Hadron production measurements for improving neutrino flux predictions with the NA61/SHINE spectrometer

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Outline

✓ introduction

✓ NA61/SHINE experiment

✓ measurements with thin and thick targets

✓ future plans - beyond 2020

✓ summary
Hadron production measurements for neutrino experiments related to accelerator-generated neutrino beamlines. NA61/SHINE is capable of measuring these interactions!
NA61/SPS Heavy Ion and Neutrino Experiment

- fixed-target experiment at CERN’s SPS
- operating with ion and hadron beams in range 13 - 400 GeV/c
- momentum, charge and $dE/dx$ measurements provided by TPC tracking system
- particle ID with TPC and TOF detectors
- facilitating both thin and replica target measurements
Reference hadron production measurements

**Thin target** - a few % of nuclear interaction length $\lambda$

- $p, \pi^\pm, K^\pm$ beams on thin C, Be, Al, etc. targets
- examine single interactions:
  - inelastic and production cross-sections
  - differential cross-sections $\left( \frac{d^2\sigma}{dp d\theta} \right)$ of produced hadrons

**Thick target (replica target)** - a few $\lambda$

- $p$ beams on replica targets
- study multiple interactions inside target:
  - differential hadron multiplicities on target surface
  - beam survival probability and related production cross-section
    $$P_{\text{survival}} = e^{-Ln\sigma_{\text{prod}}}(L \text{ target length}; n \text{ number of atoms per unit volume})$$

T2K replica target:
an identical copy of the 90cm long graphite T2K target
$$L = 1.9\lambda$$
Results from p@31GeV/c on 2cm C target for T2K

✓ 2007: first measurements; 0.7M events
  - inelastic and production cross-sections and $\pi^\pm$ spectra (Phys.Rev.C84 (2011) 034604)
  - $K^0_S$ and $\Lambda$ spectra (Phys.Rev.C89 (2014) 025205)

✓ 2009: 5.2M events
  - inelastic and production cross-sections and $p$, $\pi^\pm$, $K^0_S$ and $\Lambda$ spectra (EPJ C76 (2016) 84)

**NA61/SHINE 2007 and 2009 cross-section results**
Results from hadron+$A$ interactions for Fermilab $\nu$ beams

✓ 2015 data:
  - inelastic and production cross-sections \cite{Phys.Rev.D98, No.5 052001 (2018)}

✓ 2016 data:
  - inelastic and production cross-sections for $p@60\text{GeV/c}$ on C, Be, Al and $p@120\text{GeV/c}$ on C, Be targets \cite{collaboration review}
  - inelastic and production cross-sections and $p$, $\pi^{\pm}$, $K^{\pm}$, $K_S^0$ and $\Lambda$ spectra in $\pi^+@60\text{GeV/c}$ on C and Be targets \cite{collaboration review}

✓ 2017 data:
  - first data set with forward TPCs \cite{calibration}

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<thead>
<tr>
<th>2015</th>
<th>reaction</th>
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<tbody>
<tr>
<td>$p+C$ 31 GeV/c</td>
<td>0.4M*</td>
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<td>$\pi^+ + C$ 31 GeV/c</td>
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<td>$\pi^+ + C$ 60 GeV/c</td>
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<td>$\pi^+ + Al$ 60 GeV/c</td>
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<tr>
<td>$K^+ + C$ 60 GeV/c</td>
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<tr>
<td>$K^+ + Al$ 60 GeV/c</td>
<td>0.5M*</td>
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<td>$p+C$ 120 GeV/c</td>
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<td>$\pi^− + C$ 60 GeV/c</td>
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<td>$p+C$ 90 GeV/c</td>
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<td>$p+C$ 120 GeV/c</td>
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<tr>
<td>$p+Be$ 120 GeV/c</td>
<td>4.0M**</td>
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</tbody>
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* no B field  
** with FTPCs and forward ToF
Results from hadron+A interactions for Fermilab $\nu$ beams

✓ 2015 cross-section results ($\pi^+$ and $K^+$ beams)

- greatly improves precision for kaon interactions as NuMI simulation assumes an uncertainty of 10 – 30% for kaon reinteractions

✓ 2016 preliminary cross-section results (proton beam)

- first measurement for p@120 GeV
- improved precision for 60 GeV/c protons
Measurements of p@31GeV/c on T2K replica target

✓ 2007: 0.2M events
  • pilot runs, development of calibration and analysis procedures, $\pi^{\pm}$ yields (NIM A701 (2013) 99)

✓ 2009: 2.8M events
  • $\pi^{\pm}$ differential multiplicities on target surface (EPJ C76 (2016) 617)

✓ 2010: 0.2Tm field, 10.1M events
  • $\pi^{\pm}$, $p$, $K^{\pm}$ differential multiplicities on target surface (EPJ C79, no.2 100 (2019))

✓ 2010: maximum 9Tm field, 1.2M events
  • proton beam survival probability (ongoing analysis)
A glimpse at T2K replica target results: $\pi^+$ from Z1 bin

$\pi^+$ double differential multiplicities alongside MC predictions

- T2K flux uncertainty is expected to drop down to $\sim 5\%$ taking into account $\pi, K, p$ differential multiplicities
Thick target measurements for Fermilab $\nu$ beams

$p@120\text{GeV/c on the 1.2 m long NuMI replica target (graphite fins)}$

- total of 5 weeks data taking in 2018
- aided with vertex distributions monitoring

- $\sim 18\text{M recorded events awaiting calibration and analysis}$
Prospects beyond 2020

**Upgrades to the NA61/SHINE spectrometer**
- data taking rate increase to about 1 kHz - TPC readout, new DAQ and trigger systems, etc.
- new ToF wall with mRPC

**Planned neutrino-related measurements**
- with T2K replica target
- with T2K-II/Hyper-K target material and/or replica target
- with DUNE replica target, if prototype is available
- kaons on thin targets
Summary

✓ direct hadron production measurements constrain neutrino flux predictions

✓ thin target measurements by NA61/SHINE improved T2K flux uncertainty down to $\sim 10\%$

✓ thick target results will further reduce the uncertainty to $\sim 5\%$

✓ broad data taking programme for Fermilab $\nu$ experiments

✓ after LS2, NA61 plans for more and diverse hadron production measurements, building on past experience!
NA61/SHINE collaboration: $\sim 150$ physicists from $\sim 30$ institutes

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Thank you for your attention!