Electroweak Interactions & Unified Theories, March 24 2021

Results and future of COHERENT

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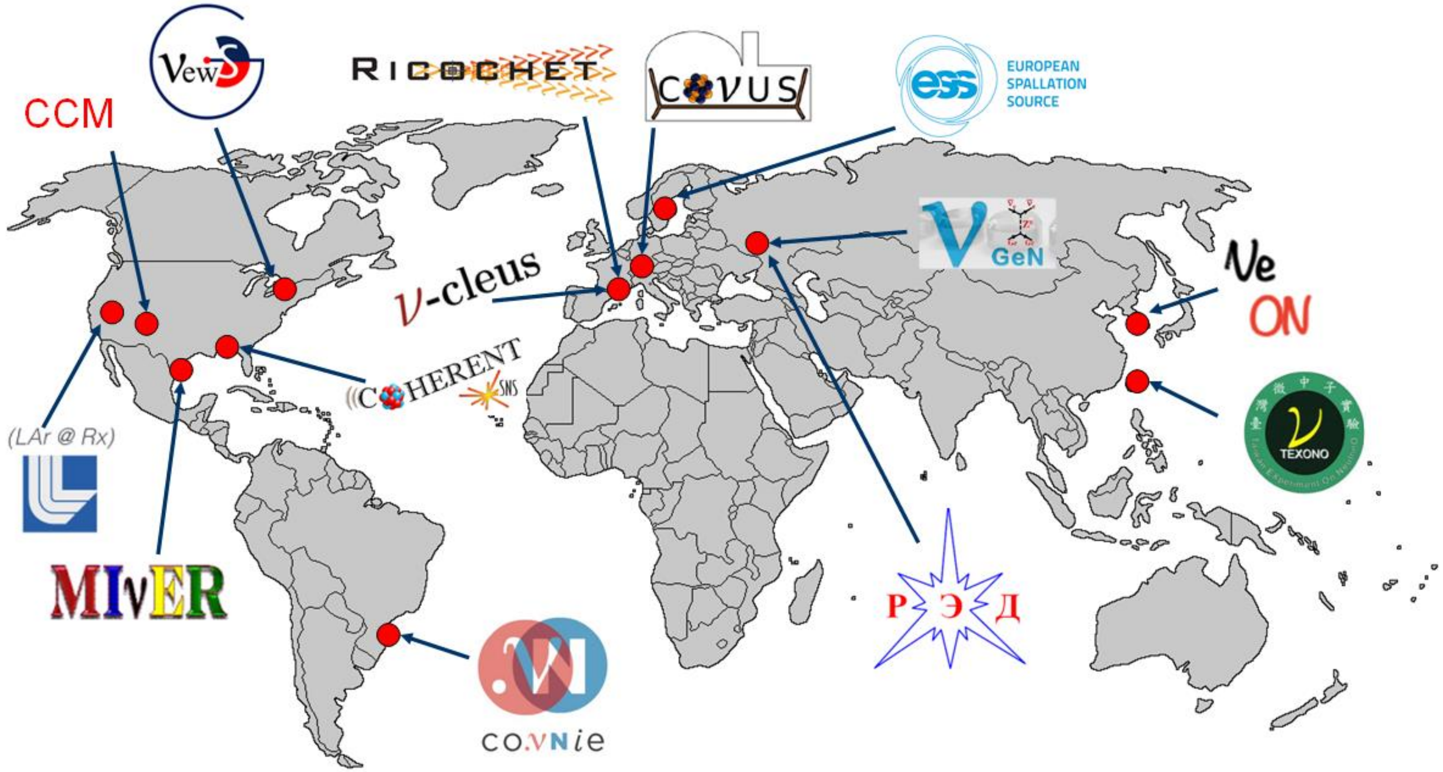
Collaboration

19 institutions from 4 countries (USA, Russia, Canada, S. Korea)

The main goal is to look for new physics using coherent elastic ν–nucleus scattering



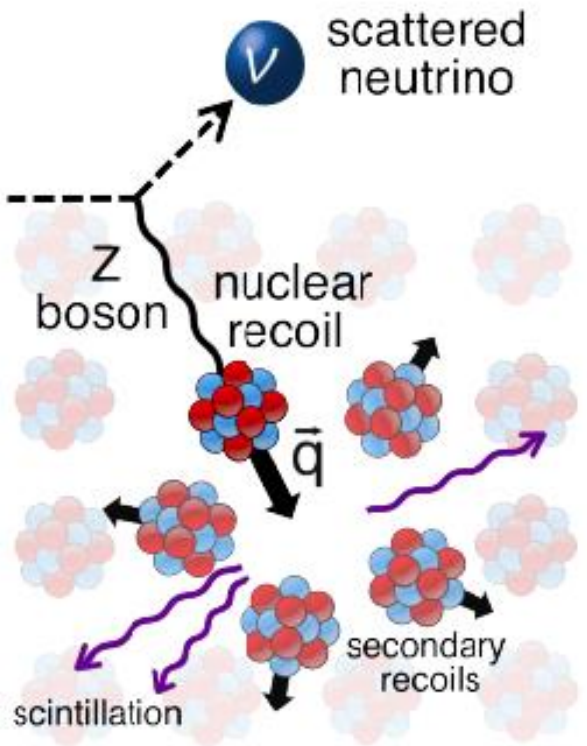
CEvNS search and study experiments around the world

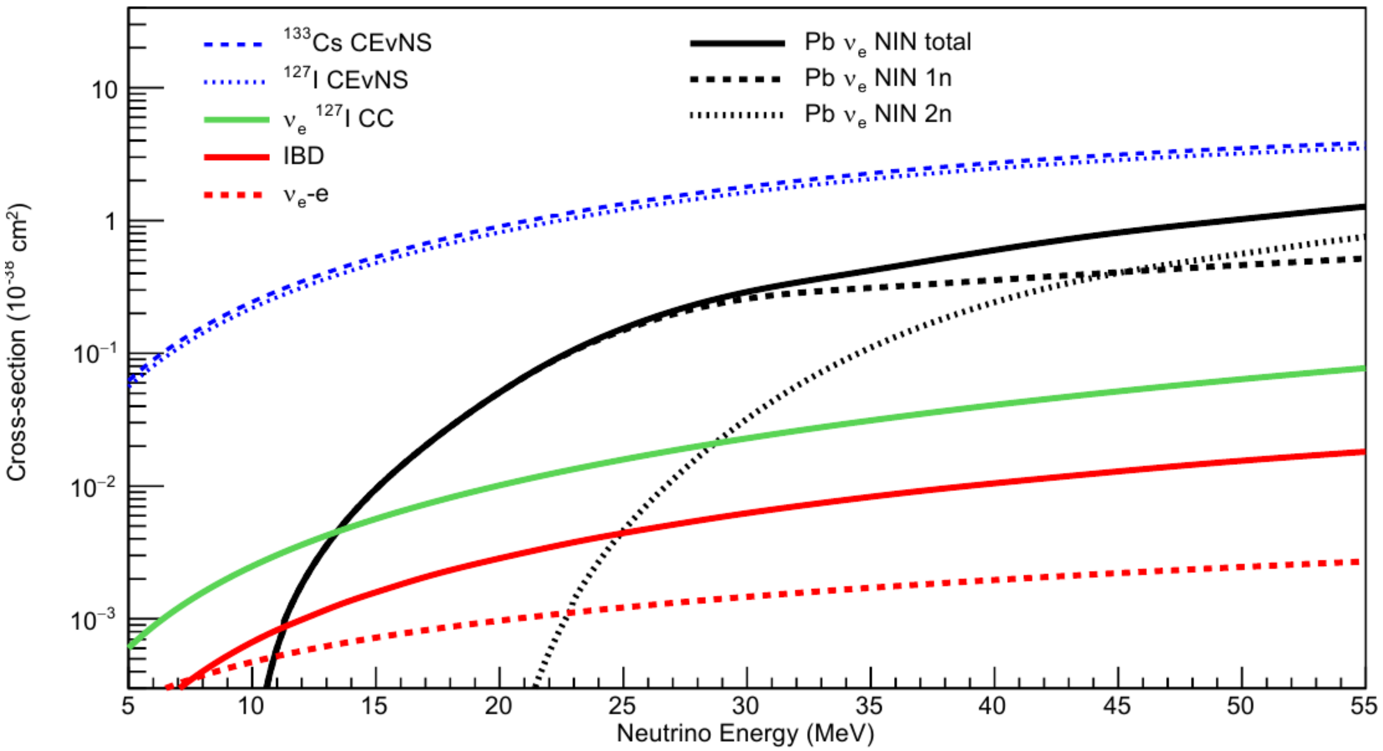
Coherent elastic neutrino-nucleus scattering (CEvNS)

Predicted in

"Coherent effect of a weak neutral current", D. Freedman, PRD v.9, n.5 (1974)

"Isotopic and chiral structure of neutral current", V.Kopeliovich, L. Frankfurt, ZhETF. Pis. Red., v.19 n.4 (1974)





CEvNS cross section in the SM:

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi}\Big([1-4\sin^2\theta_W]Z - N\Big)^2\Big[1-\frac{T}{T_{max}}\Big]F_{nucl}^2(q^2)$$

$$T_{max} = 2E_\nu^2/(M+2E_\nu)$$

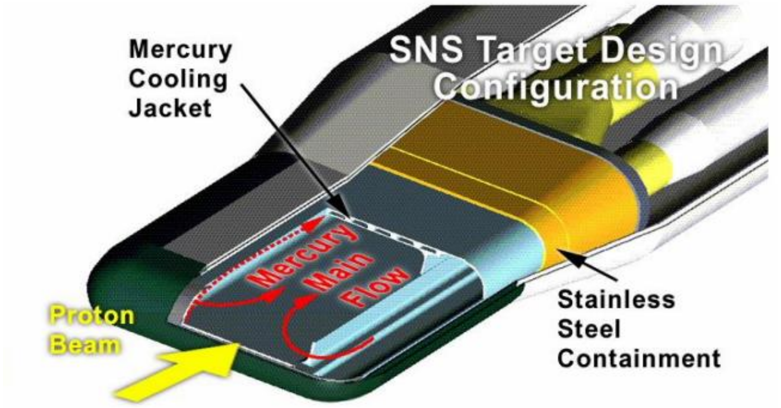
Nucleus	T_{max}, keV (E_ν =5 MeV)	T_{max}, keV (E_ν =30 MeV)
^{12}C	4.44	159.0
^{23}Na	2.32	83.2
^{40}Ar	1.33	47.9
^{74}Ge	0.72	25.9
^{133}Cs	0.40	14.4

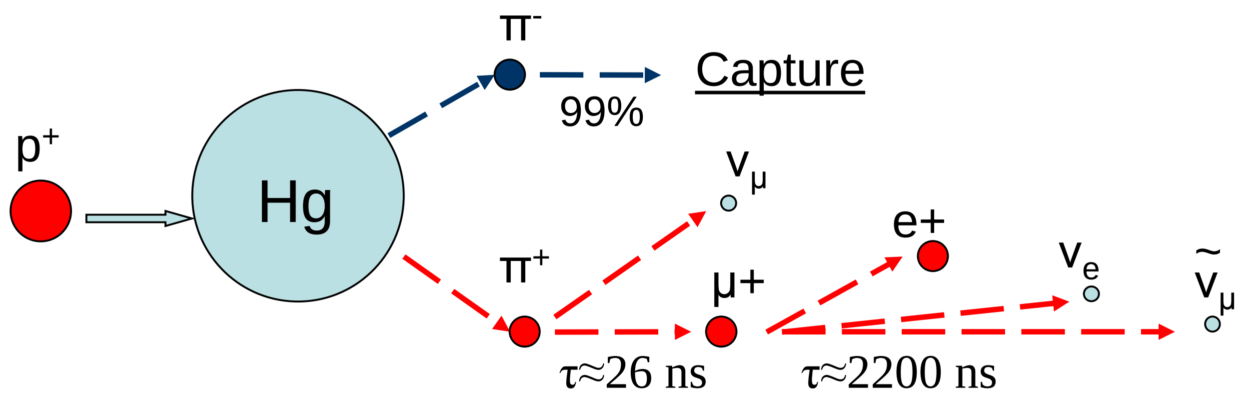
SNS facility at ORNL

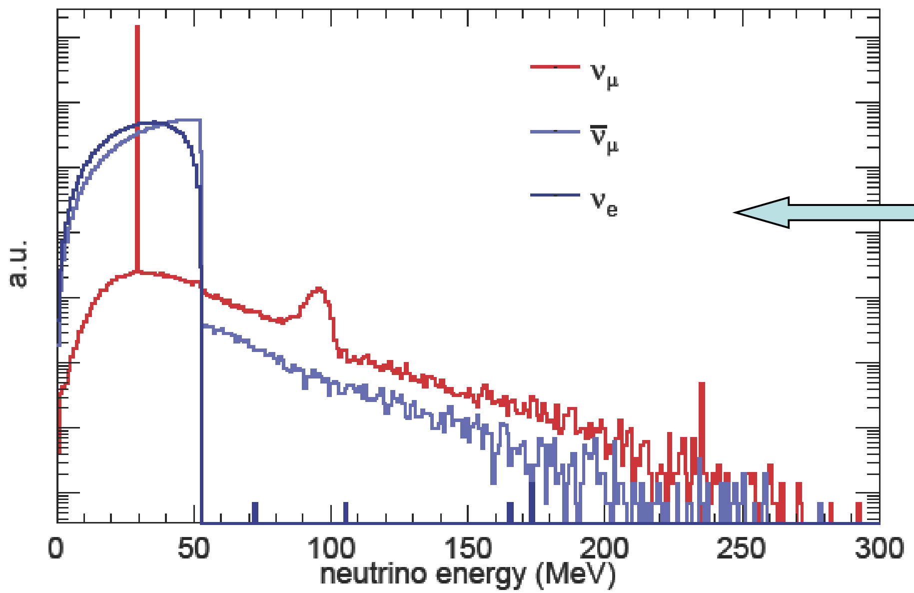
Bunches of ~1 GeV protons on the Hg target with 60 Hz frequency

Proton bunch time profile with FWHM of ~350 ns

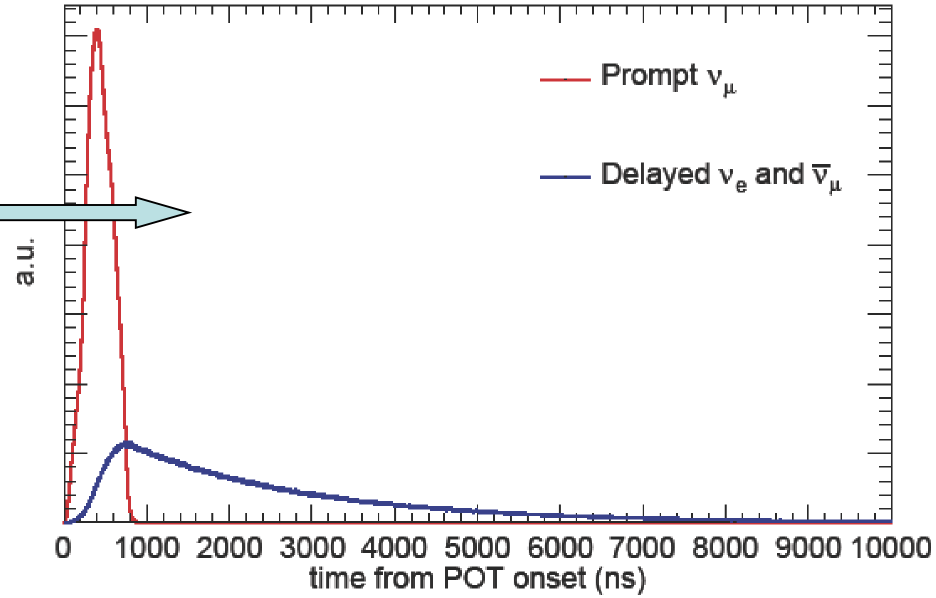
*Total neutrino flux of $4.3 \cdot 10^7$ cm^{-2}*s^{-1} at 20m*



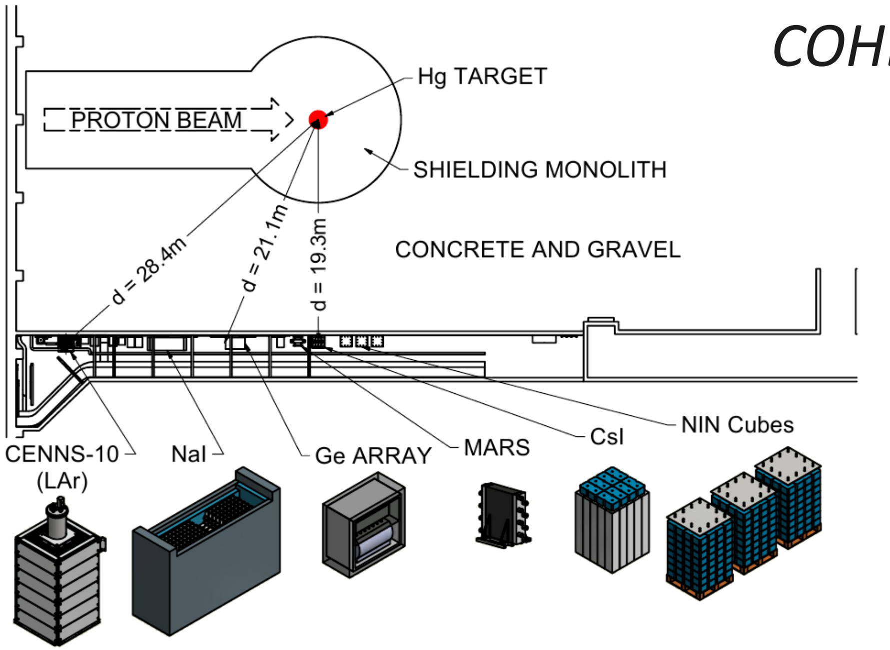




ν energy and timing suit well for CEvNS search



Physics with COHERENT detectors



COHERENT detectors are hosted by the target building basement

20 m of steel, concrete and gravel with no voids in the direction of the target

8 MWE vertical overburden

Large background suppression comes from the construction materials and beam timing

Multiple detectors complement each other in a chase for rich physics

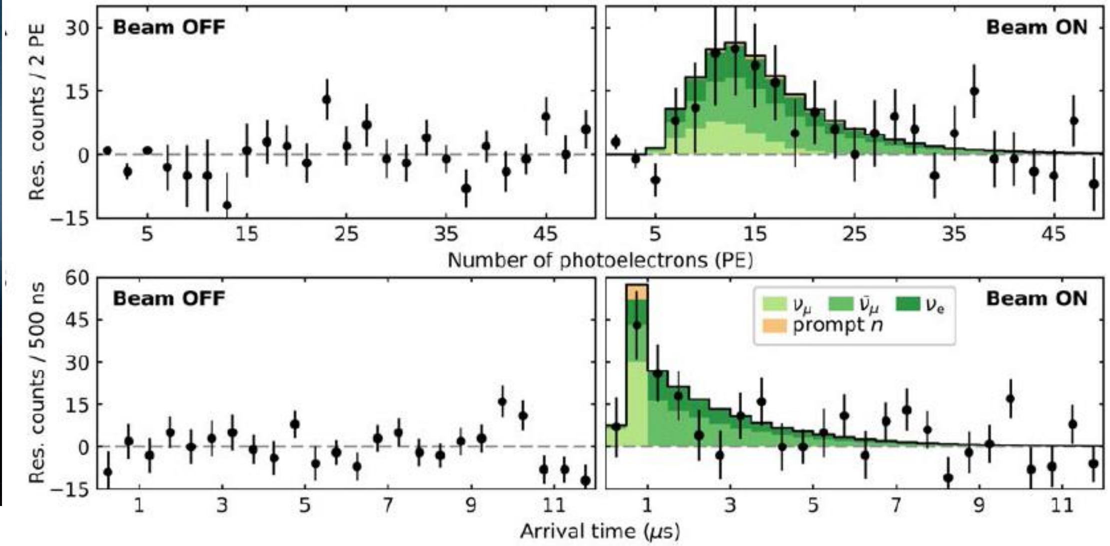
Topic	CsI	Ar	NaI	Ge	Nubes	D_2O
Non-standard neutrino interactions	✓	✓	✓	✓		
Weak mixing angle	✓	✓	✓	✓		
Accelerator-produced dark matter	✓	✓	✓	✓		
Sterile oscillations	✓	✓	✓	✓		
Neutrino magnetic moment		✓	✓	✓		
Nuclear form factors	✓	✓	✓	✓		
Inelastic CC/NC cross-section for supernova		✓			✓	✓
Inelastic CC/NC cross-section for weak physics		✓	✓		✓	✓

The sum is greater than the individual measurements

All measurements benefit from neutrino flux normalization

First CEvNS observation and its impact

First CEvNS observation was performed by COHERENT with the help of 14.6 kg CsI[Na]



6.7σ significance result was reported in 2017, 43 years after prediction

Bjorn Sholz (U.Chicago) thesis (2017), Grayson Rich (NCU) thesis (2017), D. Akimov et al., Science vol. 357 (2017)

Non-standard neutrino interactions and properties

J.Liao, D. Marfatia., PLB 775 (2017)

O. G. Miranda et al., JHEP 07 (2019)

P.Coloma et al., PRD 96 (2017)

M. Caddedu et al., PRD 101 (2020)

D. Papoulias and T. Kosmas, PRD 97 (2018)

Y. Farzan et al., JHEP 66 (2018)

Nuclear structure

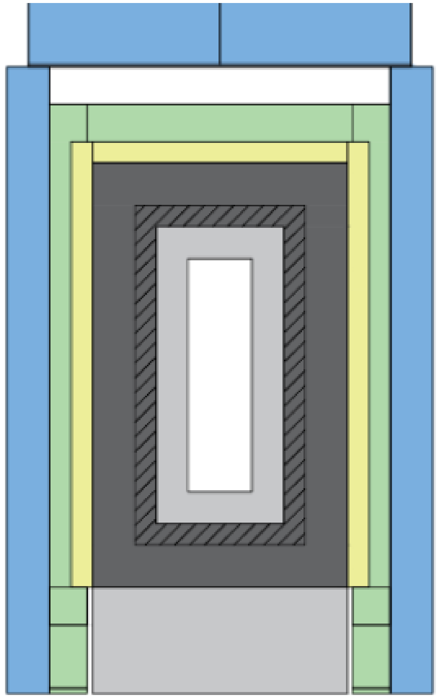
M. Caddedu et al., PRL 120 (2018)

Xu-Run Huang, Lie-Wen Chen, PRD 100 (2019)

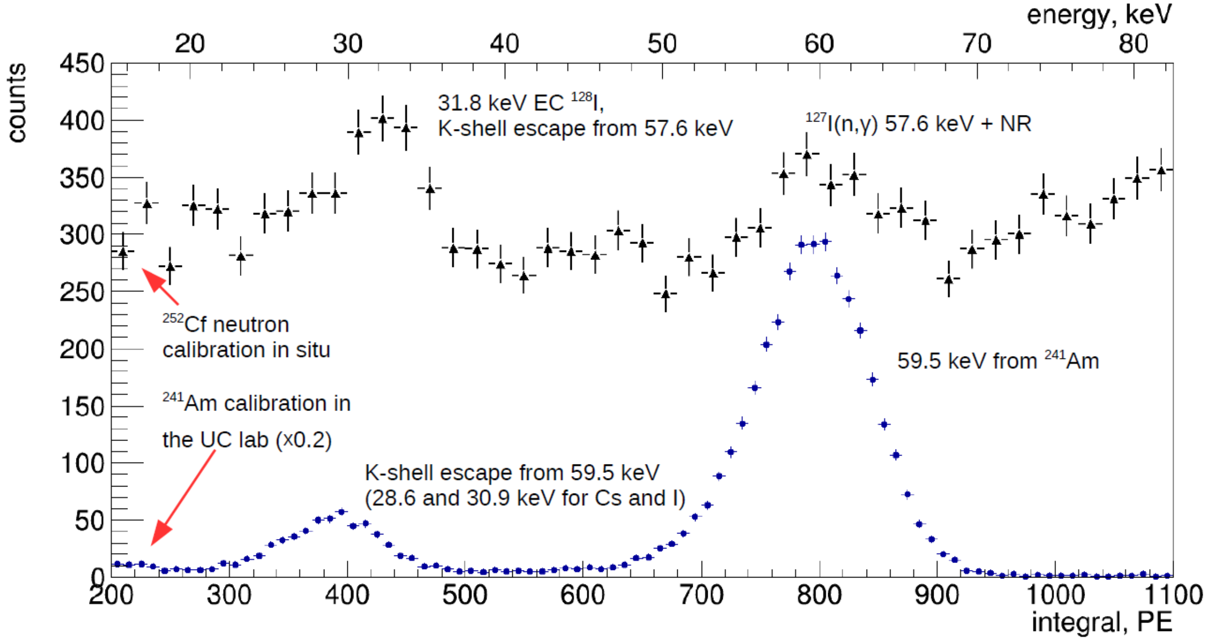
D. Papoulias et al., Physics Letters B 800 (2020)

CsI[Na] experiment

Crystal manufactured by Amcrys-H, Ukraine; set up created in the University of Chicago



Length	*34 cm*
Diameter	*11 cm*
Weight	*14.6 kg*



Read out by single R877-100 PMT

Light yield of the crystal is ~13.3 PE/keV and it's uniform within 3% across the crystal length

Shielding design

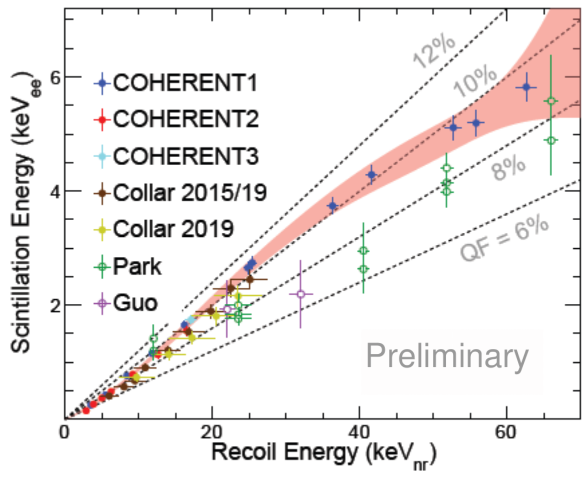
Layer	HDPE	Low backg. lead	Lead	Muon veto	Water
Thickness	3''	2''	4''	2''	4''
Colour					

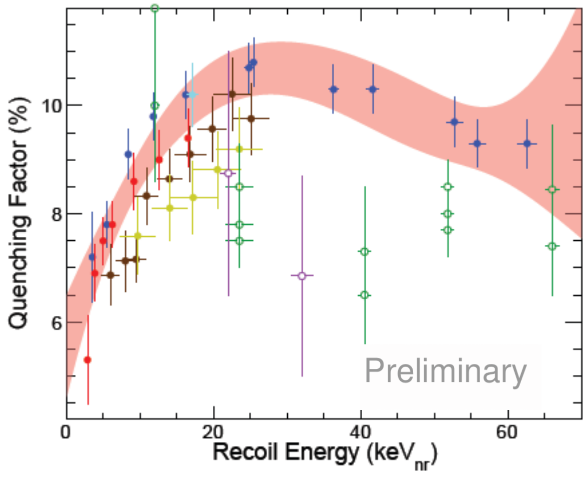
More information in *J. Collar et al., NIM A773, 56 (2015)* *B.J. Scholz PhD thesis (2017)*

New CsI CEvNS result: refinements in the analysis

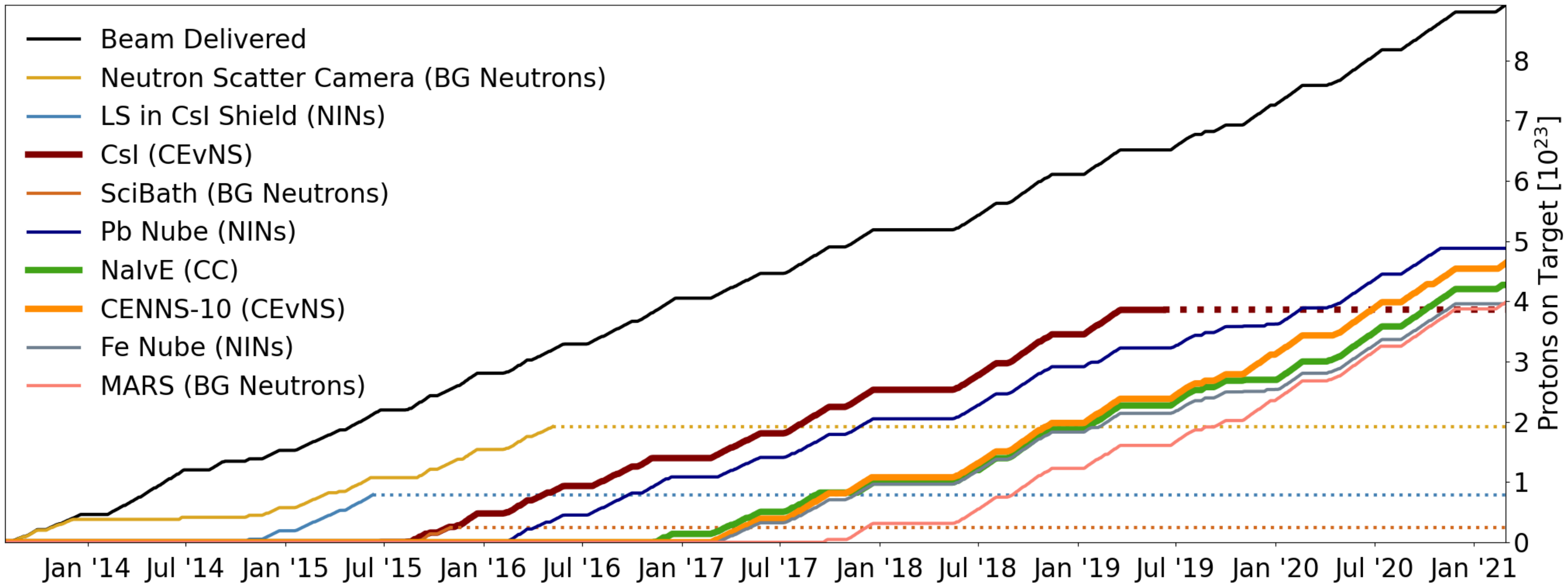
Refinements:

1. New CsI[Na] QF measurements and global fit
2. Better model of the steady state background
3. Better understanding of detector resolution



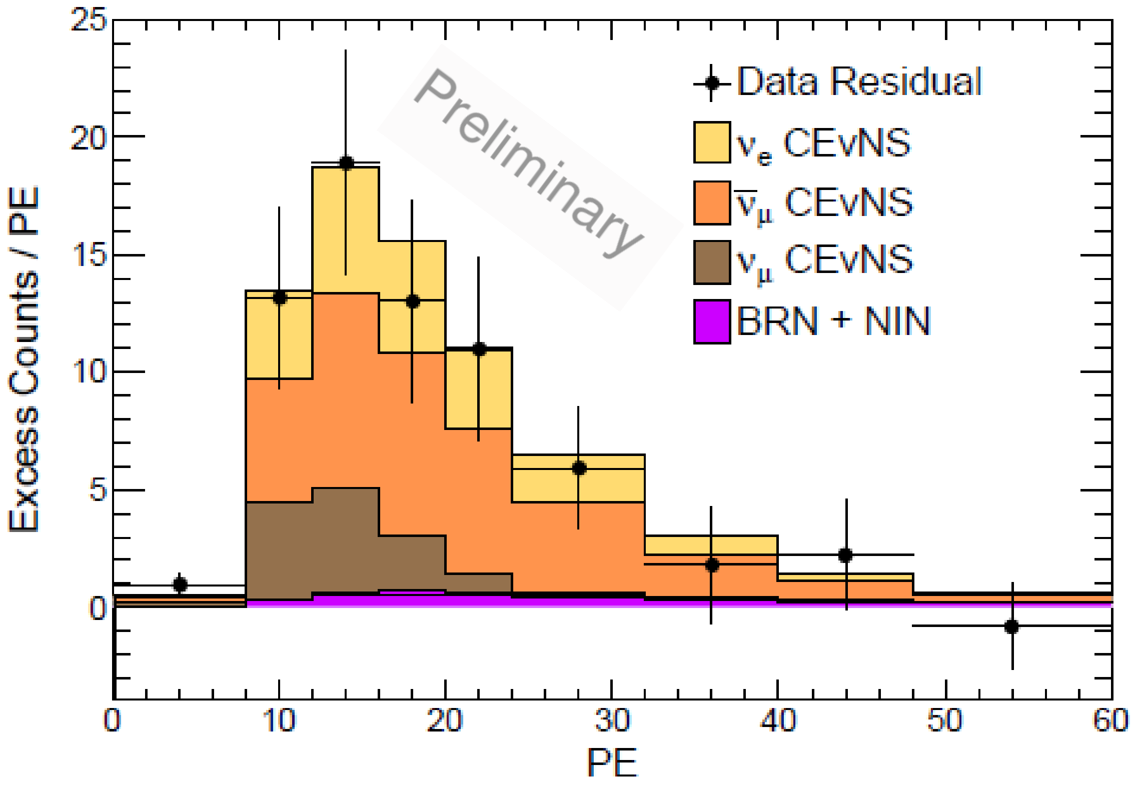


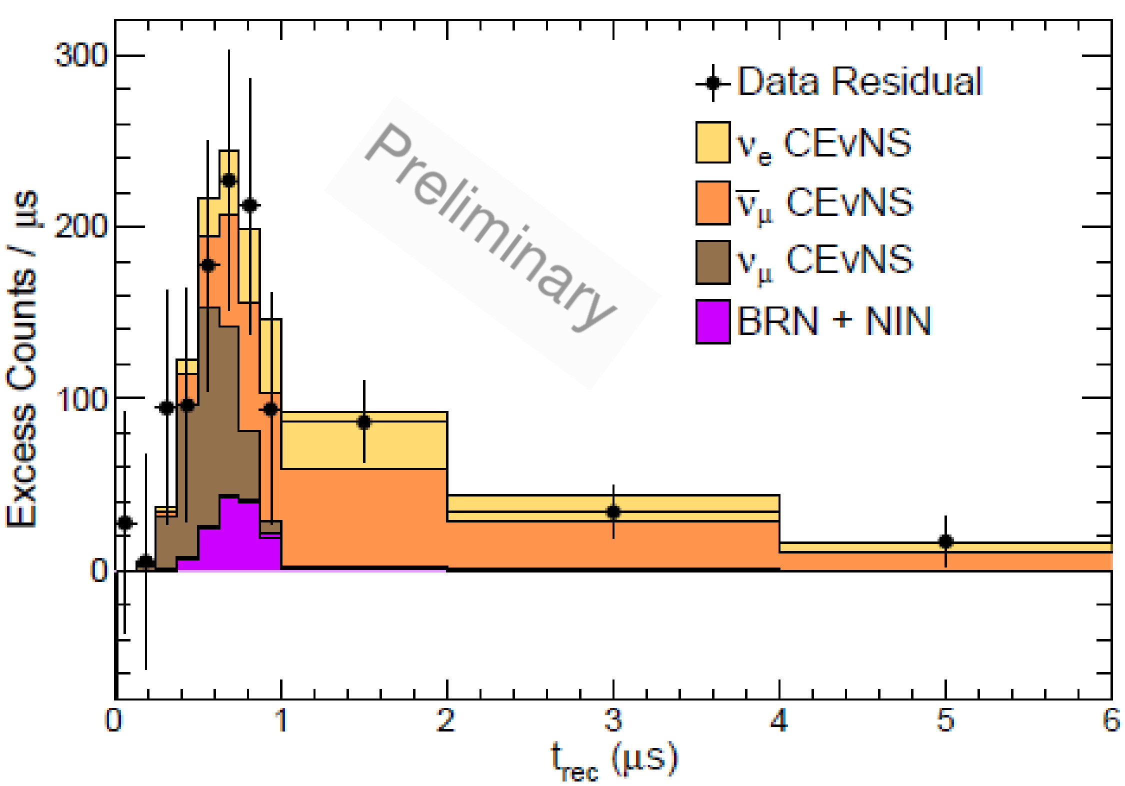
More details on QF in the backup



Full dataset has more than 2x statistics

New CsI CEvNS result: experimental spectra

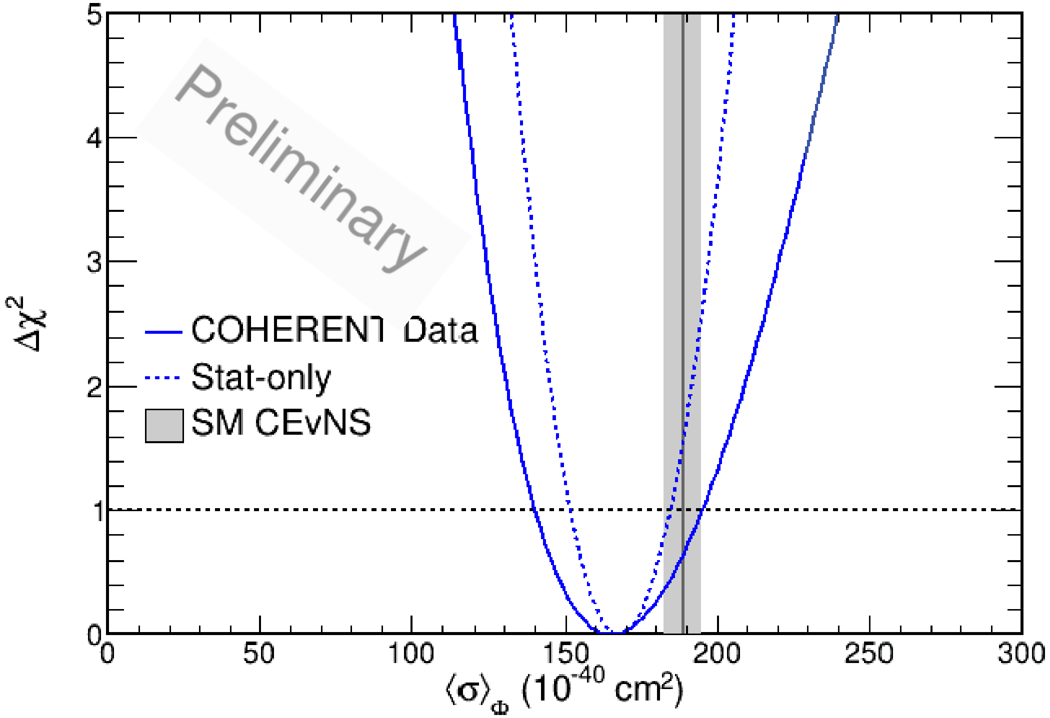




After 2D likelihood fit with systematic pulls incorporated

	Prior Prediction	Best Fit Total
Steady-state background	1286 ± 27	1273 ± 24
BRN	18.4 ± 4.6	17.3 ± 4.5
NIN	5.6 ± 2.0	5.5 ± 2.0
CEvNS	–	306 ± 20

New CsI CEvNS result: cross section



No CEvNS rejection	*11.6 σ*
SM CEvNS prediction	*341±11(th.)±42(exp.)*
Fit CEvNS events	306±20
Fit χ^2/dof	82.6/98
CEvNS cross section	$165^{+30}_{-25} \times 10^{-40}$ cm^2
SM cross section	$(189 \pm 6) \times 10^{-40}$ cm^2

We observe high significance CEvNS consistent with the SM prediction!

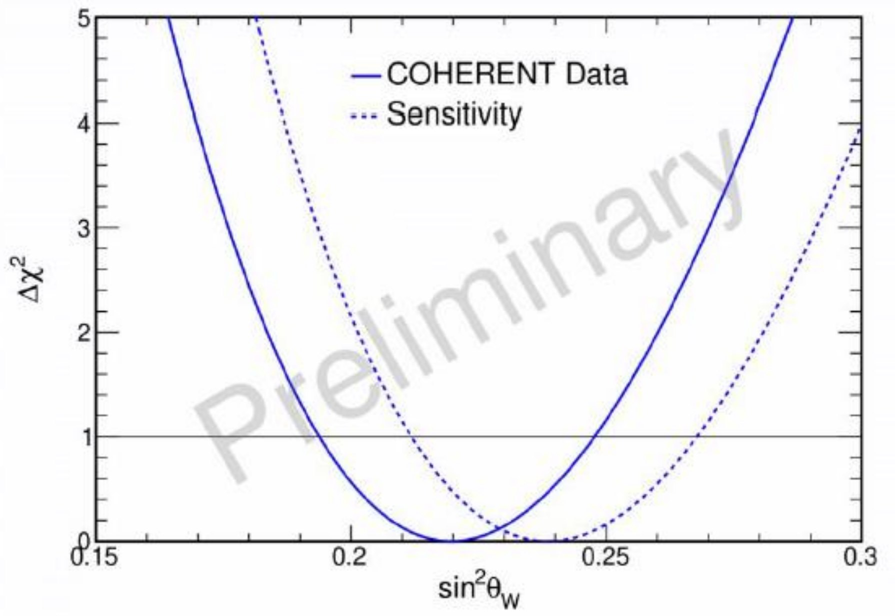
Systematics summary

Uncertainty	Effect on CEvNS
Neutrino flux	10%
SSBg rate	3.0%
BRN rate	0.9%
NIN rate	0.5%
Nuclear form factor	3.4% (theory) 0.6% (exp.)
Quenching factor	3.8%
CEvNS efficiency	4%

New CsI CEvNS result: electroweak mixing angle

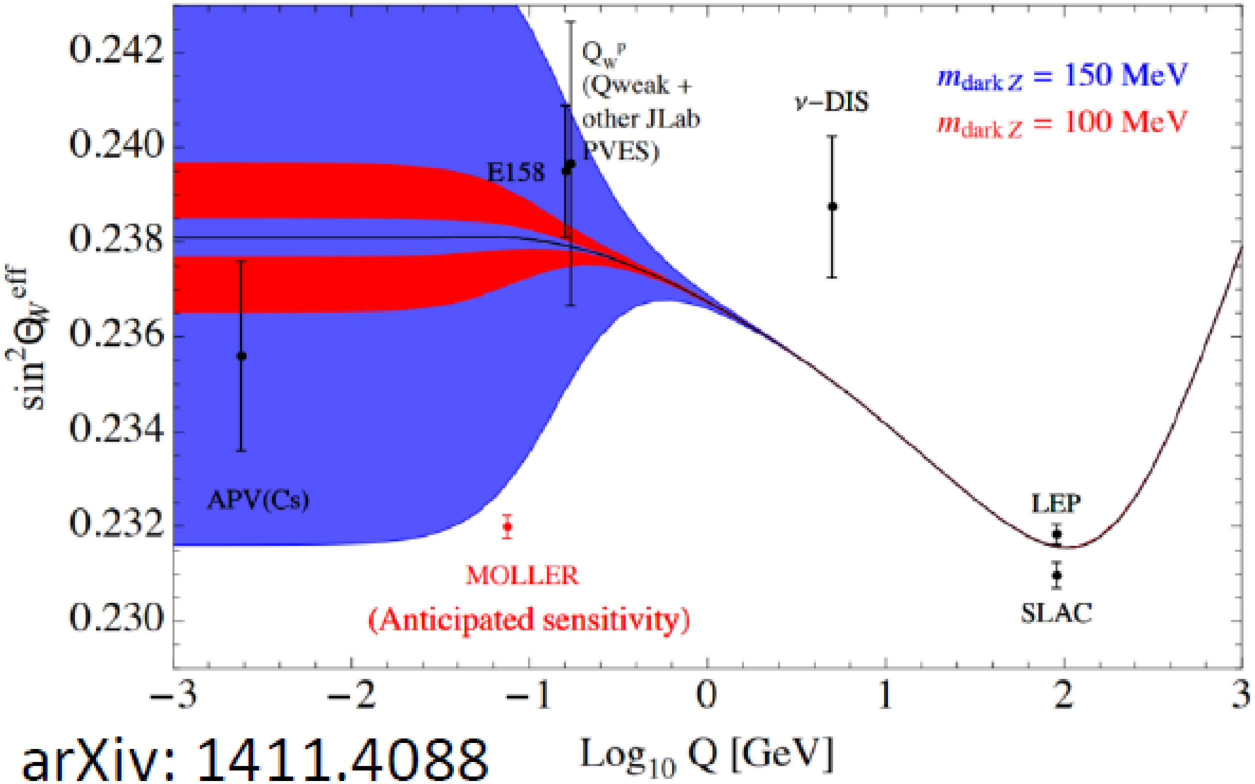
Sensitivity through proton weak charge contribution

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi}\Big([1 - \underline{4\sin^2\theta_W}]Z - N\Big)^2\left[1 - \frac{T}{T_{max}}\right]F_{nucl}^2(q^2)$$



The best fit value is

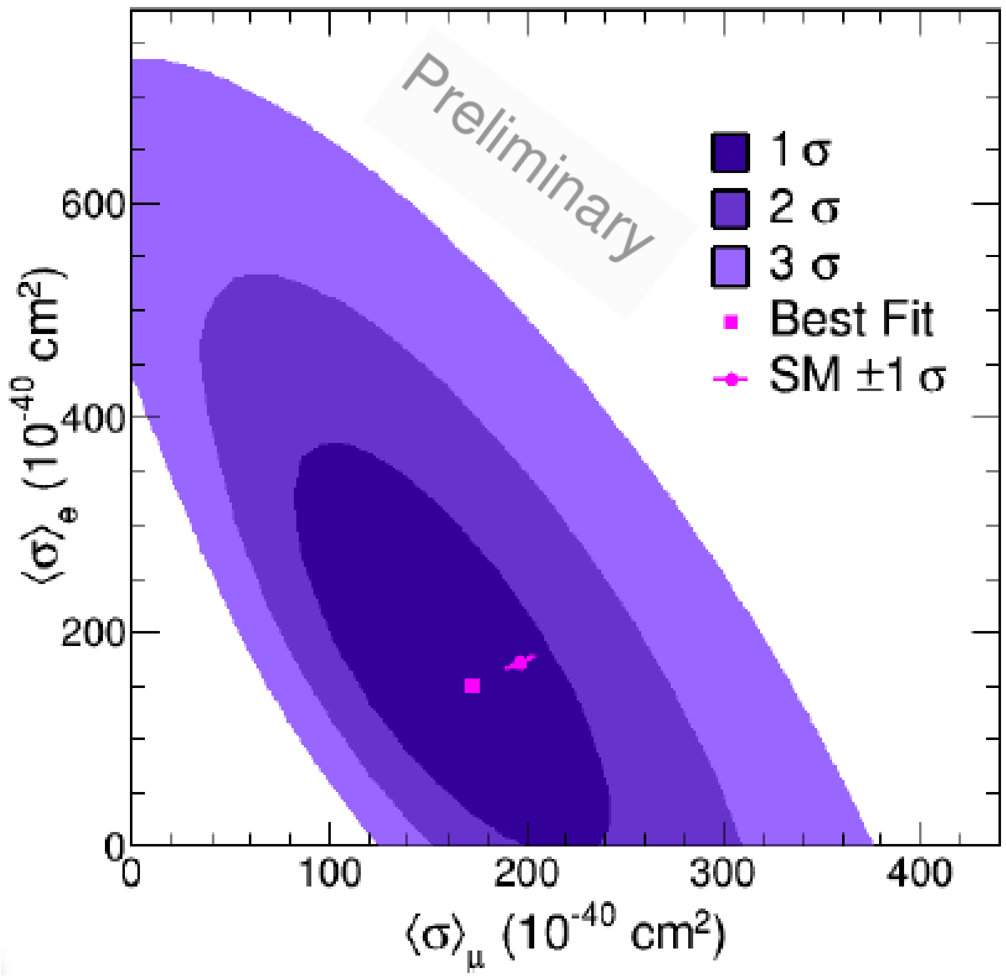
$$\sin^2\theta_W = 0.22^{+0.028}_{-0.026}$$



arXiv: 1411.4088

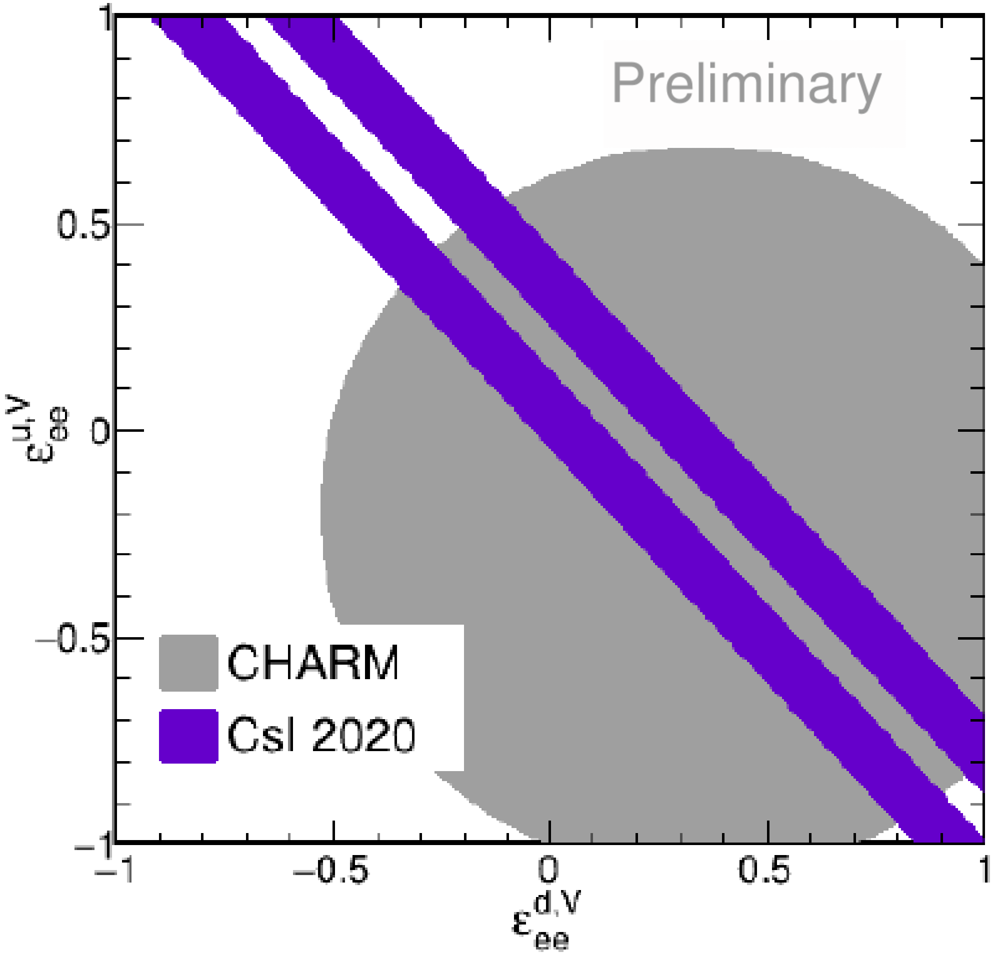
Parity violation experiments are much more precise (2%)... so far

Flavored CEvNS



In case there's a flavor-dependent NSI

Vector like neutrino-quark NSI

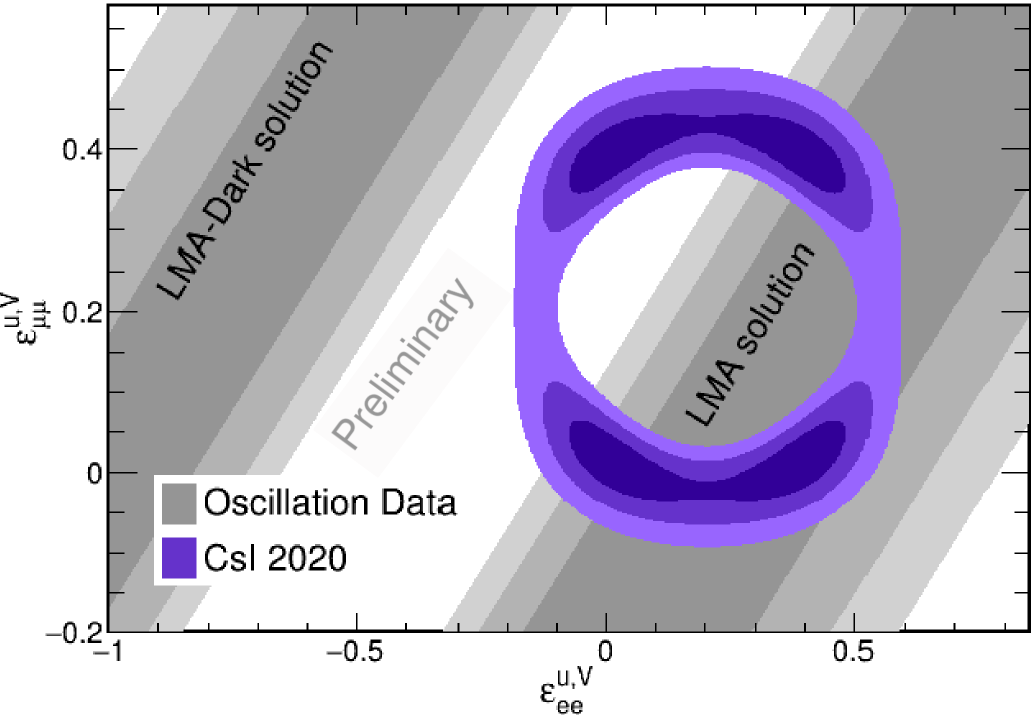


For mediator mass >> momentum transfer

Other limits on vector-like NSI: COHERENT LAr – PRL 126, 012002 (2021); XENON1T - arXiv:2012.02846

New CsI CEvNS result: LMA-Dark

See PRD96 11 115007



Measurement of PMNS parameters with neutrino oscillation experiments can be confused in NSI scenarios

In particular, there is ambiguity between the large mixing angle (LMA) solution to solar oscillations and the LMA-Dark dark model

- Would flip the θ_{12} octant: $\theta_{12} \rightarrow \pi/2 - \theta_{12}$

LMA-Dark would require non-zero $\varepsilon_{ee}^{u,V}$ and $\varepsilon_{\mu\mu}^{u,V}$, which we can test given with our flavored cross section result

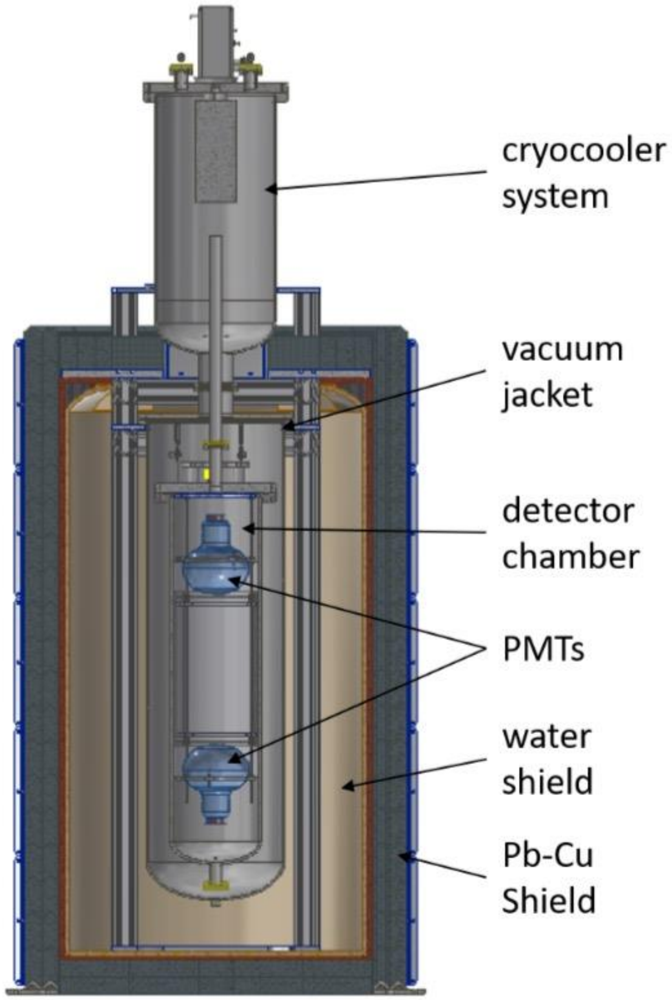
LMA-Dark solution is in tension with the CsI[Na] CEvNS measurement

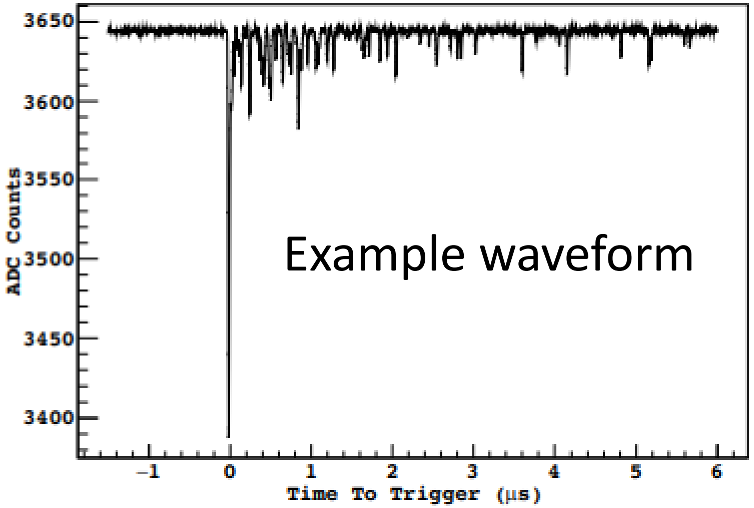
We expect many more results RE nuclear structure and general neutrino NSI after the new CsI[Na] result data release

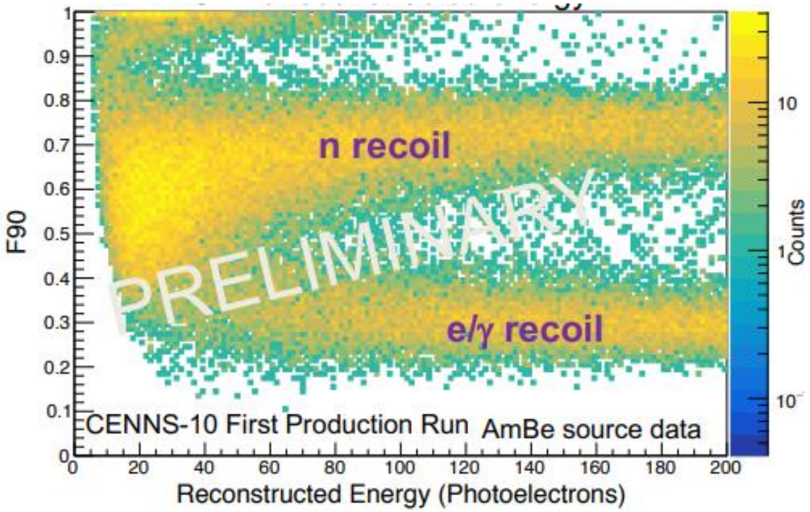
CENNS-10 LAr detector

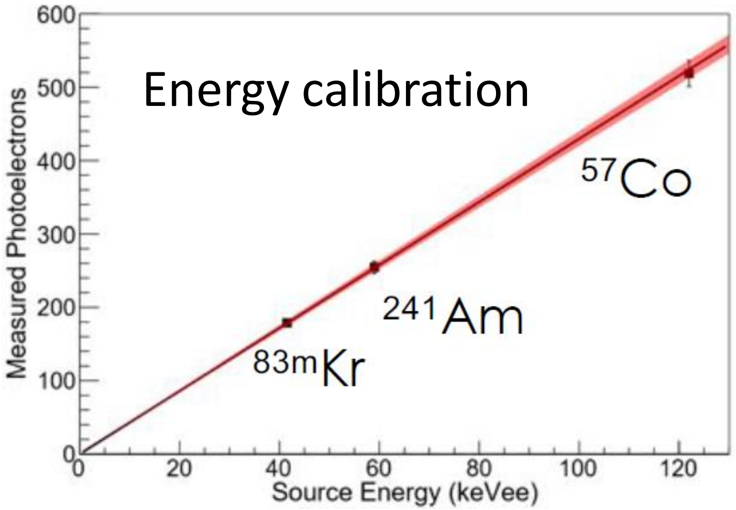
Built by J. Yoo et al. in Fermilab, moved to SNS late 2016

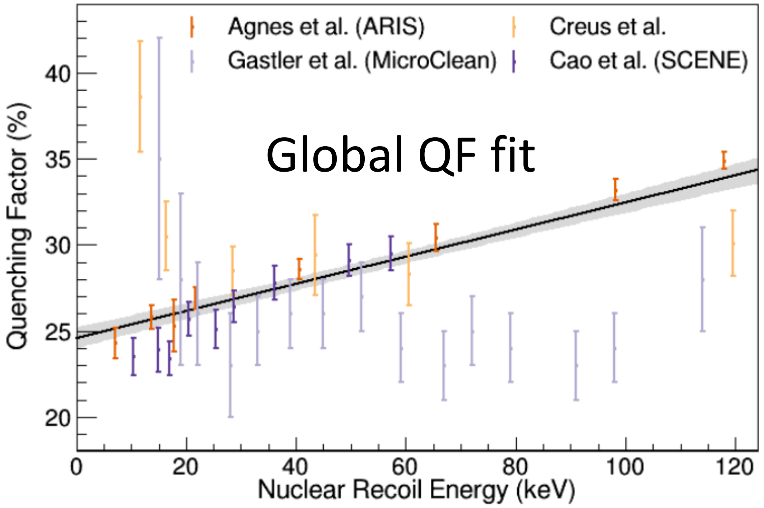
After light collection upgrade of 2017 single phase LAr detector with fiducial mass of 24 kg provides the light yield of 4.5 PE/keV$_{ee}$ and a ~20 keV$_{nr}$ threshold







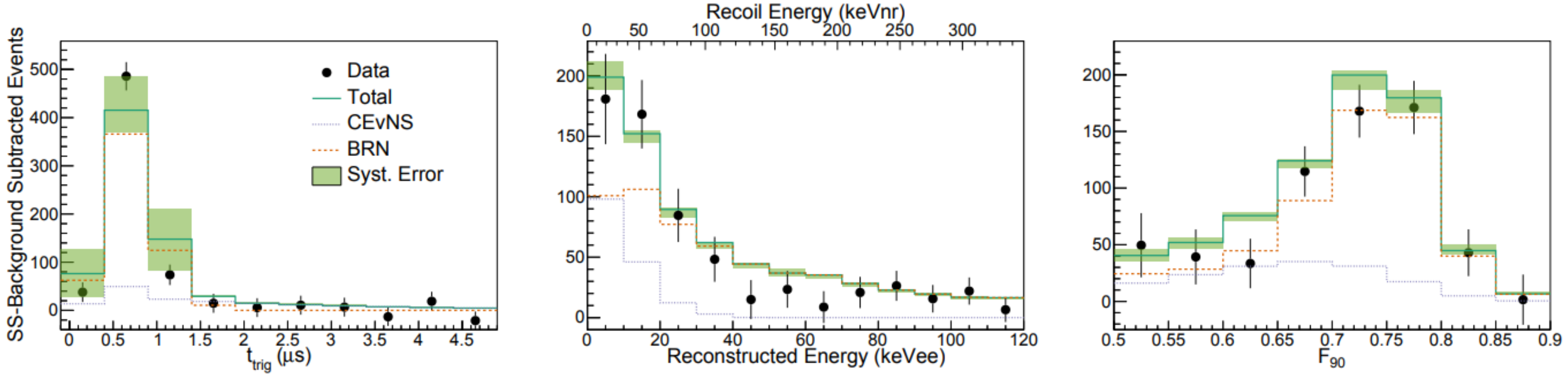




Matthew Heath (IU) thesis (2019), D. Akimov et al., PRD 100, 115020, J. Zettlemoyer (IU) thesis (2020)

First CEvNS detection on LAr

Combined fit in (time, energy, PSP) space suggest >3σ CEvNS detection significance



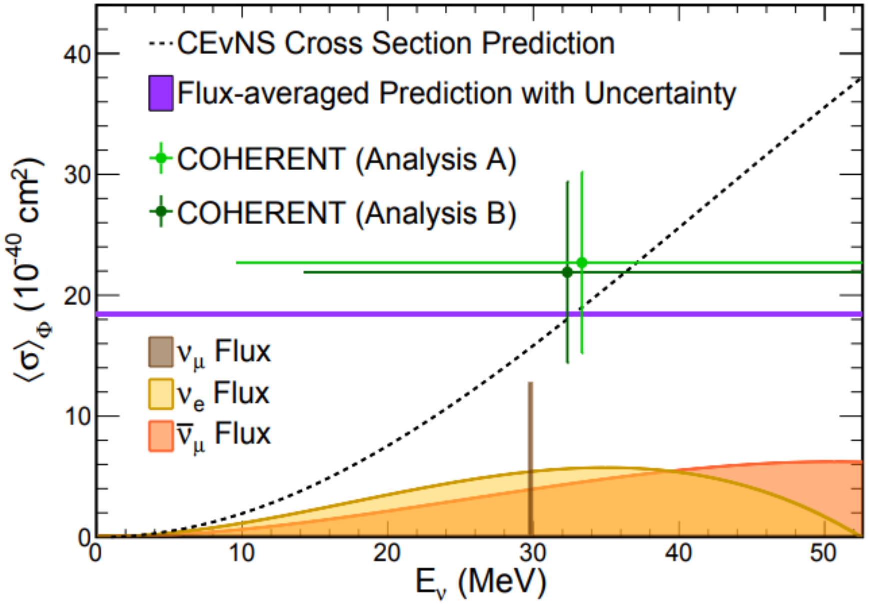
Dominant backgrounds:

1. ^{39}Ar beta decay
2. Beam related neutrons

Two independent blind analyses results agree with the SM CEvNS rate prediction

PRL 126, 012002 (2021)

arXiv:2006.12659 – LAr data release



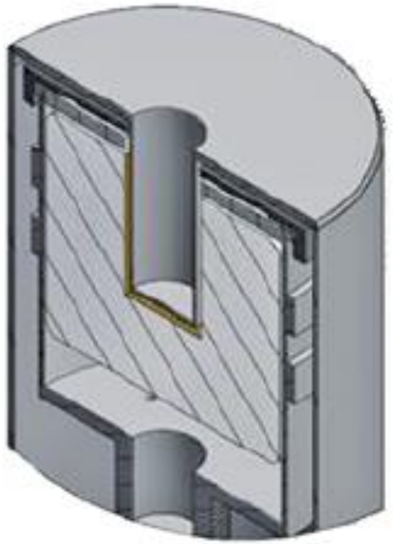
	Analysis A	Analysis B
SM-predicted ($\times10^{-39}$ cm^2)	1.8	
fit CEvNS events	159 ± 43	121 ± 36
cross section systematic errors:		
detector efficiency	3.6%	1.6%
energy calibration	0.8%	4.6%
F_{90} calibration	7.8%	3.3%
quenching factor	1.0%	1.0%
nuclear form factor	2.0%	2.0%
neutrino flux	10%	10%
total cross section sys. error	13%	12%
measured ($\times10^{-39}$ cm^2)	2.3 ± 0.7	2.2 ± 0.8

The result accuracy is dominated by statistical uncertainty at this point

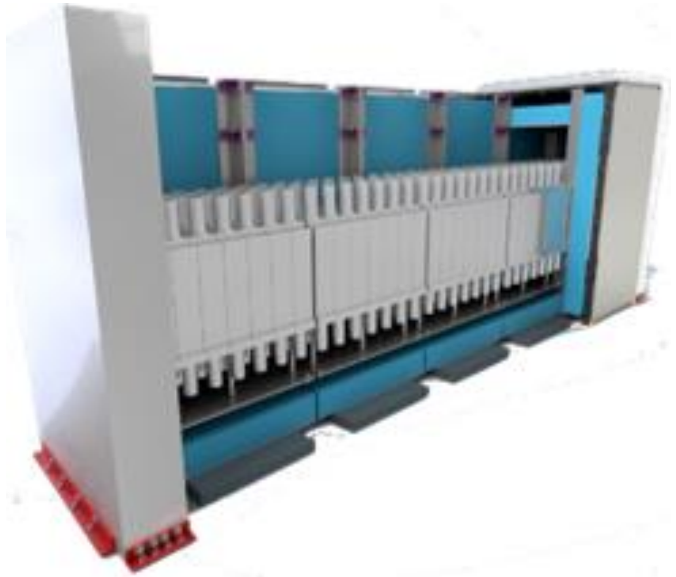
CENNS-10 continues data taking and 5σ significance is expected by the end of the year 2020

2021: commissioning two CEvNS detectors

Germanium–HPGE PPC (“COH-Ge-1”):



- *16 kg total mass, all 8 detectors delivered*
- *500+ CEvNS/year at E_{rec}>0.3 keV_{ee} with good energy resolution*
- *detector characterization and finalization of the shielding design*
- *may compete for ν_μ magnetic moment limit (best is* $6 \cdot 10^{-10}\ \mu_B$ from LSND*)*



Multi-ton NaI[Tl] array (“COH-NaI-2”):

- *3.4T to be deployed, crystals available*
- *13 keVnr threshold (Na recoils), 3σ/year expected*
- *lightest COHERENT nucleus, sensitive to axial current*

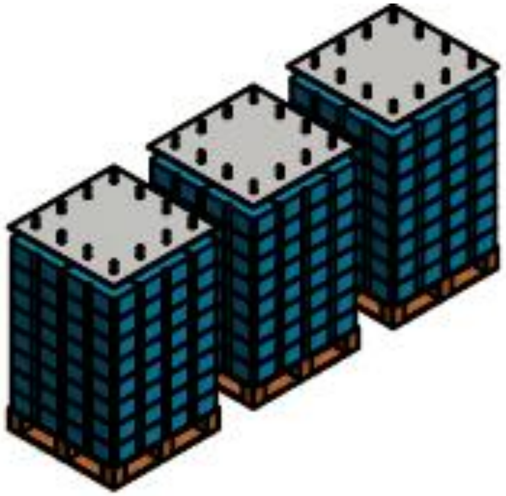
Both to be deployed at SNS summer 2021

NaIvE ("COH-NaI-1")

185 kg deployed, used for the background rate studies for the ton-sale CEvNS and charged current on Iodine

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

Nubes



Liquid scintillator cells in Pb/Fe shielding to study neutrino induced neutron backgrounds + interesting as a Supernovae neutrinos detecting mechanism

$$\nu_e + {}^{208}Pb \rightarrow e^- + {}^{208}Bi,$$

$$\nu + {}^{208}Pb \rightarrow \nu + {}^{208*}Pb$$

+ decay of a nucleus with neutrons in the final state

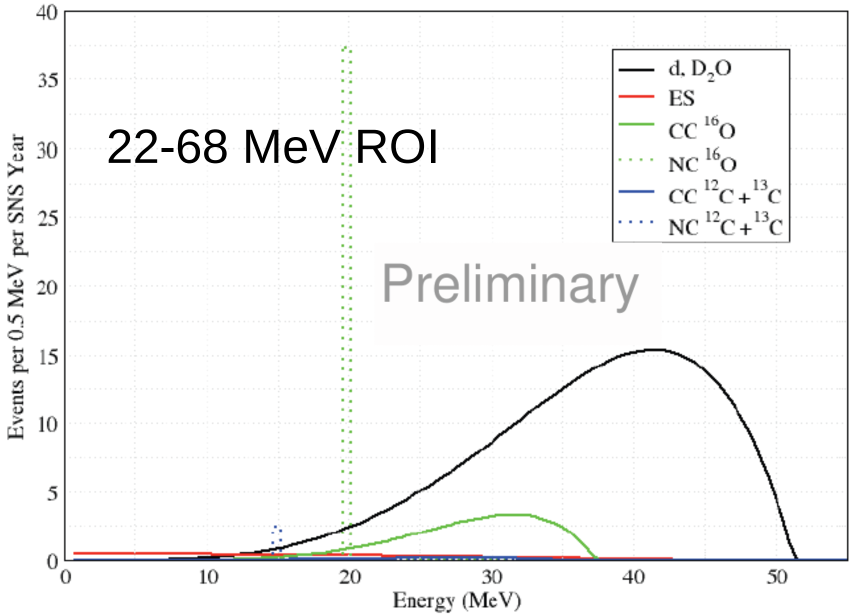
+ MARS – portable neutron flux detector: scintillator covered with Gd paint

COHERENT future: D_2O

Precise flux normalization with a D_2O Cherenkov detector: $\nu_e + d \rightarrow p + p + e^-$

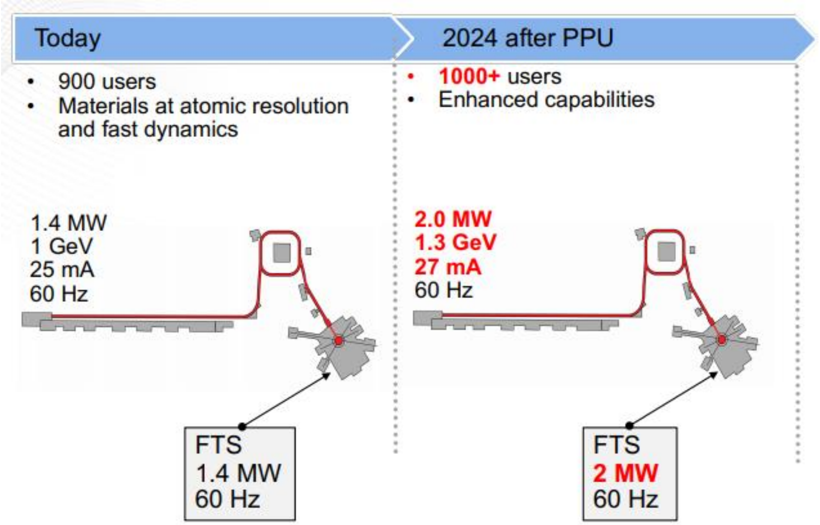
Status: R&D

- *592 kg planned, heavy water secured*
- *2-3% theoretical uncertainty**
- *calorimetry: no ring imaging*
- *5% statistical unc-ty in 2 years*



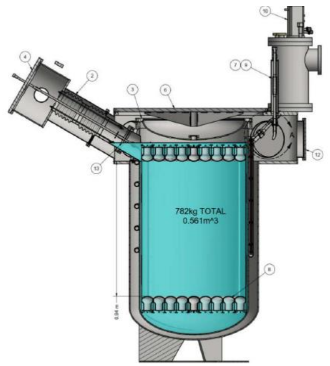
	Total Events	Events in Region of Interest
$\nu_e + D$	1070	912
$\nu_e + O$	390	159
Cosmics	20200	293

*S.Nakamura et. al.
Nucl.Phys. A721(2003) 549



Need to launch fast – SNS switching to 1.3 GeV in 2024

COHERENT future: LAr

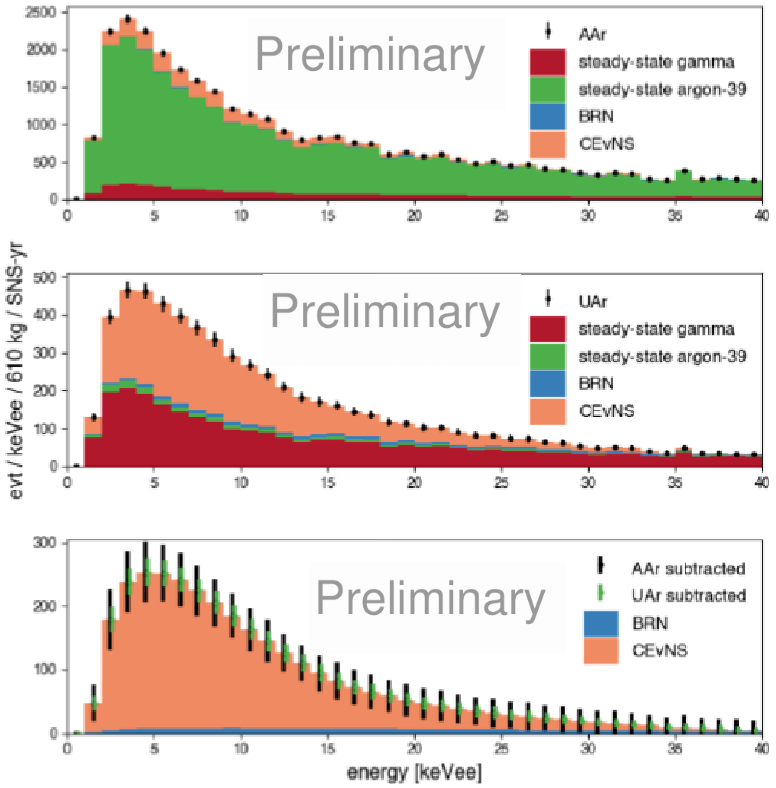


"COH-Ar-750" – LAr based detector for precision CEvNS, inelastics and DM

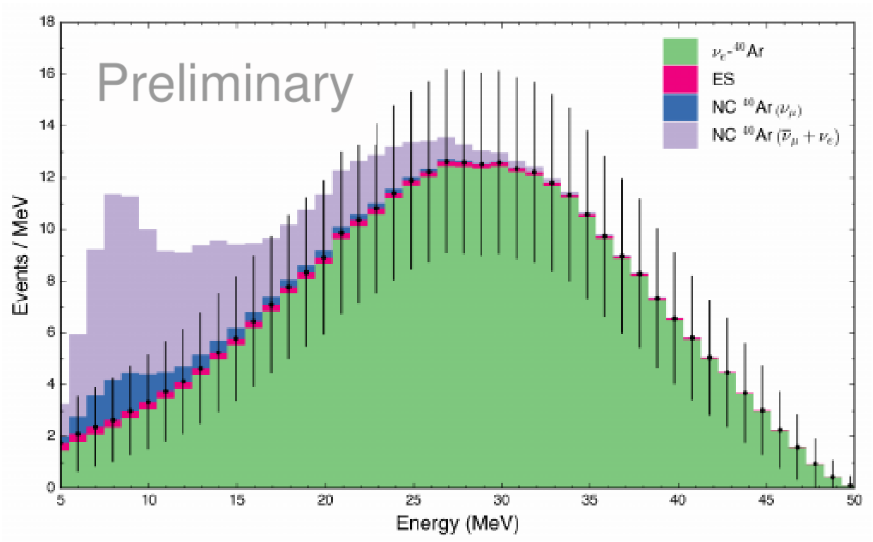
- *Single phase, scintillation only, 750 kg total (610 kg fiducial)*
- *3000 CEvNS/year, ~400 inelastics/year*

Status: R&D

CEvNS



Inelastic Interactions

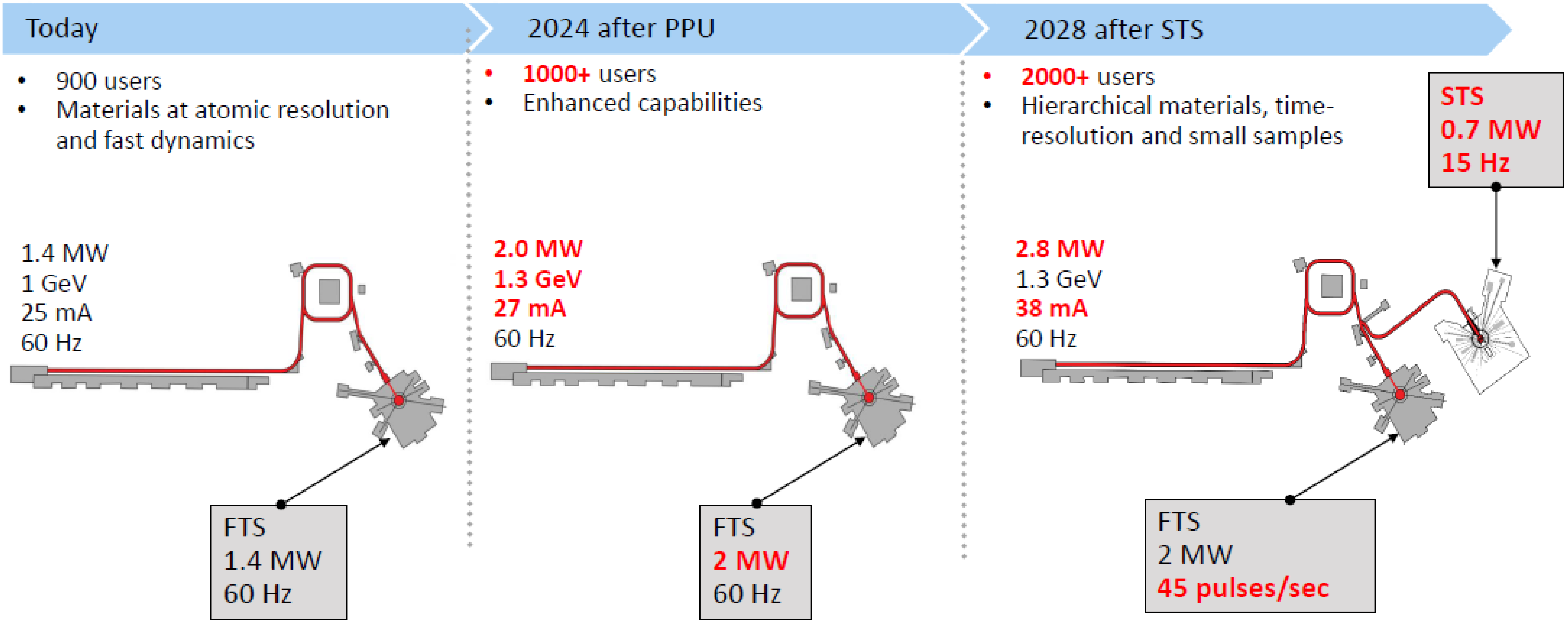


Also quite sensitive to the vector/baryonic portal dark matter candidates

P. deNiverville et al., PRD 95 (2017)

B. Batell et al., PRD 90 (2014)

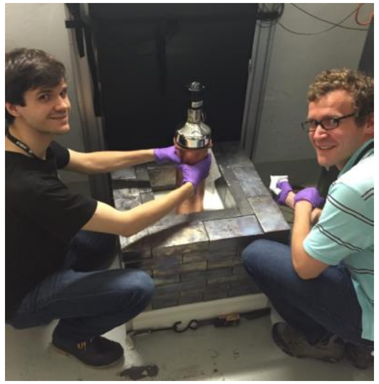
SNS Second Target Station



STS provides opportunity for more dedicated neutrino physics space

COHERENT is in contact with ORNL on this matter (space/background level optimization)

Summary





- *We measured CEvNS with CsI[Na] [reduced systematics, increased statistics]*
- *LAr results confirm feasibility of COHERENT multi-target program*
- *HPGe and NaI to be deployed summer 2021*

Looking forward to precision CEvNS measurement by ~1T LAr with reduced flux uncertainty from the D_2O and keeping the eye on the STS for future activities

COHERENT SNS

Backup: Accelerator produced Dark Matter

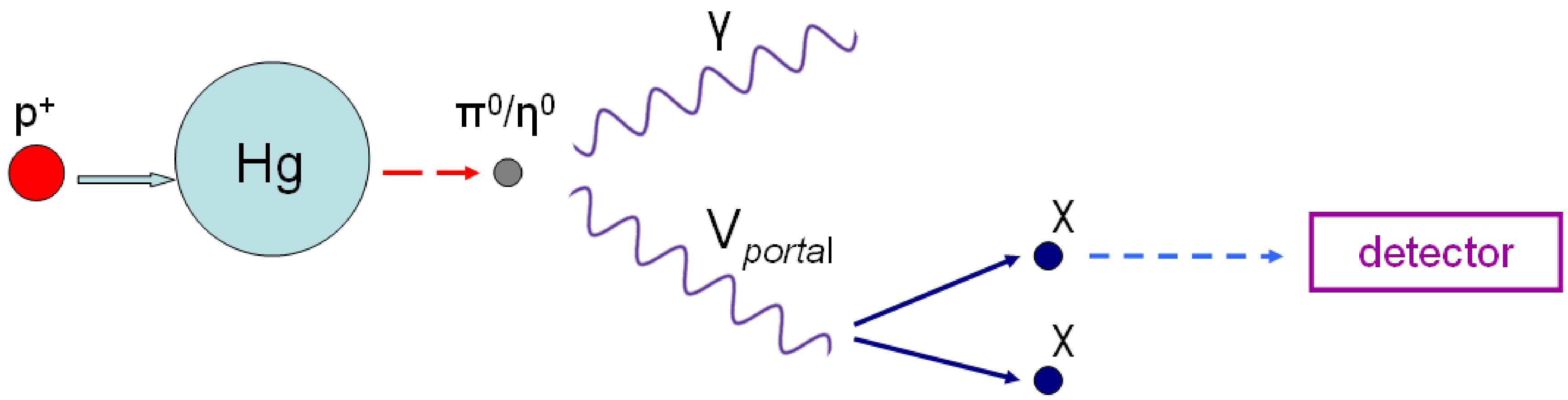
Vector portal: mixing of the vector mediator with photons in π^0/η^0 decays

P. deNiverville et al., PRD 95 (2017)

B. Batell et al., PRD 90 (2014)

Leptophobic portal: mediator coupling only to baryons

+ decay into "DM"-like χ



χ arrives to the detector with prompt ν and beam-related neutrons

may be constrained by "delayed" ν CEvNS

constrained from the dedicated measurements

A "DM" particle interact with the target [detector nuclei] coherently → σ enhancement!

COHERENT DM sensitivity paper:

arXiv:1911.06422

Exact sensitivity limits are currently re-evaluated, stay tuned!

See also:

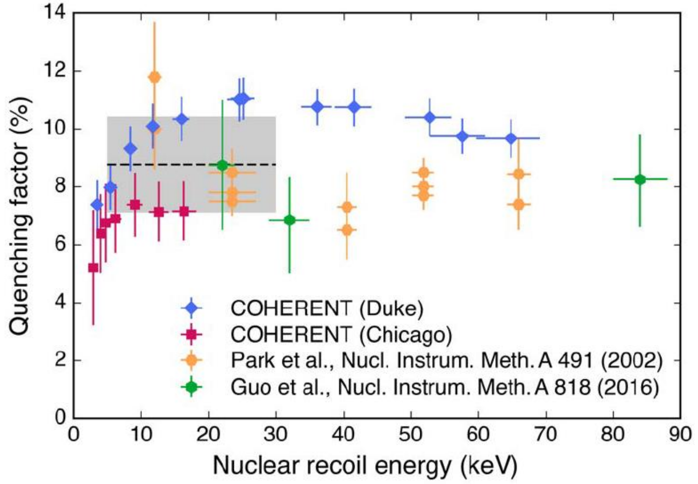
B. Dutta et al., arXiv:2006.09386

N. Hurtado et al., arXiv:2005.13384

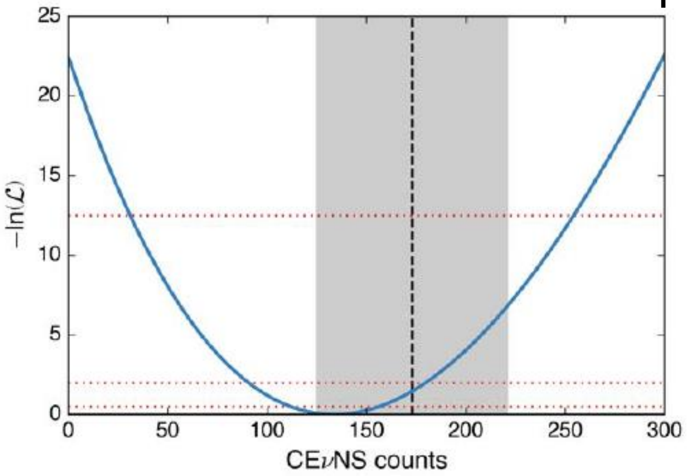
Backup: CsI[Na] quenching factor

At the time of the first CEvNS observation (2017) the QF value uncertainty dominated the prediction uncertainty

Gray marks 8.8 ±1.7% value



134 ± 22 observed vs. 173 ± 48 predicted

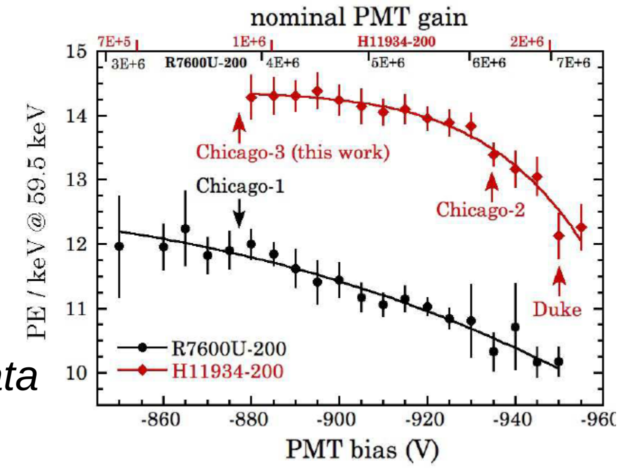


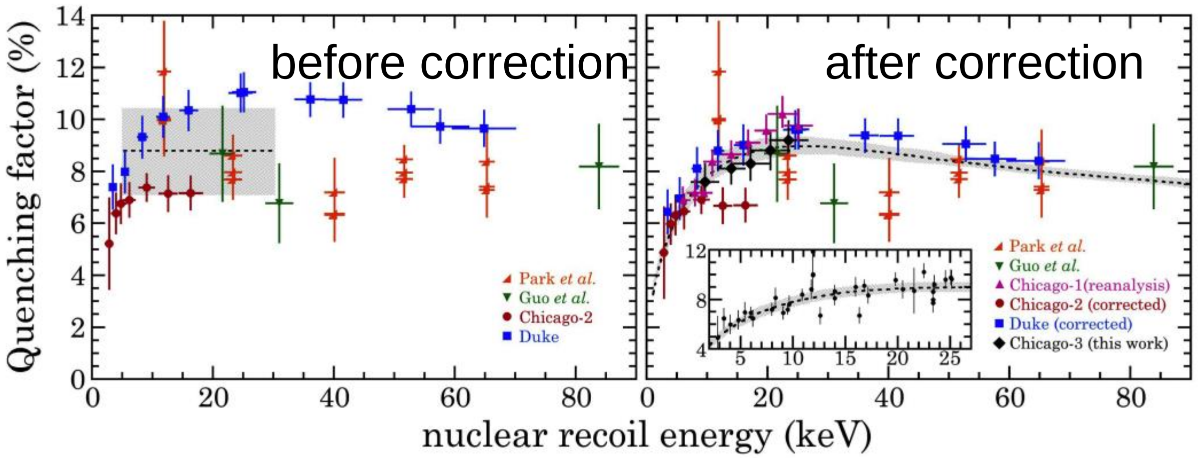
The uncertainty was estimated by discrepancy in results of two measurements by COHERENT

Over the following years there were Prof. J. Collar's and COHERENT updates on QF values issue

J. Collar et al., PRD 100 (2019):

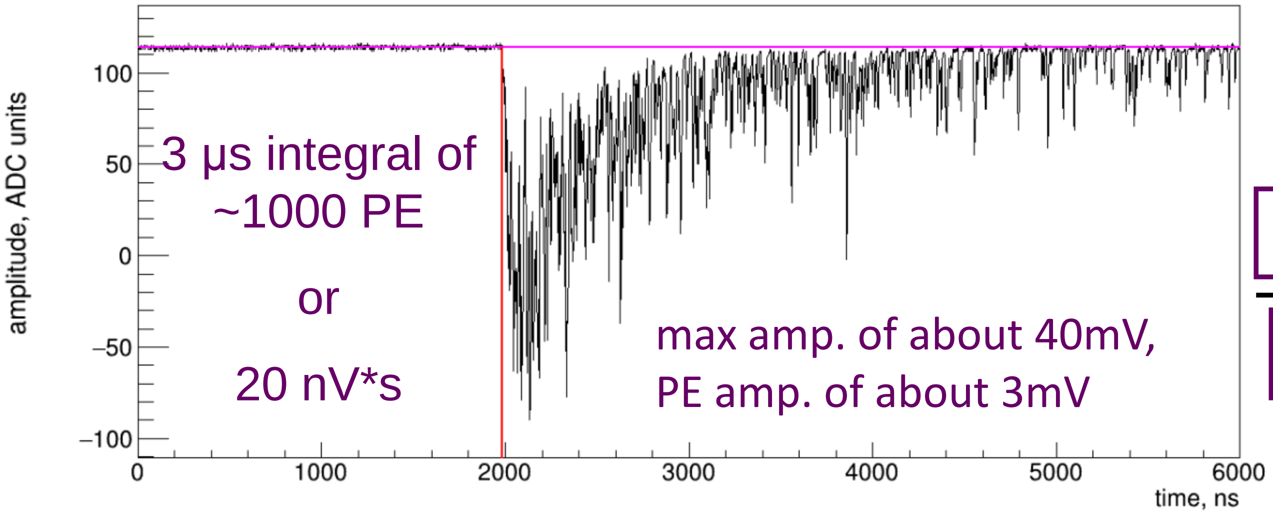
1. *New Chicago-3 data*
2. *Re-analysis of Chicago-1*
3. *PMT non-linearity claim and corrections to COHERENT data*





Backup: Scrutiny of H11934-200 PMT non-linearity claim

Scale of the 59.5 keV signals in COHERENT-2 measurement (-935V)



Crude estimate from the manufacturer's info

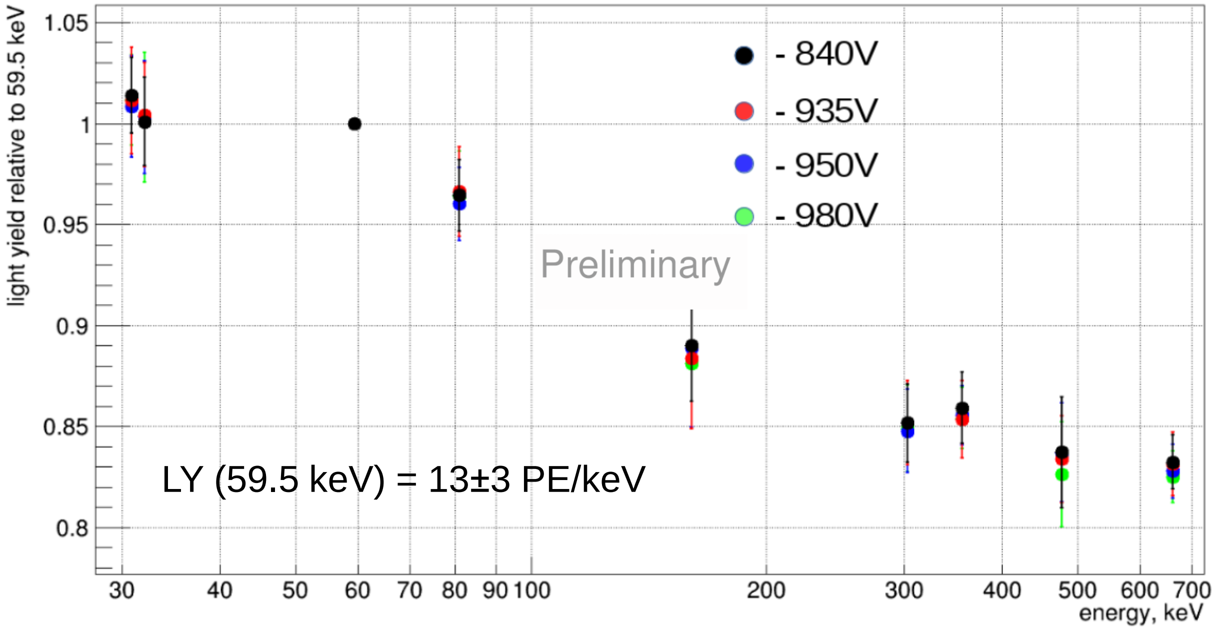
Let it be 1200 PE signal from the PMT at -950V

Let the gain be $2{\cdot}10^6$ at 950V (from the manufacturer info)

$$\frac{2.4{\cdot}10^9\ e \approx 4{\cdot}10^{-10}\ C}{300\ ns\ (vs.\ 3\mu s)} = 1.3\ mA$$

vs. ± 2% at 20mA from Hamamatsu info

Tests with the crystal – relative light yield



No change in the rel. LY in 840V-980V bias voltage for the lines in [30, 662] keV energy range

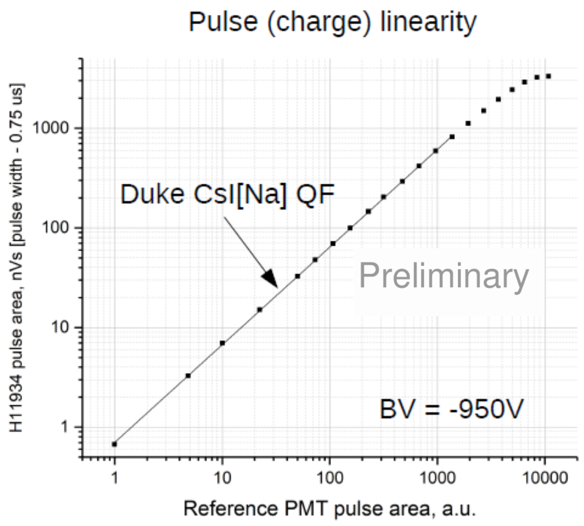
Change in the rel. LY with energy comes from the CsI[Na] non-kinearity and is consistent with the literature

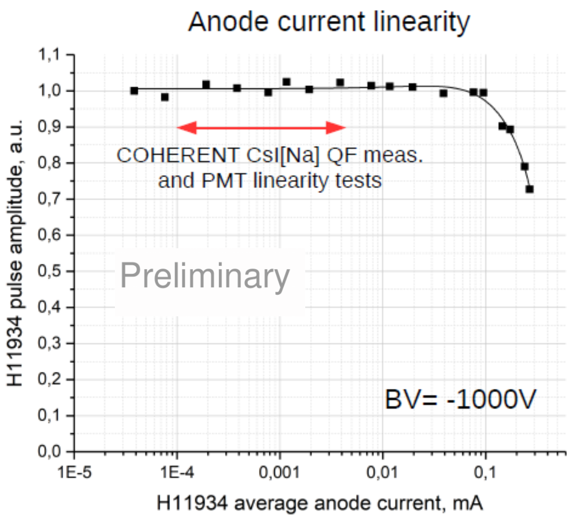
G. K. Salakhutdinov et al., Instr. Exp. Tech. 58 (2015)

W. Mengesha et al., IEEE TNS 45 (1998)

P. R. Beck et al., IEEE TNS 62 (2015)

Backup: H11934-200 PMT characterization with controlled light sources





*The test of H11934-200 vs. the reference FEU-143 suggests the charge non-linearity scale at ~ 1000 nV*s / 0.75 μs -> 30 mA, which is close to manufacturer's info (± 2% at 20 mA, ± 5% at 60 mA)*

Linearity in the signal ROI scale is also confirmed by the two pulse method in 935-1000V within 4%

COHERENT data are not affected by the anode current non-linearity either

Thanks to Yu. Melikyan (INR RAS) for help

We refute the H11934-200 non-linearity claim with the PMT which was used for the measurements and don't agree with the corrections applied to QF measurements in PRD 100 (2019) paper

Backup: COHERENT CsI[Na] QF measurements

QF efforts on COHERENT side:

1. COHERENT-1(2017) cross-check →

ex. COHERENT (Duke)

Cross-check confirms results of initial analysis, few corrections:

1. *Issue in the energy calibration (-3% to QF values)*
2. *Mean afterglow contribution of 0.3PE – included in unc-ty*

2. COHERENT-2 (2017) →

Cross-check doesn't confirm the initial results, full scaled re-analysis is performed

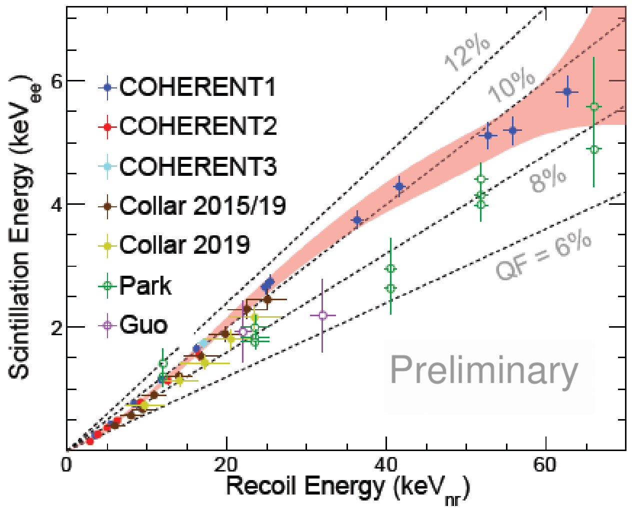
Initial authors don't agree, but were not available for the joint re-analysis

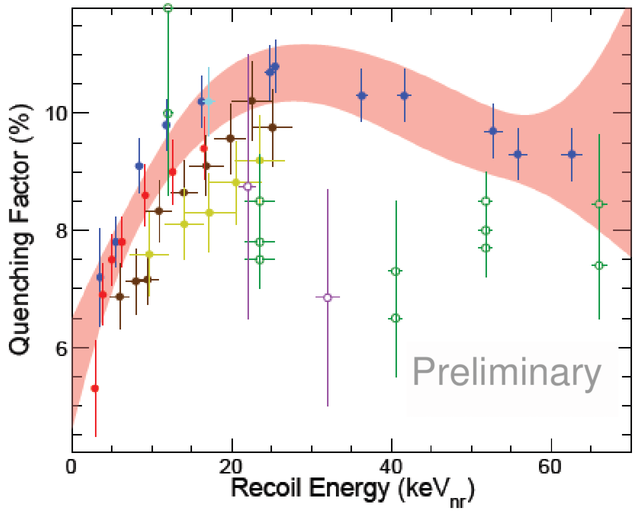
ex. COHERENT (Chicago) / Chicago-2 in PRD 100 (2019)

3. COHERENT-3 (2020) → *Single ~17.5 keV NR energy measurement, confirms COHERENT-1*

4. COHERENT-4 (2020) [“The endpoint” measurement] → *No NR energy tagging, continuous NR spectrum for hypothesis test, confirms COHERENT-1*

Global QF data fit





For the global QF fit we utilize data from:

Chicago-1 (2015/2019)

COHERENT-1 (2017)

COHERENT-2 (2017/2020)

Chicago-3 (2019)

COHERENT-3 (2020)

all with the same small CsI[Na] crystal, produced by the manufacturer of the SNS crystal from the same

The global fit is performed in the “scintillation energy [keV$_{ee}$]” vs. “recoil energy [keV$_{nr}$]” to avoid double counting of E_{nr} uncertainty.