrad
- $250 < \theta < 300$ mrad

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$V^0$ measurement from thin target data

*K$ multiplicity in p+C at 31 GeV/c

**K$ multiplicity in p+C at 31 GeV/c

**K$ 09 - stat.

- **K$ 09 - syst.

- FTF_BIC - G410
- FTF_BIC - G496
- FTF_BIC - G495

**Λ multiplicity in p+C at 31 GeV/c

**Λ 09 - stat.

- FTF_BIC - G410
- FTF_BIC - G496
- FTF_BIC - G495
From NA61/SHINE data to T2K neutrino flux prediction


A Simulation of the T2K 2\textsuperscript{ary} beamline

Interaction in the target: Fluka

Propagation in the beamline: Geant3+GCALOR

B Apply weights computed from external data

NA61/SHINE data used in priority. For interactions not covered by external data, scaling hyp. is used. Weights computed w.r.t. Fluka and GCALOR predictions.

C Get tuned flux

Flux (cm\(^{-2}\)50MeV/10\(^{21}\)p.e.)

ν\(_{\mu}\) at SK

D Compute flux errors

Main sources: hadronic production, p beam profile, alignment, horn position & current...

A) NA61 π\(^{+}\) Weights w.r.t Fluka predictions

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T2K flux uncertainty


Only 2007 NA61 data here is included ($\pi^\pm$, K+)

Breakdown of the hadronic interactions uncertainty

Breakdown of all sources of flux uncertainty

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Short term improvement

→ p-θ phase space of parents leading to neutrinos in SK

→ NA61/SHINE p-θ coverage
  - - - with 2007 data
  with 2009 data

• Better coverage of π± and K+

• Measurement of new hadronic production

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Long term improvement

• Neutrinos are coming from hadrons produced by the primary interaction and from various re-interactions that can occur in the long target and in the beamline material.

• Use of the NA61 long target data to constrain up to 90% of the flux → Method already tested with the 2007 dataset

• Coherent simulation of T2K and NA61 experiments, with the same physics model. The method is currently tested with a Geant4, using Fritiof-based models.

• Upgrade of beam monitor detectors in the J-PARC beamline

Conclusions

• Release of $\pi^{\pm}$, $K^{\pm}$, $p$, $K^{0}$s and $\Lambda$ spectra with NA61/SHINE 2009 thin target dataset:
  - Wider $p$-$\theta$ coverage compared to 2007 results
  - Lowered statistical uncertainty
  - Systematic uncertainty estimated

  - Comparisons with Fluka2011 shows a good agreement with our data
  - Some predictions from Geant4’s physics list FTF_BIC is good, further work needed

• Long target data analysis is ongoing

• The 5% precision on T2K flux prediction is reachable once all data from NA61 will be analyzed and included in the re-weighting chain.

• A good knowledge of the neutrino flux is very important for T2K goals, but mandatory for future neutrino experiments (LAGUNA-LBNO, LBNE, Hyper-Kamiokande) which aim at $\sim 2\%$ precision on the prediction of their fluxes
Production cross section measurement

Trigger system in NA61/SHINE

Inelastic cross section measured from triggers: \( C_1 \cdot \overline{C}_2 \cdot S_1 \cdot S_2 \cdot \overline{V} \cdot \overline{S_4} \)

- Biases due to \( S_4 \) corrected with MC based on Geant4 using Fritiof-based physics lists.

The production cross section is computed from: \( \sigma_{\text{prod}} = \sigma_{\text{inel}} - \sigma_{\text{QE}} \)

Where the quasi-elastic contributions is also estimated with MC based on Fritiof-based models from Geant4.

\[
\sigma_{\text{prod}}^{2007} = 229.3 \pm 1.9(\text{stat.}) \pm 9.0(\text{syst.}) \text{ mb}
\]

\[
\sigma_{\text{prod}}^{2009} = 233.5 \pm 2.8(\text{stat.}) \pm 4.2(\text{model}) \pm 1.0(\text{trigger}) \text{ mb}
\]

\( \rightarrow \) Systematic uncertainty significantly reduced

A QE interaction happens when a proton elastically scatters off a nuclei. From MC:

\( \sigma_{\text{QE}} = 27.8 \pm 0.2 \pm 3.6 \text{ mb} \)
Charged hadron measurements from thin target data

3 analysis techniques:

1. **h analysis**: Consider that almost all negative tracks are $\pi^-$, small MC-based corrections to subtract K$^-$ and anti-p.

2. **dE/dx analysis**: Charged tracks are identified via their energy losses, up to $p \sim 1$ GeV/c

3. **ToF+dE/dx analysis**: Combined informations from Time of Flight [$m^2$] and energy loss to identify $\pi^\pm$, p, K$^\pm$ for $p > 1$ GeV/c → 2009 data

π$^-$ multiplicities in p+C at 31 GeV/c

2007 results

The 3 analysis techniques are overlaid
Charged hadron measurements from thin target data

\[ \pi^- \text{ multiplicity in p+C at 31 GeV/c} \]

\[ p \text{ multiplicity in p+C at 31 GeV/c} \]

\[ \text{Data - 2009, Data - 2007, Fluka2011} \]
Charged hadron measurements from thin target data

**π⁻ multiplicity in p+C at 31 GeV/c**

0 < θ < 10 mrad

20 < θ < 40 mrad

40 < θ < 60 mrad

60 < θ < 100 mrad

100 < θ < 140 mrad

**p multiplicity in p+C at 31 GeV/c**

0 < θ < 10 mrad

20 < θ < 40 mrad

40 < θ < 60 mrad

60 < θ < 100 mrad

100 < θ < 140 mrad

**π⁻ multiplicity**

Data - 2009

Data - 2007

**p multiplicity**

FTF_BIC - G495

FTF_BIC - G496

FTF_BIC - G410

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Charged hadron measurements from thin target data

π⁻ uncertainty in p+C at 31 GeV/c

<table>
<thead>
<tr>
<th>Angle Range</th>
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</tr>
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<tbody>
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p uncertainty in p+C at 31 GeV/c

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Uncertainty

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Charged hadron measurements from thin target data

K⁻ multiplicity in p+C at 31 GeV/c

Data - 2009
Fluka2011
Charged hadron measurements from thin target data

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Neutrino fluxes

- Neutrino fluxes as a function of energy in GeV for 295 km Far Detector.
- Flux/50 MeV/cm²$/10^{21}$ P.O.T.
- Different types of particles: Pions, Muons, K0L, Kaons-2, Kaons-3.
- Diagrams show the flux distribution for $\nu_e$, $\nu_\mu$, $\bar{\nu}_e$, and $\bar{\nu}_\mu$.