The NA61/SHINE Hadron Production Measurements for the T2K Experiment

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on behalf of the NA61/SHINE collaboration
Motivation

- Interactions and re-interactions in the target and the beam elements → hadrons ($\pi^\pm$, $K^\pm$, $K^0_s$, $K^0_L$, $\Lambda$, ...) → neutrinos

- Neutrino flux is simulated with the MC models → huge uncertainties of the hadron production models → huge uncertainties of the neutrino oscillation parameters

Hadron production measurements are needed for reducing flux uncertainties!!!
T2K (Tokai to Kamioka) Experiment

- Neutrino beam produced at J-PARC, off-axis method (2.5°)
- Length of the baseline: 295 km
- Near detector: 280 m from the target
- Physics goals: measurement of $\theta_{13} > 0$, $\Delta m^2_{23}$, $\theta_{23}$, $\delta_{CP}$, neutrino cross section measurements
J-PARC Neutrino Beam Facility and Beam Simulation

- Proton beam: 31 GeV/c, target: 90 cm long graphite rod
- Flux simulation: FLUKA 2011 + GEANT 3
- Flux uncertainty before had. prod. measurements: ~30%

Muon monitor
Decay tunnel
~94 m
He gas filled
Target
Graphite
L = 90 cm
r = 1.3 cm

Beam dump
3 Horns
I = ± 250 kA
Beam monitors
Primary beamline

$E_K = 30$ GeV
$P_{beam} = 300$ kW
Fast extracted beam

The T2K Requirements

- REQUIREMENT: Spectra of hadrons in the bins of polar angle $\theta$ and momentum $p$
- Only experiment capable of providing such measurements: NA61/SHINE

- Neutrino mode
- Antineutrino mode
NA61/SHINE Experiment

**SPS Heavy Ion and Neutrino Experiment**

- **Search for the critical point of strongly interacting matter (p+p, p+A, A+A)**
- **Precise hadron production measurements for the neutrino flux re-weighting in the T2K and Fermilab neutrino experiments**
- **More reliable simulations of the cosmic-ray air showers**

p + T2K replica target @ 31 GeV/c

* under construction
Hadron Production Measurements for the T2K Experiment

Thin carbon target

- $2.5 \times 2.5 \text{ cm}^2$, $L = 2 \text{ cm} = 0.04 \lambda_{int}$
- Measurement of the production cross section and the spectra of $\pi^\pm$, $K^\pm$, $K_s^0$, $p$, $\Lambda$

60% of T2K neutrino flux is due to primary interactions in the target

T2K replica target

- $L = 90 \text{ cm} = 1.9 \lambda_{int}$, $r = 1.3 \text{ cm}$
- Measurement of the charged pion spectra exiting the target

90% of T2K neutrino flux is due to primary interactions and re-interactions in the target

<table>
<thead>
<tr>
<th>Beam</th>
<th>Target</th>
<th>Year</th>
<th>Triggers [$10^6$]</th>
<th>Status</th>
<th>Comment</th>
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<tr>
<td>protons at 31 GeV/c</td>
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<td>2007</td>
<td>0.7</td>
<td>published $(\pi^\pm, K^+, K_s^0, \Lambda)^1,^2$</td>
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<td>published $(\pi^\pm)^3$</td>
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<td>2009</td>
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<td>recently published $(\pi^\pm, K^\pm, p, K_s^0, \Lambda)^4$</td>
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<td>2010</td>
<td>10.2</td>
<td>analysis in progress</td>
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</tbody>
</table>

Inelastic and Production Cross Section (p + C @ 31 GeV/c)

- Trigger inefficiencies → corrected with MC
- Production cross section $\sigma_{prod} = \sigma_{inel} - \sigma_{qel}$ → production of a new particle
- $\sigma_{qel}$ - quasi-elastic cross section

$\sigma_{inel} = 258.4 \pm 2.8(stat) \pm 1.2(det)_{-2.9}^{+5.0}(mod) \, mb$

$\sigma_{prod} = 230.7 \pm 2.7(stat) \pm 1.2(det)_{-3.4}^{+6.3}(mod) \, mb$
Analysis of the p + C Interactions at 31 GeV/c (2009)

Charged hadrons ($\pi^\pm, K^\pm, p$)
- Complementary analyses in different momentum ranges
  - $dE/dx$
  - $dE/dx$-tof
  - $h^-$ (no PID, just for $\pi^-$)

Neutral hadrons ($K_s^0, \Lambda$)
- V0 analysis - 2 body decays of the neutral hadrons
- Sample of $K_s^0$ or $\Lambda$ is selected by cuts
- Invariant mass fits

\[ \text{Entries} \]

\[ m^2 \text{[GeV}^2\text{]} \]

\[ p \text{[GeV/c]} \]

\[ dE/dx \text{[mip]} \]

\[ \alpha = (p^-_1 p^+_2)(p^+_1 p^-_2) \]

\[ m_{\pi^0}(K_s^0) \text{[GeV/c]} \]

\[ m_{\pi^0}(\Lambda) \text{[GeV/c]} \]
Systematic uncertainties

- PID ($dE/dx - tof$, $dE/dx$, 2% for $\pi^\pm$ and up to 20% for $K^\pm$)
- Feed-down and $\Lambda$ weighting (data based feed-down correction for $\pi^-$), 30% of correction factor
- Track cuts (1%)
- Reconstruction efficiency (2%)
- Forward acceptance (4%)
- Analysis specific errors (TOF efficiency, hadron loss, $K^-$ and $\bar{\rho}$ contamination, etc.), 1-5%
Results

- RESULTS: Double differential multiplicities v.s. momentum in polar angle bins

Comparison with models

- Venus 4.12, EPOS 1.99, GiBUU 1.6
- GEANT4: FTF_BIC-G495, FTF_BIC-G496, FTF_BIC-G410, QGSP_BERT-G410

Two additional hypotheses for $K^0_s$

- Based on our $K^\pm$ results
- Isospin symmetry in kaon production:
  \[ N(K^0_s) = \frac{1}{2}(N(K^+) + N(K^-)) \]

- Quark counting:
  \[ n = u_v/d_v \]
  \[ N(K^0_s) = \frac{1}{8}(3N(K^+) + 5N(K^-)) \]

Nucl. Phys. A528, 754 (1991)
T2K Flux Uncertainty

- Flux uncertainty after re-weighting with the p + C at 31 GeV/c results is around 10%
- T2K goal is to reach uncertainty below 5% → replica target results are needed

With NA61/SHINE measurements from 2007
With NA61/SHINE measurements from 2009

2. Flux Tuning and Uncertainty Updates for the 13a Flux (http://www.t2k.org/docs/technotes/217)
Analysis of the p + T2K Replica Target Data (2009)

- $dE/dx$-tof and $h^-$ analysis
- Vertex position is not required → tracks are extrapolated towards the target surface
- Shape of the neutrino spectra depends on the track position ($z$) on the target surface → additional binning in $z$
- Systematics: up to 10% (track extrapolation)
- Limited statistics → only $\pi^\pm$ spectra obtained
Ongoing Analysis of the p + T2K Replica Target Data (2010)

- 3.5× previous statistics → extraction of $K^\pm$ and $\rho$ yields is possible
- Part of the dataset is taken with high magnetic field → better forward acceptance
- Special trigger which selects beam profile similar to the J-PARC beam
- $dE/dx$-tof analysis is ongoing
  - Current status: uncorrected spectra of hadrons

\[ z = 90 \text{ cm}, 0 < \theta < 20 \text{ mrad}, 3.33 < p < 4.67 \text{ GeV/c} \]
Uncorrected spectra of the charged hadrons

$\pi^+$

$\pi^-$

$K^+$

$K^-$

$18 \leq z < 36 \text{ cm}, 110 \leq \theta < 130 \text{ mrad}$

Preliminary
Summary and Conclusions

- Precise measurement of the neutrino oscillation in the accelerator based neutrino experiments is not possible without dedicated hadron production measurements.

- Hadron production measurements for the T2K were performed by the NA61/SHINE collaboration.

- New results from 2009 measurements:
  - Spectra of hadrons in p-C interactions at 31 GeV/c → successfully used in the T2K beam simulation.
  - $\pi^\pm$ spectra exiting the surface of the T2K replica target.
  - The results provide useful information for the model builders.

- Analysis of 2010 p+T2K replica target dataset is ongoing.
  - Extraction of $K^\pm$ and $\rho$ yields is possible.

- New hadron production measurements for the Fermilab neutrino experiments will be performed (2016.-2018.). STAY TUNED!
BACKUP
T2K neutrino flux

run1-6a at ND280

Flux (cm$^{-2}$/50MeV/10$^{-21}$p.o.t)

$\nu_\mu$, $\nu_e$

$\bar{\nu}_\mu$, $\bar{\nu}_e$

E$_{\nu}$ (GeV)

$\phi^{2.5\text{km}}_{\nu_\mu}$ (A.U.)

OA 0.0$^\circ$, OA 2.0$^\circ$, OA 2.5$^\circ$
Inelastic and Production Cross Section (p + C @ 31 GeV/c)

- Elastic cross section $\sigma_{el}$ - i.e. excitation of a nucleus
- Inelastic cross section $\sigma_{inel} = \sigma_{tot} - \sigma_{el}$
- Quasi-elastic cross section $\sigma_{qe}$ - i.e. nucleon is ejected from the nucleus
- Production cross section - production of a new particle (i.e. pion), $\sigma_{prod} = \sigma_{inel} - \sigma_{qe}$

Interaction probability

\[ P = \frac{n}{N} \]

Number of beam triggers

Number of beam interaction triggers

Nonzero probability of interaction outside the target

$\rightarrow$ 2 datasets: target inserted and target removed

\[ P_{int} = \frac{P_{TI} - P_{TR}}{1 - P_{TR}} \]

- $P_{int}$ - interaction probability inside the target
- $P_{TI}$ - interaction probability in target inserted sample
- $P_{TR}$ - interaction probability in target removed sample

\[ \sigma_{trig} = \frac{1}{\rho L_{eff} N_A / A} P_{int} \]

- $\sigma_{trig}$ - trigger cross section
- $\rho$ - target density
- $N_A$ - Avogadro’s number
- $A$ - atomic number
- $L_{eff} = \lambda_{abs} \left( e^{-L/\lambda_{abs}} \right)$ - effective target length
- $\lambda_{abs} = \frac{A}{\rho N_A \sigma_{trig}}$ - absorption length

\[ \sigma_{inel} = \left( \sigma_{trig} - f_{el} \sigma_{el} \right) \frac{1}{f_{inel}} \]

\[ \sigma_{prod} = \left( \sigma_{trig} - f_{el} \sigma_{el} - f_{qe} \sigma_{qe} \right) \frac{1}{f_{prod}} \]

- $f_{el}, f_{qe}, f_{inel}, f_{prod}$ - trigger efficiencies, obtained from MC
Inelastic and Production Cross Section ($p + C @ 31$ GeV/c)

$f_{prod} = 0.993 \pm 0.000 (det)^{+0.001}_{-0.012} (mod)$

$f_{inel} = 0.998^{+0.001}_{-0.008} (det)^{+0.000}_{-0.008} (mod)$

$f_{el} \sigma_{el} = 50.4^{+0.6}_{-0.5} (det)^{+4.9}_{-2.0} (mod)$

$f_{qe} \sigma_{qe} = 26.2^{+0.4}_{-0.3} (det)^{+3.9}_{-0.0} (mod)$
Charged Hadron Production in p + C @ 31 GeV/c (2009)

Differential multiplicities

\[ \frac{dn_h}{d\theta dp} = \frac{1}{\sigma_{\text{prod}}} \frac{\sigma_{\text{trig}}}{1-\epsilon} \left( \frac{1}{N^I} \frac{\Delta n^I_h}{\Delta \theta \Delta p} - \frac{\epsilon}{N^R} \frac{\Delta n^R_h}{\Delta \theta \Delta p} \right) \]

- \( h \) - particle species
- \( \epsilon = (12.03 \pm 0.04)\% \) - fraction of the out-of-target interactions in the target inserted sample
- \( N^I, N^R \) - number of selected events for target inserted and target removed sample
- \( \Delta n^I_h, \Delta n^R_h \) - corrected number of particles for target inserted and target removed sample for a given bin
- \( \Delta \theta, \Delta p \) - polar angle and momentum bin size

Corrections

- Geometrical acceptance
- Reconstruction efficiency
- Off-target interaction
- Feed-down from decays of neutral strange particles
- Analysis specific corrections (e.g. ToF-F efficiency, PID, \( K^- \), \( \bar{p} \) contamination, etc.)
π+

π−
Re-weighting with replica target data

Fractional error of the $\nu_\mu$ flux at SK

- At peak energy (0.6 GeV) 90% of the flux is coming from the pions exiting the target
- At 4 GeV only 10% of $\nu_\mu$ flux is coming from the pions exiting the target
- At peak energy 90% of the flux has hadron production uncertainty of 4%, but at 4 GeV only 10% of the flux has hadron production uncertainty of 4%
- $K^\pm$ multiplicities are needed to further constrain neutrino flux

IMPORTANT: Only component of the $\nu_\mu$ flux coming from the pions exiting the target