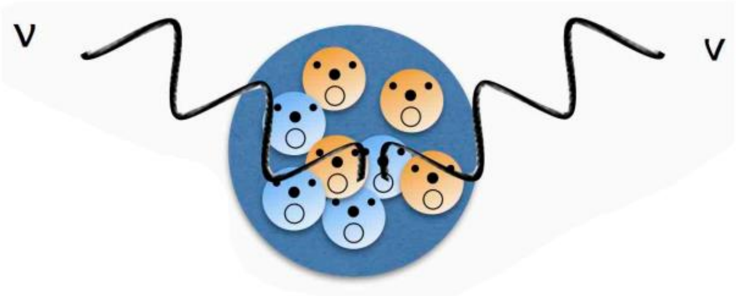
40th International Conference on High Energy Physics, July 28 2020



The COHERENT Experiment at the Spallation Neutron Source

Alexey Konovalov (ITEP, MEPhI)

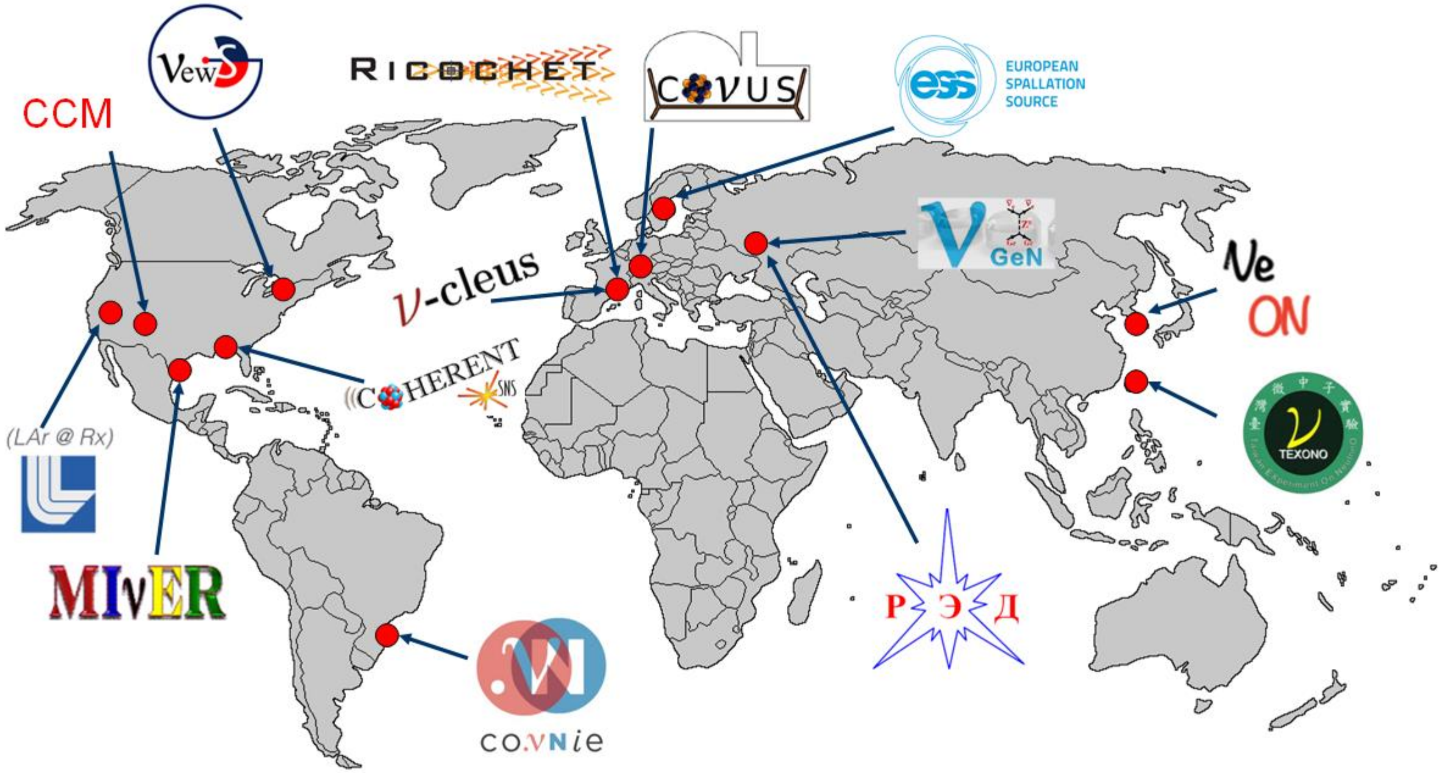
Collaboration

Carnegie Mellon University
THE UNIVERSITY OF CHICAGO
Duke UNIVERSITY
UF UNIVERSITY of FLORIDA
KAIST
Laurentian University Université Laurentienne
Los Alamos NATIONAL LABORATORY EST. 1943
MEPhI
NORTH CAROLINA CENTRAL UNIVERSITY
NC STATE UNIVERSITY
NM STATE UNIVERSITY
OAK RIDGE National Laboratory
Sandia National Laboratories
UNIVERSITY OF SOUTH DAKOTA
THE UNIVERSITY of TENNESSEE UT KNOXVILLE
TUNL
VIRGINIA TECH
UNIVERSITY of WASHINGTON

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

COHERENT uses the SNS facility neutrino source (ORNL)

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



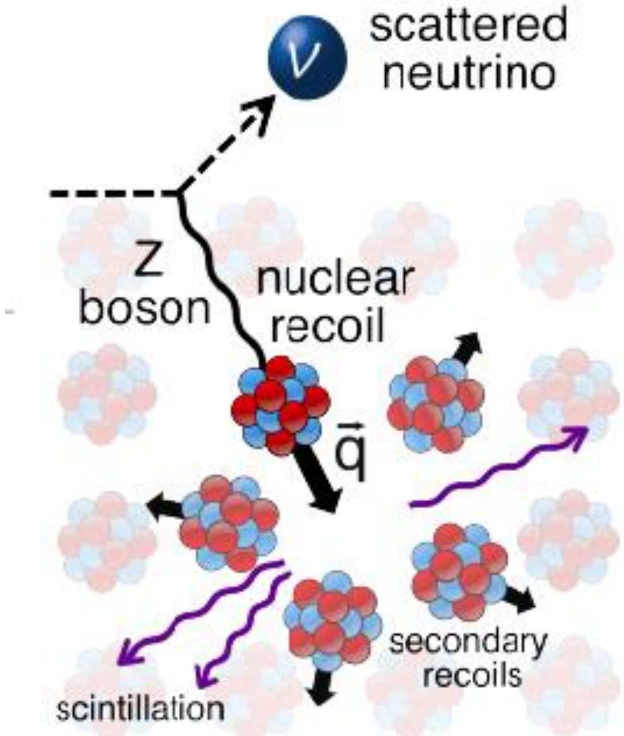
CEvNS search and study experiments around the world

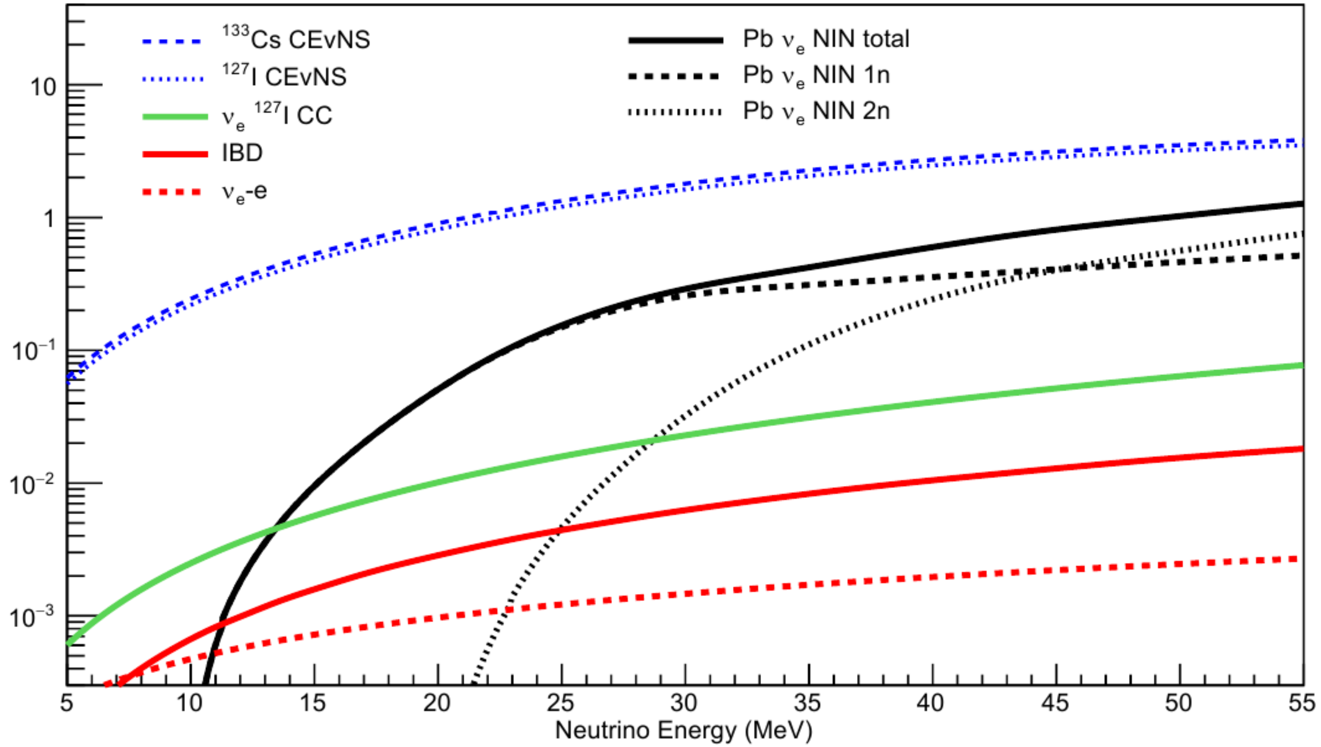
Coherent elastic neutrino-nucleus scattering (CEvNS)

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:

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

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

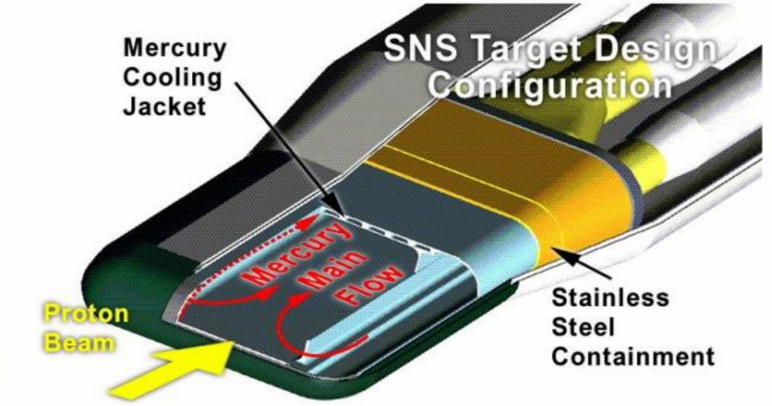
Nucleus	T_{max}, keV (E_ν =5 MeV)	T_{max}, keV (E_ν =30 MeV)
^{12}C	4.44	159.0
^{23}Na	2.32	83.2
^{40}Ar	1.33	47.9
^{74}Ge	0.72	25.9
^{133}Cs	0.40	14.4

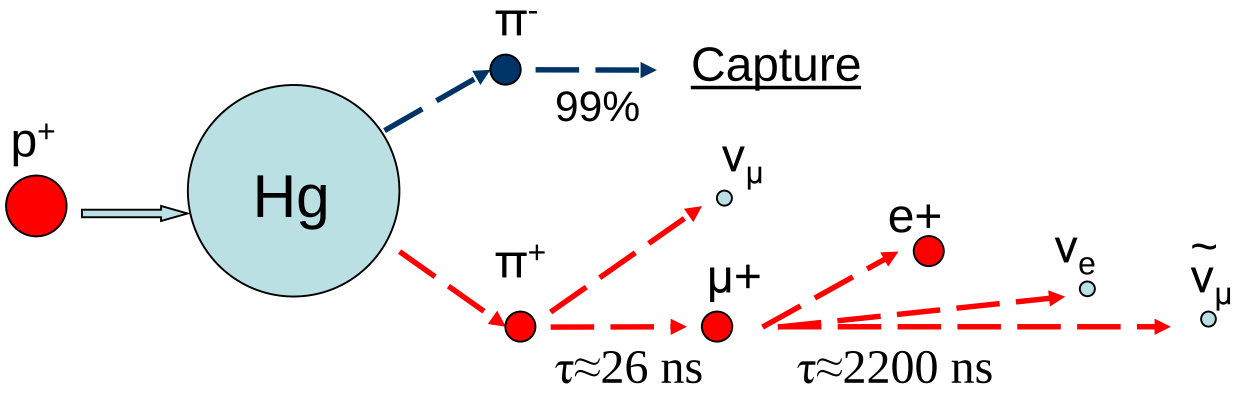
SNS facility at ORNL

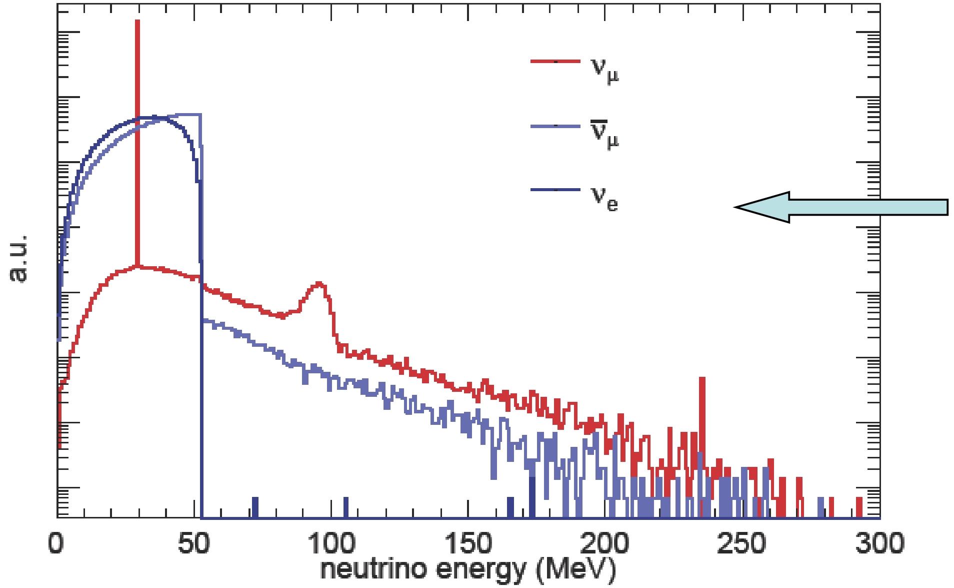
Bunches of ~1 GeV protons on the Hg target with 60 Hz frequency

Proton bunch time profile with FWHM of ~350 ns

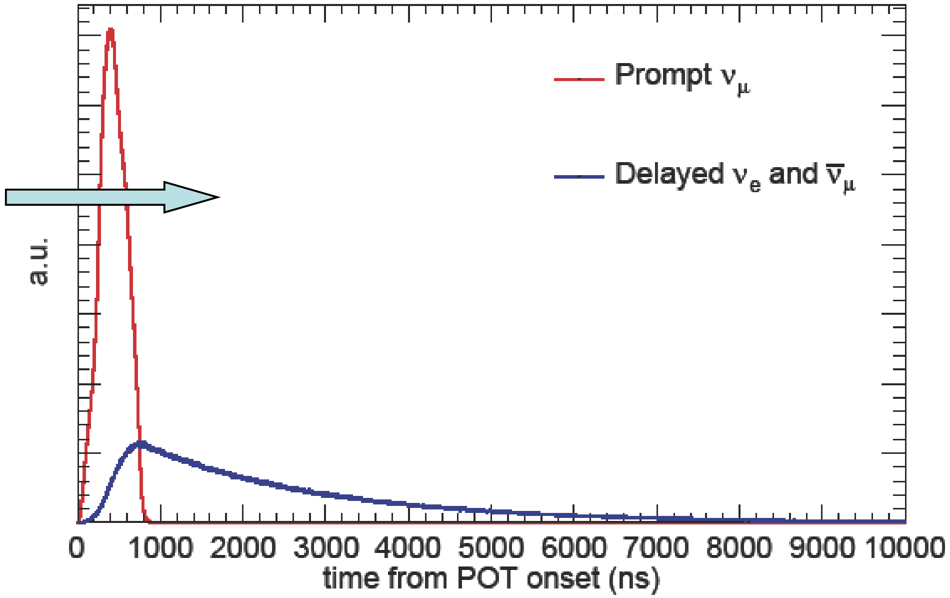
Total neutrino flux of $4.3\cdot10^{7}$ $cm^{-2}*s^{-1}$ at 20m



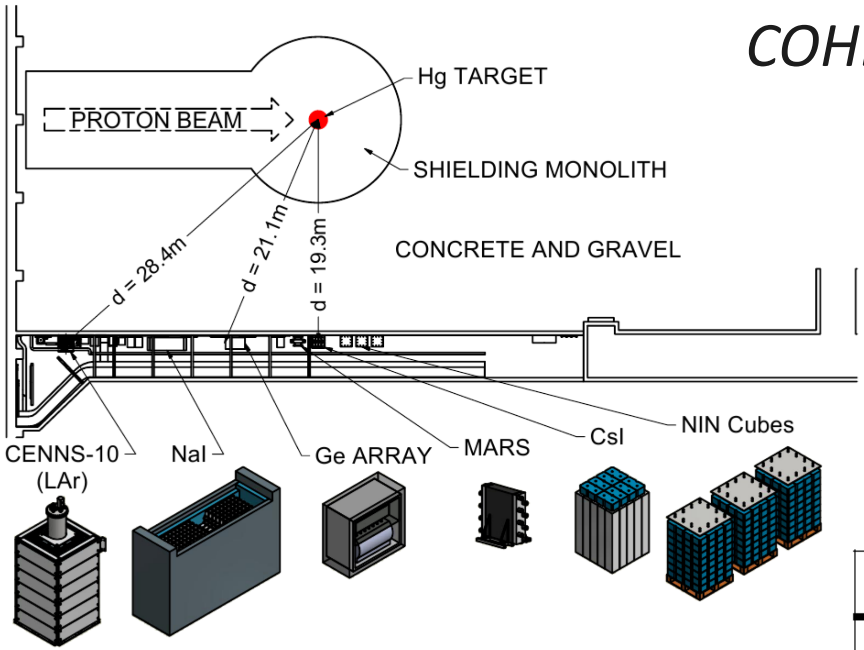




ν energy and timing suit well for CEνNS search



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		✓	✓		✓	✓

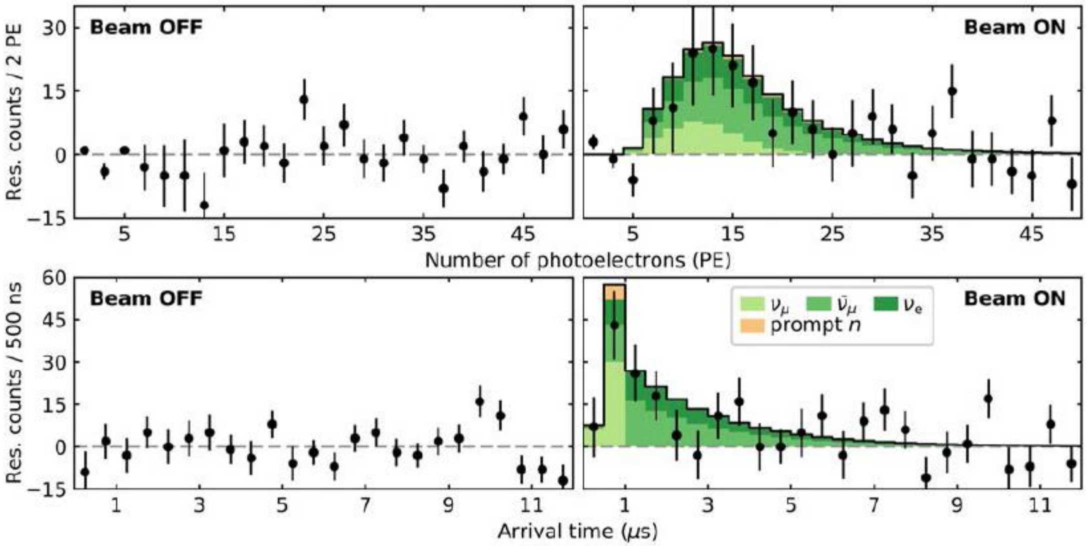
🟩 The sum is greater than the individual measurements

⬜ All measurements benefit from neutrino flux normalization

First CEvNS observation and its impact

First CEvNS observation was performed by COHERENT with the help of 14.5 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)

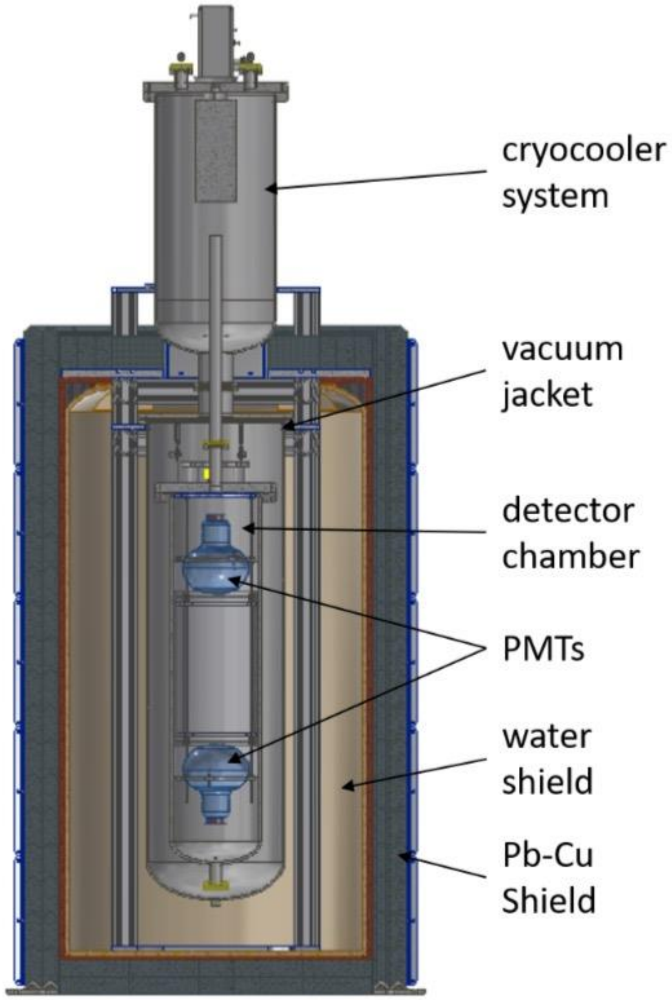
Xu-Run Huang, Lie-Wen Chen, PRD 100 (2019)

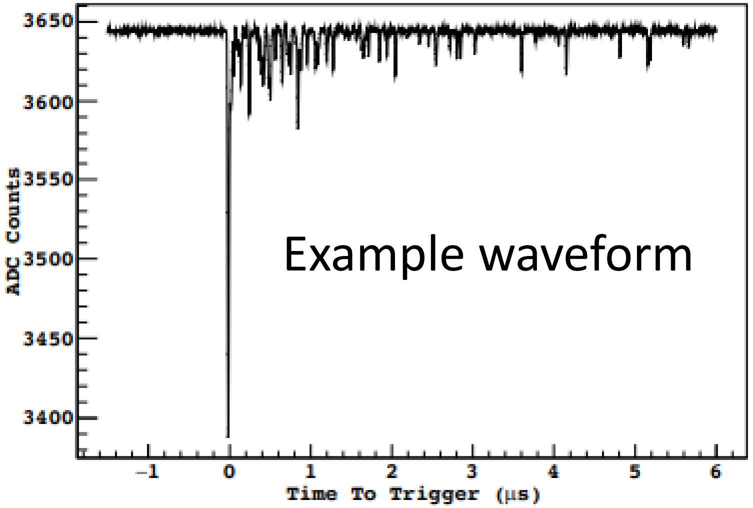
D. Papoulias et al., Physics Letters B 800 (2020)

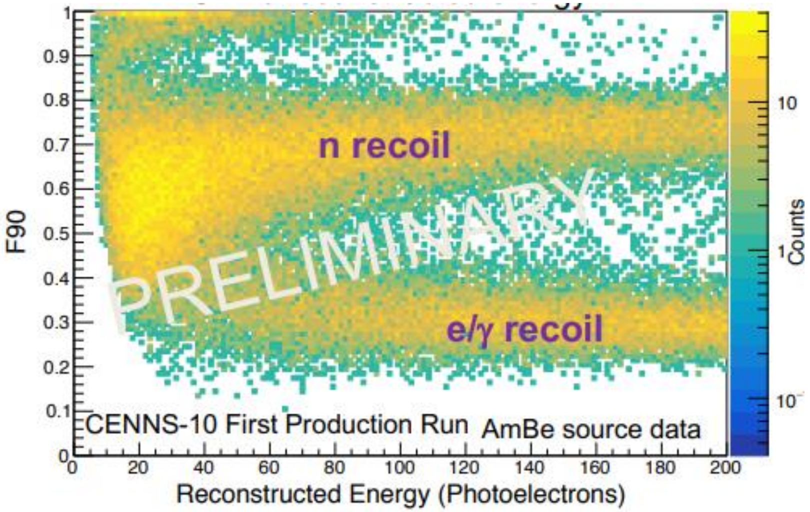
CENNS-10 LAr detector

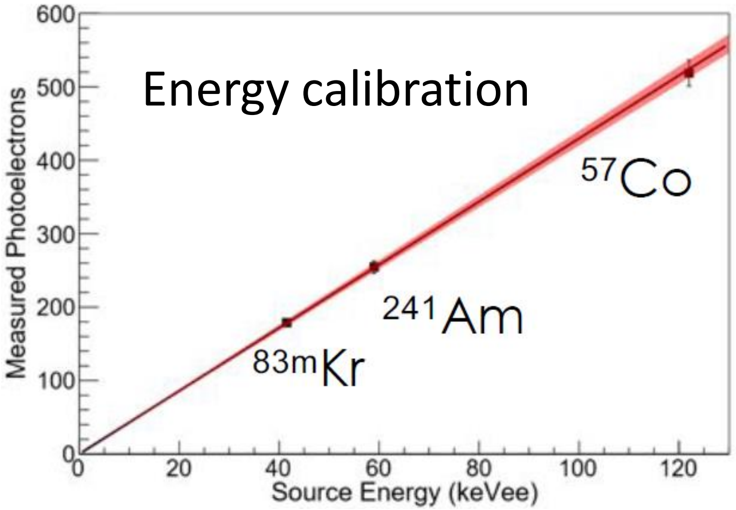
Built by J. Yoo et al. in Fermilab, moved to SNS late 2016

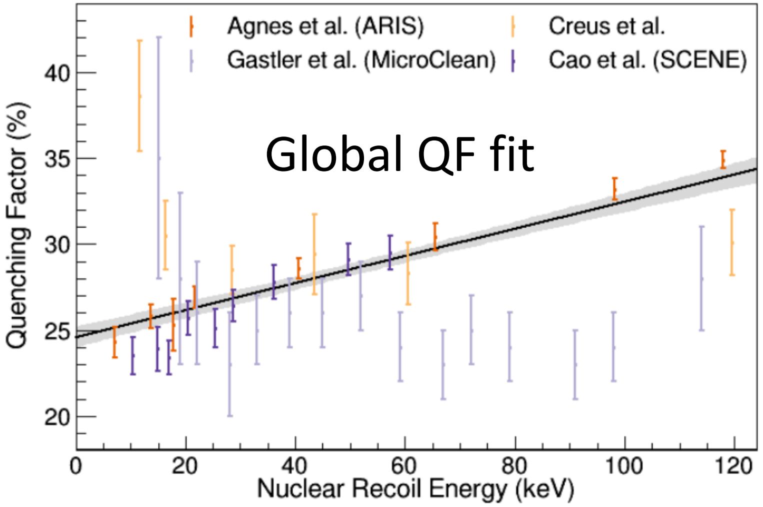
After light collection upgrade of 2017 single phase LAr detector with fiducial mass of 24 kg provides the light yield of 4.5 PE/keV$_{ee}$ and a ~20 keV$_{nr}$ threshold







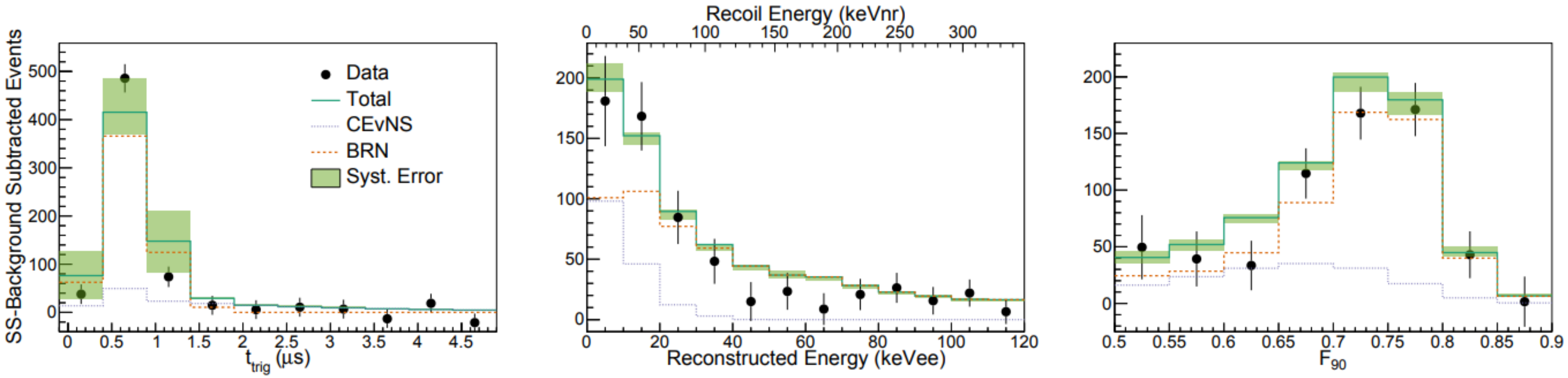




Matthew Heath (IU) thesis (2019), D. Akimov et al., PRD 100, 115020, J. Zettlemoyer (IU) thesis (2020)

First CEvNS detection on LAr

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



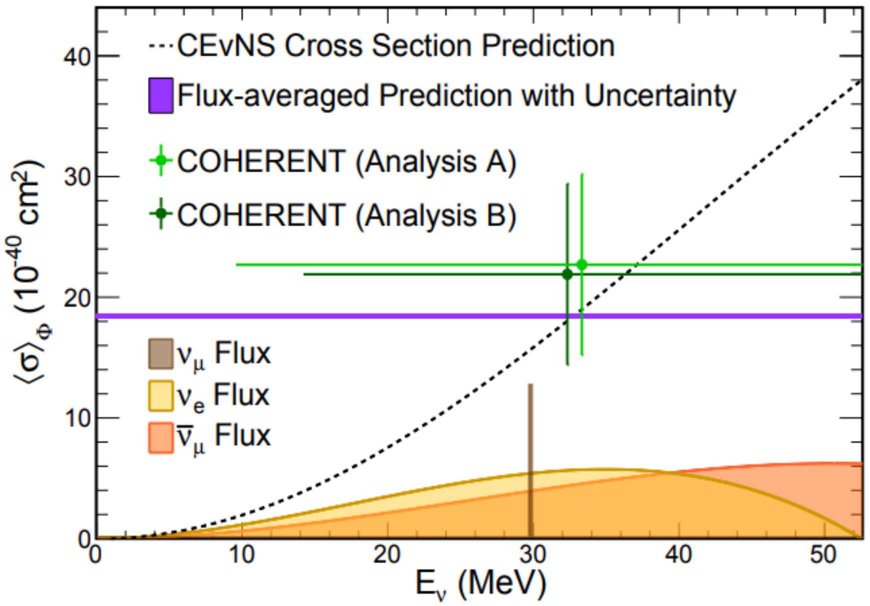
Dominant backgrounds:

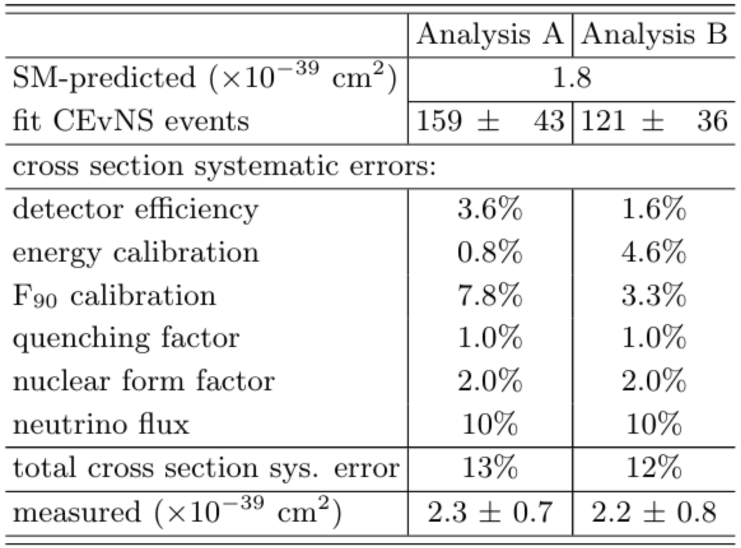
1. ^{39}Ar beta decay

2. Beam related neutrons

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

arXiv:2003.10630





	Analysis A	Analysis B
SM-predicted ($\times 10^{-39}$ 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 ($\times 10^{-39}$ cm^2)	2.3 ± 0.7	2.2 ± 0.8

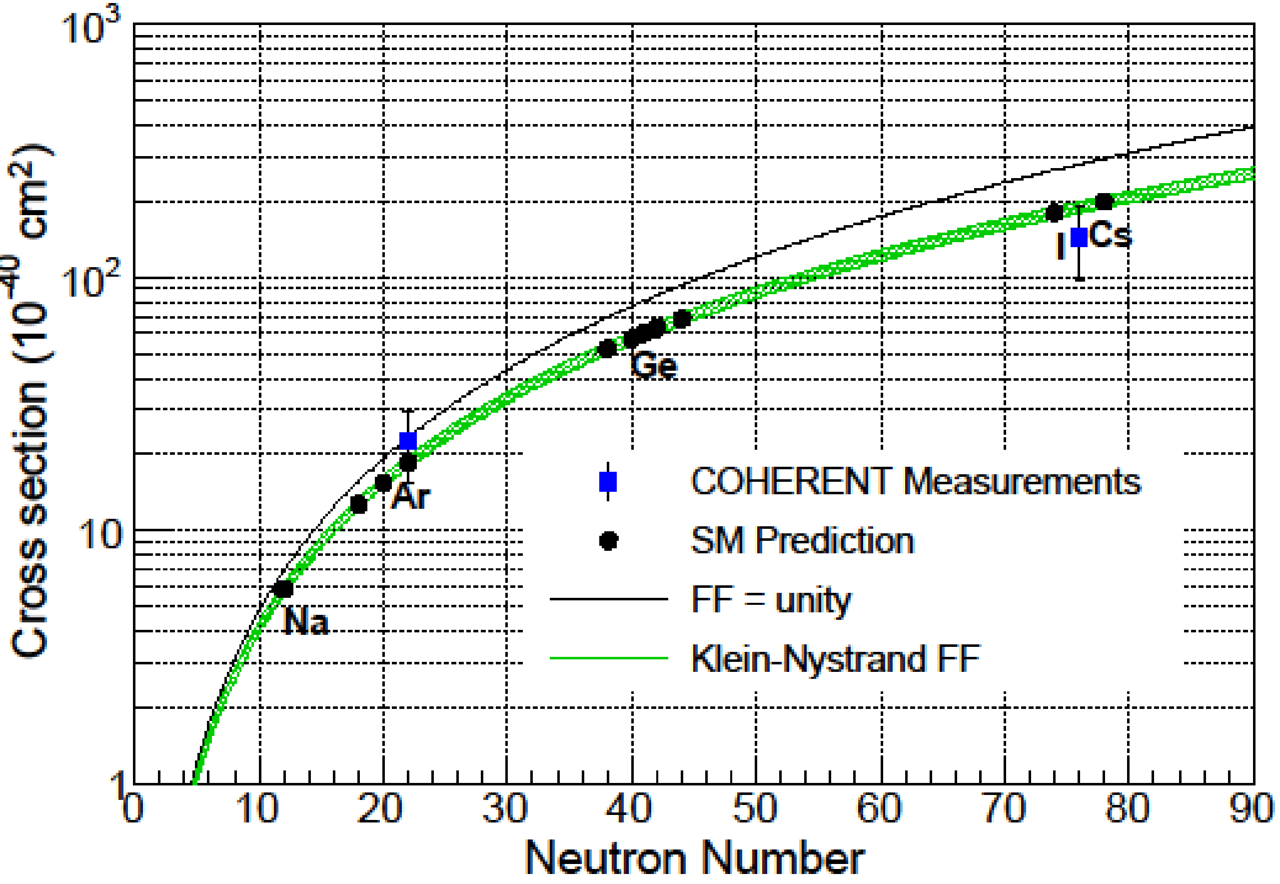
arXiv:2006.12659 – LAr data release

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

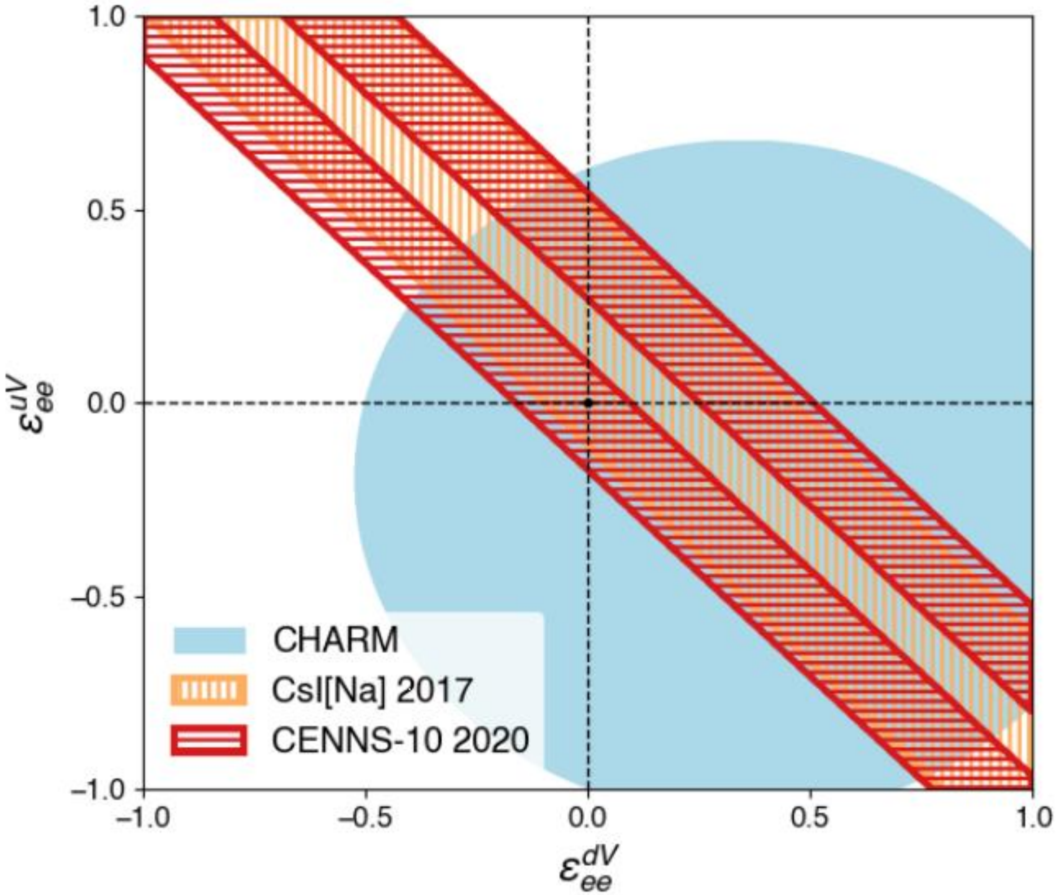
Implementation of LAr results

Test of CEvNS rate N^2 dependence



Two nuclei are measured, more to come!

Combined NSI exclusion limits



Assuming vector current-like NSI couplings:

$$\left(g_V^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV}\right) Z + \left(g_V^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV}\right) N$$

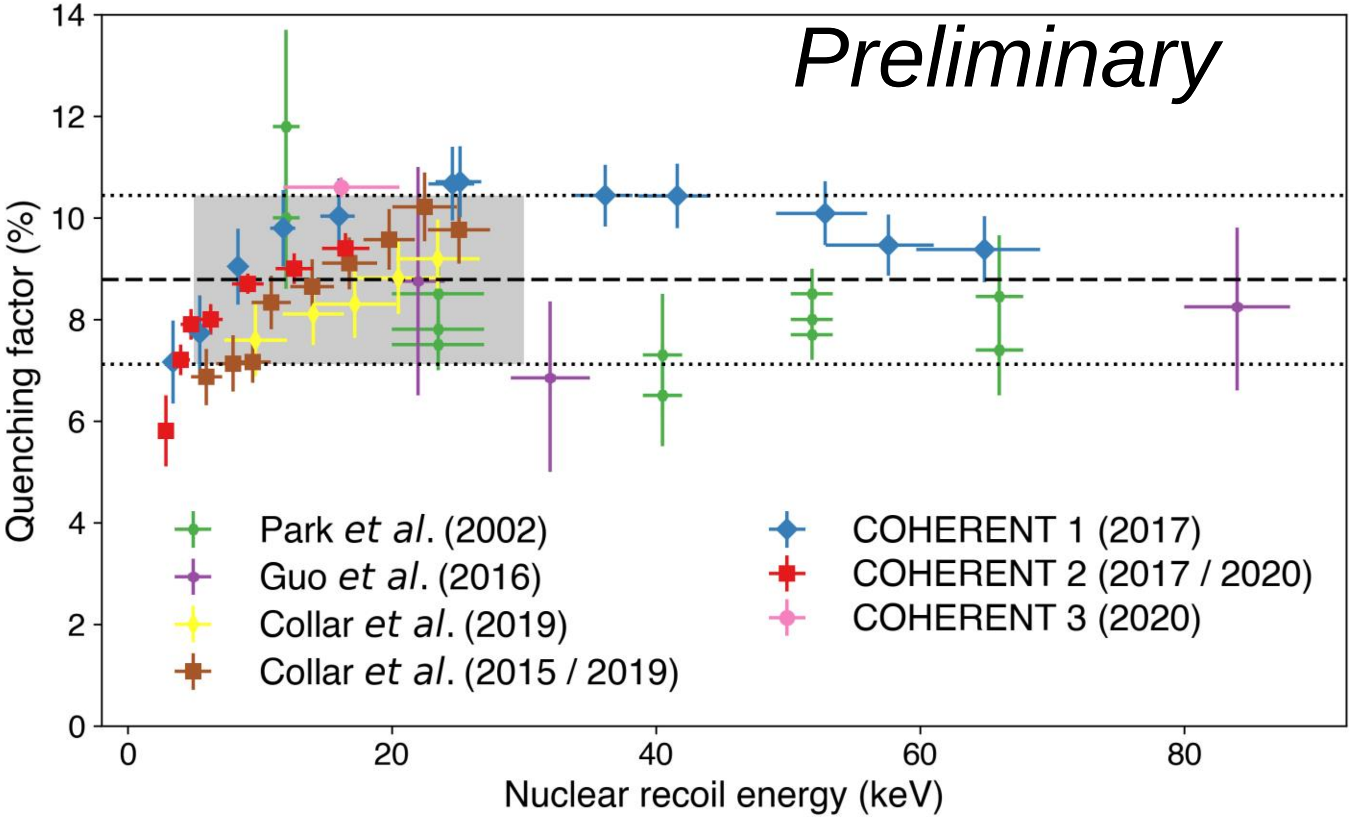
CsI[Na] QF and plans

The CsI[Na] data taking at SNS stopped June 2019, two times more stat. is available relative to the 2017 dataset

The main source of syst. in the 2017 result is due to QF data discrepancy, the adopted value of 8.78 ± 1.66% in [5,30] keV was used in 2017 (grey region in the plot)

COHERENT efforts:

- analysis cross-check of 2017 data
- new data with a tagged recoil (COHERENT-3)
- new "endpoint" measurement provides an opportunity to verify QF vs. energy behavior



More on the COHERENT CsI[Na] QF results and the PMT linearity discussion in the backup

Only stat. uncertainties for COHERENT-2 and COHERENT-3, ongoing study of systematic effects

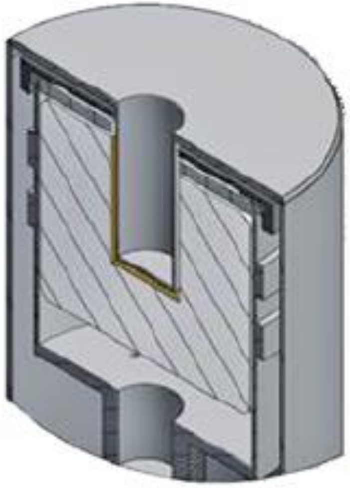
The current plan is to present the finalized QF results and updated CsI[Na] CEvNS result at one of the "Magnificent CEvNS" seminars, September 18 (http://magnificentcevns.org/seminars)

CEvNS first light experiments and supporting science

NaIve – segmented NaI[Tl] crystals:

185 kg deployed →3.4T to be deployed in 2020, ~13 keVnr threshold (Na recoils), 3σ/year expected, funded by DOE-ECA

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

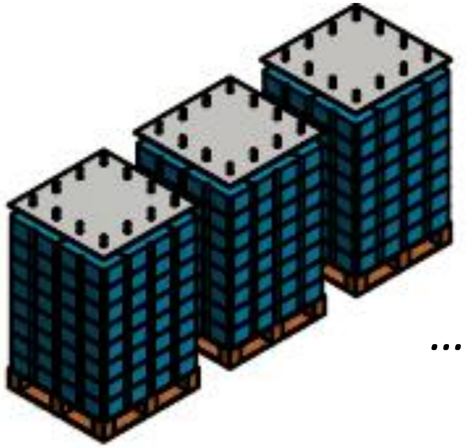


Germanium–HPGE PPC:

8 detector units, total mass of 16 kg, ~300 eV threshold, detectors ordered, first detector to be delivered in August, detector per month thereafter

500/600 CEvNS/year expected

Nubes – LS cells



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

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

+ decay of a nucleus with neutrons in the final state

…and reactions of the same kind for Fe, Cu

Interesting for HALO and as a background for CEvNS

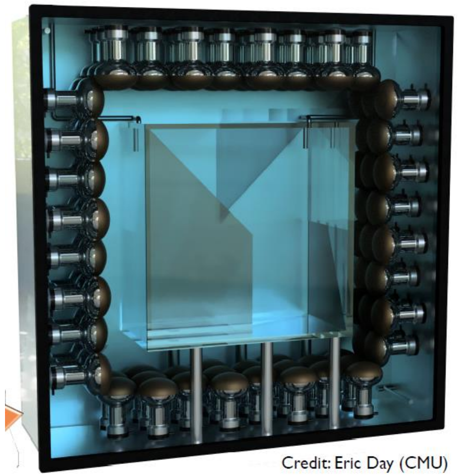
MARS

Plastic scintillator interleaved with Gd coated Mylar sheets

Study of a neutron flux in “neutrino alley”

COHERENT future initiatives

Precise flux normalization

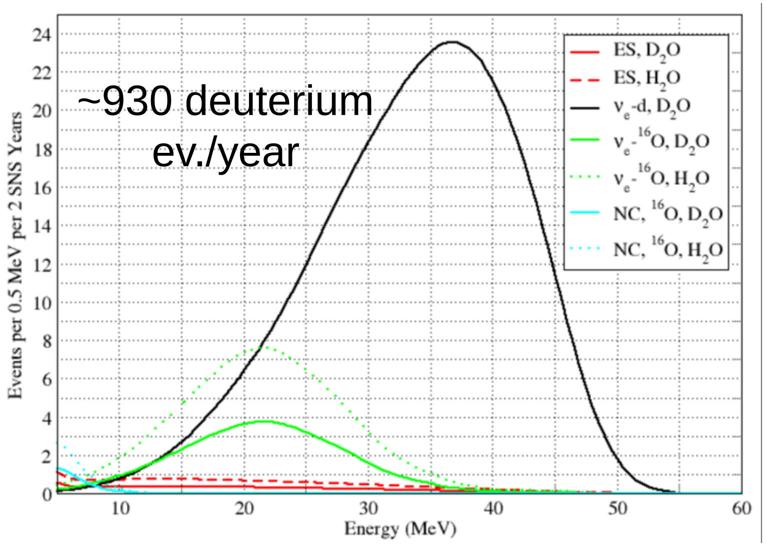


Deuteron Charged Current

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

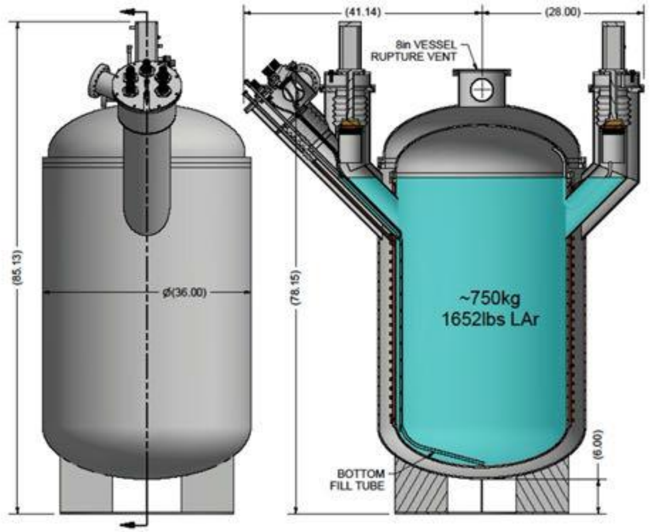
- *2-3% theoretical uncertainty**
- *calorimetry: no ring imaging*
- *2.5% statistical unc-ty in 2 years*

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



2 years run time to 3.5% statistical precision

High count rate CEvNS

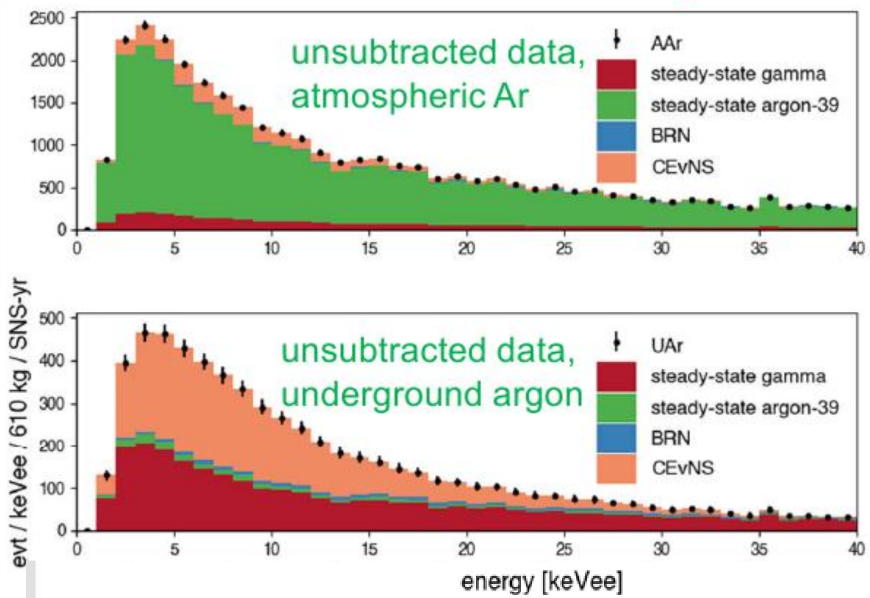


Single phase LAr with mass of 750 kg

Ongoing R&D, huge benefit from underground argon if available

~3000 CEvNS/year expected

plus 440 CC/NC events/yr
$(\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K)$



Future of neutrinos at SNS

Proton Power Upgrade

PPU project: Double the power of the existing accelerator structure

- First Target Station (FTS) is optimized for thermal neutrons
- Increases the brightness of beams of pulsed neutrons
- Provides new science capabilities for atomic resolution and fast dynamics
- Provides a platform for STS

Larger Neutrino Experimental Hall
Possible at STS: 2 10-ton Detectors

Second Target Station

STS project: Build the second target station with initial suite of beam lines

- Optimized for cold neutrons
- World-leading peak brightness
- Provides new science capabilities for measurements across broader ranges of temporal and length scales, real-time, and smaller samples

FTS 2021	2022	2024	2028 **STS Neutrino Hall**
1.4 MW	1.7 MW	2.0 MW	FTS: 2.0 MW @ 45 Hz STS: 0.7 MW @ 15 Hz

Slide from Ken Herwig, Workshop on Fundamental Physics at the Second Target Station (FPSTS18)

Accelerator produced Dark Matter

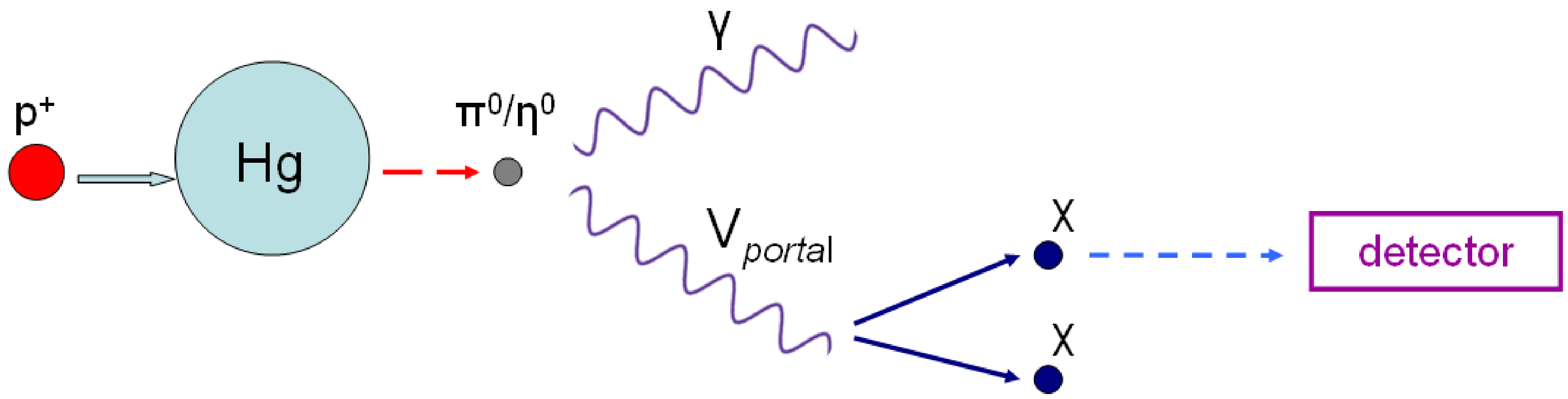
Vector portal: mixing of the vector mediator with photons in π^0/η^0 decays

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

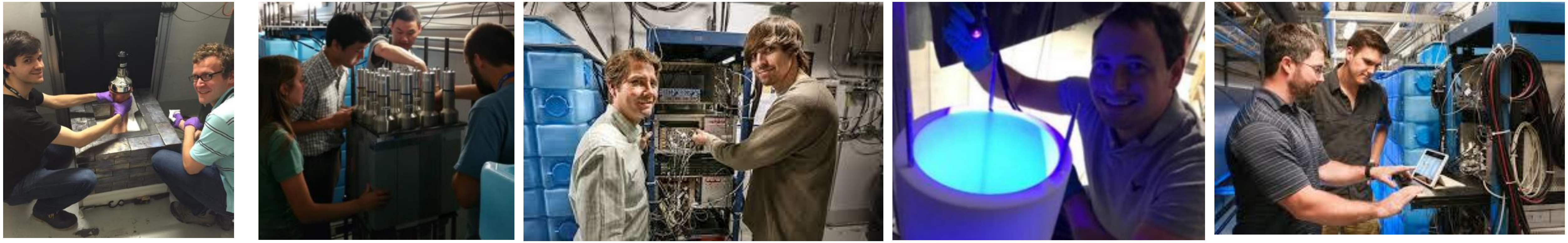
See also:

B. Dutta et al., arXiv:2006.09386

N. Hurtado et al., arXiv:2005.13384

Conclusion

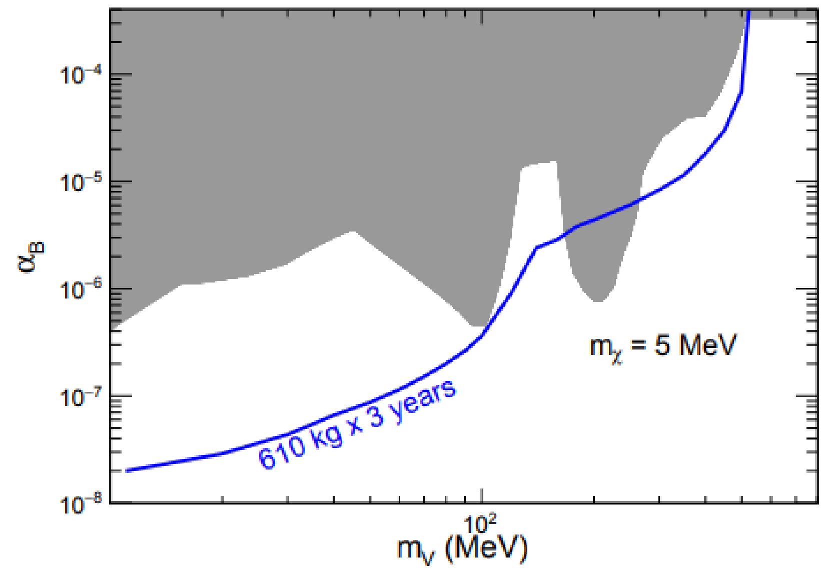
COHERENT demonstrated the ability to measure CEvNS with multiple targets at SNS



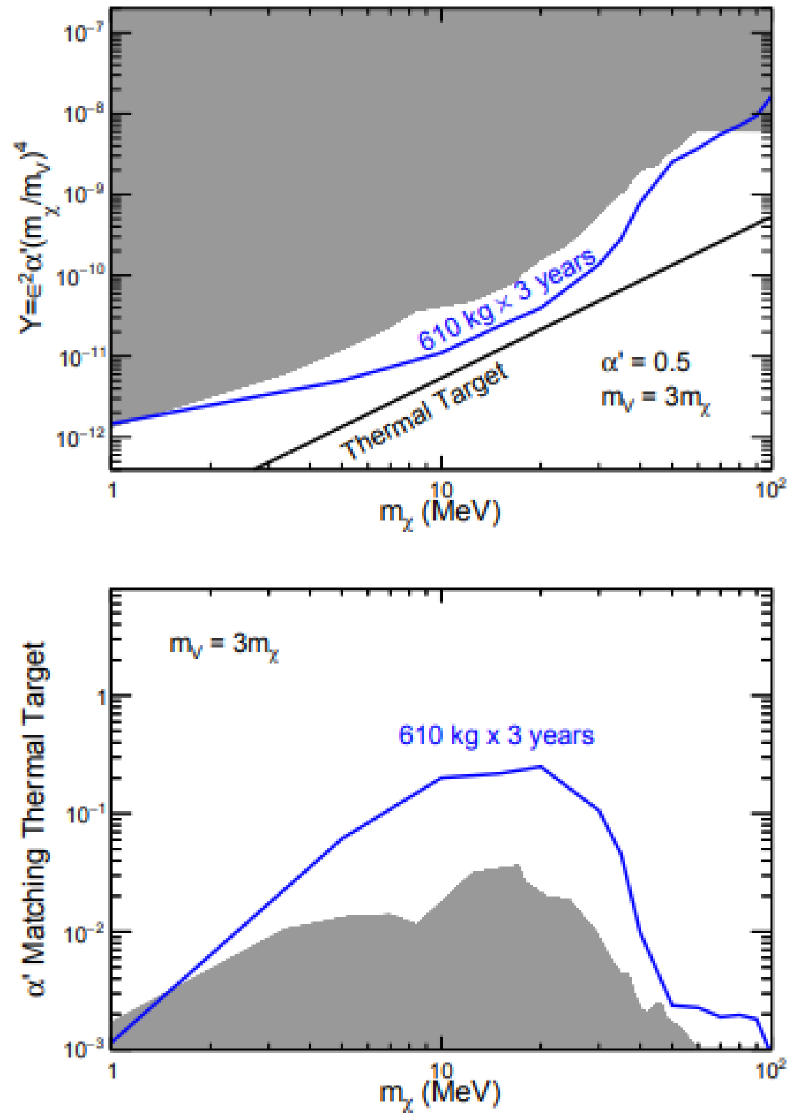
More detectors and nuclei are on the way to rich physics with implications in neutrino NSI, nuclear structure, electroweak interaction parameters and accelerator-produced dark matter search

COHERENT
SNS

Backup – accelerator produced dark matter at SNS with LAr 1T

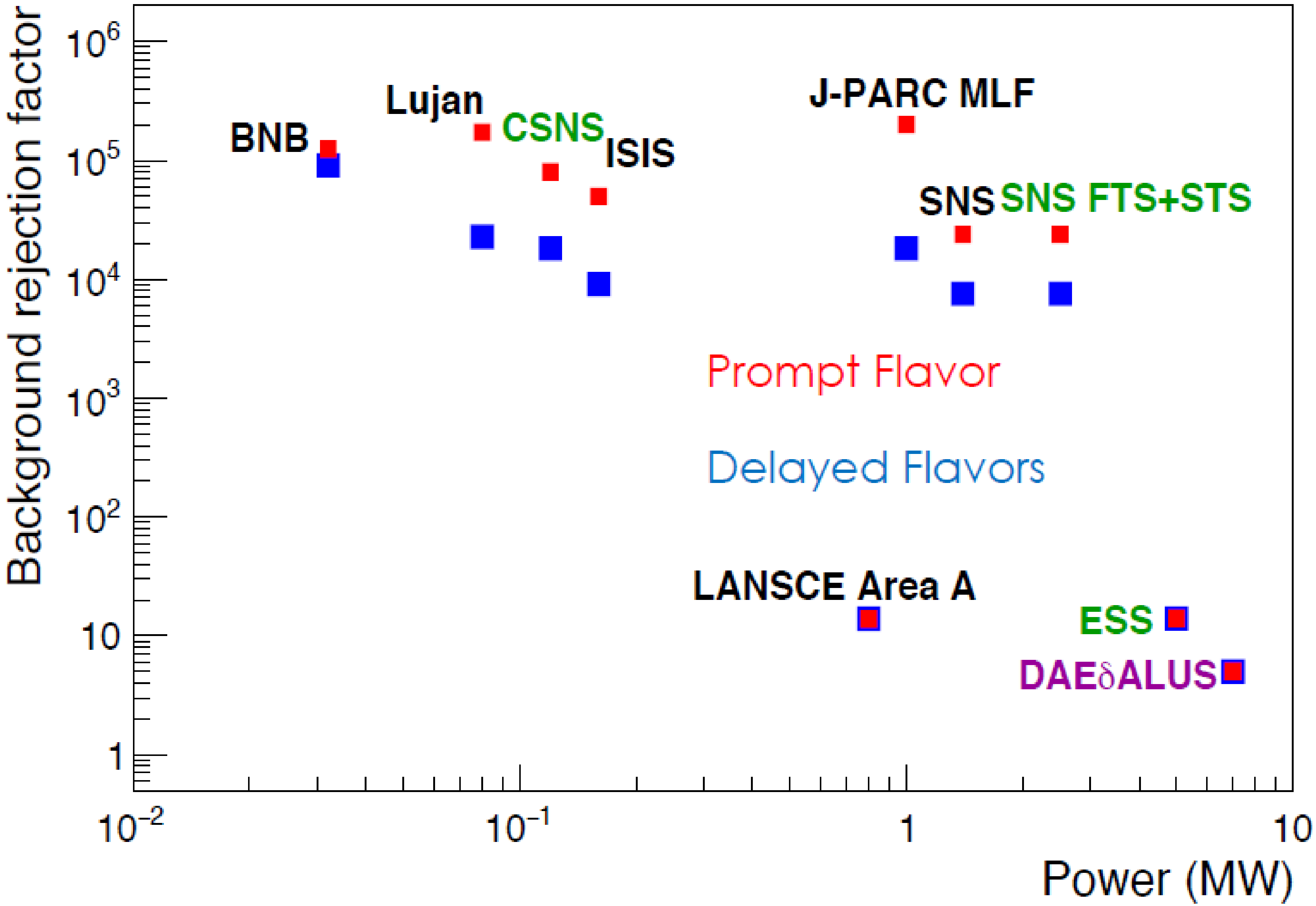


LAr 1T expected "Leptophobic portal" constraints, m_χ = 5 MeV



LAr 1T expected "Vector portal" constraints

Backup – π-DAR sources around the world

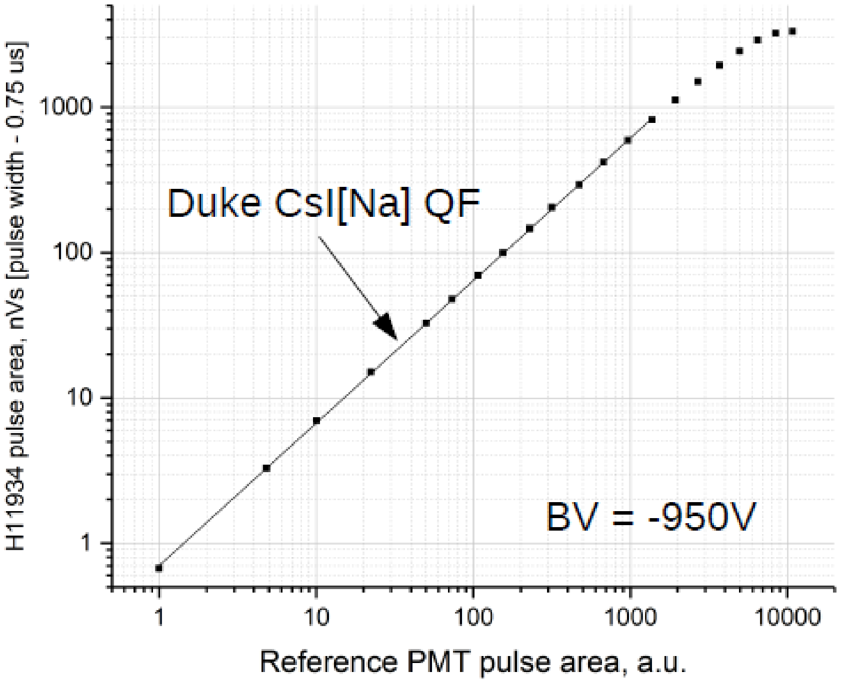


Backup - CsI[Na] QF discussion: linearity of H11934-200 PMT

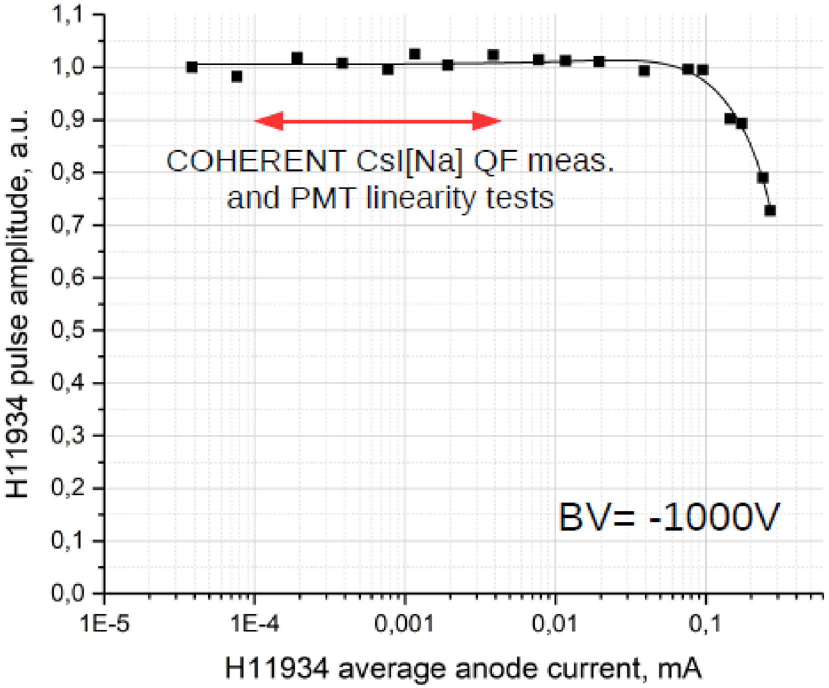
The claim of non-linearity of the PMT used in the Chicago-2 and Duke measurements stated in J. Collar et al., PRD 100 (2019) was scrutinized both in the tests with the CsI[Na] crystal (see A. Konovalov's talk at "Magnificent CEvNS") and in a laboratory

LED/laser light pulses were tuned to be both larger in amplitude and faster than CsI[Na] signals of the same charge (response to 59.5 keV gamma from ^{241}Am). Stability of the light sources was monitored with a reference PMT (FEU-143).

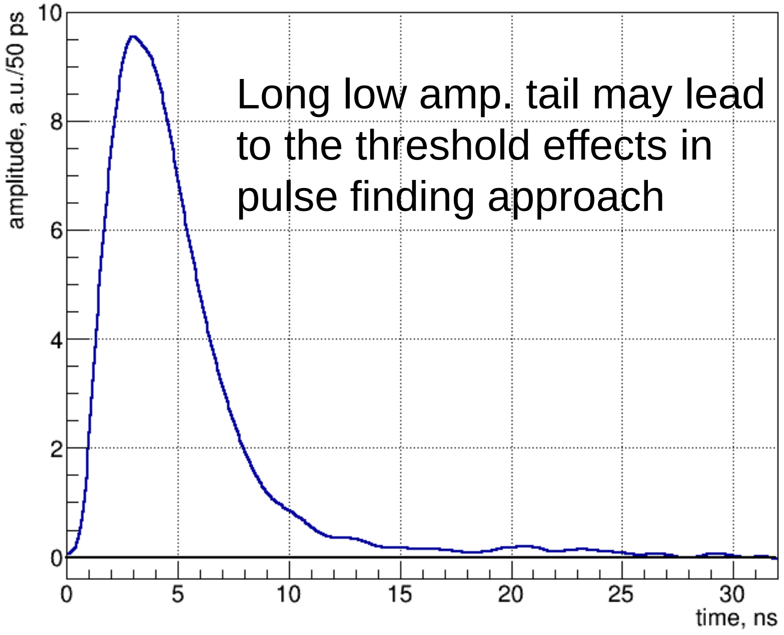
Pulse (charge) linearity



Anode current linearity



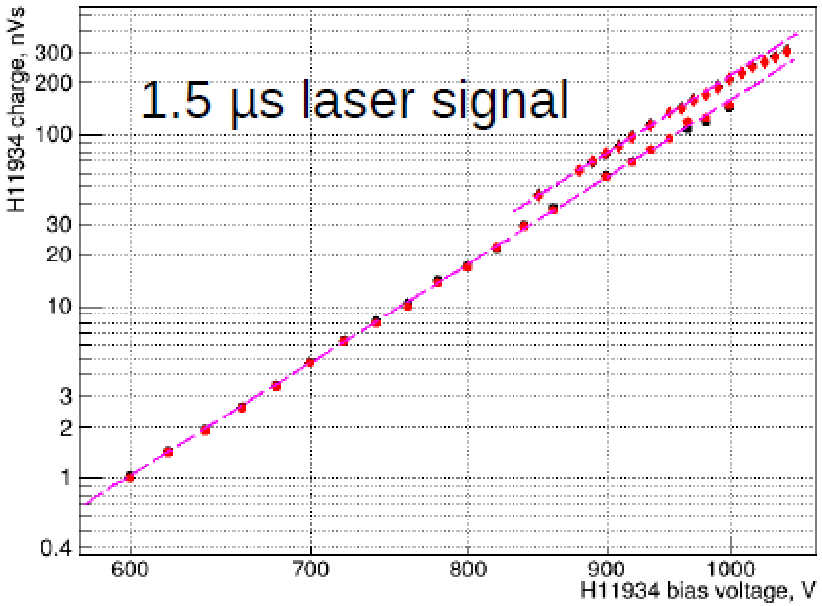
PMT time response (30 ps pulse)



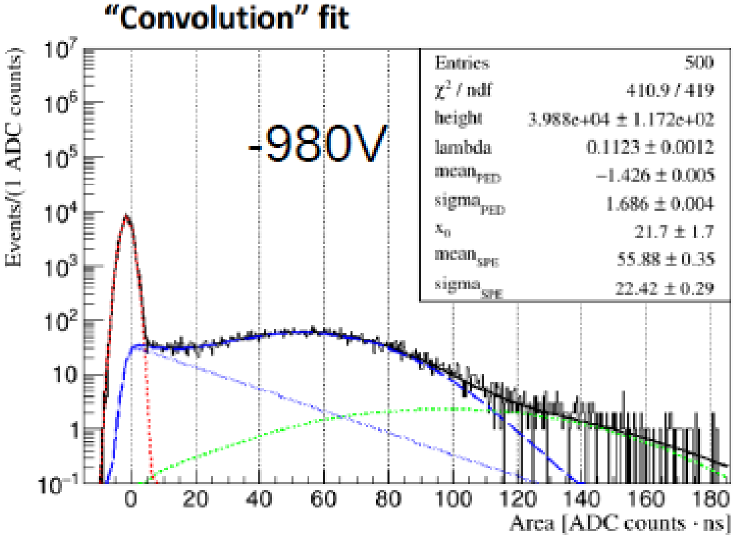
Long low amp. tail may lead to the threshold effects in pulse finding approach

Obtained linearity limits and time response match quite well to manufacturer's info

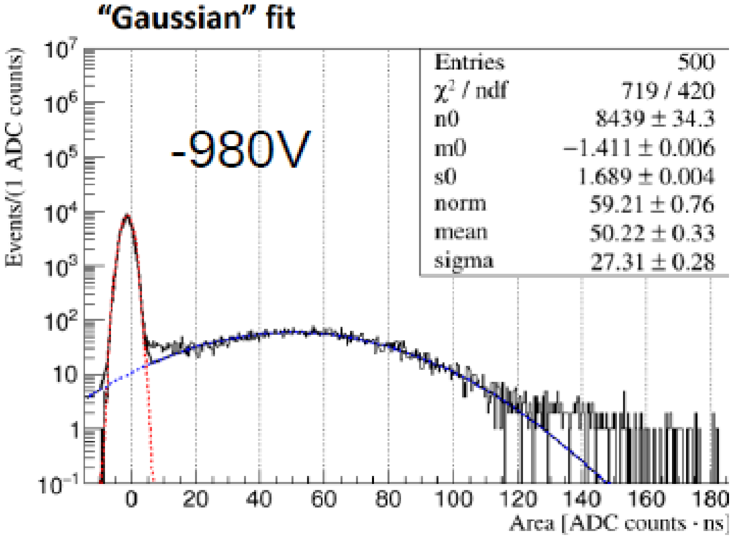
Backup - CsI[Na] QF discussion: linearity of H11934-200 PMT

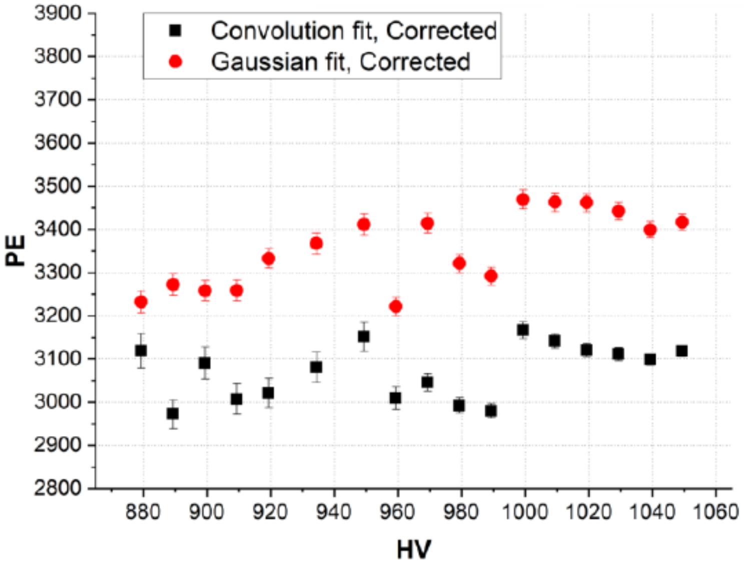


“Convolution” fit



“Gaussian” fit





We don’t observe 15% drop in the light yield (signal size in PE) vs. bias voltage claimed in J. Collar et al, PRD 100 (2019) on the scale 3 times larger than CsI[Na] response to 59.5 keV gamma

Two pulse method also confirms absence of non-linearity in the signal ROI

We are grateful to Yu. Melikyan (INR RAS) for help with the H11934-200 characterization

*— correction based on the reference PMT to take into account laser intensity fluctuations

** — only fit stat. errors included

Backup - CsI[Na] QF discussion – new COHERENT measurements

COHERENT “The endpoint” measurement:

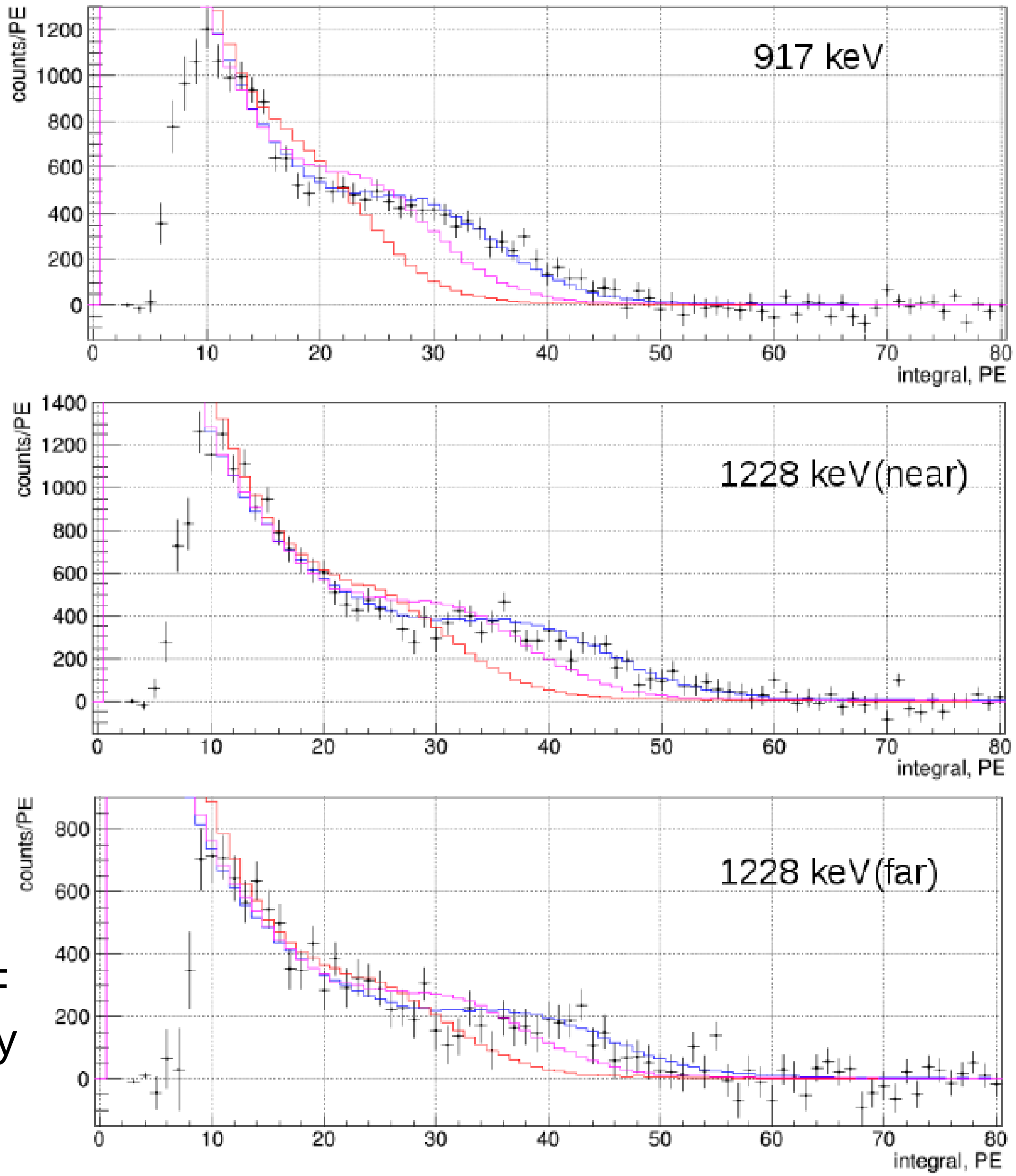
preformed in TUNL with ^{7}Li(p,n)^{7}Be source, two beam energies: 917 and 1228 keV identified by neutron TOF, two stand off distances for 1228 keV beam energy

The NR spectrum endpoints around 28 keV and 37 keV

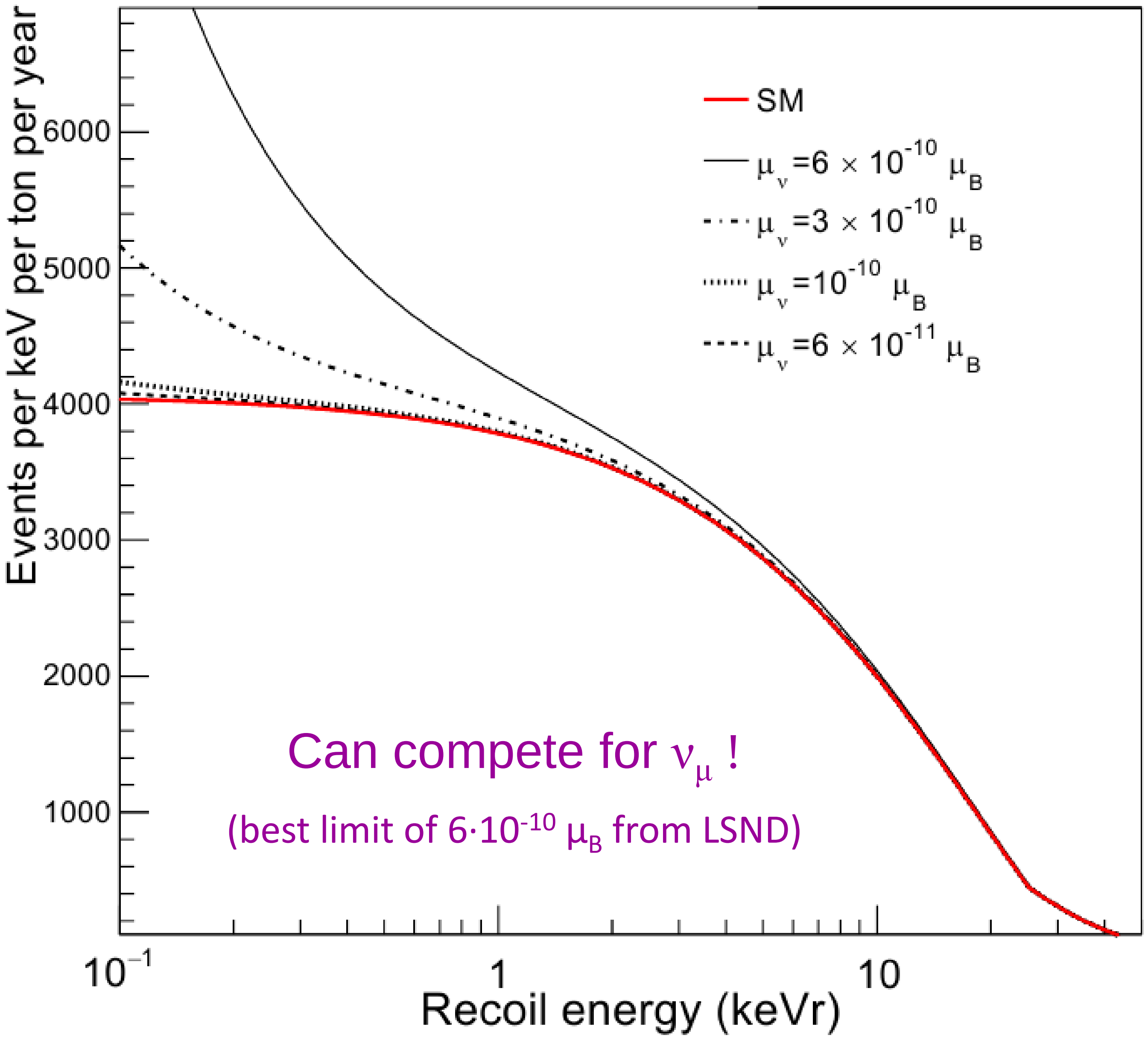
The measurement can be used as a hypothesis test of QF data available in the literature:

1. Constant QF of 7.2% - red in the plots
2. J. Collar et al. (2019), best fit model – magenta
3. COHERENT-1 (2017) - blue

The reanalysis of COHERENT-2(2017) QF data suggests larger QF values, inconsistent with initial ~7.2% result in [6,17] keV NR energy



Backup – Magnetic moment

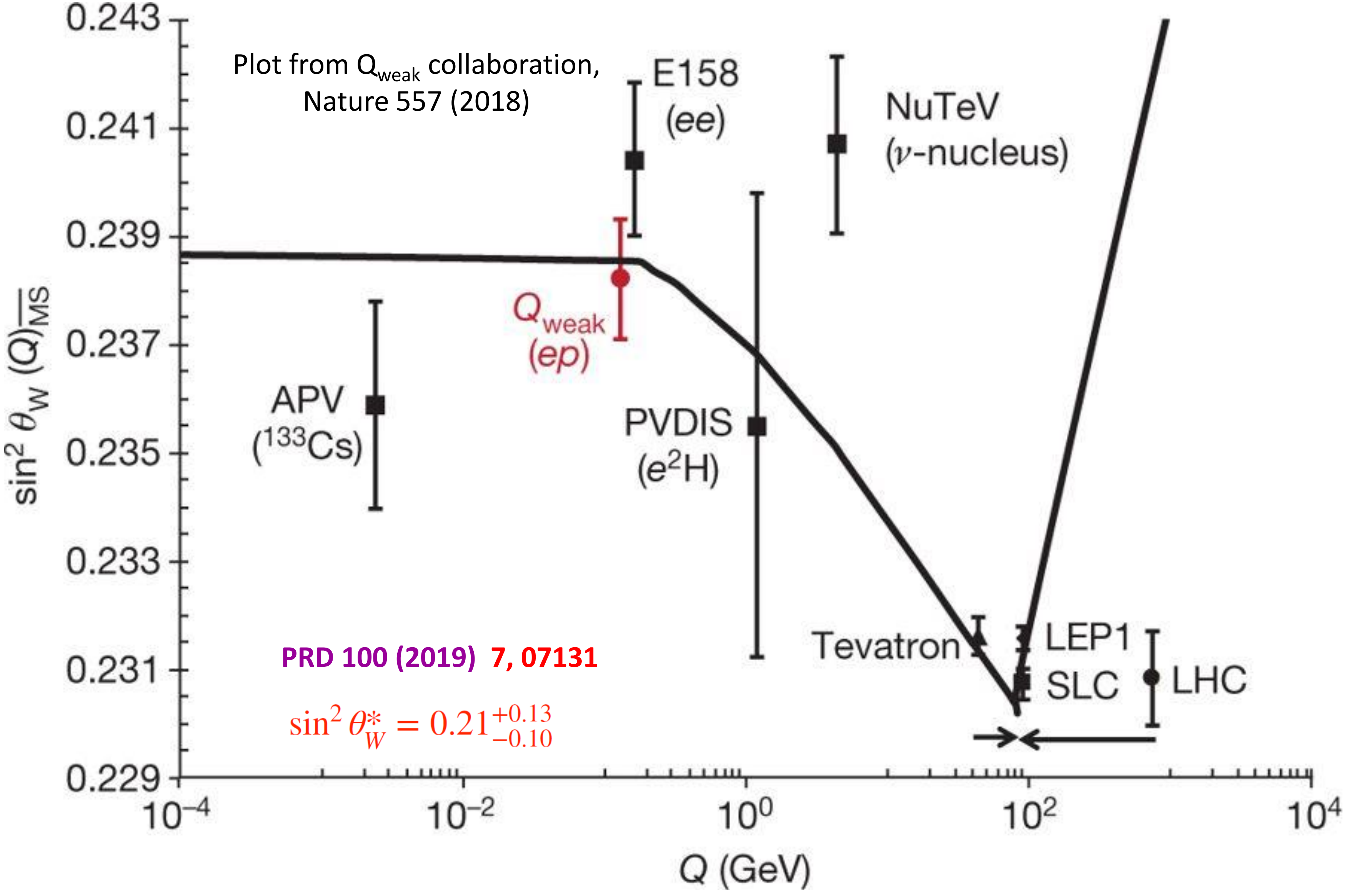


Can compete for ν_μ !

(best limit of $6{\cdot}10^{-10}\ \mu_B$ from LSND)

Possible with 16 kg of low threshold HPGe PPC, however can hardly be competitive with ν-e scattering results for ν_e (current limit ~$3{\cdot}10^{-11}\ \mu_B$)

Backup – EW mixing angle

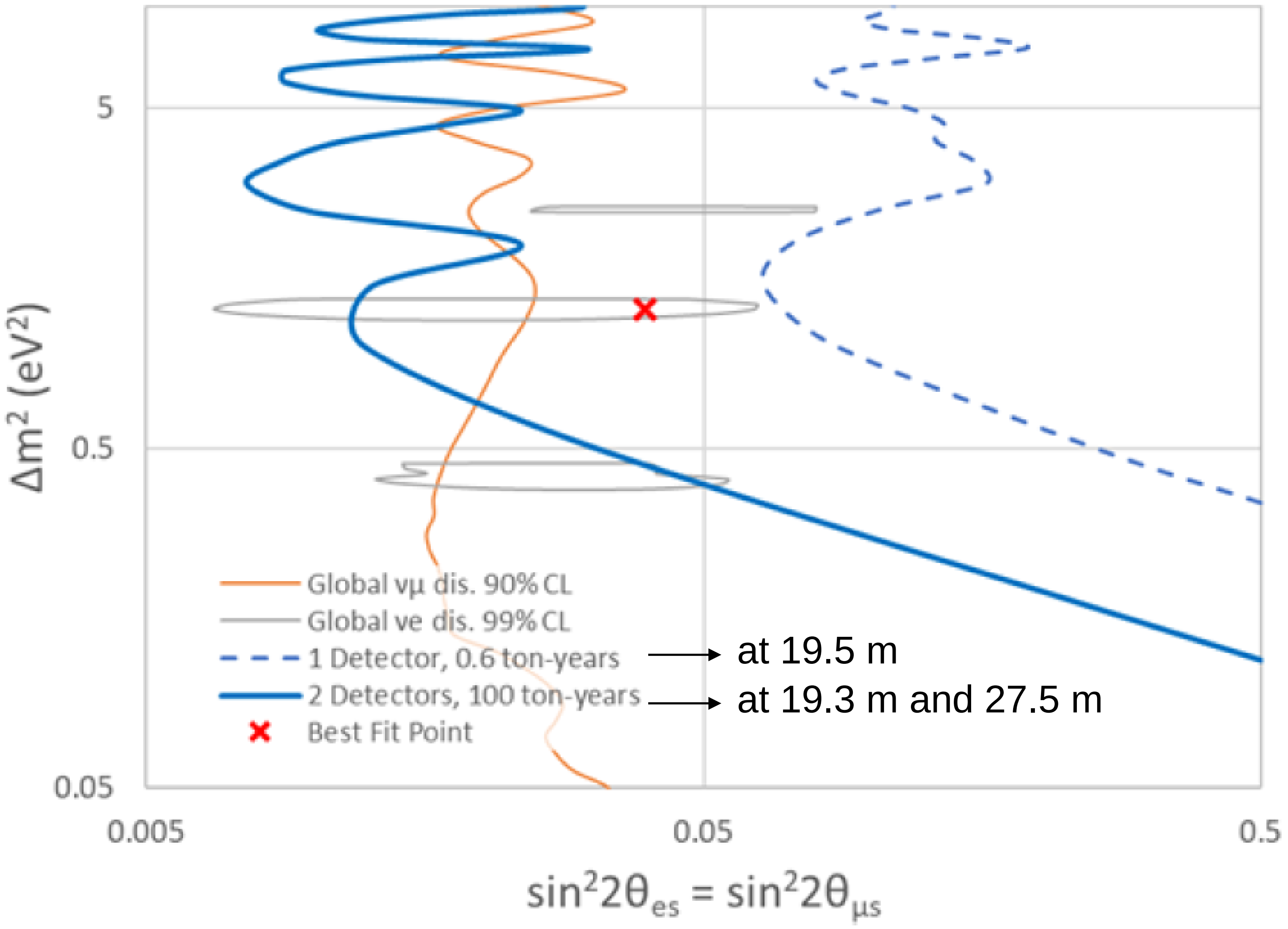


Plot from Q_{weak} collaboration,
Nature 557 (2018)

PRD 100 (2019) 7, 07131

$$\sin^2\theta_W^* = 0.21^{+0.13}_{-0.10}$$

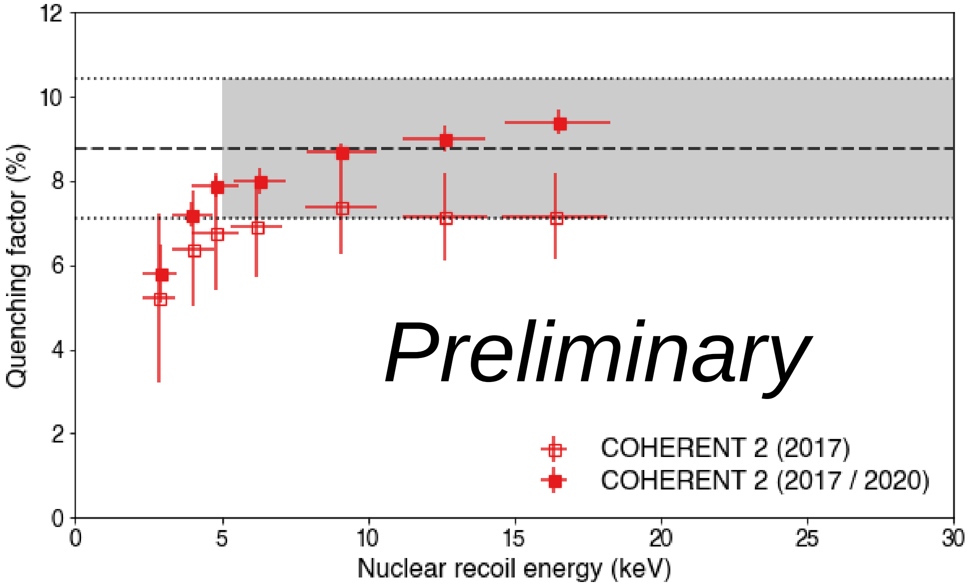
Backup – Sterile neutrino



→ at 19.5 m

→ at 19.3 m and 27.5 m

Backup – COHERENT-2 (2017/2020) re-analysis



2020 re-analysis is stat. uncertainties only currently

Naming convention for COHERENT CsI[Na] QF data

QF Dataset	Name in Science, 357 (2017)	Reference	Neutron source
COHERENT-1 (2017)	COHERENT (Duke)	Grayson Rich (NCU) thesis (2017)	TUNL, $E_n \approx 3.8$ MeV
COHERENT-2 (2017)	COHERENT (Chicago)	Bjorn Sholz (U.Chicago) thesis (2017)	TUNL, $E_n \approx 3.8$ MeV
COHERENT-3 (2020)	n/a	n/a	TUNL, $E_n \approx 4.5$ MeV