COHERENT experiment with LAr: First results and Current status

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on behalf of COHERENT Collaboration

Moscow, 09.10.2020, ICPPA-2020

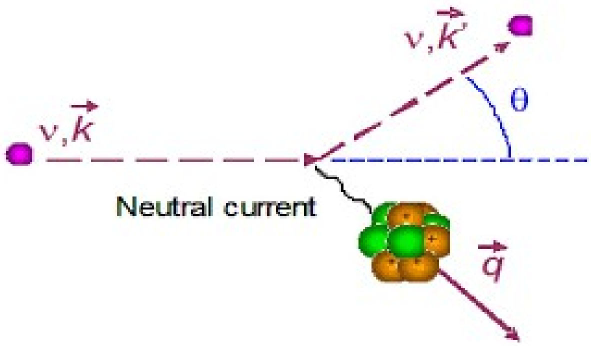
Coherent Elastic Neutrino Nucleus scattering

CEvNS is a fundamental process predicted in 1974 and observed for the first time by the COHERENT Collaboration in 2017

10.1126/science.aao0990

$$\nu + A \rightarrow \nu' + A'$$

D.Z. Freedman, Phys. Rev. D 9 (1974)
V.B. Kopeliovich and L.L. Frankfurt, ZhETF Pis. Red. 19 (1974)

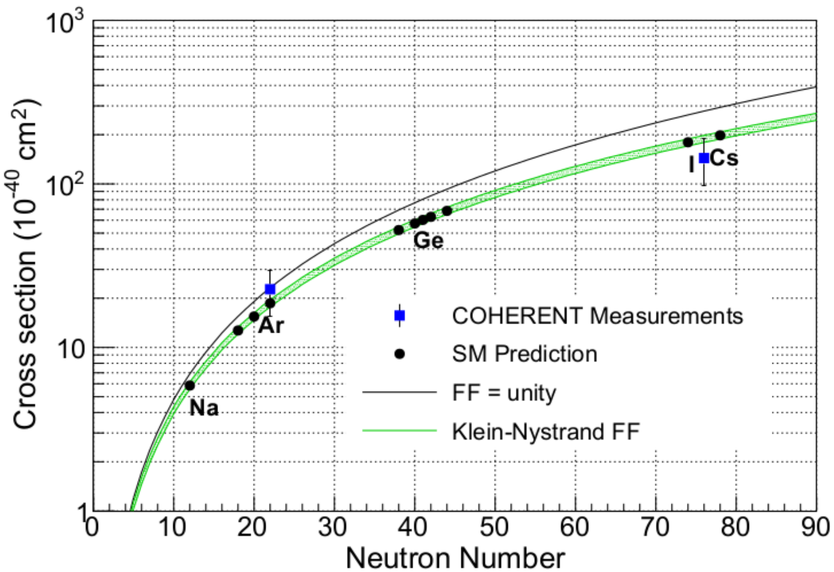


Total cross section of the process can be described by the formula:

$$\sigma_{tot} = \frac{G_F^2 E_\nu^2}{4\pi}[Z(1-4\sin^2\theta_W)-N]^2 F^2(Q^2)$$

$$\sigma_{tot} \approx \frac{G_F^2 N^2}{4\pi} E_\nu^{\ 2} \ \sim \ N^2 \qquad Q \leq \frac{1}{R}$$

$\sigma_{CEvNS} > \ \sigma_{IBD} \sim 10^{-42}\, cm^{-2}$ at least by 2 orders of magnitude



S. R. Klein and J. Nystrand., Phys. Rev. C 60, 014903 (1999)

The COHERENT Collaboration

~80 members,
~20 institutions
4 countries

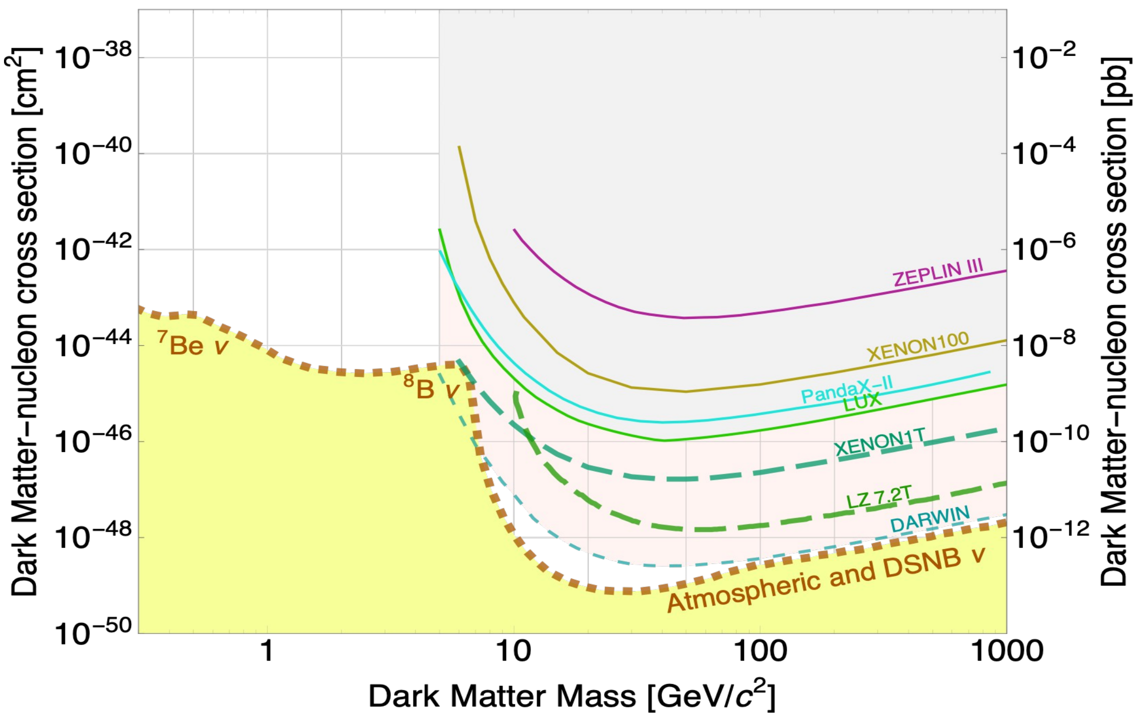
http://coherent.ornl.gov/

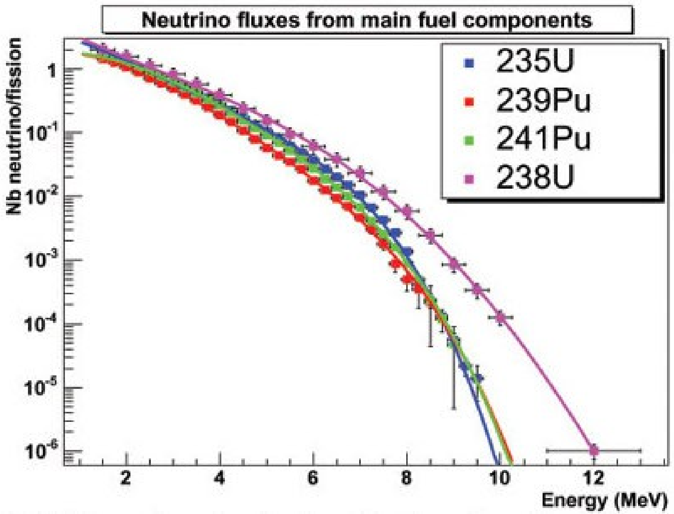
Physics Implications

The most important physics implications of CEvNS are:

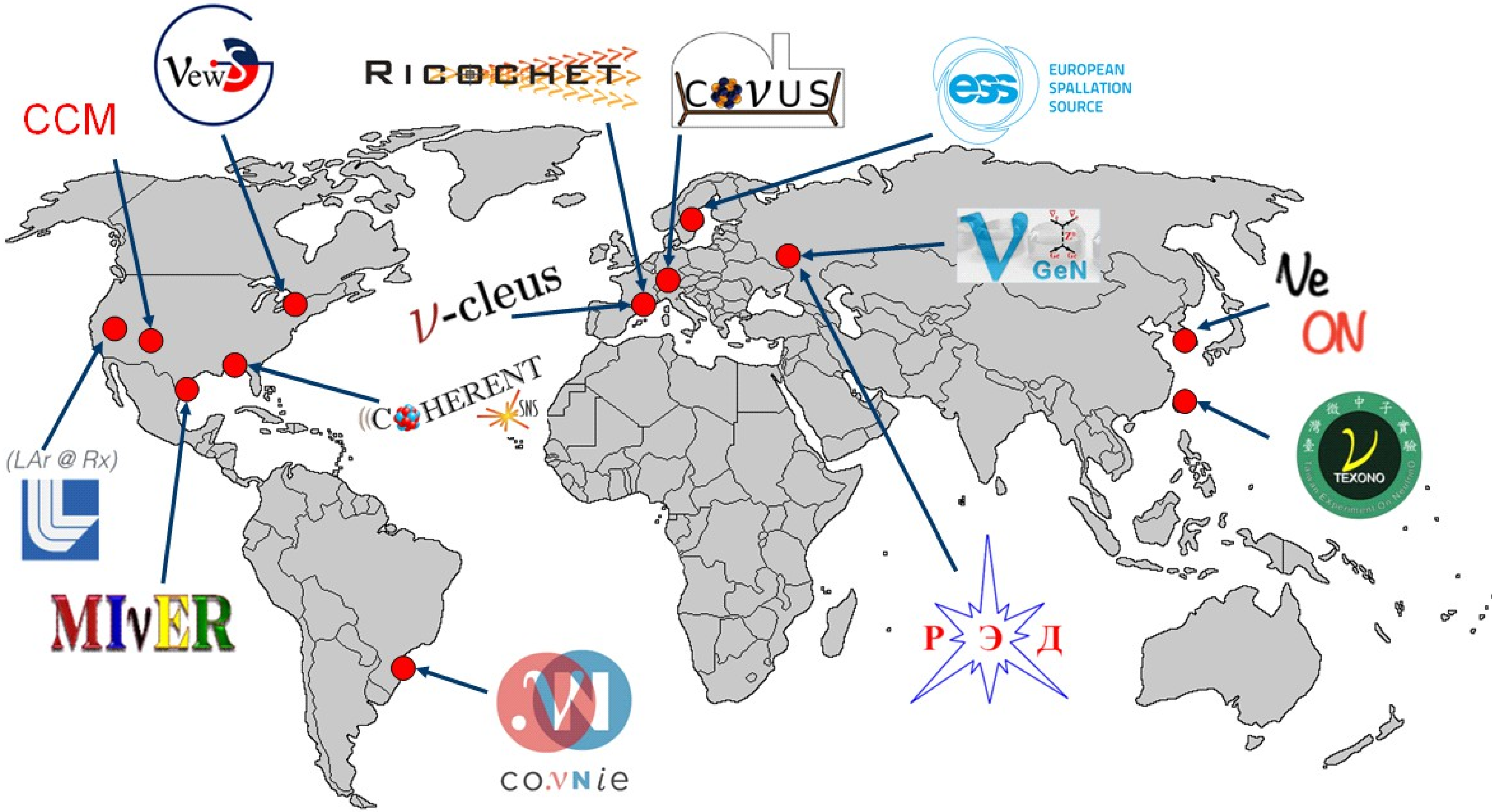
- Physics Beyond the Standard Model
  - Non Standard Interactions
  - Background to Dark Matter searches
- Reactor Monitoring

http://cdms.berkeley.edu/limitplots/



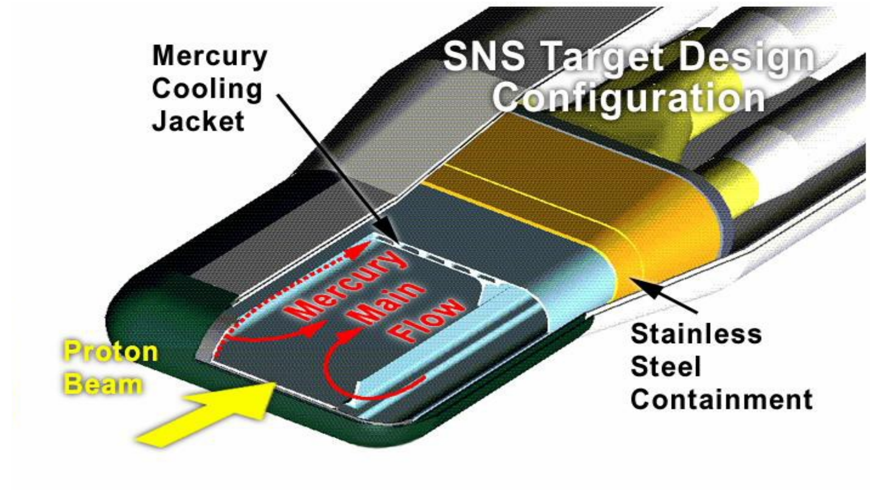


CEvNS Around The World



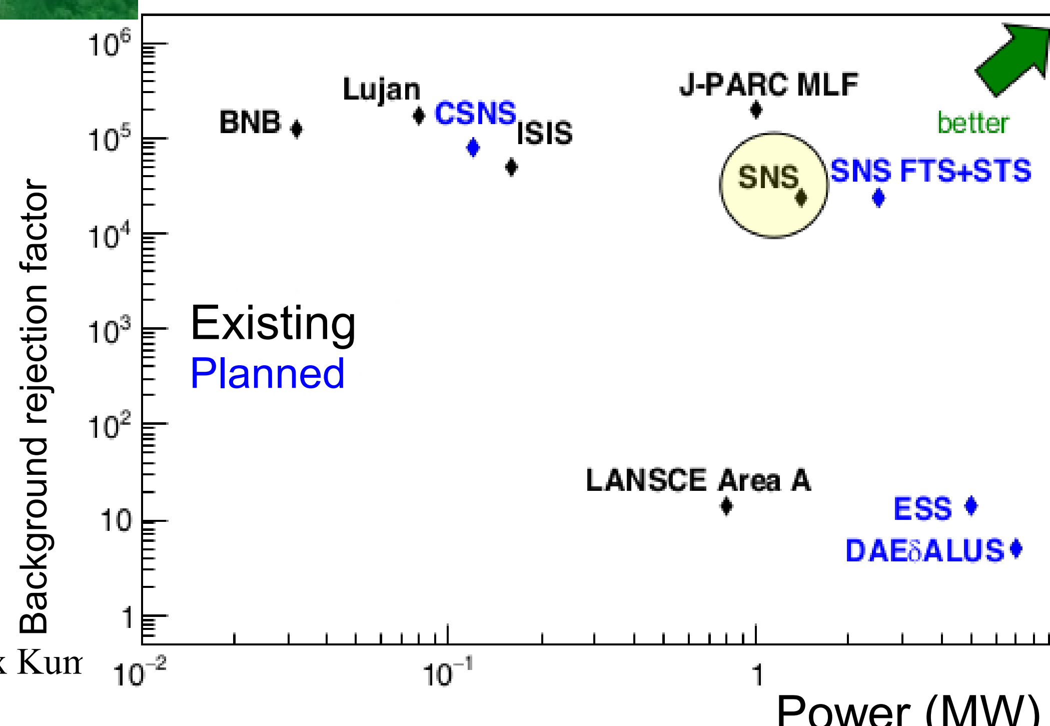
Spallation Neutron Source (SNS)

Oak Ridge, Tennessee, USA

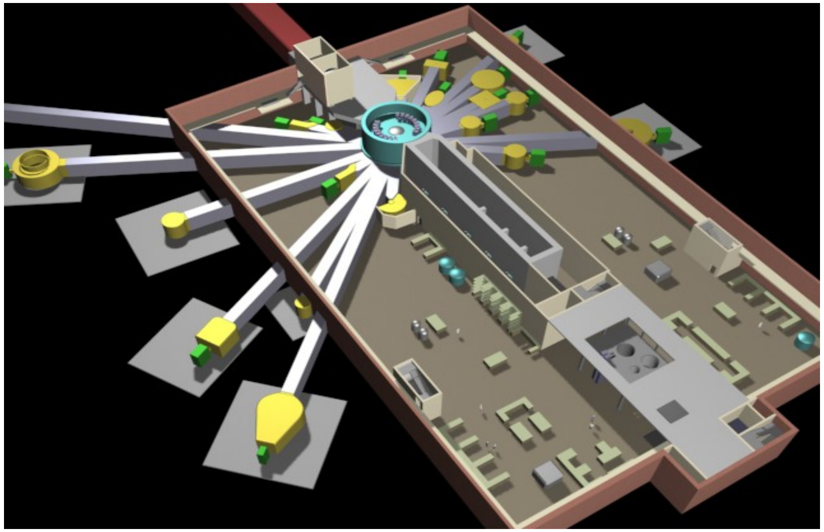


At the moment SNS has the best combination of:

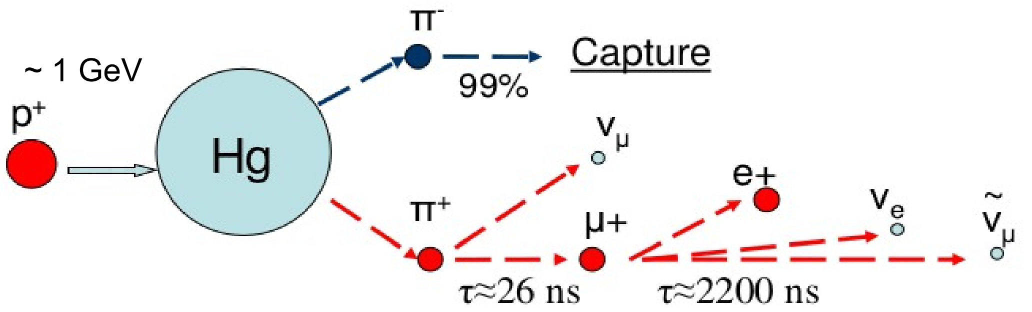
- Beam Power (1.4 MW)
- Mercury Target
- Background rejection factor due to its duty cycle



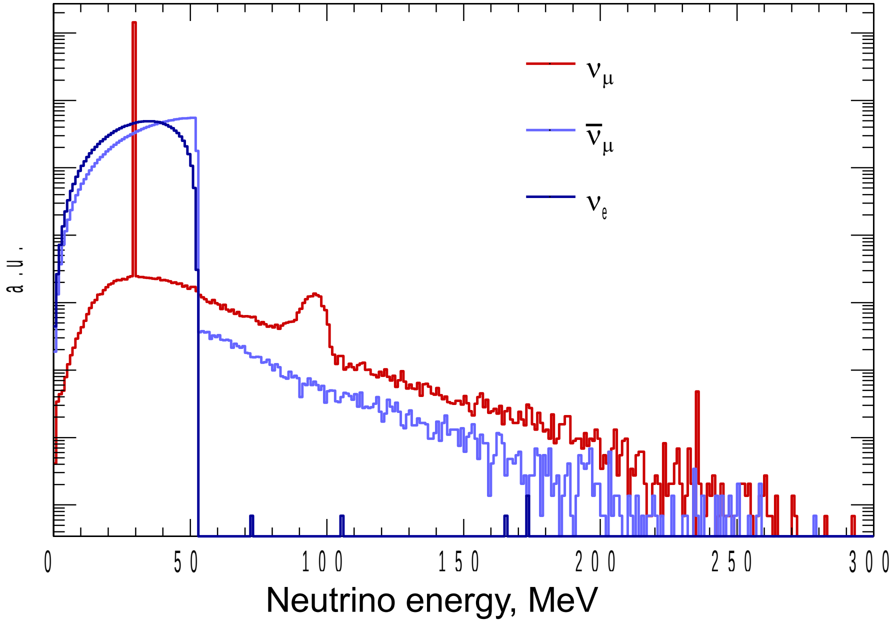
SNS as a neutrino source



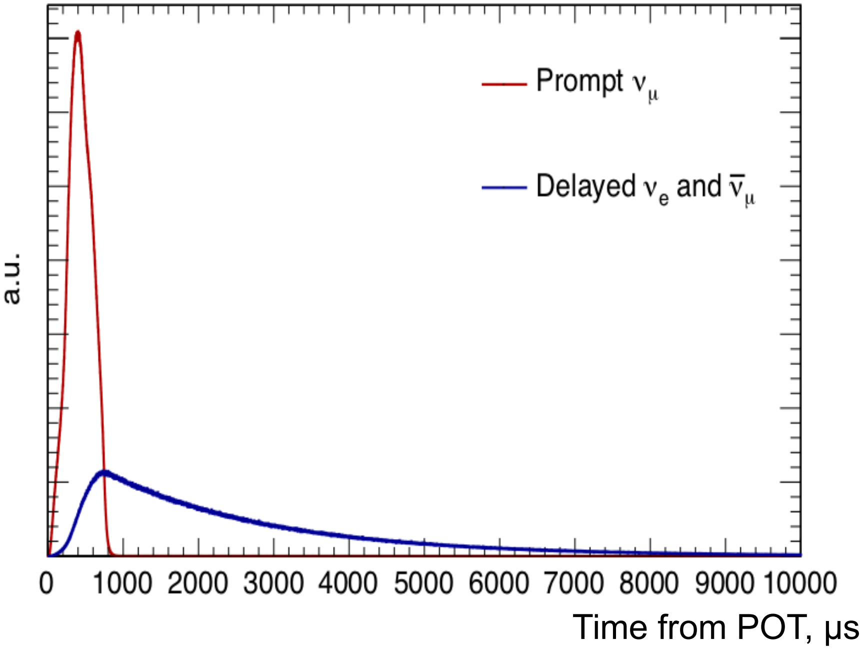
Proton beam energy ~ 1 GeV
Repetition rate — 60 Hz (bunch FWHM is 350 ns)
Neutrino Flux — $4.3 \cdot 10^7$ $cm^{-2}s^{-1}$ at 20 m



SNS neutrino energy spectrum



SNS neutrino timing



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COHERENT at the SNS

Location in **basement** of SNS target building (**"Neutrino Alley"**)

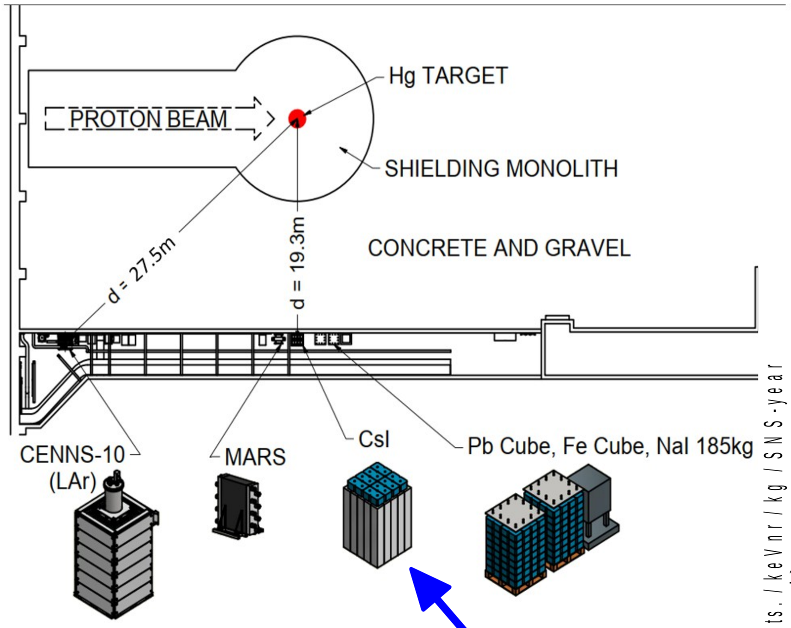
- 19-28 meters from Hg target
- Extremely low backgrounds

Multitarget experiment

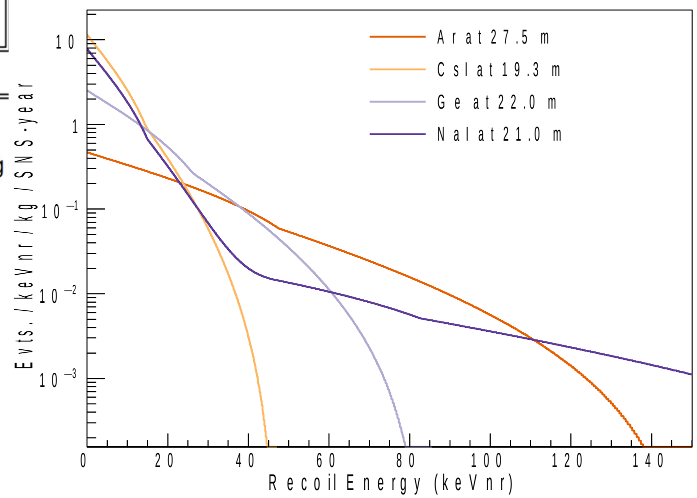
Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil Threshold (keVnr)
CsI[Na]	Scintillating crystal	14.6	19.3	6.5
LAr	Single-phase	24	27.5	20
NaI[Tl]	Scintillating crystal	185 → 3338	28	13
Ge	HPGe PPC	16	20	2-2.5

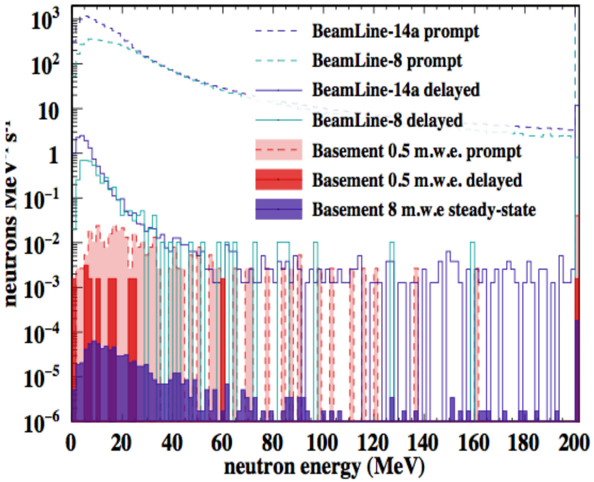
Result is obtained

Will be deployed



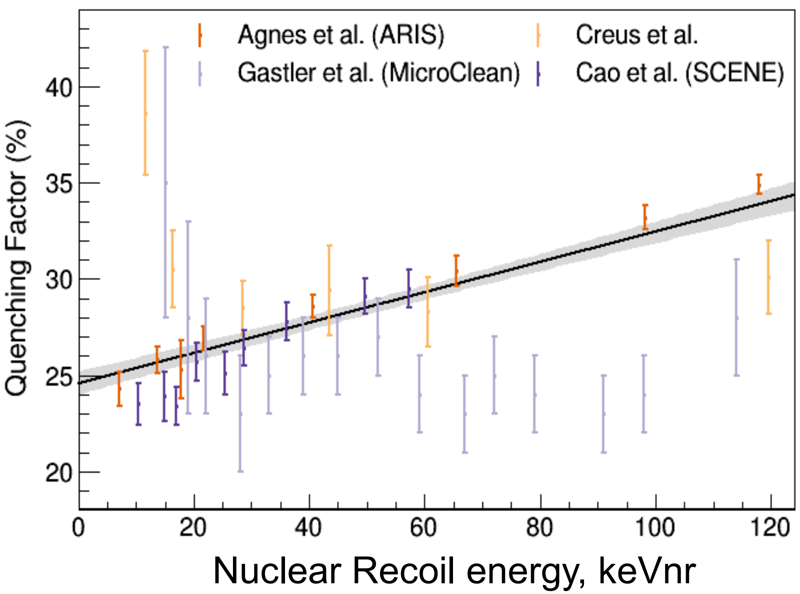
First observation

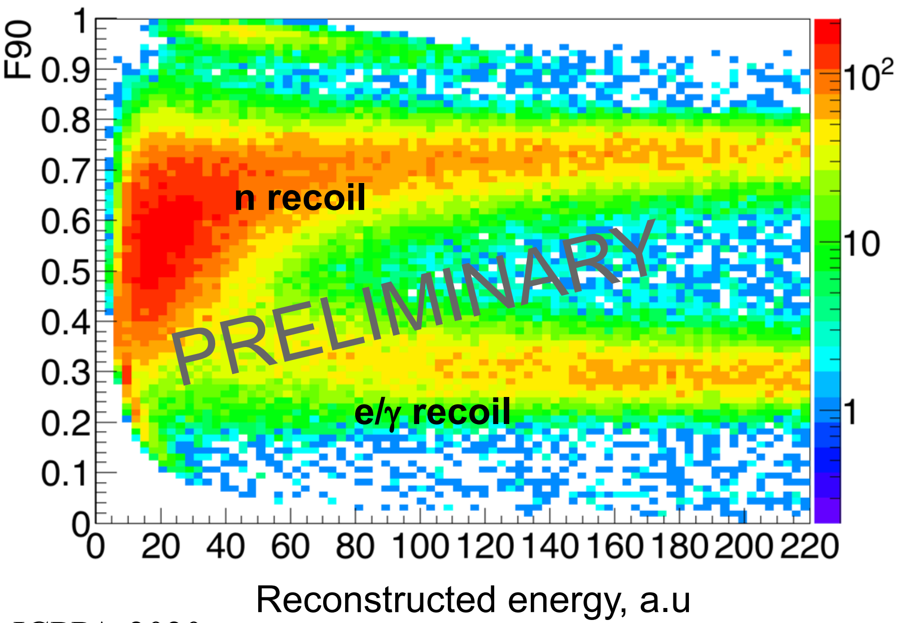




Liquid Argon for CEvNS

- Low N nucleus for CEvNS measurement
- Large scintillation yield of ~ 40 photons/keVee
- Well-measured quenching factor
- Pulse shape discrimination (PSD)/Particle ID (PID) capabilities for nuclear/electron recoil separation
  - ~6 ns singlet light
  - ~1.6 μs triplet light
- Electron recoil (ER) events mostly triplet light, Nuclear recoil (NR) events mostly singlet light



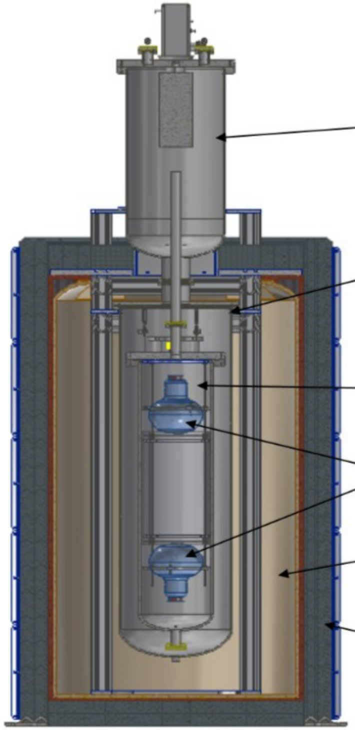


CENNS-10 Liquid Argon Detector

CENNS-10 was deployed at the SNS at 2016

Detector key features:

- 24 kg fiducial volume
- 2 x 8” Hamamatsu PMTs, 18% QE at 400 nm
- Tetraphenyl butadiene (TPB) coated side reflectors and PMT windows
- Pb (10 cm), Cu (1.25 cm), H_2O (20 cm) shielding
- Engineering Run (early 2017): high threshold, no lead shielding: **(Phys. Rev. D100 (2019) no.11, 115020)**
- First Production Run (July 2017-December 2018): improved threshold, blind analysis with two parallel groups. **(arXiv:2003.10630)**



Parallel Blind Analyses

To reduce potential bias on result during analysis procedure CENNS-10 First Production Run was analysed by 2 different groups (A and B):

1. Common CENNS-10 Monte Carlo model was created;
2. SNS beam-on data were not seen until cuts finalized;
3. No cut-values or results shared between groups before data opening

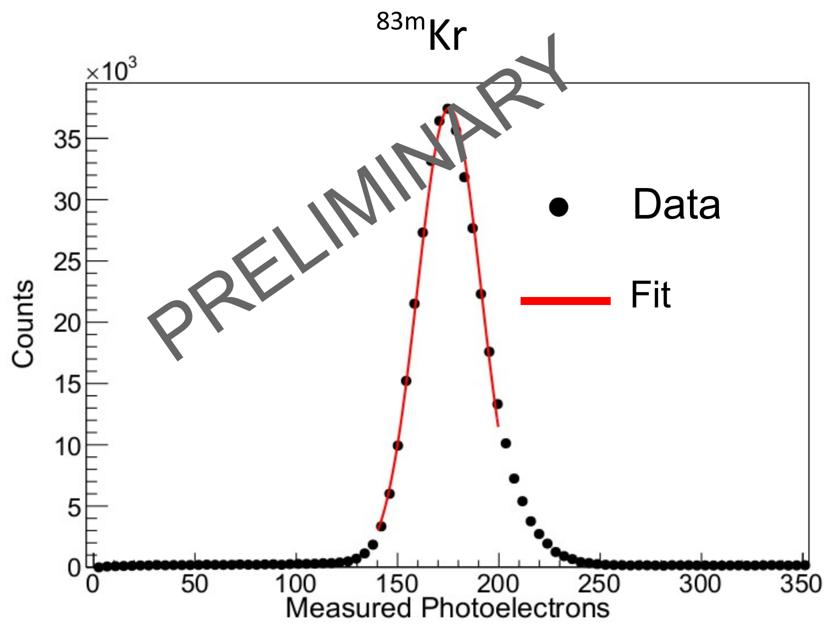
CENNS-10 Calibrations

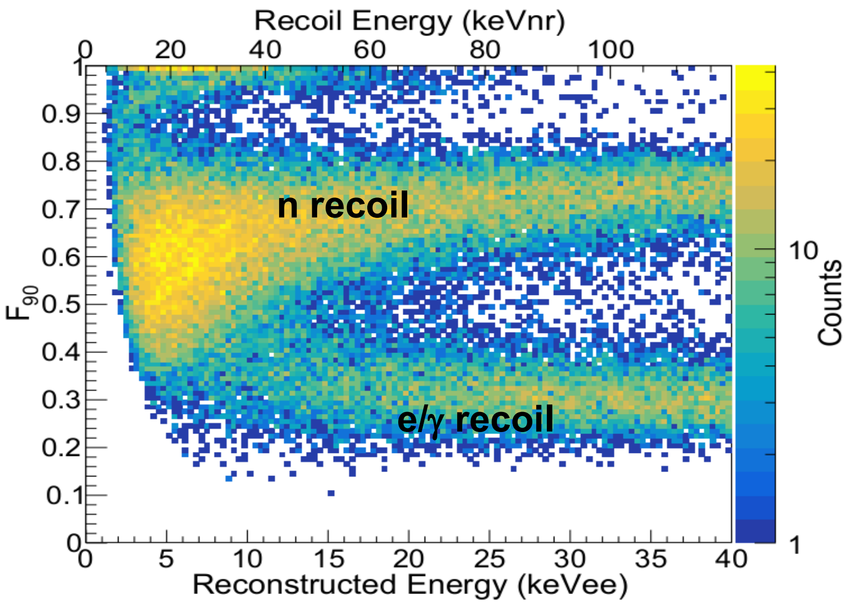
- Calibrate detector with different gamma sources:
  - ^{57}Co
  - ^{83m}Kr
  - ^{241}Am

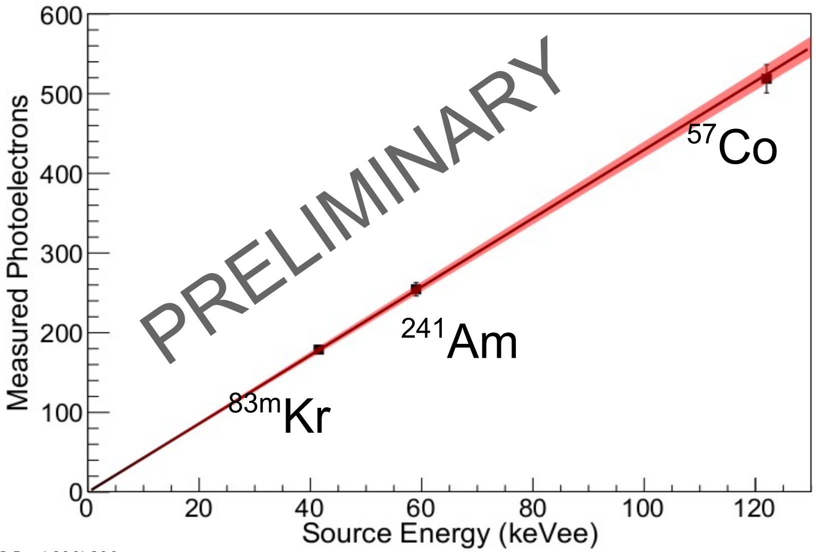
- Measured light yield: 4.6 ± 0.4 PE/keV

- Detector resolution is ~9% at 41.5 keV

- Calibrate detector nuclear recoil response using AmBe source



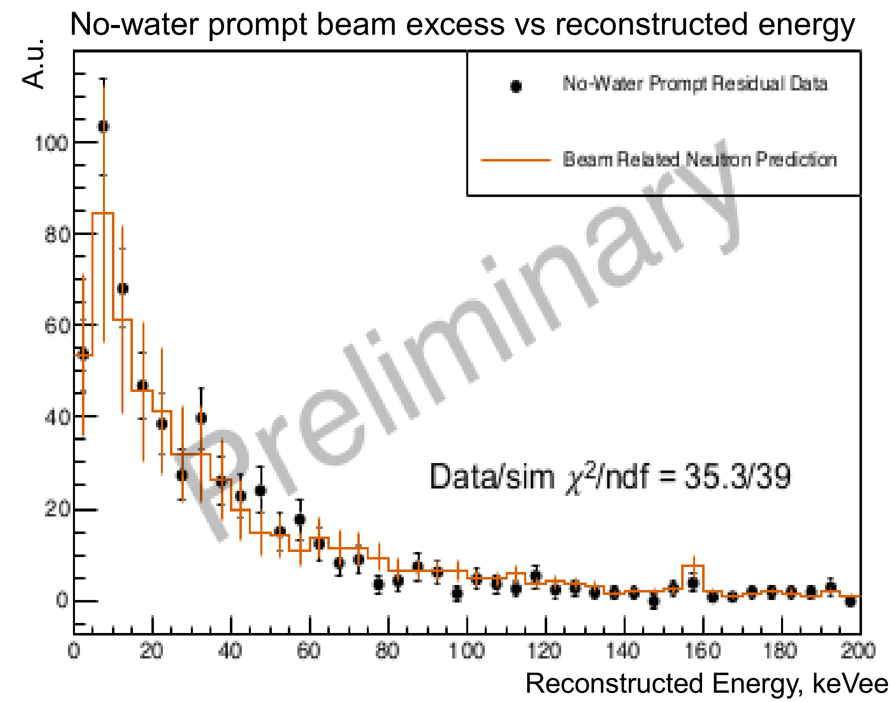


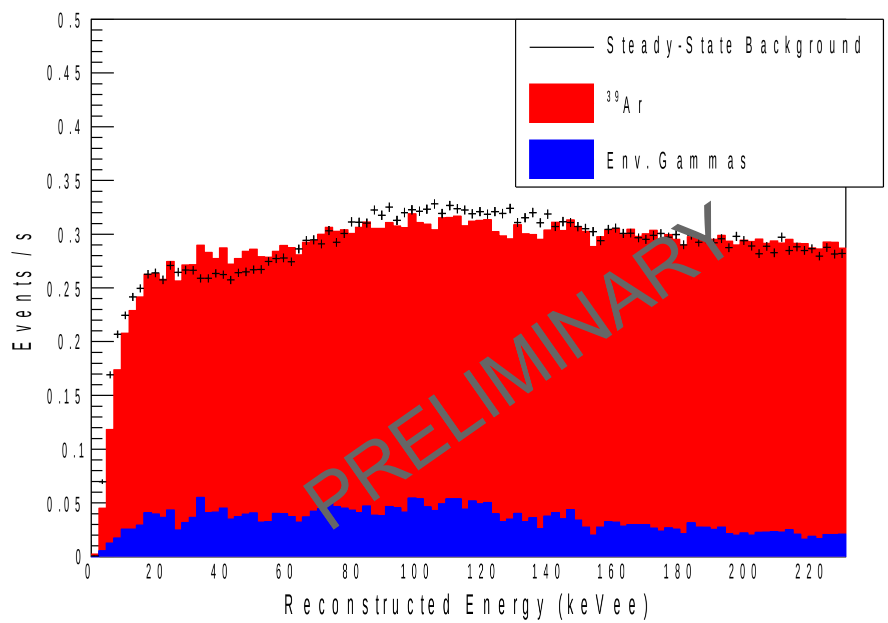


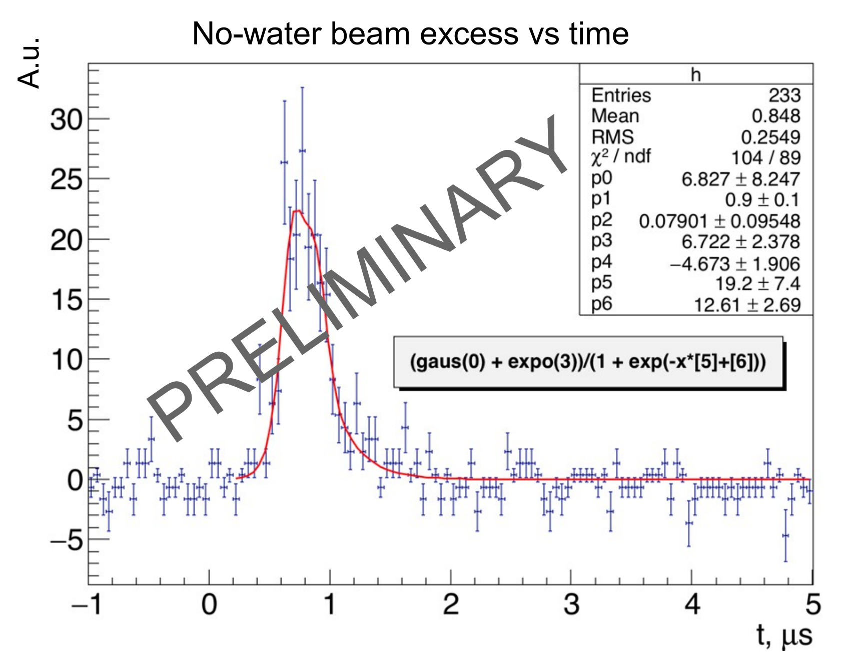
Backgrounds

Background components:

- Beam related neutron (BRN) normalization from no-water shielding data
- Main beam-unrelated component is ^{39}Ar with full shielding
    - Directly measured through off-beam triggers







Predicted Event Distributions for Likelihood Analysis (B)

Perform 3D binned likelihood analysis in energy, F90, and time:

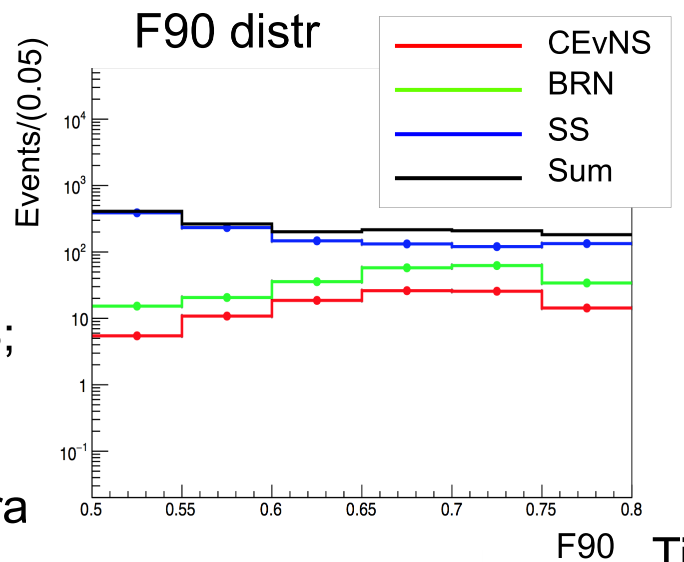
Cuts for analysis B:

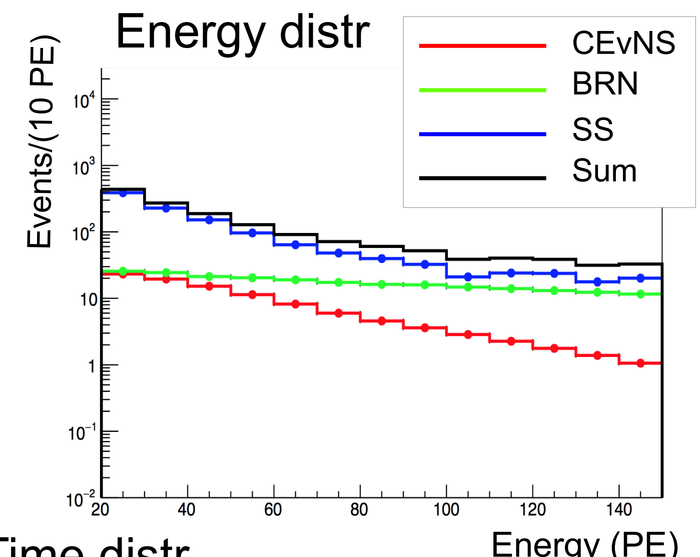
- Quality cut;
- Time cut -1 - 8 us;
- Energy cut 20-150 PE;
- Fiducial volume cut 0.2-0.8;
- F90 cut 0.5-0.8;

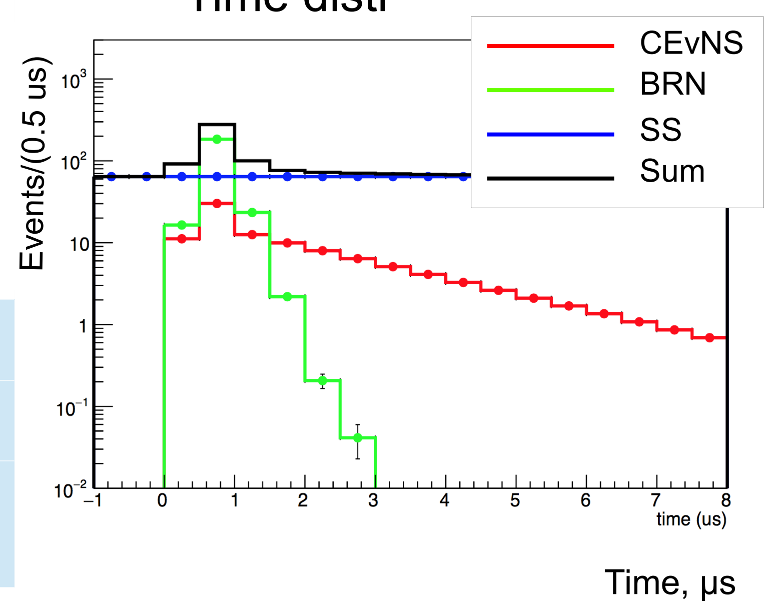
Neutrons and neutrino spectra were simulated

Steady-State background was extracted from "strobe" (off-beam) data

Shapes of distributions for analysis B





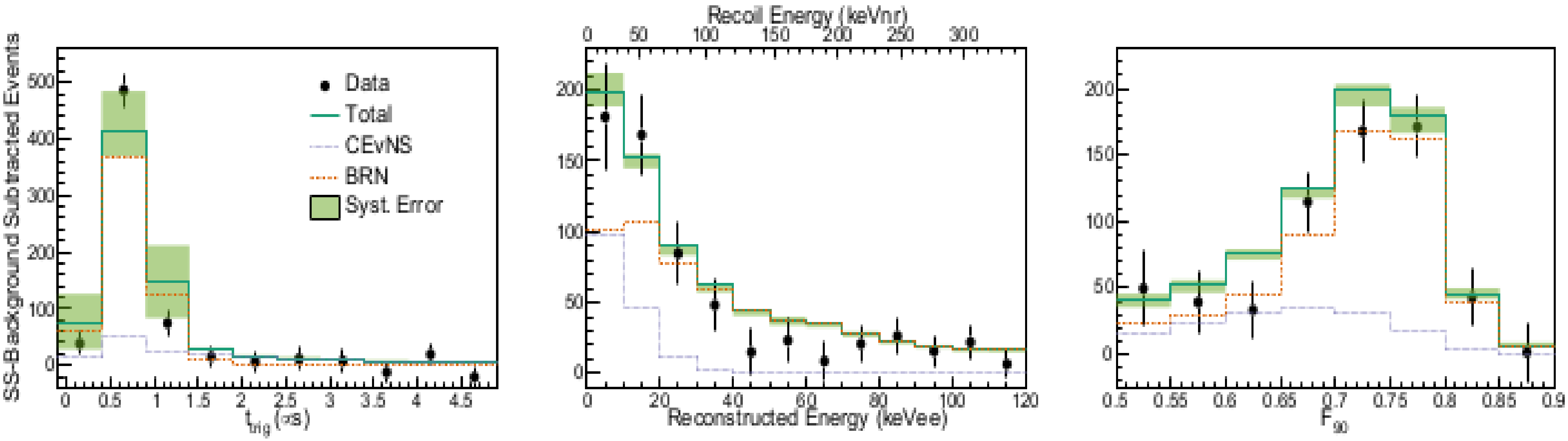


Predictions for analysis B

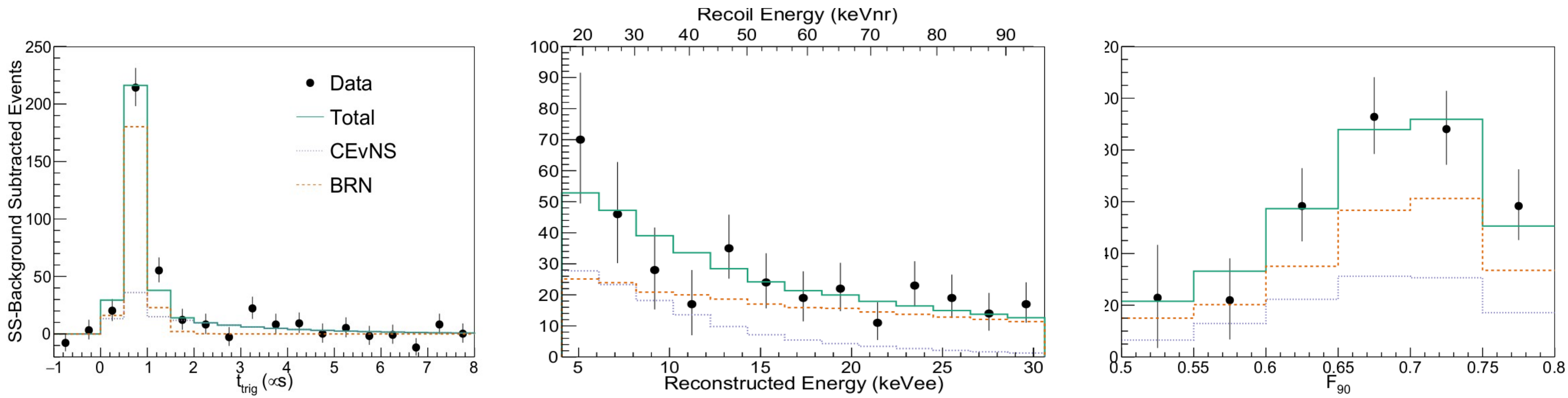
CEvNS	101 ± 12
Beam Related Neutrons (BRN)	226 ± 33
Steady-State Bkg (SS)	1155 ± 45

After all the preparations were done beam data were opened

Experimental Data Fit



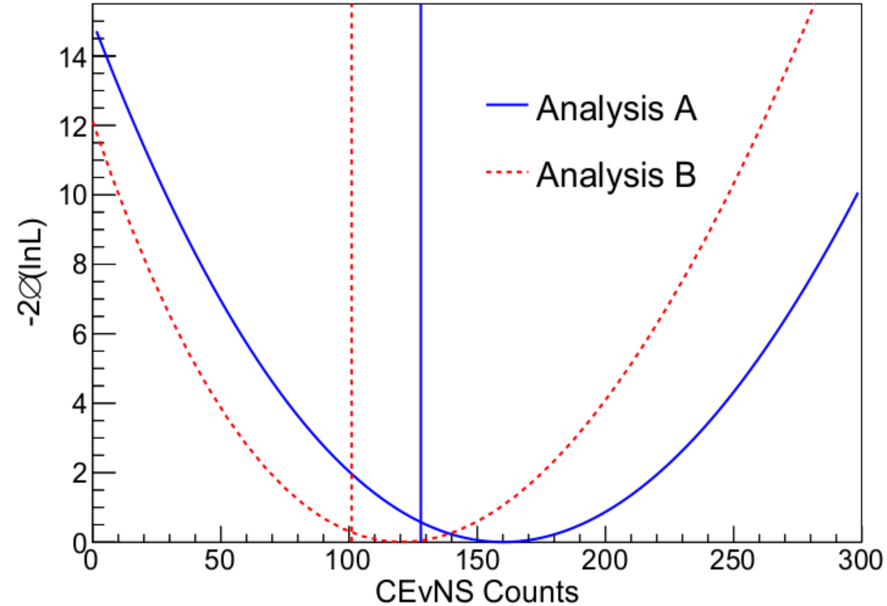
Projection of the best-fit maximum likelihood probability density function (PDF) from A (top) and B (bottom) Analyzes on ttrig (left), reconstructed energy (center), and F90 (right) along with selected data and statistical errors. The fit SS background has been subtracted to better show the CEvNS component



Likelihood Fit Results

fit ranges	Analysis A	Analysis B
F_{90}	0.5 – 0.9	0.5 – 0.8
E (keVee)	0.0 – 120.0	4.1 – 30.6
t_{trig} (μs)	−0.1 – 4.9	−1.0 – 8.0
total events selected	3752	1466
predicted		
CEvNS	128 ± 17	101 ± 12
BRN, prompt	497 ± 160	226 ± 33
BRN, delayed	33 ± 33	
SS	3152 ± 25	1155 ± 45
total events predicted	3779	1482
fit		
CEvNS	159 ± 43	121 ± 36
BRN, prompt	553 ± 34	222 ± 23
BRN, delayed	10 ± 11	
SS	3131 ± 23	1112 ± 41
total events fit	3853	1455
fit systematic errors		
CEvNS F_{90} E dependence	4.5%	3.1%
CEvNS t_{trig} mean	2.7%	6.3%
BRN E dist.	5.8%	5.2%
BRN t_{trig} mean	1.3%	5.3%
BRN t_{trig} width	3.1%	7.7%
total CEvNS sys. error	8.5%	13%
fit results		
null significance (stat. only)	3.9σ	3.4σ
null significance (stat.+sys.)	3.5σ	3.1σ

arXiv: 2003.10630



3D binned likelihood analysis in energy, F90, time space

Best fit CEvNS counts of:

- 159 ± 43 (stat.) ± 14 (syst.) for analysis A
- 121 ± 36 (stat.) ± 15 (syst.) for analysis B

- Result (stat. only) rejects null hypothesis at least at 3.4 σ
- Result (stat. + syst.) rejects null hypothesis at least at ~ 3.1 σ
- Best fit result is within 1σ of SM prediction

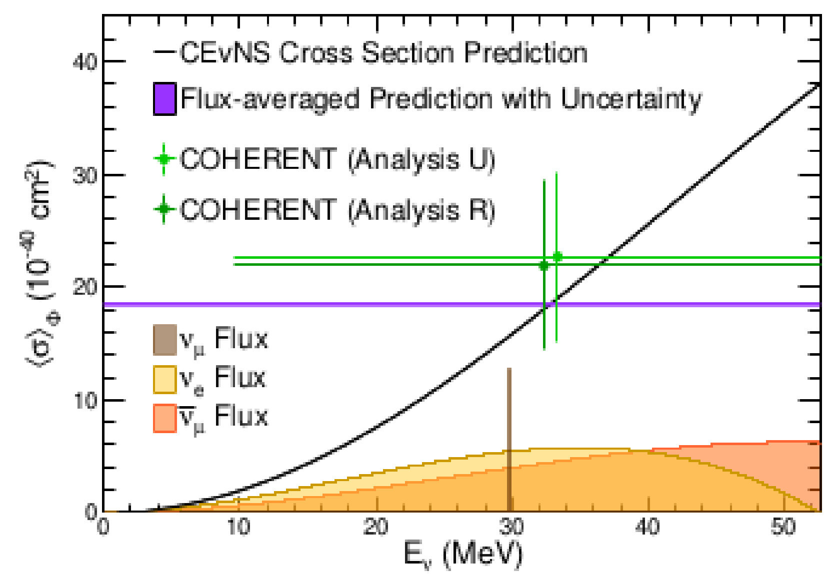
Analysis results comparison

	Analysis B		Analysis A	
Data Component	Predictions	Analysis results	Predictions	Analysis results
CEvNS	101 ± 12	121 ± 36 (stat.) ± 15 (syst.)	128 ± 17	159 ± 43 (stat.) ± 14 (syst.)
BRN	226 ± 33	222 ± 23	497 ± 160	553 ± 34
SS Bkg	1155 ± 45	1112 ± 41	3154 ± 25	3131 ± 23

Flux averaged CEvNS cross-section:

$$\sigma_{meas} = \frac{N_{meas}}{N_{SM}} \sigma_{SM} = (2.2 \pm 0.7) \times 10^{-39} \ cm^2$$

arXiv: 2003.10630

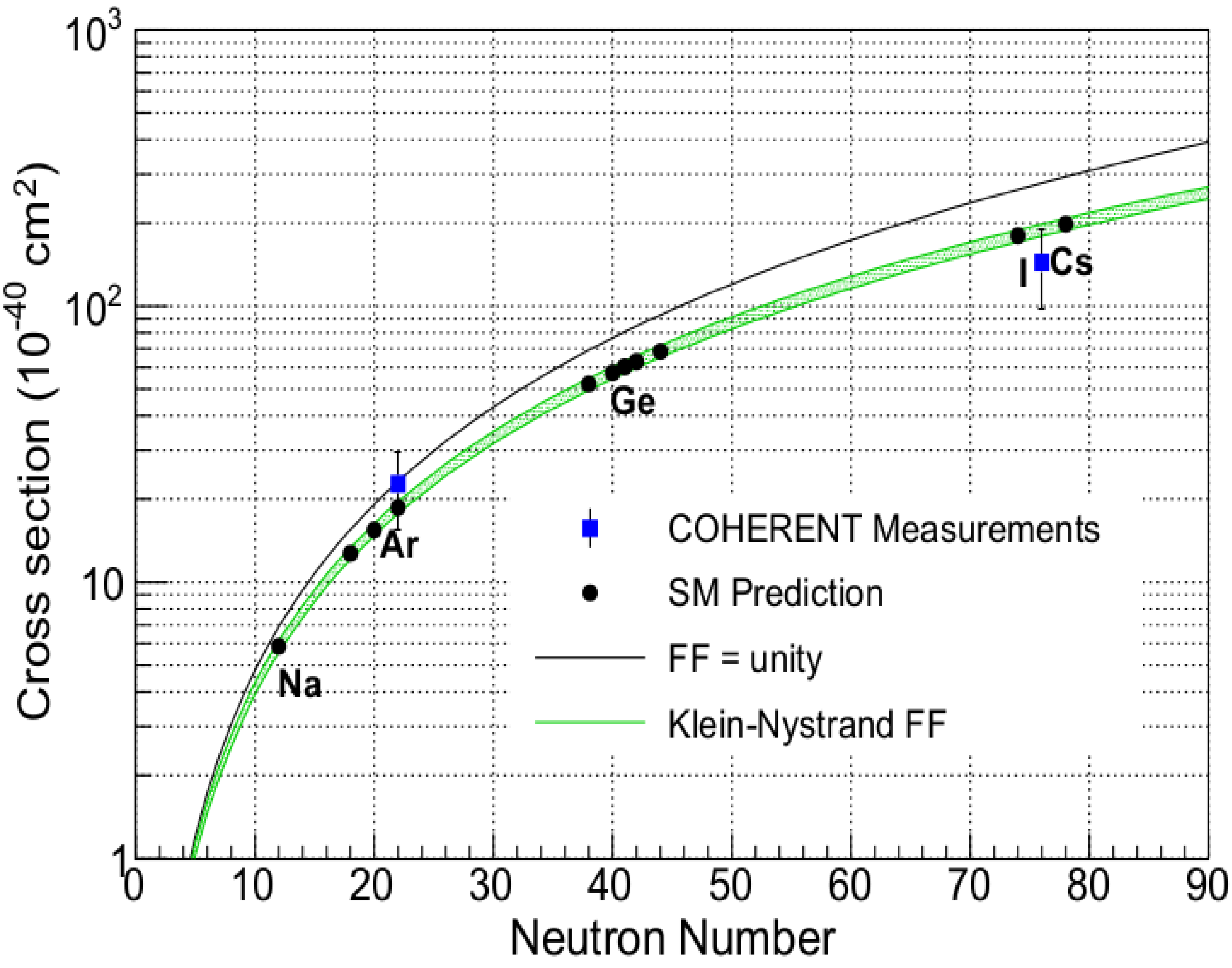


Both analyses find significant excess of events within 1σ of SM predictions

arXiv:2006.12659 – LAr data release

CENNS-10 continues data taking and 5σ (analysis A) significance is expected in 2021

CevNS cross section



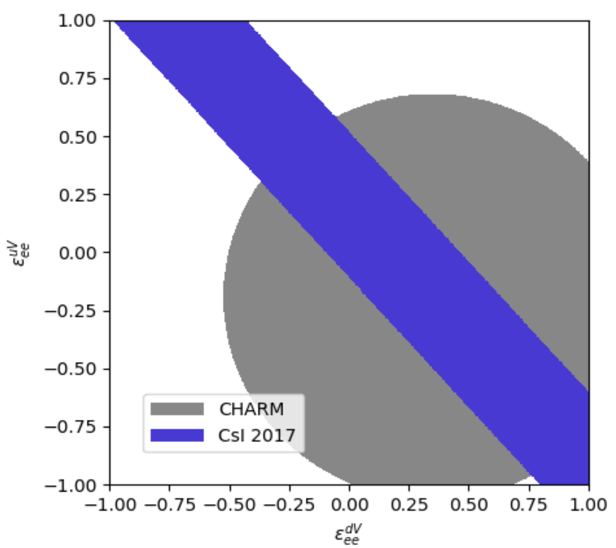
Non-Standard Interactions (NSI)

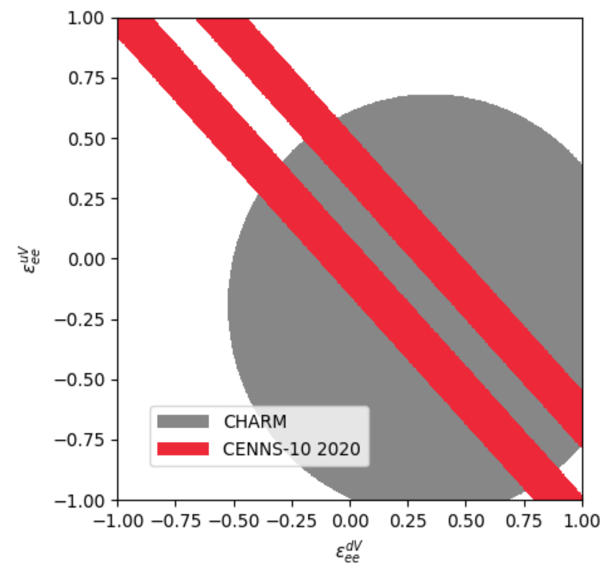
Compute allowed regions in NSI parameter space

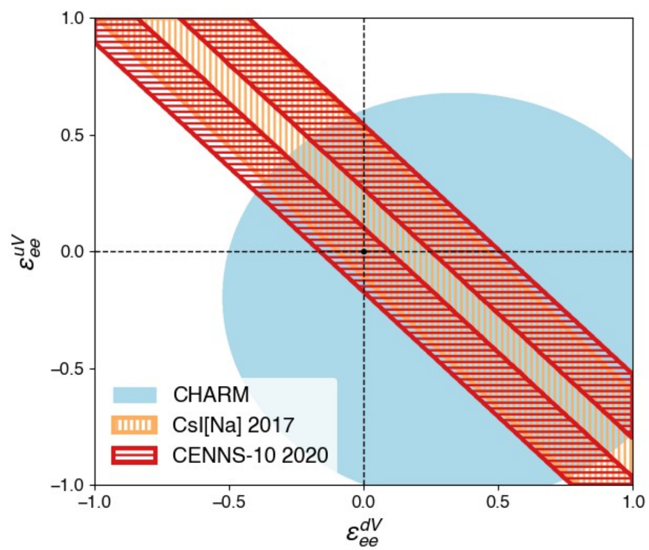
$$Q_W^2 \to Q_{\rm NSI}^2 = 4\left[N\left(-\frac{1}{2} + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV}\right) + Z\left(\frac{1}{2} - 2\sin^2\theta_W + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV}\right)\right]^2$$

Limitations:

- Specifically ν_e flavor-preserving quark-vector coupling parameter space
- Set all other ε = 0







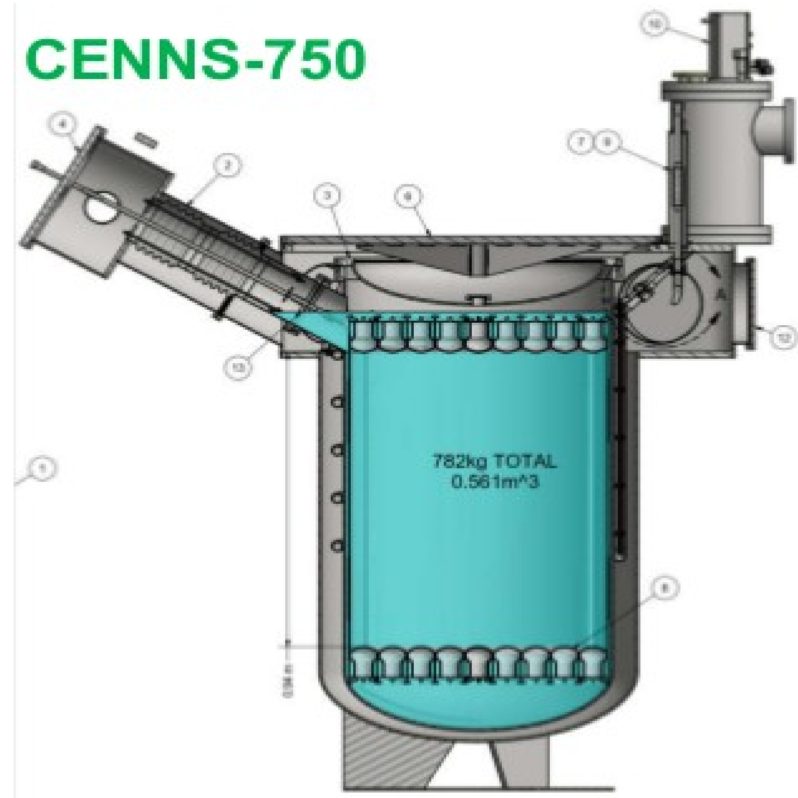
Large Liquid Argon detector

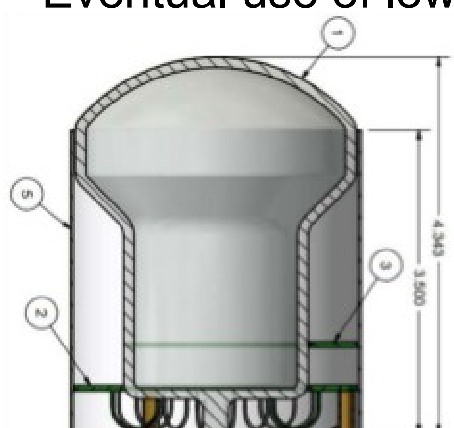
To study detailed characteristics of CEvNS process larger detector is needed to achieve higher event rate and lower threshold.

Ton-scale LAr detector **CENNS-750** is under development.

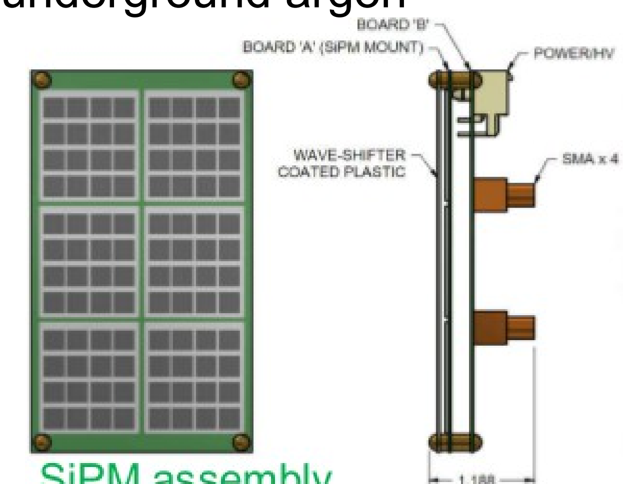
Key features:

- Based on experience of work with CENNS-10 detector;
- Single-phase LAr detector with 750 kg of total mass and **610 kg of fiducial volume**;
- Light collection system includes **TPB** coated reflectors and 3' PMTs/SiPMs;
- Eventual use of low ^{39}Ar underground argon





3" PMT assembly

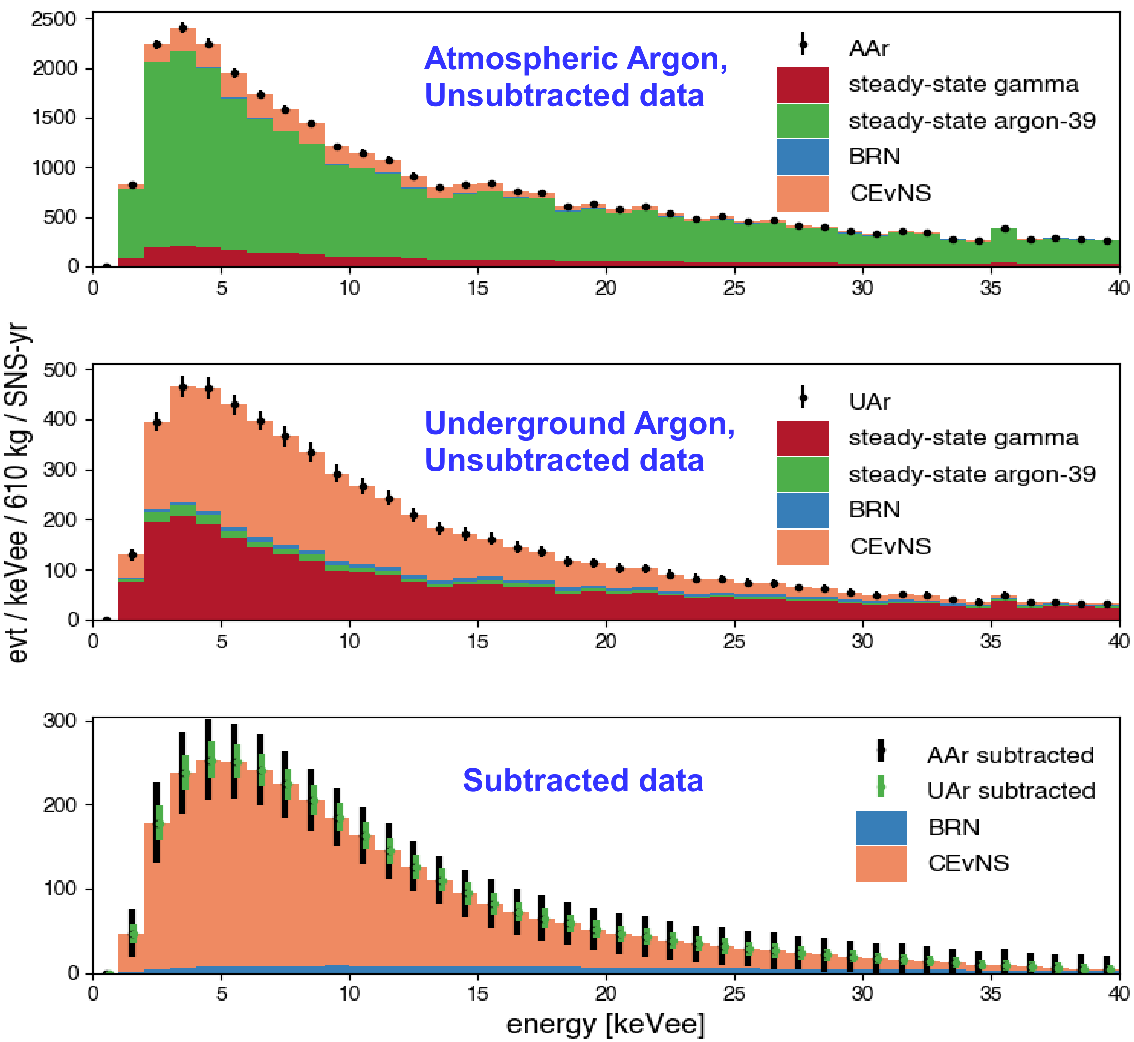


SiPM assembly

CENNS-750 simulations

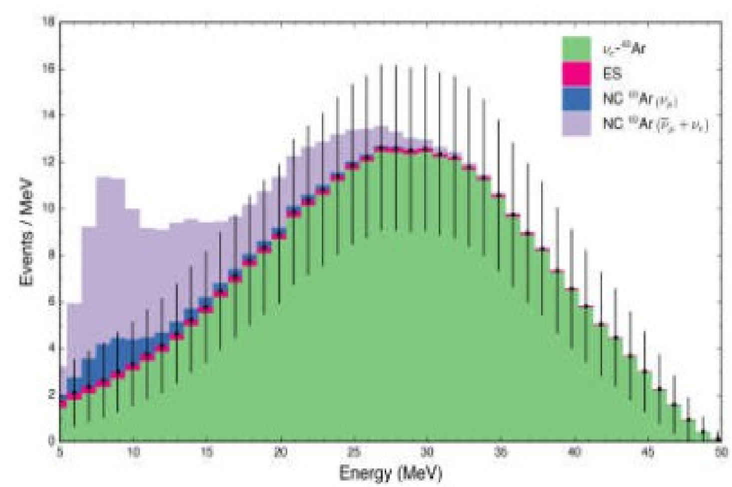
Event rates in 610 kg fiducial volume of ton-scale detector:

~ 3000 CEvNS events per year



~440 inelastic CC/NC events/yr

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



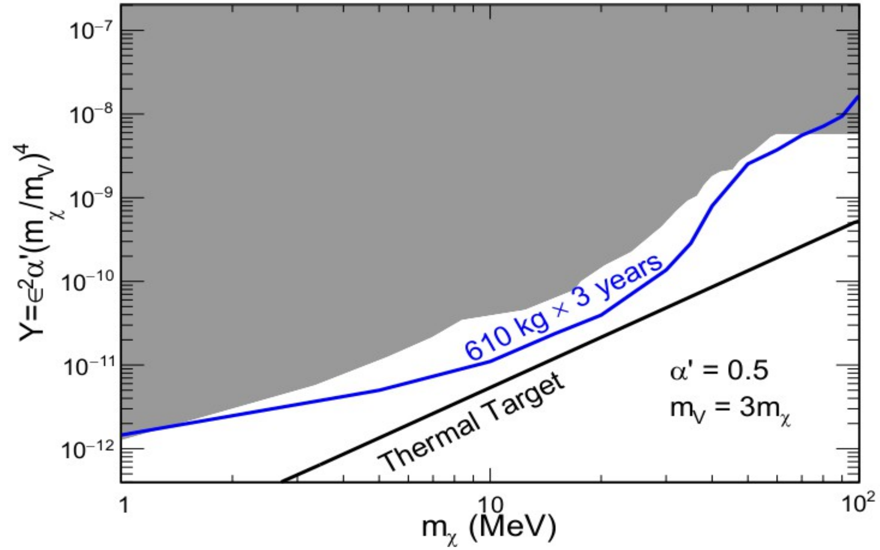
Beam-induced light Dark Matter

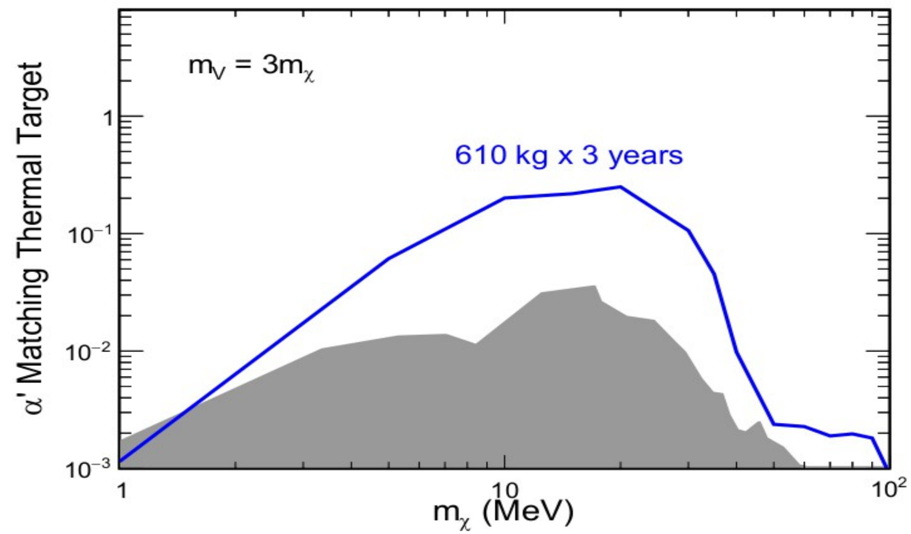
Light weakly-coupled states as sub-GeV mass Dark Matter

CENNS-750 put better limits on the parameter space in 1-100 MeV mass range

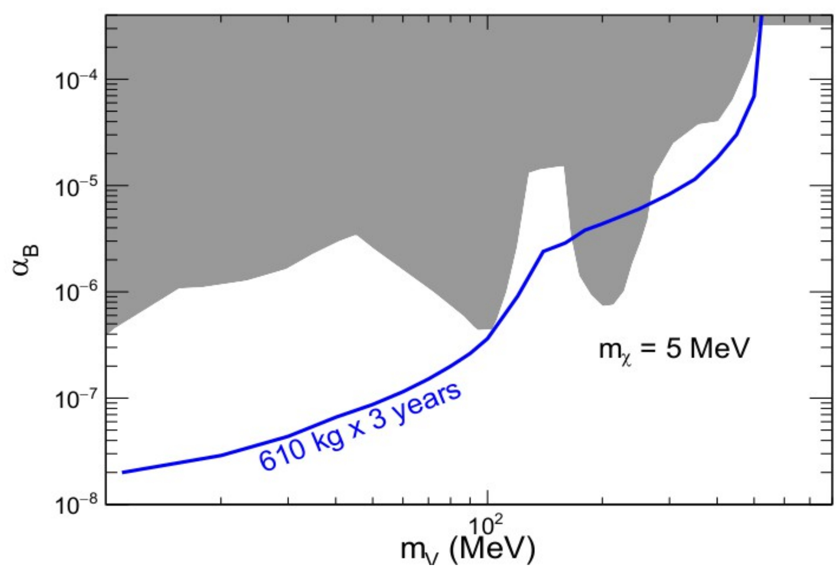
$$\pi^0 \to \gamma + V^{(*)} \to \gamma + \chi^\dagger + \chi$$

$$\pi^- \to n + V^{(*)} \to n + \chi^\dagger + \chi$$





“Vector portal” constraints



“Leptophobic portal” constraints, mχ= 5 MeV

arXiv:1911.06422

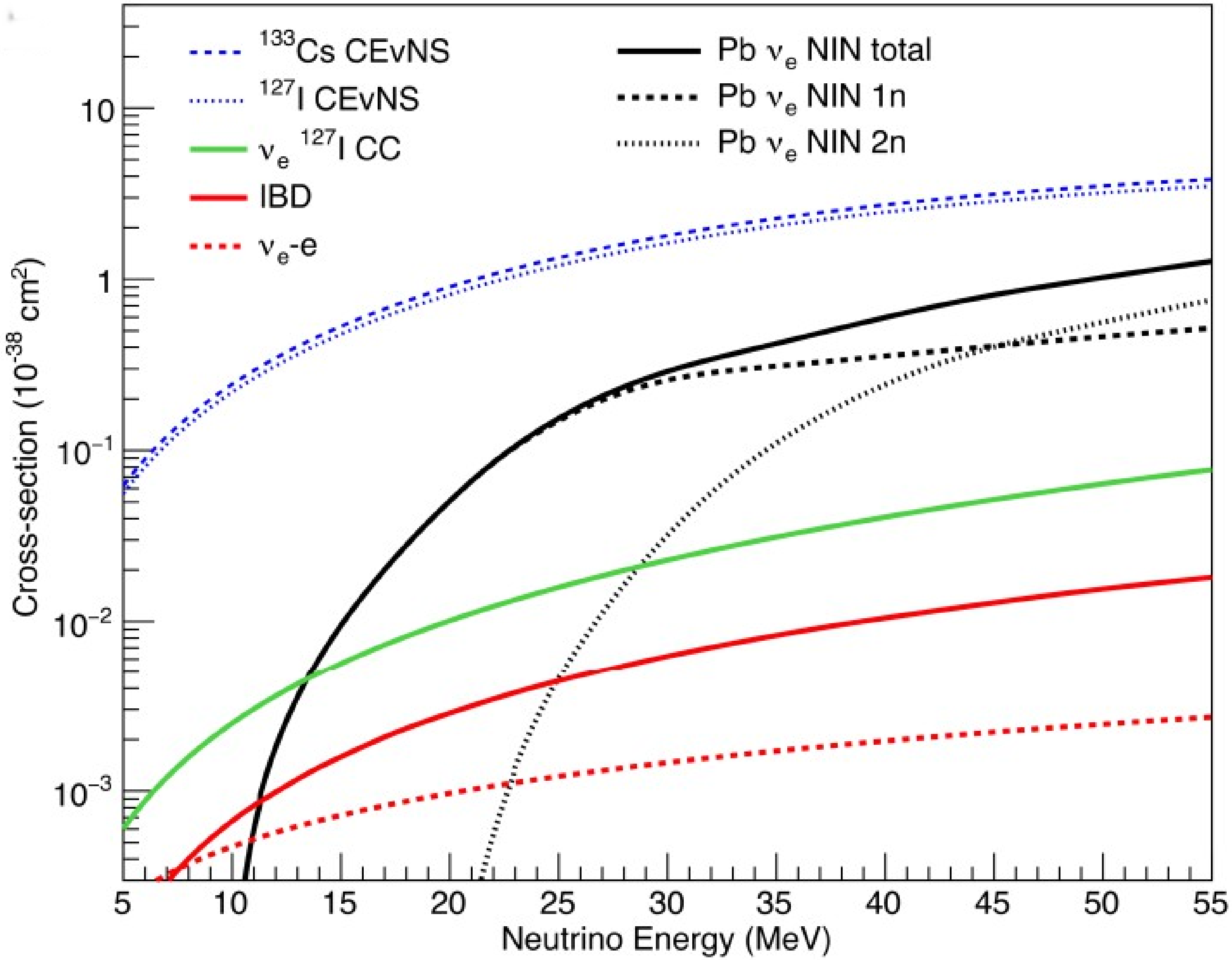
Summary

Using CENNS-10 detector the COHERENT experiment at the SNS successfully registered CEvNS on ^{40}Ar nuclei:

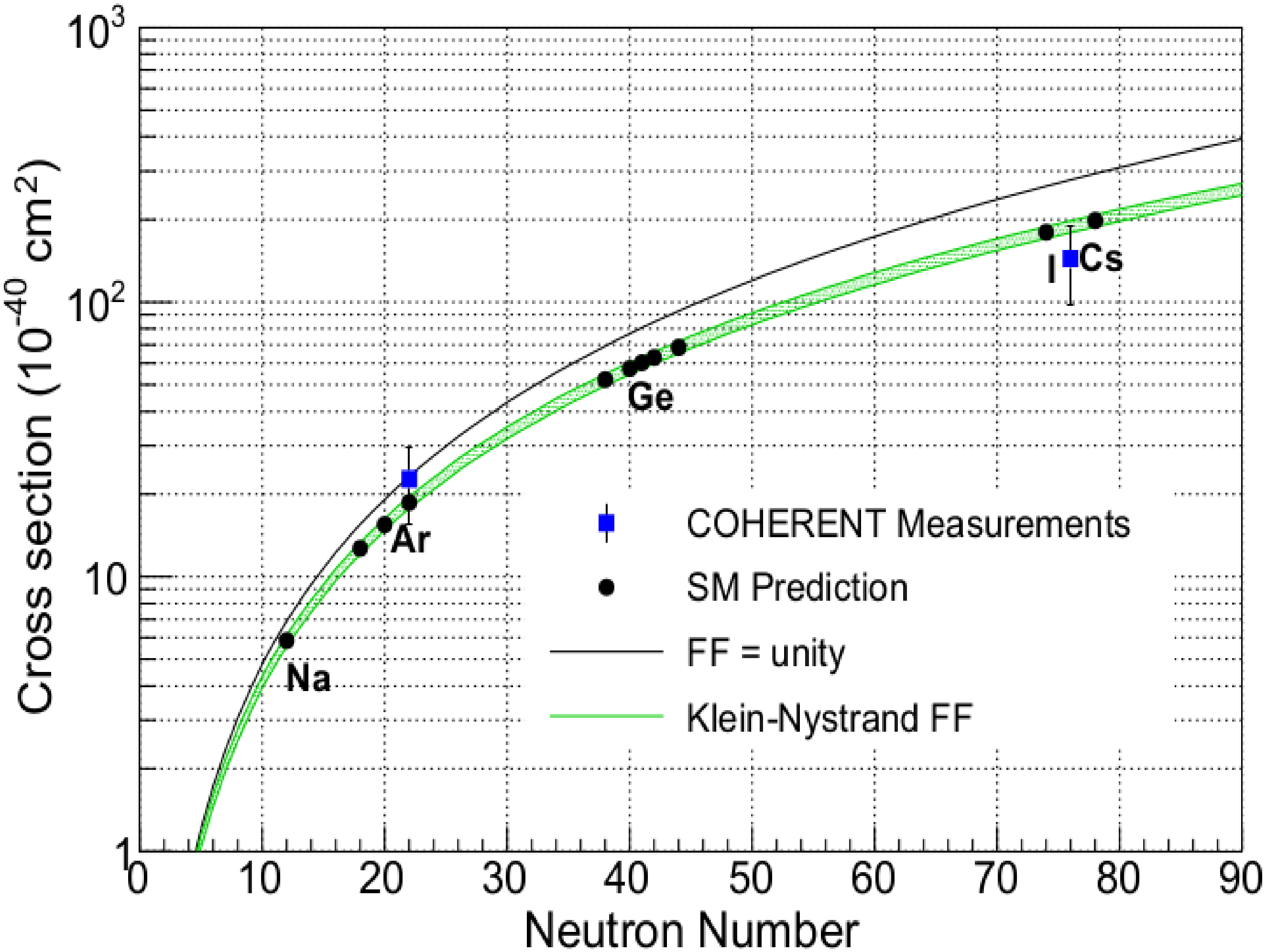
- First low-*N* measurement of CEvNS on ^{40}Ar with CENNS-10 detector
  - More then 3σ detection of CEvNS in ^{40}Ar with first production data
  - ~5σ significance is expected in 2021
- Results are consistent with predictions of the Standard Model
- To study CEvNS in details a large liquid argon detector CENNS-750 is under development.

BackUp

Neutrino processes cross-section



CEvNS Cross Section

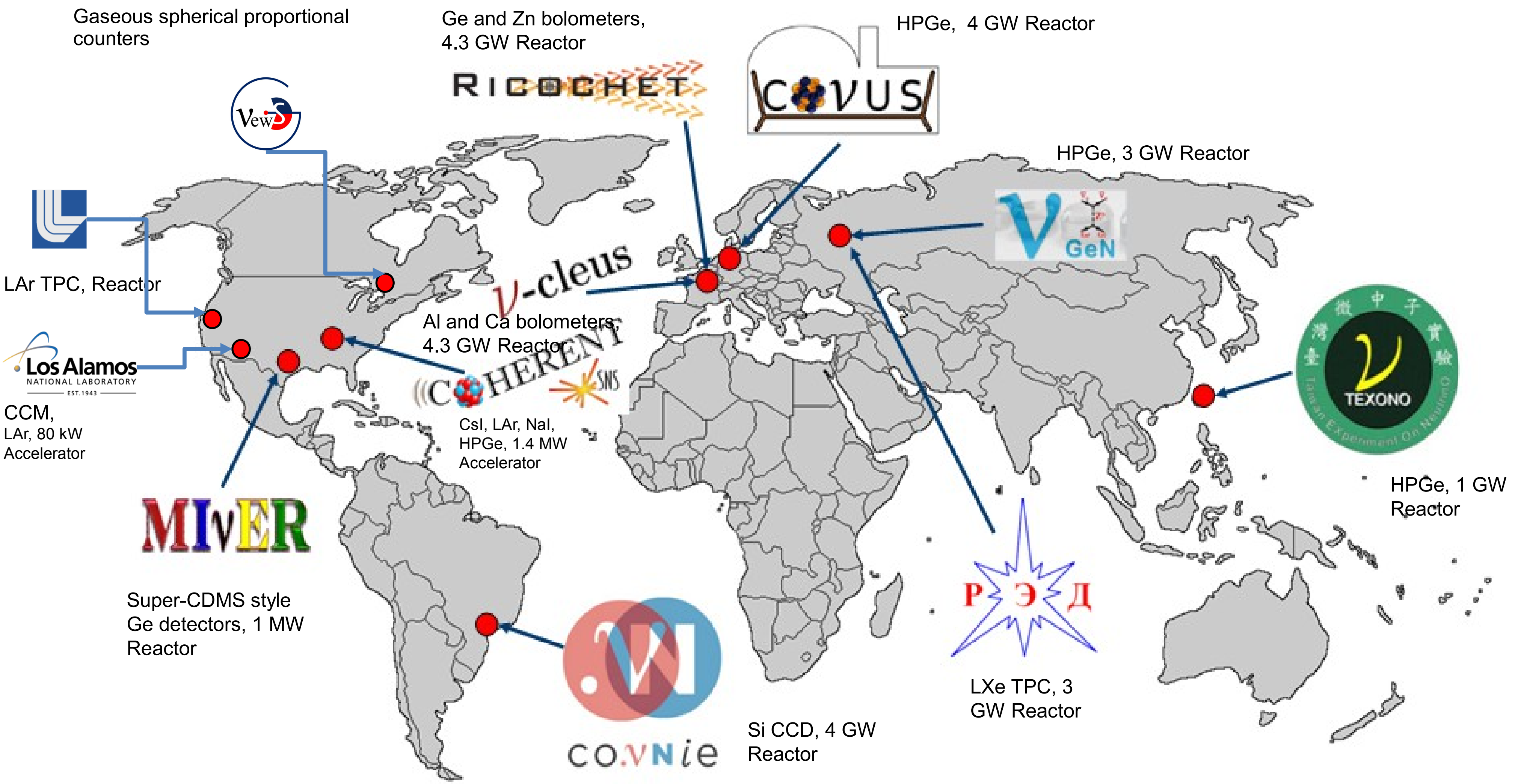


$$\frac{N_{meas}}{N_{SM}} = 1.2 \pm 0.4$$

Flux averaged CEvNS cross-section:

$$\sigma_{meas} = \frac{N_{meas}}{N_{SM}} \sigma_{SM} = (2.2 \pm 0.7) \times 10^{-39} \; cm^2$$

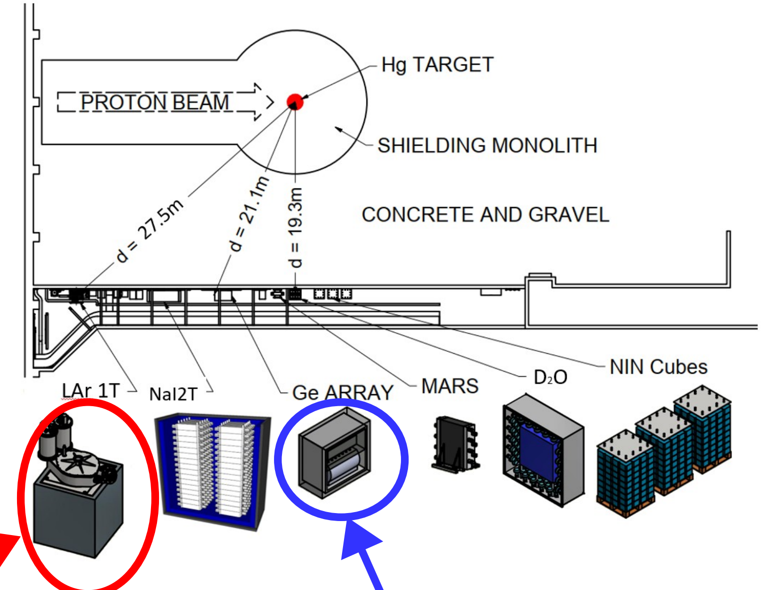
CEvNS Around The World



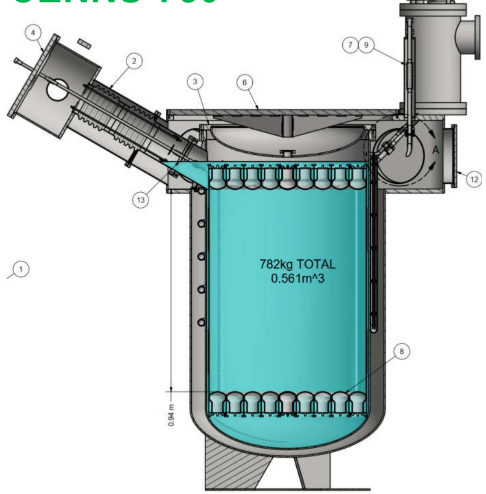
Future COHERENT Efforts: CENNS-750 & HPGE

CENNS-750:

- Single-phase LAr calorimeter, 610 kg fiducial mass
- Based on the successful work with CENNS-10
- Expect ~20 keVnr threshold in ~25x LAr volume, push for lower

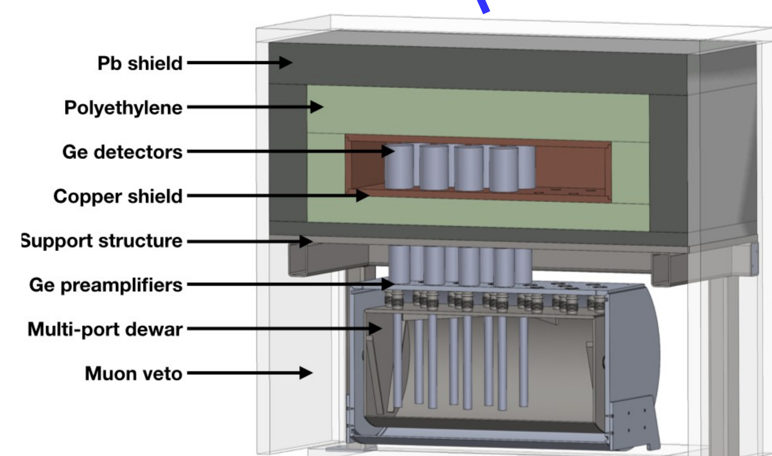


CENNS-750



COHERENT LAr 1T conceptual design

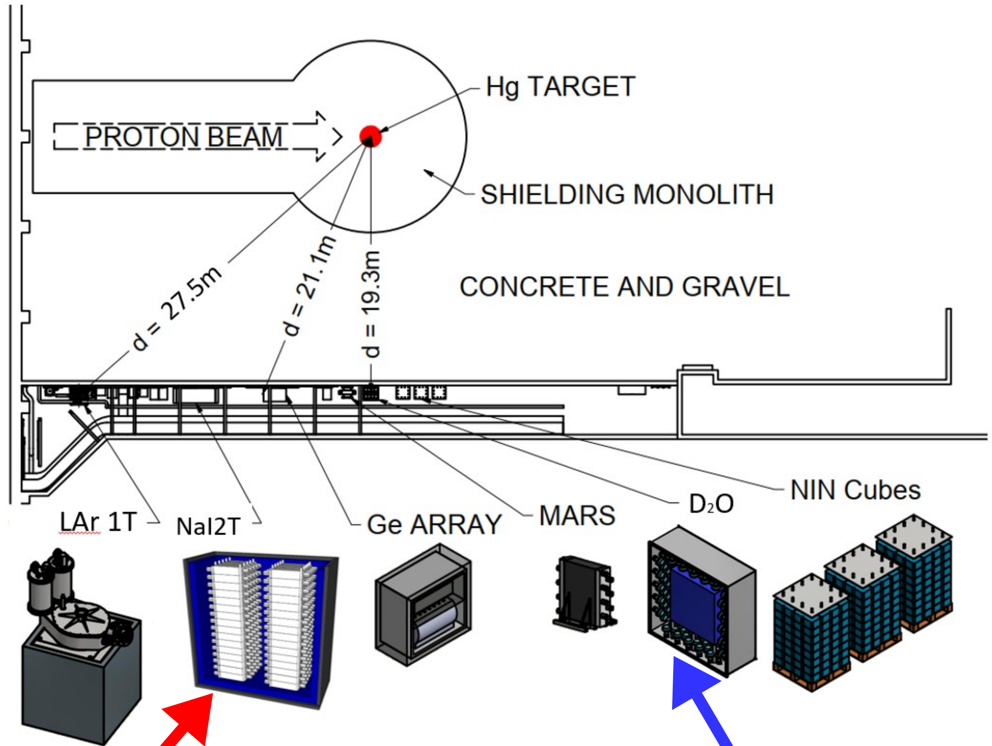
16 kg of HPGe detectors for CEvNS measurement

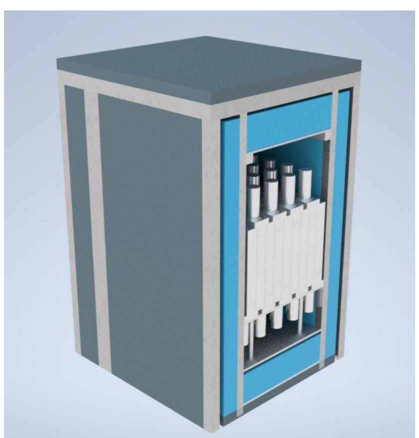


COHERENT Ge conceptual design

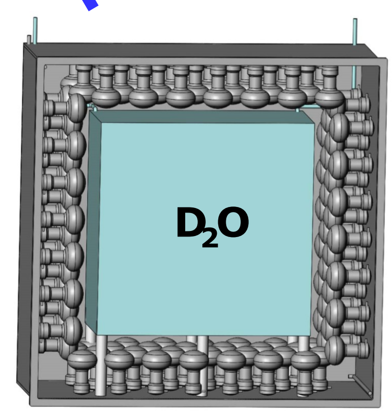
Future COHERENT efforts: NaI[Tl] & D_2O

- Ton-scale NaI[Tl] detector array for simultaneous CEvNS/^{127}I charged current measurements
- Ton-scale D_2O Cherenkov detector to reduce neutrino flux uncertainty:
  - ν_e-d charged current cross section theoretically known to 2-3%





Modular ton-scale NaI[Tl] concept



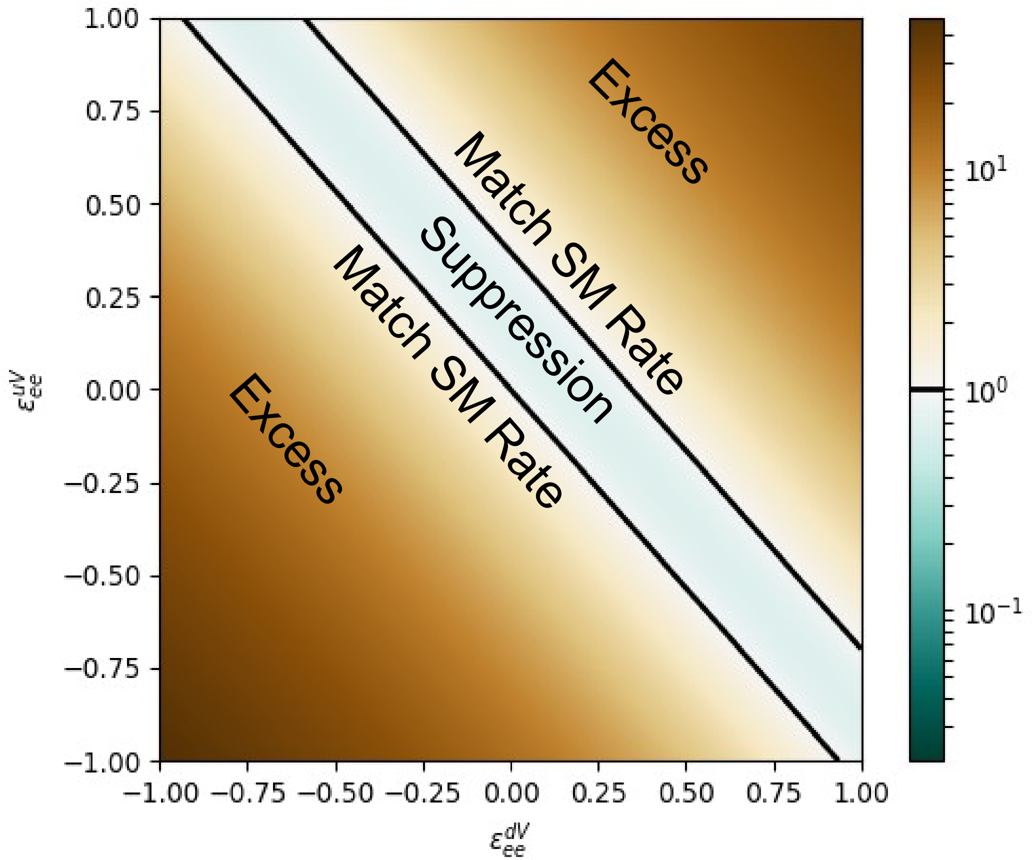
Ton-scale D_2O concept

Non-Standard Interactions (NSI)

- Addition to SM Lagrangian

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

  - Modifies weak charge
  - NSI manifest as scaling of
  - expected CEvNS cross section
- CEvNS sensitive to both non-universal and flavor changing neutra currents



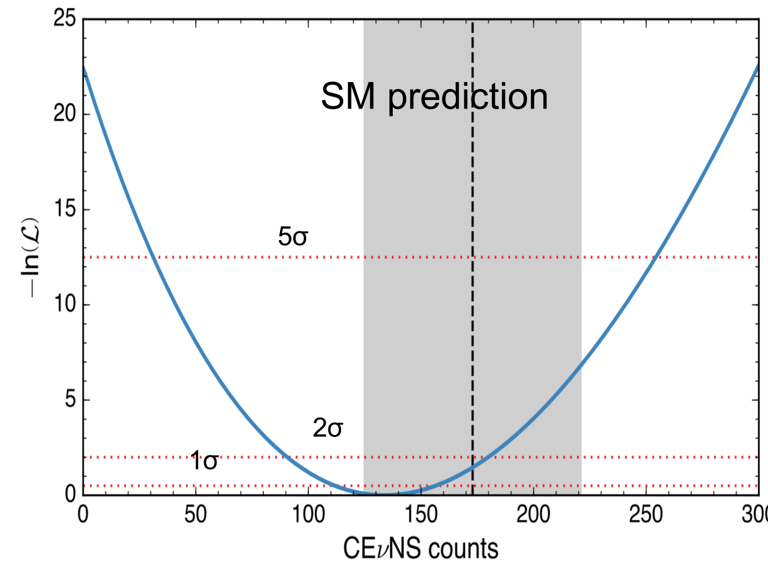
J. Barranco *et al.* , Phys. Rev. D 76 (2007)

J. Billard, J. Johnston, B. Kavanagh, arXiv:1805.01798

$$Q_W^2 \to Q_{\text{NSI}}^2 = 4\left[N\left(-\frac{1}{2} + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV}\right) + Z\left(\frac{1}{2} - 2\sin^2\theta_W + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV}\right)\right]^2$$

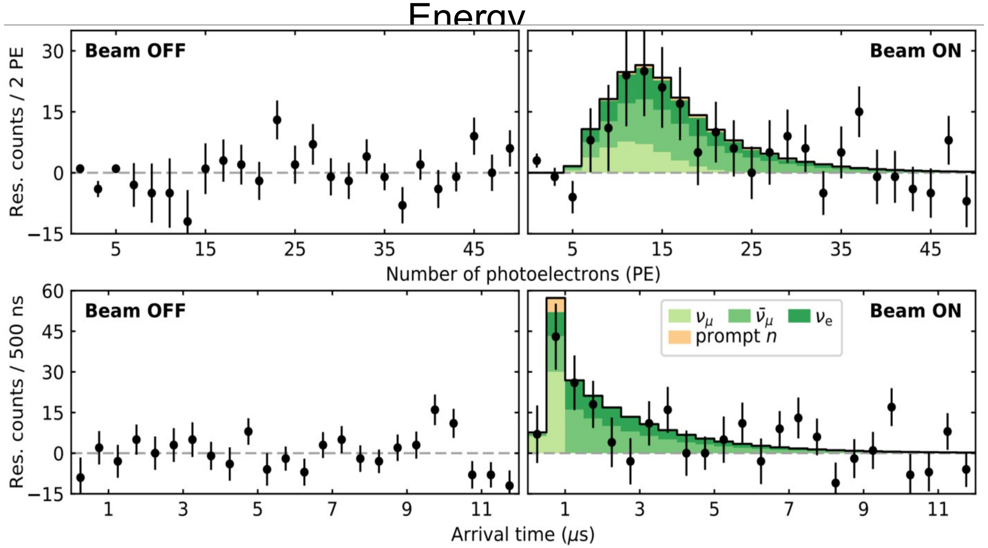
Discovery of CEvNS

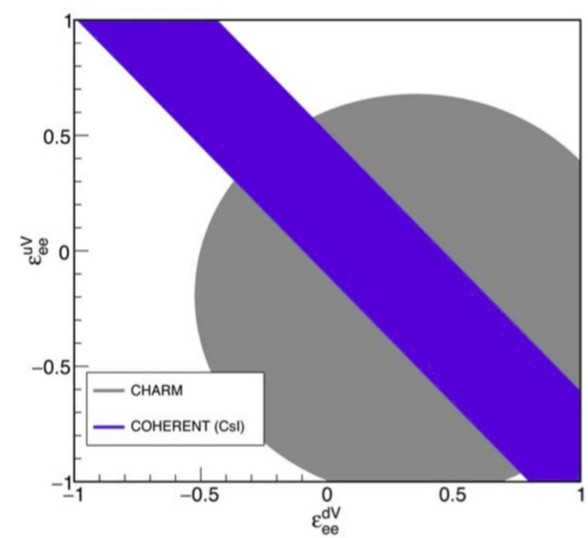
- 14.6 kg CsI crystal
- Maximum Likelihood fit to data gives: 134 ± 22 CEvNS events
- Standard model predicts 173 ± 48 CEvNS events
- Null result rejected at 6.7σ
- New constraints on NSI
- More data available



10.1126/science.aao0990

Energy

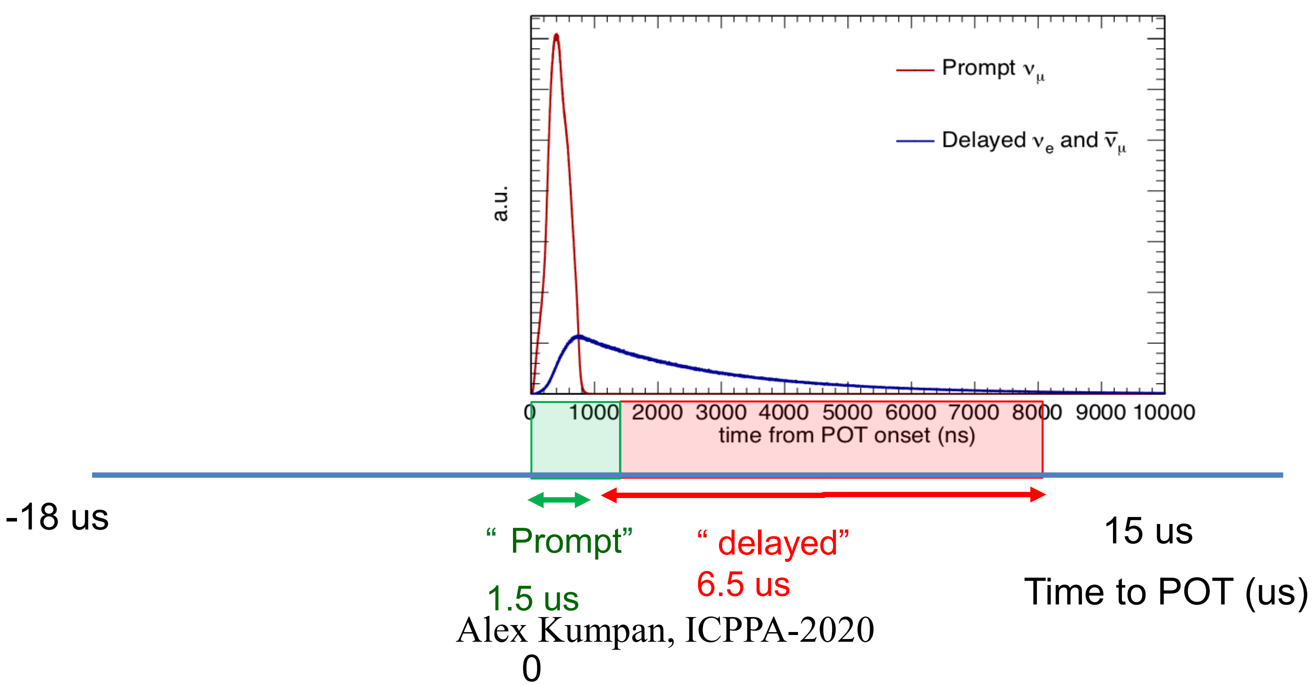




Time relative to beam pulse

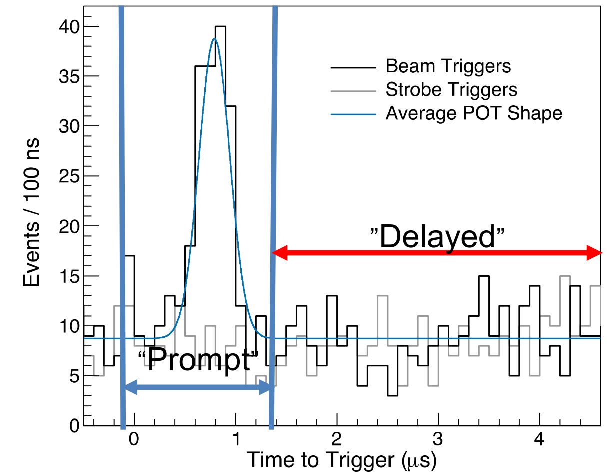
SNS Trigger

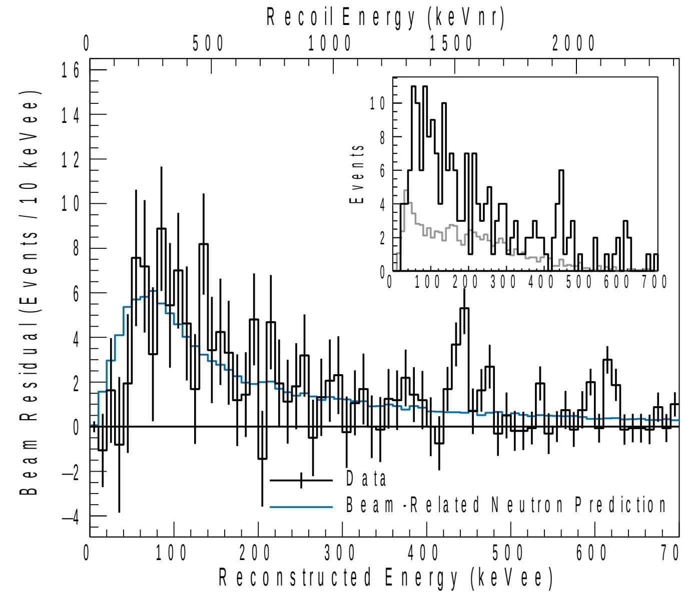
- SNS provides neutrinos in two regions after protons on target (POT): ”prompt” (0-1.5 μs after POT) and “delayed” (1.5-5 μs after POT).
- Beam-related neutron background measured only in prompt window. Delayed neutron measurements consistent with zero.
- Identical off-beam trigger 14 ms after accelerator trigger to measure beam-unrelated backgrounds in-situ.



Neutron Background Characterization

- Data from Engineering Run, analysis of 1.8 GWhr of SNS beam data from February-May 2017
- TPB coated acrylic backed by Teflon reflector and TPB coated acrylic disk
- Threshold (80 keVnr) not low enough for 0.2 sensitive CEvNS search
- Optimized cuts based on signal/noise
- Beam-related excess consistent with previous measurements/simulations
  - Delayed window excess consistent with zero due to high threshold and small beam sample
  - Use to constrain prompt beam-related neutron backgrounds for FirstProduction Run
- Also, place limit on CEvNS cross section





Engineering Run results:

Phys. Rev. D100 (2019) no.11, 115020
M. R. Heath (IU PhD Thesis) (2019)
http://inspirehep.net/record/1744690?ln=en

PRD Editor's Suggestion

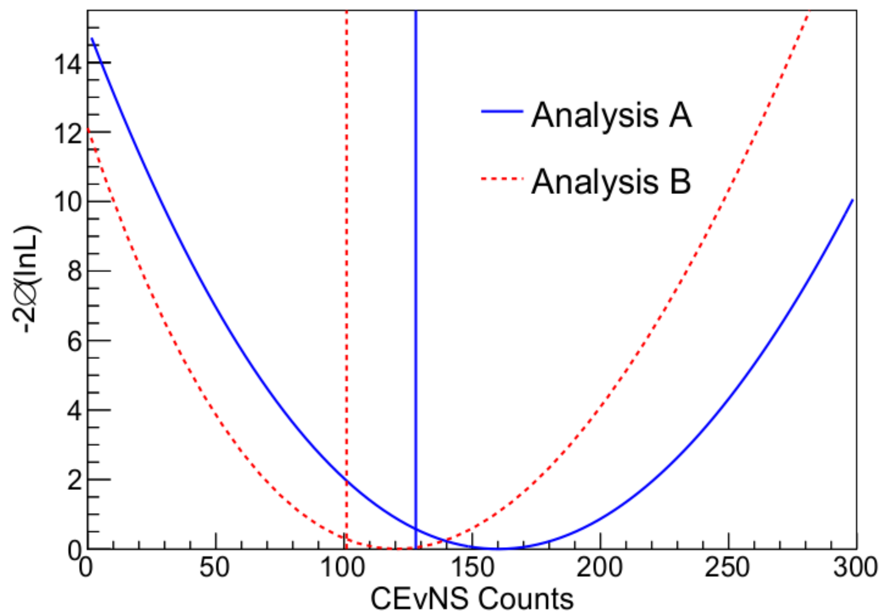
Likelihood Fit Results

3D binned likelihood analysis in energy, F90, time space

Best fit CEvNS counts of:

121 ± 36 (stat.) ± 15 (syst.)

- Result (stat. only) rejects null hypothesis at 3.4 σ
- Result (stat. + syst.) rejects null hypothesis at ~ 3.1 σ
- Best fit result within 1σ of SM prediction



Event Selection

Quality cuts:

- Signal start is on 20 ns window
- Waveform has only one event

Time cut:

- Event should be inside prompt or delayed time window

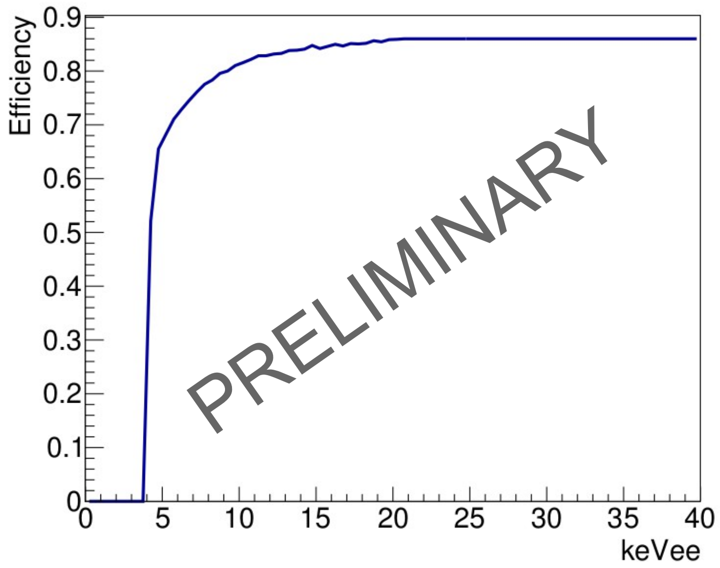
Energy cut:

- Region 4-30 keVee allowed;

Fiducial Volume (F.V.) cut:

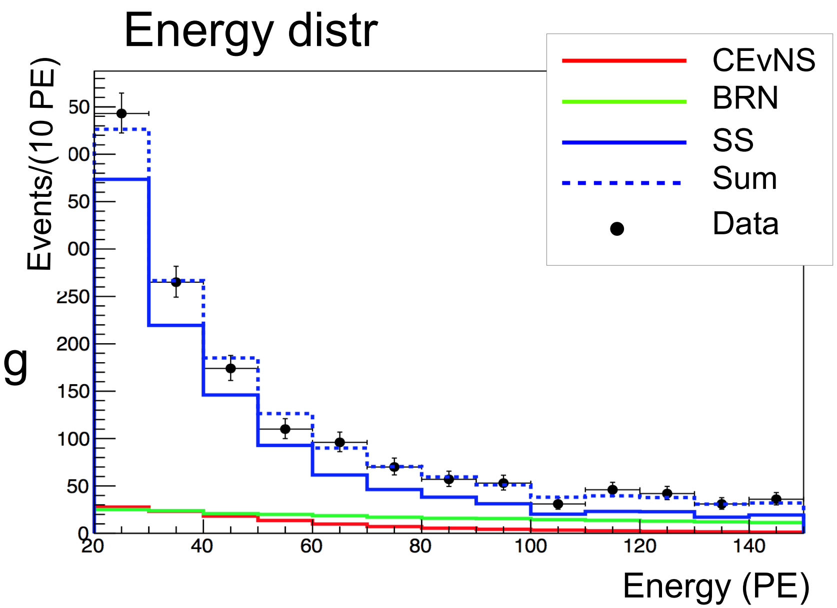
- Ratio of top PMT light to full amount of light detected is 0.2-0.8;

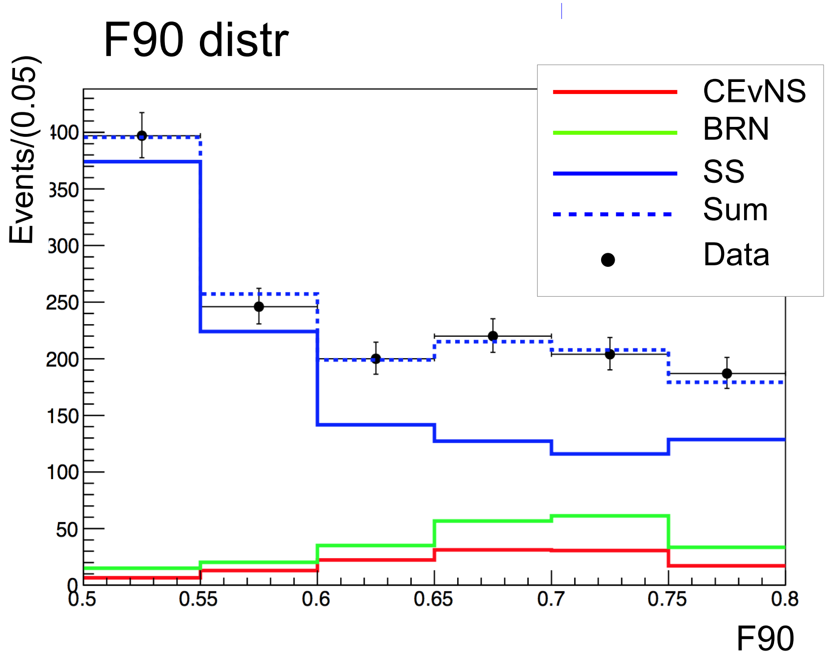
- PSD cut

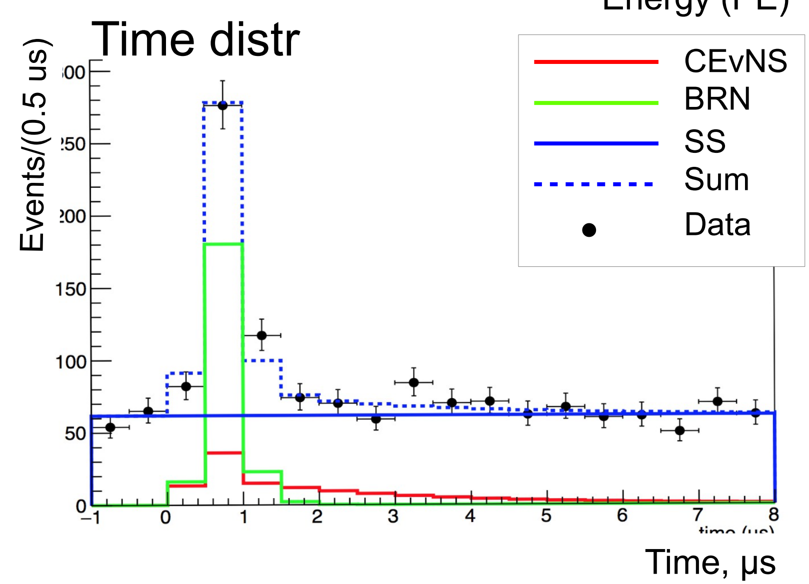


Experimental Data Fit

- Presence of CEvNS fits data well
- Fit systematic error is ~ 13%
  - Obtained on Monte Carlo before unboxing







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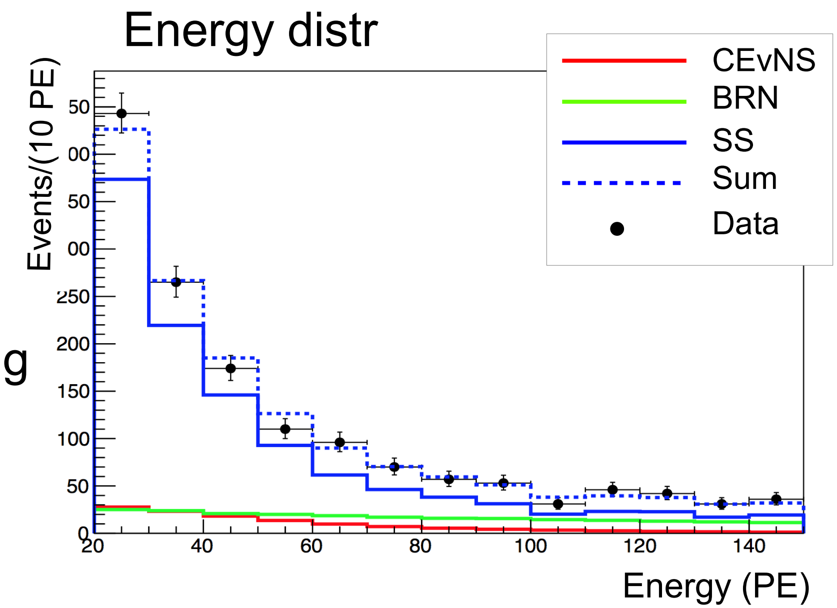

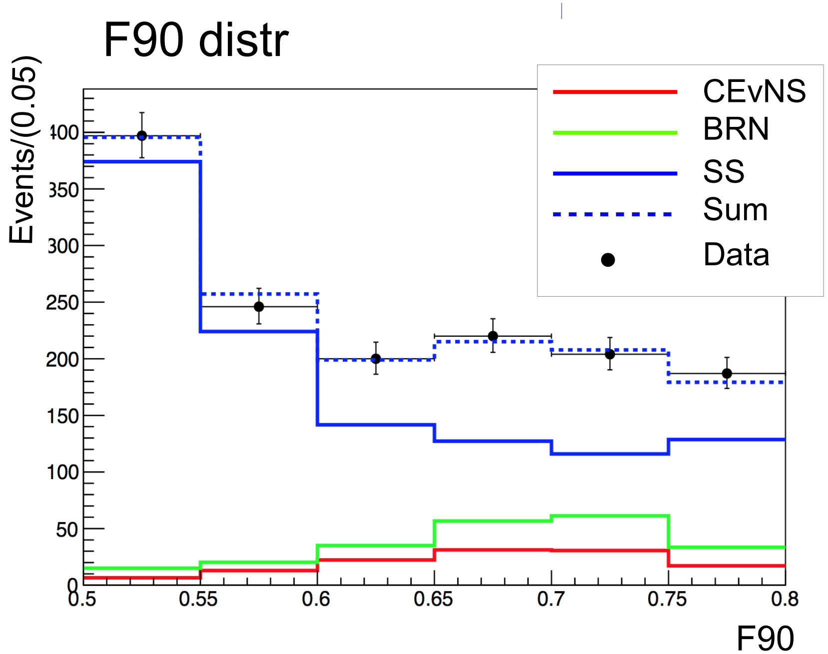

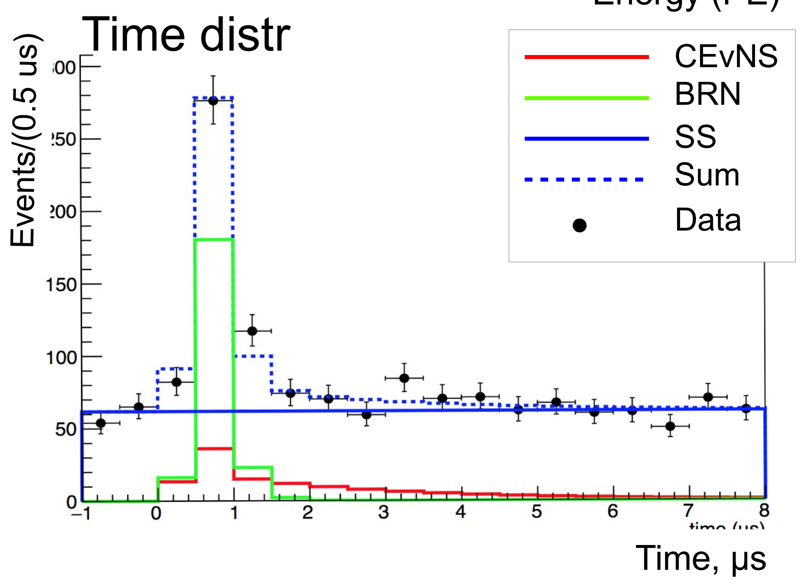

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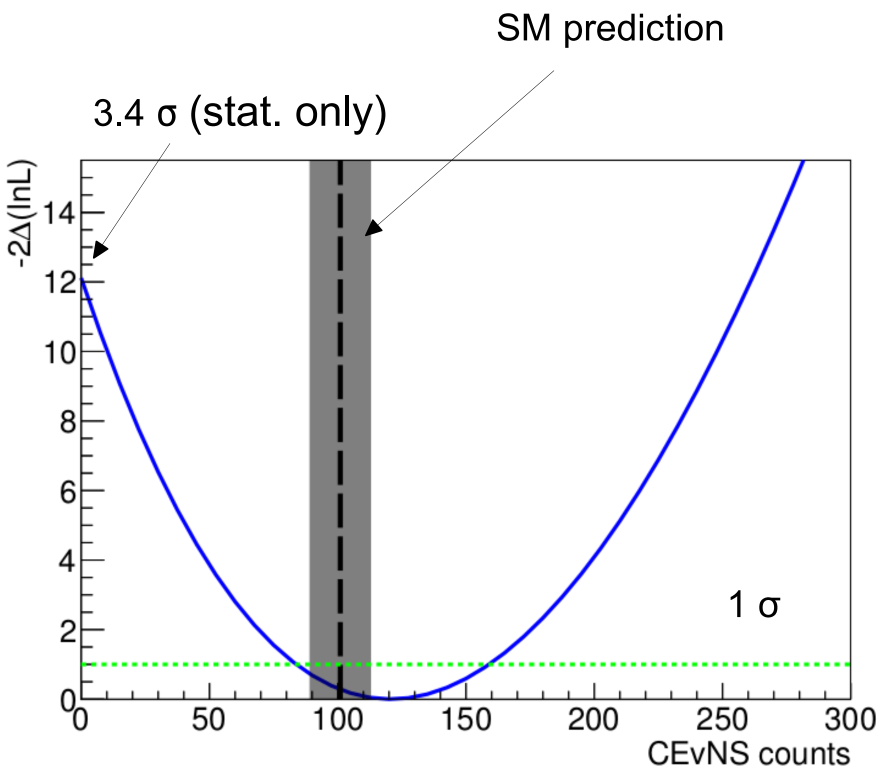


Predictions and analysis results

Data component	Predictions	Analysis results
CEvNS	101 ± 12	121 ± 36 (stat.) ± 15 (syst.)
BRN	226 ± 33	222 ± 23
SS	1155 ± 45	1112 ± 41

Systematic Errors

CEvNS Rate Measurement Errors

Error Source	Uncertainty
Energy region	4.7%
PSD distribution shape	3.3%
Fiducial Volume	1.2%
Nuclear Form Factor	3%
SNS Predicted Neutrino Flux	10%
Other systematic sources	1%
Total Error:	**12.0%**

Additional Likelihood Fit Shape-Related Errors

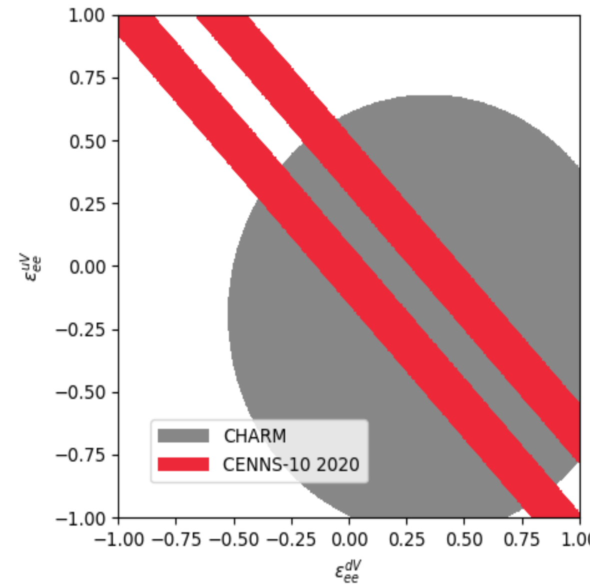
Error Source	Uncertainty
PSD distribution shape	3.1%
CEvNS Arrival Mean Time	6.3%
BRN Arrival Time Mean	5.3%
BRN Arrival Time Width	7.7%
BRN distribution shape	5.2%
Other systematic sources	<1%
Total Error:	**12.8%**

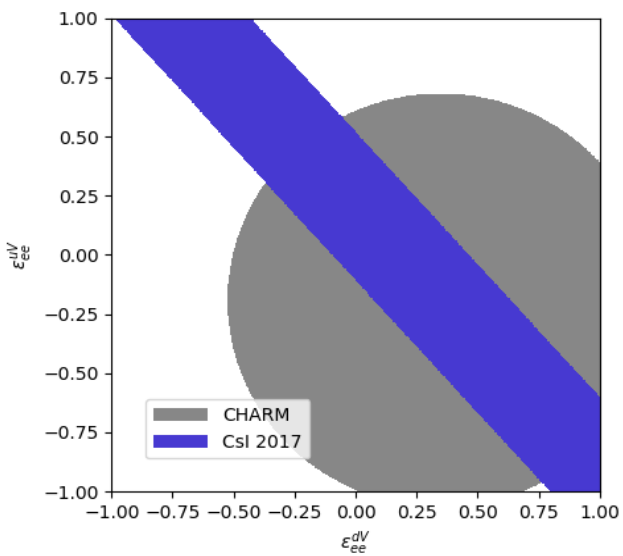
Non-Standard Interactions (NSI)

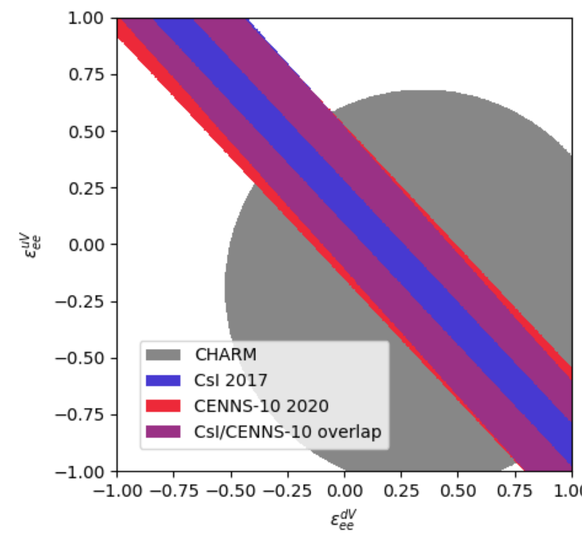
Compute allowed regions in NSI parameter space

Limitations:

- Specifically ν_e flavor-preserving quark-vector coupling parameter space
- Set all other $\varepsilon = 0$







Plots from G. Sinev (Duke)