Neutrino flux and hadron production

- Why is neutrino flux important?
- Strategies for constraining hadron production
- Experiments doing hadron production now
- Future prospects
Why is neutrino flux important?

- Neutrino flux is generally modeled poorly by Monte Carlo packages
- Neutrino oscillation measurements (even with near detectors) depend on understanding the neutrino source:
  - Only partial cancellation of flux errors in long-baseline near/far ratios
  - Neutrino oscillation measurements depend on precise understanding of neutrino interaction cross-sections
  - No near/far cancellation in neutrino cross-section measurements, which are essential for oscillation measurement precision
Hadron production measurement strategy

- **In situ** measurements
  - Measurements in the decay region
    - Hadron monitors in the decay region (hard)
    - Meson decay product detection in the decay region (very hard!)
  - Muon measurements downstream of hadron absorber (measurements are feasible, interpretation is difficult)

- **Ex situ** measurements
  - Thin-target measurements for precise measurement of production cross-sections
  - Replica targets for constraints on entire primary/secondary interaction chain
In-situ measurements

- Muon measurements
  - Mostly used for stability monitoring
  - Very limited ability to constrain neutrino flux
- Other measurements in beamline
  - Pion monitors in the decay region (hard)
  - Meson decay product detection in the decay region (very hard!)
- ENUBET: proposed sign-selected neutrino beam with fully instrumented decay region.
- See Andrea Longhin’s talk tomorrow
Ex-situ measurements

• Thin-target measurements for precise measurement of production cross-sections
• Replica targets for constraints on entire primary/secondary interaction chain
• Generally, these measurements need:
  • Well-tagged beam with many particle types and wide momentum range available
  • Large-acceptance spectrometer with good particle ID
  • Ability to accommodate a variety of long and short targets
Ex-situ measurements

• History
  • CERN NA49: 158 GeV/c $p+C$ measurements, used for NuMI with momentum scaling
  • E907/MIPP: some data for NuMI
  • HARP (CERN PS) and E910 (BNL): used for Booster Neutrino Beam, K2K
  • Single-arm spectrometers
    • Several measurements from 1970s/80s still useful for some low-momentum and secondary processes

• Present and future
  • NA61/SHINE
  • EMPHATIC
NA61: The SPS Heavy Ion and Neutrino Experiment

- Fixed-target experiment using H2 beam at CERN SPS
- ~150 collaborators. Spokespeople: Marek Gazdzicki, EDZ (deputy)
- Designed around the former NA49 heavy-ion spectrometer
- Primary proton beam from CERN SPS, Secondary beams ~25 to 350 GeV/c

Diverse physics program includes
- heavy ion physics
- hadron production for neutrino beams
- cosmic ray production
NA61 detector system

- Detailed beam instrumentation including PID and tracking before the target
- Several large-acceptance TPCs, two superconducting analysis magnets
- Scintillator-based time-of-flight detectors
- Projectile Spectator Detector: forward hadron calorimeter
Neutrino-related accomplishments from NA61’s first phase


![Figure 2. The total T2K flux uncertainties are shown for $\nu_\mu$ (left) and $\bar{\nu}_\mu$ (right) enhanced beam modes together with all the sources which contribute to the T2K flux predictions.]

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**References**

Recent result: full yields from T2K replica target

- e-Print: arXiv:1808.04927
- Showing $\pi^+$ for illustration. Also have $\pi^-$, $K^\pm$, $p$ yields
- One more analysis (high magnetic field run) in progress
A second phase of NA61 neutrino measurements

- Four US-based groups joined NA61 in 2014 to make measurements specifically for the FNAL-based neutrino program.
- Motivation: new coverage will be needed for DUNE, can help NuMI as well in shorter term.
- US-funded project made specific upgrades:
  - Forward tracking system
  - DRS4-based readout for TOF systems
  - Data collection in 2015-18 for this program.
DUNE flux uncertainties with current production data

- Dominated by
  - Pion and Kaon re-interactions
  - Nucleon interactions not covered by data
  - Errors on existing pC data

![Graph showing fractional uncertainty vs. neutrino energy](chart.png)

- Osc maxima

Laura Fields | LBNF Hadron Production
L. Fields

Osc maxima
Secondaries Contributing to DUNE Flux

- Weighted by contribution to DUNE FD flux, for Nov 2017 DUNE Optimized and Engineered Beam design (120 GeV/c protons)
- New forward TPCs make measurements of important secondary protons possible
- Acceptance is now well-matched to secondaries that generate neutrinos in DUNE
Forward TPCs

- FTPCs installed 2016-17, used in 2017 and 2018 data run
- Chambers work well
- Event display above from 2017 data with local (green) tracks reconstructed
- New global tracking algorithm in final development stage
Electronics upgrade

- Replacement of TOF electronics with a modern system based on the DRS4 chip
- Pittsburgh-Geneva collaborative effort
- Goal is to replace 3500 channels during LS2
- Initial deployment in 2017 in Forward TOF wall, where previous system not functional and improved time resolution is most helpful
- Extend to all compatible detectors during Long Shutdown
Performance of DRSv4 in 2017 data

- First forward TOF TDC data with DRS4
- After preliminary voltage, local, and global time calibration the timing resolution is \(~40\text{ps}\)
First result: total production cross-sections on nuclear targets

- 2015 data set collected with no magnetic field due to failure of old superconducting magnets: no momentum measurements
- Recently published total production and total inelastic cross section measurements for data without magnetic field
- Note: here $\sigma_{prod} = \sigma_{total} - \sigma_{el} - \sigma_{qe}$, requires new hadrons to be produced. Also $\sigma_{inel} = \sigma_{total} - \sigma_{el}$. This terminology not always used consistently in community or in hadronic event generators.
## NA61 2016-17 neutrino data

### Thin targets

<table>
<thead>
<tr>
<th>2016</th>
<th>2017</th>
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<tbody>
<tr>
<td>$p + C @ 120 \text{ GeV/c}$</td>
<td>$\pi^+ + \text{Al} @ 60\text{GeV/c}$</td>
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<tr>
<td>$p + \text{Be} @ 120 \text{ GeV/c}$</td>
<td>$\pi^+ + C @ 30 \text{GeV/c}$</td>
</tr>
<tr>
<td>$p + C @ 60 \text{ GeV/c}$</td>
<td>$\pi^- + C @ 30 \text{GeV/c}$</td>
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<td>$p + \text{Al} @ 60 \text{ GeV/c}$</td>
<td>$p + C @ 120 \text{GeV/c} (w \text{FTPCs})$</td>
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<tr>
<td>$p + \text{Be} @ 60 \text{ GeV/c}$</td>
<td>$p + \text{Be} @ 120 \text{GeV/c} (w \text{FTPCs})$</td>
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<tr>
<td>$\pi^+ + C @ 60\text{GeV/c}$</td>
<td>$p + C @ 90 \text{GeV/c} (w \text{FTPCs})$</td>
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<td>$\pi^+ + \text{Be} @ 60 \text{ GeV/c}$</td>
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**Highest analysis priority**
• 120 GeV $p$ on NOvA replica target provided by Fermilab

• 15M events recorded in summer; a final run next week should add 30-50%
Post-2020 plans

- Previously-approved run ends this year; Long Shutdown 2 begins
- NA61 is working with CERN SPSC and European Strategy Update on proposed data collection beyond LS2
- SPSC recommends 2021 running
- European Strategy update will address 2022-24 runs
NA61 running beyond 2019-20 accelerator shutdown

- Many measurements motivated by strong interactions (esp. open charm) and cosmic ray physics
- Neutrino-related measurements in 2021-22 era:
  - When available (could be after 2022): replica target for LBNF/DUNE
  - New measurements for T2K-II/Hyper-K to reduce flux uncertainties to ~3%
    - New ceramic target material?
    - Replica target data with improved upstream tracking
    - Study of low-energy secondary interactions (needs work on beam)
  - More secondary processes for LBNF; beryllium if needed
    - Detailed list to be developed as current analysis efforts proceed, LBNF beam MC develops and needs are better known
  - Low-energy measurements for atmospheric neutrino flux
- See talks at workshop on NA61 Beyond 2020 workshop at Geneva, August 2017: https://indico.cern.ch/event/629968/
Post-2020 plans

• NA61 is planning significant upgrades to the detector for 2021+
  • New forward Projectile Spectator Detector module, reconfiguration of existing detector
  • Replacement of old TPC electronics with system from ALICE
  • New silicon vertex detector for open charm studies
  • RPC-based replacement for TOF-L/R walls
  • New close-in tracking detectors for improved vertex resolution in long targets
  • New trigger/DAQ, combined with new electronics, will give a major upgrade in data collection rate

Relevant for neutrino running
Post-2020 plans

- These upgrades are not fully funded yet. Some funding agency applications are under review, others to be submitted.

- They are, however, essential if we are to preserve NA61 as a resource for the neutrino community.

- New collaborators are welcome to join: opportunities to work on the upgrade as well as to analyze existing data.
A new hadron production experiment: EMPHATIC

Experiment to Measure the Production of Hadrons At a Testbeam In Chicagoland

• “Tabletop-scale” hadron production experiment
• First version took data in a Fermilab test beam in January 2018
• Goal is to measure
  • the reactions important to T2K that aren’t covered by existing NA61 data
  • hadron production for atmospheric neutrino flux modeling
• Mostly means low energy (<15 GeV) that NA61’s beam can’t deliver as currently configured. Beam has momenta 2-120 GeV/c
• Complementary to NA61
EMPHATIC layout in 2018 run

- Graphite, aluminum, steel targets
- Emulsion targets with graphite
Physics goals of current detector

- Measurement of total, elastic and quasi-elastic cross section
- (No magnetic field yet — similar situation to NA61 2015)

\[ \frac{d\sigma}{d\omega} [\text{cm}^2/\text{sr}] \]

\[ \langle |t| \rangle = p^2 \theta^2 \]

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

4-momentum transfer (raw data)

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

Coulomb-nuclear interference region (CNI)

Elastic region

Quasi-elastic region

*Lines on top of the data points are not fits

M. Pavin

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

Total cross section from optical theorem

Coherent elastic scattering

Quasi-elastic scattering (scattering on a single nucleon)
Future EMPHATIC configuration

- Permanent magnet (Halbach array)
- With Si strip detectors, momentum resolution of 2% possible
- TOF + aerogel RICH for particle ID
- Plan to run with B, BN, B$_2$O$_3$ for atmospheric flux studies
- More C, Al, Fe for accelerator neutrino beams, including beam proton survival probability measurements
Summary

• Dedicated hadron production experiments have proven essential to bringing flux errors down to manageable sizes in current neutrino experiments.

• NA61/SHINE’s program of T2K-related measurements is almost done; next-to-last result in publication.

• NA61 is concluding its current program of neutrino measurements with data for NuMI experiments, including replica NOvA target and thin-target measurements useful for DUNE.

• Plan to run with further detector upgrades after LS2, with several high-priority measurements planned including LBNF/DUNE replica target when available — but resources are still necessary.

• New experiment EMPHATIC is joining the game: complementary to NA61.