Experiment to Measure the Production of Hadrons At a Test beam In Chicagoland

Tetsuro Sekiguchi (KEK, IPNS)
on behalf of
EMPHATIC Collaboration

August 27, 2019

21st International Workshop on Neutrinos from Accelerators (NuFact2019)
Outline

• Introduction

• EMPHATIC

• 2018 test run

• Summary
Neutrino Flux Prediction

- It is difficult to measure neutrino flux itself in our detectors
  - We just measure flux $\times$ cross-section
  - $\nu$-e scattering $\rightarrow$ low statistics
  - In-situ direct measurement of secondary hadrons is very challenging (high radiation area)
- Need Monte Carlo simulations to predict neutrino flux
  - $\sim$30% differences between models $\rightarrow$ large systematic uncertainty
  - Hadron production data is used to tune the models
Hadron Production Measurements

Hadron interactions in target

- Primary int. (p+C) ~60%
- Secondary/tertiary int. (π,K+C) ~30%

- Hadron production experiments
  - NA49, HARP, MIPP, NA61/SHINE, etc
    - T2K uses mainly NA61 data (both thin and replica)
    - NOvA uses NA49, MIPP, (NA61) data

- Flux uncertainties successfully reduced to 10% level (5% in near future)
  - Can we improve more?

ND280: Neutrino Mode, $\nu_\mu$

![Graph showing fractional error vs. $E_\nu$](image)

- Multiplicity
- Nuclear
- Interaction Length
- Pion Rescatter
- Thin Tuning Total
- $\Phi \times E_\nu$, Arb. Norm.

ND280: Neutrino Mode, $\nu_\mu$

- Multiplicity
- Nuclear
- Interaction Length
- Pion Rescatter
- Unconstrained Interactions
- Replica Tuning Total
- Thin Tuning Total
- $\Phi \times E_\nu$, Arb. Norm.
What Do We Need?

- Dominant flux uncertainty in NOvA comes from 40% XSEC uncertainty on interactions in target or horns that were not measured (well)
  - Lack of proton and pion scattering data at low energies
- T2K flux uncertainty at low energies is limited by untuned interactions out of target
  - \( \pi^\pm + \text{Al (Fe)} \rightarrow \pi^\pm + X \text{(Fe)} \)
  - \( K^\pm + \text{Al (Fe)} \rightarrow K^\pm + X \text{(Fe)} \)
- Nearly 50% of wrong-sign neutrinos come from interactions out of target
- Measurement of \( \pi, K \) interactions at low energies (<10 GeV/c) is quite important for future experiments
  - Existing data are very limited
**EMPHATIC**

- Experiment to Measure the Production of Hadrons At a Test beam In Chicagoland
- Uses the Fermilab Test Beam Facility (FTBF)
- Table-top size experiment focused on hadron production measurements with $p_{\text{beam}} < 15 \text{ GeV/c}$, but will also make measurements with beam from 20-120 GeV/c.
- International collaboration from US, Japan, and Canada: 20~30 researchers

**Ultimate design:**
- Thin target (~5% int. length)
- Precision tracking with SSDs
- Momentum measurement with O(1)T permanent magnet
- PID for secondary particles
  - Aerogel RICH and ToF counters
- Large phase space coverage (~350mrad)
- Compact size
  - Low overall cost
  - Simple systematics
Fermilab Test Beam Facility (FTBF)

- 2-120 GeV/c beam including p, π, K, e, μ
- Beam intensity up to ~100 kHz
- 4-sec-long spill once a minute
- Many beam instrumentation available (SSD, gas Čerenkov, MPPC, etc)
Beam Particle ID

- **Beam PID**
  - Gas Cherenkov detectors: can be used for $p > 6$ GeV/c
    - No p/K separation for $p < 18$ GeV/c
  - PID for low momentum beam
    $\Rightarrow$ Threshold aerogel Cherenkov counters

- **Beam aerogel counter**
  - Developed by Chiba Univ. (aerogel expert)
  - Very low index ($n=1.004$) aerogel newly developed for EMPHATIC
    - Can cover 5-10 GeV/c region
    - Very high transparency, but low light yield
  - Prototype being tested with electron beam at Tohoku Univ.
    - $n=1.004 \rightarrow N_{PE} = 5.7$ (detection eff. $>99\%$)
    - $n=1.012 \rightarrow N_{PE} = 16.8$
    - $n=1.045 \rightarrow N_{PE} = 41.0$

### Table: Threshold momenta (GeV/c)

<table>
<thead>
<tr>
<th>$n$</th>
<th>$\pi$</th>
<th>$K$</th>
<th>$p$</th>
</tr>
</thead>
<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>
Magnet

Made from segments of Neodymium permanent magnets

Halbach Array

EMPHATIC Dipole Magnet
16 NdFeB (N52) segments
104 kg

all measurements are in mm
Magnetic Field Simulation

Field maps generated using COMSOL simulation $\Rightarrow 1.4$ T max.
Silicon Strip Detectors

- Large-area SSDs available from Fermilab SiDet facility.
- Resolution good enough (122μm) for downstream tracking
- Upstream tracking to be done by existing SSDs (60μm pitch) at the FTBF
Momentum Resolution

- Tracking simulation using GEANT4
- Preliminary study based on COMSOL magnetic field maps.
- SSD resolution taken into account
- Momentum resolution $< 6\%$ below 8 GeV/c, $< 10\%$ below 17 GeV/c
  - Resolution dominated by multiple scattering at low momentum
Aerogel RICH

- Proximity-focusing RICH based on Belle II ARICH detector
- Aerogels with lower indices of refraction \(n=1.03-1.04\) and good transmittance
- Light detected by multi-anode PMTs (6mm-pitch) or possibly MPPC (3mm-pitch)
  - 20ps-timing resolution by GSI TRB3 TDCs
- \(2\sigma\) \(\pi-K\) separation for \(p<7\) GeV/c.
- Beam test at TRIUMF ongoing in this summer
ToF Counters

- PID for low momentum particles below Cherenkov threshold
- Start counter: X-shaped Cherenkov counter (Acrylic + MPPC)
- Stop counter: Multi-gap Resistive Plate Chamber (RPC)
- Developed by J-PARC E50 group
- Timing resolution as good as 70 ps
## EMPHATIC Measurement Plan

<table>
<thead>
<tr>
<th>Phase</th>
<th>Date</th>
<th>Sub-system</th>
<th>Momenta</th>
<th>Targets</th>
<th>Goals</th>
</tr>
</thead>
</table>
| 1     | Spring 2020| Beam Aerogel counter FTBF SSDs Small aperture magnet Aerogel RICH ToF counters Lead glass calorimeter | 4, 8, 12, 20, 31, 60, 120 GeV/c | C, Al, Fe | • Improved elastic and quasi-elastic scattering measurements  
  • Low-acceptance (150mrad) hadron production measurements |
| 2     | Spring 2021| Beam Aerogel counter FTBF SSDs Large-area SSDs Full aperture magnet Aerogel RICH ToF counters Lead glass calorimeter | 4, 8, 12, 20, 31, 60, 120 GeV/c | C, Al, Fe, H$_2$O, Be, B, BN, B$_2$O$_3$ | • Full-acceptance (350mrad) hadron production with PID up to 8 GeV |
| 3     | Spring 2022| Same as Phase 2 + Extended RICH                                              | 20, 31, 60, 80, 120 GeV/c | Same as Phase 2 + Ca, Hg, Ti | • Full-acceptance (350mrad) hadron production with PID up to 15 GeV |
Proof-of-Principle Test

- EMPHATIC performed beam test in January 2018 for proof-of-principle
  - Detector development (Aerogel counters and emulsion detector)
  - Precise scattering measurements with high resolution trackers (SSD, emulsion)
- Initial beam test
  - January 10-24, 2018 for three weeks
  - 20M triggers collected in 7 days of running
  - 2, 10, 20, 30, 120 GeV/c beam on C, Al, Fe (and empty) targets

<table>
<thead>
<tr>
<th>Beam momentum</th>
<th>Graphite</th>
<th>Aluminum</th>
<th>Iron</th>
<th>Empty</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 GeV/c</td>
<td>1.63M</td>
<td>0</td>
<td>0</td>
<td>1.21M</td>
</tr>
<tr>
<td>30 GeV/c</td>
<td>3.42M</td>
<td>976k</td>
<td>1.01M</td>
<td>2.56M</td>
</tr>
<tr>
<td>-30 GeV/c</td>
<td>313k</td>
<td>308k</td>
<td>128k</td>
<td>312k</td>
</tr>
<tr>
<td>20 GeV/c</td>
<td>1.76M</td>
<td>1.76M</td>
<td>1.72M</td>
<td>1.61M</td>
</tr>
<tr>
<td>10 GeV/c</td>
<td>1.18M</td>
<td>1.11M</td>
<td>967k</td>
<td>1.17M</td>
</tr>
<tr>
<td>2 GeV</td>
<td>105k</td>
<td>105k</td>
<td>183k</td>
<td>108k</td>
</tr>
</tbody>
</table>
Beam Test Setup

- Targets with 2% interaction length
- Target can be changed remotely using motion table
Beam Test Setup

Gas CH1

Gas CH2

Trigger
Scintillator

Upstream
SSD

Si-pixel
detector

Target

Downstream
SSD

AC1
(1.013/
1.0046)

AC2
(1.045)

AC3
(1.026)

Lead glass
calorimeter

10cm

Emulsion bricks

5cm

- Emulsion bricks include target and emulsion films
- Talk by Fukuda-san on Thursday
Forward Scattering Measurements

- Elastic and quasi-elastic scattering cross-sections can be determined by forward scattering data.
- 20, 30, 120 GeV/c p + C data have been analyzed.
- ~0.3 mrad resolution was achieved with FTBF SSDs (60 \( \mu \)m pitch).

Momentum transfer \( t \approx p^2 \theta^2 \) (\( p \): incident momentum, \( \theta \): scattering angle).
Forward Scattering Results

- Differential cross section for 30 GeV/c p + C data
- Measurement uncertainties <10%
  - Dominated by statistical uncertainty
  - Systematic uncertainties estimated with both data and MC ⇒ <5%
  - Dominant error is due to efficiency estimation by MC (model dependence) ~4%
Forward Scattering Results

- Differential cross section for 120 GeV/c p + C data
- Measurement uncertainties <10%
  - Dominated by statistical uncertainty
  - Systematic uncertainties estimated with both data and MC ⇒ <4%
    - Dominant error is due to efficiency estimation by MC (model dependence) ~3%
    - Large pixel interaction error in lower bins
Impact of Current Results (I)

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

![Graph showing Hadron Production Uncertainties Before and After with Neutrino energy (GeV) on the x-axis and Fractional Uncertainties on the y-axis.](image)

![Graph showing Projected HP Uncertainties Before and After with Neutrino energy (GeV) on the x-axis and Fractional Uncertainties on the y-axis.](image)
Impact of Current Results (II)

- EMPHATIC results can reduce thin target reweighting uncertainty in T2K
- Thin vs. replica differences (under investigation)

\[ \sigma_{\text{pro}} = \sigma_{\text{inel}} - \sigma_{\text{qe}} \]

Dominant uncertainty on \( \sigma_{\text{pro}} \) comes from uncertainty on \( \sigma_{\text{qe}} \)

Different lines show uncertainties after reducing production cross-section uncertainty to 30, 20, and 10 mb
Current Status

- Preparing a paper for 2018 results → to be submitted soon
- Budget situation
  - Funding for detector construction approved in Japan and Canada
  - Severe situation in US
- Proposal submitted to Fermilab PAC in July 2019
- Detector development ongoing toward 2020 run
  - Beam aerogel counter
  - Magnet
  - Aerogel RICH
  - ToF
  - Lead glass calorimeter
- New collaborators are really welcome !!
Summary

• Hadron production measurements played significant role in reducing neutrino flux uncertainties to 5-10% level

• Measurements of π and K at low energies important for future neutrino experiments, but current data are very limited

• EMPHATIC aims to perform precise hadron production measurements using high resolution trackers and compact spectrometer

• Measurements with various targets across various momenta planned in 2020-2022

• Detector development ongoing for 2020 run

• Performed a pilot run in January 2018 and forward scattering results with 10% uncertainties which can improve flux uncertainties
Backup
Forward Scattering Results

p+C @ 20 GeV/c

p+C @ 30 GeV/c

p+C @ 120 GeV/c
Systematic Error Estimation

![Graphs showing systematic error estimation for p+C at 20 GeV/c, 30 GeV/c, and 120 GeV/c. Each graph represents different error components: Total Error, Statistical Error, Systematic Error, Efficiency Error, Normalization Error, Pixel Int. Error, and PID Error. The graphs are labeled as Preliminary.]