Status and Future of the COHERENT Liquid Argon Program

Jacob Daughhetee

The Magnificent CEvNS
Nov 19th , 2020

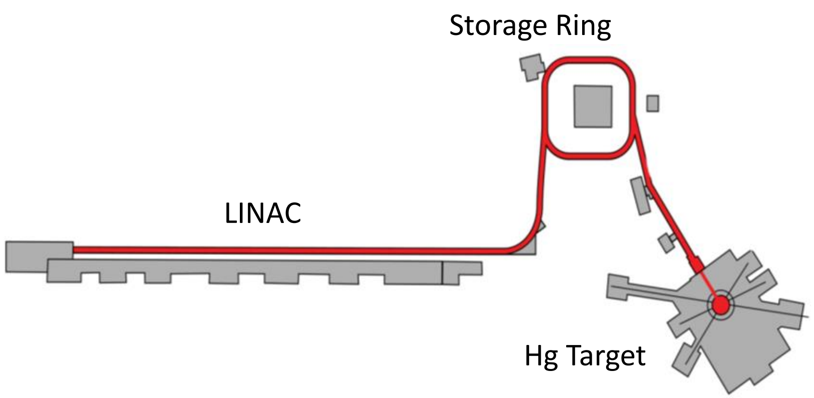
COHERENT
SNS

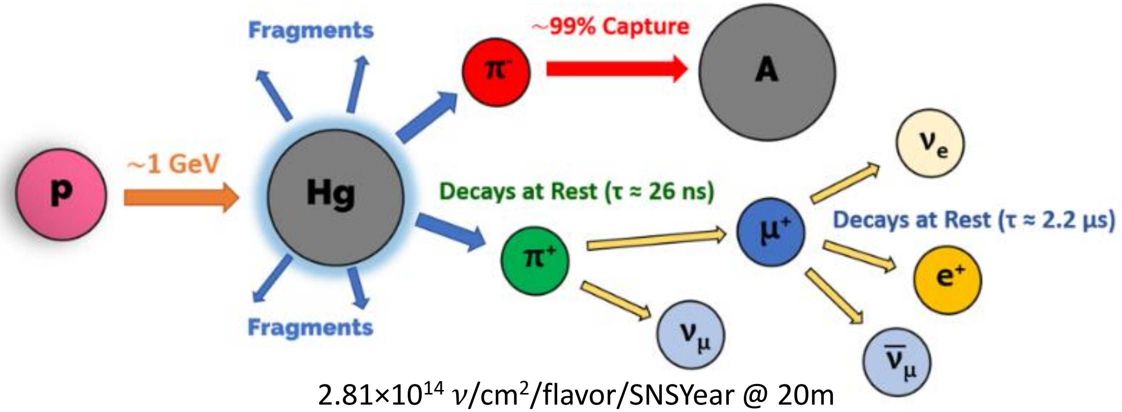
U.S. DEPARTMENT OF ENERGY | Office of Science

OAK RIDGE National Laboratory

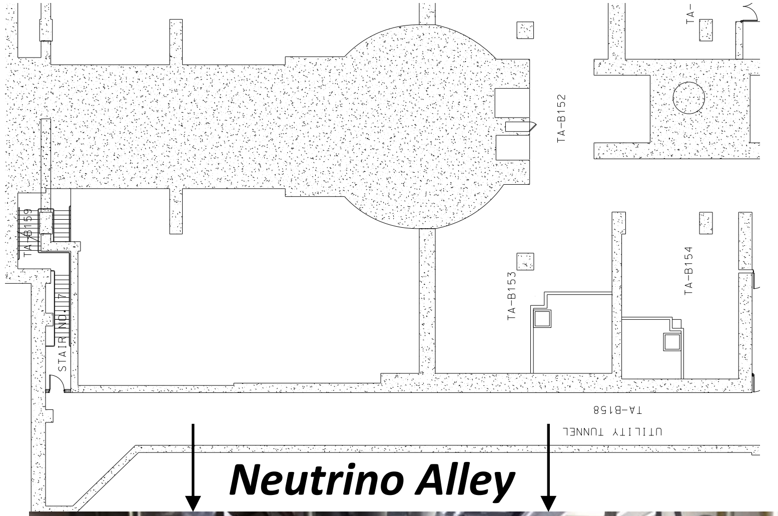
THE UNIVERSITY OF TENNESSEE KNOXVILLE

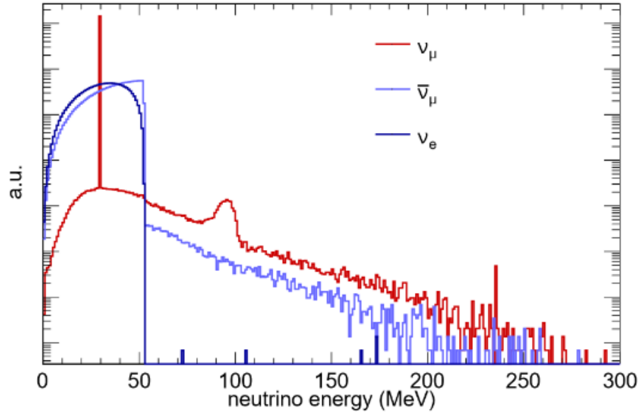
COHERENT at the SNS

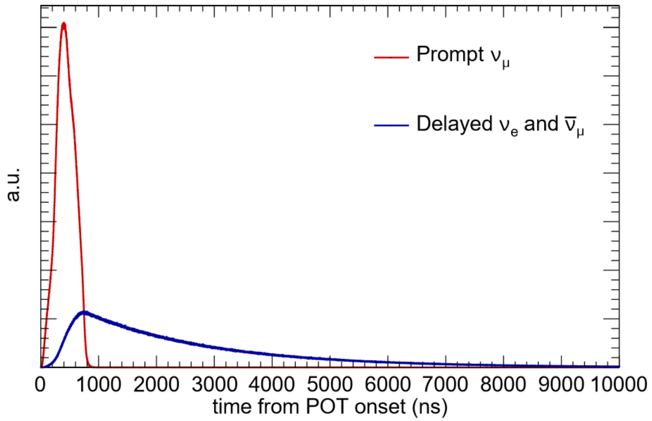




$2.81{\times}10^{14}\ \nu/\text{cm}^2/\text{flavor}/\text{SNSYear @ 20m}$



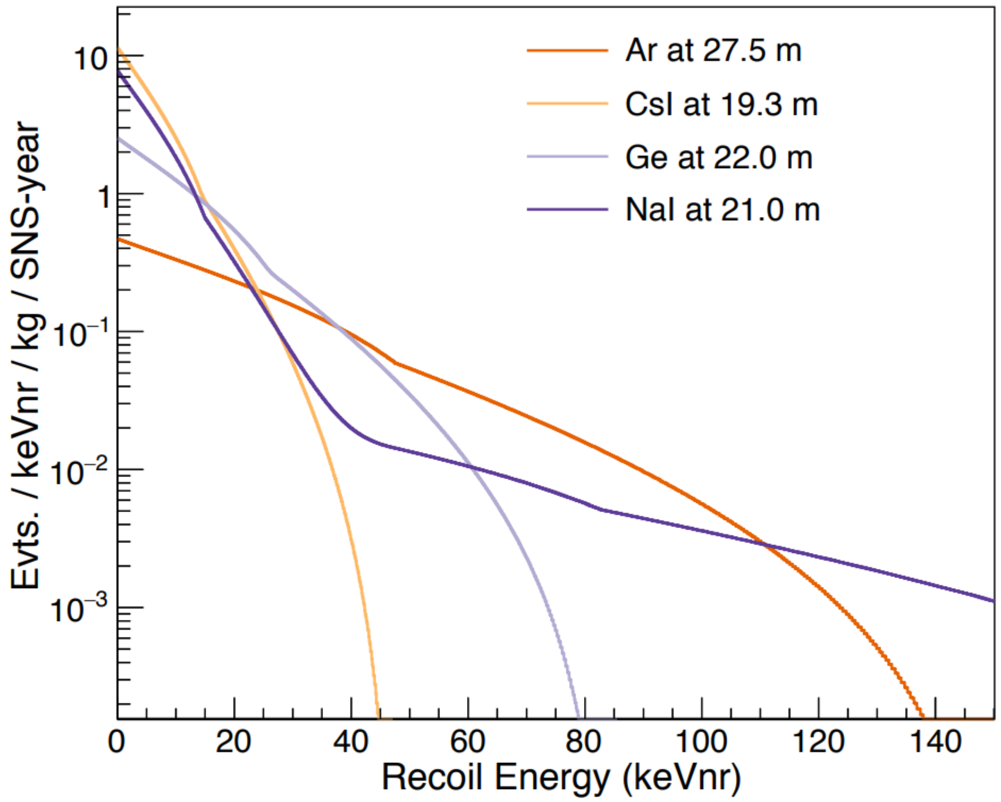


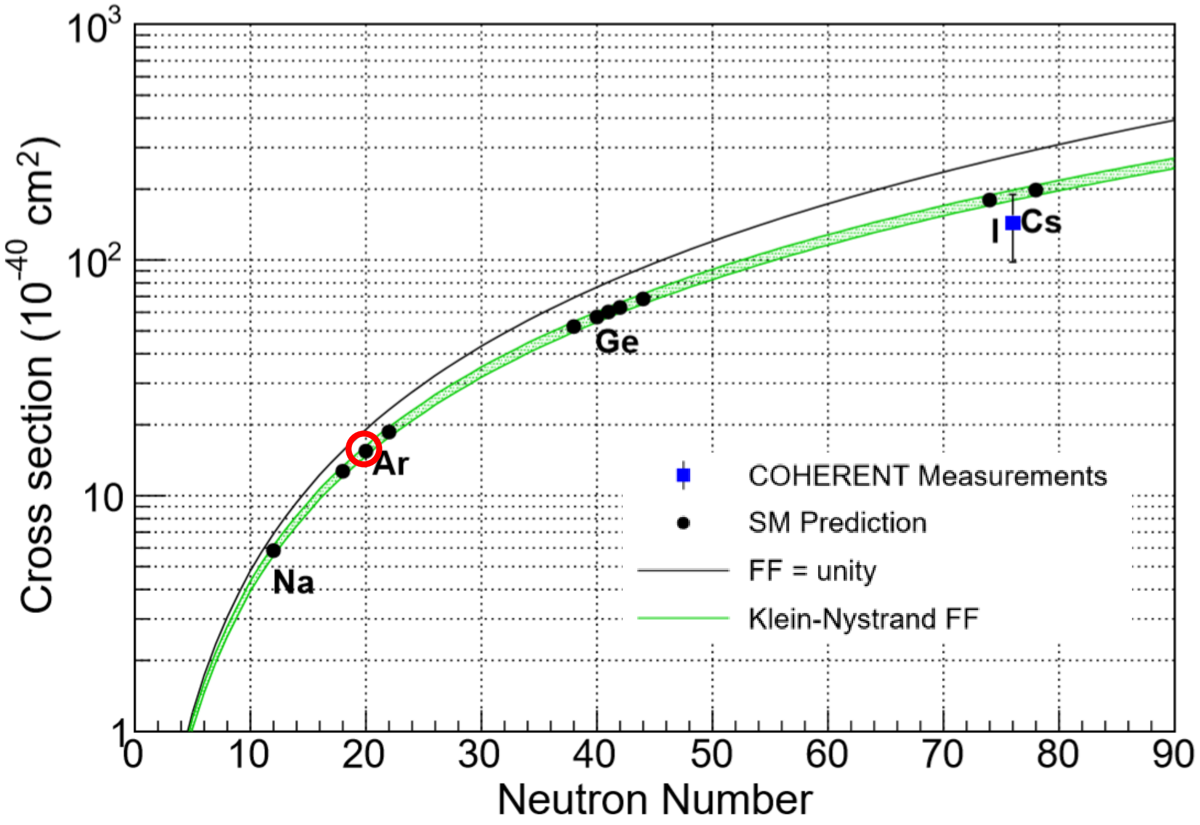


COHERENT Program

Multi-target program to measure CEvNS cross section over wide range of *N*

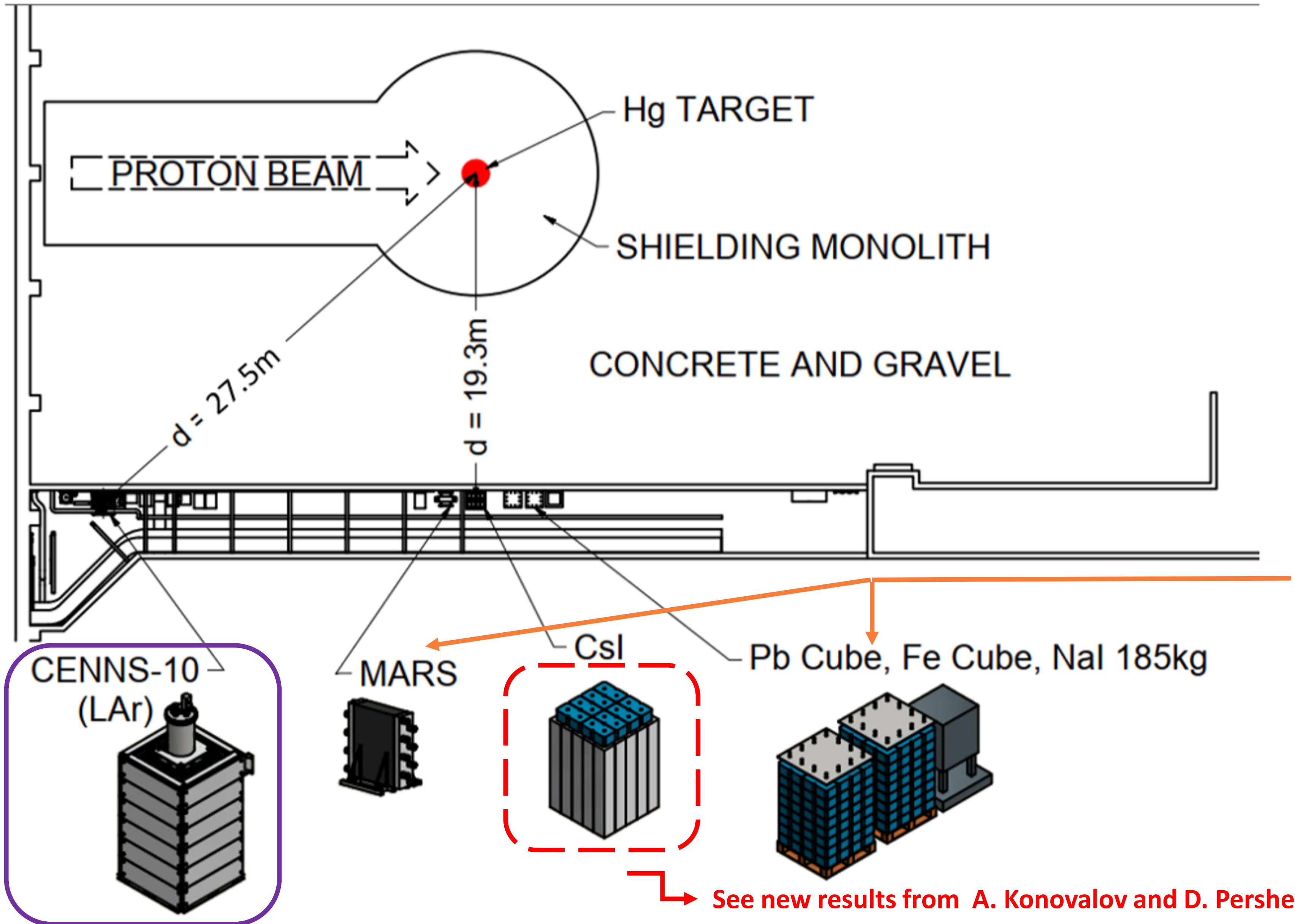
CEvNS-induced recoil spectra





Staged approach: ***Observation -> Precision***

COHERENT Current Operations



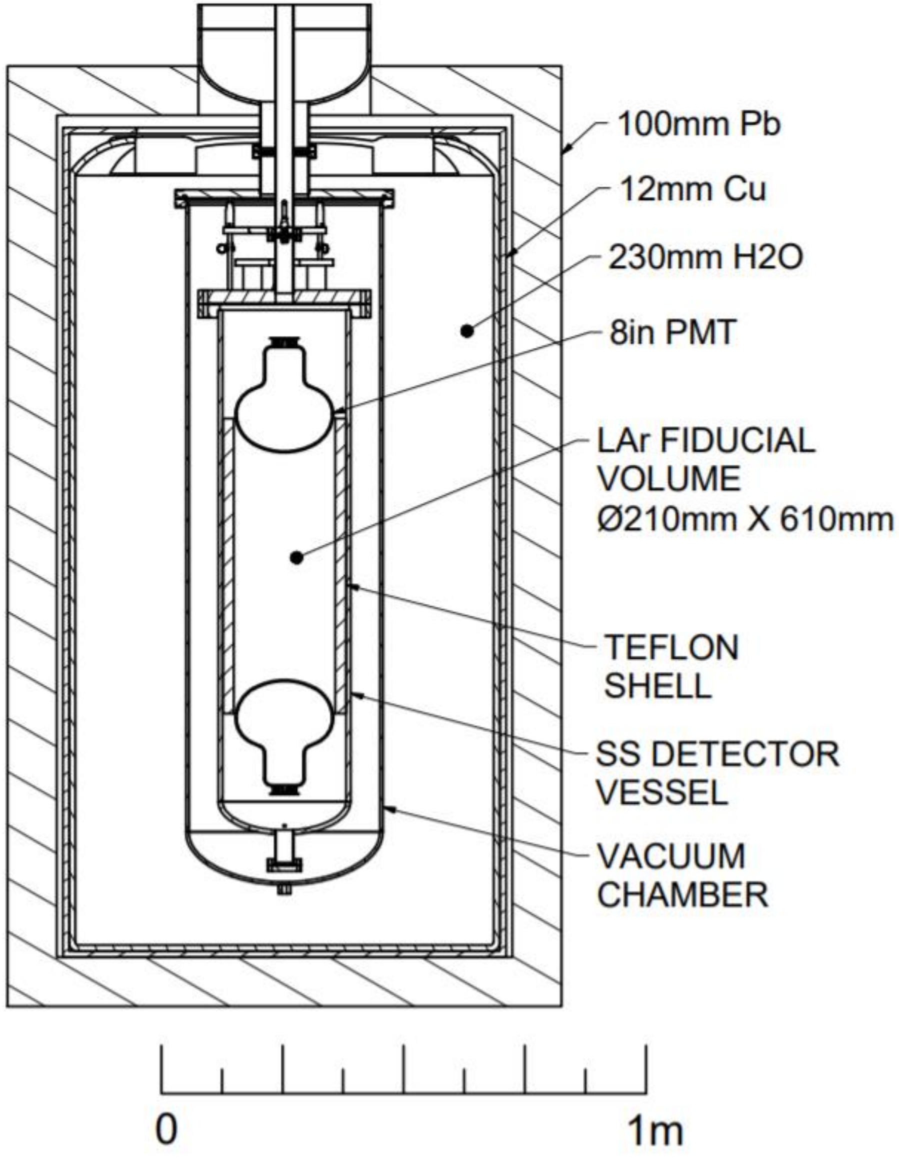
Data Analysis Underway

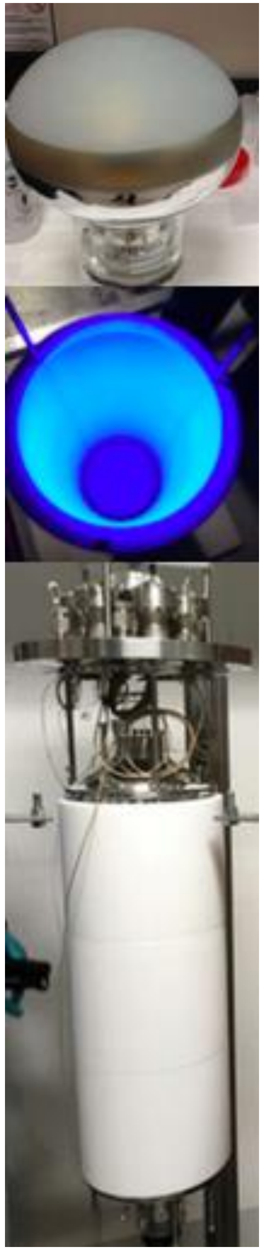
See new results from A. Konovalov and D. Pershey

CENNS-10

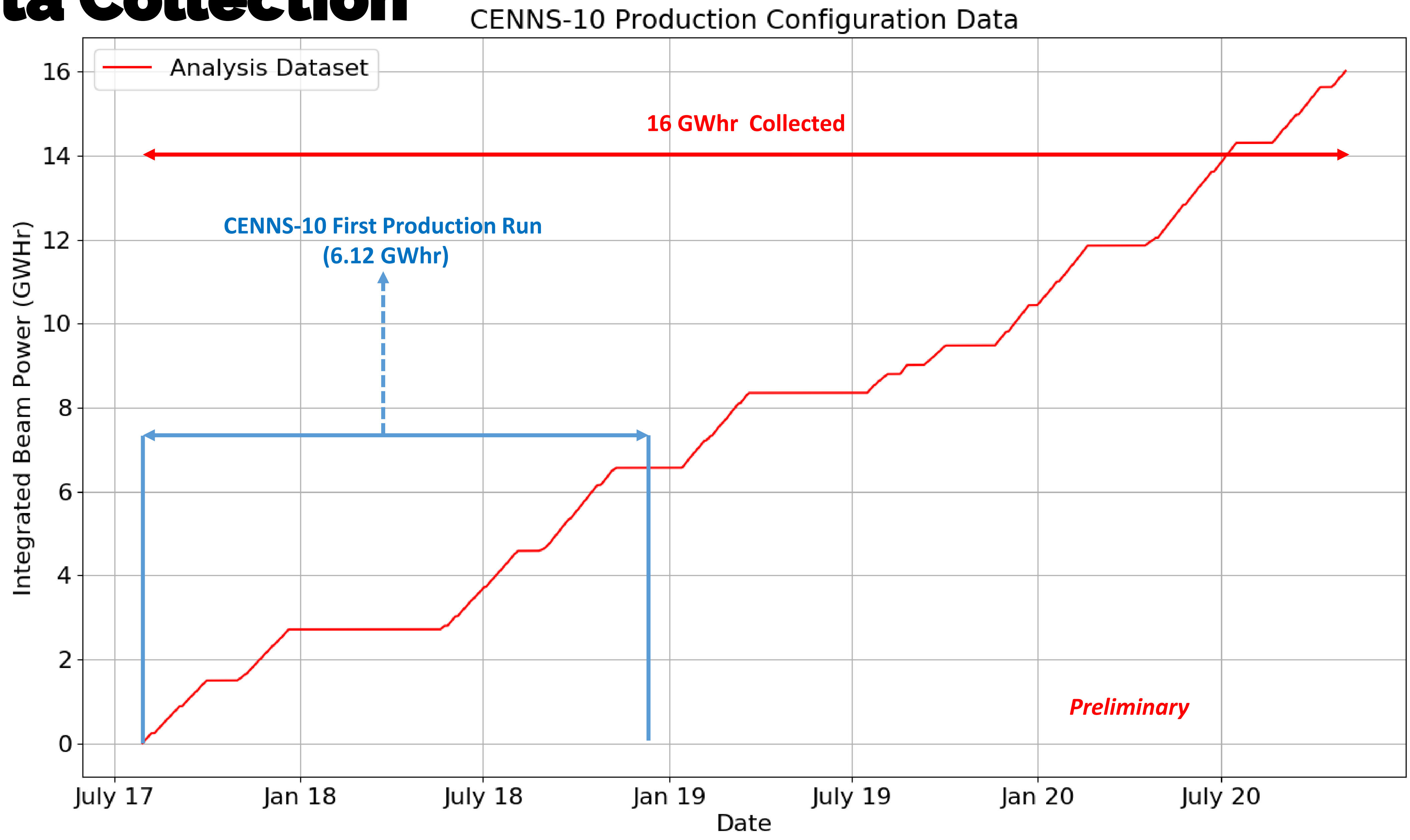
- Loaned from J. Yoo *et al* from Fermilab.
- Single-phase liquid Ar scintillation detector located 28 m from SNS target (~2 x 10^7 ν / s)
- **Engineering Run:** Dec 2016 -> May 2017
  - 80 keVnr threshold
  - No Pb shielding
  - Analysis Results -> Phys. Rev. D100 (2019) no. 11, 115020
- **First Production Run:** July 2017 -> December 2018
  - Dramatically improved light yield results in lower threshold (20 keVnr)
  - 2x 8" Hamamatsu PMTs with 18% eff @ 400 nm
  - Tetraphenyl butadiene (TPB) wavelength shifter coating Teflon walls and PMT glass.
  - 24 kg fiducial volume.

arXiv:*2003.10630*





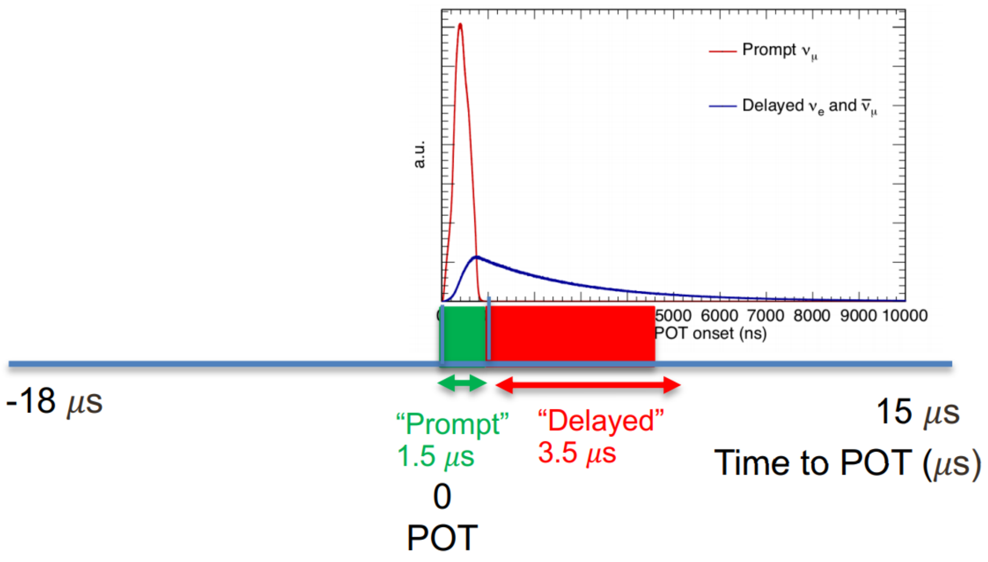
Data Collection

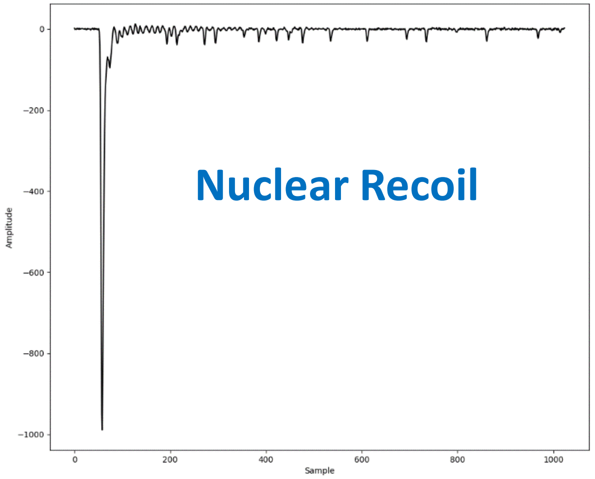


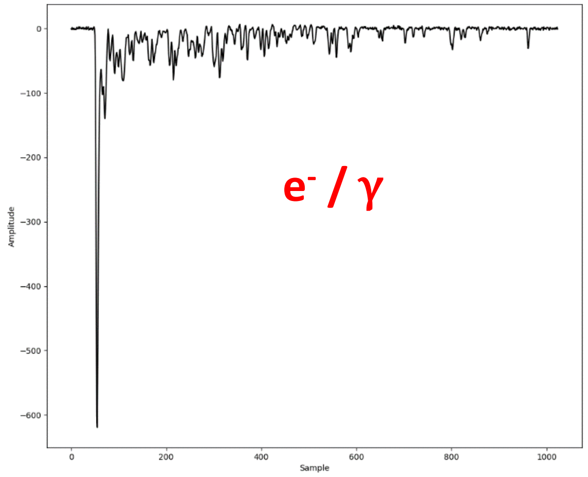
Data Selection / Analysis Steps

- 33 µs readout window roughly centered about POT time.
- Identical readout performed after delay of 14 ms to **directly measure** steady-state backgrounds while SNS is operating.
- Pulse finding algorithm applied to triggered waveforms; requirement of 2 photons in first 90ns on both PMTs.
- Pulse-shape discrimination variable "F90" is computed:
  (Integral of WF in first 90 ns / Total WF Integral)
- Beam-related neutrons (BRN) measured with dedicated 'neutron' runs which lack water shielding.
- Cuts on energy, F90, and time established prior to box-opening.
- 3D Likelihood fit applied to final dataset .

POT Trigger Window







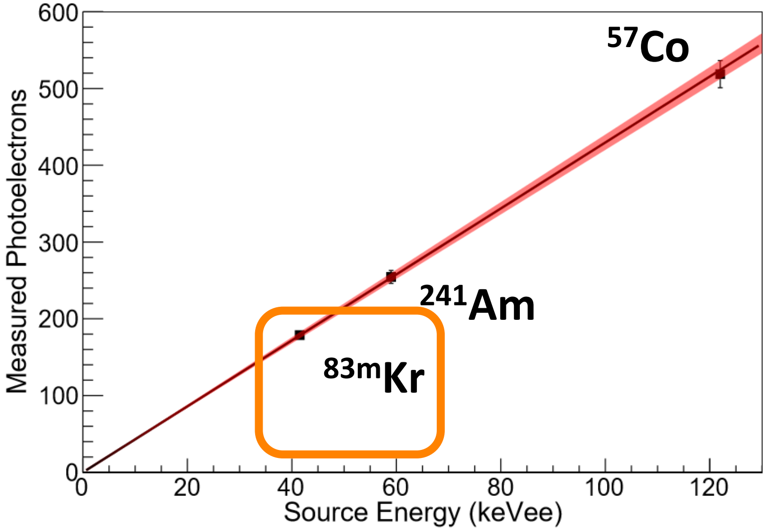
Energy Calibrations

- Calibrations performed using multiple gamma sources (^{57}Co, ^{241}Am, ^{83m}Kr).
- Observed light yield: 4.6 ± 0.4 p.e./keVee
- 9.5% resolution at 41.5 keVee.
- Provides ADC -> keVee conversion. (ee – electron equivalent).
- Global QF fit provides keVnr->keVee conversion.

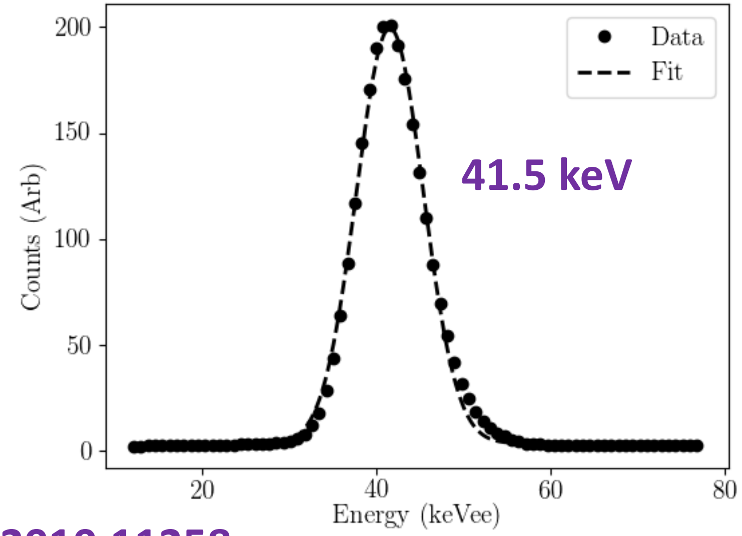
Neutron Calibrations

- **AmBe** – Used to measure NR response in detector and model CEvNS signal.
- **DT Generator** – Used to confirm veracity of external neutron simulations

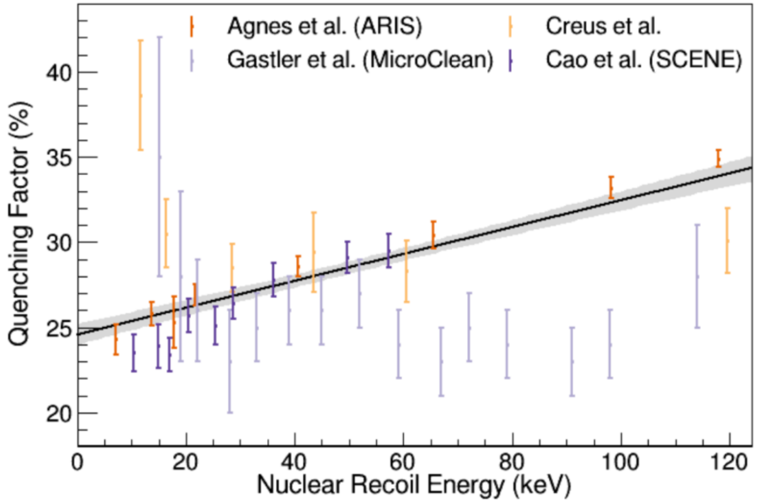
See poster by E. Kozlova

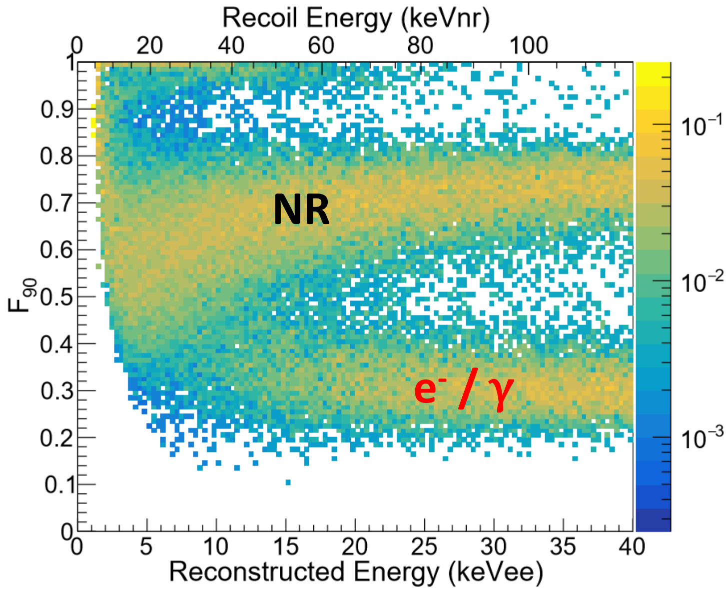


^{83m}Kr Calibration

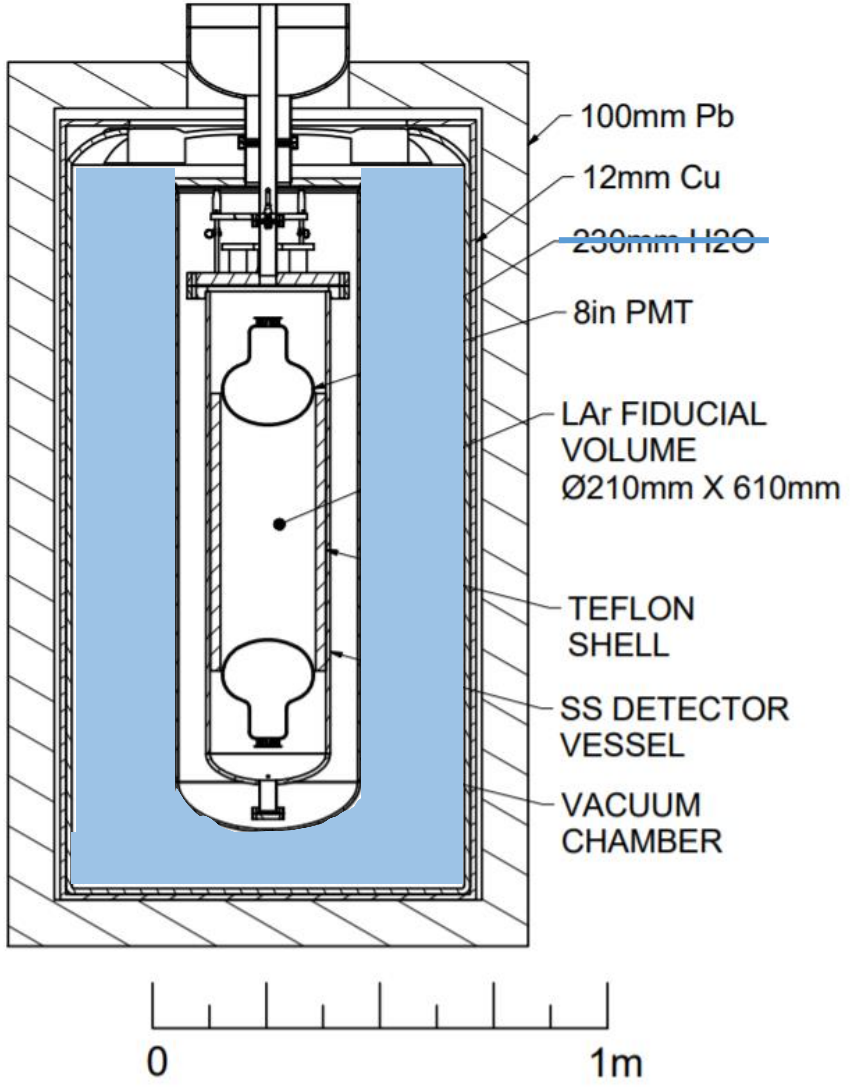


arXiv:2010.11258



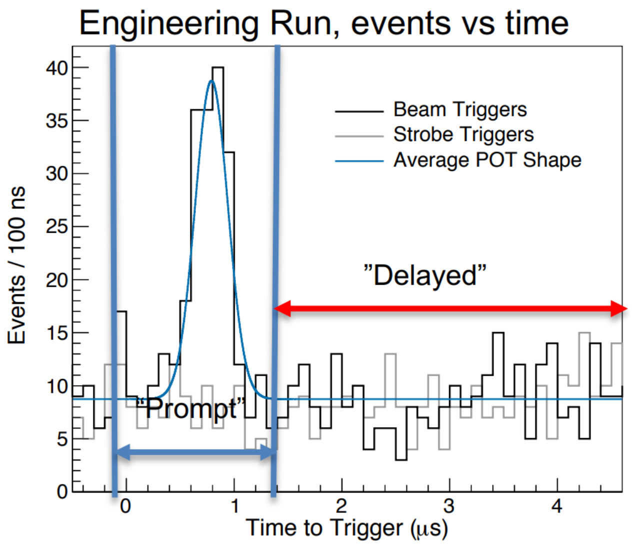


Beam-Related Neutrons

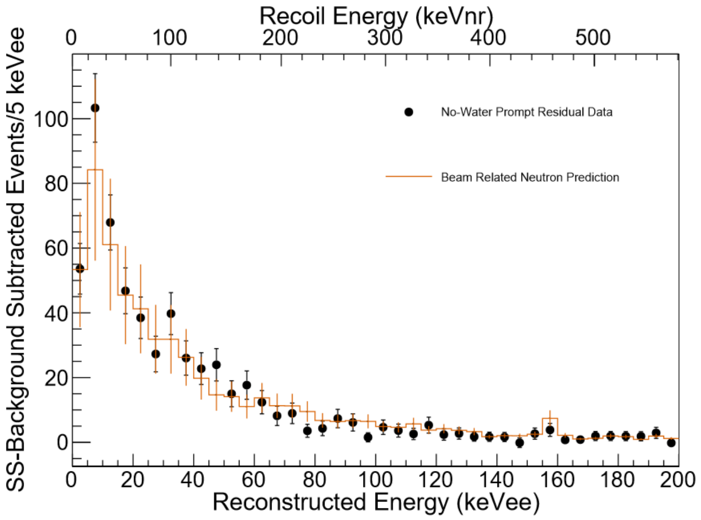


BRN increase by an order of magnitude with tank drained.

- Understanding beam-related neutrons is essential for CEvNS analysis due to ability to mimic signal.
- Previous measurement by SciBath detector provided information on BRN flux and spectral shape in CENNS-10 location.
- Multiple data taking periods without water shielding (0.54 GWhr of integrated beam power).
- Data from these “neutron” runs as well as data from earlier detector configuration show no evidence for delayed neutrons.


Engineering Run, events vs time

M.R. Heath PhD thesis (IU 2019)
Phys. Rev. D **11** 115020 (2019)



Neutron runs are ultimately used to tune GEANT4 simulation.

Predictions and Systematics

- 3D binned likelihood fit in energy, F90, and time.
- Waveform / event quality cuts.
- Analysis Cuts:
    - Energy -> 0-120 keVee
    - F90 -> 0.5-0.9
    - Time -> -0.1-4.9 µs

Sample Predictions

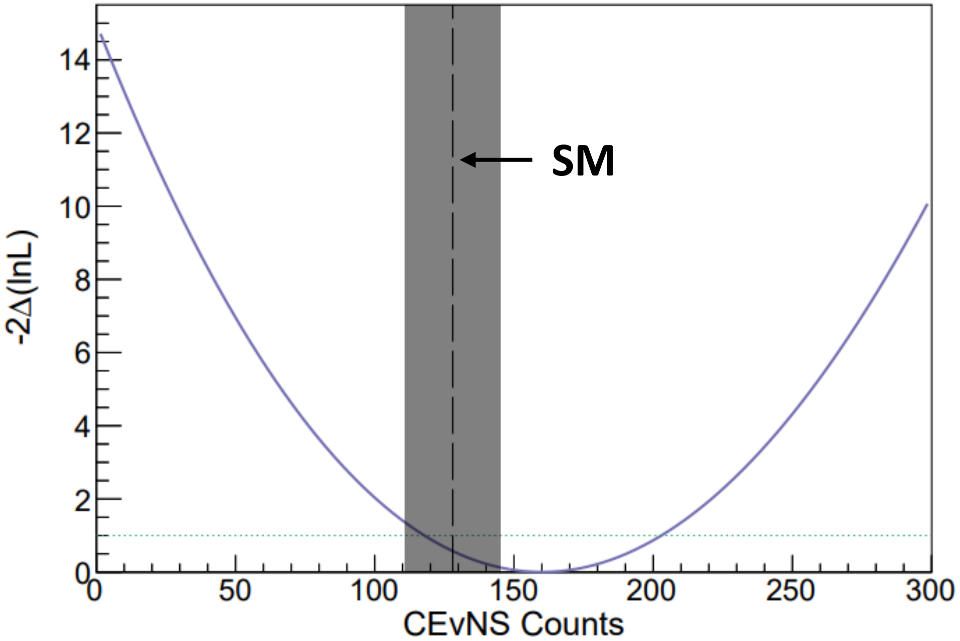
Predicted SM CEvNS	128 ± 17
Predicted Beam Related Neutrons	497 ± 160
Predicted Beam Unrelated Background	3154 ± 25
Predicted Late Beam Related Neutrons	33 ± 33

Largest Systematics

CEvNS Rate Measurement Systematic Errors	
Error Source	Total Event Uncertainty
Quenching Factor	1.0%
Energy Calibration	0.8%
Detector Model	2.2%
Prompt Light Fraction	7.8%
Fiducial Volume	2.5%
Event Acceptance	1.0%
Nuclear Form Factor	2.0%
SNS Predicted Neutrino Flux	10%
Total Error	13.4%

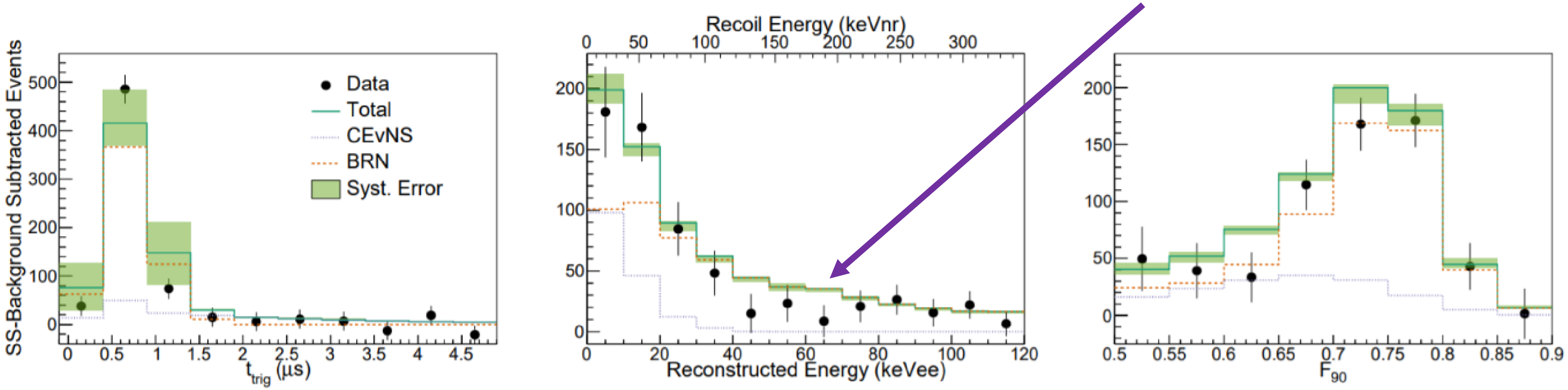
Additional Likelihood Fit Shape-Related Errors	
Error Source	Fit Event Uncertainty
CEvNS Prompt Light Fraction	4.5%
CEvNS Arrival Mean Time	2.7%
Beam Related Neutron Energy Shape	5.8%
Beam Related Neutron Arrival Time Mean	1.3%
Beam Related Neutron Arrival Time Width	3.1%
Total Error	8.5%

Fit Results

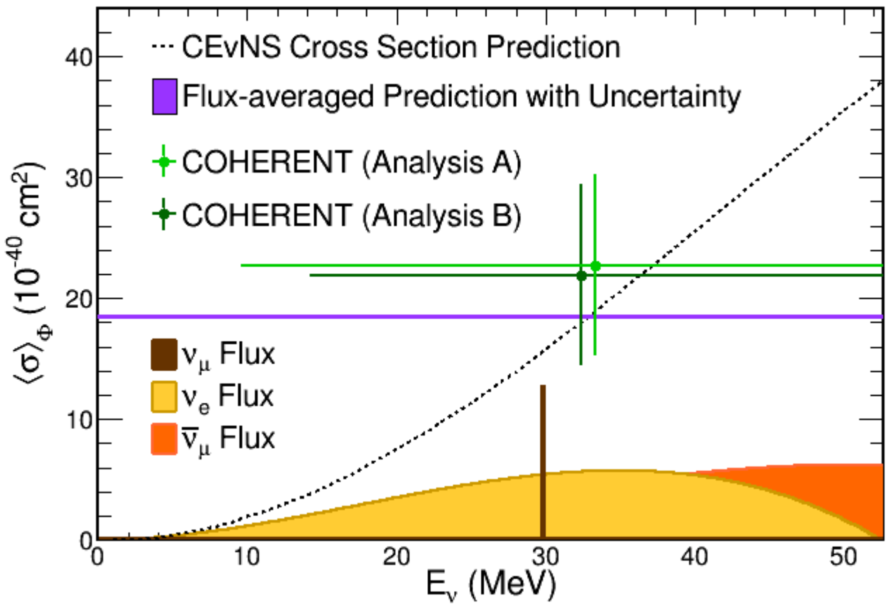


Data Events	3752
Fit CEvNS	159 ± 43 (stat.) ± 14 (syst.)
Fit Beam Related Neutrons	553 ± 34
Fit Beam Unrelated Background	3131 ± 23
Fit Late Beam Related Neutrons	10 ± 11
2Δ(-lnL)	15.0
Null Rejection Significance	3.5σ (stat. + syst.)

- Null hypothesis rejected at **3.5σ** (stat+syst).
- Parallel analysis rejects null at 3.1σ.
- **Result within 1-σ of SM prediction.**
- **BRNs constrained by high-energy data.**



CENNS-10 Physics Results

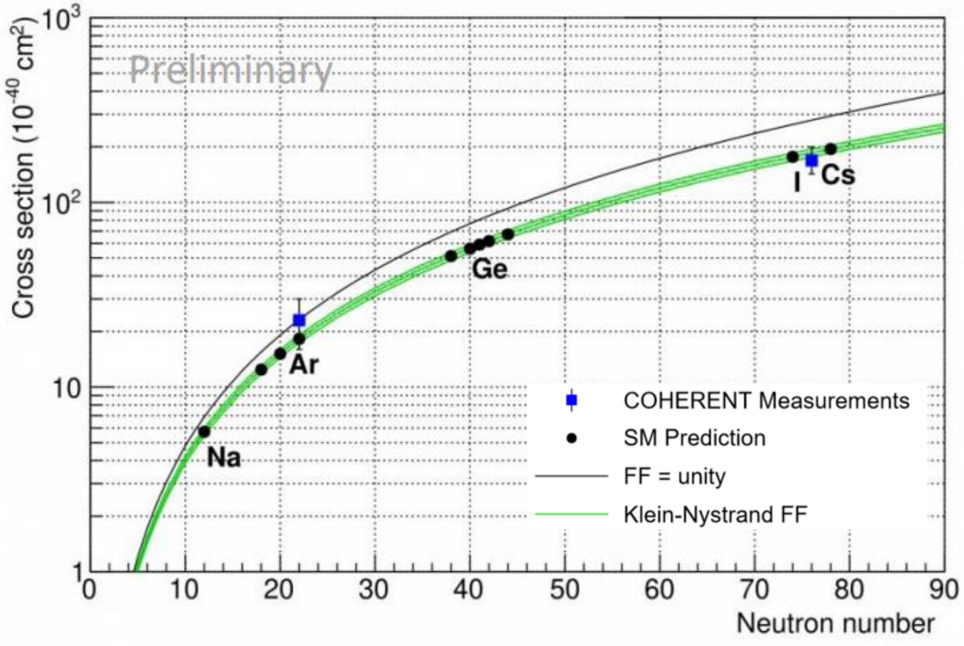


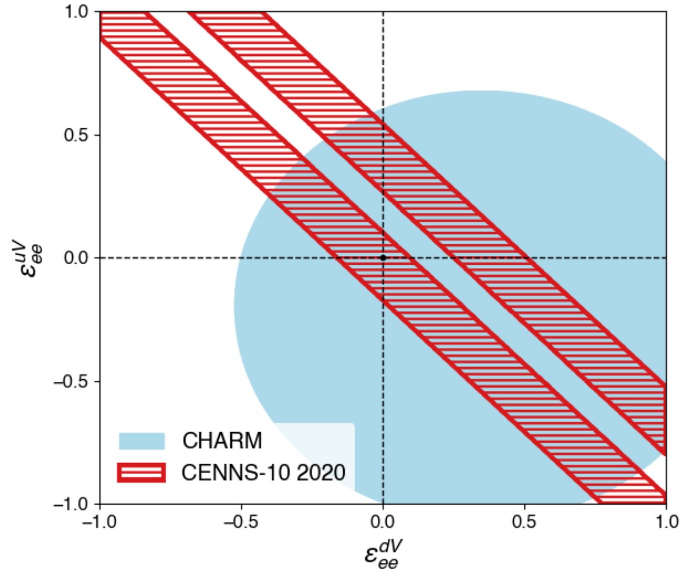
- Combine best fit CEvNS counts with flux, fid. volume, efficiency uncertainties.

$$\frac{N_{meas}}{N_{SM}} = 1.2 \pm 0.4$$

- Obtain flux-averaged cross section:

$$\sigma_{meas} = \frac{N_{meas}}{N_s \phi \epsilon} = \underbrace{(2.3 \pm 0.7)}_{\text{stat dominated}} \times 10^{-39}\ cm^2$$





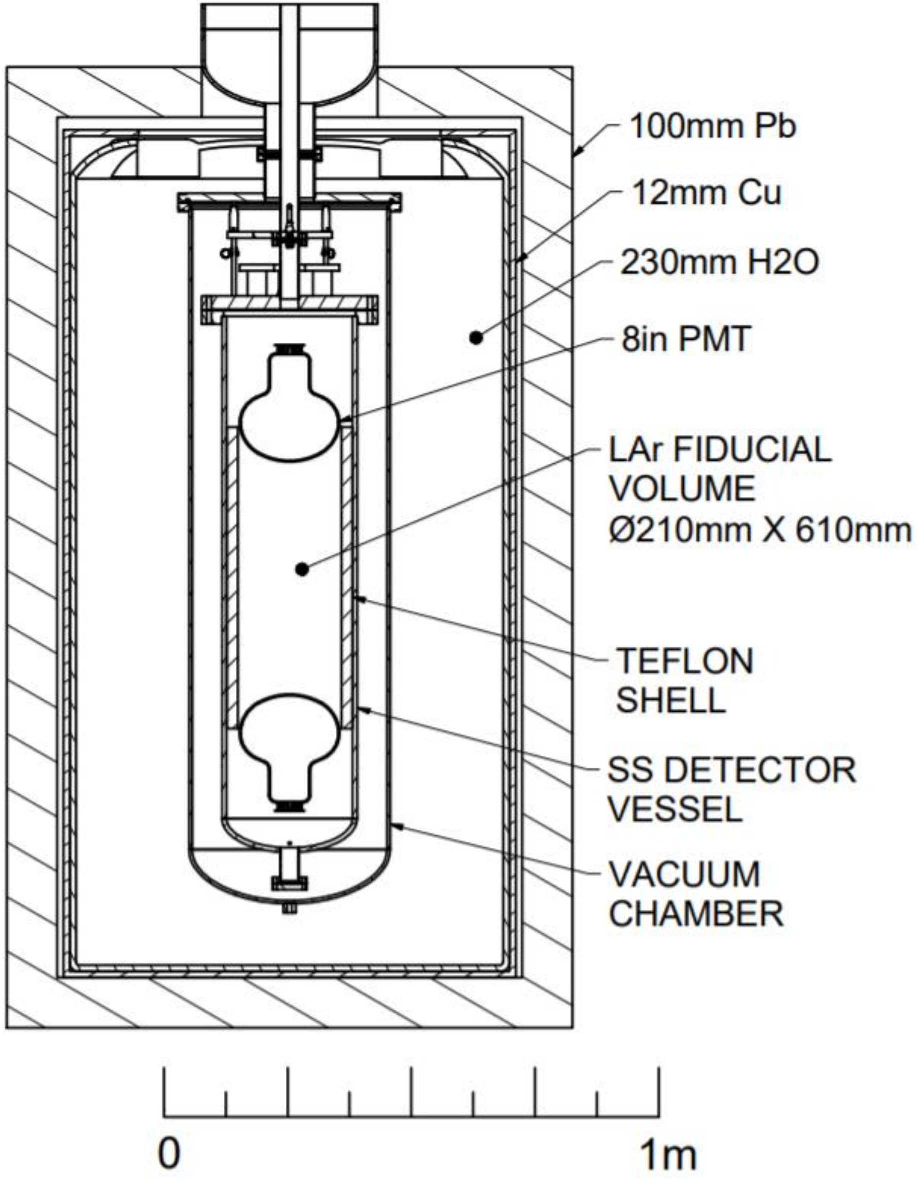
NSI Constraints: Assume non-zero electron flavor-diagonal vectorlike NSI (all other ε set to 0).

arXiv:*2003.10630*

Future of CENNS-10

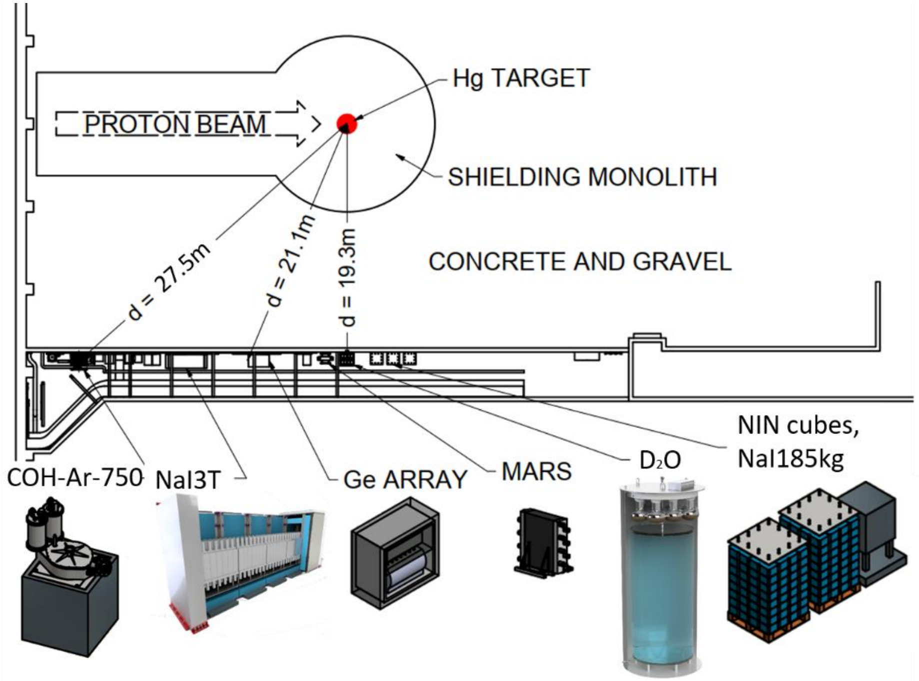
- Additional data to be analyzed (**16** GWhr accumulated in current configuration) with potential improvements in analysis methods and understanding of systematics.

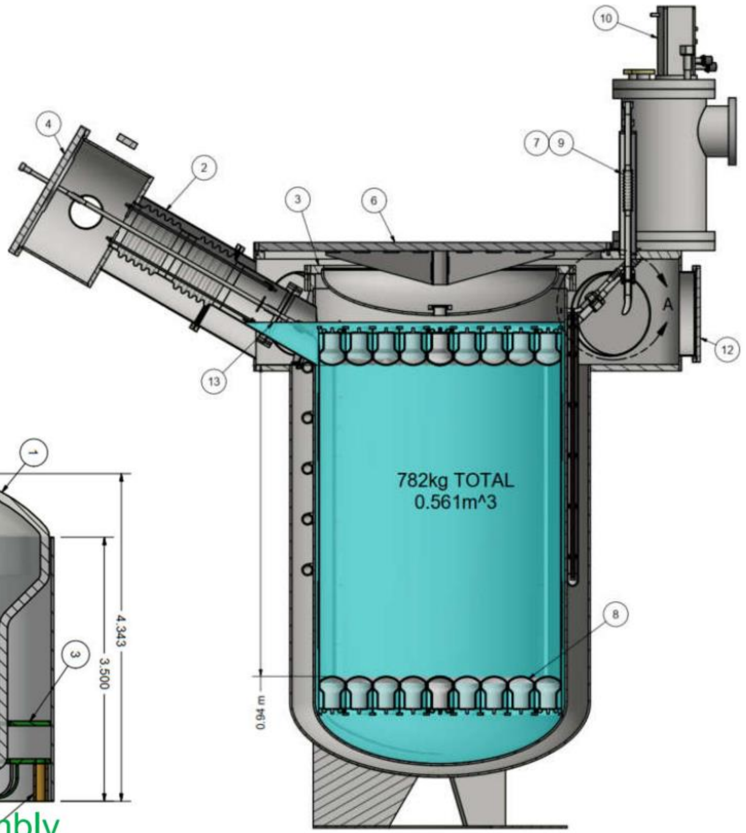
- Potential modifications / testing:
  - Reduced steady-state bkg with underground Ar.
  - Xe-doping for increased light output.
  - Test machine learning techniques for reconstruction and background rejection.
  - Test photon detection schemes for planned **ton-scale detector.**

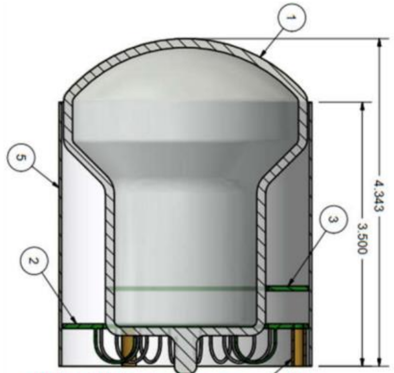


COH-Ar-750

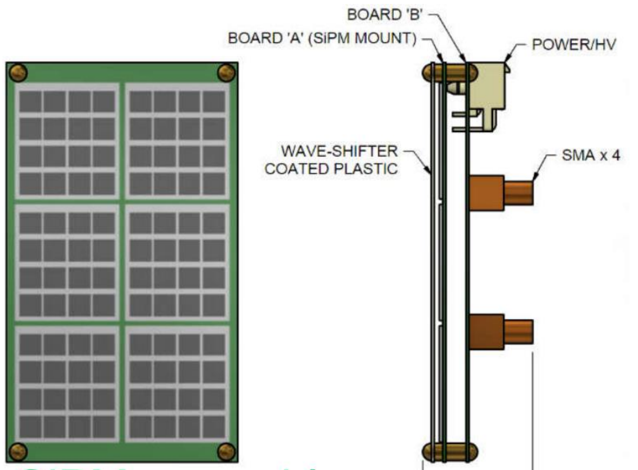
- Scaled up single-phase LAr detector featuring 610 kg fiducial mass.
- Photon detection system designed to maintain or exceed 20 keVnr threshold.
- Will fit in existing CENNS-10 location.
- Two possible configurations (SiPMs or 3” PMTS)
- Ongoing R&D at IU, ORNL, and Tufts.





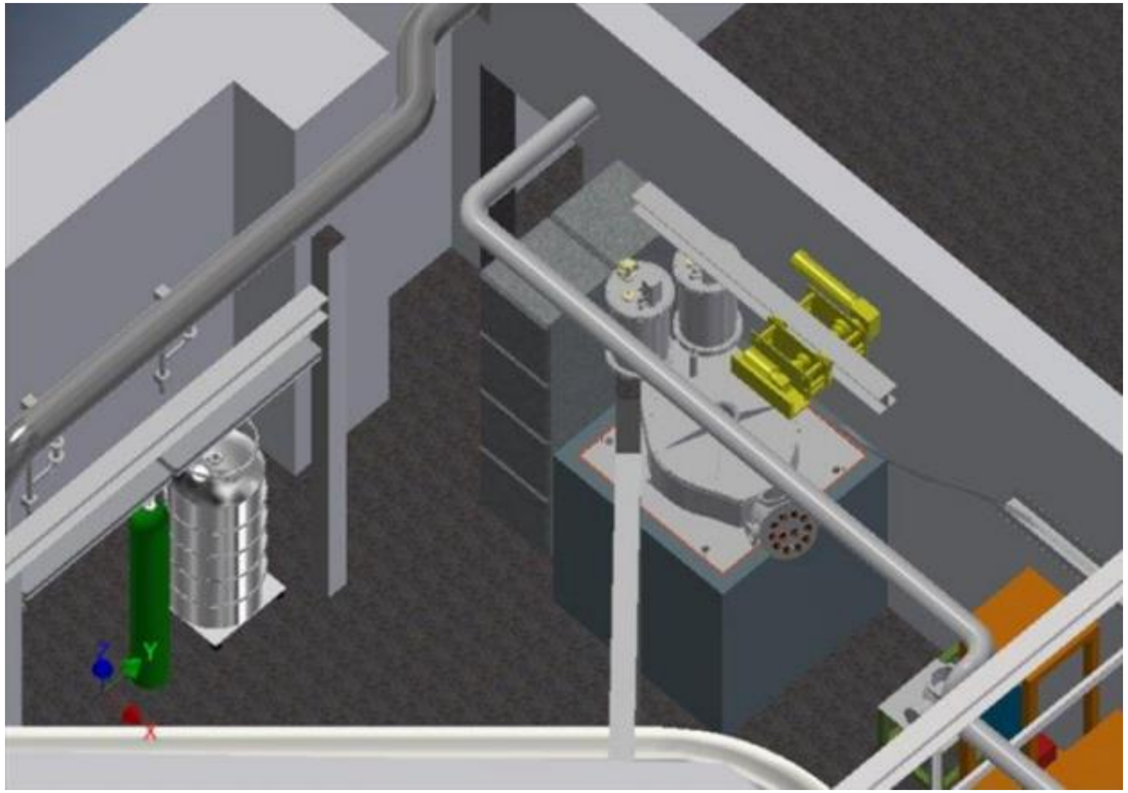


3” PMT assembly



SiPM assembly

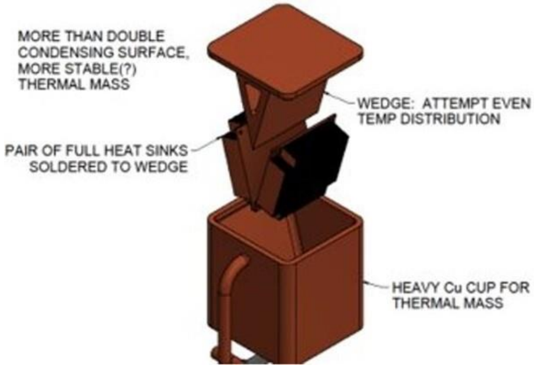
COH-Ar-750 Development



Design in hand which accounts for spatial constraints in deployment.

Testing of light collection at cryogenic temperatures underway.

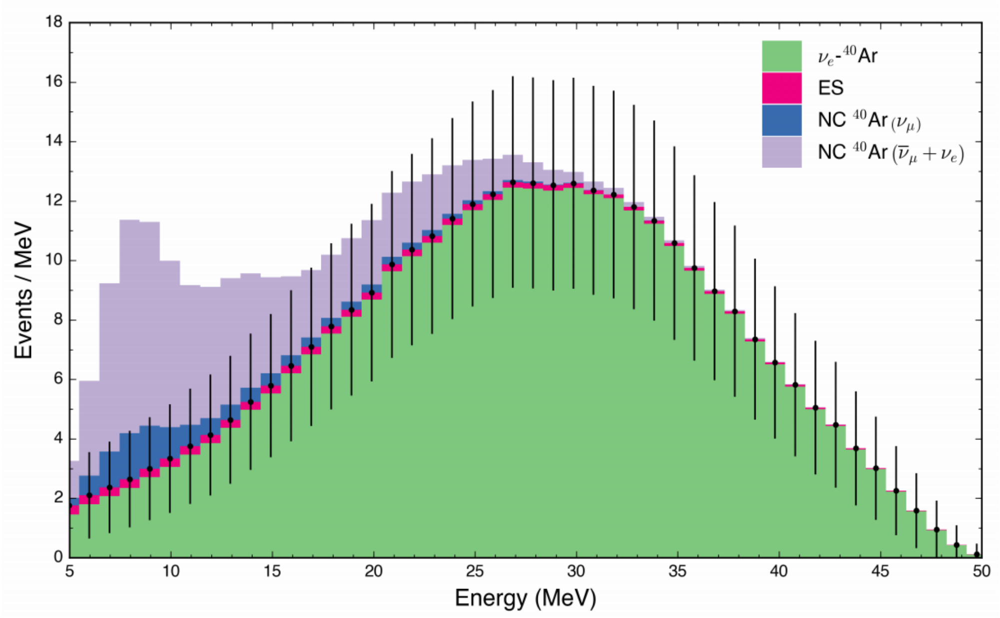
Copper liquefier cup designed and assembled.



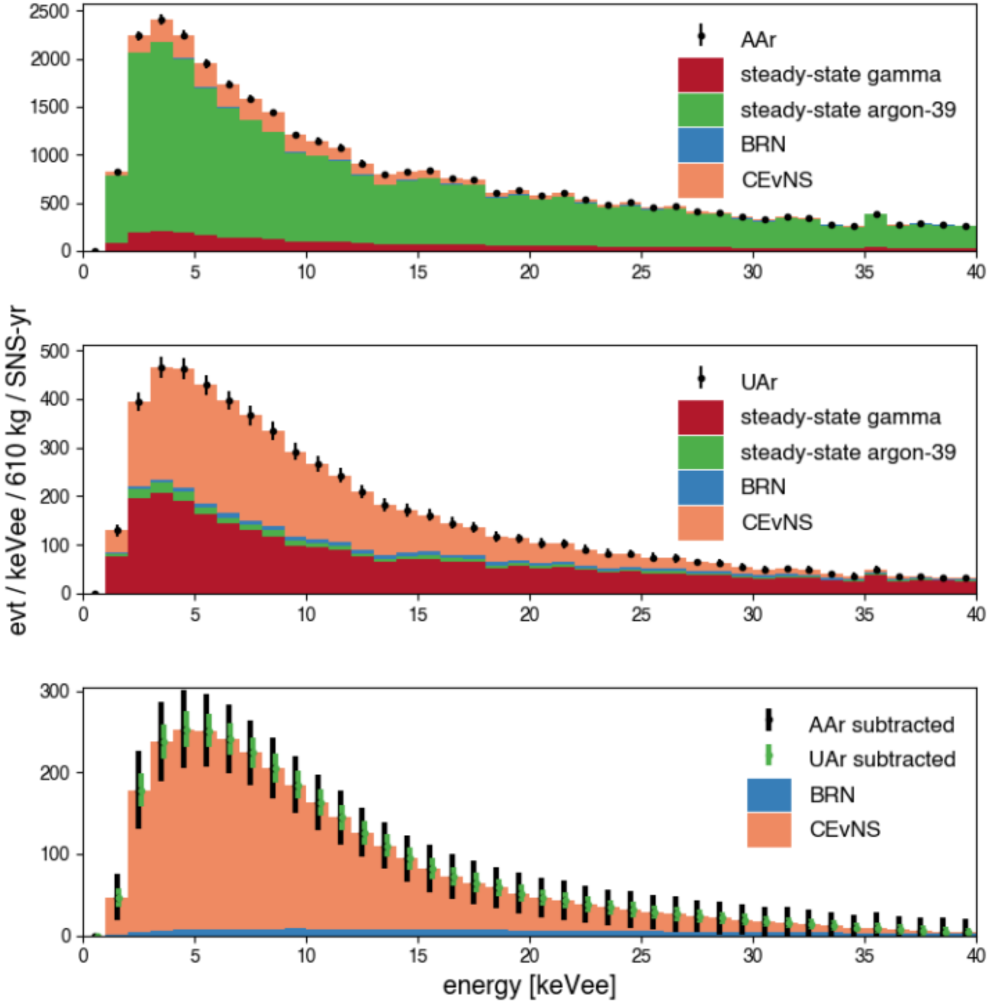
Precision Physics with COH-Ar-750

- Design capable of handling dynamic range necessary for inelastic neutrino interactions as well as CEvNS recoils.
- Signal expectation of ~3000 CEvNS per SNS-year
- Approx. 400 inelastic CC and NC events per SNS-year

Inelastic Interactions

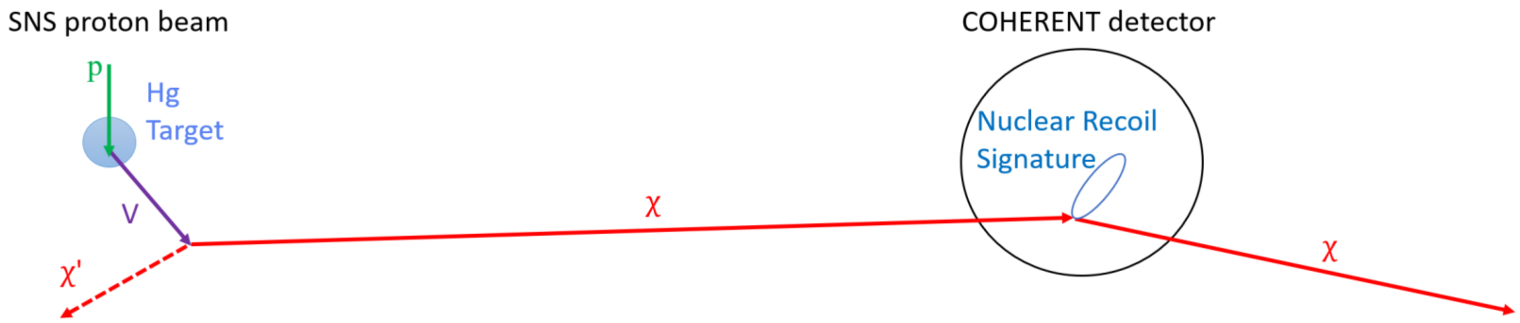


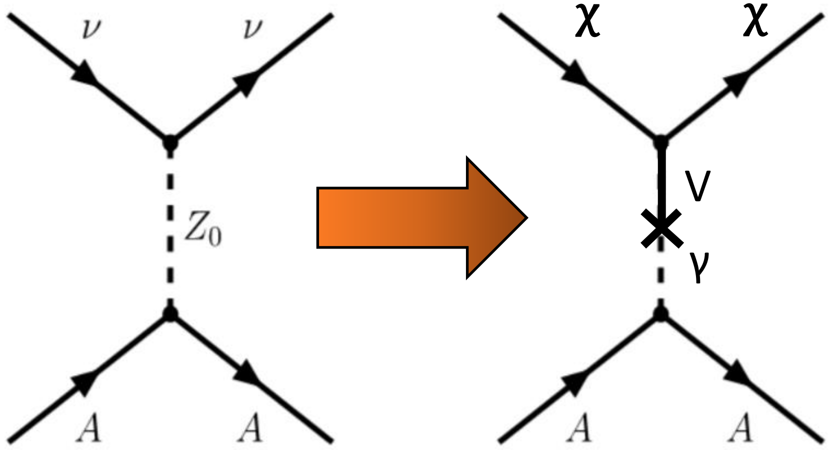
CEvNS



Use of UAr would dramatically reduce steady-state bkg.

Accelerator-Produced Dark Matter





- Potential for portal DM via neutral pions produced at the target:

Vector portal: $\mathcal{L} = \mathcal{L}_\chi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{\kappa}{2}V^{\mu\nu}F_{\mu\nu}$

Baryonic portal: $\mathcal{L}_B = \mathcal{L}_\chi - \frac{1}{4}V^B_{\mu\nu}V^B_{\mu\nu} + \frac{1}{2}m_B^2 V^B_\mu V^B_\mu + \sum_{N=n,p} i\bar{N}\,\not{D}N$

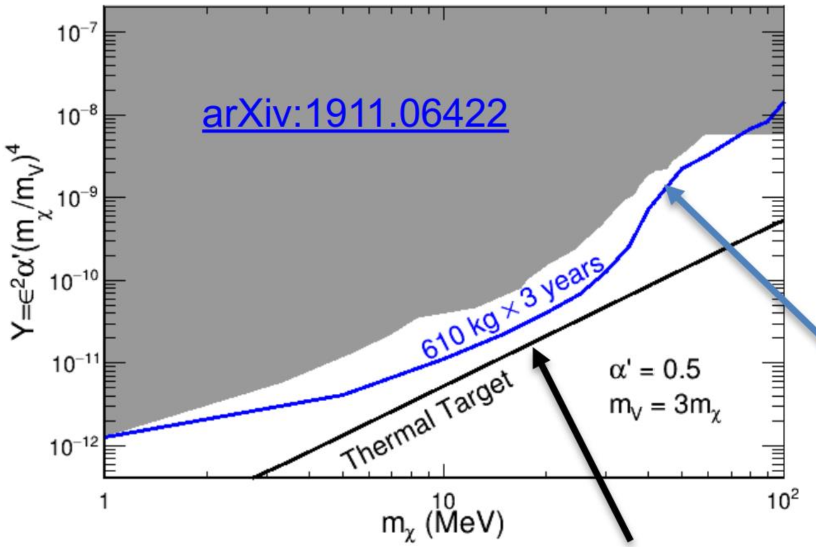
deNiverville et al.,
Phys Rev **D92** 095005 (2015)

- Signal Expectation:
  - NR events with beam timing profile
  - Recoil spectrum depends on mediator and DM mass.
  - Harder spectrum than CEvNS

- Improved understanding and mitigation of beam-related neutrons improves sensitivity.

Accelerator-Produced Dark Matter

Vector Portal

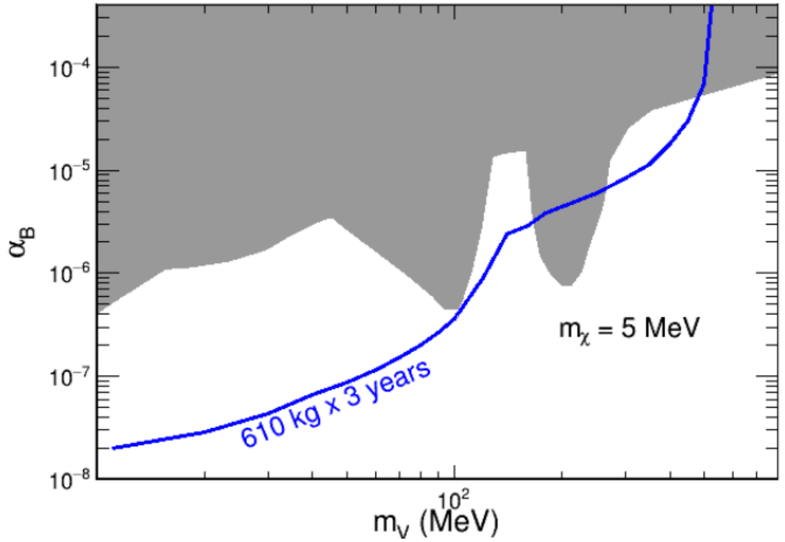


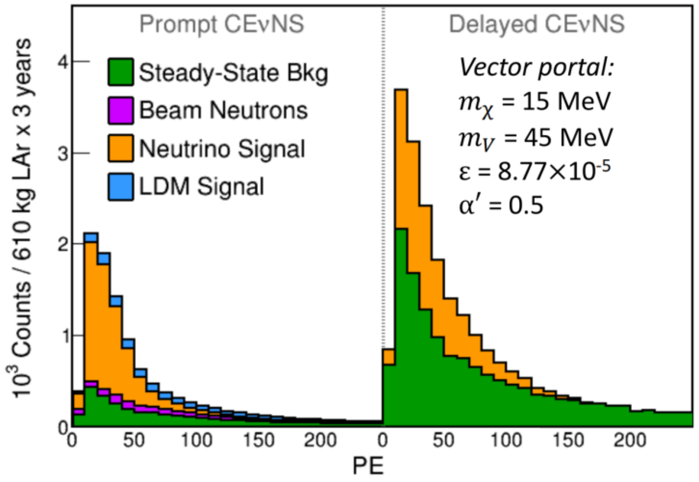
arXiv:1911.06422

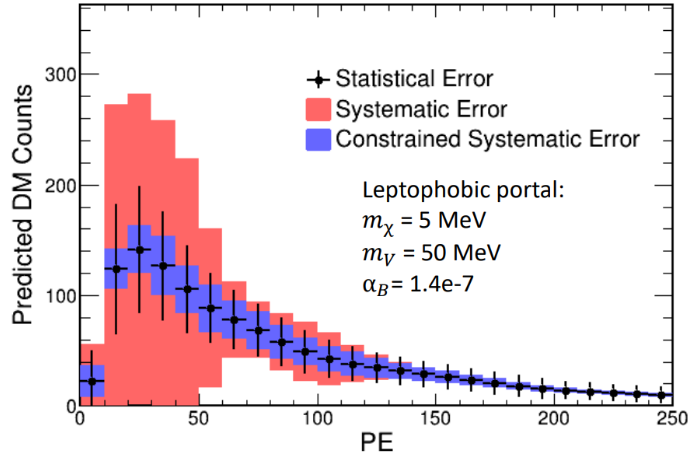
3 years of COH-Ar-750 @ SNS

Relic density

Baryonic Portal







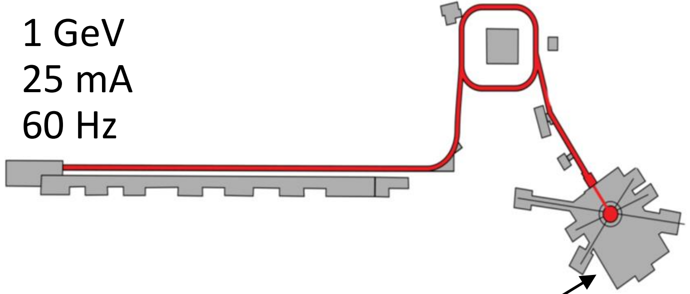
- Significant constraints on DM models can be place with 3 years of COH-Ar-750 data.
- Prompt CEvNS events represent primary background, but delayed sideband analysis can constrain error on prompt CEvNS estimate.
- Knowledge of beam T_0 is important; recent dedicated timing studies have helped reduce this uncertainty.

Future Opportunities

Today

- 900 users
- Materials at atomic resolution and fast dynamics

1.4 MW
1 GeV
25 mA
60 Hz

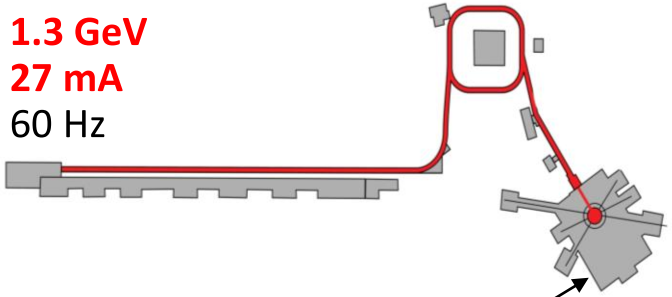


FTS
1.4 MW
60 Hz

2024 after PPU

- **1000+** users
- Enhanced capabilities

2.0 MW
1.3 GeV
27 mA
60 Hz



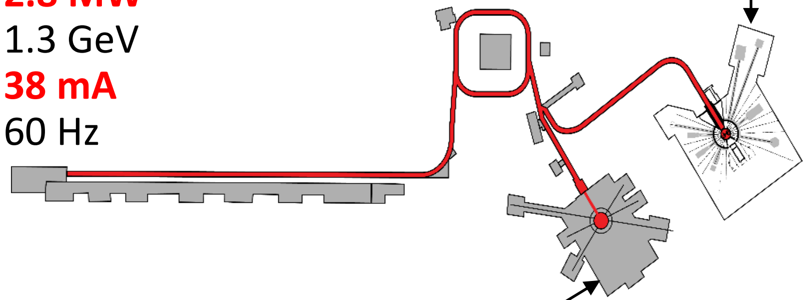
FTS
2 MW
60 Hz

2028 after STS

- **2000+** users
- Hierarchical materials, time-resolution and small samples

STS
0.7 MW
15 Hz

2.8 MW
1.3 GeV
38 mA
60 Hz



FTS
2 MW
45 pulses/sec

Second Target Station

- Neutrino Alley has served as an excellent location, but new target station provides opportunity for a more dedicated neutrino physics space.
- Potential for two larger mass detectors (~*10 tons*) with one likely being LAr.
- Accelerator DM production will be boosted in beam direction; possibility to deploy detectors at smaller angles w.r.t. beam axis.
- Understanding neutron propagation and necessary shielding is important!

Summary

- Analysis of CENNS-10 data has resulted in the first detection of CEvNS on Ar.
- Upcoming analysis will feature more than double the statistics.
- R&D underway for successor COH-Ar-750 detector with CENNS-10 serving as a testbed for new ideas.
- COH-Ar-750 offers rich physics potential for CEvNS and accelerator dark matter.
- Future upgrades to SNS power and the addition fo the STS present an excellent opportunity for larger detectors and interesting physics!

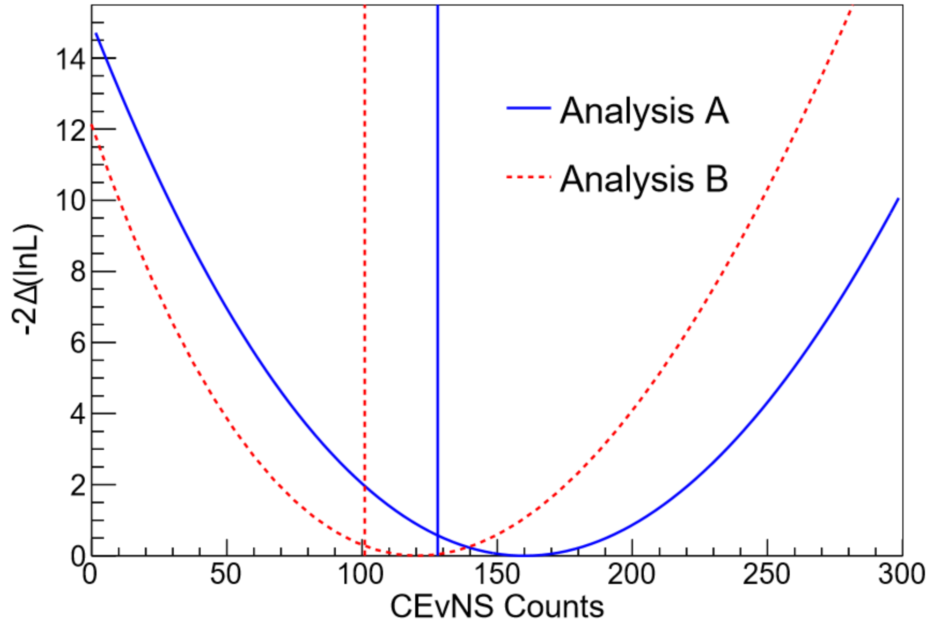
Auxiliary Slides

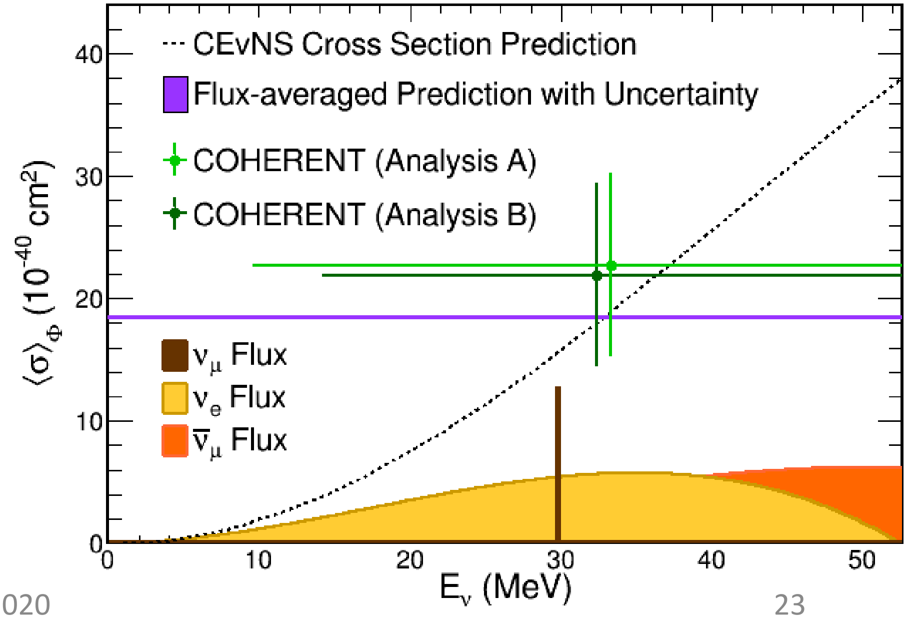
Parallel Analysis Comparison

- Separate blind analysis performed by Russian collaborators.
- Independent reconstruction software and stricter cuts for analysis level dataset.
- Results consistent with US analysis.

Moscow analysis results

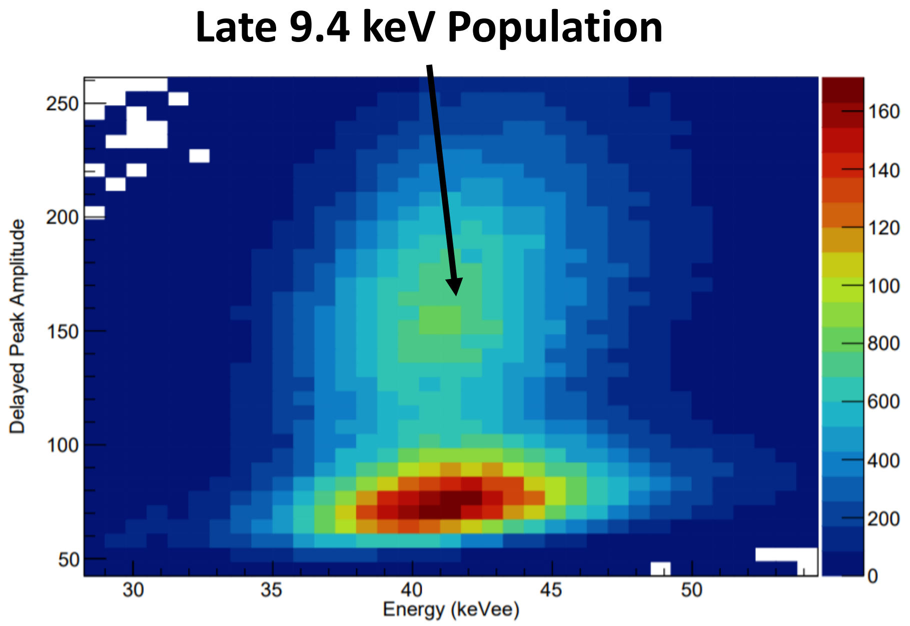
Predicted CEvNS	101 ± 12
Fit CEvNS	121 ± 36 (stat.) ± 15 (syst.)
$2\Delta(\text{-lnL})$	12.1
Null Rejection Significance	3.1σ (stat. + syst.)

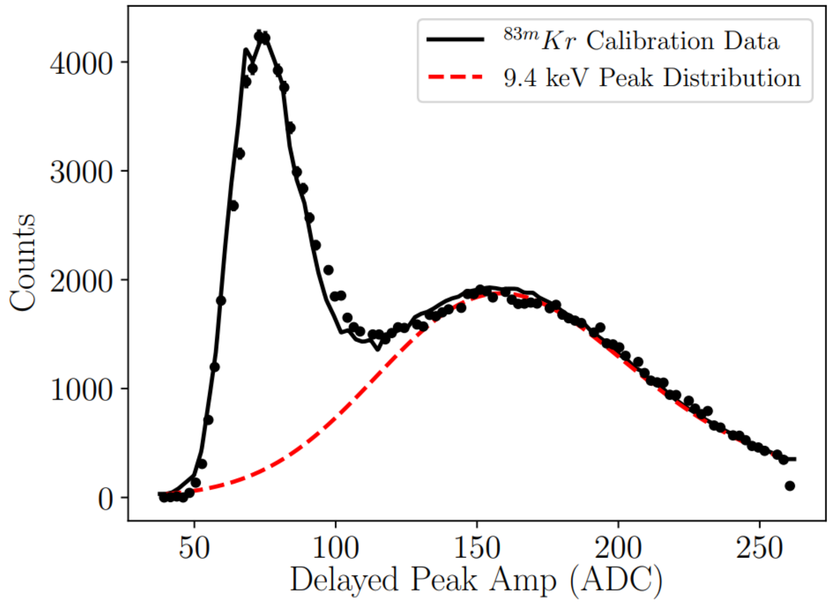


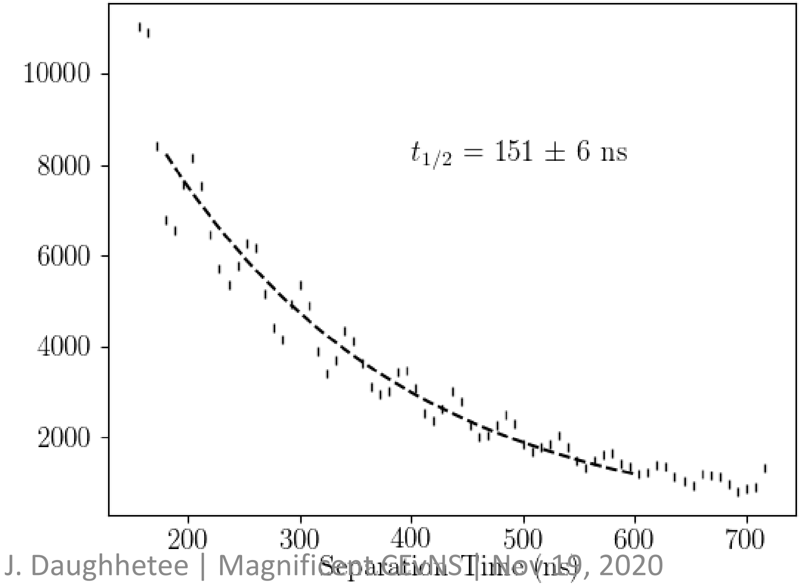


^{83m}Kr Component Analysis

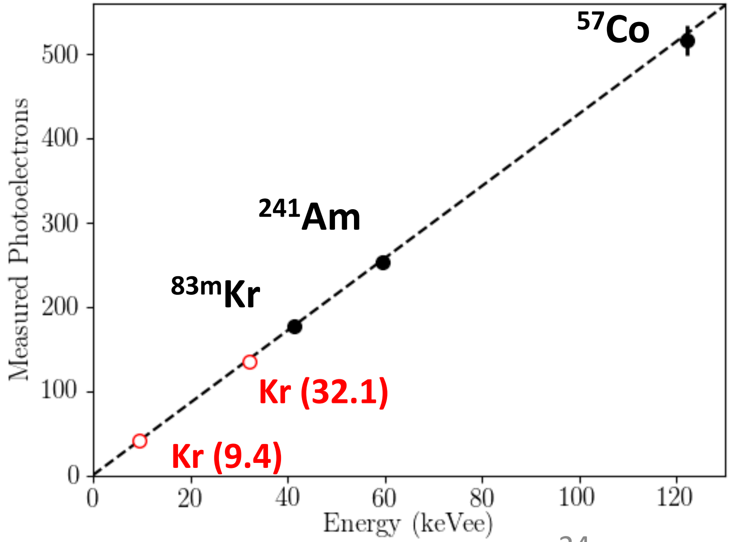
- For ER events, relationship between peak height and total event integral can be established.
- Search for delayed peak (> 152 ns) in combined waveform which comes from 9.4 keV electron.
- Average amplitude of late peak distribution can be converted to expected total integral.


Late 9.4 keV Population





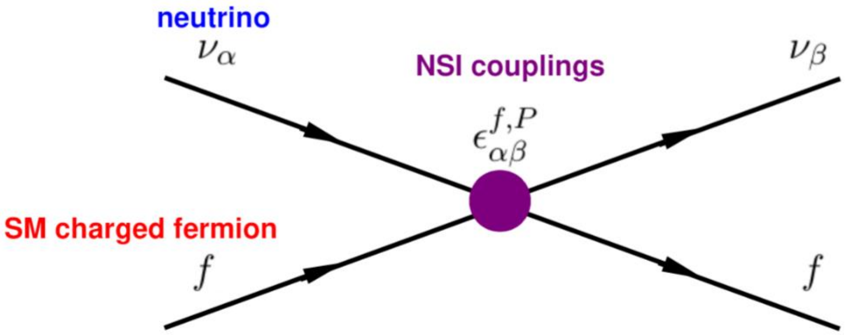
Confirmation of detector linearity well into CEvNS energy ROI.



Non-Standard Interactions

Potential Non-SM Vector Interactions

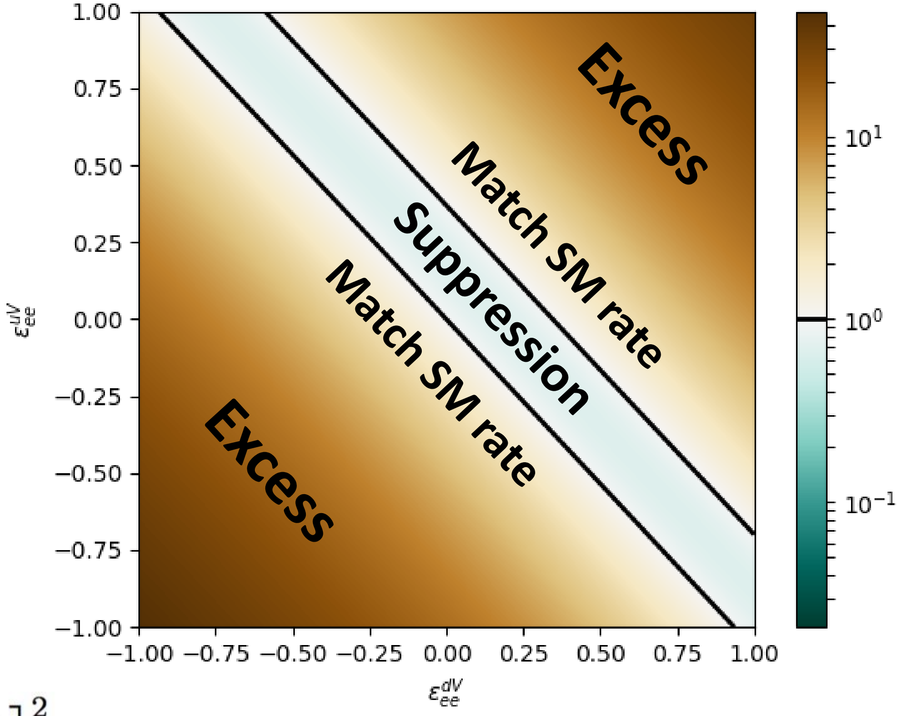
$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} (\epsilon^{f,P}_{\alpha\beta})(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$



Assuming heavy NSI mediators

Modified Cross Section

$$Q_W^2 \to Q_{\rm NSI}^2 = 4\left[N\left(-\frac{1}{2} + \epsilon^{uV}_{ee} + 2\epsilon^{dV}_{ee}\right) + Z\left(\frac{1}{2} - 2\sin^2\theta_W + 2\epsilon^{uV}_{ee} + \epsilon^{dV}_{ee}\right)\right]^2 + 4\left[N(\epsilon^{uV}_{e\tau} + 2\epsilon^{dV}_{e\tau}) + Z(2\epsilon^{uV}_{e\tau} + \epsilon^{dV}_{e\tau})\right]^2 .$$



J. Barranco *et al*. Phys Rev D **76** (2007)
J. Billard, J. Johnston, B. Kavanagh. arXiv:1805.01798

Presence of these interactions can lead to suppression or enhancement of CEvNS rate w.r.t. Standard Model.