NA61/SHINE and EMPHATIC measurements for neutrino physics

Matej Pavin,
on behalf of NA61/SHINE and EMPHATIC collaboration

Outline

- Hadron production measurements for neutrino experiments
  - NA61/SHINE experiment
    - Data taken for T2K
    - Data taken for Fermilab neutrino programme
    - How did NA61/SHINE data improved T2K flux uncertainty?
  - EMPHATIC experiment
    - Physics programme
    - Test beam measurements in January 2018
    - Future measurements
Motivation

- Neutrino flux in accelerator-based and atmospheric neutrino experiments is produced from decays of hadrons and muons.
- Neutrino flux uncertainty is the dominant uncertainty in many neutrino measurements.
- Single detector measurements are mostly affected (neutrino-nucleus cross-section measurements, sterile neutrino searches, measurement of CP violation in atmospheric neutrinos).
- Accelerator-based neutrino oscillation experiments with near and far detector are less affected (far to near ratio).
- **Monte Carlo simulations are used to estimate neutrino flux (different models give different predictions).**
Hadron production measurements

- Hadron production measurements can be used to tune models

1. Thin target measurements
   - Re-weight interaction probability
   - Re-weight hadron yields
   - Repeat for all particle generations

2. Replica target measurements
   - Re-weight hadron yields on the target surface

- NA61/SHINE collaboration took data for neutrino experiments for a decade
North Area 61 / SPS Heavy Ion and Neutrino Experiment NA61 / SHINE

- Precise hadron production measurements for neutrino flux re-weighting in T2K and Fermilab neutrino experiments

*Setup used in hadron production measurements for neutrino experiments*
Capabilities of the NA61/SHINE detector

- Beam momentum between 13 and 160 AGeV/c
- Beam purity for hadrons is very high (p at 31 GeV/c > 99.9%)
- Large acceptance (for T2K measurements 400 mrad)
- PID: dE/dx + tof
Thin target measurements for T2K

- 2 cm thick carbon target (around 5% interaction length)
- Measurements of hadron yields and production cross section

\[ \sigma_{\text{prod}} = \sigma_{\text{tot}} - \sigma_{\text{el}} - \sigma_{\text{qel}} \]

<table>
<thead>
<tr>
<th>Year</th>
<th># of Int. triggers ([10^6])</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>0.7</td>
<td>(\pi^\pm, K^+, K^0_s, \Lambda) yields and (\sigma_{\text{prod}})([1,2])</td>
</tr>
<tr>
<td>2009</td>
<td>5.4</td>
<td>(\pi^\pm, K^\pm, K^0_s, p, \Lambda) yields and (\sigma_{\text{prod}})([3])</td>
</tr>
</tbody>
</table>

Replica target measurements for T2K

- Around 2 interaction lengths
- Interaction vertices are not reconstructed → TPC tracks are extrapolated to the target surface
- Measurement of the production cross section is not necessary

<table>
<thead>
<tr>
<th>Year</th>
<th>POT $[10^6]$</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>0.2</td>
<td>proof of concept [1]</td>
</tr>
<tr>
<td>2009</td>
<td>4.0</td>
<td>$\pi^\pm$ yields [2]</td>
</tr>
<tr>
<td>2010</td>
<td>10.2</td>
<td>$\pi^\pm$, $K^\pm$, $p$ yields [3]</td>
</tr>
</tbody>
</table>

Replica target measurements for T2K (2010)

- Measurements are done as a function of momentum \( (p) \), polar angle \( (\theta) \) and longitudinal position of the exit point on the target surface \( (z) \)
- 5 \( z \) bins (18 cm in size) + downstream target face
- \( p \) and \( \theta \) bin size depend on the statistics

\[
\begin{array}{ccccccc}
\text{mode} & \pi^+ [\%] & \pi^- [\%] & K^+ [\%] & K^- [\%] & p [\%] & \text{Tot [\%]} \\
\nu & 99.22 & 97.47 & 84.50 & 83.08 & 71.65 & 96.92 \\
\text{anti-}\nu & 97.03 & 98.89 & 72.56 & 89.61 & 69.66 & 96.62 \\
\end{array}
\]
π⁺ yields (60 \leq \theta < 80 \text{ mrad})
$\pi^-$ yields ($60 \leq \theta < 80$ mrad)

- $0 \leq z < 18$ cm
- $18 \leq z < 36$ cm
- $36 \leq z < 54$ cm
- $54 \leq z < 72$ cm
- $72 \leq z < 90$ cm
- $z = 90$ cm
$K^+$ yields ($0 \leq \theta < 60$ mrad)

- $0 \leq z < 18$ cm
- $18 \leq z < 36$ cm
- $36 \leq z < 54$ cm
- $54 \leq z < 72$ cm
- $72 \leq z < 90$ cm
- $z = 90$ cm

Graphs showing the distribution of $K^+$ yields for different $z$ intervals.
K⁻ yields (0 ≤ θ < 60 mrad)

- 0 ≤ z < 18 cm
- 18 ≤ z < 36 cm
- 36 ≤ z < 54 cm
- 54 ≤ z < 72 cm
- 72 ≤ z < 90 cm
- z = 90 cm

Graphs showing the distribution of K⁻ yields with respect to momentum (p [GeV/c]) for different ranges of z.

Legend:
- NA61/SHINE K⁻
- NuBeam G4.10.03
- QGSP_BERT G4.10.03
\( p \) yields \((20 \leq \theta < 40 \text{ mrad})\)

\[\times 10^{-3}\]

- \(0 \leq z < 18 \text{ cm}\)
- \(18 \leq z < 36 \text{ cm}\)
- \(36 \leq z < 54 \text{ cm}\)
- \(54 \leq z < 72 \text{ cm}\)
- \(72 \leq z < 90 \text{ cm}\)
- \(z = 90 \text{ cm}\)

Graphs showing data distributions for different ranges of \(z\) and \(p\) [GeV/c].
T2K neutrino flux uncertainty

Only $\pi^\pm$ replica-target measurements from 2009 data were used
Measurements for Fermilab neutrino programme

- Data-taking 2012 - 2018
- Data-taking will finish in October
- NOvA replica target data taken this summer
- Most of the data is still being analyzed

<table>
<thead>
<tr>
<th></th>
<th>31 GeV/c</th>
<th>60 GeV/c</th>
<th>90 GeV/c</th>
<th>120 GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Be</td>
<td>C</td>
<td>Al</td>
<td>NOvA</td>
</tr>
<tr>
<td></td>
<td>Be</td>
<td>C</td>
<td>Al</td>
<td>NOvA</td>
</tr>
<tr>
<td></td>
<td>Be</td>
<td>C</td>
<td>Al</td>
<td>NOvA</td>
</tr>
<tr>
<td></td>
<td>Be</td>
<td>C</td>
<td>Al</td>
<td>NOvA</td>
</tr>
<tr>
<td></td>
<td>p</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>π⁺</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>π⁻</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>K⁺</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

● Data taken with magnets on
● Data taken with magnets off
Measurements of total production cross sections

- NUMI beam uses 120 GeV/c protons
- Measurements at lower momenta are used to re-weight re-interactions

A. Aduszkiewicz et al., arXiv:1805.04546 [hep-ex]
To appear in PRD
Interactions below 15 GeV/c

- NA61/SHINE beam cannot go below 13 AGeV/c
- Why we need lower beam momentum?
  - Low momentum re-interactions are starting to be limiting factor for T2K (π+Al, K+Al, ...)
  - The same limitations will apply to T2HK
  - Sub-GeV sample in atmospheric neutrino oscillations is sensitive to CP violation → size of the effect is around 3-4% → atmospheric flux uncertainty is larger and comes from low energy pion production
- Low momentum beam is available at Fermilab Test Beam Facility
- Compact hadron production experiment (1m in size) can be designed to measure low momentum interactions → EMPHATIC
EMPHATIC

- **Experiment to Measure the Production of Hadrons At a Testbeam In Chicagoland**
- **Complementary to NA61/SHINE**
- Physics goals:
  - Measurement of untuned interactions in the T2K neutrino beam simulation
  - Measurements for NUMI beam simulation
  - Hadron production measurements for atmospheric neutrinos
  - Cross-check of the NA61/SHINE production cross-section measurement
EMPHATIC data-taking in January 2018

Upstream Cherenkov → Scint. 1 → Trigger → Pixel Telescope → MT6.1-A

Silicon Strip Detectors

MT6.1-A → Target → MT6.1-B → Lead glass calorimeter

Aerogel Cherenkov Detectors

Downstream Cherenkov → Scint. 2
Targets and beam

- Graphite, aluminum and steel targets
- Emulsion targets with graphite
- Beam momentum: 2 - 120 GeV/c
- Beam composition:
  - $p < 10 \text{ GeV/c} \rightarrow \text{fraction of } e^{\pm} > 50\%$
  - $p = 30 \text{ GeV/c} \rightarrow \text{fraction of } p \sim 45\%, \ K \sim 3\%, \ π \sim 50\%$
What can we do with the data?

- **Measurement of total, elastic and quasi-elastic cross section**
- Momentum measurement is not necessary
- PID is not necessary

\[ |t| \approx p^2 \theta^2 \]

 beam momentum

 scattering angle

 total cross section from optical theorem

 coherent elastic scattering

 quasi-elastic scattering (scattering on a single nucleon)

 Bellettini et al., Nucl.Phys. 79 (1966) 609-624
4-momentum transfer (raw data)

Events

$10^5$

$10^4$

$10^3$

$10^2$

$10$

$0.00$ $0.02$ $0.04$ $0.06$ $0.08$ $0.10$ $0.12$

$p^2\theta^2 \ [\text{GeV}/c]^2$

Coulomb-nuclear interference region (CNI)

Elastic region

Quasi-elastic region

*p* + C @ 30 GeV/c

*Lines on top of the data points are not fits*
Future EMPHATIC measurements

- Permanent magnet (Halbach array) \(\Rightarrow\) fields > 1T are possible
- Magnet + Si strip detectors \(\Rightarrow\) momentum resolution for 2 GeV/c particles is around 2%
- PID: TOF + aerogel RICH
- B, BN and B\(_2\)O\(_3\) for atmospheric neutrinos
- C, Al and Fe targets for accelerator based experiments
Conclusions

- Hadron production measurements are necessary for precise measurements of neutrinos
- NA61/SHINE took hadron production data for a decade
- Very successful T2K programme → flux uncertainty reduced from > 20% to around 5%
- A lot of data was taken for the Fermilab neutrino programme
- Measurements with low momentum beams are needed
- EMPHATIC → a table top experiment which can take low momentum data
- First EMPHATIC data is being analysed
Uncertainties
π⁺ uncertainties

0 ≤ z < 18 cm
18 ≤ z < 36 cm
36 ≤ z < 54 cm
54 ≤ z < 72 cm
72 ≤ z < 90 cm
z = 90 cm

Stat.
Syst.
Total

Fraction

p [GeV/c]
$K^+$ uncertainties

[Diagrams showing $\theta$ vs $p$ for different $z$ ranges, with panels labeled Stat., Syst., and Total.]
$K^-$ uncertainties
p uncertainties

Stat.

Syst.

Total

\(0 \leq z < 18 \text{ cm}\)

\(18 \leq z < 36 \text{ cm}\)

\(36 \leq z < 54 \text{ cm}\)

\(54 \leq z < 72 \text{ cm}\)

\(72 \leq z < 90 \text{ cm}\)

\(z = 90 \text{ cm}\)
Beam profile re-weighting

- hadron yields on the target surface depend on the beam profile
- narrower beam profile $\rightarrow$ suppression of hadron yields for low $\theta$ and upstream $z$ bins
- Only important parameter is radial position on the upstream target face
- T2K beam profile $\neq$ NA61 beam profile

$r_b = 0.65 \text{ cm, } \theta = 20 \text{ mrad} \rightarrow \Delta z = 32.5 \text{ cm}$

$\theta = 250 \text{ mrad} \rightarrow \Delta z = 2.5 \text{ cm}$

$r_b = 1.00 \text{ cm, } \theta = 20 \text{ mrad} \rightarrow \Delta z = 15.0 \text{ cm}$

$\theta = 250 \text{ mrad} \rightarrow \Delta z = 1.2 \text{ cm}$
- T2 beam width > T2K beam width > T3 beam width → when using this data in T2K any bias would be smaller