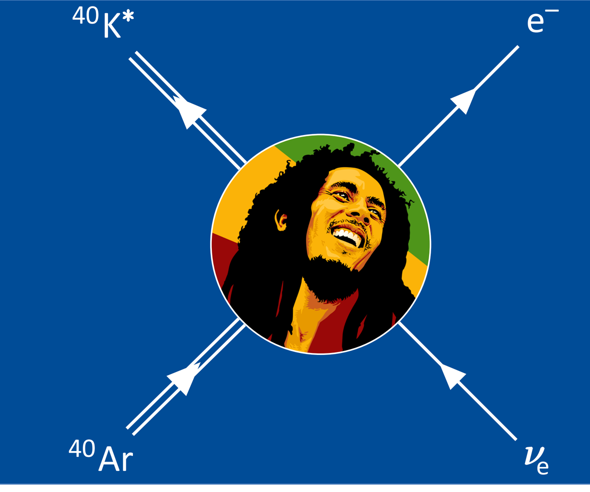
Physics model enhancements in MARLEY version 2

Steven Gardiner, Fermi National Accelerator Laboratory

FERMILAB-POSTER-26-0081-CSAID

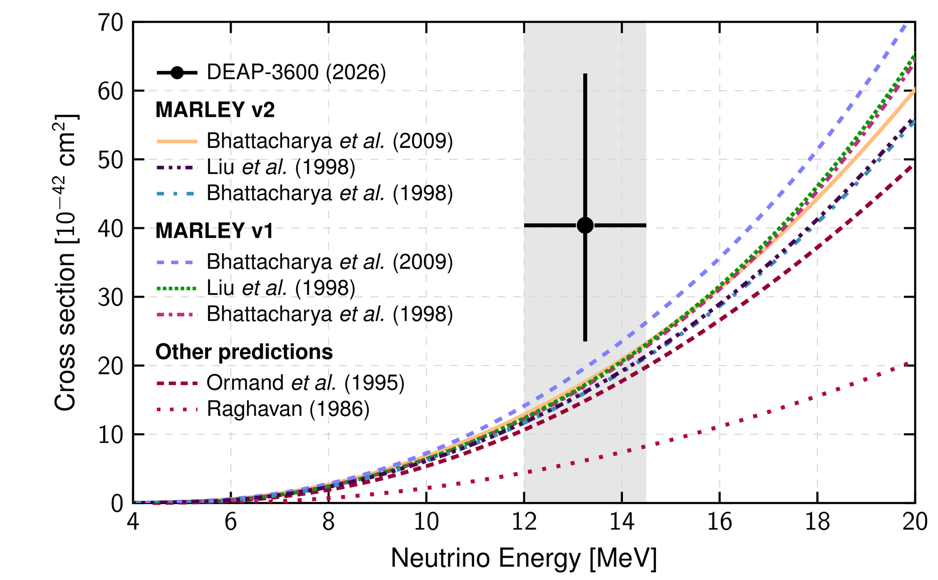


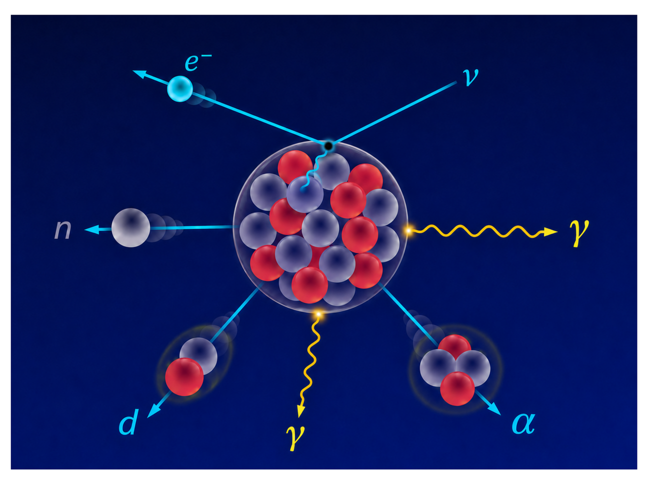
What is MARLEY?

MARLEY (Model of Argon Reaction Low-Energy Yields) is a Monte Carlo event generator for low-energy (≲ 100 MeV) neutrino scattering, especially neutrino-argon interactions. Version 1 of the code has become widely used in the community, including for analyses by DUNE, COHERENT, and DEAP-3600. The version 2 release series (v2.0.0 is expected in July 2026) will bring many technical and physics enhancements. This poster provides a preview of the latter.

Improved neutrino cross-section model

Charged-current (CC) primary interactions in MARLEY v1 are simulated using the *allowed approximation*: the nuclear current is evaluated under the long-wavelength ($q \to 0$) and slow-nucleon ($|\mathbf{p}_{Ni}| \ll m_N$) limits. In v2, this rough treatment is replaced with a more sophisticated hybrid model. Allowed discrete nuclear transitions are data-driven with approximate corrections for momentum transfer dependence. Continuum transitions are modeled via a Hartree-Fock Continuum Random Phase Approximation (HF-CRPA) approach, including forbidden transitions up to multipole order J = 5.

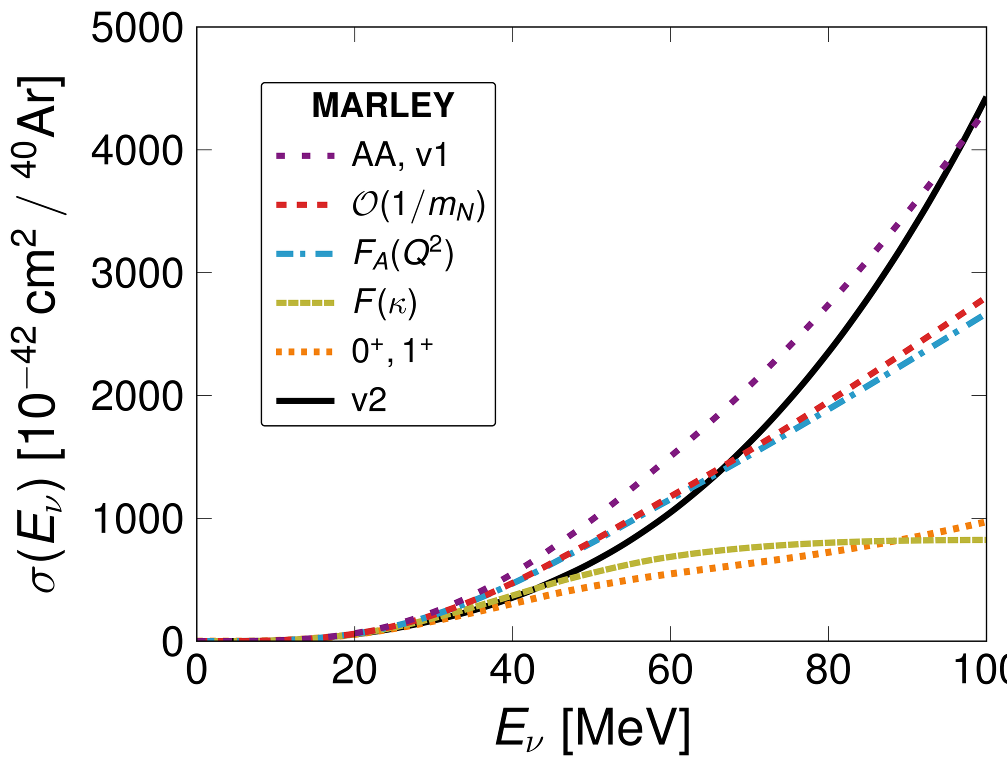




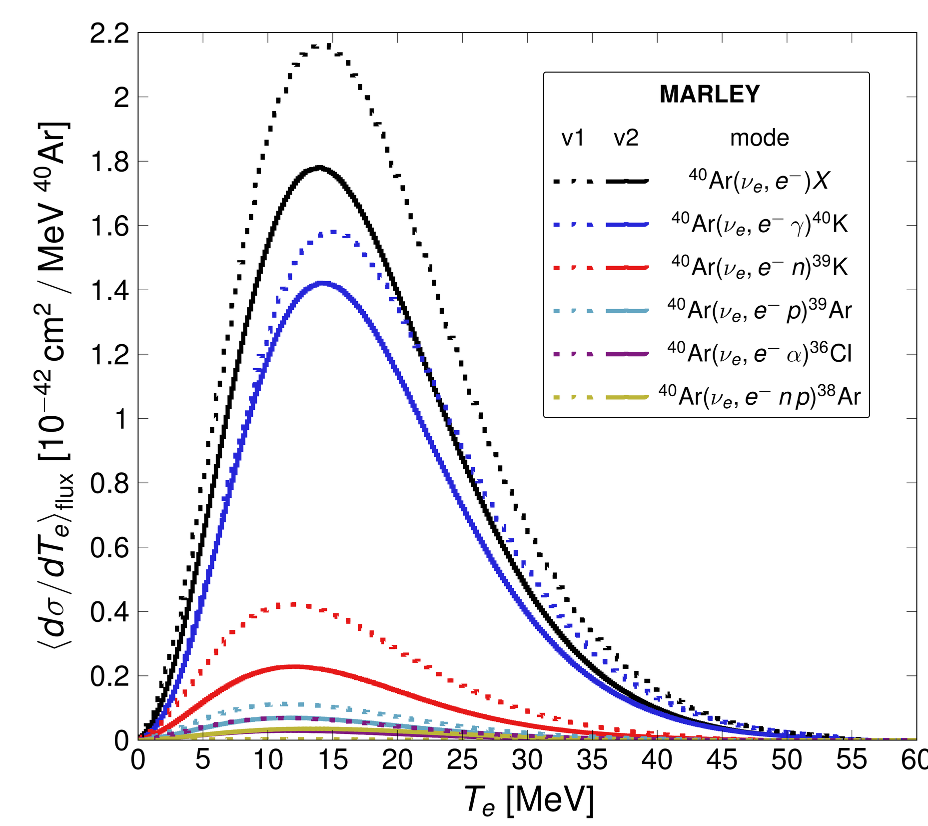
Read the full v2 CC cross-section paper here! Many thanks to my co-authors: Pablo Barham Alzás, Alexis Nikolakopoulos, Luca H. Abu El-Haj, Natalie Jachowicz, and Vishvas Pandey.

arXiv:2604.26801

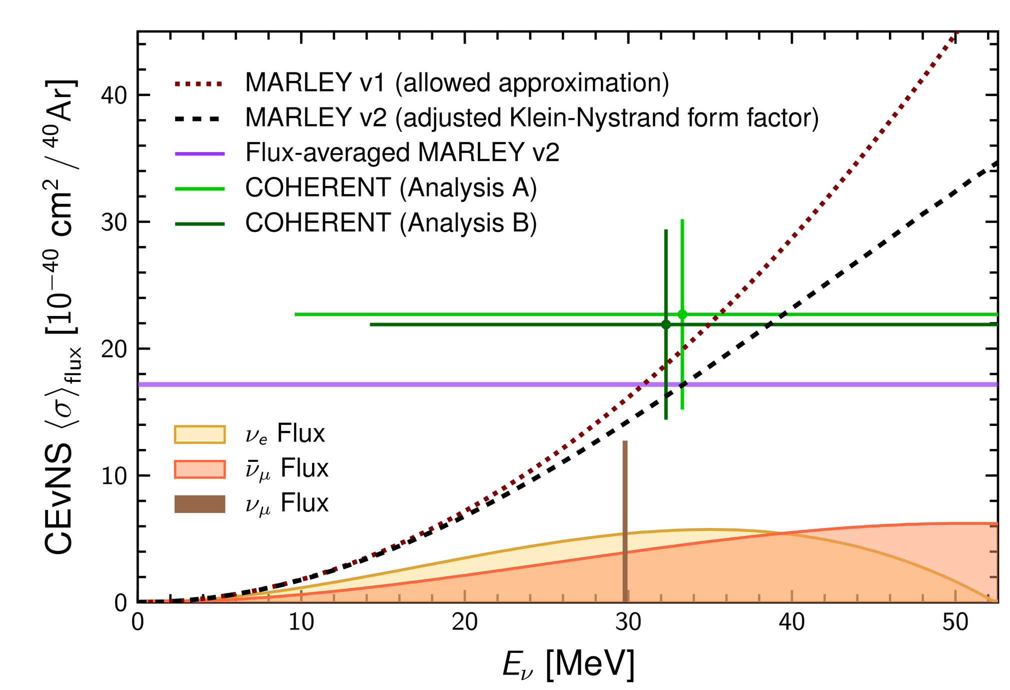
Evolution of MARLEY CC ν_e-^{40}Ar total cross section from v1 to v2 as various corrections are applied.



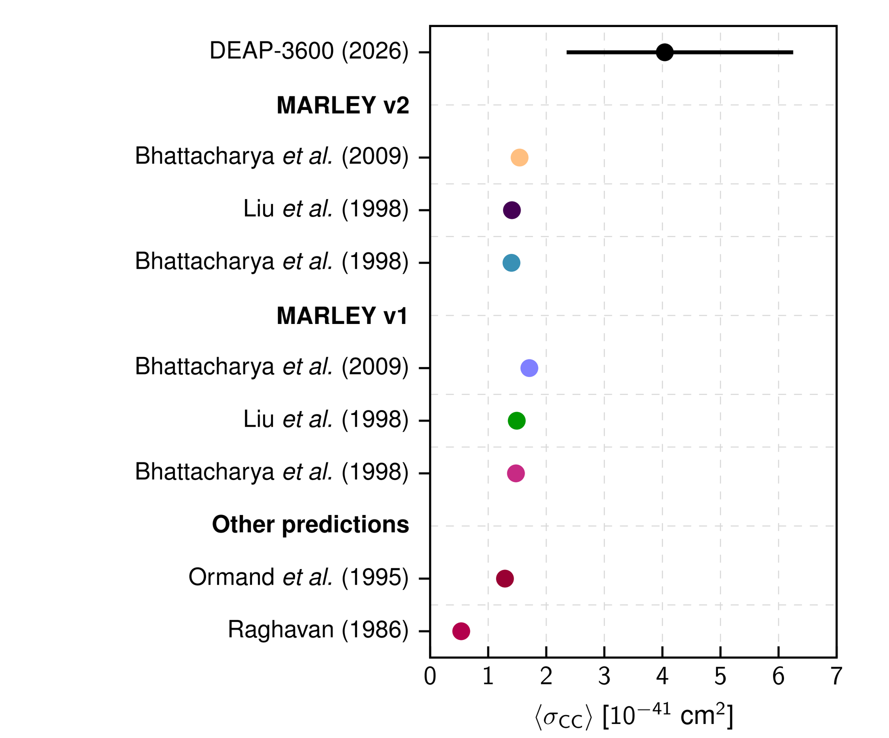
~20% reduction of supernova ν_e event rate from v1 → v2



Improvements for v2.0.0 also extend to realistic nuclear form factors for coherent elastic neutrino-nucleus scattering (CEvNS), a neutral-current process.



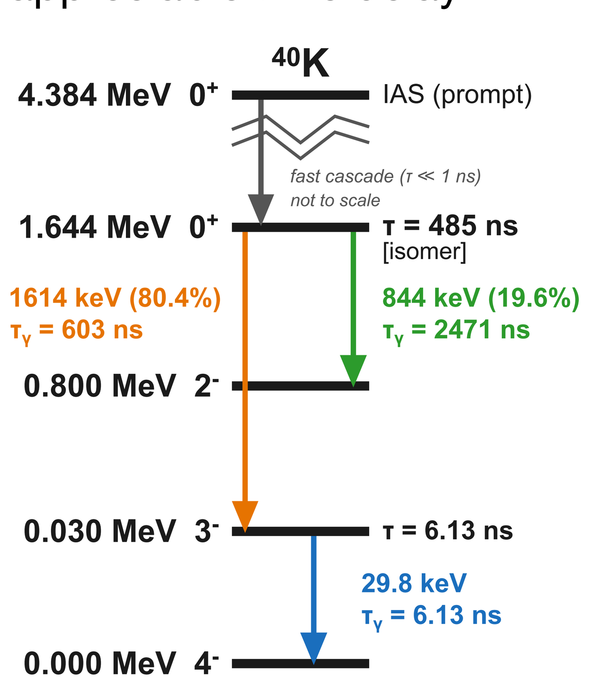
Comparisons of MARLEY predictions to DEAP-3600 solar neutrino cross-section data (arXiv:2605.12769)



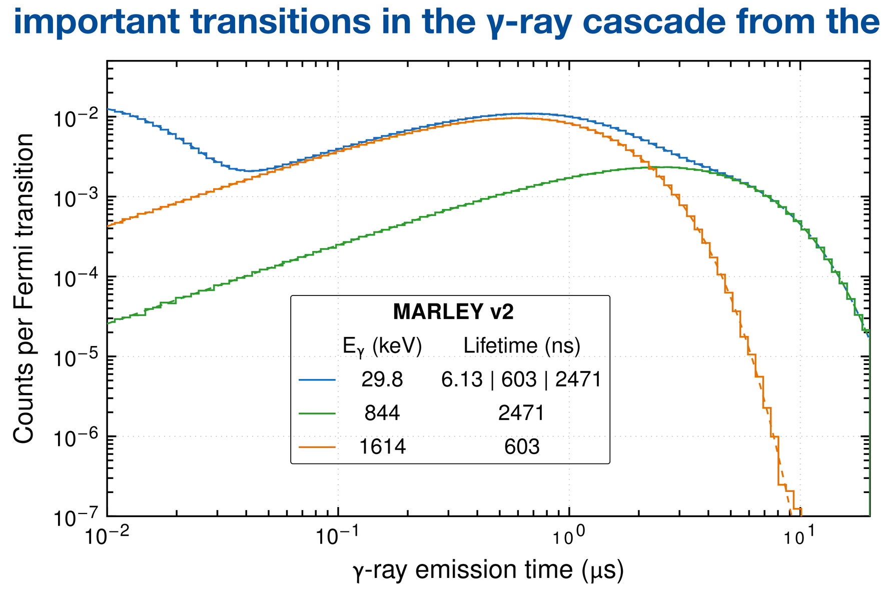
Emission times for γ-rays

Thanks to Everardo Granados Vázquez for help with the timing implementation!

Nuclear de-excitations in MARLEY v1 are treated as instantaneous. Version 2 includes γ-ray time delays when these are known from nuclear structure data. Notably, the important Fermi transition from the ^{40}Ar ground state to its isobaric analog state (IAS) in ^{40}K* (E_X = 4.384 MeV) has several γ-ray lines with an appreciable time delay.



Validation of MARLEY v2 timing distributions for important transitions in the γ-ray cascade from the IAS.

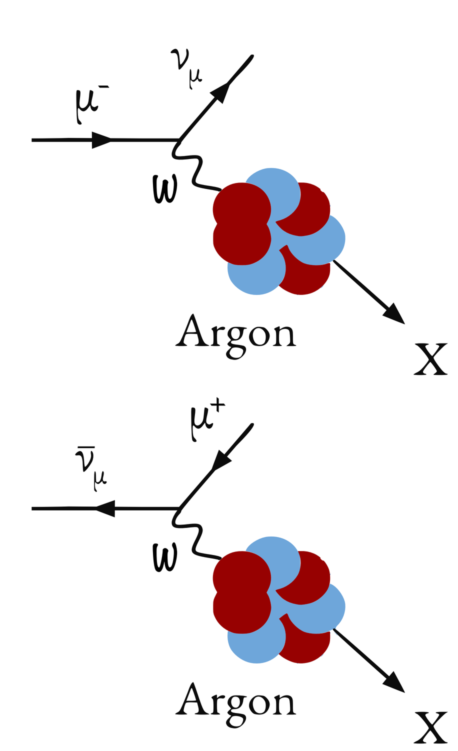


The distribution for the 29.8 MeV γ-ray has three components based on how the 0.030 MeV excited state is accessed.

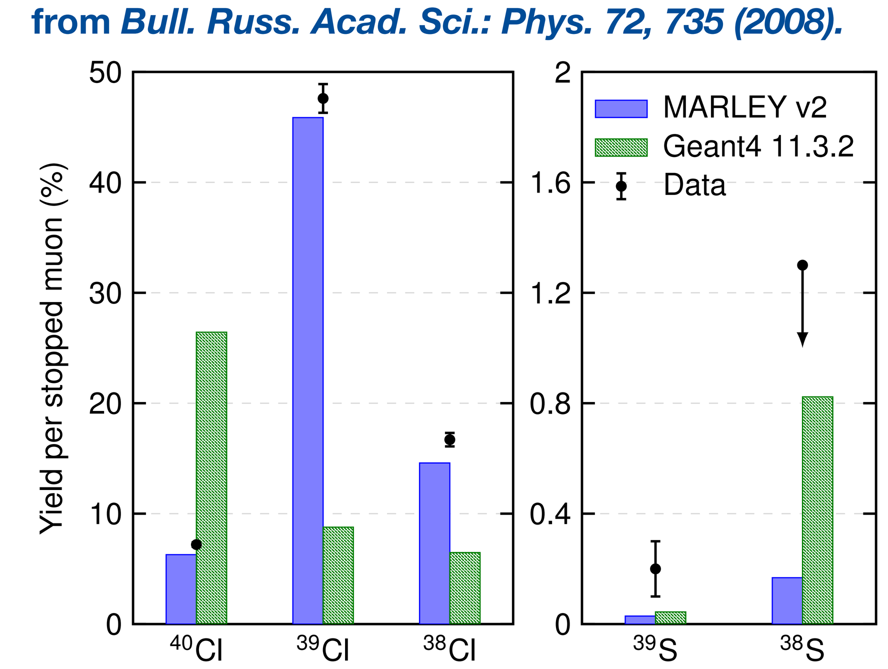
Muon capture

Thanks to Baker Wong for help implementing muon capture!

Low-energy (anti)neutrino-nucleus scattering is closely related to muon capture via crossing symmetry. Detailed data are available for μ capture on argon, enabling powerful model constraints. A future MARLEY v2 release will be the first simulation with a consistent model of both processes.



MARLEY and Geant4 predictions compared to measured isotopic yields for μ capture on Ar. Data from *Bull. Russ. Acad. Sci.: Phys. 72, 735 (2008)*.

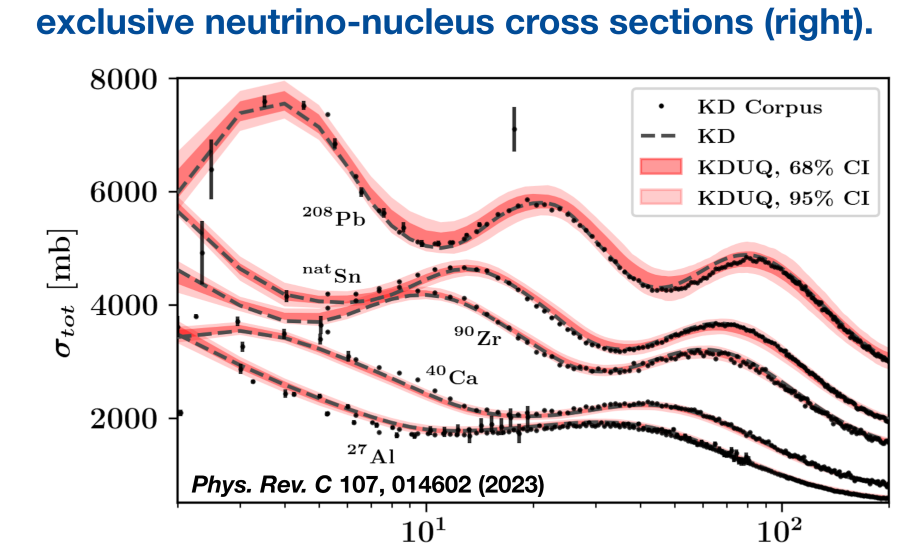


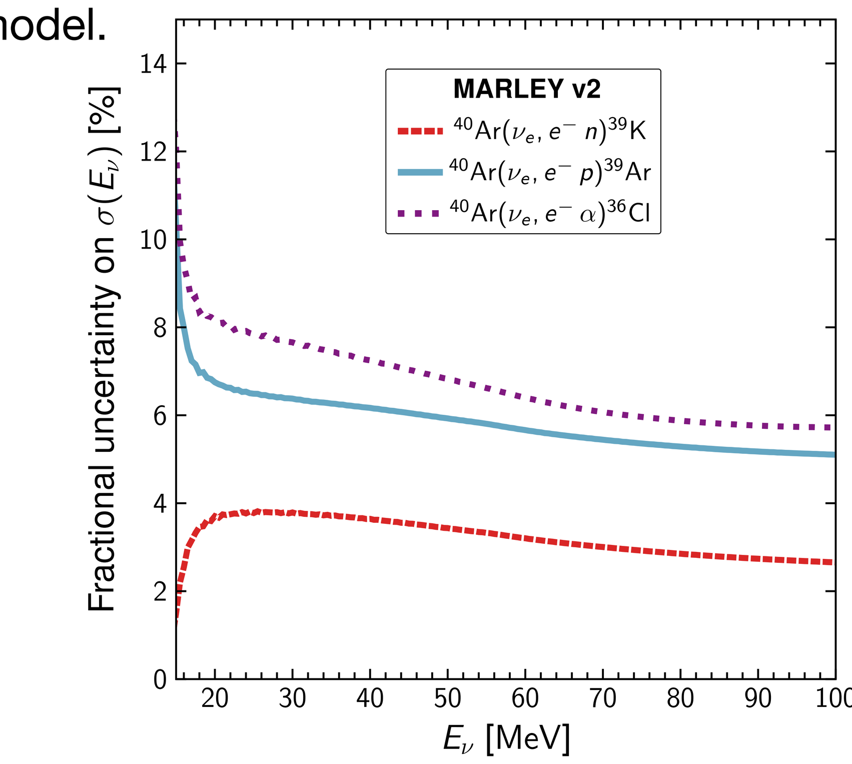
Uncertainty Quantification

Thanks to Pablo Barham Alzás and Luca H. Abu El-Haj for help implementing optical potential uncertainties!

Upcoming low-energy measurements with the DUNE far detector will require a thorough assessment of MARLEY modeling uncertainties. Event reweighting infrastructure has been added to the code to support this goal. An initial set of uncertainties is provided for the 46-parameter Koning-Delaroche optical potential used in the nuclear de-excitation model.

Uncertainties from nucleon scattering data (below) can be directly propagated into predictions of exclusive neutrino-nucleus cross sections (right).





S.G. received support under award number DE-SCL0000022 from the Early Career Research Program, U.S. Department of Energy, Office of Science, Office of High Energy Physics. This poster has been authored by Fermi Forward Discovery Group, LLC under Contract No. 89243024CSC000002 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.