Over 150 Physicists from 30 institutions and 15 countries

The NA61/SHINE Collaboration
The NA61/SHINE Experiment

- SPS Heavy Ion and Neutrino Experiment
- Broad physics program
  - Heavy Ion
    - Study the onset of deconfinement
    - Critical point search
  - Cosmic Ray
    - Hadron production measurements to tune simulations of cosmic ray showers
  - Neutrino
    - Hadron production measurements to improve precision of neutrino flux estimations
- Capable of receiving secondary beam of charged hadrons (pions, kaons and protons) \([\sim 13, 350] \text{ GeV/c}\)
- Light ions from Pb fragmentation \([13A, 150A] \text{ GeV/c}\)
- Primary Ar, Xe and Pb \([13A, 150A] \text{ GeV/c}\) and primary protons \([400] \text{ GeV/c}\)
- Accepts many solid thin targets, liquid hydrogen and replica targets for neutrino experiments
- Capable of recording over 500,000 events per day
Necessity for Hadron Production Measurements

- Near detectors are insufficient for understanding neutrino flux at the far detector
  - Different angular acceptance and often different interaction material at near and far sites
- Neutrino cross section measurements depend on precise neutrino flux
- Which interactions do we need to understand?
  - Primary interactions of protons with target and beam material (eg. Al, Ti) at the beam energy
  - Secondary interactions of protons, pions and kaons with target and beam material at lower energies
- NA61 is capable of studying most of these interactions

### Neutrino Parents in T2K

<table>
<thead>
<tr>
<th>Parent</th>
<th>$\nu_\mu$</th>
<th>$\bar{\nu}_\mu$</th>
<th>$\nu_e$</th>
<th>$\bar{\nu}_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>60.0(55.6)%</td>
<td>41.8(2.5)%</td>
<td>31.9(0.4)%</td>
<td>2.8(0.0)%</td>
</tr>
<tr>
<td>$K^\pm$</td>
<td>4.0(3.7)%</td>
<td>4.3(0.3)%</td>
<td>26.9(0.3)%</td>
<td>11.3(0.0)%</td>
</tr>
<tr>
<td>$K^0_L$</td>
<td>0.1(0.1)%</td>
<td>0.9(0.1)%</td>
<td>7.6(0.1)%</td>
<td>49.0(0.1)%</td>
</tr>
<tr>
<td>Tertiary</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>34.4(31.9)%</td>
<td>50.0(3.0)%</td>
<td>20.4(0.2)%</td>
<td>6.6(0.0)%</td>
</tr>
<tr>
<td>$K^\pm$</td>
<td>1.4(1.3)%</td>
<td>2.6(0.2)%</td>
<td>10.0(0.1)%</td>
<td>8.8(0.0)%</td>
</tr>
<tr>
<td>$K^0_L$</td>
<td>0.0(0.0)%</td>
<td>0.4(0.1)%</td>
<td>3.2(0.0)%</td>
<td>21.3(0.0)%</td>
</tr>
</tbody>
</table>

Phys Rev D 87 012001 (2013)
The NA61/SHINE Detector System

- TPC system tracks charged particles and measures $dE/dx$ ($\sigma_{dE/dx}/<dE/dx> \approx .04$)
- Two Vertex TPCs are contained inside two superconducting vertex magnets (with 9 Tm of bending power)
- Two large Main TPCs
- Gap TPC and three new Forward-TPCs provide forward acceptance
- Time of Flight systems measure $m^2$ (~100 ps resolution)
Earlier Measurements for the T2K Experiment

- Thin target measurements from data recorded in 2007 and 2009
- T2K replica target measurements from 2007, 2009 and 2010

<table>
<thead>
<tr>
<th>Beam</th>
<th>Target</th>
<th>Year</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>(p@31 \text{ GeV/c})</td>
<td>C 2 cm</td>
<td>2007</td>
<td>(\pi^\pm, K^\pm, K^0_S, \Lambda^0)</td>
</tr>
<tr>
<td>(p@31 \text{ GeV/c})</td>
<td>C 2 cm</td>
<td>2009</td>
<td>(\pi^\pm, K^\pm, p, K^0_S, \Lambda^0)</td>
</tr>
<tr>
<td>(p@31 \text{ GeV/c})</td>
<td>C 90 cm</td>
<td>2007</td>
<td>(\pi^\pm)</td>
</tr>
<tr>
<td>(p@31 \text{ GeV/c})</td>
<td>C 90 cm</td>
<td>2009</td>
<td>(\pi^\pm)</td>
</tr>
<tr>
<td>(p@31 \text{ GeV/c})</td>
<td>C 90 cm</td>
<td>2010</td>
<td>(\pi^\pm, K^\pm, p, \text{preliminary release})</td>
</tr>
<tr>
<td>(p@31 \text{ GeV/c High Field})</td>
<td>C 90 cm</td>
<td>2010</td>
<td>Production cross section analysis in progress</td>
</tr>
</tbody>
</table>

7. https://edms.cern.ch/document/1828979/1
Effect on Neutrino Flux Prediction

- Thin target beam MC reweighting with the 2007 and 2009 (higher stats) NA61 thin target datasets has already improved the T2K flux estimation.
- A method has been developed to implement the replica target results into the flux estimation - it is expected to reduce uncertainties related to hadron production to < 5% everywhere.

Select 2010 T2K Replica Target Results

- Plots are for the second longitudinal bin along the replica target
- Statistical errors reduced by factor of 2 compared to 2009 data
- Eg. for $\pi^+$: statistical typically < 4%, systematics typically < 3%
- Preliminary results released: https://edms.cern.ch/document/1828979/1
Total Cross Section Measurements from 2015 Data

- Magnets not operational in 2015, so spectra analysis was not possible
- Total inelastic and total production cross sections were measured for 6 different reactions
- Paper submitted to PRD

\[ \sigma_{\text{prod}} = \sigma_{\text{inel}} - \sigma_{\text{qe}} \]
2016 Spectra Data for Neutrino Experiments

- Data for 7 different reactions were recorded - calibration ongoing
- $\pi^+ + C @ 60\text{GeV/c}$ and $\pi^+ + \text{Be} @ 60\text{GeV/c}$ are currently being analyzed
  - Total inelastic and total production cross sections
  - Differential cross sections of charged pions, kaons and protons
  - Differential cross sections of neutral $K^0_S$, $\Lambda$ and $\bar{\Lambda}$

<table>
<thead>
<tr>
<th>Beam Particle</th>
<th>Beam Momentum</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+$</td>
<td>60 GeV/c</td>
<td>C</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>60 GeV/c</td>
<td>Be</td>
</tr>
<tr>
<td>$p$</td>
<td>60 GeV/c</td>
<td>C</td>
</tr>
<tr>
<td>$p$</td>
<td>60 GeV/c</td>
<td>Al</td>
</tr>
<tr>
<td>$p$</td>
<td>60 GeV/c</td>
<td>Be</td>
</tr>
<tr>
<td>$p$</td>
<td>120 GeV/c</td>
<td>C</td>
</tr>
<tr>
<td>$p$</td>
<td>120 GeV/c</td>
<td>Be</td>
</tr>
</tbody>
</table>
dE/dx Analysis

- Charged tracks are reconstructed to a main interaction vertex
- Reconstructed momenta are obtained from the vertex fits
- Energy loss is calculated from charge collected in the TPCs
- $e^\pm, \pi^\pm, K^\pm$, protons and deuterons fall along their Bethe-Bloch curves (dE/dx from p+C@31GeV/c interactions shown)
- Fits are performed in kinematic bins to discriminate particle species
A reconstruction algorithm identifies decay vertices of neutral particles by searching for secondary vertices with 1 positively charged track and 1 negatively charged track.

Fits are performed to the invariant mass distributions for $K_S^0$, $\Lambda$ or $\bar{\Lambda}$ in each kinematic bin.

Analysis of Weakly Decaying Neutral Particles

Armenteros-Podolansky, $\pi^+ + C @ 60 \text{GeV/c}$

$N_S = 1098.17$

$N_{BG} = 5871.83$

$f_s = 0.1576$

$\alpha = \frac{p_t^+ - p_t^-}{p_t^+ + p_t^-}$
Recent Hardware Upgrades: FTPCs and Electronics

- Forward TPCs fill the void in the forward acceptance
- Particularly important for measuring forward scattering of protons and pions
- Began upgrading the readout to a more modern DRS4 system
  - Enabling easier maintenance and customization of detector components
### 2017 Spectra Data for Neutrino Experiments

- Variety of interactions were studied
  - Including first data to be recorded with the FTPCs installed!
  - New reconstruction framework will be used to reconstruct these datasets
  - Have local tracking, but full reconstruction in progress

<table>
<thead>
<tr>
<th>Beam Particle</th>
<th>Beam Momentum</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+$</td>
<td>60 GeV/c</td>
<td>Al</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>30 GeV/c</td>
<td>C</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>60 GeV/c</td>
<td>C</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>60 GeV/c</td>
<td>C</td>
</tr>
<tr>
<td>p</td>
<td>120 GeV/c</td>
<td>C</td>
</tr>
<tr>
<td>p</td>
<td>120 GeV/c</td>
<td>Be</td>
</tr>
<tr>
<td>p</td>
<td>90 GeV/c</td>
<td>C</td>
</tr>
</tbody>
</table>
Combined dE/dx and ToF Analysis

- With the Forward Time-of-Flight system in place, we can perform a combined dE/dx and ToF analysis
- Improves particle identification for momenta less than 10 GeV/c especially in the Bethe-Bloch crossing regions
Data Taking Plans for 2018

- 120 GeV/c protons on NOνA replica target ~ 4 weeks in July 2018 - interactions being recorded now!
- 120 cm target composed of graphite fins
- Replica target installed in NA61 beam
- 1 week of 60 GeV/c K⁺ on thin carbon target scheduled for Fall 2018
NA61 Beyond 2020

- Will resume the NA61 experiment after Long Shutdown 2

- Upgrades to the beamline are being considered
  - Possible tertiary beam allowing for lower energy hadron beams

- Upgrades to NA61 being considered - addendum to the SPSC report: [https://cds.cern.ch/record/2309890](https://cds.cern.ch/record/2309890)
  - Upgrades to TPC readout and DAQ system allowing 1 kHz readout rate
  - New ToF walls based on mRPC
  - New Beam Positions Detectors based on scintillating fibers
  - Large Acceptance Vertex Detector based on ALPIDE sensors

- Potential measurements for the neutrino program 2021-2024
  - Hadron beams below 18 GeV/c if possible - many unstudied/understudied reactions for neutrino experiments could be studied
  - Replica target measurements and dedicated thin target measurements for DUNE
  - Interactions with T2K-II/Hyper-K target material and possibly replica target measurements
  - Low energy measurements for atmospheric neutrino flux estimations
  - Kaon interaction data if more is needed
Summary

● NA61 data has been used to improve T2K’s flux prediction and increase precision on physics results!
  ○ Even better precision will be attained by implementing latest replica target results

● NA61 has been recording interactions relevant for Fermilab neutrino experiments from 2015-2018
  ○ Paper on total cross section measurements from 2015 dataset is on the arXiv and in the process of being published
  ○ Analysis of spectra data from 2016 is ongoing
  ○ Spectra data taken with new FTPCs implemented in 2017
  ○ NOvA replica target data-taking is ongoing, K⁺+C@60GeV/c in the fall

● NA61 upgrades will enable improved measurements after LS2
  ○ Most important measurement for DUNE will be DUNE replica target measurements
  ○ Many more thin target and potentially replica target measurements will be made as well - selected reactions will depend on what is most important for DUNE and other neutrino experiments
Thank you for your Attention!

- This work is supported in part by the U.S. Department of Energy
- Thanks to all of my collaborators at NA61/SHINE

Questions?
Back-Up
Total Cross Section Data Taken in 2015 - Statistics

- No magnets in 2015, but total cross section data was taken for a variety of interactions

<table>
<thead>
<tr>
<th>Beam Particle</th>
<th>Beam Momentum</th>
<th>Target</th>
<th>Triggers x10^6</th>
</tr>
</thead>
<tbody>
<tr>
<td>π⁺</td>
<td>31 GeV/c</td>
<td>C</td>
<td>1.2</td>
</tr>
<tr>
<td>π⁺</td>
<td>31 GeV/c</td>
<td>Al</td>
<td>0.8</td>
</tr>
<tr>
<td>π⁺</td>
<td>60 GeV/c</td>
<td>C</td>
<td>0.8</td>
</tr>
<tr>
<td>π⁺</td>
<td>60 GeV/c</td>
<td>Al</td>
<td>0.7</td>
</tr>
<tr>
<td>K⁺</td>
<td>60 GeV/c</td>
<td>C</td>
<td>0.7</td>
</tr>
<tr>
<td>K⁺</td>
<td>60 GeV/c</td>
<td>Al</td>
<td>0.5</td>
</tr>
</tbody>
</table>
dE/dx Analysis - Example Fit from π^+ + C@60GeV/c Interactions

+ Tracks

- Tracks

Work in Progress
V0 Analysis

- Invariant mass is calculated with a $K_0^S$, $\Lambda$ or $\bar{\Lambda}$ hypothesis
- Fits are performed to the invariant mass distributions for each kinematic bin