Neutrino Flux Instrumentation at Spallation Neutron Sources

Snowmass NF09 Workshop: Artificial Neutrino Sources

Diana Parno, Carnegie Mellon University

3 December 2020

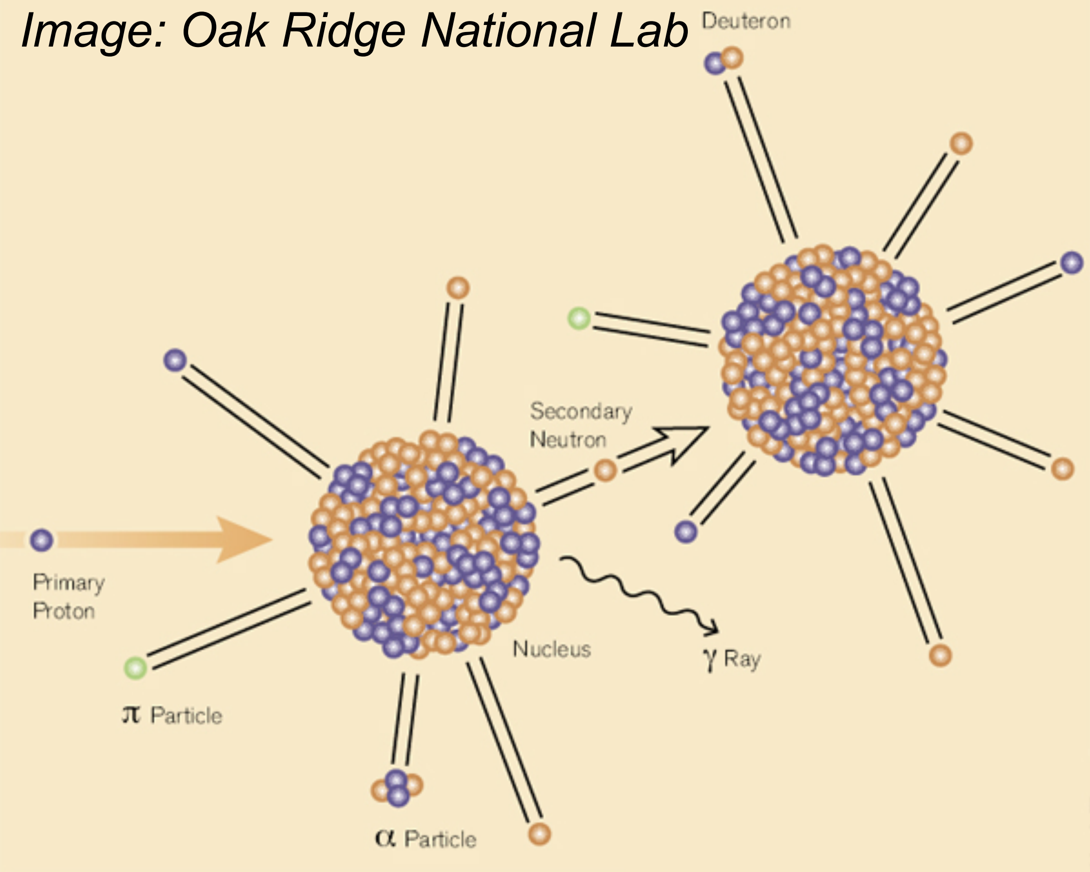
Outline

- Neutrino production at spallation neutron sources
- Modeling the neutrino flux
- Direct flux measurements

Spallation Neutron Sources

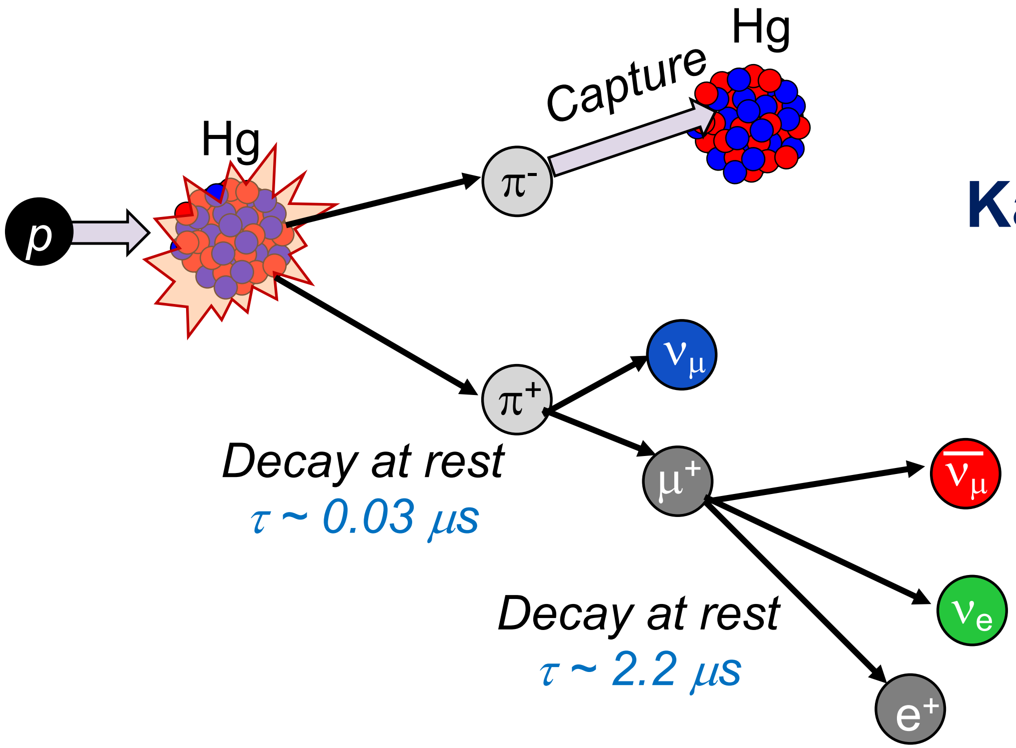
- Energetic protons (~ few GeV) strike a heavy nuclear target
- This knocks loose neutrons, protons, alphas, and deuterons – which knock loose other particles in turn
- Neutrons are moderated and guided along beamlines for various scientific purposes:
  - Materials studies
    - Glasses
    - Liquids
    - Films
    - Crystals
    - Biological structures
  - Dynamic imaging
  - Neutron science

Image: Oak Ridge National Lab



Spallation Neutrino Sources

- The initial interaction also creates mesons!
- Meson products stop in the dense source and then decay at rest



Pion decay at rest

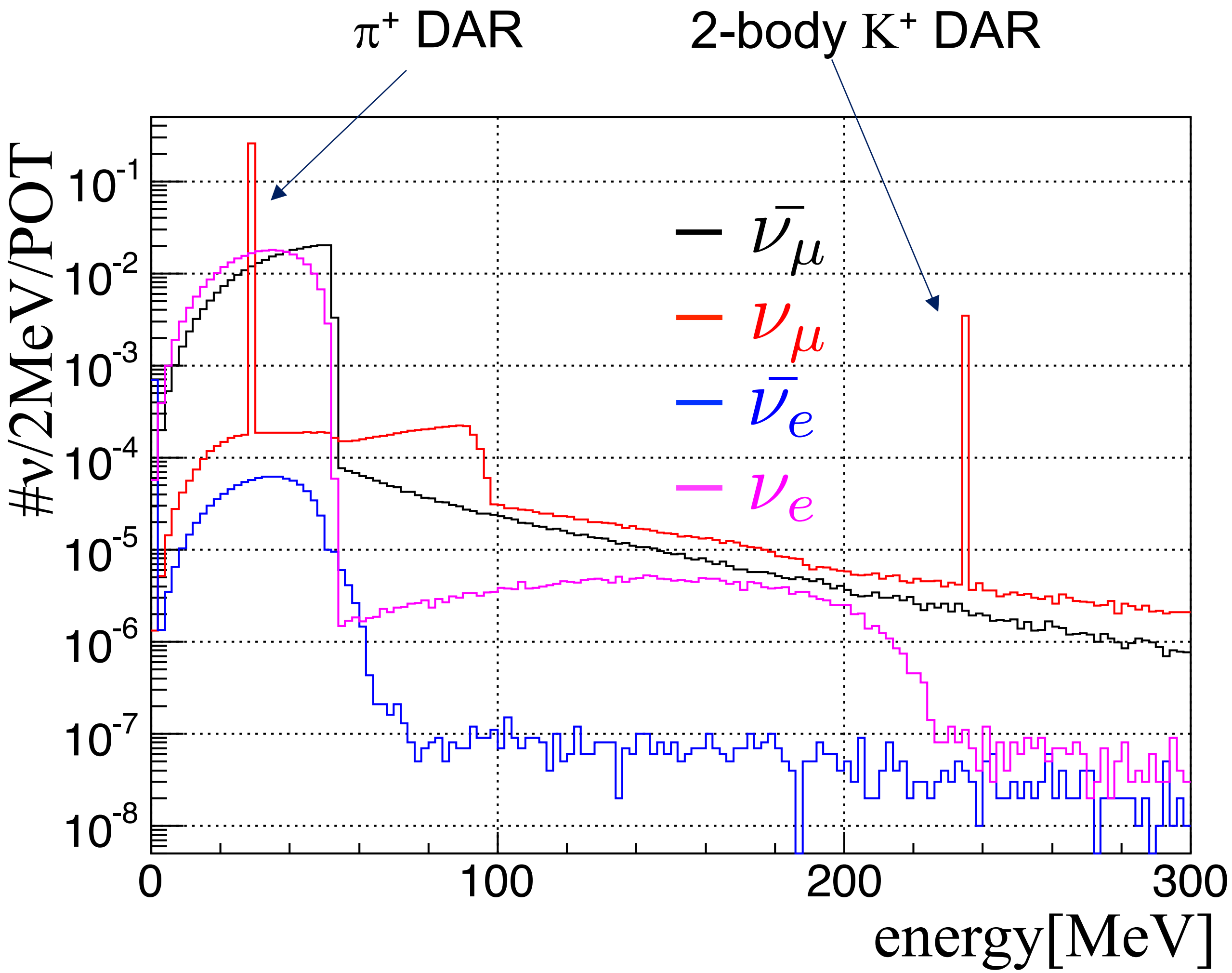
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

Kaon decay at rest

$$K^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$
$$K^+ \to \pi^0 + e^+ + \nu_e$$
$$K_L^0 \to \pi^\pm + e^\mp + \nu_e$$
$$K_L^0 \to \pi^\pm + \mu^\mp + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

Neutrino Spectra

- Decay-at-rest sources mean well-defined energy spectra
- At lower beam energies, neutrinos originate only from pion decay
- As beam energy increases, kaon decay also contributes
- Pulsed beam structure improves background through timing



Expected neutrino spectra at J-PARC MLF (3-GeV p^+ on Hg)

JSNS² Technical Design Report, arXiv:1705.08629v1

Outline

- Neutrino production at spallation neutron sources
- Modeling the neutrino flux
- Direct flux measurements

Flux Modeling

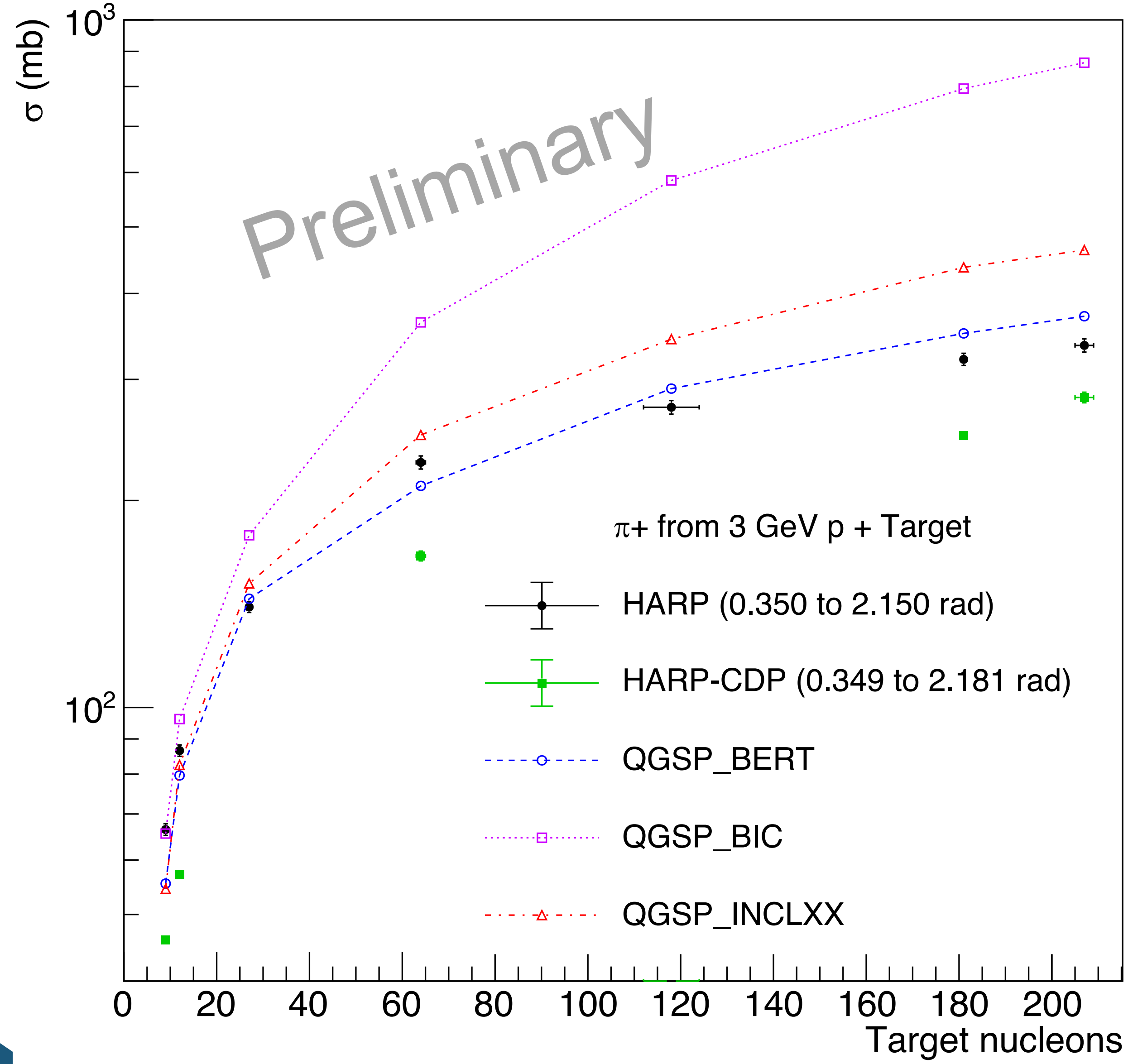
- Simulation of meson production
  - MCNP (Coherent Captain Mills, CEvNS@ESS)
  - Geant4 (CEvNS@ESS, JSNS^2, COHERENT)
  - FLUKA (CEvNS@ESS, JSNS^2)

- Peg to world pion-production data
  - Doesn't include all targets (no Hg data)
  - Mostly too high energy ($E_p \geq 3$ GeV)
    - Limited low-energy data available

Upcoming EMPHATIC experiment: multiple targets at $E_p \geq 2$ GeV

Workshop next week:
NA61/SHINE
at Low Energies
https://indico.cern.ch/event/973899/

Uncertainties in Pion Production



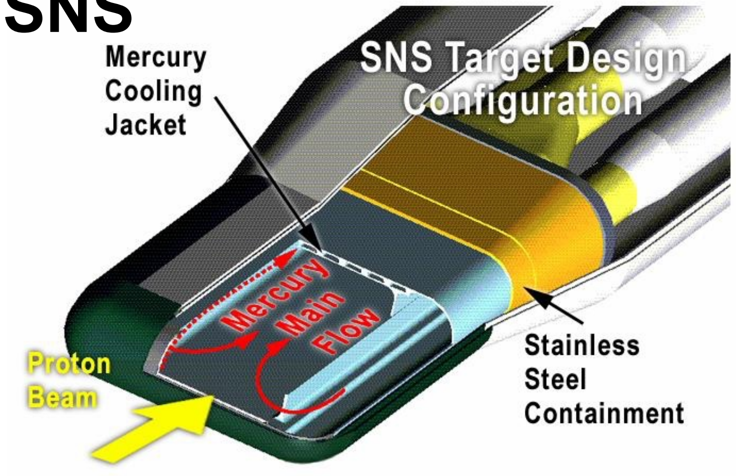
- HARP measured pion production at high precision for $E_p \geq 3$ GeV
  - Separate analyses by HARP-CDP group are available
- Double-differential cross sections in strong disagreement with Geant4 simulations
- At a DAR source, we can integrate over pion angle and momentum
  - Agreement within 10% for QGSP_BERT physics list at high *A*

Plot by Rebecca Rapp and Aria Salyapongse

Meson Production in Spallation Targets

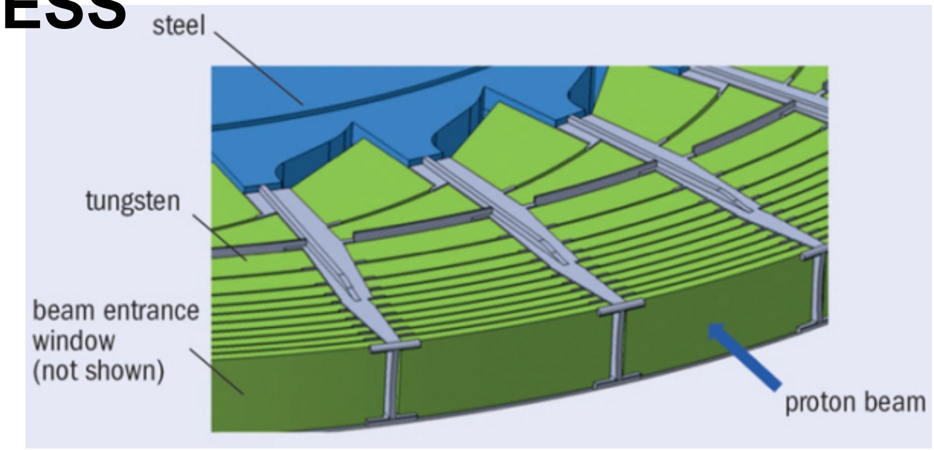
- Spallation targets are thick – and protons lose energy throughout
- Meson-production cross sections must be integrated over proton energy-loss profile in source
- Surrounding materials also contribute to meson and neutrino production
- In situ ν flux measurements can make an important contribution

SNS



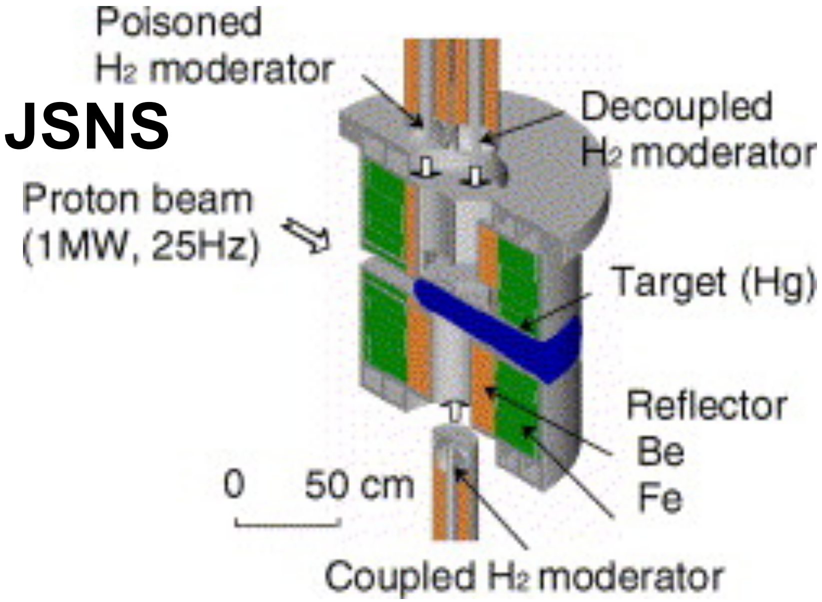
Oak Ridge National Lab

ESS



Karlsruhe Institute of Technology

JSNS



M. Teshigawara et al., J. Nucl. Mat. ***356*** *300 (2006)*

Outline

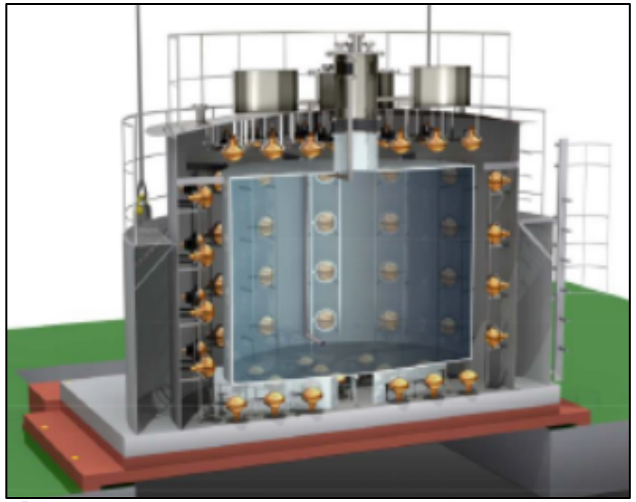
- Neutrino production at spallation neutron sources
- Modeling the neutrino flux
- Direct flux measurements

Two Sterile-Search Strategies

- At LANSCE, Coherent Captain Mills has a near/far detector combo
- At JSNS², carbon in the liquid scintillator is sensitive to ν_e

$$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}$$

$${}^{12}\mathrm{N} \rightarrow {}^{12}\mathrm{C} + e^+ + \nu_e$$



- The measured ν_e flux also corresponds to the $\bar{\nu}_\mu$ flux!
  - ~10% uncertainty due to cross section and detector efficiency

Experiment	$\sigma(^{12}C(\nu_e,e^-)^{12}N_{g.s.})$ (10^{-42} cm^2)
KARMEN (PLB332, 251 (1994))	9.1±0.5±0.8 (10.4%)
LSND (PRC64, 065501 (2001))	8.9±0.3±0.9 (10.7%)

Table from Carsten Rott

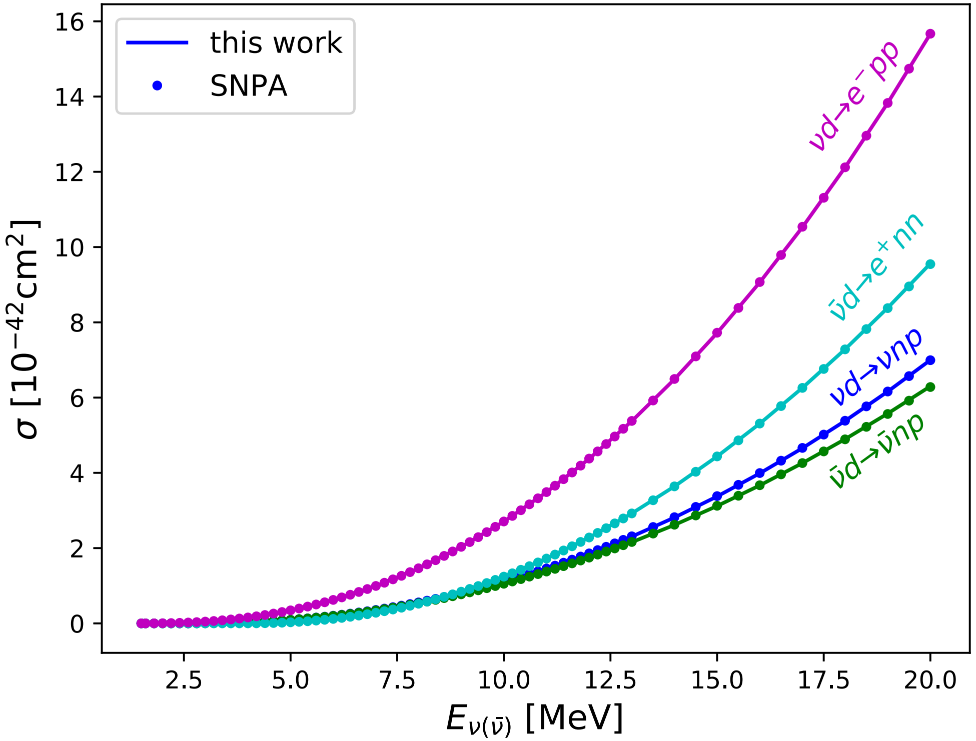
- ~50% uncertainty on $\bar{\nu}_e$ flux from μ^- decay (needed for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
- 2nd detector for JSNS²-II will dramatically reduce flux uncertainties

D_2O as Flux Tool

- Target the charged-current reaction

$$\nu_e + d^+ \rightarrow p^+ + p^+ + e^-$$

- Cherenkov detector tags fast-moving electron
- This interaction has been measured at LAMPF *(Willis et al., PRL **44** 522 (1980))*



- Predicted cross sections from different theoretical models agree within 2-3%

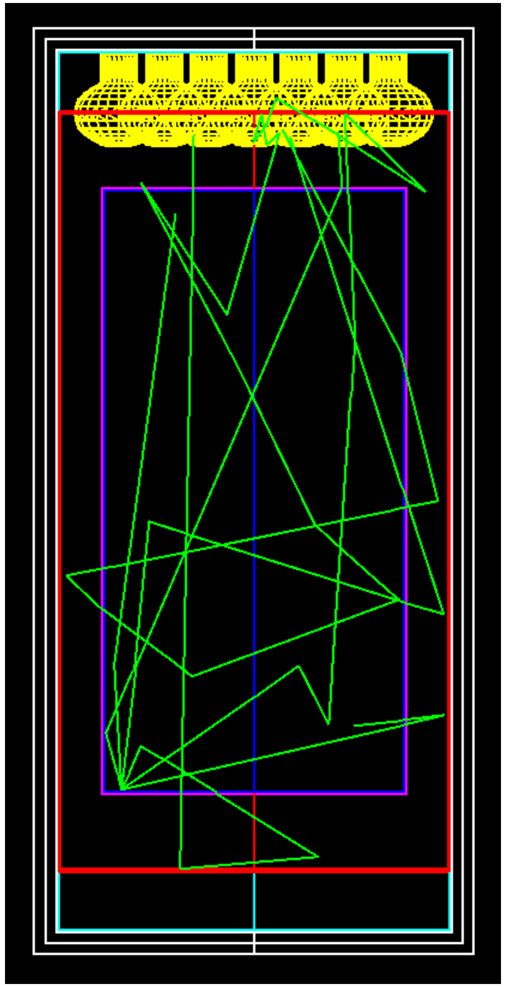
"This work": Pionless EFT from
*Ando, Song, and Hyun, PRC **101** 054001 (2020)*

"SNPA": Phenomenological Lagrangian approach from
*Nakamura, Sato, Gudkov, and Kubodera, PRC **63** 034617 (2001)*

- COHERENT and CEvNS@ESS both plan D_2O detectors to benchmark neutrino flux

COHERENT's D_2O Demonstrator Plans

Model from Eric Day, CMU



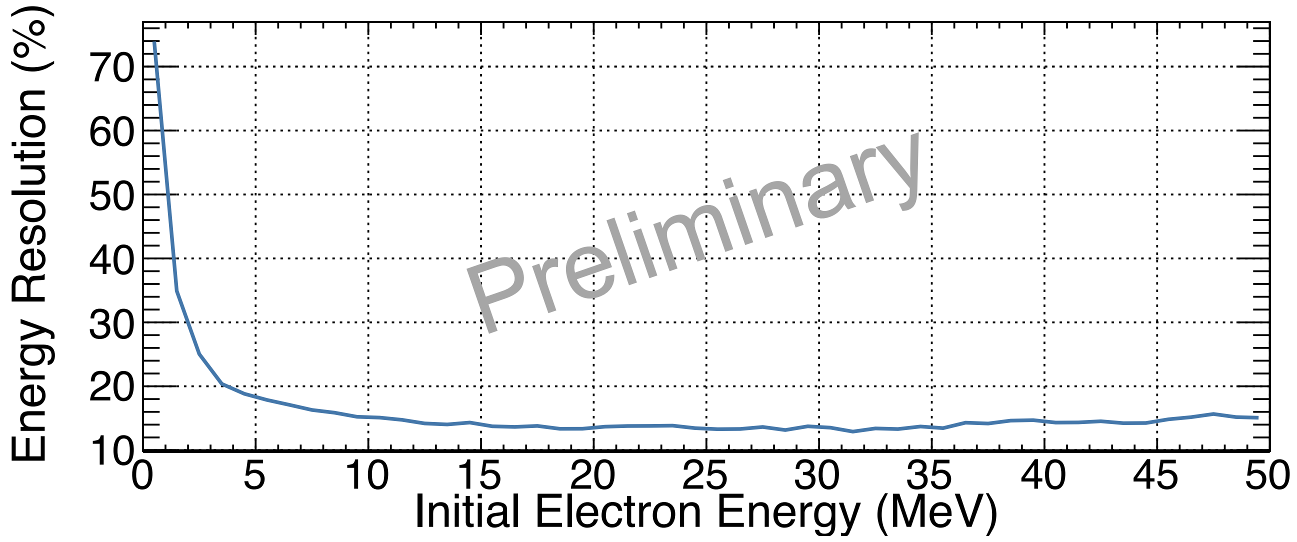
Simulation from Rebecca Rapp, CMU

- Designed around space constraints in SNS's Neutrino Alley
- 687 kg of D_2O in central fiducial volume, enclosed in transparent acrylic
- External 10-cm H_2O "tail catcher" aids energy reconstruction
- Outer steel tank lined in reflective Tyvek
- 12 PMTs view water from above
- Lead shielding and plastic-scintillator muon veto surround the steel tank

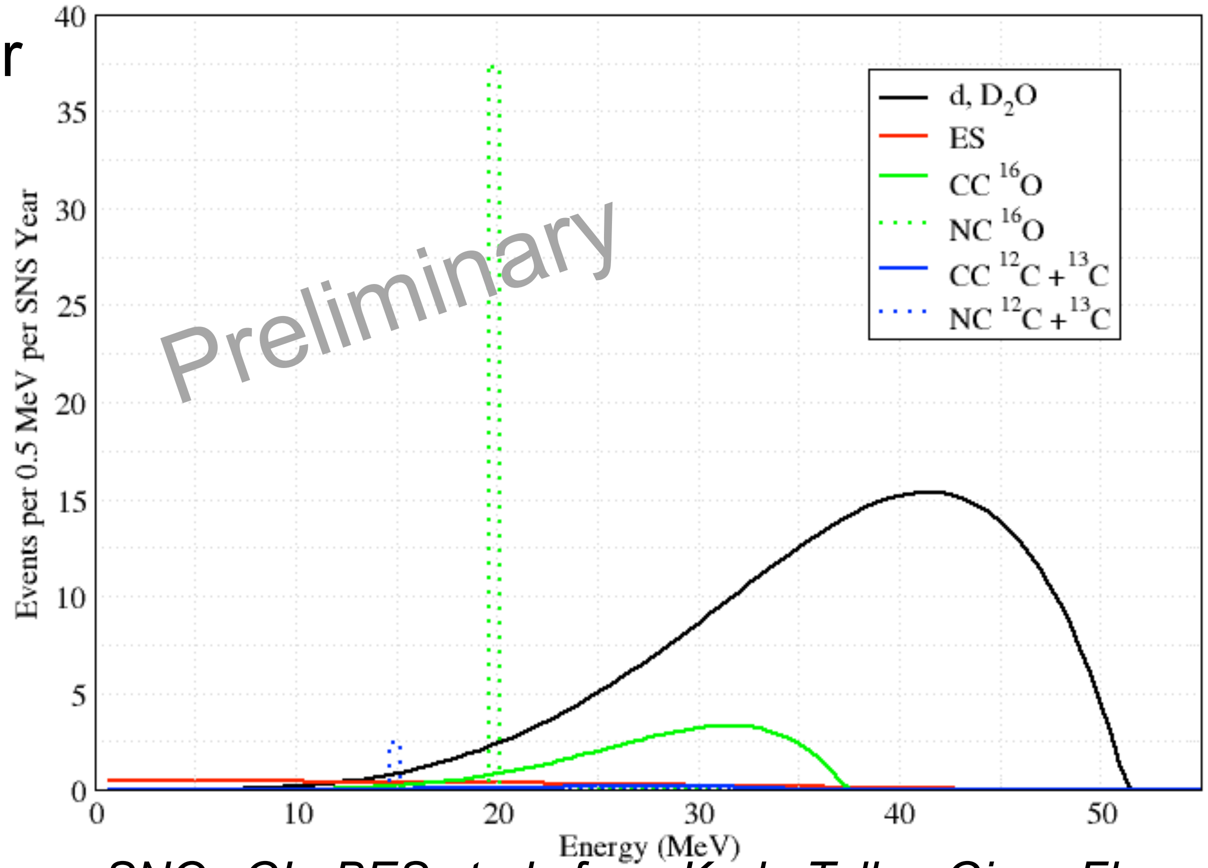
- First funding received from DOE!
  - D_2O loans received from several sources

Expected Performance

- Energy resolution ~13% for electron energies above 10 MeV
- Primary background (CC on ^{16}O) removable with energy cut
- About 630 D events expected per SNS year



Geant4 study from Matthew Heath, ORNL



SNOwGLoBES study from Karla Tellez-Giron-Flores, Virginia Tech

Outlook

- The next few years
  - COHERENT: Build, test, and deploy D_2O demonstrator module
  - COHERENT: Follow up with second module
  - JSNS^2: Measurements on carbon
- And beyond …
  - New pion-production measurements at low energies from EMPHATIC and NA61/SHINE
  - CEvNS@ESS D_2O design and deployment

Thanks to:

- The COHERENT collaboration
- Juanjo Gomez Cadenas (CEvNS@ESS)
- Takasumi Maruyama (JSNS^2)
- Richard Van de Water (Coherent Captain Mills)
- DOE Office of Science, Award Number #DE-SC0010118