Measuring the neutron induced proton-emission cross section at 2x2

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NSSC

Nuclear Science & Security Consortium

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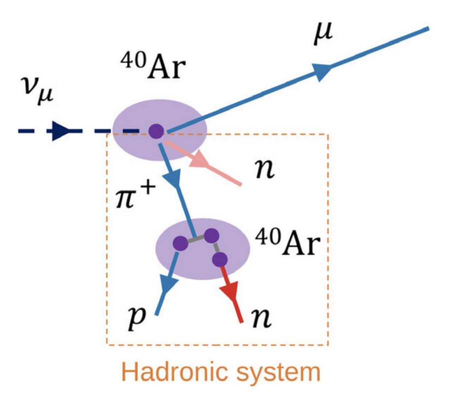
Why are neutrons important?

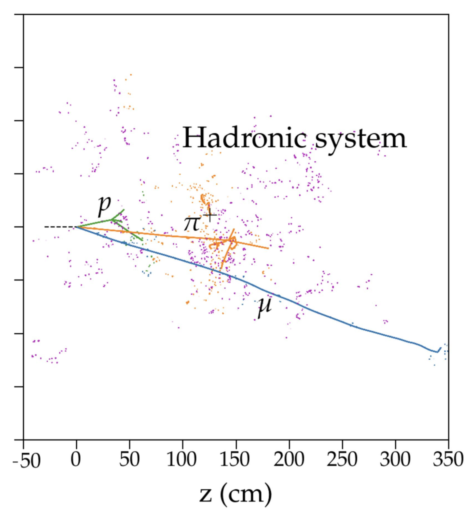
To turn neutrino physics into a precision science, we need to understand complex neutrino-nucleus interactions (specifically on Ar):

- Neutrons carry away a ***large fraction***[1] of energy.
- Neutron final states are ***model dependent***.
- Neutrons are ***difficult to detect*** in LAr.



Neutrons are also important for low-energy physics in LAr:

- e.g., modeling **supernova** and **solar** (and now **galactic**[2]) neutrino physics.



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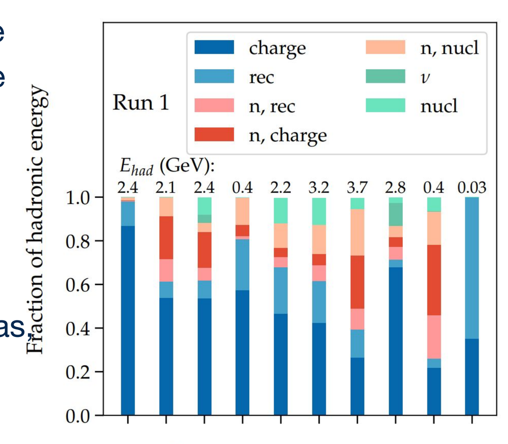
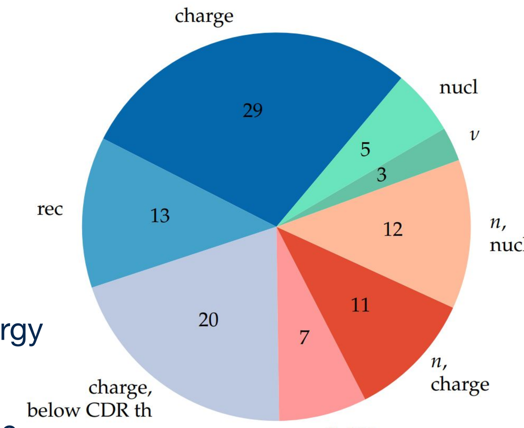
Energy Resolution?

It is necessary to be able to account for the neutron "***missing energy***" in order to make precision oscillation measurements (production and transport).



A. Friedland and W. Li (2019) characterized the sources of missing energy in LArTPCs as:

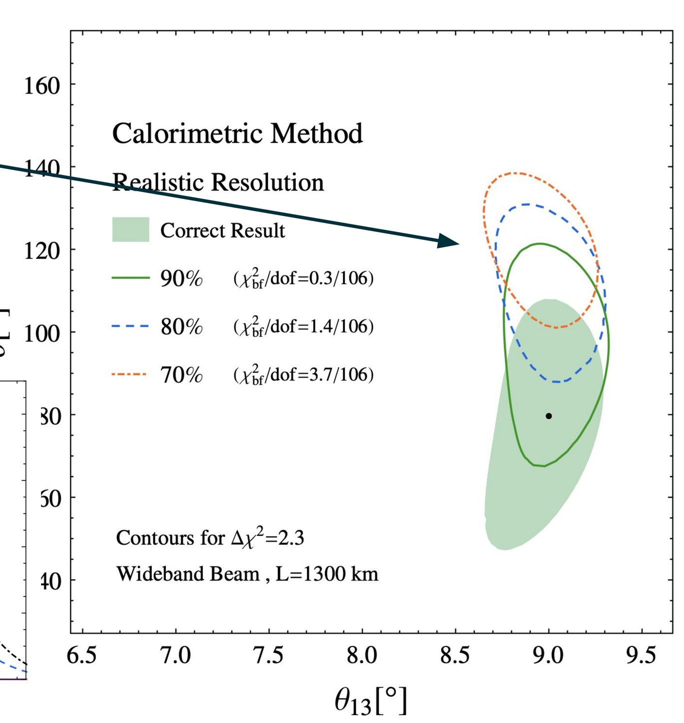
1. Electronic shower sprays (**charge**)
2. Recombination effects (**rec**)
3. Nuclear breakup (**nucl**)
4. Outgoing neutrinos (ν)
5. Subthreshold particles
6. **Primary and secondary neutrons**

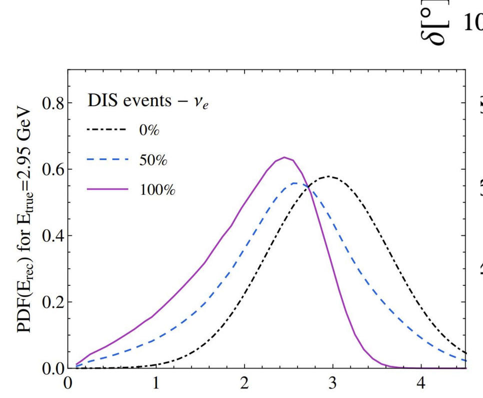


This pie chart from the same paper (2019) shows the average amount of missing energy over many events (~10K).

- Neutrons contribute nearly **~30%** of the missing energy on average!

- Measurements of the CP phase[3] are shifted by a large amount if neutrons are ignored!





Event Selection

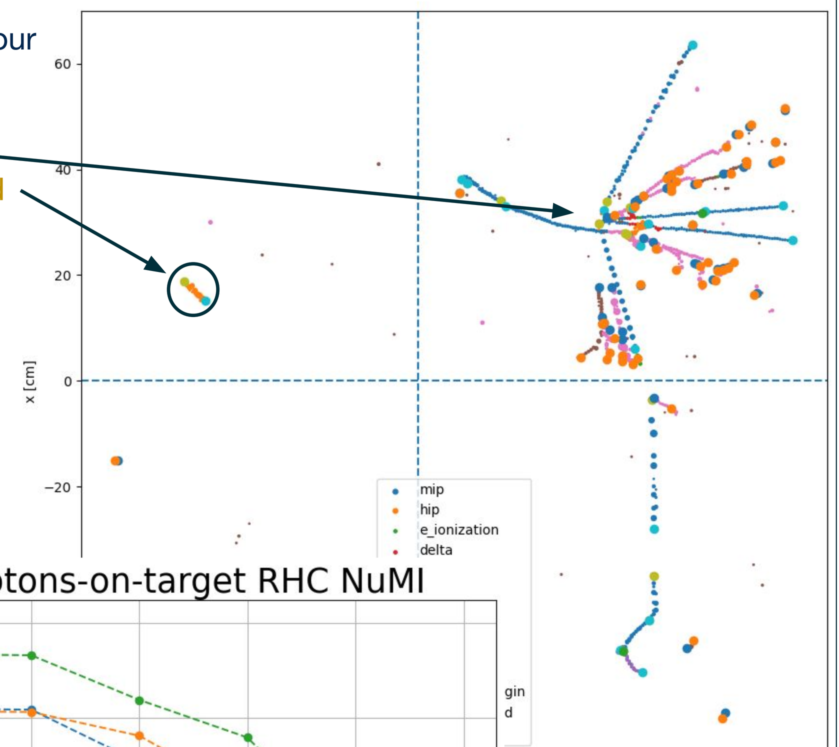
Criteria which defines our signal:

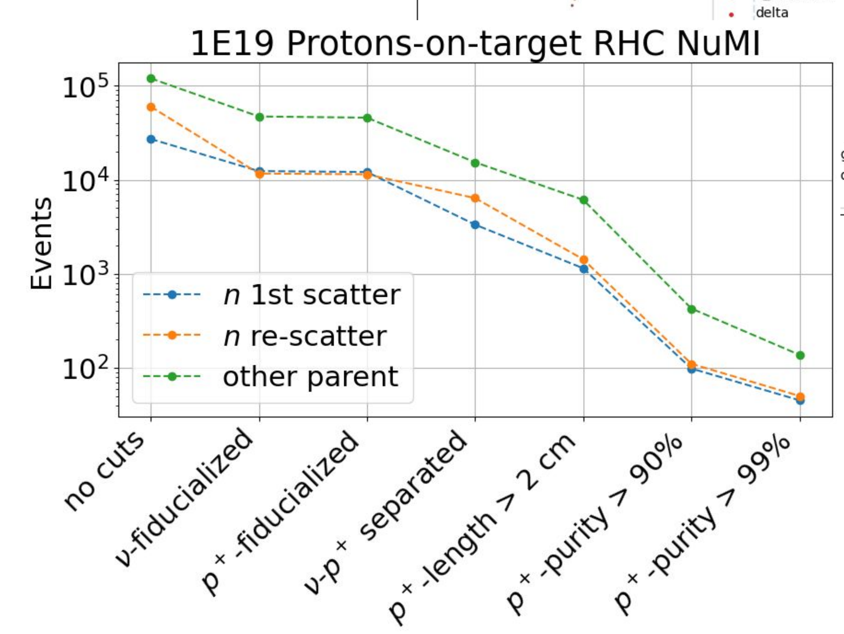
necessary;

- ν-fiducialized
- p^+ start-fiducialized

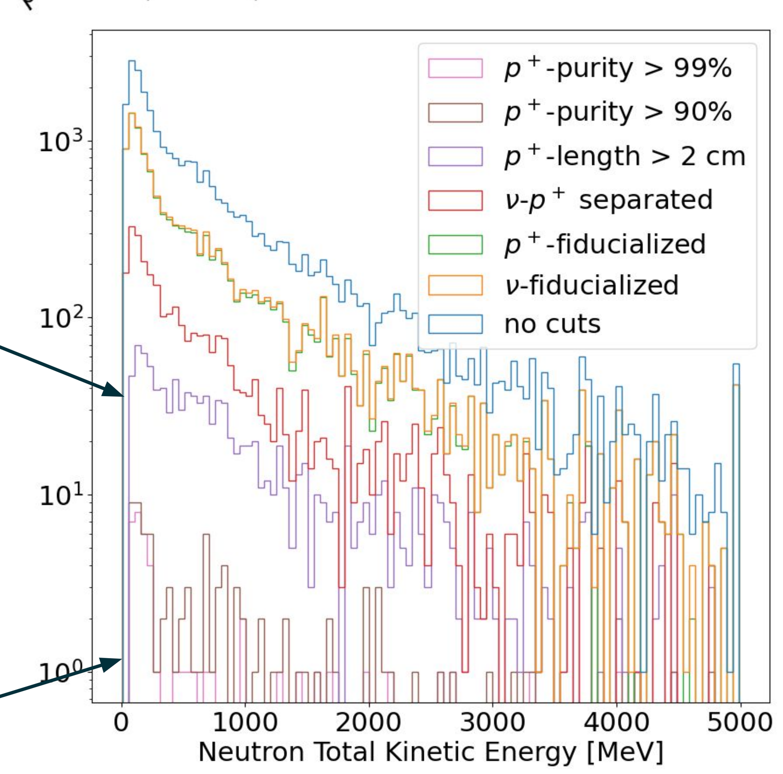
perhaps necessary:

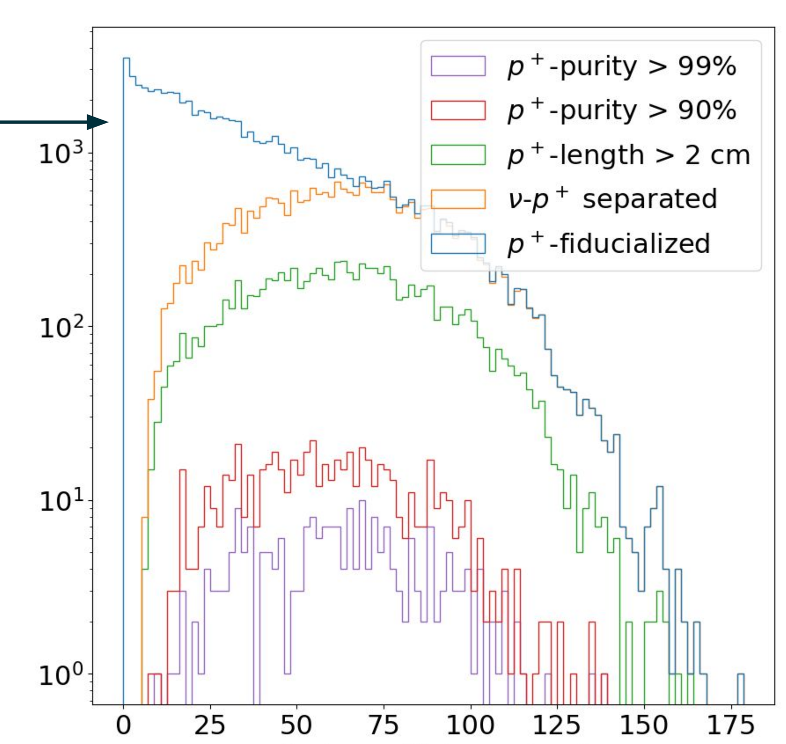
- ν-p^+ optically separated
- minimum 2 cm p^+ track
- single MIP primary
- clustering purity
- proton angle





- Nuclear theory predicts a minimum of **~12.8 MeV** for neutron induced proton emission.
- Due to Coulomb forces, an additional **~6.23 MeV** is need for the proton to escape the Argon atom.
- With the 2 cm constraint, the minimum neutron energy is **~65 MeV**.
- Some protons which are generated in a separate optical volume can still be small.
- If we can detect these small tracks ~ < 2 cm, we can improve our statistics by x2.





Why is this measurement important?

1. It gives us a handle on **missing energy** in neutrino interactions!
2. The neutron kinetic energy spectrum can **constrain GENIE modeling**!
3. We can understand and **constrain the neutron transport model** in Ar40!

Cross-section Extraction

- Determine r from neutrino vertex and proton start.
- Determine E from tof and r.
- Distribution of r vs. E.
- For each r value in each E bin, calculate cross-section as a function of E.

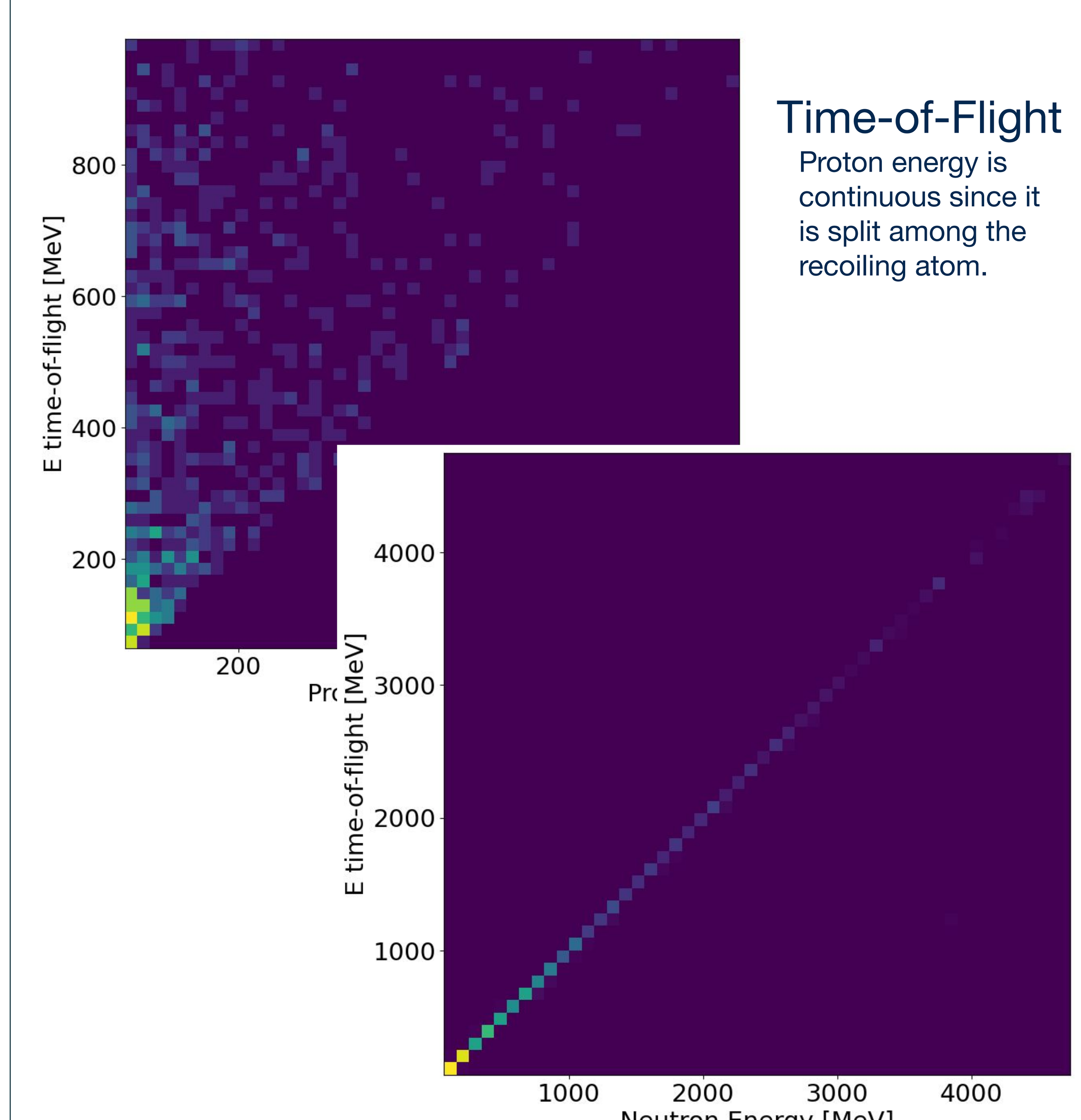
$$r_n = d(\vec{x}_0^\nu, \vec{x}_0^p)$$

$$E = mc^2\left[\frac{1}{\sqrt{1-\frac{v^2}{c^2}}} - 1\right]$$

$$v_n = \frac{d(\vec{x}_0^\nu, \vec{x}_0^p)}{t_0^p - t_0^\nu}$$

$$\phi(r, E) = \phi(0, E)e^{-n\sigma(E)r}$$

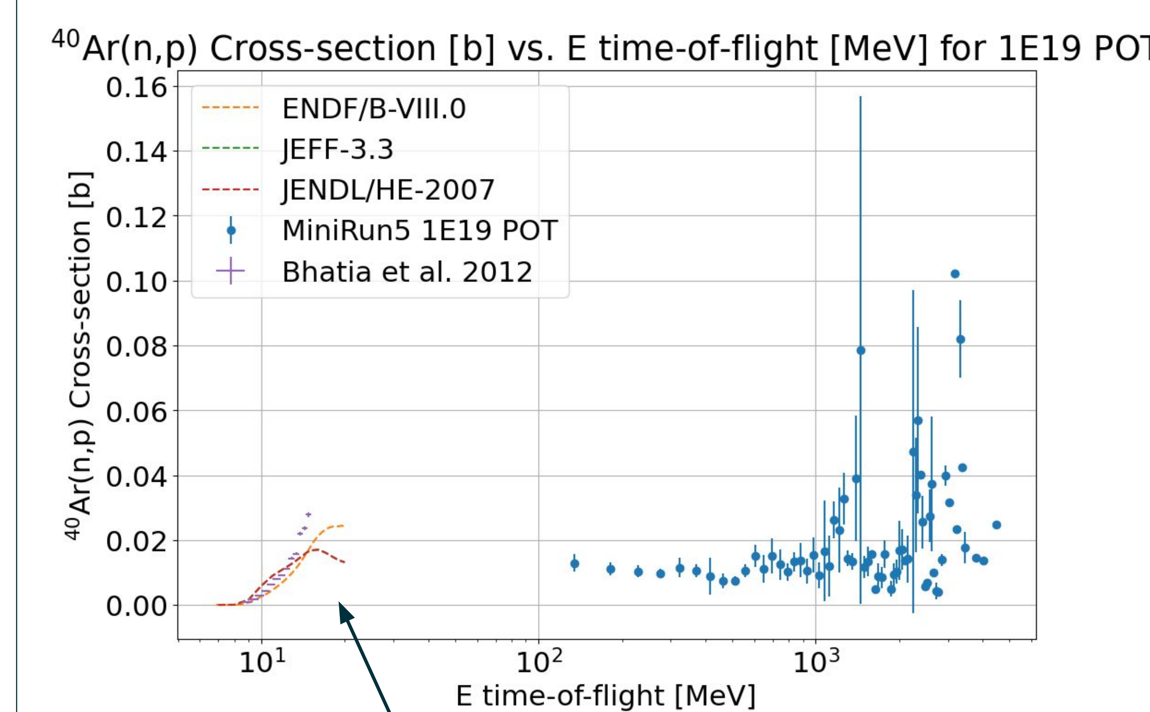
$$\sigma(E) = -\frac{1}{n\hat{r}}\left[\log(N_{r>\hat{r},E}) - \log(N_E)\right]$$



Time-of-Flight

Proton energy is continuous since it is split among the recoiling atom.

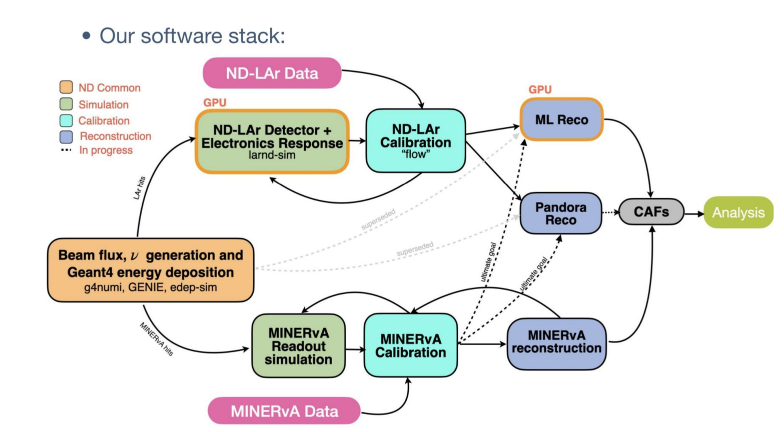
Cross-section from 2x2 Simulation



ENDF only to 20 MeV

Future Work

- **Evaluate suitability of existing light waveform signal processing for t0 extraction.**
- Investigate edep-sim (GEANT) cross-section assumptions.
- Investigate ENDF evaluations (why do they end at 20 MeV?).
  - (Cross-sections are determined from a complex nuclear model)
- Determine systematic uncertainties for each measurement (neutron energy, cross-section, etc.).



References

[1] 1 A. Friedland and W. Li, *Understanding the energy resolution of liquid argon neutrino detectors*, Physical Review D, **99**, 2019

[2] ICECUBE Collaboration, *Observation of high-energy neutrinos from the Galactic plane*, Science, **380**, 2023

[3] A. M. Ankowski et al., *Missing energy and the measurement of the cp-violating phase in neutrino oscillations*, Phys. Rev. D, **92** 2015

[4] M. Buizza Avanzini, *Comparisons and challenges of modern neutrino-scattering experiments*, Phys. Rev D, **105** 2022

[5] The GENIE Collaboration, *Recent highlights from GENIE v3*, Eur. Phys. J. Spec. Top. (2021)

Mission Relevance

Neutrons and neutrinos both play a critical role in nuclear physics,, specifically nuclear reactions coming from reactors or nuclear weapons. Liquid argon TPCs are an evolving technology which shows great promise for neutrino physics. Understanding the subtleties of neutron and neutrino interactions in liquid argon is important not only for the success of the DUNE program, but also for nuclear safety.

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