(#160) Understanding the NuMI Neutrino Flux at ICARUS

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**ICARUS at Fermi National Accelerator Laboratory**

- 430 t fiducial volume liquid argon neutrino detector,
- On axis of the Booster Neutrino Beam (BNB),
- 5.7° (100 mrad) off-axis above the Neutrinos at the Main Injector (NuMI) beam.

![ICARUS setup](image)

**Interaction chain**

- Example interaction chain leading to production of $\nu_e$.
- Three interactions: two p+C and one $n$+Al.
- Other particles possibly produced in these interactions and their interactions are not part of the chain.

**Off-axis vs on-axis NuMI beam**

- Decays to neutrinos which reach ICARUS occur closely to the target, before the second horn magnet.
- Horn focusing reduced. Difference between fluxes of $\nu$ and $\bar{\nu}$ smaller than for the on-axis experiments.
- Hadron parents of neutrinos travel at higher angles and interact more often with beam line material.
- 0.7 more hadron interactions before $\nu$ production,
- more re-interactions in the target, but also more interaction

**NuMI beam in ICARUS for DUNE**

Opportunity to measure cross sections of $\nu$ and $\bar{\nu}$ interactions on argon in the energy range of 2–4 GeV, relevant for DUNE.

**NuMI flux prediction**

Flux prediction is as significant for the cross-section uncertainty as the neutrino interaction measurement itself.

- **Input:** NuMI beam simulation: interaction of the beam proton, and chain of all subsequent hadron interactions in the beam line, leading to production of a neutrino (1).
- **Study of impact of hadron production model uncertainties:** Package to Predict the Flux (PPFX) [2, 3] compares cross-section of simulated hadron interactions with experimental data,
- each neutrino entry is weighted according to corrections to all interactions that contributed to its production.
- **Results:**
  - flux prediction corrected for model imperfections,
  - flux uncertainty and covariance due to modeling uncertainties and beamline uncertainties,
  - identified dominant sources of uncertainties.

**Beam line uncertainties**

- Input simulation includes variants with varied horn currents and positions, beam spot size, divergence and position, thickness of the horn cooling water layer and Earth magnetic field.
- Comparison of simulation variants $\rightarrow$ ~1% beam line uncertainties.

**Hadron interaction modeling precision**

- PPFX generates variants of simulation in 100 universes,
- In each universe hadron cross sections are corrected and randomized according to experimental uncertainties.

**Hadron interaction model uncertainties**

- Width of flux distribution in 100 universes $\rightarrow$ uncertainty,
- Procedure repeated for various interaction types individually to derive their contributions,
- Dominant contribution: interactions of mesons, and interactions of nucleons other than p+C.

**Total integrated flux uncertainty**

- Excluding lowest energy range, affected by the cross-section threshold and reconstruction efficiency.
- Strong correlation between various neutrino flavors.

**NuMI flux prediction**

- Average flux in 100 universes $\rightarrow$ corrected flux,
- Combined beam line, model and statistical uncertainties.

**Outlook**

- Needed data on hadron interactions at tens of GeV/c.
- Awaiting results from NA61/SHINE [4] and EMPHATIC [5].
- Implementing experimental data in PPFX: poster #75 [6].
- Details and numerical results: note in preparation [6].

**References**


**Details and numerical results:** note in preparation [6].

https://www.neutrino2022.org/

May 30–June 4, 2022, Neutrino 2022, Virtual Seoul

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