Measurements of p+C differential cross-section at 20, 30, and 120 GeV/c in EMPHATIC

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on behalf of the EMPHATIC collaboration

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What is EMPHATIC?

- **Experiment to Measure the Production of Hadrons At a Testbeam In Chicagoland**
- ~20 people
- Hadron production measurements for neutrino experiments (T2K, NOVA, HyperK, DUNE)
- Fermilab Test Beam Facility (FTBF)
Motivation

- Next generation of accelerator long-baseline neutrino experiments (HyperK, DUNE) will be limited by systematics
- HK-Canada group is trying to reduce all of the major systematics which will affect HyperK
- One of the major systematics is neutrino flux uncertainty
  - Dominant uncertainty in single detector measurements (neutrino-nucleus cross-section, sterile neutrino searches, ...)

<table>
<thead>
<tr>
<th>Measurement of (anti)$\nu_\mu$ charged current inclusive cross-sections in T2K ND</th>
<th>Statistics [%]</th>
<th>Flux [%]</th>
<th>Cross-section model [%]</th>
<th>Detector [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(\nu)$</td>
<td>0.87</td>
<td>9.14</td>
<td>1.16</td>
<td>2.63</td>
</tr>
<tr>
<td>$\sigma(\text{anti-}\nu)$</td>
<td>3.22</td>
<td>9.37</td>
<td>2.13</td>
<td>1.82</td>
</tr>
<tr>
<td>$\sigma(\text{anti-}\nu)/\sigma(\nu)$</td>
<td>3.22</td>
<td>3.58</td>
<td>1.56</td>
<td>1.11</td>
</tr>
</tbody>
</table>

Phys.Rev. D96 (2017) no.5, 052001
Neutrino beams in accelerator neutrino experiments

- T2K, NOvA, MINERvA, **HK, DUNE**
- Proton beam is directed toward a thick target
- Produced hadrons are (de)focused by a set of magnetic horns
- Neutrinos are produced from pion, kaon and muon decays
- Other particles are stopped in the beam dump

\[
\begin{align*}
\pi^+ & \rightarrow \mu^+ \nu_\mu \\
K^+ & \rightarrow \mu^+ \nu_\mu \\
\mu^+ & \rightarrow e^+ \bar{\nu}_\mu \nu_e \\
K_{L}^0 & \rightarrow \pi^- e^+ \nu_e
\end{align*}
\]
Neutrino flux uncertainty in T2K and HyperK

- MC models are used to simulate neutrino flux
- Hadron production measurements are used to constrain the models
- Particle production in p + C interaction at 30 GeV/c was measured by NA61/SHINE → current $\nu_\mu$ flux uncertainty in T2K is around 5% at peak energies

- Hadron interactions outside of the target contribute significantly to (anti-)$\nu_e$ fluxes
  - $\pi^\pm + \text{Al} \rightarrow \pi^\pm + X$ and $K^\pm + \text{Al} \rightarrow K^\pm + X$
  - p < 15 GeV/c
  - No measurements which cover interactions of interest
  - $\nu_e$ flux uncertainty can impact E61/IWCD/NuPrism measurements (see talk by John Walker)
EMPHATIC physics goals

- Measurement of untuned interactions in the T2K neutrino beam simulation
- Hadron production measurements for atmospheric neutrinos
- Measurements for Booster neutrino programme
- Low momentum meson interactions in NuMI
- Cross-check of the NA61/SHINE measurements
- Resolve inconsistencies between the data
- High momentum measurements for NuMI beam simulation

Beam test in January 2018 (Fermilab Test Beam Facility)

- Test of the FTBF capabilities (silicon strip tracking, gas Cherenkov detectors)
- Test of the aerogel threshold Cherenkov detectors
- Test of the particle tracking with emulsions
- Measurement of the forward proton scattering (coherent elastic and quasi-elastic)
EMPHATICIC data-taking in January 2018

Silicon strip detectors

Trigger scintillator

Beam

Pixel telescope (dead material)

~2.2 m

Target

Moving table

Room MT6.1-A

Silicon strip detectors
Targets and beam

- Graphite, aluminum, steel and empty targets
- Emulsion targets with graphite
- The same graphite is used in T2K
- Beam momentum: 2, 10, 20, 30, 120 GeV/c

Beam profiles
What can we do with the data?

- $p + C @ 20, 30, 120 \text{ GeV/c}$ data
- Measurement of forward scattering

$$|t| \approx p^2 \theta^2$$

Beam momentum  
Scattering angle

- Total cross section from optical theorem
- Coulomb-nuclear interference region
- Coherent elastic scattering
- Quasi-elastic scattering (scattering on a single nucleon)

Bellettini et al., Nucl. Phys. 79 (1966) 609-624
$N_{\text{pot}} \rightarrow$ number of particles on target

$N_i \rightarrow$ corrected number of measured tracks after the target

$nd \rightarrow$ number density $\otimes$ target thickness

$\Delta t_i \rightarrow$ four momentum bin size

$i \rightarrow$ bin number

\[
\left( \frac{d\sigma}{dt} \right)_i = \frac{1}{N_{\text{pot}}} \frac{N_i}{nd\Delta t_i}
\]
$\chi^2 = 190.5$

$dof = 37$

$\chi^2 = 179.0$

$\chi^2 = 90.8$
Impact of the current results

- Quasi-elastic cross-section measurements can significantly impact the flux uncertainty in NOvA
- Assuming 10% uncertainty on proton-nucleus quasi-elastic interactions
Future measurements and upgrades

● Measurements of particle production and interaction probability (total cross-section, elastic, inelastic, ...)
  ● $p, \pi, K + C, Al, Fe, @ 4, 8, 12, 20, 31, 60, 120$ GeV/$c$
  ● 5, 10 and 20% $\lambda_1 C$ targets
  ● Additional targets $B, BN, B_2O_3$ for atmospheric neutrinos

● We need momentum measurement and PID
Threshold aerogel detector

- Beam PID at lower momenta not possible with gas Cherenkov detectors
- Aerogel threshold Cherenkov
- Beam test
  - $n = 1.004 \Rightarrow N_{p.e.} = 5.7$ (detection efficiency > 99%)
  - $n = 1.012 \Rightarrow N_{p.e.} = 16.8$
  - $n = 1.045 \Rightarrow N_{p.e.} = 41.0$

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<tbody>
<tr>
<td>1.004</td>
<td>1.6</td>
<td>5.5</td>
<td>10.5</td>
</tr>
<tr>
<td>1.012</td>
<td>0.9</td>
<td>3.2</td>
<td>6.0</td>
</tr>
</tbody>
</table>
Aerogel RICH

- Based on Belle II RICH detector
- Advances in aerogel production (Chiba U.)
- Beam test at TRIUMF in August
- $2\sigma$ π/K separation < 7 GeV/c
- $1\sigma$ π/K separation < 10 GeV/c
Particle tracking

- Large silicon strip detectors for tracking
- Compact NdFeB Halbach array → small NdFeB segments are stacked to mimic the field inside a strong dipole magnet
- Current magnet design: $\varnothing 30 \text{ cm} \otimes 15 \text{ cm}$ ($\sim 100 \text{ kg}$), 350 mrad coverage
- Whole tracking region is only 40 cm long
- Momentum resolution 4% - 10% for $p < 20 \text{ GeV/c}$

![Graph showing $\sigma/p$ vs. $p$ in [GeV/c]](image)
Conclusions

- Neutrino flux is the dominant uncertainty in single detector neutrino measurement
- Significant fraction of hadron interactions below 15 GeV/c are unconstrained → we rely on models → large systematic uncertainties (> 10%)
- EMPHATIC is a table-top hadron production experiment at FTBF
- Main physics goal is to measure hadron interaction below 15 GeV/c
- Preliminary beam test was done in 2018
  - Test of the FTBF capabilities
- We were able to measure forward p+C scattering
- The results can already have significant impact on the NOVA systematics
- Future runs and upgrades are planned
BACKUP
Hadron production measurements

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
   - Use thin target data for out-of-target interactions

Both approaches are necessary to completely constrain neutrino flux!
Thin vs. replica target tuning

- T2K neutrino flux simulation with the NA61/SHINE replica target tuning predicts 5% lower flux
- Differences between thin vs. replica tuning were also observed when MIPP data was used at Fermilab
- Problems with interaction probability?

Uncertainty is dominated by differences between production cross-section measurements.

T. Vladisavljevic, arXiv:1804.00272
CP violation in atmospheric neutrino oscillations

- Small effect (~2%) in sub-GeV neutrino sample
- The uncertainty is dominated by hadron production below 15 GeV (\(\pi^+/\pi^-\) ratio)
- Only HARP data covers the important region

G.D. Barr et al., PRD 74 (2006) 094009
Differential cross-section measurement

- No PID or momentum measurement → contamination from secondary particles and production events
- \( p + C \rightarrow p + X, \quad K + C \rightarrow K + X \)
- \( p \) or \( K \) are leading hadrons (highest momentum particle)
  - This definition minimizes MC corrections
Particle tracking

Trigger scintillator
Silicon strip planes
Pixel planes
Target

220 cm
Monte Carlo simulation

- Geant4.10.03.p02 simulation of the EMPHATIC setup
  - FTFP_BERT
  - QGSP_BERT
- FLUKA 2011.2x
- Beam profile and divergence distributions from the data are used to generate beam particles
- Simulation includes silicon strip planes, pixel planes, trigger scintillator, and the target
- Good agreement between angular resolution in the data and Monte Carlo (<4%)

$p+C @ 30 \text{ GeV/c}$

\[
\sigma (\text{data}) = 0.207 \text{ mrad} \\
\sigma (\text{MC}) = 0.209 \text{ mrad}
\]
Upstream selection

- Gas Cherenkov selection
- Single upstream track
- Maximum number of clusters
- Upstream track $\chi^2 < 6$
- Beam divergence cut (remove SSD interactions)
- Beam profile cut

Remove upstream interactions

[K + C analysis]

$p + C$ analysis

Target In

Target Out
Upstream selection

- Gas Cherenkov selection
- Single upstream track
- Maximum number of clusters
- Upstream track $\chi^2 < 6$
- Beam divergence cut (remove SSD interactions)
- Beam profile cut

Remove upstream interactions

- Interactions in the trigger
- Interactions in the upstream silicon planes
- Non-interacting beam particles

$p+C @ 120$ GeV/c

$z_{\text{vert}} \rightarrow$ interaction point
Upstream selection

- Gas Cherenkov selection
- Single upstream track
- Maximum number of clusters
- Upstream track $\chi^2 < 6$
- Beam divergence cut (remove SSD interactions)
- Beam profile cut

Remove upstream interactions

Interactions in the trigger

Non-interacting beam particles

Interactions in the upstream silicon planes

Tracks

$p+C @ 120 \text{ GeV/c}$

$z_{\text{vert}} \rightarrow$ interaction point

$z_{\text{vert}} \geq -60 \text{ cm}$
$-100 \leq z_{\text{vert}} < -60 \text{ cm}$
$z_{\text{vert}} < -100 \text{ cm}$
Downstream selection

- Single downstream track
- Maximum number of clusters (6)
- Downstream track $\chi^2 < 4$
- $\delta x$ and $\delta y$ cuts $\rightarrow$ difference in upstream and downstream $x(y)$ track position at target z position

If the position difference is $> 3\sigma$, event is removed
Interactions in the pixel detector

Before selection

After selection

MC

Data

Upstream SSD

Downstream SSD

Target

Pixel planes
Pixel interactions

- Selected pixel interactions → shape correction only in forward bins
- Lost particles on target → normalization correction

<table>
<thead>
<tr>
<th>POT correction [%]</th>
<th>p+C @ 20 GeV/c</th>
<th>p+C @ 30 GeV/c</th>
<th>p+C @ 120 GeV/c</th>
<th>K+C @ 30 GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.2</td>
<td>4.5</td>
<td>4.3</td>
<td>2.9</td>
</tr>
</tbody>
</table>
Efficiency

$$\epsilon_i = \frac{N_i^{MC \text{ true, down. sel.}}}{N_i^{MC \text{ true}}}$$

Includes: reconstruction + acceptance + selection

Differences between datasets are due to the beam size and acceptance effects.
Secondary particles

- Secondary hadrons produced in the target and reconstructed in downstream layers
  - pions, kaons, and non-leading protons in p+C
  - pions, protons, and non-leading kaons in K+C
Systematic uncertainties

Strategy:
- Use data to estimate systematics
- If not possible use MC → largest difference between models

1. Beam contamination (kaons in proton beam) → negligible << 1% contamination
2. Upstream interactions in the trigger scintillator or SSDs → negligible < 0.5%
3. Pixel interactions (shape) → only forward bins negligible above $t=0.01 \text{ GeV}^2$
4. Secondary particles (not leading protons or kaons) <6%
5. Efficiency uncertainty (model dependance) <3%
6. Normalization (target thickness and density + pixel POT correction)
   a. Dominated by density uncertainty (2%) + pixel normalization uncertainty (0.5%)
Bellettini et al.

- Angular coverage 1.5 - 20 mrad
- Momentum measurement → contamination of inelastic events 1%
- Uncertainties are not known

EMPHATIC and Bellettini do not measure the same thing!

- EMPHATIC includes resonance production

Bellettini et al., Nucl.Phys. 79 (1966) 609-624