Experimental Measurements of Charged-Current Neutrino Scattering at the SNS

Samuel Hedges

3rd New Physics Opportunities at Neutrino Facilities Workshop: Astrophysical Neutrinos

July 12th, 2023

Outline

- Motivation
- The COHERENT collaboration and neutrinos at the SNS
- Inclusive charged-current interactions on ^{127}I

$$\nu_e + {}^{127}\mathrm{I} \longrightarrow e^- + \mathrm{X}$$

- Neutrino-induced Neutrons on Lead

$$\nu_e + {}^{208}\mathrm{Pb} \longrightarrow e^- + {}^{208-\mathrm{x}}\mathrm{Bi} + \mathrm{x}n$$

- Future inelastic measurements at COHERENT

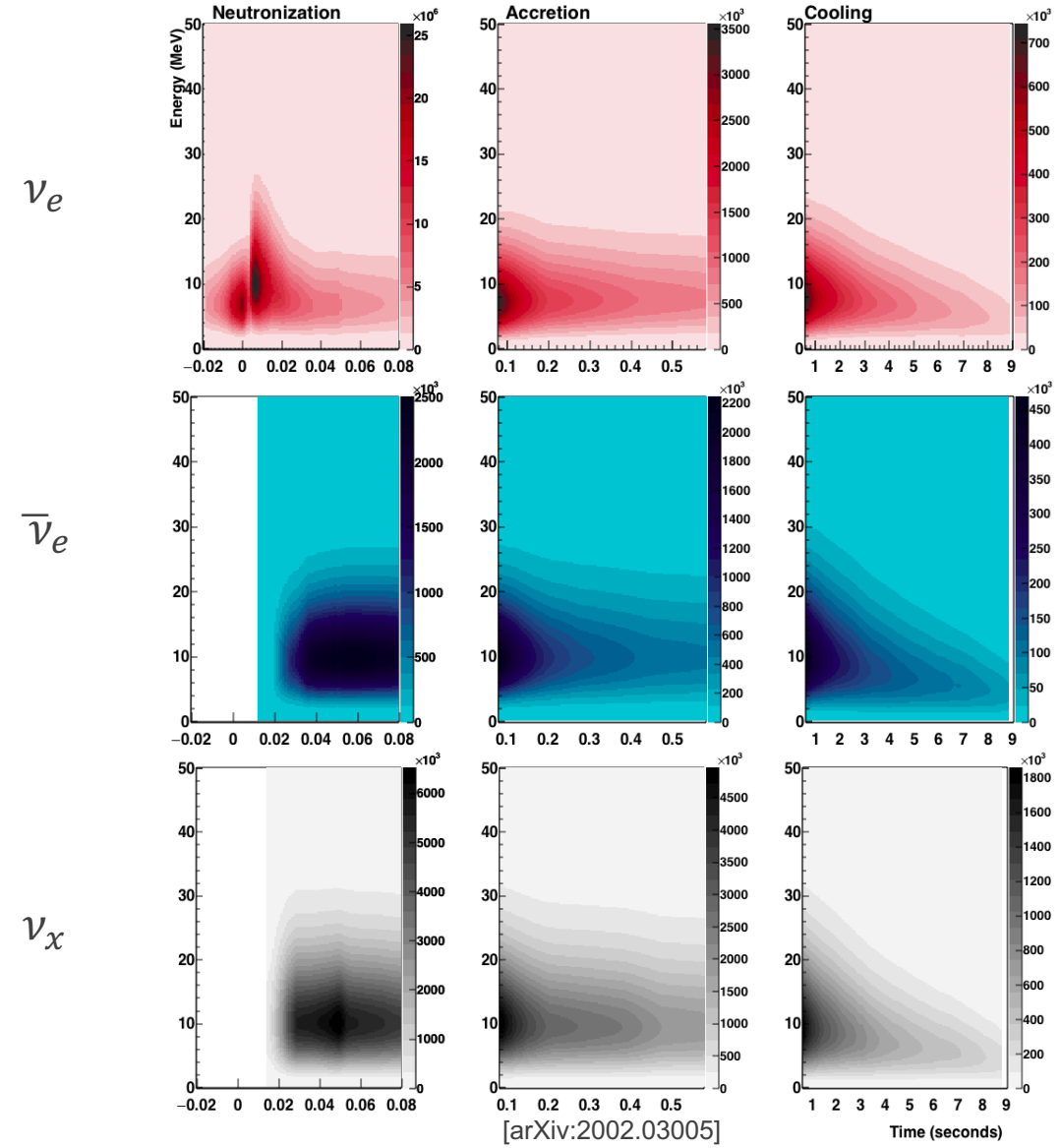
Motivation

- When a supernova occurs, ideally collect as much information as possible
  - Want to be prepared—it's not a matter of if, but when
- Neutrinos arrive ahead of photons, can provide early warning
  - Can potentially point toward source
- Neutrinos provide a unique window into the evolution of the supernova as a function of time, neutrino impact on nucleosynthesis
- Intense flux of neutrinos produced can be used to study fundamental properties of the neutrino

[wikipedia.org/wiki/Supernova_remnant]

Motivation

- Time-evolution of neutrino flux, energies will help us understand the supernova explosion
- Three main components:
  - ν_e: charged−current scattering on nuclei, elastic neutrino−electron scattering,
  - $\overline{\nu}_e$: inverse-beta decay, elastic neutrino−electron scattering,
  - ν_x: CEνNS, inelastic NC, elastic neutrino-proton scattering
- To reconstruct neutrino energy, need to understand the events that are produced



[arXiv:2002.03005]

Motivation

- Knowing only the inclusive cross section is not enough!
  - We need to understand the nuclear response (excitation, de-excitation products) to reconstruct incident neutrino energy
- MARLEY is a recent tool to generate signal predictions for inelastic neutrino-nucleus scattering at energies relevant for supernova
- MARLEY handles allowed components of neutrino-interactions
  - Approximation for SN neutrino energies, but forbidden transitions still contribute
  - Impact of forbidden transitions varies from target-to-target
  - Some work from developer to incorporate theoretical contributions
- Required inputs are B(GT) and B(F) matrix elements, can be measured by beta-decay, charge-exchange interactions, or calculated
- Very limited existing experimental data to test MARLEY

Motivation

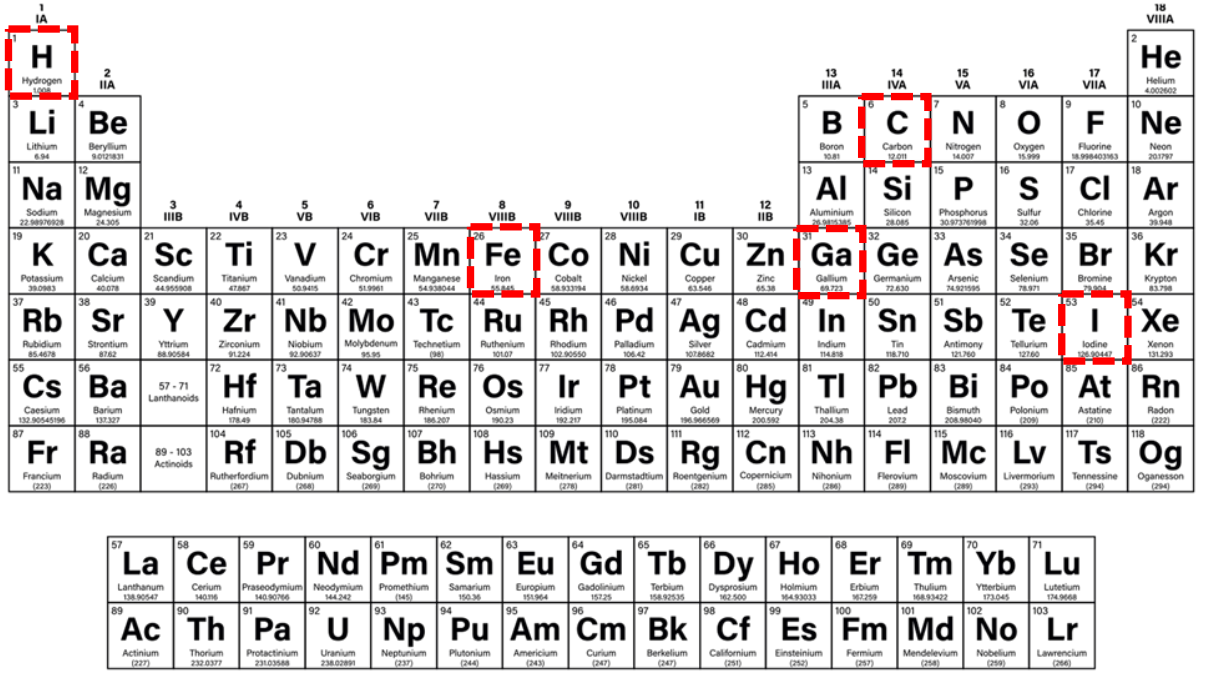
List of <300 MeV neutrino-nucleus measurements with terrestrial sources

Isotope	Reaction Channel	Source	Experiment	Measurement (10^{-42} cm^2)	Theory (10^{-42} cm^2)
^{2}H	$^{2}\mathrm{H}(\nu_e, e^-)\mathrm{pp}$	Stopped π/μ	LAMPF	$52 \pm 18(\mathrm{tot})$	54 (IA) (Tatara *et al.*, 1990)
^{12}C	$^{12}\mathrm{C}(\nu_e, e^-)^{12}\mathrm{N}_{\mathrm{g.s.}}$	Stopped π/μ	KARMEN	$9.1 \pm 0.5(\mathrm{stat}) \pm 0.8(\mathrm{sys})$	9.4 [Multipole](Donnelly and Peccei, 1979)
		Stopped π/μ	E225	$10.5 \pm 1.0(\mathrm{stat}) \pm 1.0(\mathrm{sys})$	9.2 [EPT] (Fukugita *et al.*, 1988).
		Stopped π/μ	LSND	$8.9 \pm 0.3(\mathrm{stat}) \pm 0.9(\mathrm{sys})$	8.9 [CRPA] (Kolbe *et al.*, 1999b)
	$^{12}\mathrm{C}(\nu_e, e^-)^{12}\mathrm{N}^*$	Stopped π/μ	KARMEN	$5.1 \pm 0.6(\mathrm{stat}) \pm 0.5(\mathrm{sys})$	5.4-5.6 [CRPA] (Kolbe *et al.*, 1999b)
		Stopped π/μ	E225	$3.6 \pm 2.0(\mathrm{tot})$	4.1 [Shell] (Hayes and S, 2000)
		Stopped π/μ	LSND	$4.3 \pm 0.4(\mathrm{stat}) \pm 0.6(\mathrm{sys})$	
	$^{12}\mathrm{C}(\nu_\mu, \nu_\mu)^{12}\mathrm{C}^*$	Stopped π/μ	KARMEN	$3.2 \pm 0.5(\mathrm{stat}) \pm 0.4(\mathrm{sys})$	2.8 [CRPA] (Kolbe *et al.*, 1999b)
	$^{12}\mathrm{C}(\nu, \nu)^{12}\mathrm{C}^*$	Stopped π/μ	KARMEN	$10.5 \pm 1.0(\mathrm{stat}) \pm 0.9(\mathrm{sys})$	10.5 [CRPA] (Kolbe *et al.*, 1999b)
	$^{12}\mathrm{C}(\nu_\mu, \mu^-)\mathrm{X}$	Decay in Flight	LSND	$1060 \pm 30(\mathrm{stat}) \pm 180(\mathrm{sys})$	1750-1780 [CRPA] (Kolbe *et al.*, 1999b) 1380 [Shell] (Hayes and S, 2000) 1115 [Green's Function] (Meucci *et al.*, 2004)
	$^{12}\mathrm{C}(\nu_\mu, \mu^-)^{12}\mathrm{N}_{\mathrm{g.s.}}$	Decay in Flight	LSND	$56 \pm 8(\mathrm{stat}) \pm 10(\mathrm{sys})$	68-73 [CRPA] (Kolbe *et al.*, 1999b) 56 [Shell] (Hayes and S, 2000)
^{56}Fe	$^{56}\mathrm{Fe}(\nu_e, e^-)^{56}\mathrm{Co}$	Stopped π/μ	KARMEN	$256 \pm 108(\mathrm{stat}) \pm 43(\mathrm{sys})$	264 [Shell] (Kolbe *et al.*, 1999a)
^{71}Ga	$^{71}\mathrm{Ga}(\nu_e, e^-)^{71}\mathrm{Ge}$	^{51}Cr source	GALLEX, ave.	$0.0054 \pm 0.0009(\mathrm{tot})$	0.0058 [Shell] (Haxton, 1998)
		^{51}Cr	SAGE	$0.0055 \pm 0.0007(\mathrm{tot})$	
		^{37}Ar source	SAGE	$0.0055 \pm 0.0006(\mathrm{tot})$	0.0070 [Shell] (Bahcall, 1997)
^{127}I	$^{127}\mathrm{I}(\nu_e, e^-)^{127}\mathrm{Xe}$	Stopped π/μ	LSND	$284 \pm 91(\mathrm{stat}) \pm 25(\mathrm{sys})$	210-310 [Quasi-particle] (Engel *et al.*, 1994)

[J. A. Formaggio & G. P. Zeller, Rev. Mod. Phys **84** (2012)]

Existing Low-Energy Neutrino-Nucleus Measurements

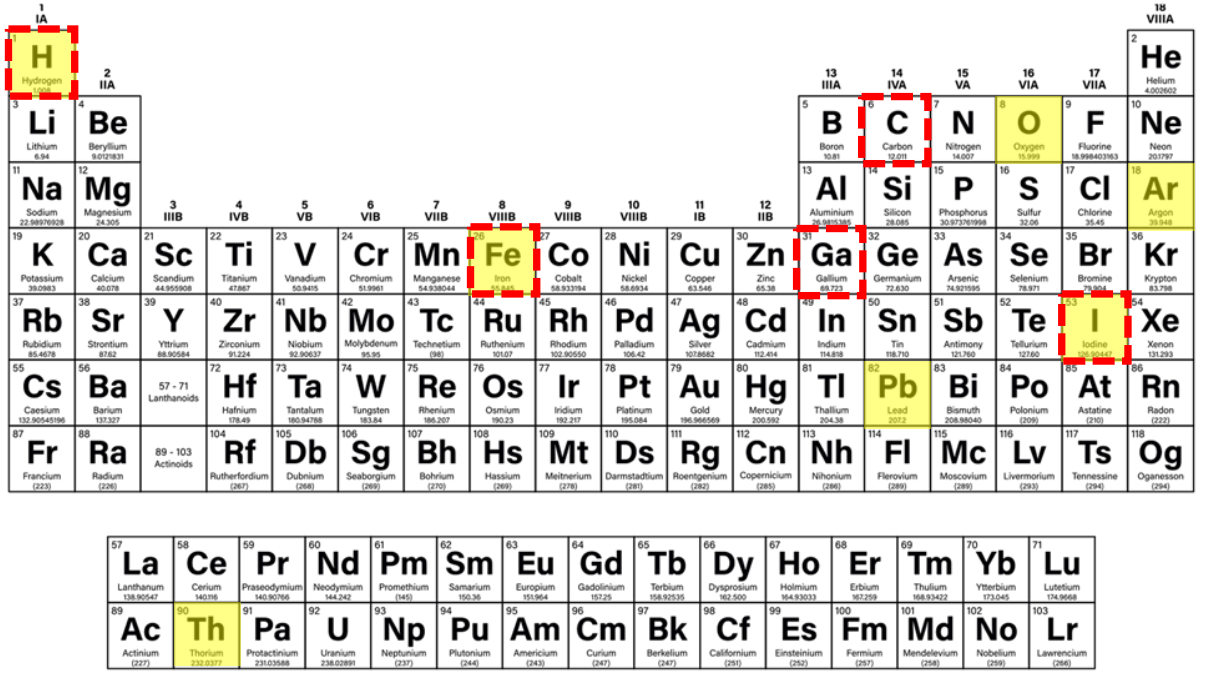
= existing measurements for low-energy (<300 MeV) neutrinos from terrestrial sources



COHERENT's Inelastic Detectors

= existing measurements for low-energy (<300 MeV) neutrinos from terrestrial sources

= COHERENT's current & planned detectors



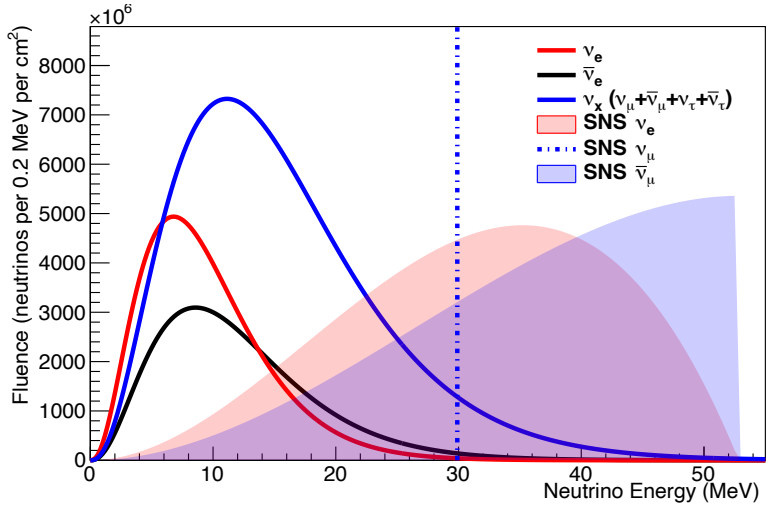
Name	Target	Channel	Deployment Date
Lead Neutrino Cube	Lead	$\mathrm{Pb}(\nu_e, e^- + xn)$	1/2016
Iron Neutrino Cube	Iron	$\mathrm{Fe}(\nu_e, e^- + xn)$	2/2017
NaIνE (COH-NaI-185)	^{127}I	$^{127}\mathrm{I}(\nu_e, e^- + x)$	6/2016
CENNS-10 (COH-Ar-10)	Argon	$\mathrm{Ar}(\nu_e, e^- + x)$	2017
νThor	Thorium	$\mathrm{Th}(\nu_e, e^- + x)$	2022
CENNS-750 (COH-Ar-750)	Argon	$\mathrm{Ar}(\nu_e, e^- + x)$	future
D_2O	^{2}H/O	$^2\mathrm{H/O}(\nu_e, e^- + x)$	future

Results presented today!

The COHERENT Collaboration and Neutrinos at the SNS

The COHERENT Collaboration

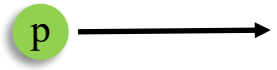
- ~100 members, 23 institutions
- Formed to observe CEvNS, study physics in multiple targets, including N^2 scaling of cross section
- Use neutrinos produced by the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL)
- Intense flux of low-energy pulsed neutrinos useful for studying inelastic neutrino-nucleus interactions as well
  - Similar energy range as those produced by supernovae



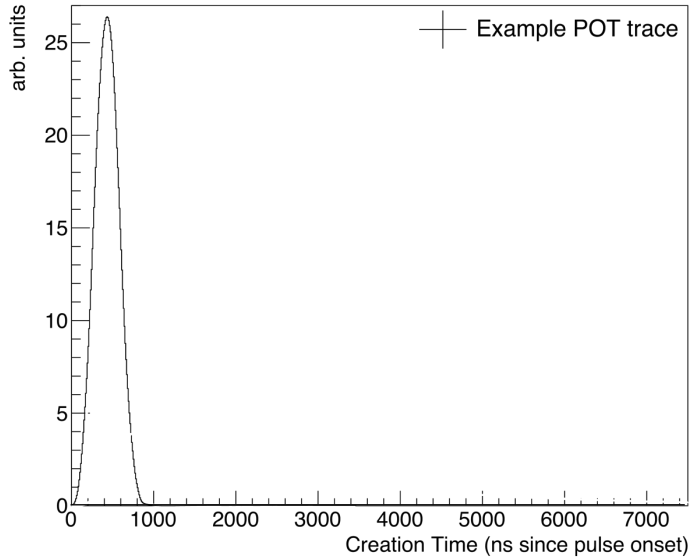
[image courtesy of K. Scholberg]

Neutrino Production at the SNS

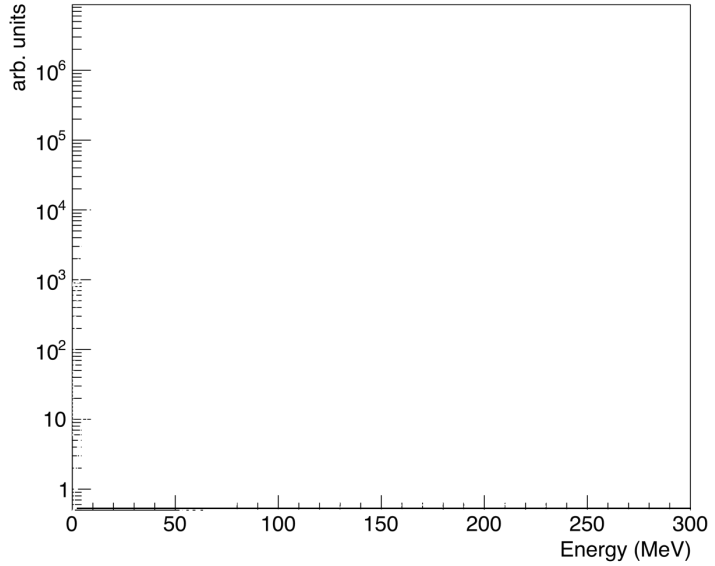
1 GeV protons
1.4 MW power
375-ns FWHM
60Hz



Timing:



Energy:



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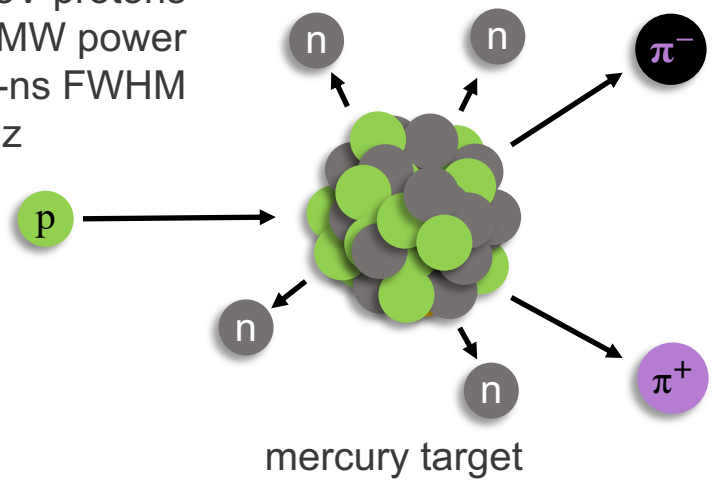

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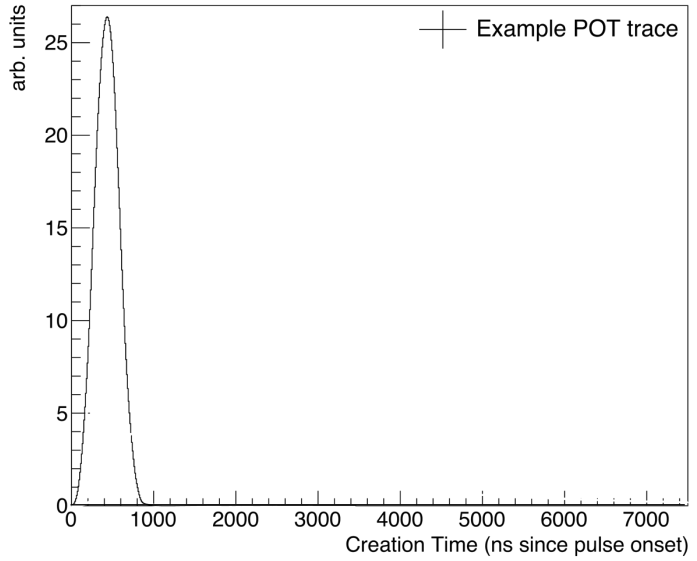

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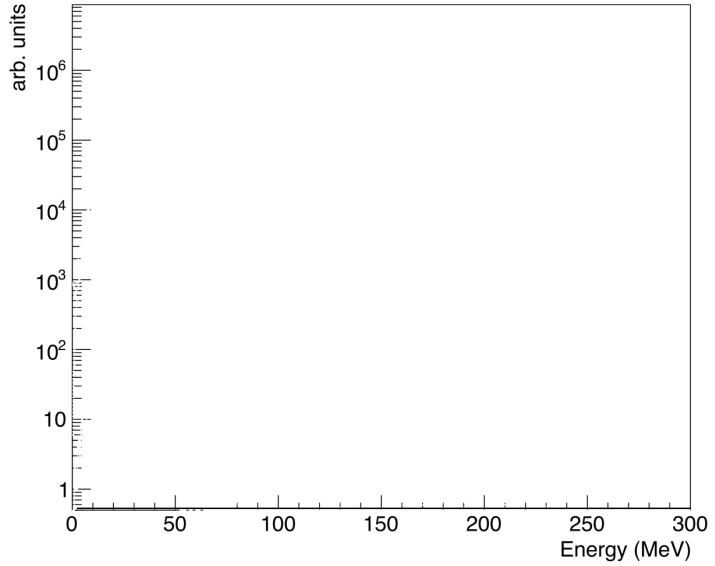
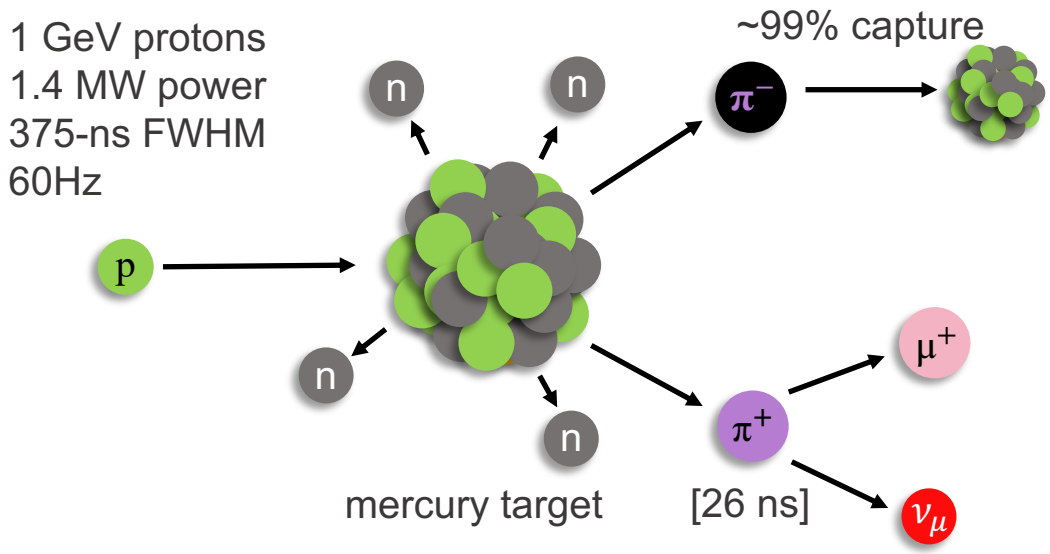
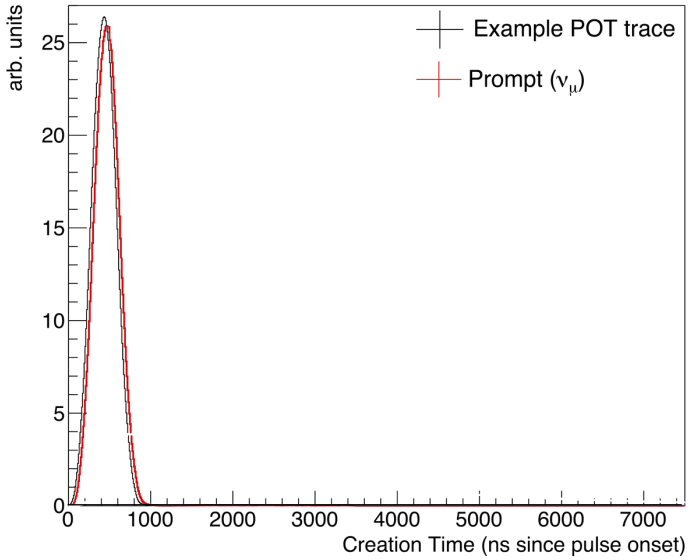


Neutrino Production at the SNS



Timing:



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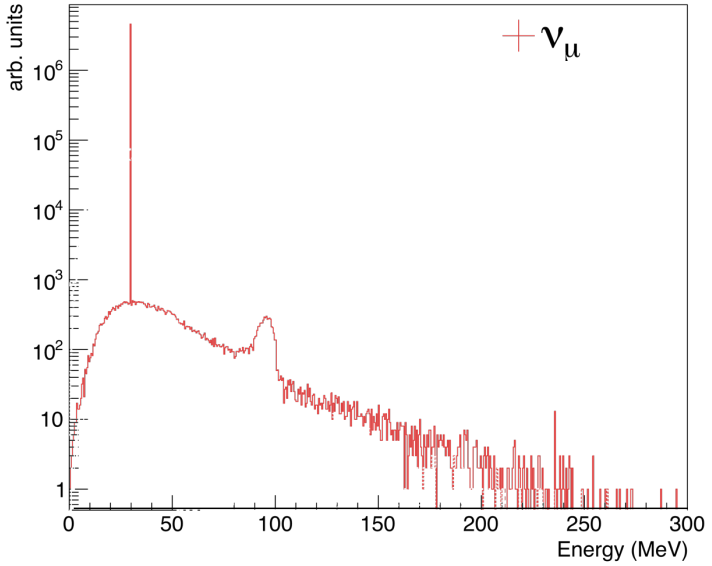

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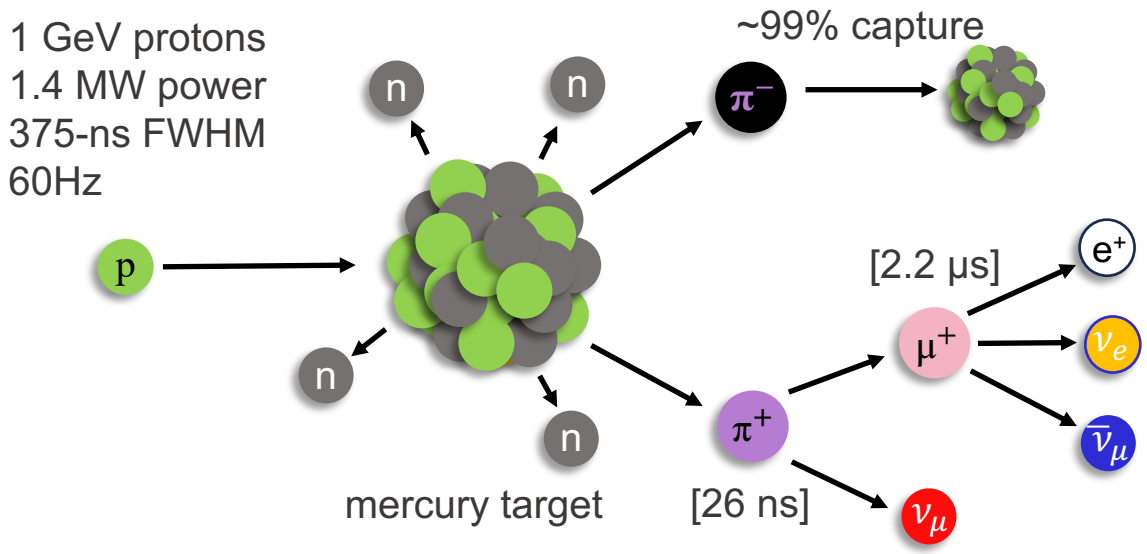

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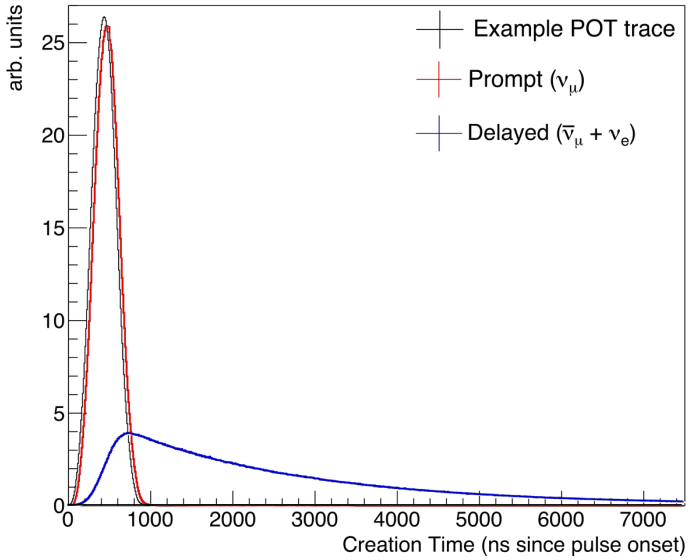

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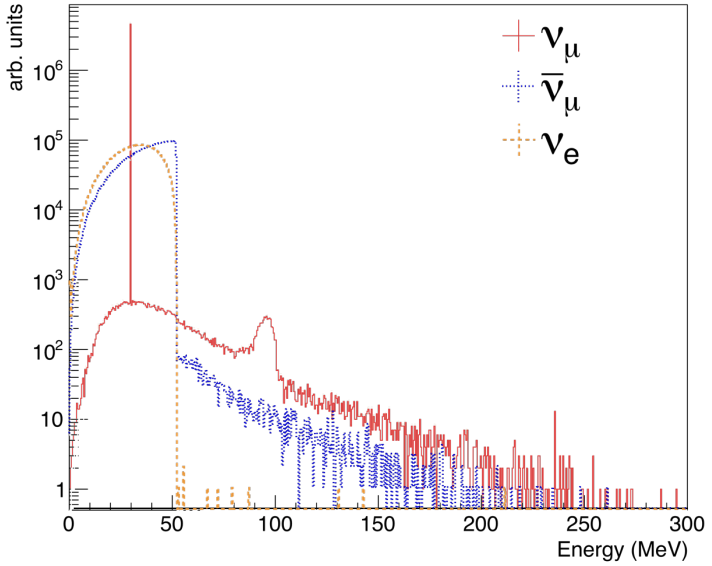
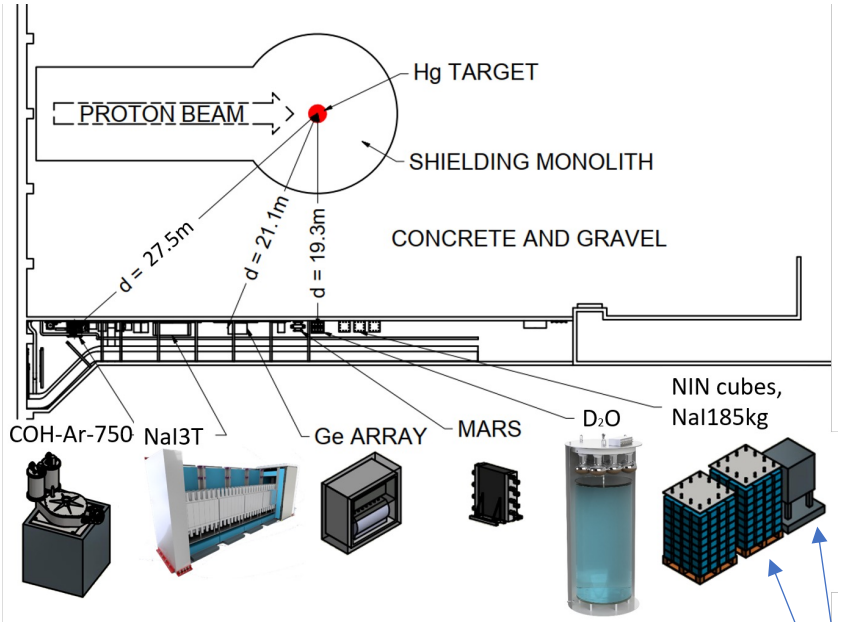
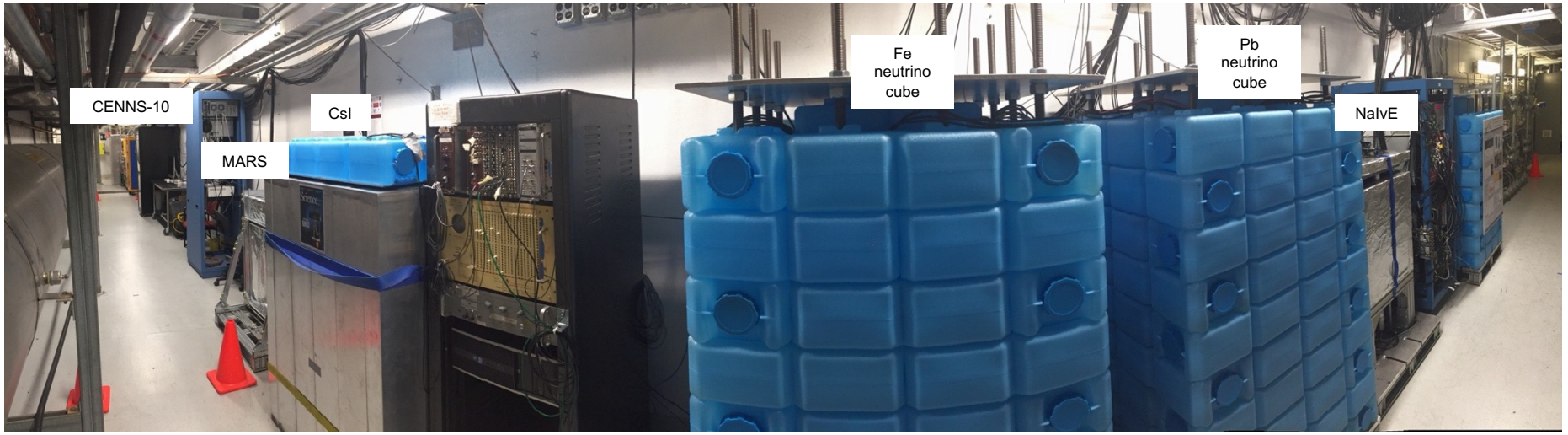


Neutrino Alley

- COHERENT's detectors in "Neutrino Alley" at the SNS
  - 25m long hallway, 20-30m from target
  - Not designed for neutrino detectors
  - Concrete and gravel reduce beam neutrons
- Dedicated detectors for measuring neutrons





Results shared today

Inclusive charged-current interactions on ^{127}I

$$\nu_e + {}^{127}\mathrm{I} \longrightarrow e^- + \mathrm{X}$$

Motivation for Measuring ^{127}I CC Interactions

- Original motivation was to build radiochemical detector similar to that Homestake mine, for solar, supernova neutrinos, utlizing on

$$\nu_e + {}^{127}\mathrm{I} \rightarrow e^- + {}^{127}\mathrm{Xe}^*$$

  - Low threshold gives access to ^{7}Be solar neutrinos, larger cross section than for ^{37}Cl
  - Resulting ^{127}Xe has long half-life, use similar radiochemical technique as used for ^{37}Cl
- Theoretical calculations overpredict matrix elements, solved by quenching g_A
  - By comparing theory to experiment, can determine quenching of g_A at momentum transfer higher than reached in beta-decay experiments
  - Suppression of g_A important for $0\nu\beta\beta$ experiments (nEXO, LEGEND, SNO+, CUPID), half-life depends on g_A^4

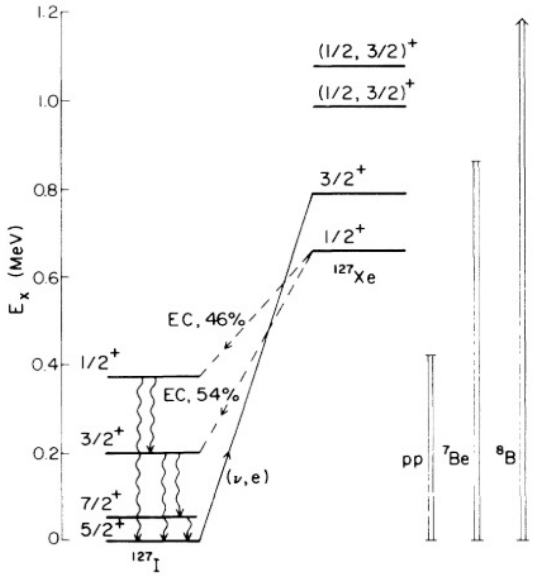


FIG. 1. Level scheme showing weak transitions between ^{127}I and ^{127}Xe.

[W. C. Haxton, Phys. Rev. Lett **60** (1988)]

J^π	$g_A = -1.0$	$g_A = -1.26$
0^+	0.096	0.096
0^-	0.00001	0.00002
1^+	1.017	1.528
1^-	0.006	0.008
2^+	0.155	0.213
2^-	0.693	1.055
3^+	0.149	0.171
3^-	0.017	0.025
total	2.098	3.096

[J. Engel, S. Pittel, & P. Vogel, Phys. Rev. C **50** (1994)]

Motivation for Measuring ^{127}I CC Interactions

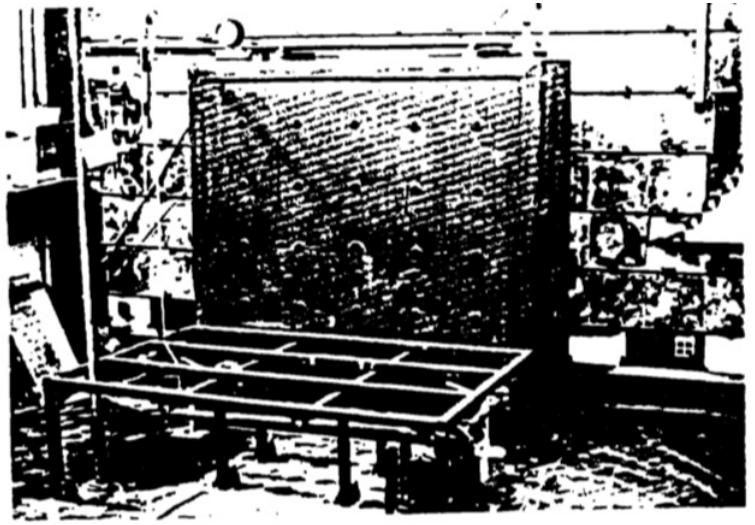
- Exclusive cross section to bound ^{127}Xe measured at LAMPF in the 1990s with radiochemical approach

$$\nu_e + {}^{127}\mathrm{I} \rightarrow e^- + {}^{127}\mathrm{Xe}_{\mathrm{bound}}$$

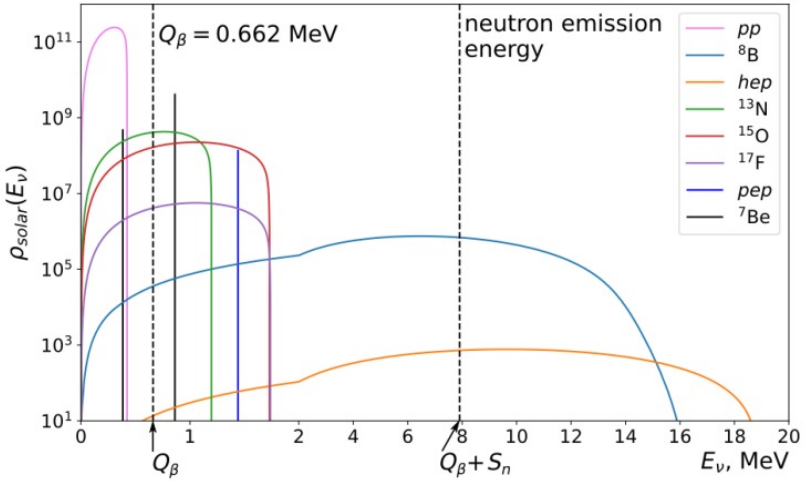
- Reported flux-averaged cross section of

$$\boldsymbol{\sigma = 2.84 \pm 0.91(stat) \pm 0.25(sys) \times 10^{-40}\ \mathrm{cm}^2}$$

  - Only measured cross section to bound states of ^{127}Xe—majority of neutrinos at DAR sources have energy above neutron emission threshold
- Suggested repetition with electronic NaI detector to measure energy-dependence of cross section
- Recently interest in looking at ^{126}Xe/^{127}Xe ratio for comparing ^{7}Be to ^{8}B/HEP neutrinos



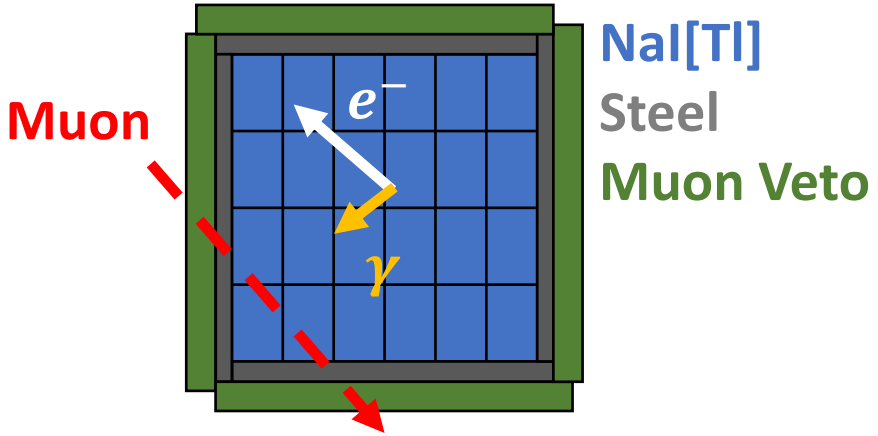
[B. T. Cleveland, et al., 23rd Int. Cosmic Ray Conf. **3** (1993)]



[Y. S. Lutostansky, et al., arXiv:2103.12325 (2021)]

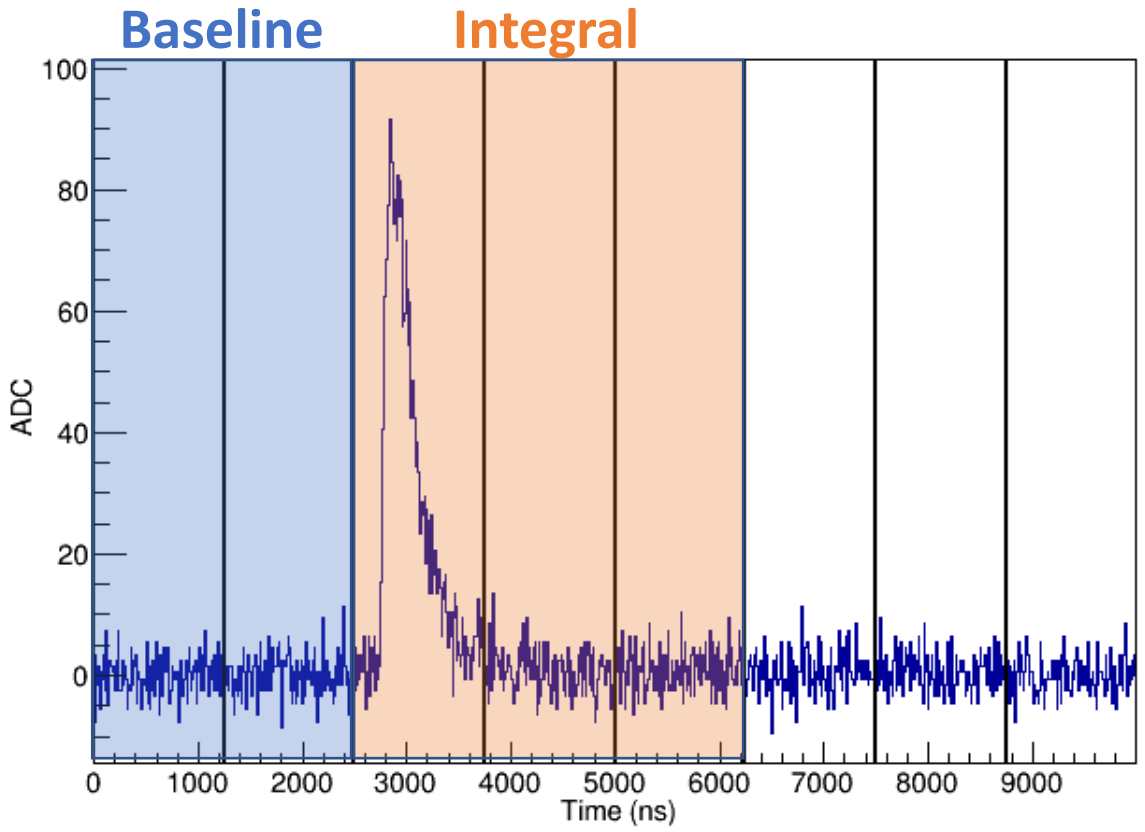
NaIνE-185 Detector

- NaI neutrino Experiment (**NaIνE**) designed to measure the inclusive charged-current cross section, energy-dependence
- Twenty-four 7.7-kg NaI[Tl] scintillator detectors (185-kg mass), deployed 2016
- Signal is “large-energy” (10-55 MeV) depositions in delayed neutrino window
- Muon veto panels to reduce cosmic muons
  - 1.5” steel between NaI and veto panels to avoid vetoing signal
- Detector also used as prototype for ton-scale NaI CEνNS detector



Data Acquisition System

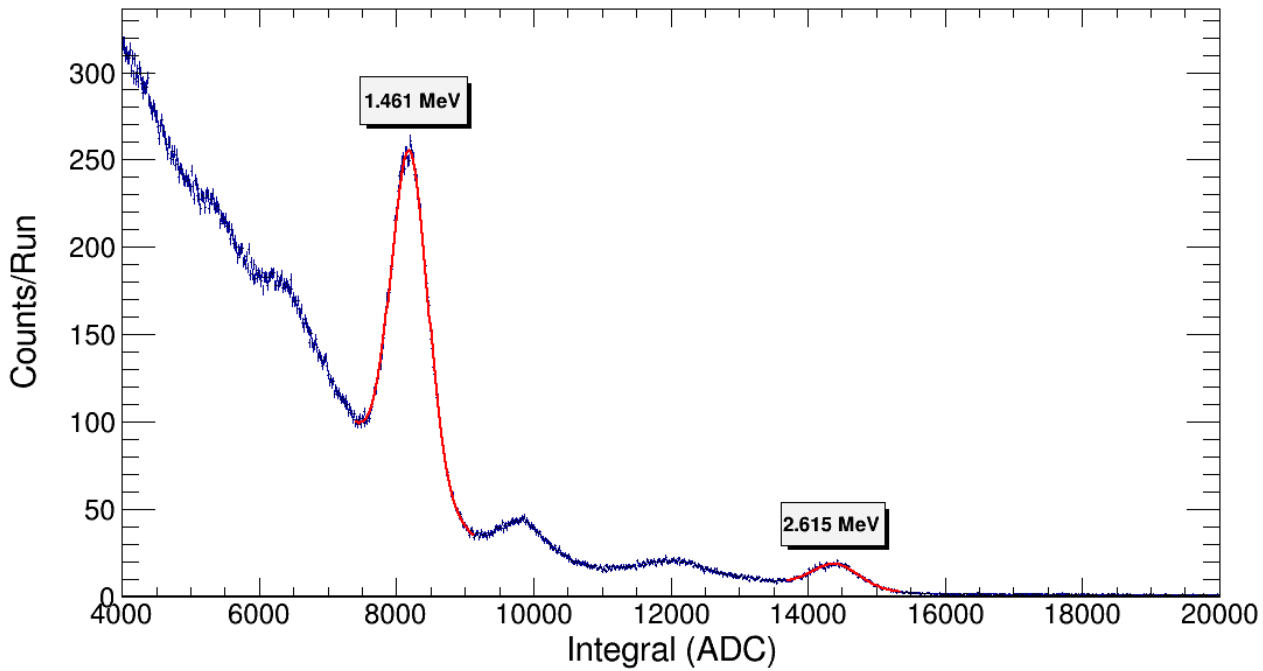
- Detector uses digitizer trigger to record scintillation in any NaI channel above a threshold (500-900 keV)
- Integrated PMT charge recorded in eight timing windows (accumulators) around the pulse to determine baseline, integral
- Muon veto panels, SNS timing pulses trigger independently, timing correlation done in software
  - Data within -2μs to +20μs of SNS timing signal blinded



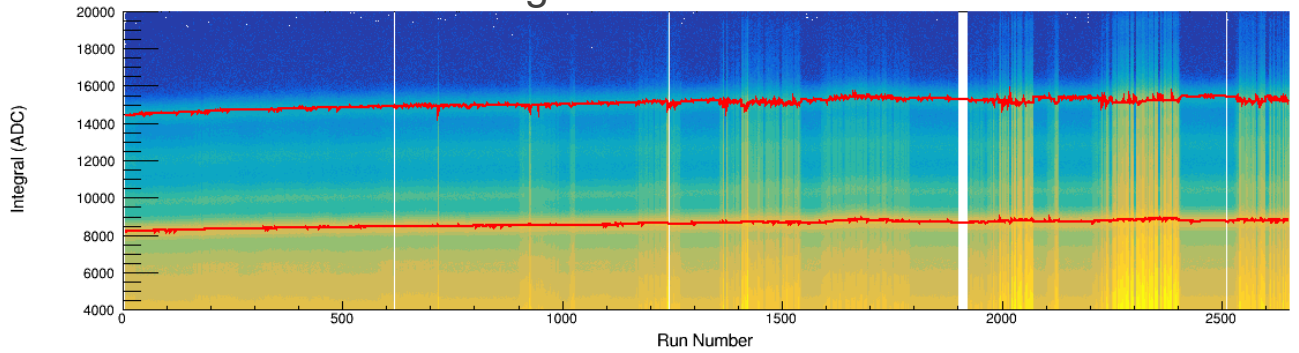
Intrinsic Background Calibrations

- Calibrate each NaI channel based on ^{40}K and ^{208}Tl intrinsic backgrounds
  - Track gain changes over time, measure energy resolution in crystals

Low energy background spectrum from one channel



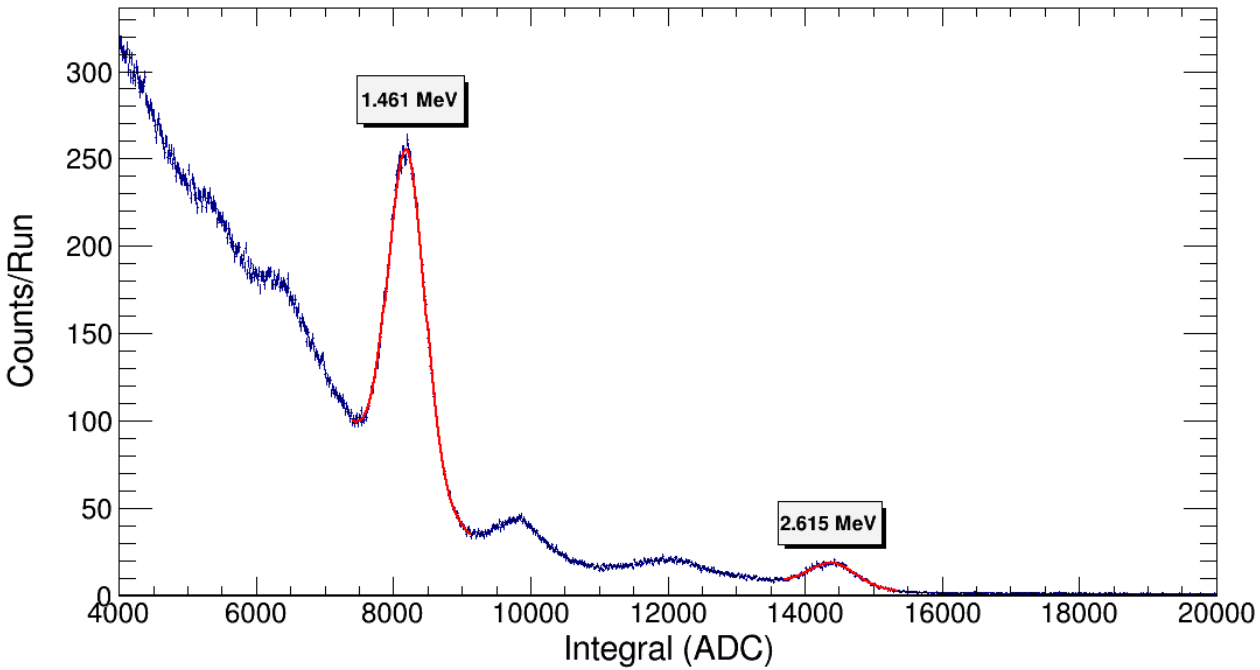
Gain changes over time in one channel



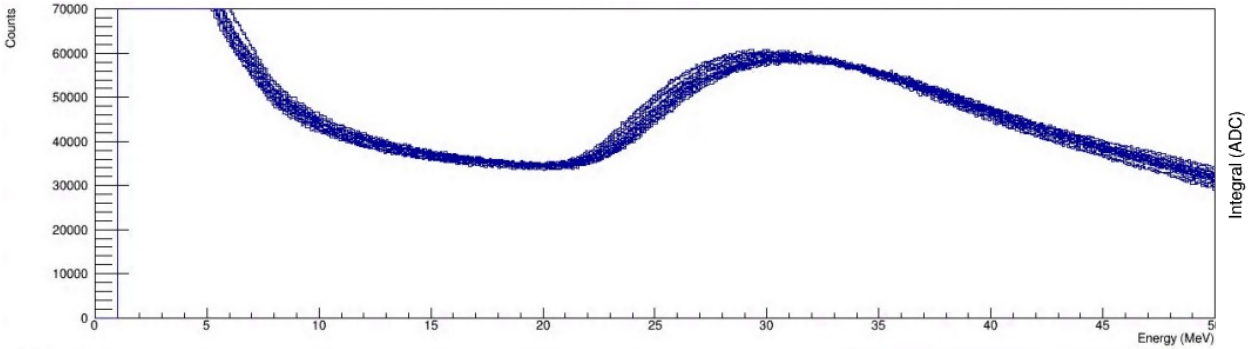
Intrinsic Background Calibrations

- Calibrate each NaI channel based on ^{40}K and ^{208}Tl intrinsic backgrounds
  - Track gain changes over time, measure energy resolution in crystals
- Extending calibration to higher-energies leads to small discrepancies in large energy background (muon) spectrum in each crystal

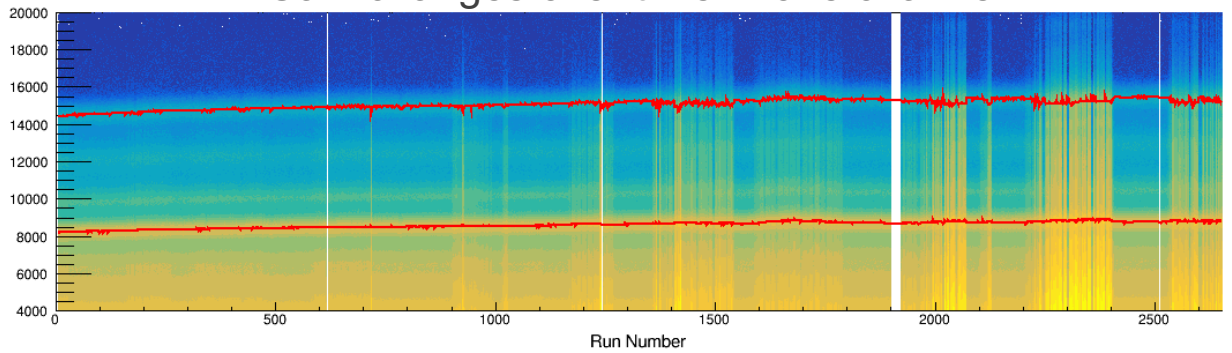
Low energy background spectrum from one channel



Muon spectrum from all 24 channels



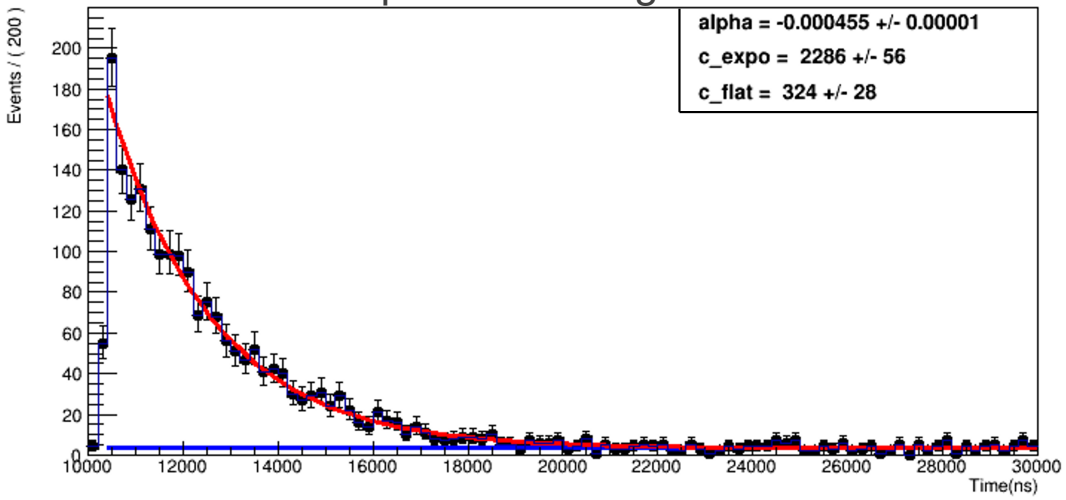
Gain changes over time in one channel



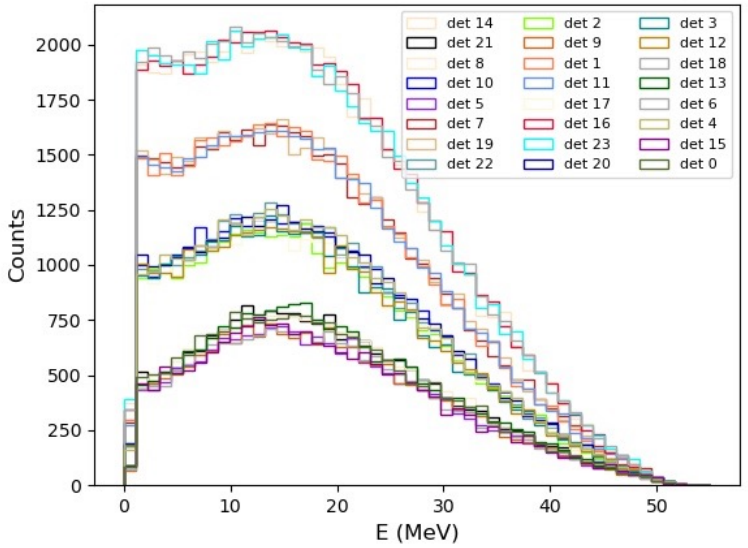
Michel Positron Correction

- Use Michel positrons to correct calibration
- Collect population of Michel events by looking for large energy depositions in crystals after a muon event (tagged with veto panels)
  - Fitting data gives anti-muon mean lifetime of $2.172 \pm 0.024\mu s$
- Simulate positrons in GEANT4, matching data selection criteria
- Fit quadratic calibration function to data that preserves low energy calibrations

Michel positron timing distribution



Simulated Michel positron spectrum in all channels



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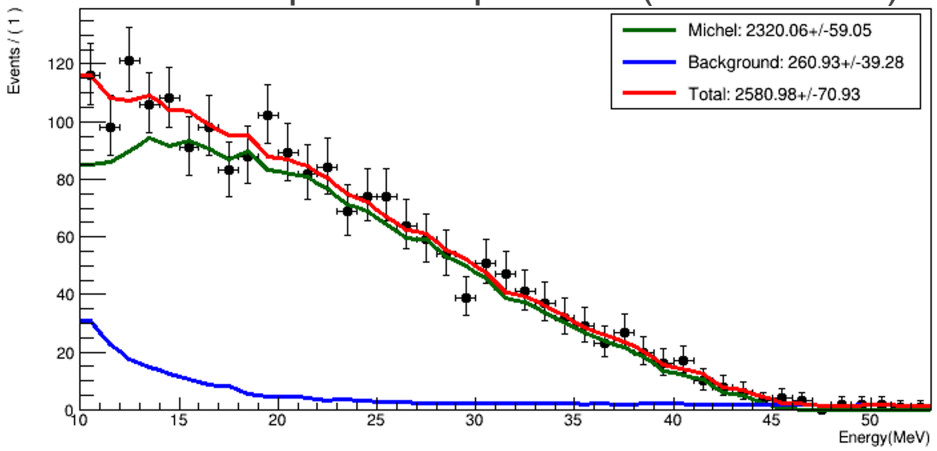
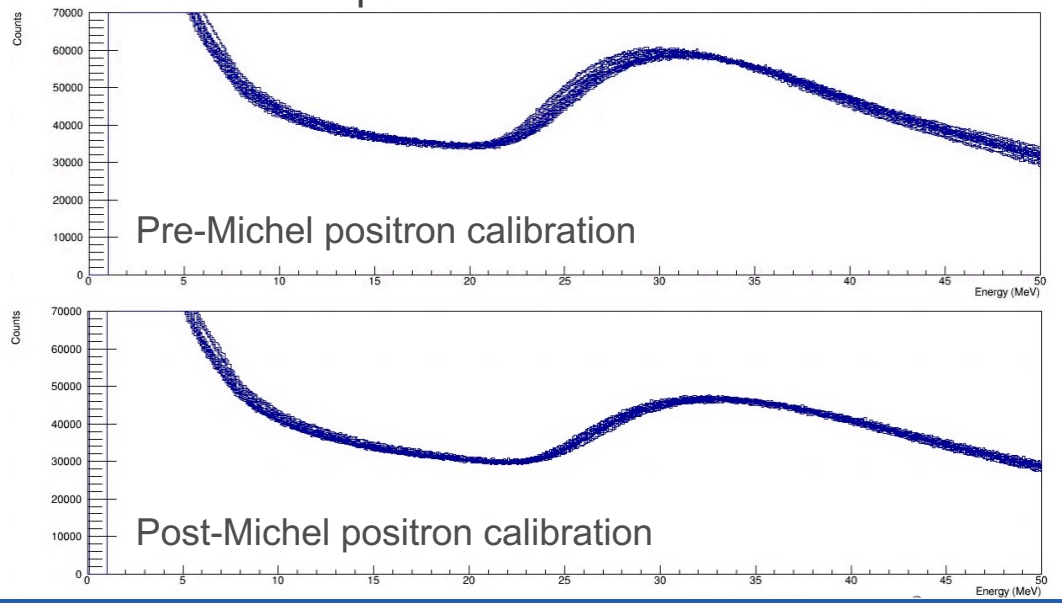
Fit Michel positron spectrum (one channel)

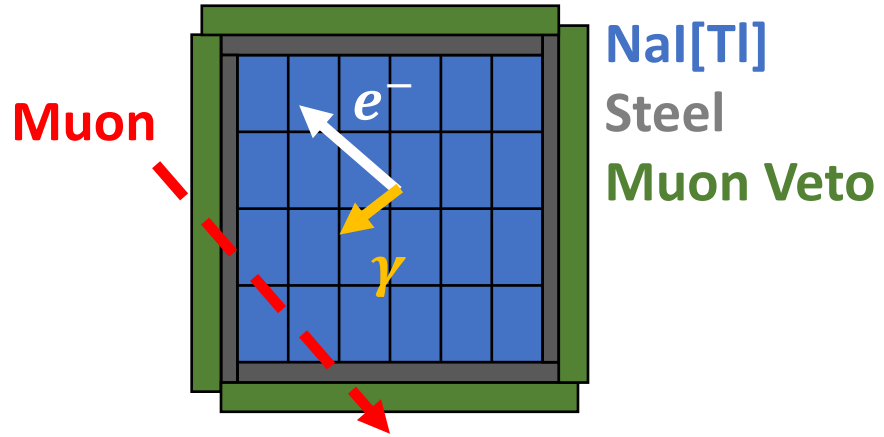


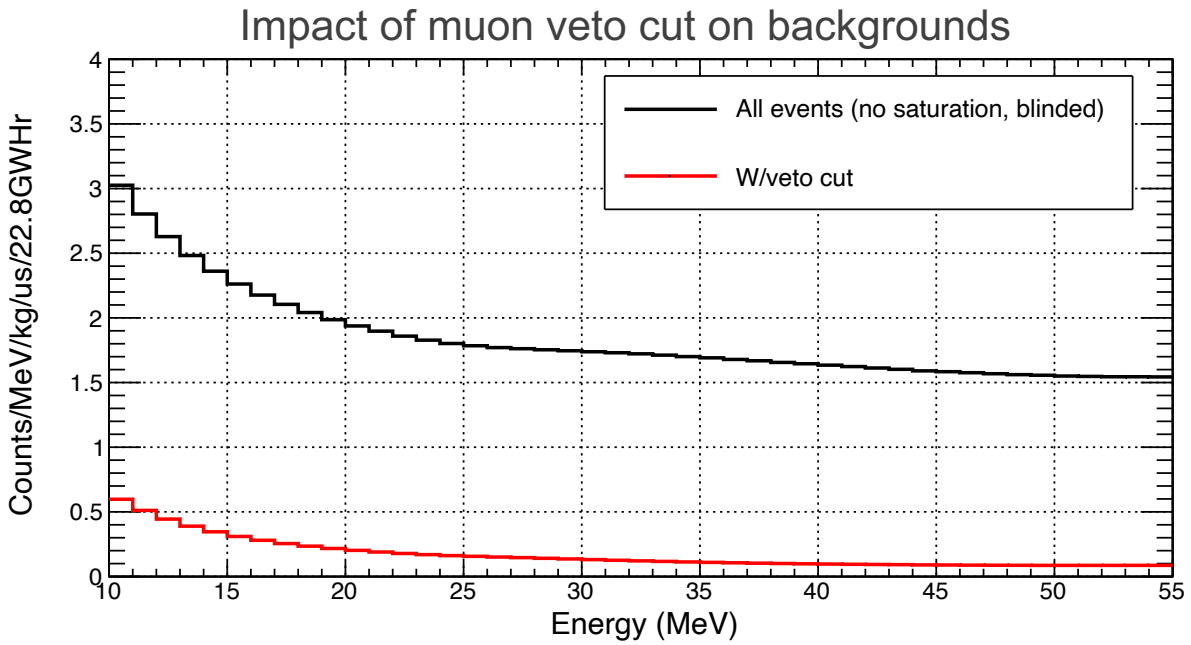
Muon spectrum from all 24 channels



Muon Veto Cut

- Cosmic muons the largest source of backgrounds for charged-current signal
- Tag NaI events close in time to muon veto panel PMT events above threshold
  - 1.5” steel between NaI crystals and veto panels to avoid vetoing signal
  - Systematic incorporated into analysis to account for uncertainty in veto thresholds
- Veto rejects ~93% of cosmic muon backgrounds between 10-55 MeV
  - Additionally benefit from looking in a small (several microsecond) window around SNS timing signal to reduce backgrounds





MARLEY predictions for ^{127}I

- MARLEY handles allowed component of neutrino-nucleus scattering
- Input B(GT$^-$) and B(F) values into MARLEY along with electron neutrino DAR spectrum
- MARLEY outputs cross sections, energies and multiplicities of emitted particles
  - Cross section for lead agrees well with existing theoretical calculations
  - Provides calculations for specific channels
- For ^{127}I, MARLEY charged-current predictions use (p,n) charge-exchange data
- MARLEY's inclusive cross section for DAR neutrinos:

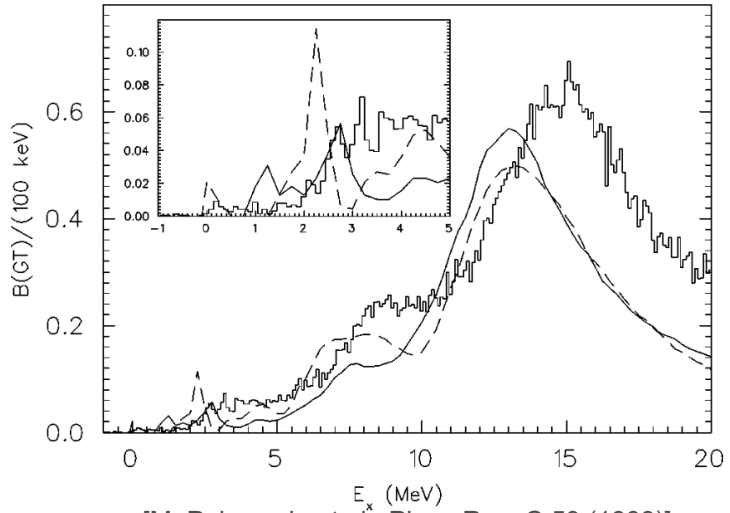
$$22.5^{+1.2}_{-6.5} \times 10^{-40}\ \text{cm}^2$$

  - Uncertainty from B(GT$^-$) normalization uncertainty
- Cross section for exclusive channel to ^{127}Xe$_{bound}$:

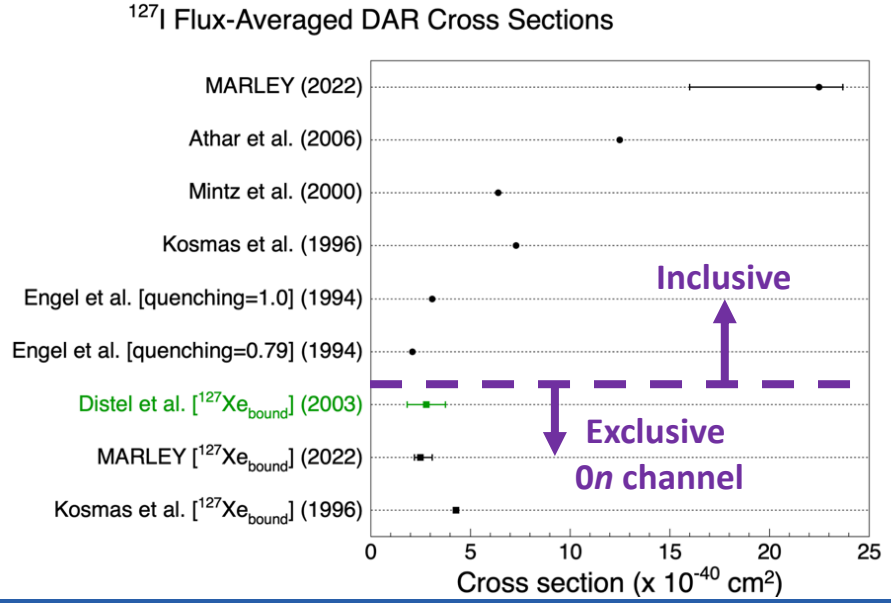
$$2.5^{+0.3}_{-0.6} \times 10^{-40}\ \text{cm}^2$$

  - Good agreement with LAMPF measured value of

$$2.84 \pm 0.91(stat) \pm 0.25(sys) \times 10^{-40}\ \text{cm}^2$$



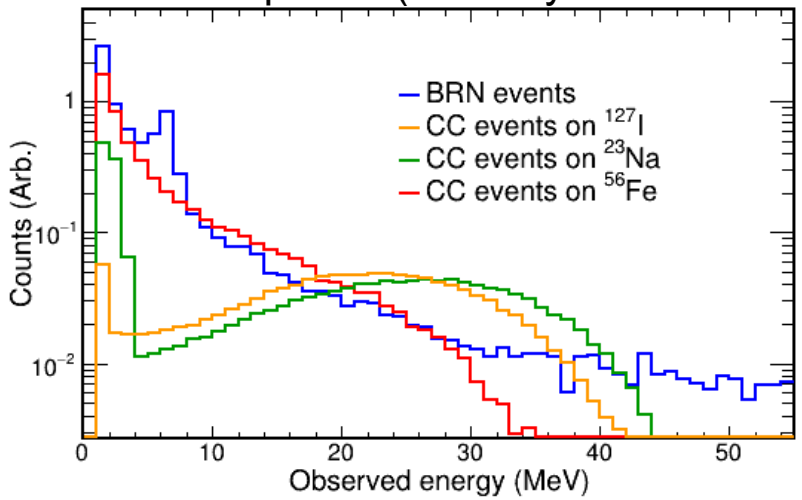
[M. Palarczyk, et al., Phys. Rev. C 59 (1999)]



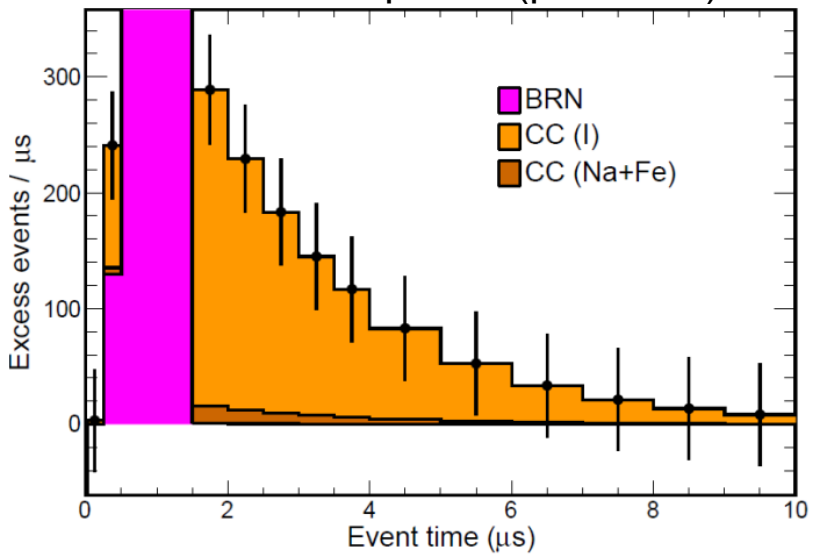
Signal Predictions

- Simulate charged-current events in GEANT4, process matching analysis cuts to arrive at signal predictions
  - Restrict to 10-55 MeV where most of signal expected to reside
    - Above neutron capture energy on ^{23}Na and ^{127}I
  - Expect 1,320 CC events on ^{127}I
  - ~61 events from CC on sodium, iron shielding
- Three main results:
  - Inclusive cross-section: 1D fit in time, 10-55 MeV
  - Spectrum of charged-current events: 1D fits in time in 5 MeV energy bins
  - 0n vs. ≥1n exclusive cross sections: highest energy events not associated with neutron production (~8 MeV threshold)

Simulated spectra (arbitrary normalization)



Simulated spectra (predicted)

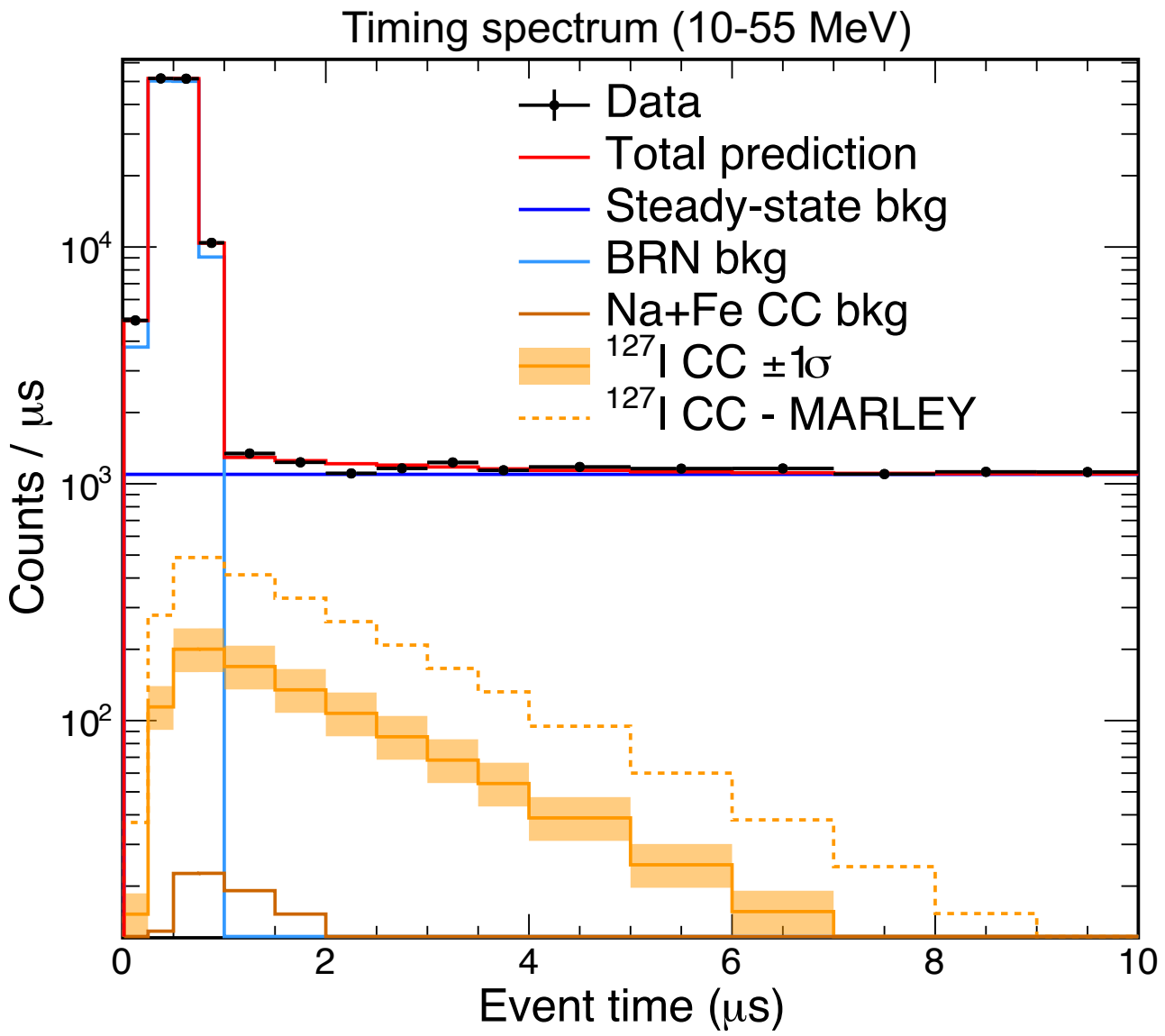


Results: Inclusive Cross Section

- Best fit gives 541^{+121}_{-108} events
  - 5.8σ evidence of CC events
  - χ^2 of 13.1, 12 d.o.f.
- Corresponds to cross section of

$$\mathbf{9.2^{+2.1}_{-1.8} \times 10^{-40}\ cm^2}$$

  - 40.9% theoretical cross section



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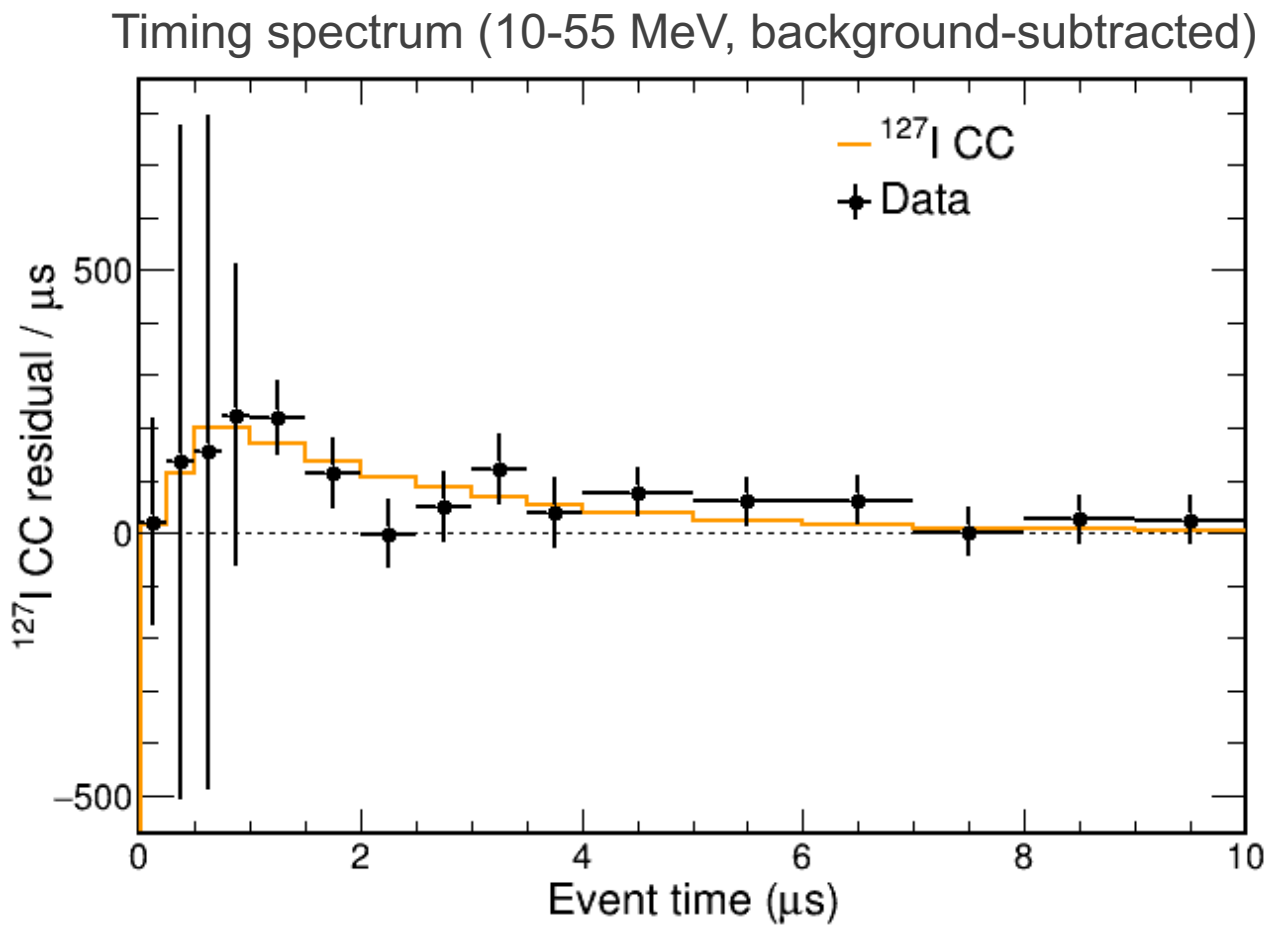
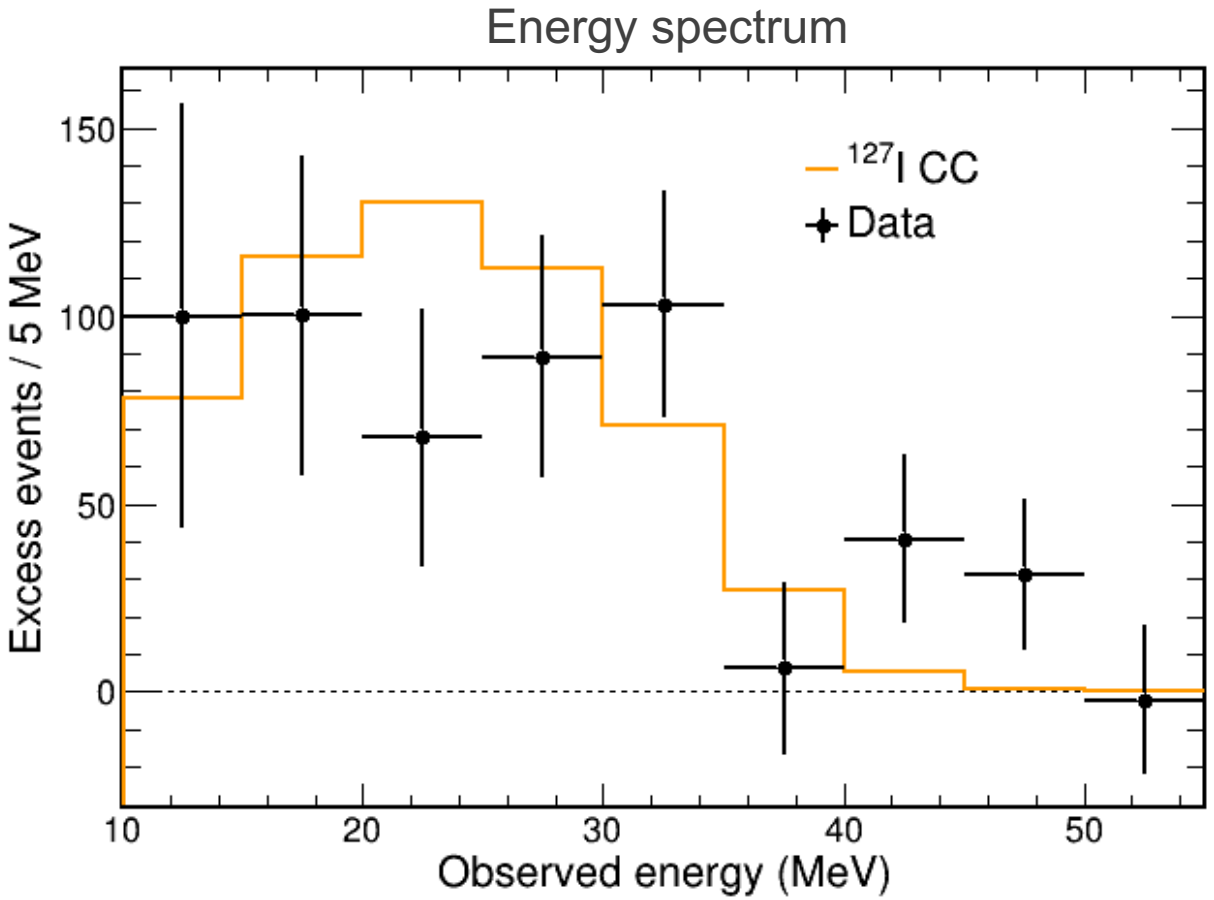
  - 40.9% theoretical cross section
- Subtract off steady-state, BRN backgrounds to form signal residuals for 1D timing fit across 10-55 MeV range



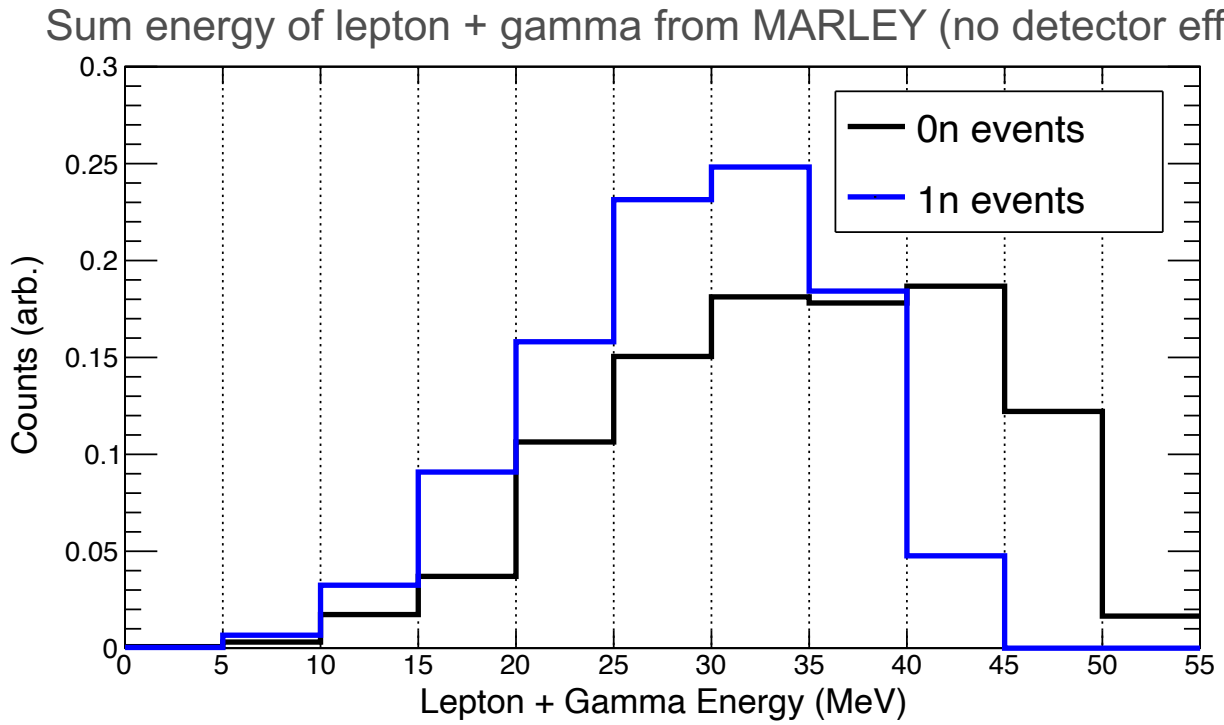
Results: ^{127}I Charged-Current Spectrum

- Fit 1D timing spectrum in 5 MeV bins from 10-55 MeV to generate an energy spectrum
  - In each bin, independent fits to timing to estimate BRN and CC amplitudes
- Does not show great agreement with theoretical model, but two caveats
  - Large error bars on due to low statistics
  - Forbidden transitions not incorporated in predictions



Result: 0*n* vs. ≥1*n* Cross Sections

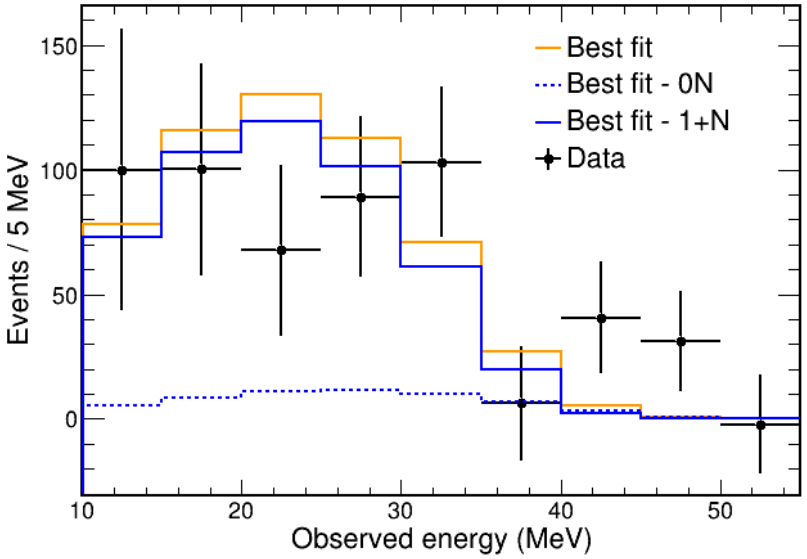
- Different spectrum of visible energy (gammas + lepton) for events with neutron emission (≥1*n*) compared to those without (0*n*)
  - Threshold for ≥1*n* emission events is 7.9 MeV compared to 0*n* threshold of 0.7 MeV
  - Plot intended to demonstrate difference in spectral shape, amplitudes arbitrary



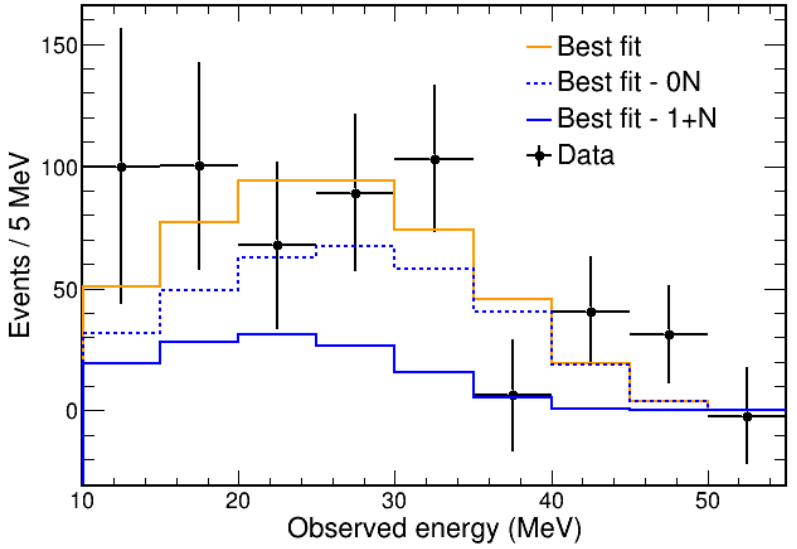
Result: 0 vs. ≥1*n* Cross Sections

- After simulating events in detector geometry, 2D fit in energy and time allowing 0*n* and ≥1*n* amplitudes to float freely
- MARLEY predicts 10.6% events are 0*n*, data favors larger fraction (72.3%) of events are 0*n*
- 0*n* cross section: $\mathbf{5.2^{+3.4}_{-3.1} \times 10^{-40} cm^2}$
  - Compare to LAMPF measured value: $\mathbf{2.84 \pm 0.91(stat) \pm 0.25(sys) \times 10^{-40}\ cm^2}$
- ≥1*n* cross section: $\mathbf{2.4^{+3.3}_{-2.4} \times 10^{-40} cm^2}$

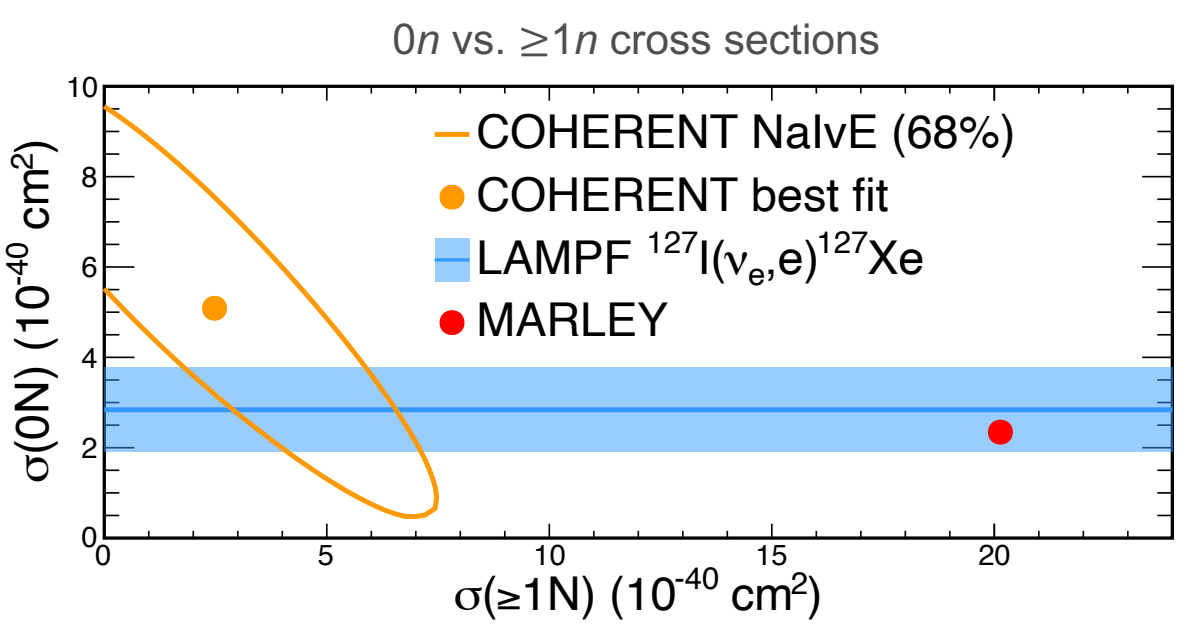
Nominal MARLEY prediction: 10.6% 0*n* events

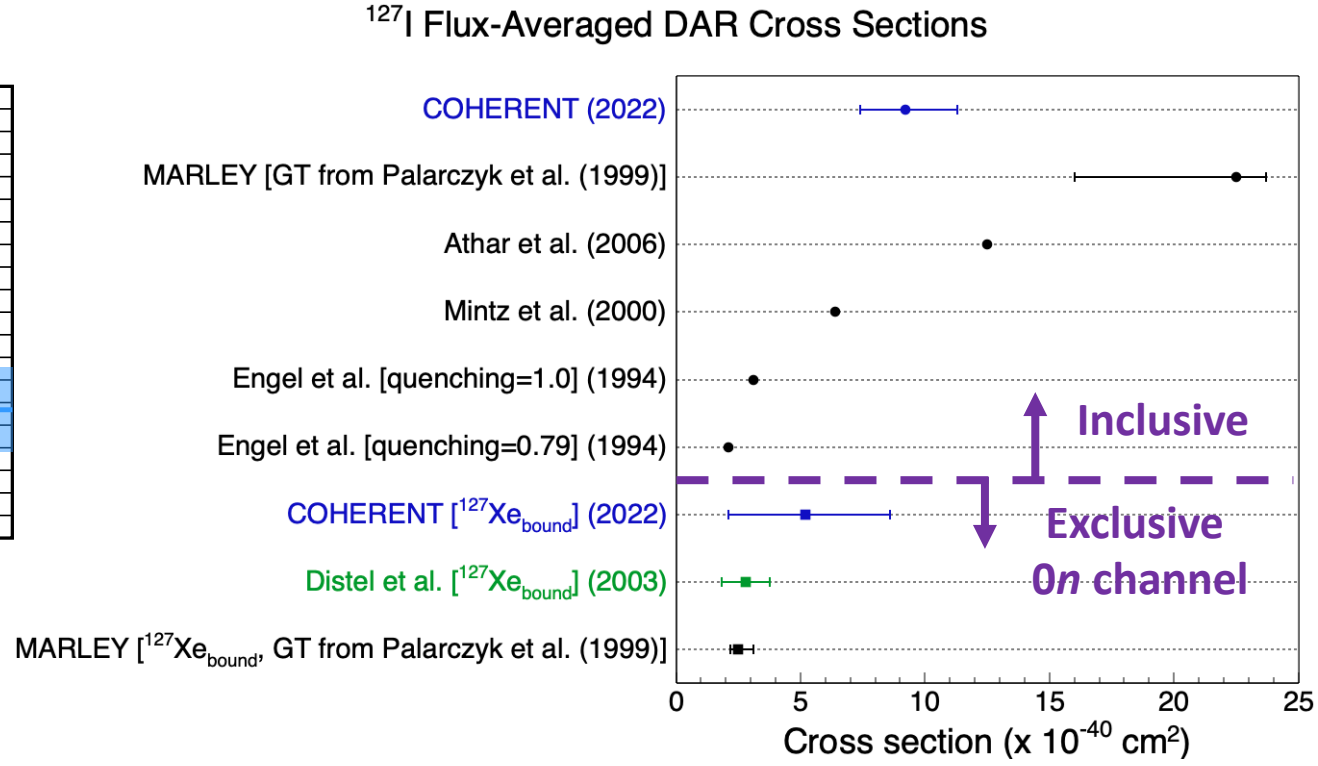


Best fit value: 72.3% 0*n* events



Comparison of Results





NaIνE: Summary

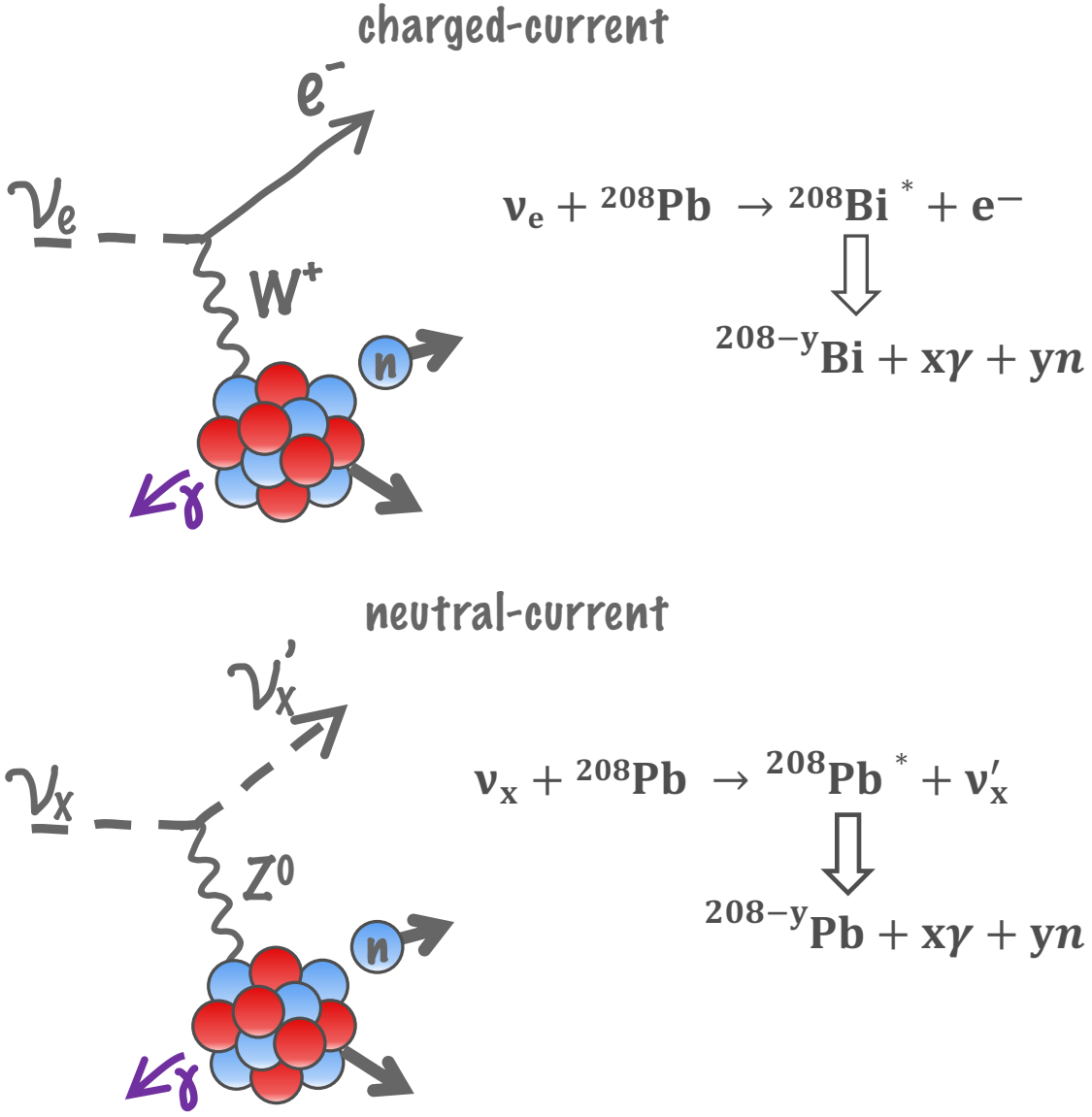
- The COHRENET NaIνE detector has observed electron neutrino charged-current interactions on ^{127}I at the SNS
  - Flux-weighted cross section smaller than predicted by MARLEY model
  - Exclusive $\geq 1n$ emission channel appears to be most of the source of the suppression
  - $0n$ emission channel consistent with MARLEY, LAMPF result
- Detector still collecting data in Neutrino Alley
- Future work:
  - Some existing work using machine-learning to reject muons, better understand signal topology
  - May be possible to look for other CC processes (^{23}Na, ^{27}Al)
    - Smaller cross section, but potential for detecting delated β^+ from ^{23}Mg decay
  - Will eventually be replaced by NaIνETe, a factor of ~13+ bigger

Neutrino-induced Neutrons on Lead

$$\nu_e + {}^{208}\mathrm{Pb} \longrightarrow e^- + {}^{208-\mathrm{x}}\mathrm{Bi} + \mathrm{x}n$$

Motivation for Measuring Neutrino-Induced Neutrons (NINs)

- Neutrino interactions in shielding (mostly lead) of COHERENT's detectors could present beam-related background
  - Neutrino interactions can generate excited nuclei that de-excite by emitting neutrons
  - Produced neutrons follow the timing distribution of the neutrinos, and can produce low energy nuclear recoils in detectors



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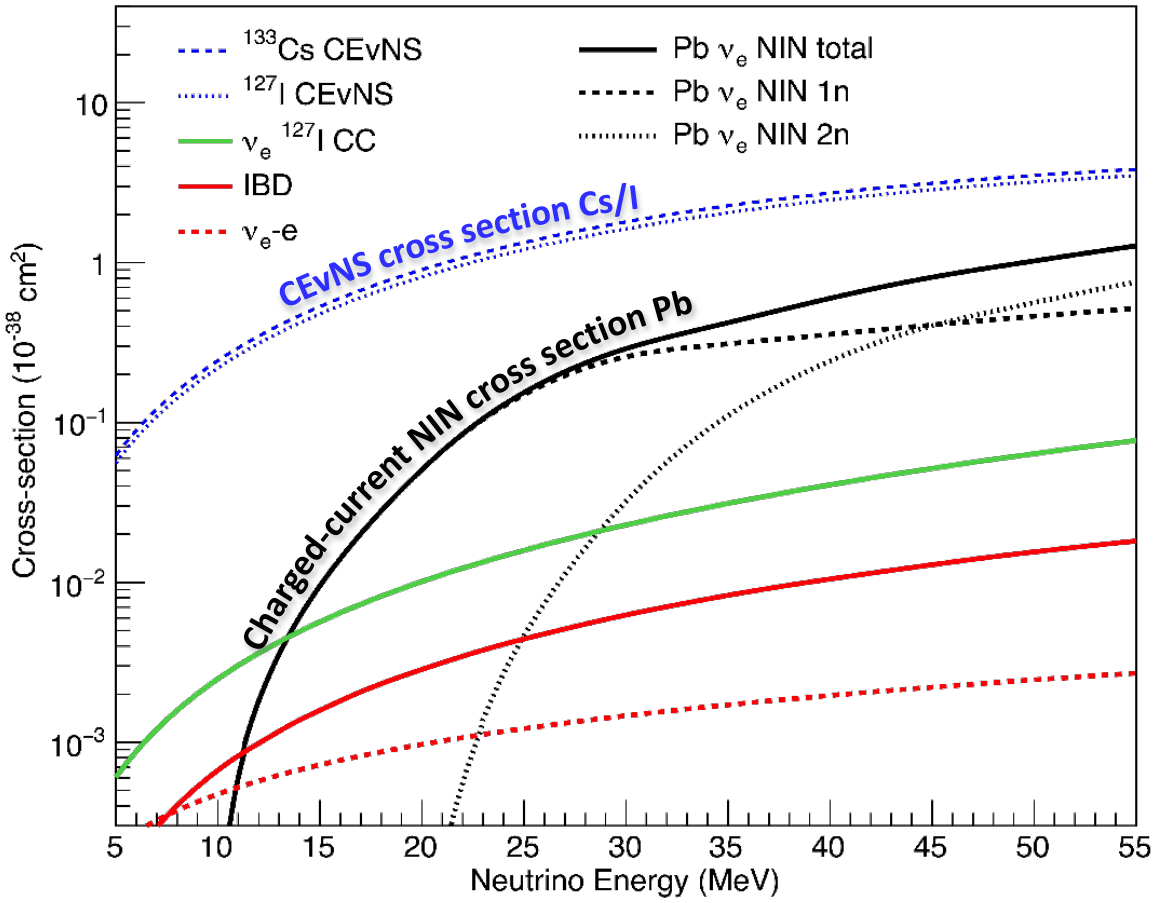

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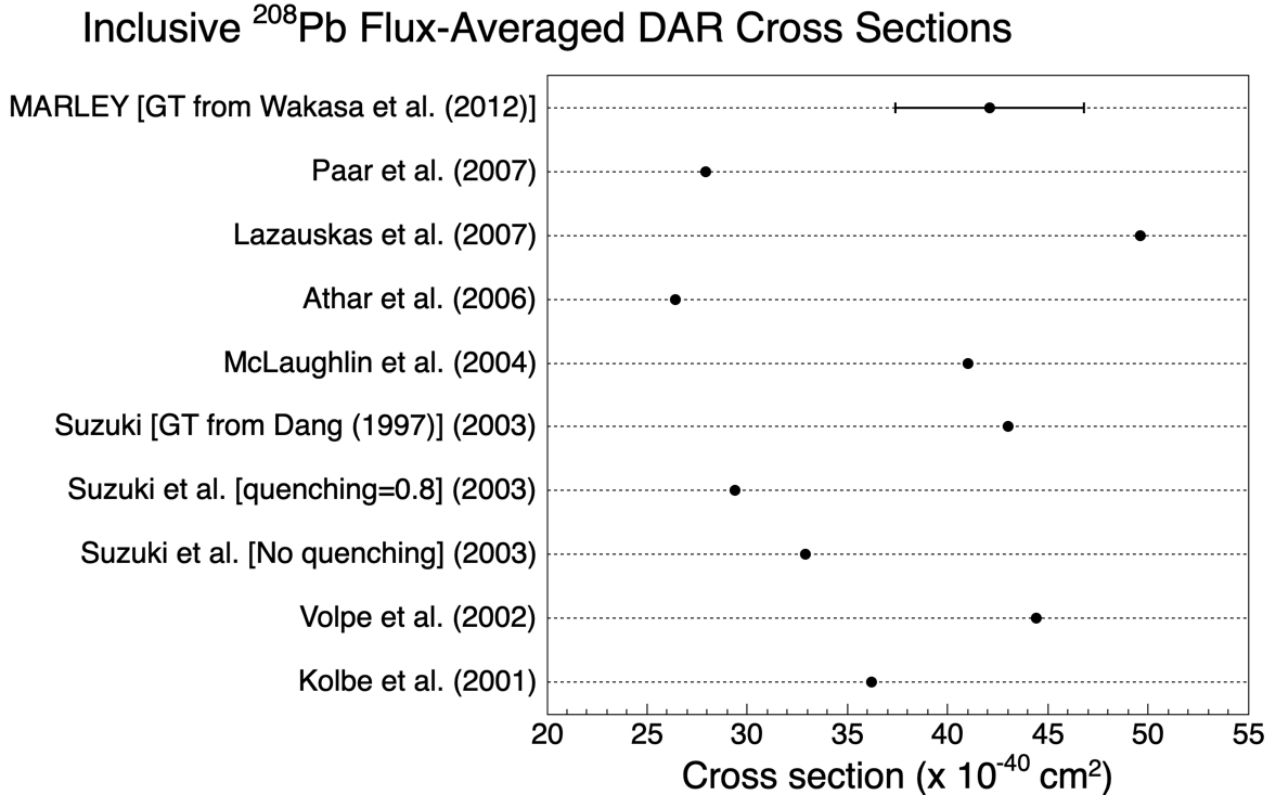

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  - Variations in calculations
  - Much greater mass of shielding than CEνNS detectors themselves

CEνNS Target	Shielding
14.6 kg CsI[Na]	2,200 kg lead
24 kg liquid argon	11,000 kg lead
16 kg Ge	3,400 kg lead
2,425 kg NaI	17,000 kg iron and lead

Motivation for Measuring Neutrino-Induced Neutrons (NINs)

- Neutrino interactions in shielding (mostly lead) of COHERENT's detectors could present beam-related background
  - Neutrino interactions can generate excited nuclei that de-excite by emitting neutrons
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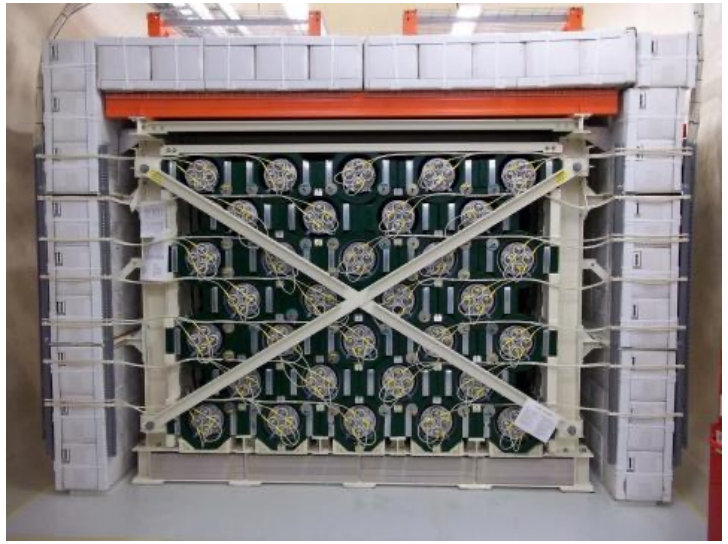
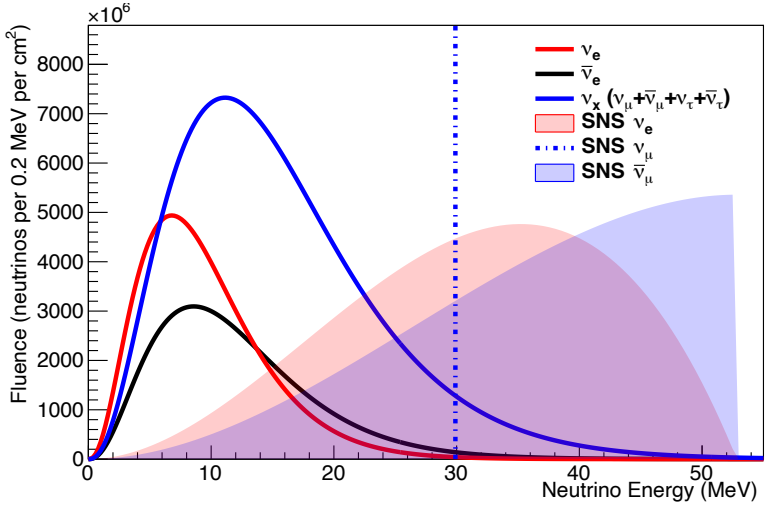
- Cross section expected to be lower than CEνNS, but previously unmeasured
  - Variations in calculations
  - Much greater mass of shielding than CEνNS detectors themselves
- Primary mechanism for HALO to detect supernova neutrinos



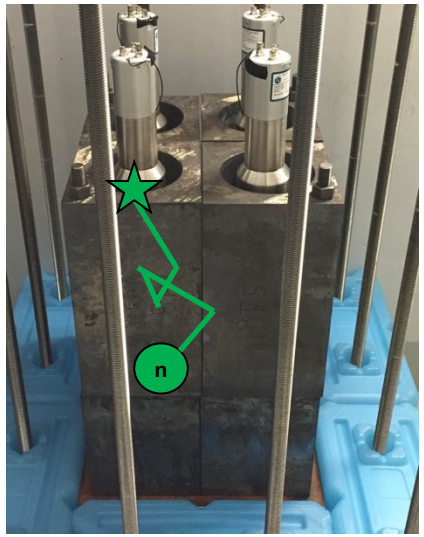
[https://www.triumf.ca/research-highlights/experimental-result/halo-operational-snolab]



[image courtesy of K. Scholberg]

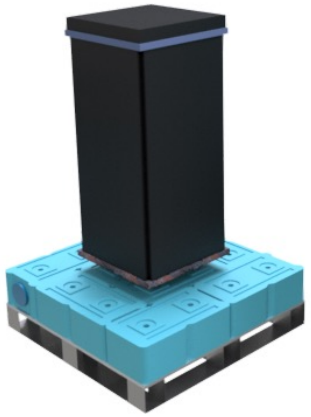
The Lead Neutrino Cube

- 900-kg lead target, 18.9m from SNS target, cavities for liquid scintillator detectors
- NINs produced in lead have small but non-zero efficiency to make their way to LS cells, identified as neutrons using PSD
- Muon veto panels surround targets to reject muon-induced neutrons
- Water shielding reduces steady-state, beam-related neutrons
- Focus on delayed neutrino window, CC cross section expected to be larger than NC, free of prompt beam-related neutron (BRN) background



LS detectors
Pb target

Muon veto panels
Water shielding

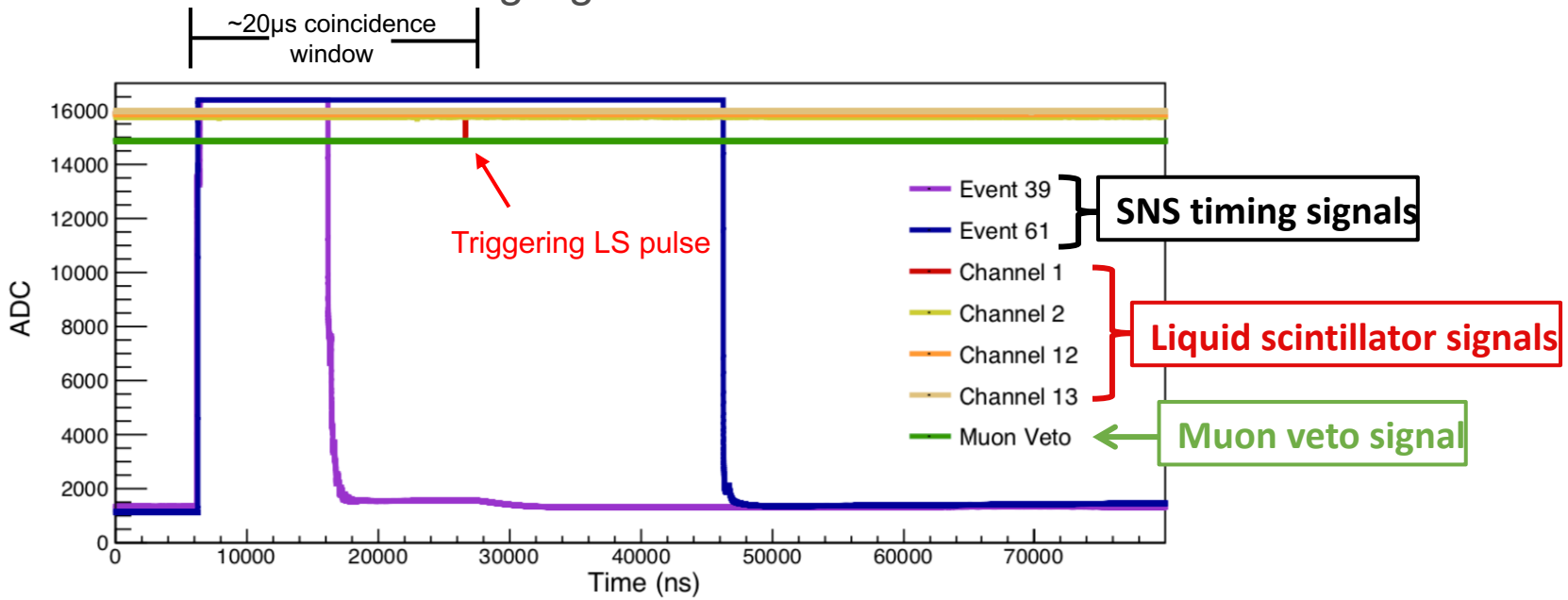


Detector Operation

- DAQ triggers on coincidences between SNS timing signals and liquid scintillator pulses in ~20μs window, record all channels when coincidence observed
- Find onset of LS pulses, integrate for 400ns to determine energy, integrate tail of pulse for PSD

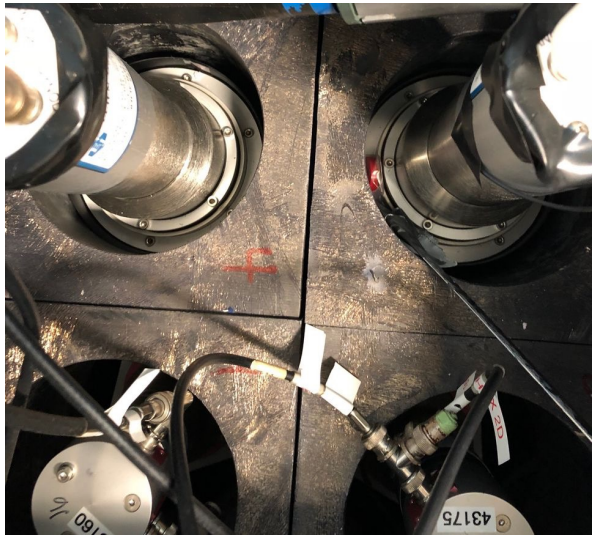
$$\mathrm{PSD} = \frac{\text{tail integral}}{\text{full integral}}$$

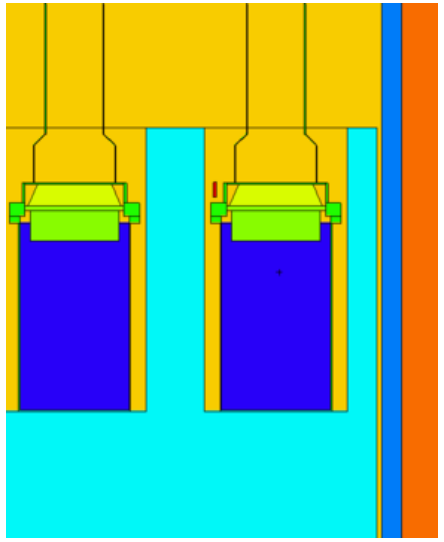
  - Dedicated gamma calibrations to set energy scale of events, neutron calibrations to optimize PSD & develop cuts
- Correlate liquid scintillator pulses with SNS timing signal, veto in software
- Events within a 14μs window around the SNS timing signal blinded



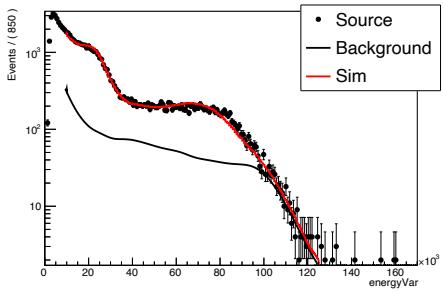
Gamma Calibrations

- Gamma calibrations necessary to understand energy scale
- Calibrated with gamma sources (^{60}Co, ^{22}Na, ^{137}Cs, ^{133}Ba) several times throughout lifetime
- Source and detector simulated in MCNP, fit to data allowing energy-resolution and ADC-to-keV calibration parameters to float

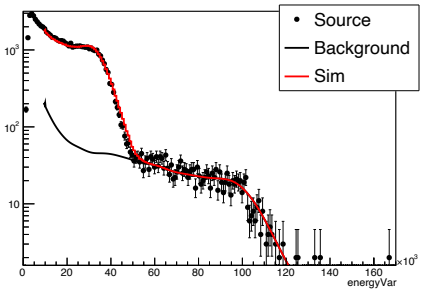




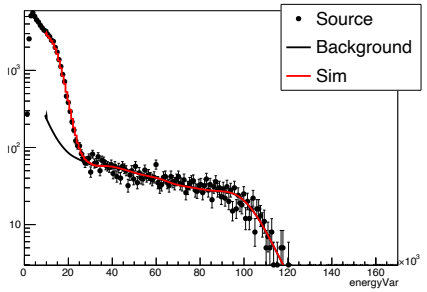
^{22}Na



^{137}Cs



^{133}Ba



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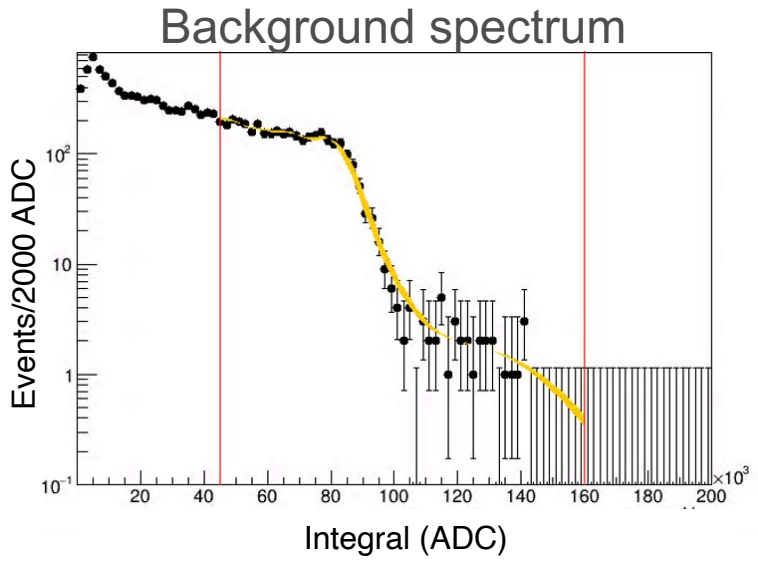
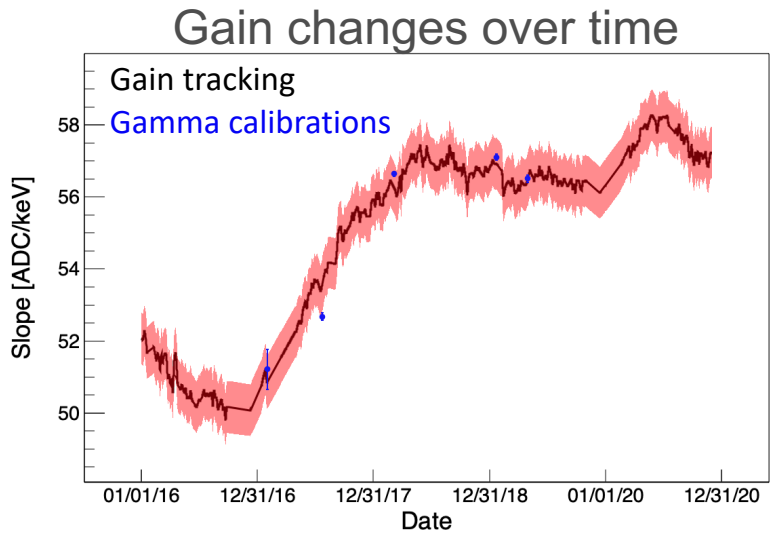
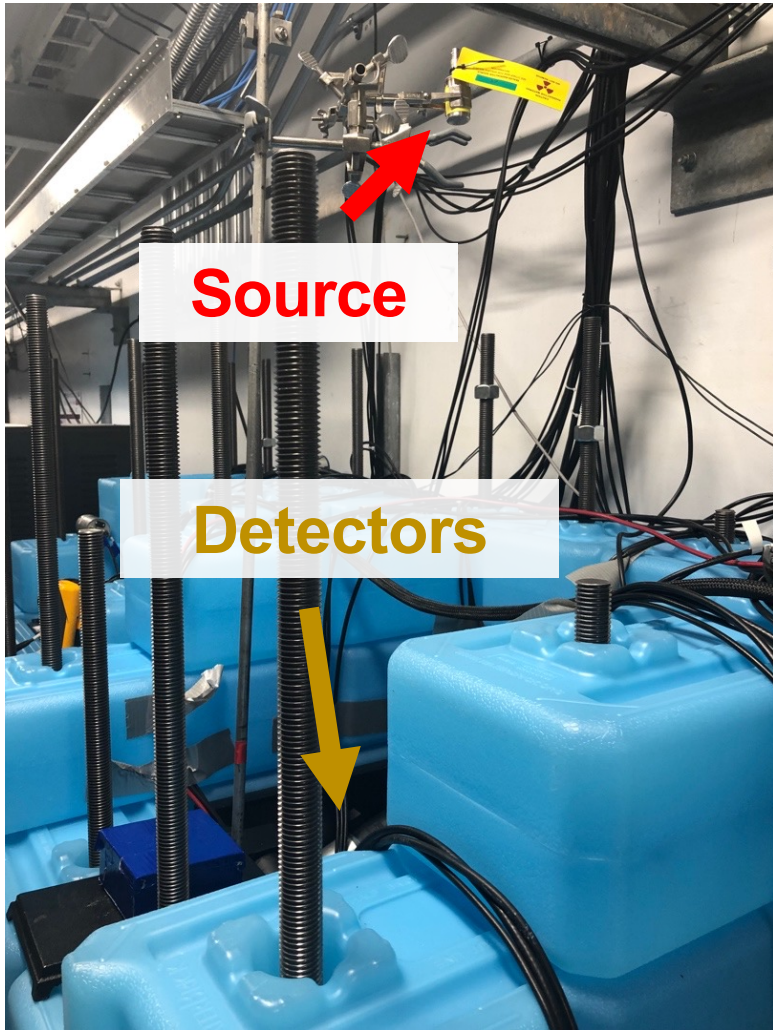
- Source and detector simulated in MCNP, fit to data allowing energy-resolution and ADC-to-keV calibration parameters to float
- Between calibrations, background spectrum fit (largely due to ^{40}K) to track gain on shorter time scales





Neutron Calibrations

- *in-situ* run with time-tagged ^{252}Cf neutron source to understand thresholds, PSD
- Time-tagged signal replaced SNS timing signal in DAQ, shielding removed to expose detectors to source, otherwise identical to running configuration



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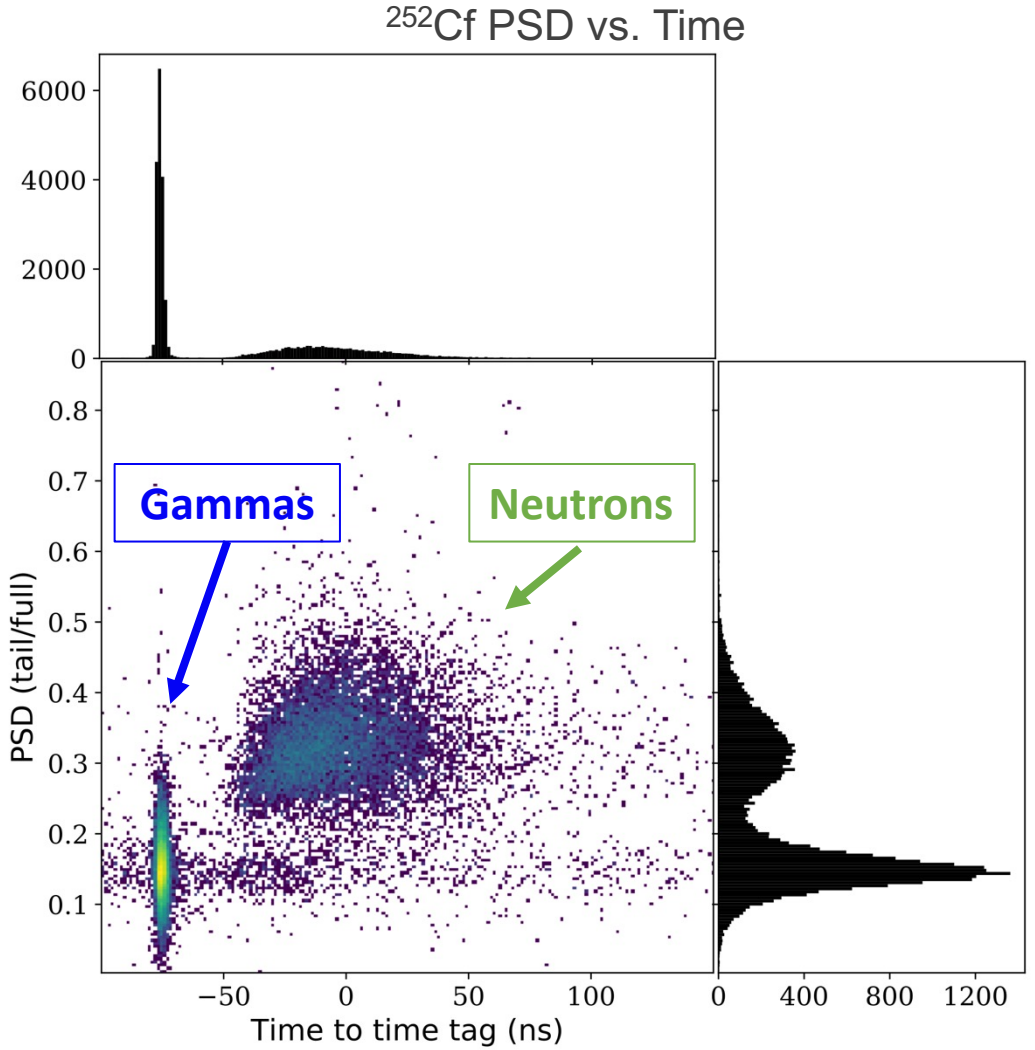
- Produced clean population of gammas, neutrons for understanding thresholds, optimizing PSD parameter



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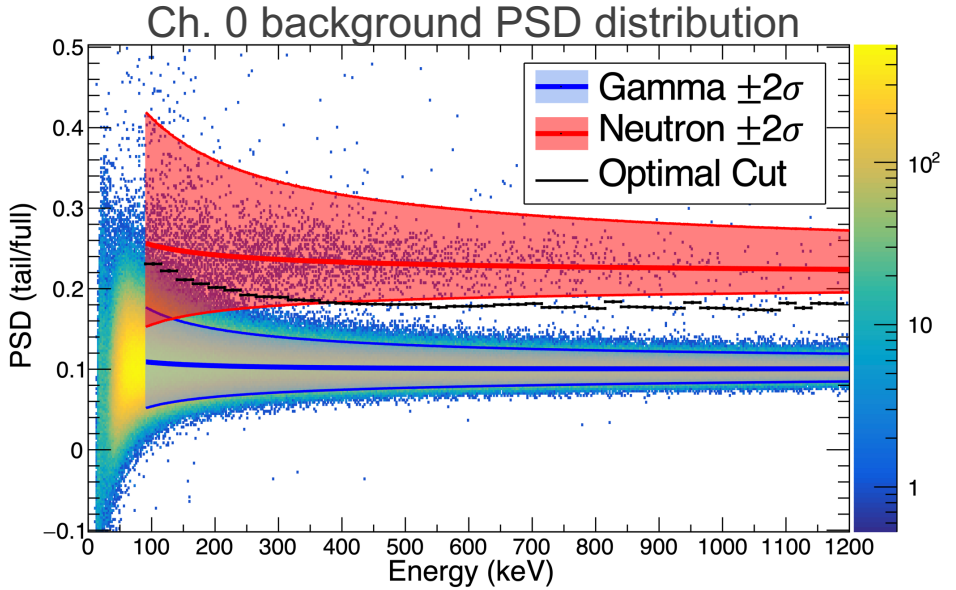
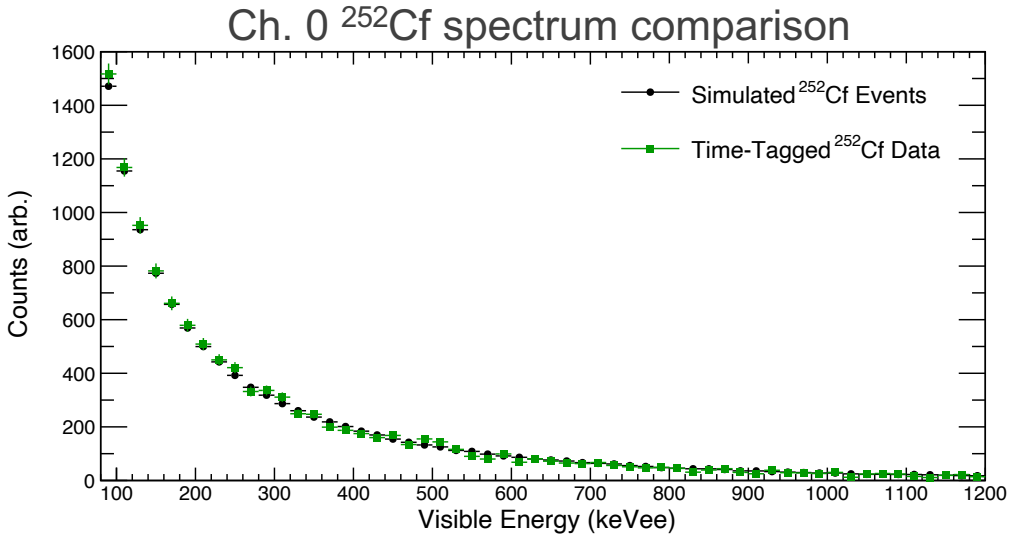
- Time-tagged signal replaced SNS timing signal in DAQ, shielding removed to expose detectors to source, otherwise identical to running configuration
- Produced clean population of gammas, neutrons for understanding thresholds, optimizing PSD parameter
- Develop neutron PSD cut
- Compare data to simulation to ensure we understand energy response





MARLEY for ^{208}Pb

- For ^{208}Pb, use (p,n) charge exchange data for B(GT) strengths

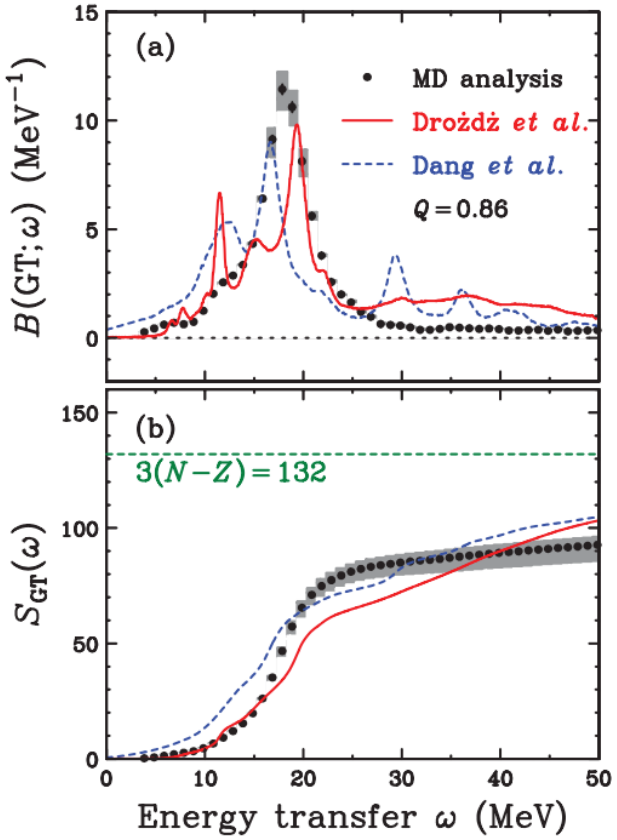
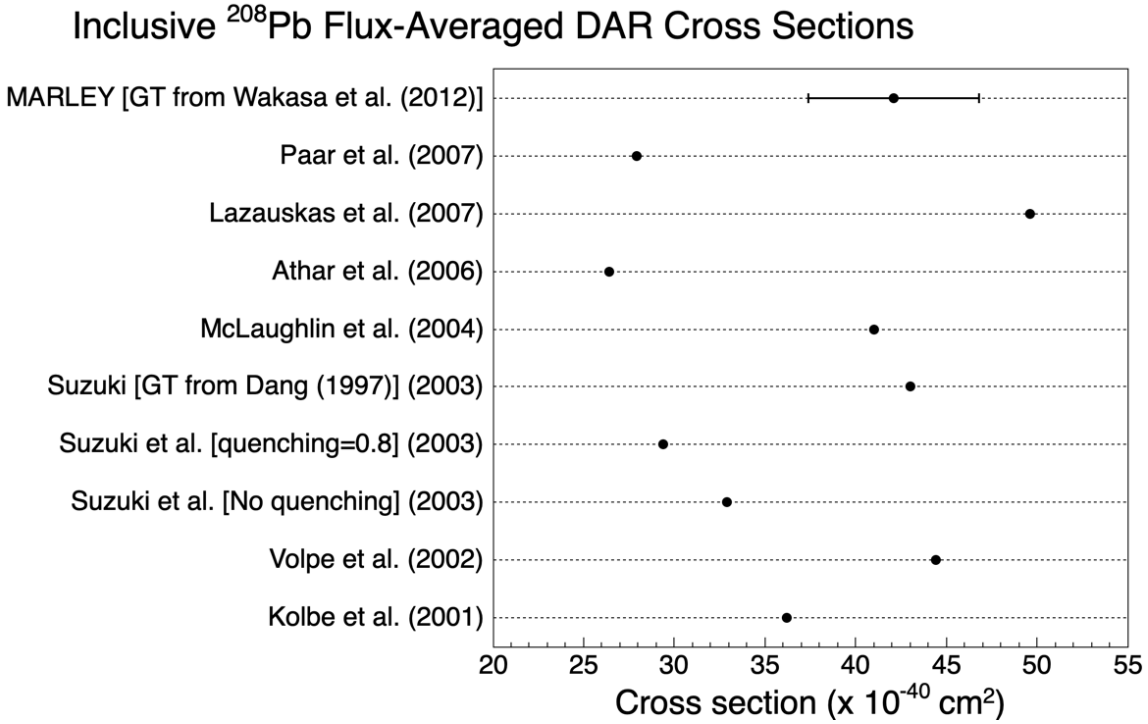


FIG. 16. (Color online) (a) The GT strength $B(\mathrm{GT};\omega)$ and (b) its integrated $S_{\mathrm{GT}}(\omega)$ distributions obtained by MD analysis of the $^{208}\mathrm{Pb}(p,n)$ reaction. The bands represent the uncertainties arising from the selection of α in Eq. (18). The solid and dashed curves are the theoretical predictions reported by Drożdż *et al.* [18] and Dang *et al.* [62], respectively, with a quenching factor $Q = 0.86$ [13].

[T. Wakasa, et al., Phys Rev. C **85** (2012)]

MARLEY for ^{208}Pb

- For ^{208}Pb, use (p,n) charge exchange data for B(GT) strengths
- MARLEY prediction agrees well with other results for inclusive cross section
  - Additionally gives predictions for exclusive charged-current cross sections

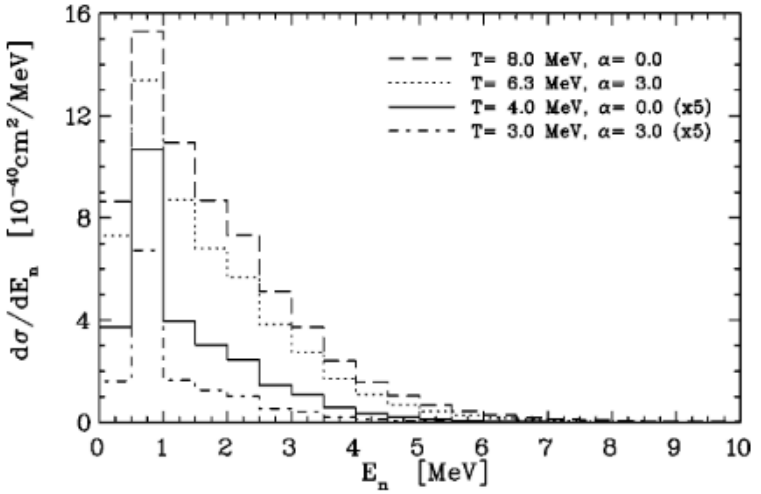


Channel	Cross section ($\times 10^{-40}$cm^2)
$^{208}\mathrm{Pb}(\nu_e, X)$	42.1
$^{208}\mathrm{Pb}(\nu_e, e^- + n)^{207}\mathrm{Bi}$	31.6
$^{208}\mathrm{Pb}(\nu_e, e^- + 2n)^{206}\mathrm{Bi}$	7.7
$^{208}\mathrm{Pb}(\nu_e, e^- + 3n)^{205}\mathrm{Bi}$	0.4

MARLEY for ^{208}Pb

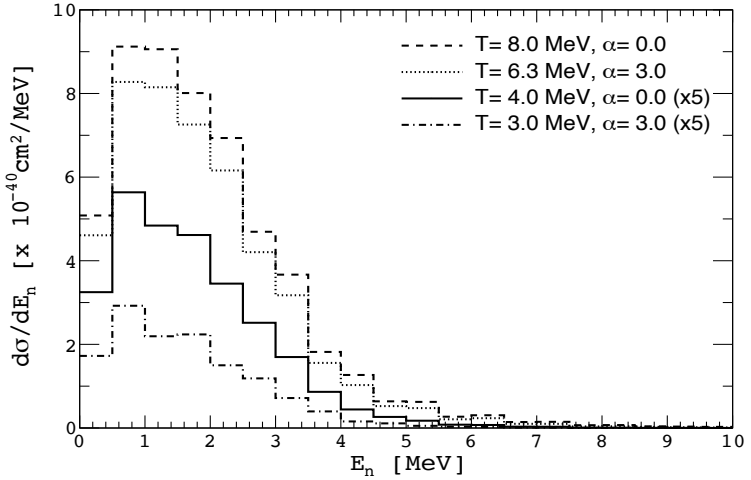
- For ^{208}Pb, use (p,n) charge exchange data for B(GT) strengths
- MARLEY prediction agrees well with other results for inclusive cross section
  - Additionally gives predictions for exclusive charged-current cross sections
- Similar neutron energy spectrum as E. Kolbe & K. Langanke, Phys. Rev. C **64** (2001) for supernova neutrinos
  - No published neutron spectrum from DAR neutrinos w/o MARLEY

Kolbe & Langanke (2001)



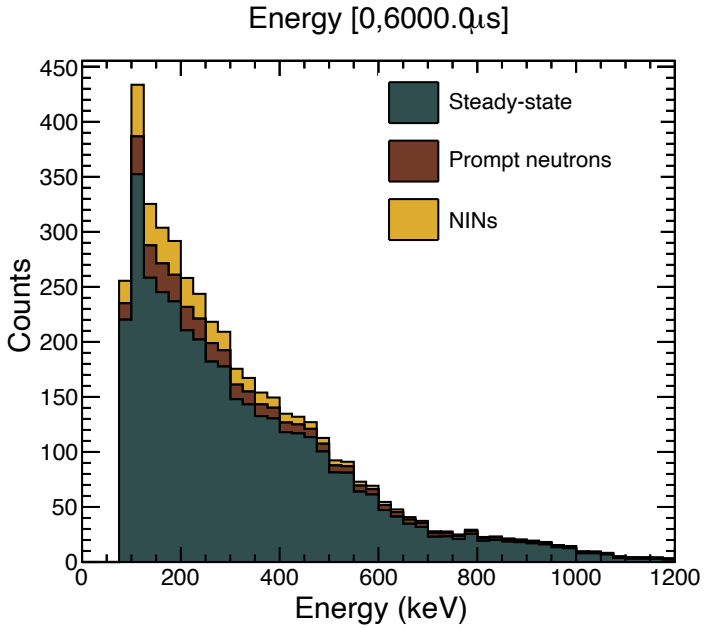
[E. Kolbe & K. Langanke, Phys. Rev. C **64** (2001)]

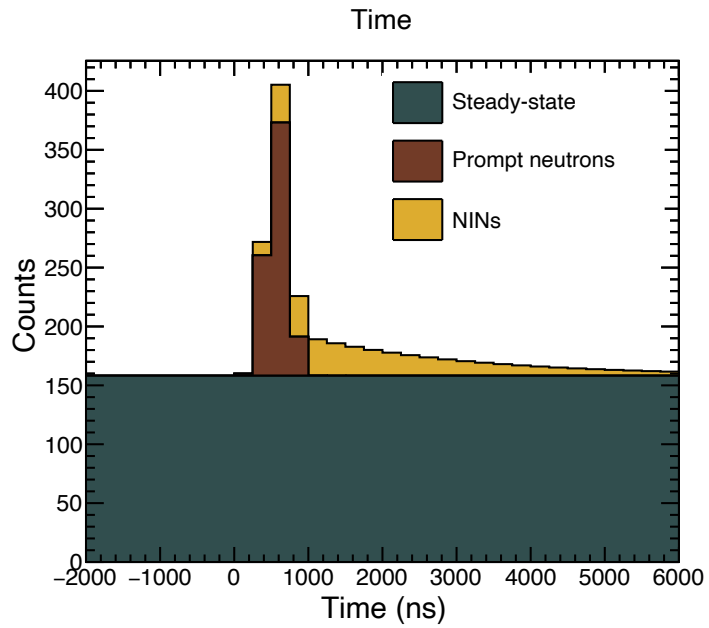
MARLEY + Wakasa B(GT^{-}) data



Signal Predictions

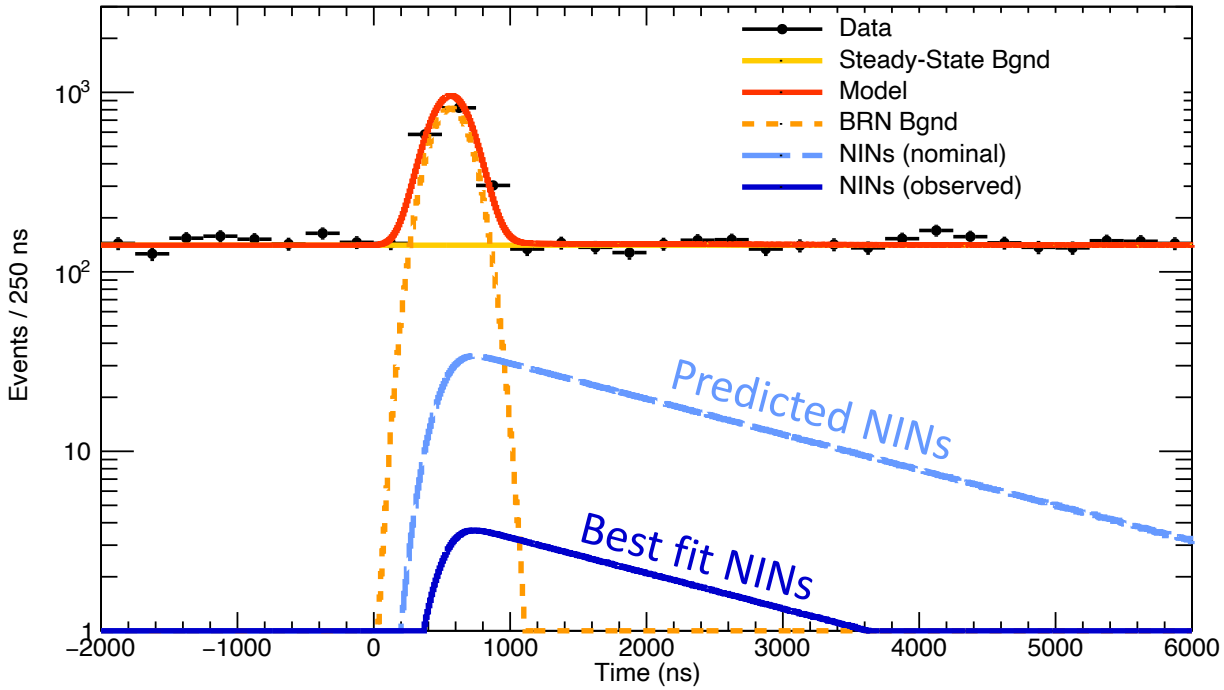
- Simulate signal in MCNP, GEANT4 to determine efficiency for NINs arriving in detector of 18.8%
- Apply measured trigger threshold, energy resolution, PSD cut, to arrive at an efficiency of detecting NINs produced in the lead of 3.3%
- One-dimensional (time-only) fit to data
- Expect 346 charged-current NIN events with cuts
  - Approx. 5σ significance with nominal cross section





Unblinded Results

- Best fit of 36^{+72}_{-36} events compared to expected 346 events
  - Cross section much lower than expected
  - See >4σ discrepancy with MARLEY model
- Agrees with NaIνE finding of suppressed neutron emission channel, although origin unknown
- Potentially affects HALO's sensitivity, but possible for neutrons to be lower in energy than predicted
  - Could test with capture-gated detector
- Inclusive cross section should be measured to check whether *0*n channel agrees with theory
    - Can do within COHERENT, also external plans (arXiv:2205.11769)



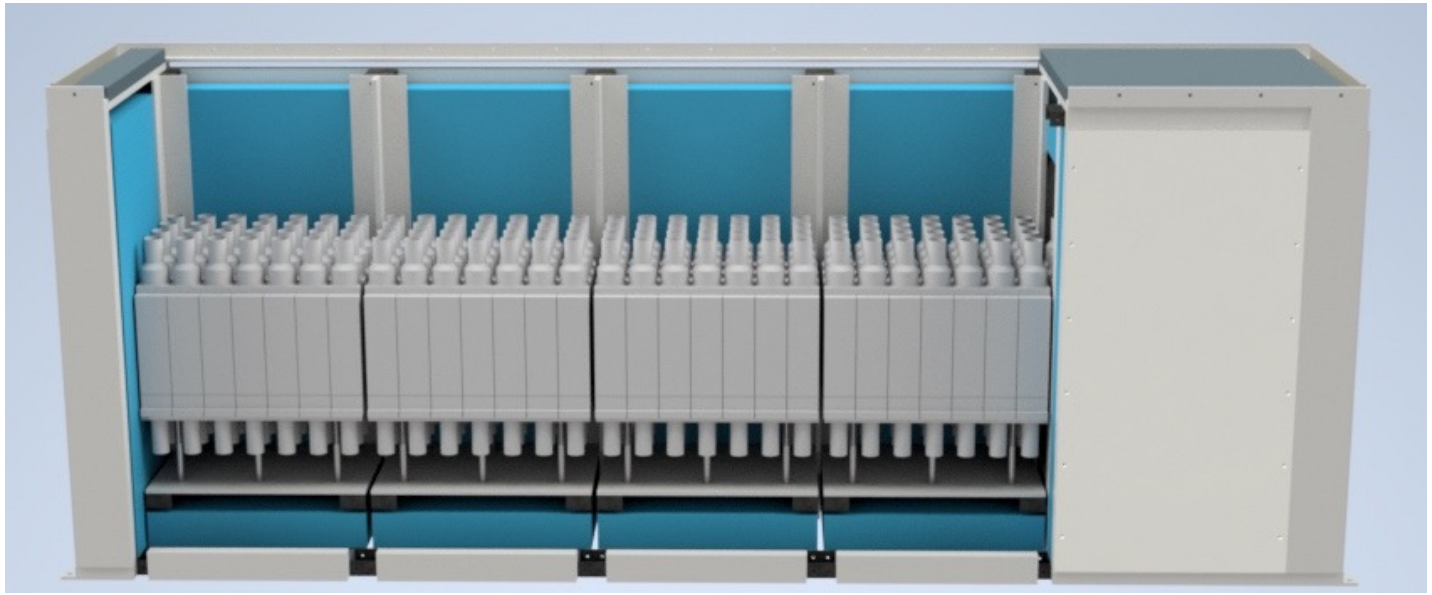
Lead Neutrino Cube: Summary

- 5 year run of the lead neutrino cube analyzed
  - See significant reduction in expected event rate
  - Future test will help illuminate the origin of this suppression
- Future work:
  - Have ~5 years of data with detector measuring NINs with an iron target, needs to be analyzed
  - Possible to look for 2n emission events in data to compare with theory
    - Lower predicted rates, but backgrounds also suppressed
  - Can potentially use event topology to reduce some prompt BRN backgrounds

Future inelastic measurements at COHERENT

NaIνETe

- NaI neutrino Experiment TonnE-scale (**NaIνETe**)
- Ton-scale version of NaIνE-185, consisting of 315 NaI detectors (2,425 kg)
- Main goal is to measure CEνNS on ^{23}Na
- Space left in design to implement muon veto panel to enable charged-current measurement
- Better gamma shielding, water shielding, and improved statistics from larger mass, may be able to go after CC on ^{23}Na as well

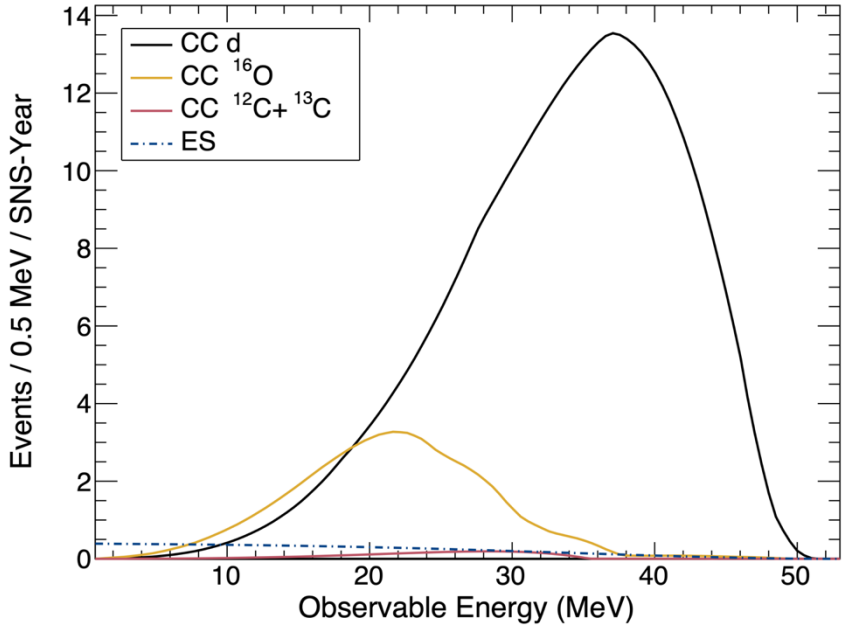


D_2O for Flux Normalization

- Neutrino flux one of largest uncertainties for neutrino measurements at SNS, ~10%
  - ν_e CC cross section on ^2H calculated to within 2-3%
- Deploying 600-kg D_2O detector measure flux, reduce uncertainties
  - Signal comes from Cherenkov light from electron interacting in water
- May also be able to measure ^{16}O charged-current events
  - Potentially useful for understanding supernova neutrinos interacting via this channel in large water detectors

$$\nu_e + {}^2H \rightarrow 2p + e^-$$

$$\nu_e + {}^{16}O \rightarrow {}^{16}F^* + e^-$$



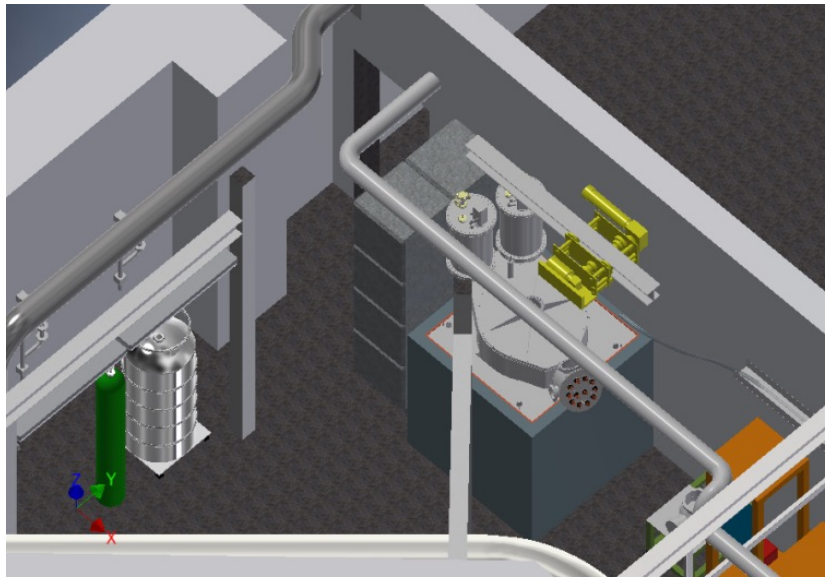
[arxiv:1910.00630.pdf]

CENNS-10/CENNS-750

- CENNS-10 single-phase liquid argon detector with 24-kg fiducial volume, deployed in 2016
  - Primary goal to measure CEνNS, data being studied to see what can be said about inelastic events on ^{40}Ar
- CENNS-750 upgrade in development, increase statistics and go after charged-current interactions on ^{40}Ar
  - Recent funding from Korea National Research Foundation (Jun 1, 2022)
  - Will study CEνNS, charged-current, and dark matter
- Useful for measuring inclusive cross section for DUNE

CENNS-10:

CENNS-750:

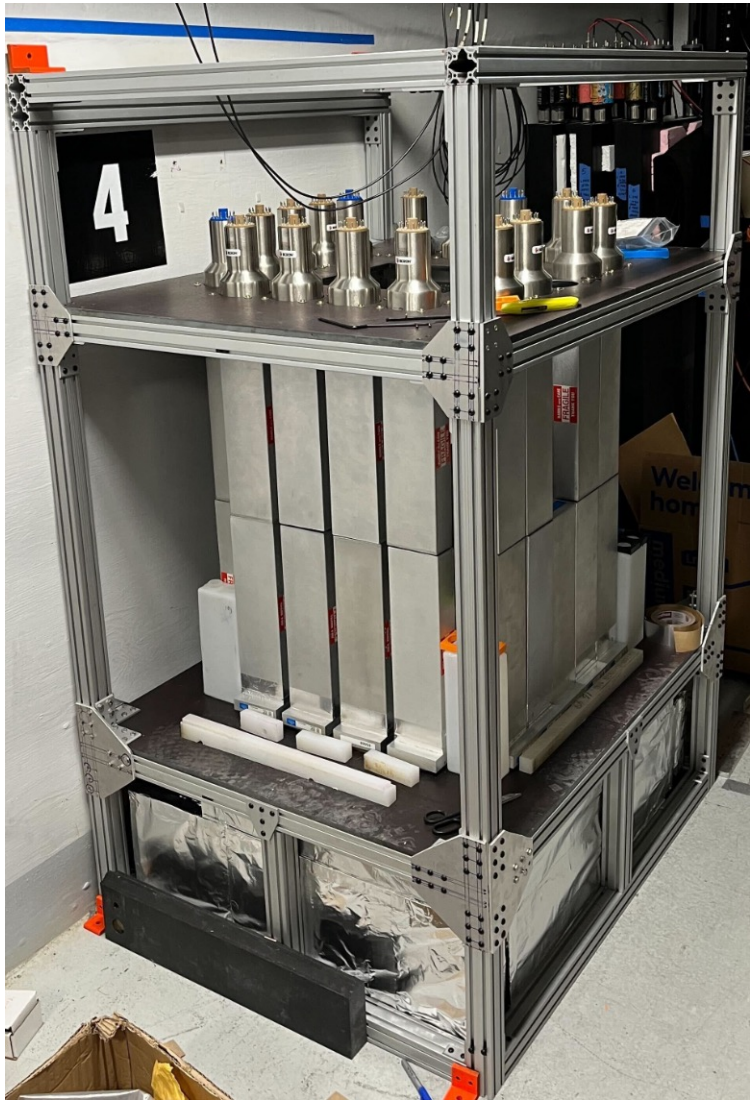


$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^{*} + e^{-}$$

NuThor: Neutrino-Induced Fission

- Detector designed to study neutrino-induced fission, a long-theorized but never observed process
- Studies neutrino interactions on approx. 50kg ^{232}Th
- Looks for neutrons from neutrino-induced fission through capture of gadolinium-doped water
  - Gd-doped water bricks surrounded by NaI[Tl] scintillators
- High neutron multiplicity of fission events key signature to discriminate backgrounds, neutron-induced neutrons in ^{232}Th
- Initial data collection has started!

$$\nu_e + {}^{232}\mathrm{Th} \rightarrow e^- + \mathrm{fission}$$



Summary

- COHERENT has results from its first searches for inelastic neutrino-nucleus scattering
  - Both detectors see suppression in measured cross section compared to predicted results
  - Important to understand and quantify theory uncertainties—would benefit from more data, and more funding on both theory and experimental sides
- Within COHERENT, more data to analyze, and more inelastic detectors coming online soon!
    - D_2O for reducing flux uncertainty, ^{16}O CC events (taking test data)
    - NuThor for neutrino-induced fission on ^{232}Th (collecting first production data)
    - NaIvETe increase stats on ^{127}I CC, potentially ^{23}Na CC as well (partially deployed)
    - CENNS-750 for ^{40}Ar (in development)

Acknowledgements

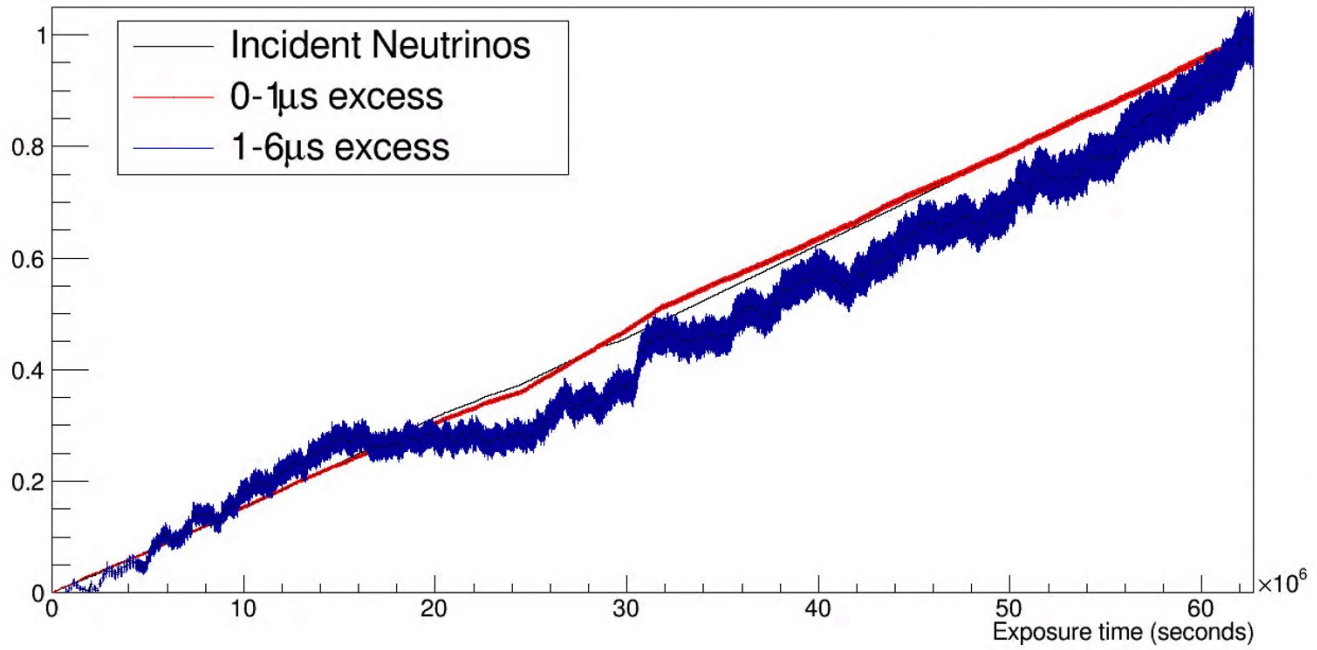
- This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Thank you for your attention!

Back-up

NaIvE: Post-Unblinding Checks

- K-S test shows good agreement between prompt and delayed excesses and delivered beam
  - With 1000 pseudo-experiments, K-S probabilities are 1.000 and 0.987 from prompt and delayed excesses



NaIvE: Post-Unblinding Checks

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  - With 1000 pseudo-experiments, K-S probabilities are 1.000 and 0.987 from prompt and delayed excesses
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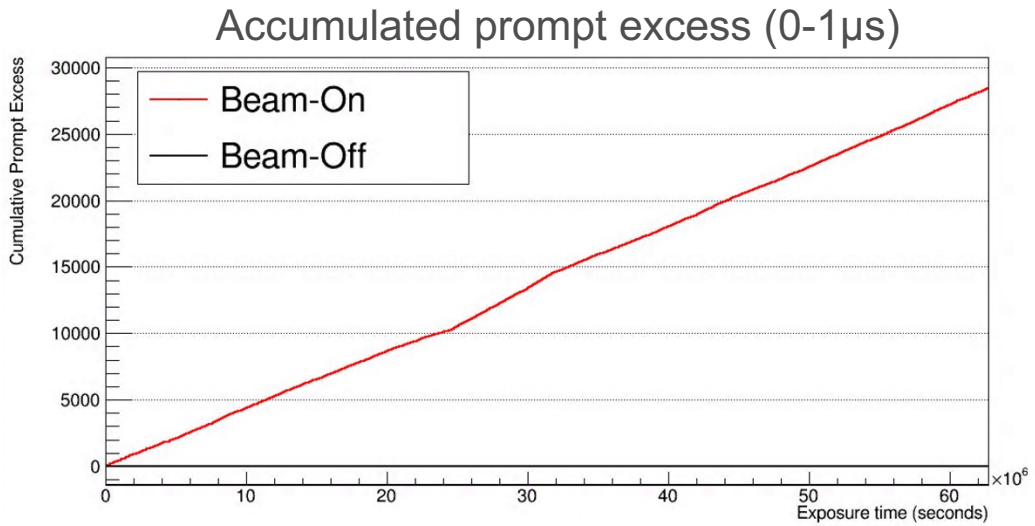

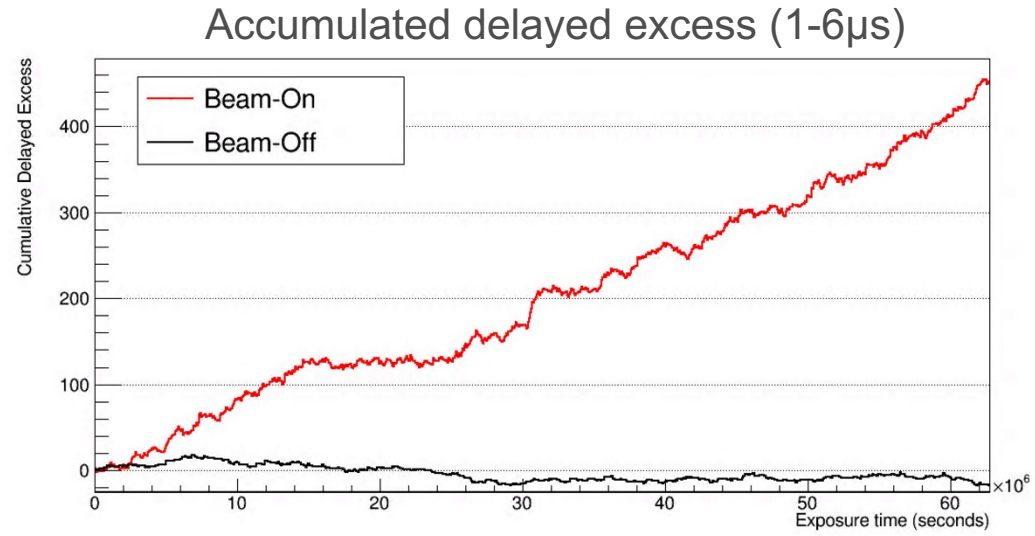

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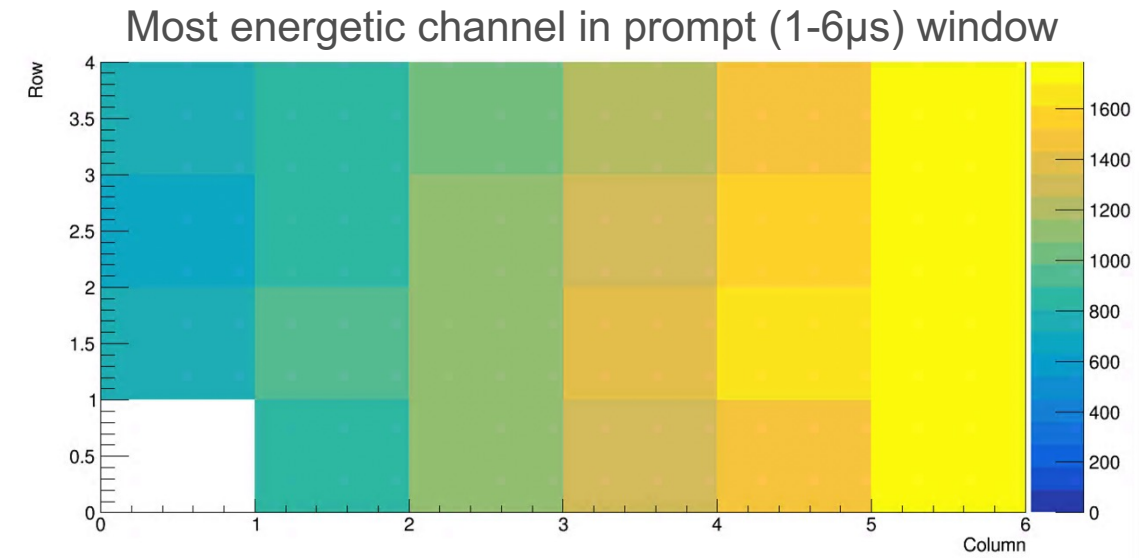
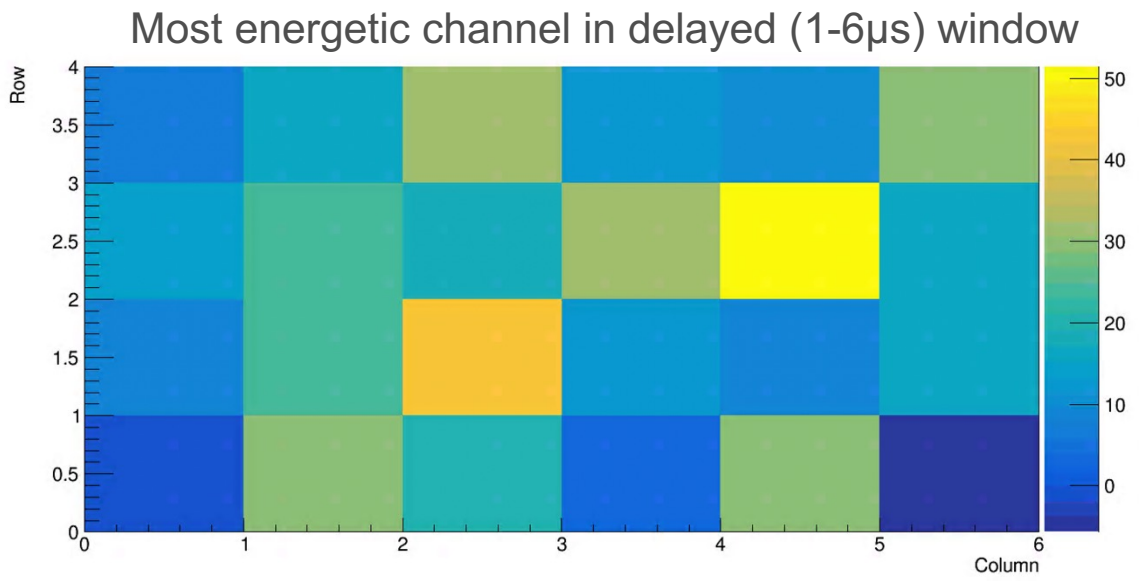
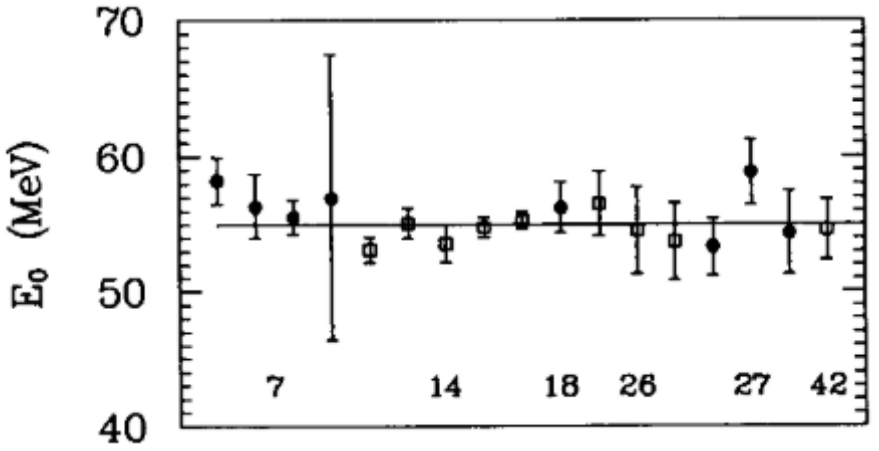
- K-S test shows good agreement between prompt and delayed excesses and delivered beam
  - With 1000 pseudo-experiments, K-S probabilities are 1.000 and 0.987 from prompt and delayed excesses
- No excess observed in prompt/delayed windows when beam not on target
- Some initial topology studies show neutrons incident on detector from side, do not see same pattern for delayed events
  - Helps understand BRN background for COHERENT's other detectors





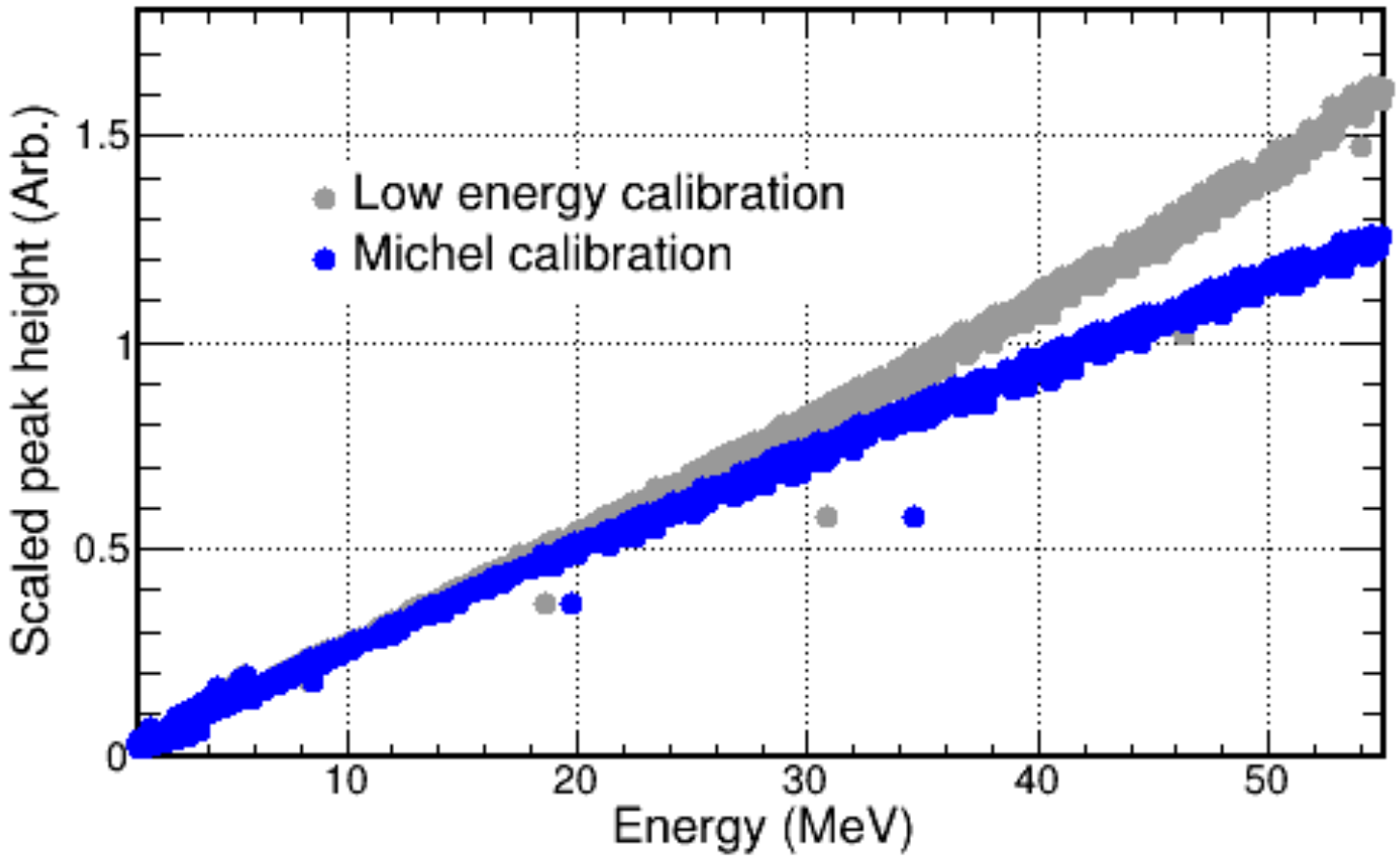
NaIvE: g_A quenching

- Definition of matrix elements in (p,n) and weak interactions differs by g_A^2
- Cannot determine the value of g_A from cross section
  - Forbidden transitions not included in MARLEY
- Can set limit on maximum value of g_A, with large caveat:
  - Normalization for B(GT) in (p,n) charge-exchange measurements assumes a value for g_A=1.26, compares 0° scattering cross sections with beta-decay half-lives
  - Heaviest element used in normalization has A=42
  - Incorrect normalization for strengths in (p,n) experiments would lead to incorrect value of g_A

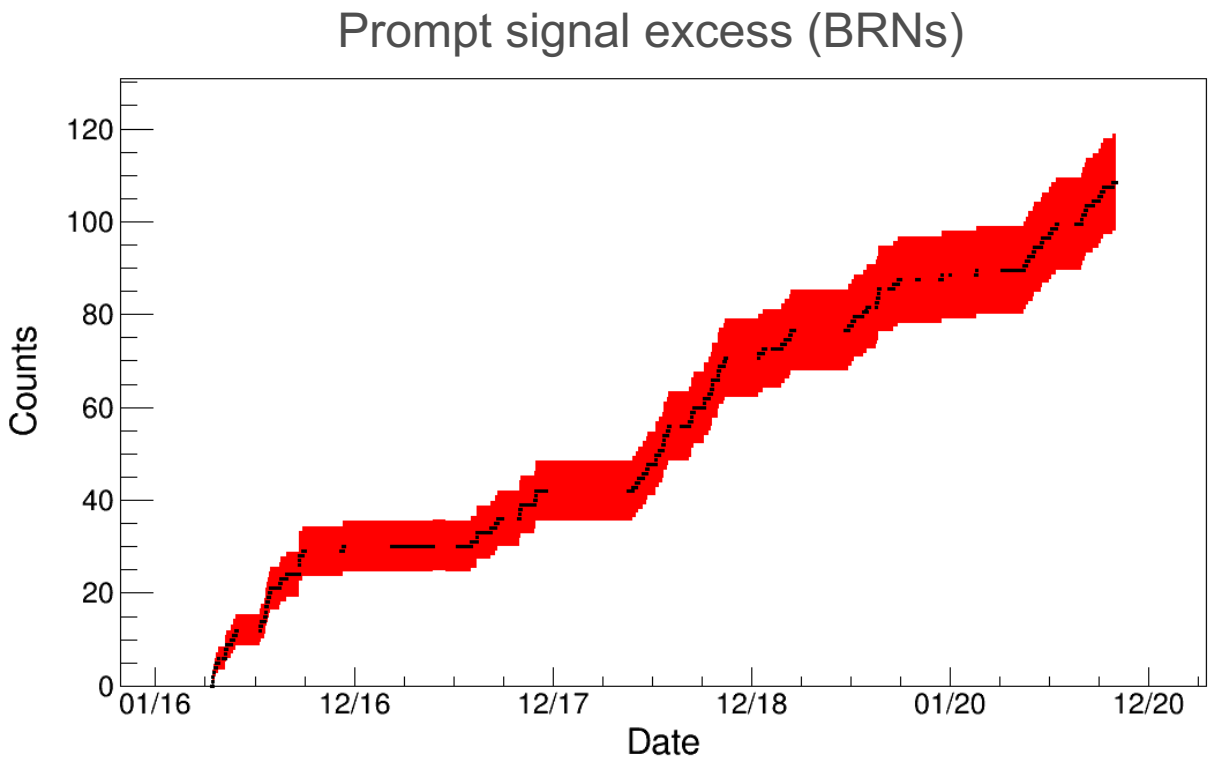


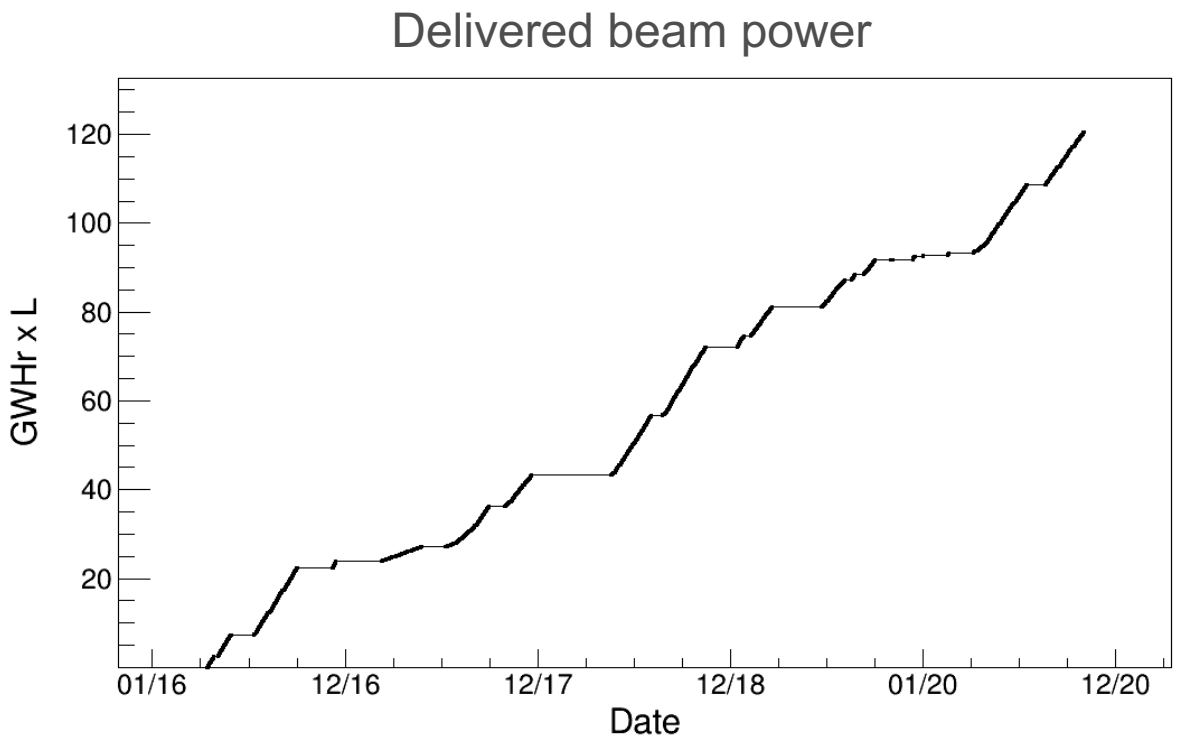
[T. Taddeucci, et al., Nuc. Phys. A 469 (1987)]

NaIνE: Michel Positron Calibration

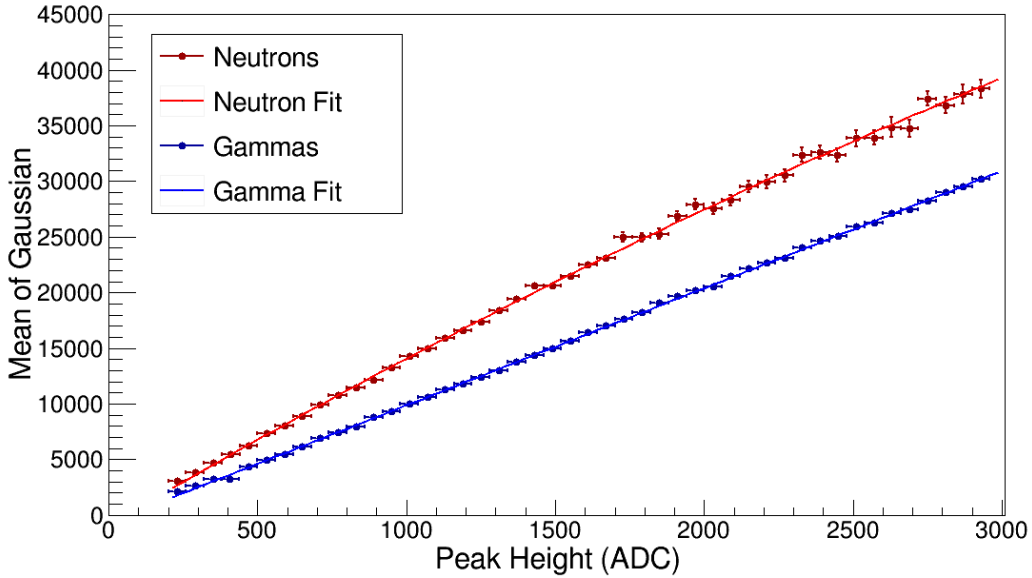


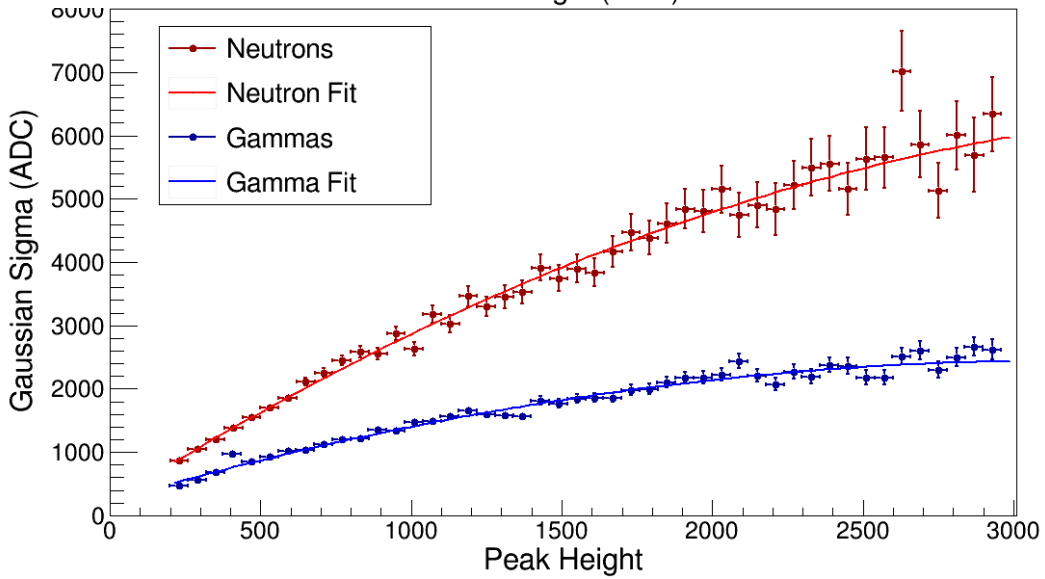
Lead Neutrino Cube: Prompt Signal vs. Beam Power

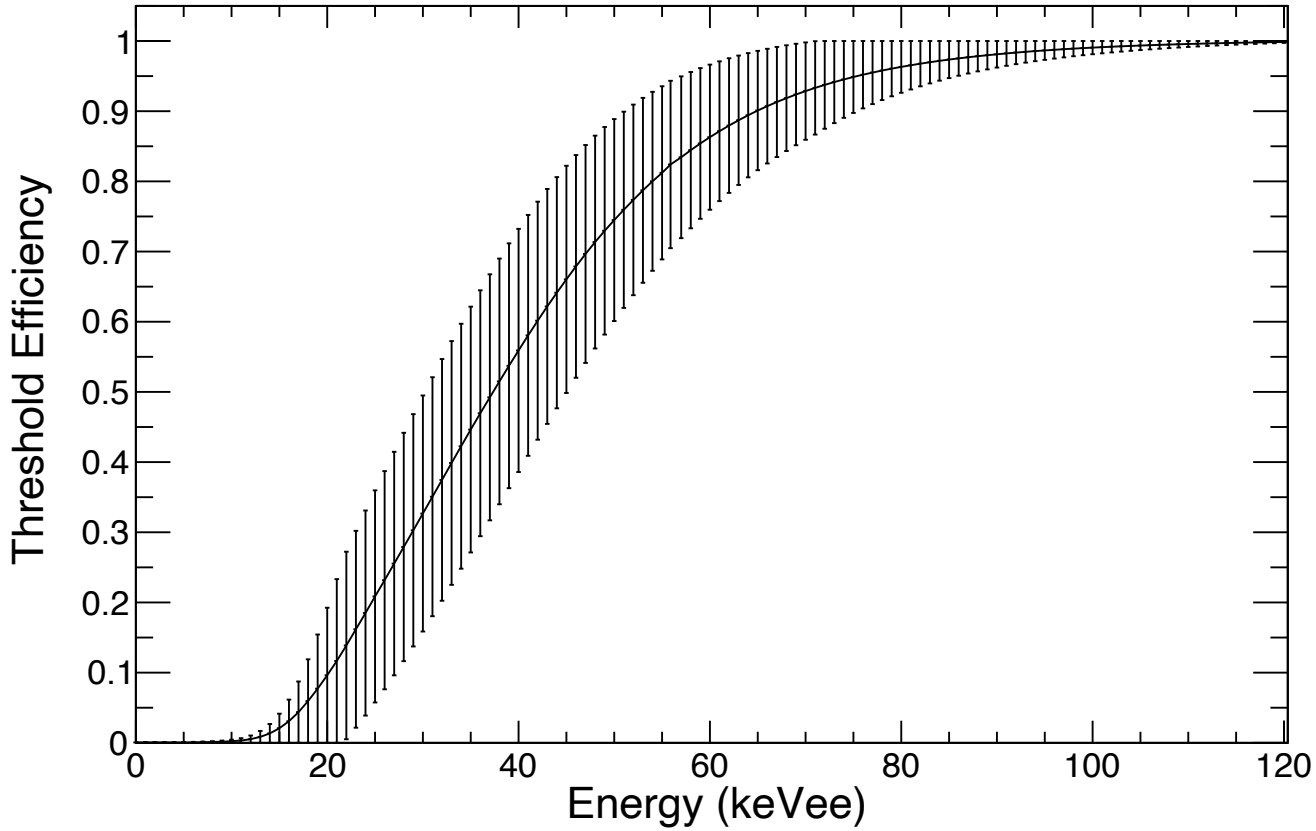




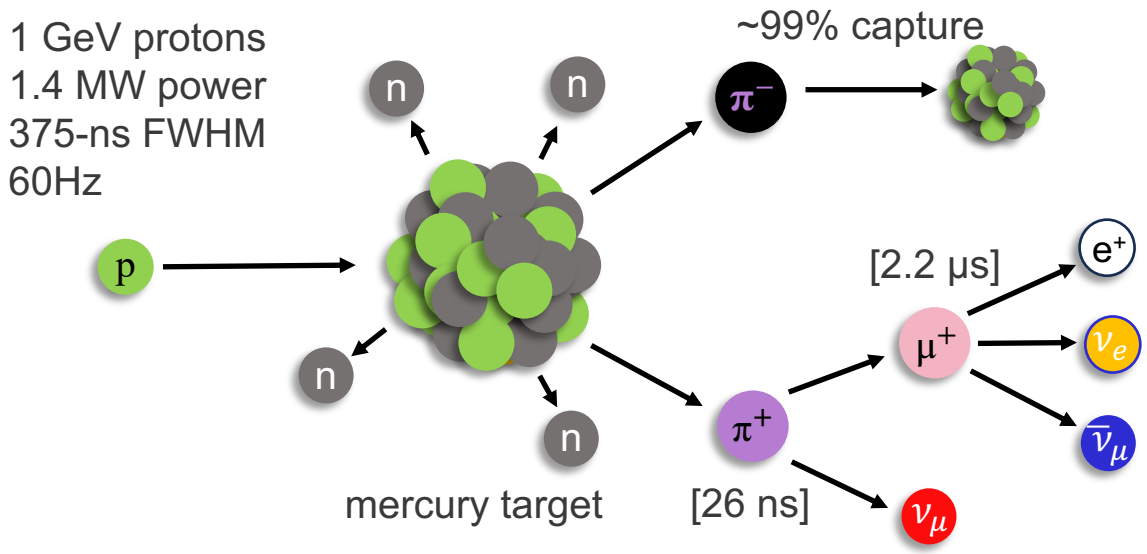
Lead Neutrino Cube: Trigger Thresholds



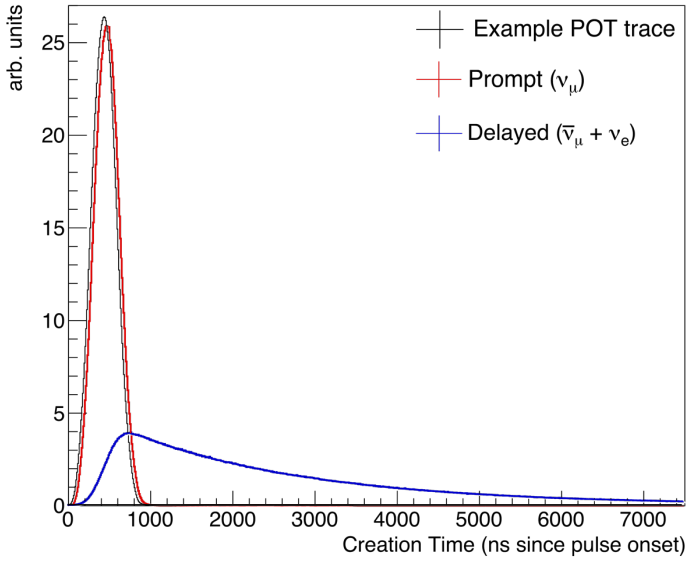




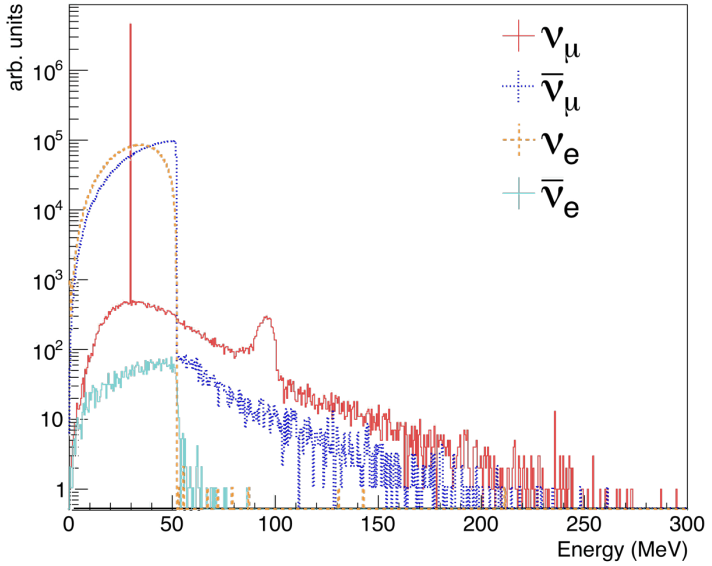
Back-up: Neutrino Production at the SNS



Timing:

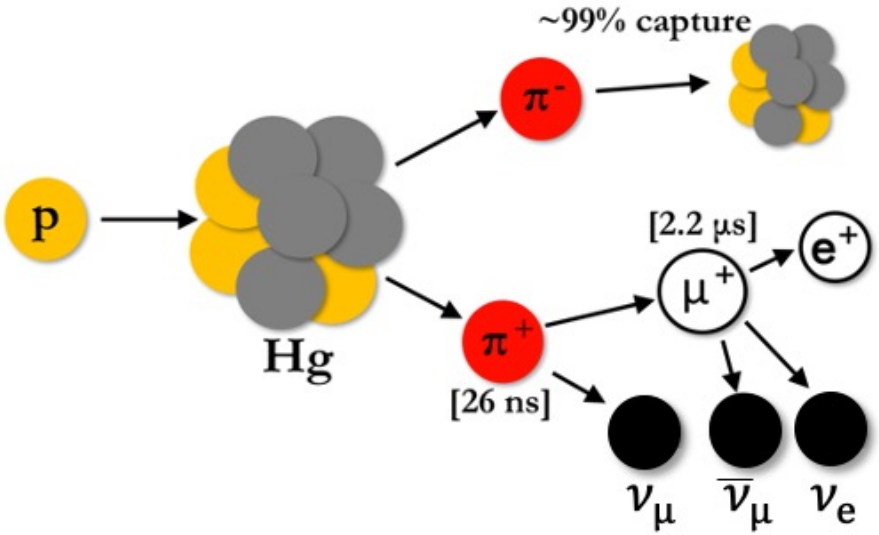


Energy:

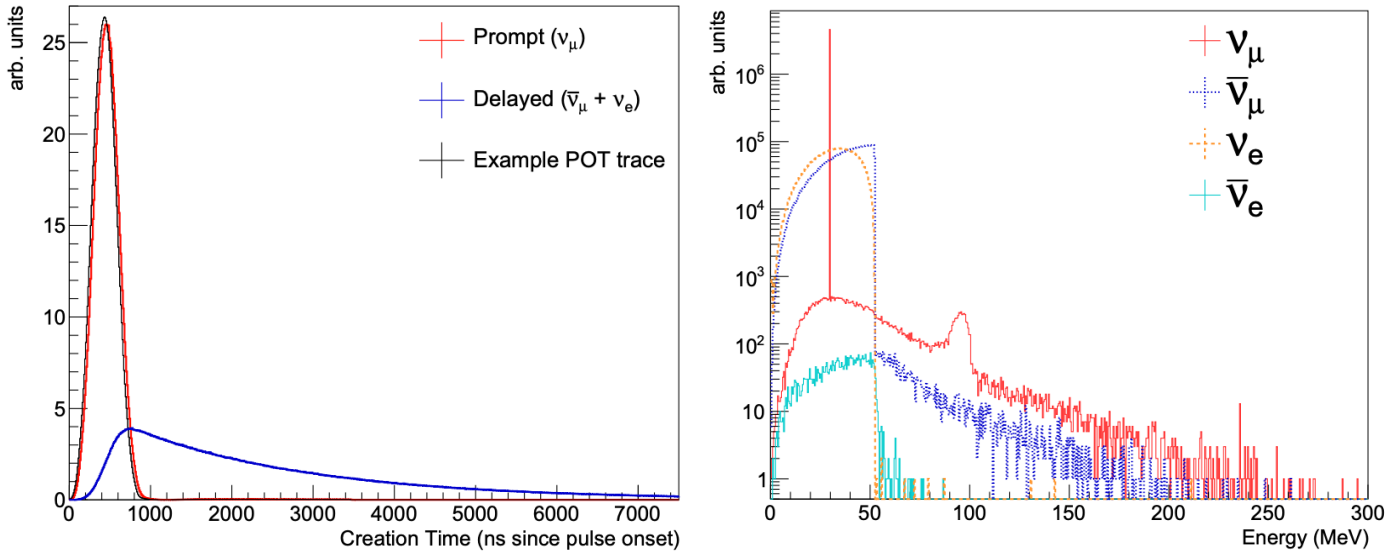


Neutrinos at the SNS

- 1 GeV protons strike Hg target at the SNS at 60Hz
  - 350ns FWHM of proton pulse
- Produces π^- and π^+ (and neutrons)
  - Neutrons are a background for our detectors, we refer to them as beam-related neutrons (**BRNs**)
- π^+ decay in ~26ns, leading to prompt ν_μ (~30 MeV) and μ^+
- μ^+ decay with lifetime of 2.2μs, producing delayed ν_e and $\bar{\nu}_\mu$ (<53 MeV)
  - ν_μ roughly in time with beam, ν_e and $\bar{\nu}_\mu$ largely free from beam-related backgrounds



Simulated timing and energy spectra



[D. Akimov, et al., arXiV:2109.11049 (2021)]