New insights into nuclear physics and weak mixing angle using electroweak probes

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New insights into nuclear physics and weak mixing angle using electroweak probes

based on arXiv:2102.06153

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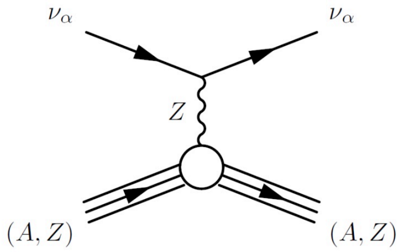
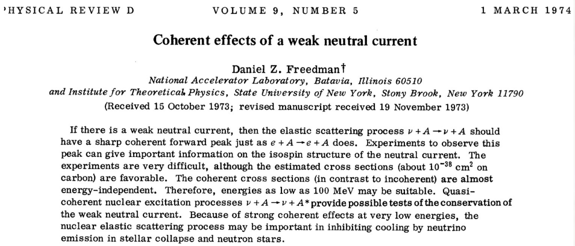
CEνNS process

- **Coherent elastic neutrino-nucleus scattering** (CEνNS): a neutrino scatters off a nucleus via the exchange of a **Z** boson, and the nucleus recoils as a whole (**coherently**)

$$\boldsymbol{\nu_\alpha + (A,Z) \to \nu_\alpha + (A,Z)}$$

- Coherency condition: $q \cdot R \ll 1$
- Predicted in **1974** by Freedman
- Observed for the first time in **2017** by **the COHERENT Collaboration**
- Very challenging to detect due to **tiny nuclear recoils**
- **Low-Energy Regime** (E_ν~few tens MeV)
- **Large cross section** ($\boldsymbol{\sigma} \propto N^2$)





ʼHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

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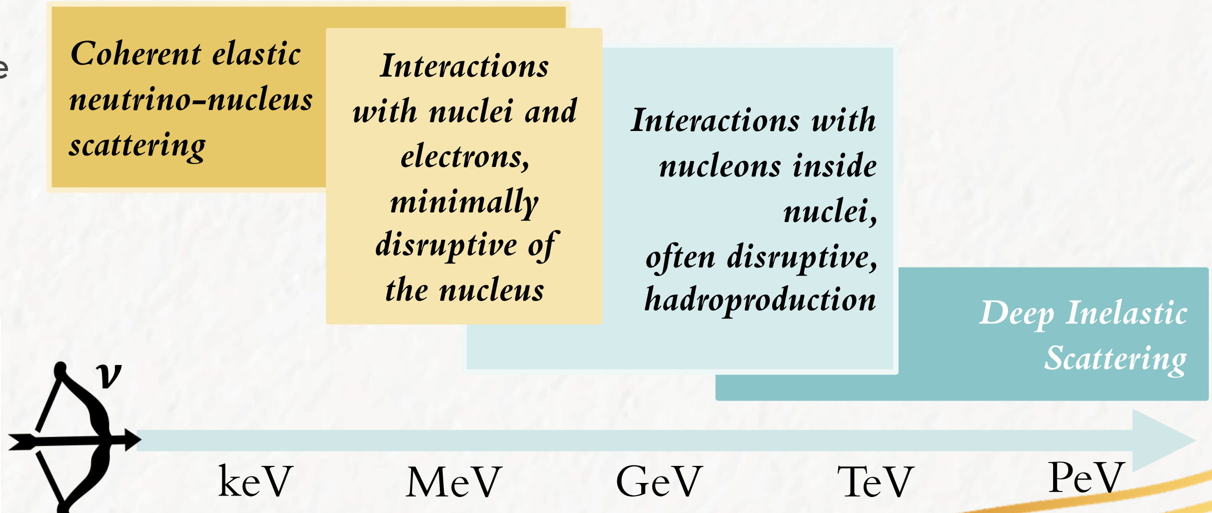
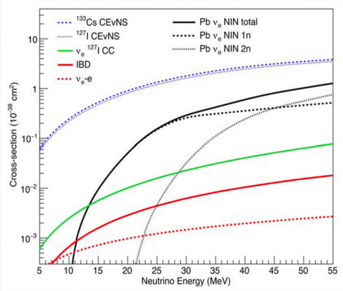
(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \to \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.



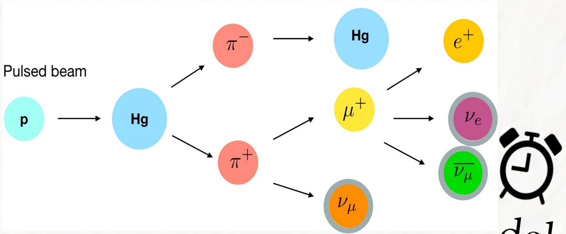
D. Akimov et al. *Science* 357.6356 (2017)

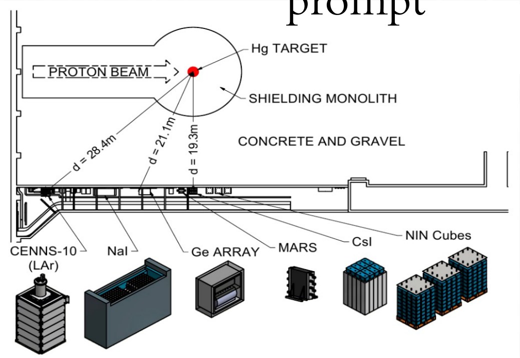


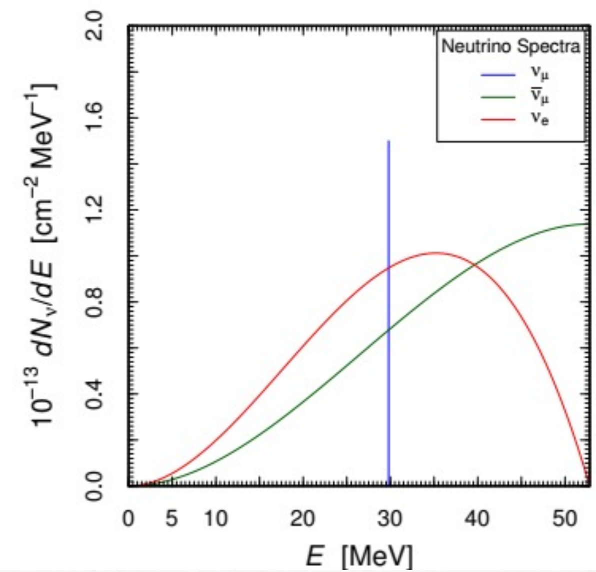
COHERENT experiment

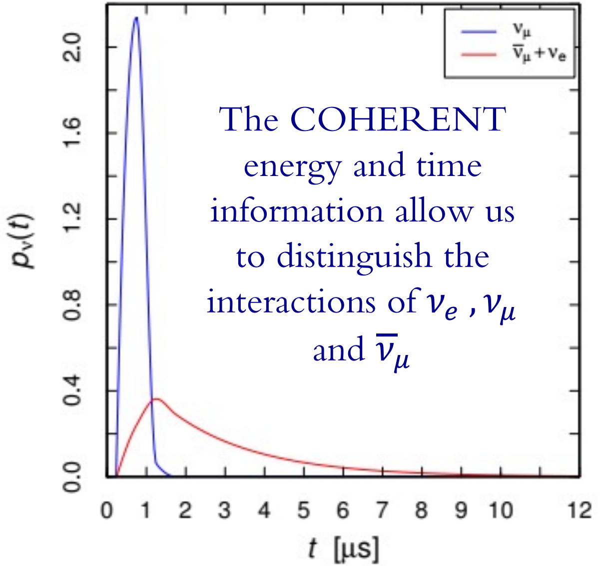
An appropriate **source of neutrinos** is needed: high flux, well understood (low uncertainties), pulsed for background rejection, multiple flavors, etc.

Spallation neutron source: neutrinos produced from the decay of pions/muons









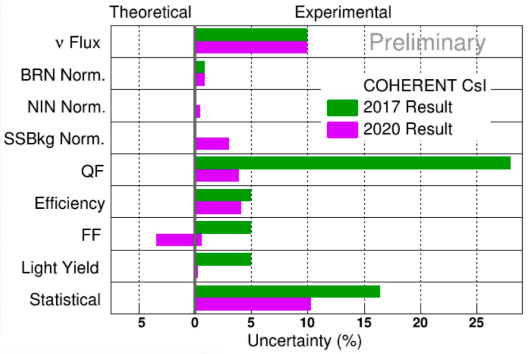
The COHERENT energy and time information allow us to distinguish the interactions of ν_e , ν_μ and $\overline{\nu}_\mu$

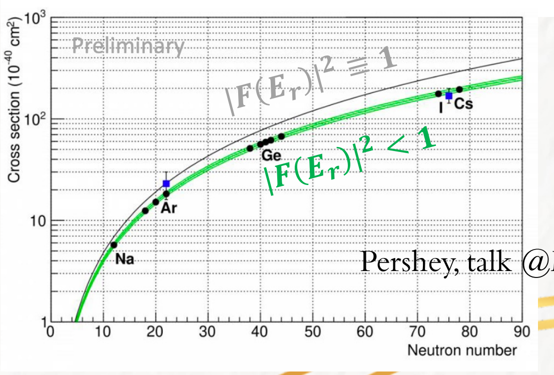
COHERENT neutrinos spectra, both **energy** and **arrival time** informations

COHERENT experiment

- COHERENT has observed for the **first time** CEνNS with a 14.6 kg CsI scintillating crystal (D. Akimov et al. ***Science*** 357.6356 (2017))
- New observation in 2020 with 24 kg LAr detector (upgrade to 750 kg), with >3σ CEvNS detection significance
- In 2020 the COHERENT Collaboration presented the **updated results** on the CsI detector:
- Increased statistics. More than 2x!
- 2D Likelihood fit in numbers of photoelectrons and reconstructed time
- Result consistent with SM prediction at 1σ
- **Flux uncertainty** now dominates the systematic
- Overall systematic uncertainty reduced: 28%→13%

COHERENT Collaboration, talks @Magnificent CEνNS '20





Observed cross section consistent with the N^2 dependence

Pershey, talk @Magnificent CEνNS '20

CEνNS cross section

- Let’s go back to the cross section we used in our analysis, where we **distinguished** the contribution of the **proton and neutron form factors**

10.1103/PhysRevD.98.113010

10.1103/PhysRevD.102.015030

10.1007/JHEP01(2021)116

New ν interactions

$$g_V^p(\nu_e) = 0.0401,$$
$$g_V^p(\nu_\mu) = 0.0318,$$
$$g_V^n = -0.5094.$$

New ν properties

Neutrino energy

Mass of the nucleus

SM vector proton coupling

SM vector neutron coupling

$$\frac{d\sigma^{CE\nu NS}(E_\nu, E_r)}{dE_r} \cong \frac{G_F^2\, m_N}{\pi}\left(1 - \frac{m_N E_r}{2E_\nu^2}\right)\left[\mathbf{g_V^p}\left(\mathbf{\sin^2}(\vartheta_W)\right) Z\, \mathbf{F_Z}\left(|\vec{\mathbf{q}}|^2\right) + \mathbf{g_V^n}\, N\, \mathbf{F_N}\left(|\vec{\mathbf{q}}|^2\right)\right]^2$$

Nuclear recoil energy

Weinberg or weak mixing angle

Proton Form Factor

Neutron Form Factor

Nuclear physics

10.1103/PhysRevD.99.033010

10.1103/PhysRevD.101.033004

EW precision

10.1103/PhysRevLett.120.072501

Nuclear Structure

- The **nuclear form factor**, F(q), represents the **Fourier transform** of a spherically symmetric ground state mass distribution (both protons and neutrons) normalized so that F(0)=1

- For a weak interaction like for CEνNS you deal with the **weak form factor**: the Fourier transform of the weak charge distribution (neutron + proton distribution weighted by the weak mixing angle)

- Most of the information we have on the nuclear size and nucleon's distribution inside the nuclei are related to the **electric charge**, and thus to the protons (informations extracted using **electron-nuclei scattering** data and **muonic x-ray** spectroscopy)

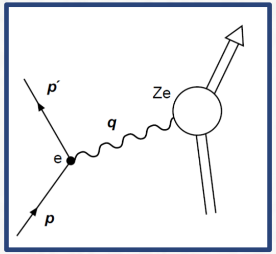
$$\frac{d\sigma}{dE_r} \cong \frac{G_F^2\, m_N}{4\pi}\left(1 - \frac{m_N E_r}{2E_\nu^2}\right) Q_W^2\, |F_{weak}(E_r)|^2$$

Weak charge × weak form factor

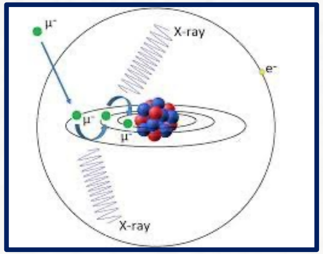
Payne et al. Phys. Rev. C 100, 061304 (2019)

$$\left[g_V^p Z F_Z(E_r) + g_V^n N F_N(E_r)\right]^2$$

Proton + Neutron from factor



Electron scattering



Muonic X-ray spectroscopy

Nuclear Structure

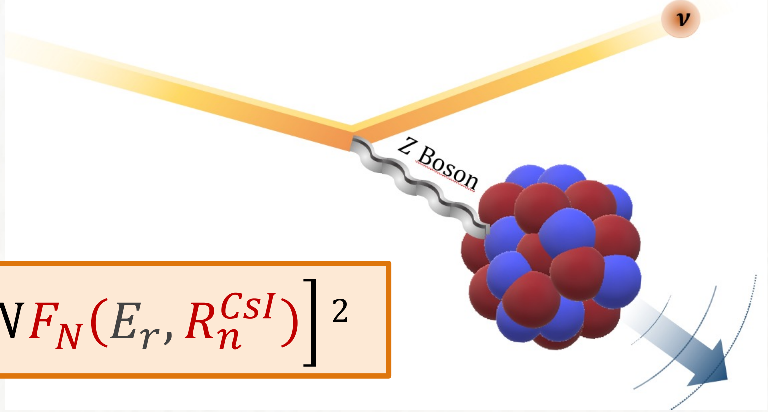
$$R^{Cs}_{ch} = 4.804 \text{ fm} \quad \text{(Cesium charge rms radius)}$$
$$R^{I}_{ch} = 4.749 \text{ fm} \quad \text{(Iodine charge rms radius)}$$

G. Fricke et al., Atom. Data Nucl. Data Tabl. **60**, 177 (1995)

From muonic X-rays data we have (for t fixed to 2.3 fm)

$$R_p^{\rm rms} = \sqrt{R^2_{ch} - \left(\frac{N}{Z}\langle r^2_{\rm n}\rangle + \frac{3}{4M^2} + \langle r^2\rangle_{SO}\right)}$$

$R_p^{Cs} = 4.821 \pm 0.005$ fm (Cesium rms proton radius)
$R_p^{I} = 4.766 \pm 0.008$ fm (Iodine rms-proton radius)



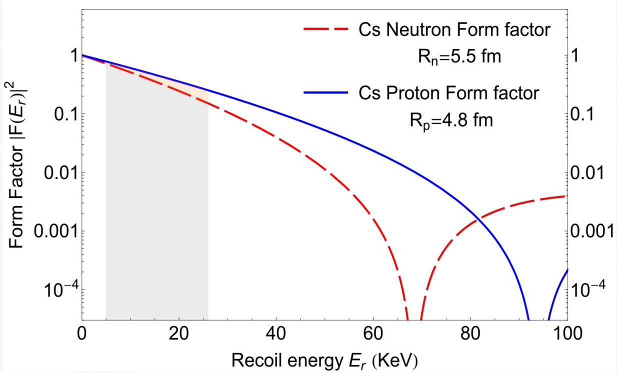
$$\frac{d\sigma}{dE_r} \cong \frac{G_F^2\, m_N}{4\pi}\left(1 - \frac{m_N E_r}{2E_\nu^2}\right)\left[g_V^p Z F_Z\left(E_r, R_p^{Cs/I}\right) + g_V^n N F_N(E_r, R_n^{CsI})\right]^2$$

$R_p^{Cs/I}$ are very well known, so we fitted COHERENT CsI data looking for R_n^{CsI} ...

Nuclear Structure

Since it is expected that also the **neutron structures of Cs and I are similar** and the current uncertainties of the COHERENT data do not allow to distinguish between them, we consider

$$F_{N,\mathrm{Cs}}(q^2) \simeq F_{N,\mathrm{I}}(q^2) \simeq F_N(q^2)$$



In order to get information on the neutron distribution of the CsI system we considered the following parametrizations of the neutron form factor

1. **Two-parameters Fermi form factor**

Neutron rms radius

$$\boxed{R_n^2 = \frac{3}{5}c^2 + \frac{7}{5}(\pi a)^2.}$$

We considered the same value of t=2.30 fm as for the proton form factor

2. **Helm form factor**

Neutron rms radius

$$\boxed{R_n^2 = \frac{3}{5}R_0^2 + 3s^2}$$

s is similar to the surface thickness. We considered the value s=0.9 fm which was determined for the proton form factor of similar nuclei.

Nuclear Structure

With COHERENT new data and the new quenching factor, our fit of the **average CsI neutron radius** gives

$$R_n^{CsI} = 5.55 \pm 0.44 \text{ fm}$$

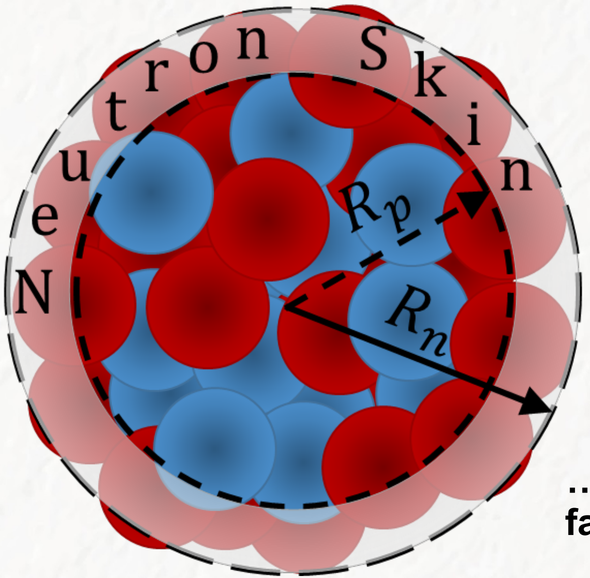
Proton rms radius for Cs and I

$R_p^{Cs} = 4.821$ fm and
$R_p^{I} = 4.766$ fm
are around 4.78 fm, with a difference of about 0.05 fm

The neutron skin

$$\Delta R_{np}^{CsI} = 0.76 \pm 0.44 \text{ fm}$$

This result is compatible with all the nuclear mean field models.



Cadeddu et al., PRD 101, 033004 (2020), arXiv:1908.06045

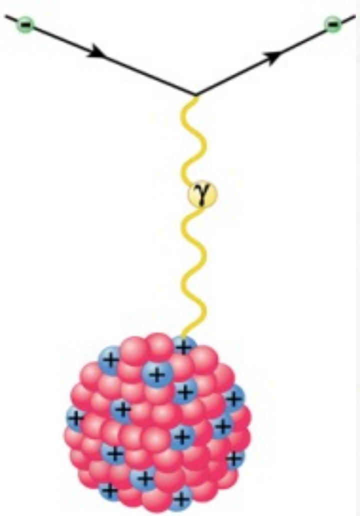
Cadeddu et al., arXiv:2102.06153

… the central value tends to favour models that predict a larger value of R_n.

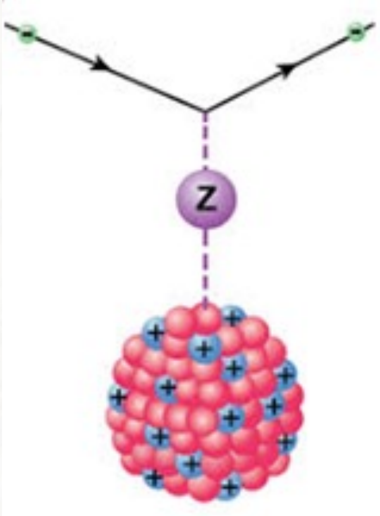
	^{127}I						^{133}Cs					
Model	R_p^{point}	R_p	R_n^{point}	R_n	$\Delta R_{np}^{\text{point}}$	ΔR_{np}	R_p^{point}	R_p	R_n^{point}	R_n	$\Delta R_{np}^{\text{point}}$	ΔR_{np}
SHF SkI3 [81]	4.68	4.75	4.85	4.92	0.17	0.17	4.74	4.81	4.91	4.98	0.18	0.18
SHF SkI4 [81]	4.67	4.74	4.81	4.88	0.14	0.14	4.73	4.80	4.88	4.95	0.15	0.14
SHF Sly4 [82]	4.71	4.78	4.84	4.91	0.13	0.13	4.78	4.85	4.90	4.98	0.13	0.13
SHF Sly5 [82]	4.70	4.77	4.83	4.90	0.13	0.13	4.77	4.84	4.90	4.97	0.13	0.13
SHF Sly6 [82]	4.70	4.77	4.83	4.90	0.13	0.13	4.77	4.84	4.89	4.97	0.13	0.13
SHF Sly4d [83]	4.71	4.79	4.84	4.91	0.13	0.12	4.78	4.85	4.90	4.97	0.12	0.12
SHF SV-bas [84]	4.68	4.76	4.80	4.88	0.12	0.12	4.74	4.82	4.87	4.94	0.13	0.12
SHF UNEDF0 [85]	4.69	4.76	4.83	4.91	0.14	0.14	4.76	4.83	4.92	4.99	0.16	0.15
SHF UNEDF1 [86]	4.68	4.76	4.83	4.91	0.15	0.15	4.76	4.83	4.90	4.98	0.15	0.15
SHF SkM* [87]	4.71	4.78	4.84	4.91	0.13	0.13	4.76	4.84	4.90	4.97	0.13	0.13
SHF SkP [88]	4.72	4.80	4.84	4.91	0.12	0.12	4.79	4.86	4.91	4.98	0.12	0.12
RMF DD-ME2 [89]	4.67	4.75	4.82	4.89	0.15	0.15	4.74	4.81	4.89	4.96	0.15	0.15
RMF DD-PC1 [90]	4.68	4.75	4.83	4.90	0.15	0.15	4.74	4.82	4.90	4.97	0.16	0.15
RMF NL1 [91]	4.70	4.78	4.94	5.01	0.23	0.23	4.76	4.84	5.01	5.08	0.25	0.24
RMF NL3 [92]	4.69	4.77	4.89	4.96	0.20	0.19	4.75	4.82	4.95	5.03	0.21	0.20
RMF NL-Z2 [93]	4.73	4.80	4.94	5.01	0.21	0.21	4.79	4.86	5.01	5.08	0.22	0.22
RMF NL-SH [94]	4.68	4.75	4.86	4.94	0.19	0.18	4.74	4.81	4.93	5.00	0.19	0.19

APV

M. Cadeddu and F. Dordei, *Reinterpreting the weak mixing angle from atomic parity violation in view of the Cs neutron rms radius measurement from COHERENT*, PRD 99, 033010 (2019), arXiv:1808.10202



Interaction mediated by the photon and so mostly sensitive to the charge (proton) distribution



Interaction mediated by the Z boson and so mostly sensitive to the weak (neutron) distribution.

Parity violation in an atomic system can be obseved as an electric dipole transition amplitude between two atomic states with the same parity, such as the 6S and 7S states in cesium

- Indeed, a transition between two atomic states with same parity (6S and 7S in Cs) **is forbidden** by the parity selection rule and cannot happen with the exchange of a photon
- However, an electric dipole transition amplitude can be induced by **a Z boson exchange** between **atomic electrons and nucleons**-> Atomic Parity Violation (APV) or Parity Non Conserving (PNC)

The quantity that is measured in this transition is the nuclear weak charge:

$$\boxed{Q_W^{SM} \approx Z\left(1 - 4\sin^2\theta_W^{SM}\right) - N}$$

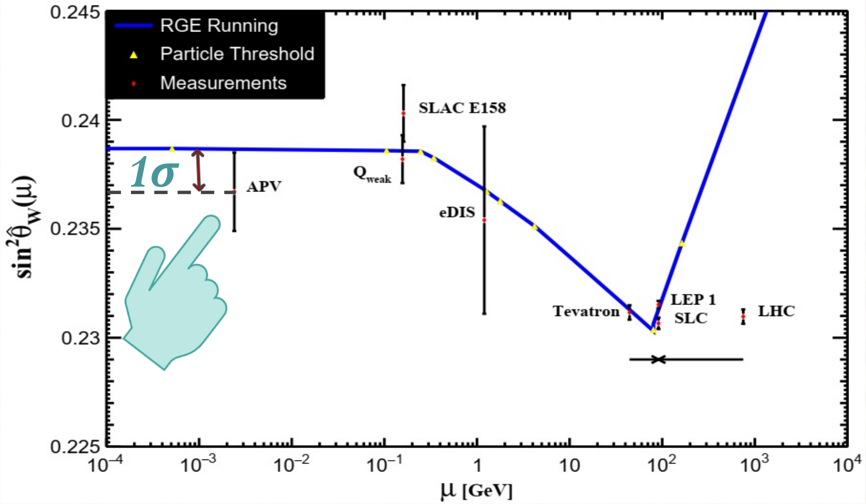
APV

Weak Charge in the SM including radiative corrections

$$Q_W^{SM+\text{r.c.}} \equiv -2\left[Z\left(g_{AV}^{ep} + 0.00005\right) + N\left(g_{AV}^{en} + 0.00006\right)\right]\left(1 - \frac{\alpha}{2\pi}\right) \approx Z\left(1 - 4\sin^2\theta_W^{SM}\right) - N$$

Using SM prediction at low energy for the Weinberg angle $\sin^2\hat{\theta}_W(0) = 0.23857(5)$, the theoretical value for the weak charge of Cesium is

$$Q_W^{SM}\left({}^{133}_{55}Cs\right) = -73.23(1)$$

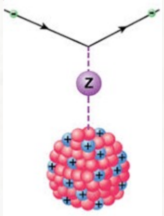


1σ

Experimental result, which then translates into a Weinberg angle determination

$$Q_W^{\text{exp.}}\left({}^{133}_{55}Cs\right) = -72.82(42)$$

$$\sin^2\theta_{\text{W}}^{\text{APV}} = 0.2367(18)$$



APV(Cs) depends crucially on the value of $R_n(\text{Cs})$ and its uncertainty

APV

$$Q_W = N\left(\frac{\mathrm{Im}\,E_{\mathrm{PNC}}}{\beta}\right)_{\mathrm{exp.}}\left(\frac{Q_W}{N\,\mathrm{Im}\,E_{\mathrm{PNC}}}\right)_{\mathrm{th.}}\beta_{\mathrm{exp.+th.}}$$

Experimental value of electric dipole transition amplitude between 6S and 7S states in Cs

$$-\mathrm{Im}\left(\frac{\mathbf{E_{PNC}}}{\boldsymbol{\beta}}\right) = 1.5935(56)\ \mathrm{mV/cm}$$

[C. S. Wood et al, Science *275*, 1759 (1997)]

Theoretical APV (or PNC) amplitude of the 6S-7S electric dipole transition

$$E_{\mathrm{PNC}} = \sum_n \left[\frac{\langle 6s|H_{\mathrm{PNC}}|np_{1/2}\rangle\langle np_{1/2}|\boldsymbol{d}|7s\rangle}{E_{6s}-E_{np_{1/2}}} + \frac{\langle 6s|\boldsymbol{d}|np_{1/2}\rangle\langle np_{1/2}|H_{\mathrm{PNC}}|7s\rangle}{E_{7s}-E_{np_{1/2}}}\right],$$

where ***d*** is the electric dipole operator, and

$$H_{\mathrm{PNC}} = -\frac{G_F}{2\sqrt{2}}Q_W\gamma_5\rho(\boldsymbol{r})$$

is the nuclear spin independent Hamiltonian describing the ***electron-nucleus weak interaction***

$\rho(\boldsymbol{r}) = \rho_p(\boldsymbol{r}) = \rho_n(\boldsymbol{r}) \rightarrow$ *neutron skin correction* needed

β*: *tensor transition polarizability

It characterizes the size of the Stark mixing induced electric dipole amplitude (external electric field)

[Bennet and Wieman,PRL 82, 2484 (1999)]
[A. Dzuba and V. Flambaum., PRA 62, 052101 (2000)]

$$\boldsymbol{\beta = 27.064(33)\ a_B^3}$$

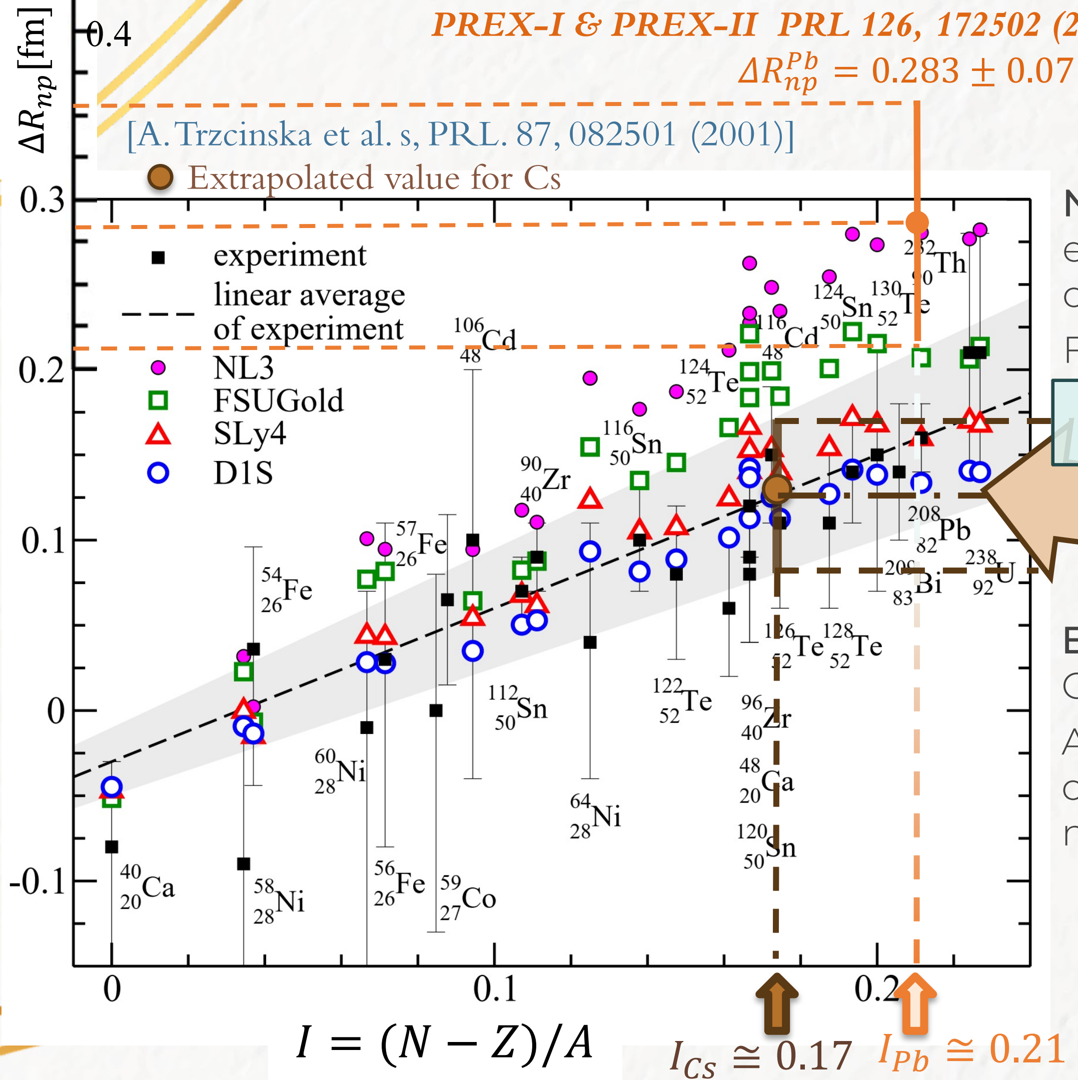
PDG2020 average

APV

PREX-I & PREX-II PRL 126, 172502 (2021)

$\Delta R_{np}^{Pb} = 0.283 \pm 0.071$ fm

[A. Trzcinska et al. s, PRL. 87, 082501 (2001)]



Neutron-skin of a variety of nuclei as extracted from **antiprotonic** data as a function of the asymmetry parameter, I.

From the linear fit one obtains:

$$\Delta R_{np}[\text{fm}] = -(0.04 \pm 0.03) + (1.01 \pm 0.15)\frac{N-Z}{A}$$

For cesium $\frac{N-Z}{A} = \frac{78-55}{133} \cong 0.17$

$\rightarrow \Delta R_{np}^{Cs} \cong 0.13 \pm 0.04$ fm

EXTRAPOLATED (not measured) value for Cesium!

Antiprotonic data: radiochemical and the other based on x-ray data constraining the neutron distribution at the nuclear periphery

[Thiel M. et al., Journal of Physics G, 46, 9 (2019), arXiv:1904.12269v1]

"[…] Thus, we must conclude that processes involving hadronic probes tend to grossly underestimate the many sources of theoretical uncertainties."

Results

Assuming to know the SM prediction at low-energy
$\sin^2\hat{\theta}_W(0) = 0.23857(5)$

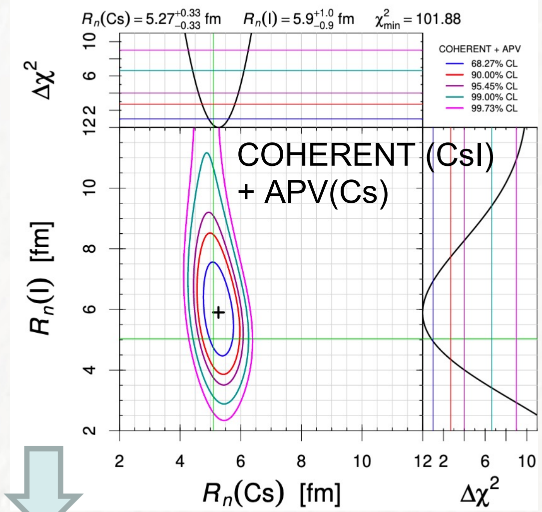
The weak charge for APV with the neutron skin contribution reads $\widetilde{Q}_W \equiv Zq_p(1-4\sin^2\vartheta_W) - Nq_n$

This coupling depends on the integrals $q_{p,n} = 4\pi\int_0^\infty \rho_{p,n}(r)f(r)r^2\mathrm{d}r$

where **ρ(r)** are the **proton** and **neutron densities** in the nucleus and f(r) is the matrix element of the electron axial current between the atomic $s_{1/2}$ and $p_{1/2}$ wave functions inside the nucleus normalized to f(0)=1.

We performed the calculations considering charge, proton and neutron distribution densities that correspond to the form factors in CEvNS cross section using both Helm and 2pF parametrization.

COHERENT depends on both Cs and I, while APV only on Cs: we can **disentangle** the contributions



Cadeddu et al., arXiv:2102.06153

$\Delta R_{np}(^{127}\mathrm{I}) = R_n - R_p = 1.1^{+1.0}_{-0.9}$ fm

$\boldsymbol{\Delta R_{np}(^{133}\mathrm{Cs}) = R_n - R_p = 0.45^{+0.33}_{-0.33}}$ **fm**

Contribution of Cs and I disentangled!!

Results

Strong linear correlation between the neutron skin of Cs and Pb among different nuclear model predictions

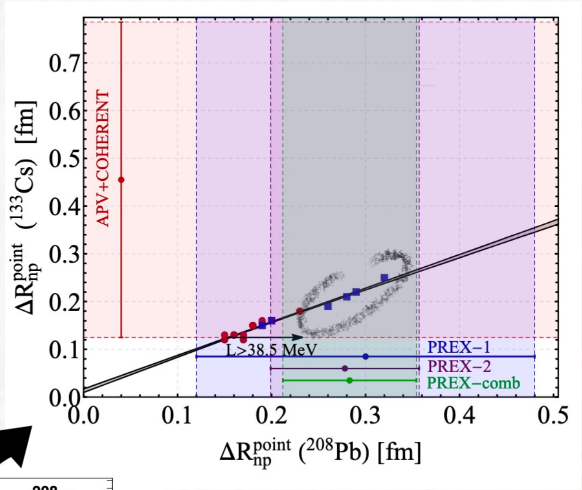
PREX: **parity-violating asymmetry** APV in the elastic scattering of longitudinally polarized electrons on ^{208}Pb

Measurement of the **lead neutron skin** through an electroweak process

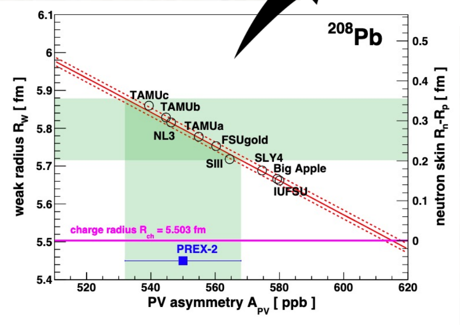
$$A_{\rm PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{G_F Q^2 |Q_W|}{4\sqrt{2}\pi\alpha Z} \frac{F_{\rm W}(Q^2)}{F_{\rm ch}(Q^2)}$$

$$\Delta \mathbf{R_{np}}\left({}^{208}\mathbf{Pb}\right) = \mathbf{0.283 \pm 0.071\ fm}$$

The neutron skin is a key parameter also for neutron stars properties



Cadeddu et al., arXiv:2102.06153

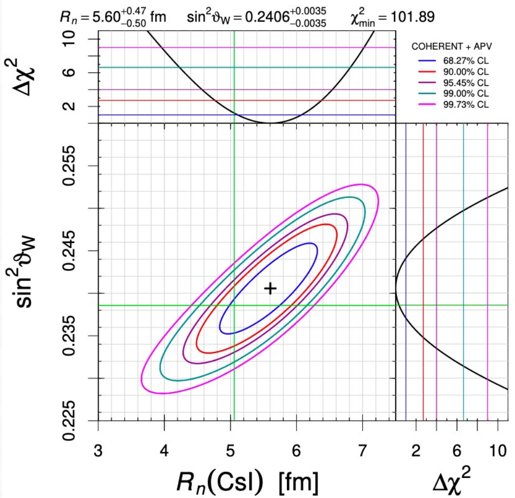


PREX, PRL 126, 172502 (2021)

Results

Both CEvNS data on CsI and APV on Cs **depend on R_n** and **$\sin^2(\vartheta_W)$**: strong interplay between nuclear physics and weak interactions. Try to exploit **correlations** in both measurements!

The COHERENT only measurement is currently not competitive due to the suppression of the proton contribution $\text{COHERENT only } \sin^2(\vartheta_W) = 0.220^{+0.028}_{-0.027}$

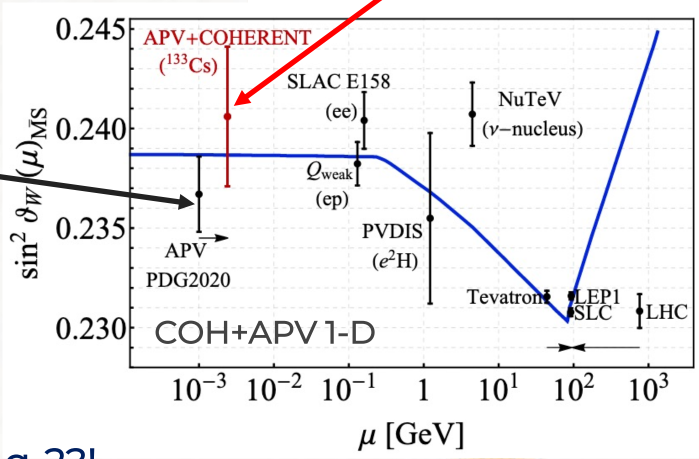


Cadeddu et al, arXiv:2102.06153

CEvNS is helpful in combination with APV measurement on ^{133}Cs in order to provide experimental constrain on R_n and $\sin^2(\vartheta_W)$ simultaneously

Here the value of $R_n(^{133}\text{Cs})$ was **extrapolated** using antriprotonic atoms, known to be affected by considerable **model dependencies**.

$\sin^2(\vartheta_W) = 0.2406^{+0.0035}_{-0.0035}$



Data driven result!

Waiting for future reduced uncertainties!

Future seems to be bright!

Maybe BSM physics or connection with g-2?!

PRD 104, L011701 (2021), 2104.03280

Thanks!

Do you have any questions?

Outline

01 **CEνNS process**
Coherent elastic neutrino-nucleus scattering

02 **COHERENT experiment**
COHERENT latest results on cesium-iodide

03 **Nuclear Structure**
Electroweak neutron skin measurement

04 **APV**
Atomic Parity Violation experiment on Cesium

05 **Results**
Our results and conclusions

CEνNS process

Coherency means that the nucleon wavefunctions in the target nucleus are in phase with each other: this is true at **low momentum transfer**.

Coherency condition: $q \cdot R \ll 1 \Longrightarrow q \ll \frac{1}{R} \sim 0.2\ \mathrm{fm}^{-1}$

Three-momentum transfer $q = \sqrt{2 m_N E_r}$

Nuclear radius (R$\sim 4-5$ fm)

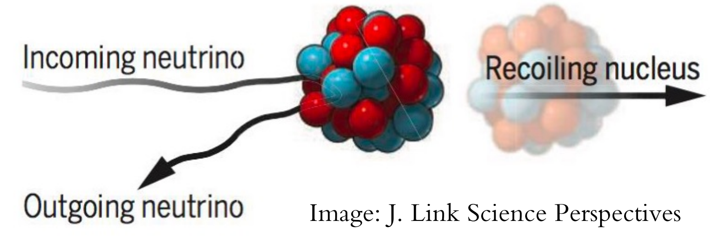


Image: J. Link Science Perspectives

The interaction is coherent up to neutrino energies $E_\nu \sim 50$ MeV for medium size nuclei, which translate to keV nuclear recoils

Despite the detection related challenges CEνNS is characterized by a **large cross section**

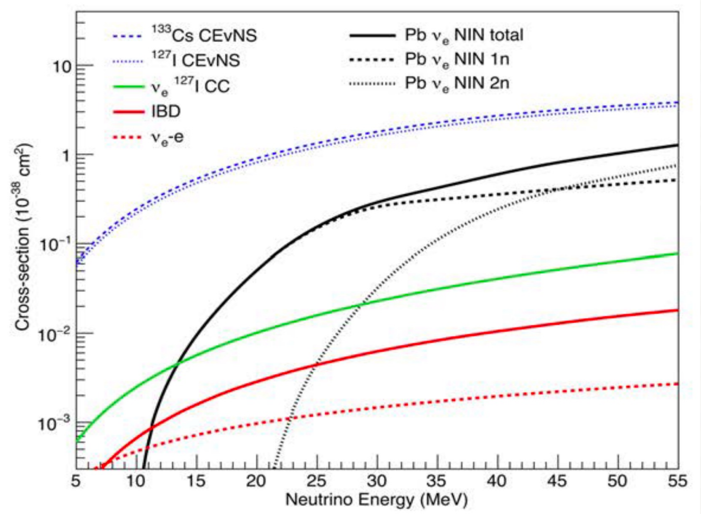
$$\frac{d\sigma^{CE\nu NS}(E_\nu, E_r)}{dE_r} \cong \frac{G_F^2}{4\pi} m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) Q_w^2\ |F(E_r)|^2$$

Nuclear weak charge

Nuclear form factor

where $Q_w = N - (1 - 4\sin^2\theta_W)\, Z \cong N.$

$\sin^2\theta_W$ is about ¼, the second term is close to zero so that the cross section scales with the neutron number squared $\sigma \propto N^2$

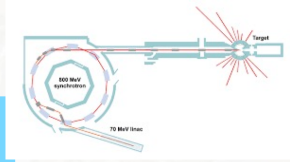


D. Akimov et al. ***Science*** 357.6356 (2017)

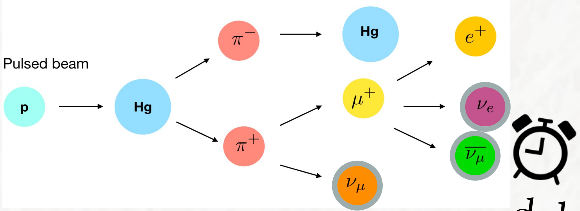
CEνNS process

An appropriate **source of neutrinos** is needed: high flux, well understood (low uncertainties), pulsed for background rejection, multiple flavors, etc.

Two types of neutrino sources are considered in experiments



Spallation neutron source: neutrinos produced from the decay of pions/muons

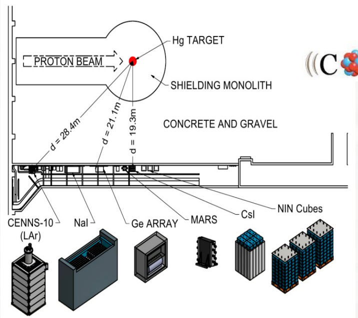


prompt

delayed

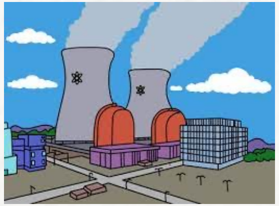
Spallation Neutron Source @Oak Ridge:

- **1 GeV** protons hit liquid Hg target
- Reached 1.4 MW
- Pulsed @60Hz: measure steady-state bkg out of beam
- **Pion-decay-at-rest** neutrino source
- **Multi-target** program to measure N^2 dependence



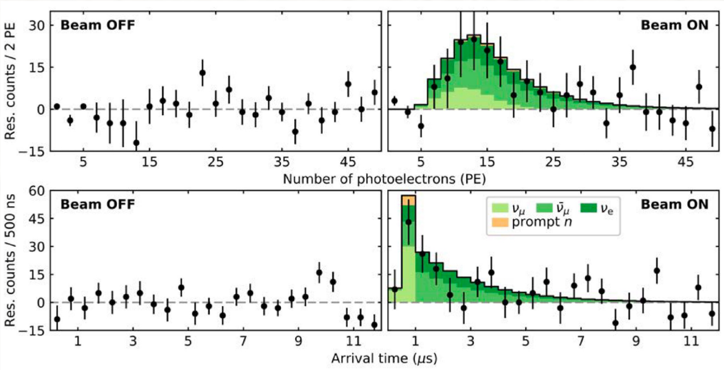
COHERENT

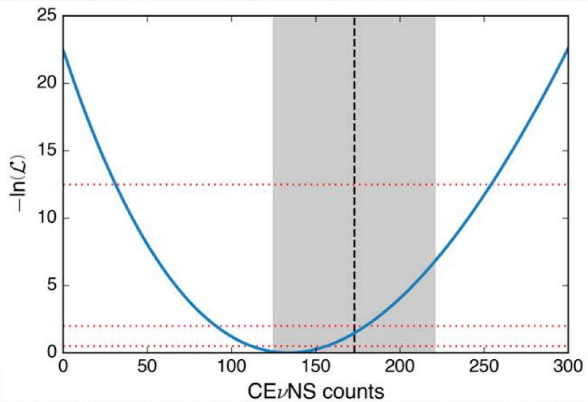
Nuclear reactors: antineutrinos produced in beta decays



COHERENT experiment

- COHERENT has observed for the **first time** CEνNS with a 14.6 kg CsI scintillating crystal
- 19.3 m from the source
- 134±22 CEνNS events: 6.7σ significance
- To be compared with prediction: 173±48 events





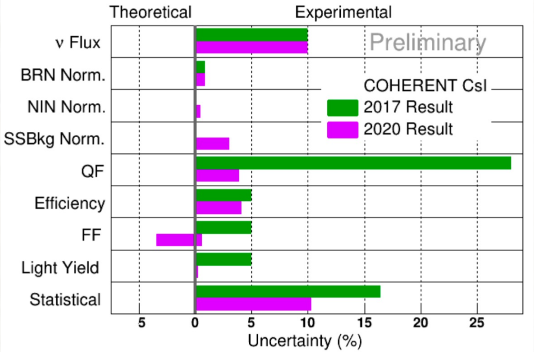
- New observation in 2020 with LAr detector

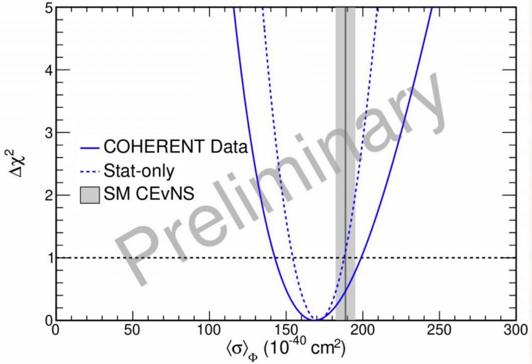
D. Akimov et al. ***Science*** 357.6356 (2017)

COHERENT experiment

- In 2020 the COHERENT Collaboration presented the **updated results** on the CsI detector:
- Increased statistics. More than 2x!
- 2D Likelihood fit in numbers of photoelectrons and reconstructed time
- Result consistent with SM prediction at 1σ
- **Flux uncertainty** now dominates the systematic
- Overall systematic uncertainty reduced: 28%→13%

No-CEνNS rejection	11.6σ
SM CEνNS prediction	333±11(th)±42(ex)
Fit CEνNS events	**306±20**
Fit χ^2/dof	82.4/98
CEνN cross section	$169^{+30}_{-26}\times10^{-40}$ cm^2
SM cross section	$189 \pm 6\times10^{-40}$ cm^2



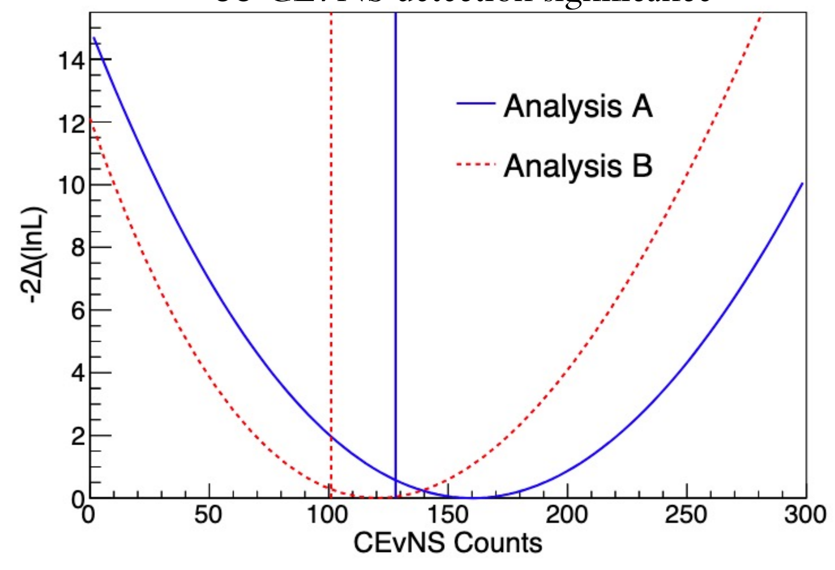


COHERENT Collaboration, talks @Magnificent CEνNS '20

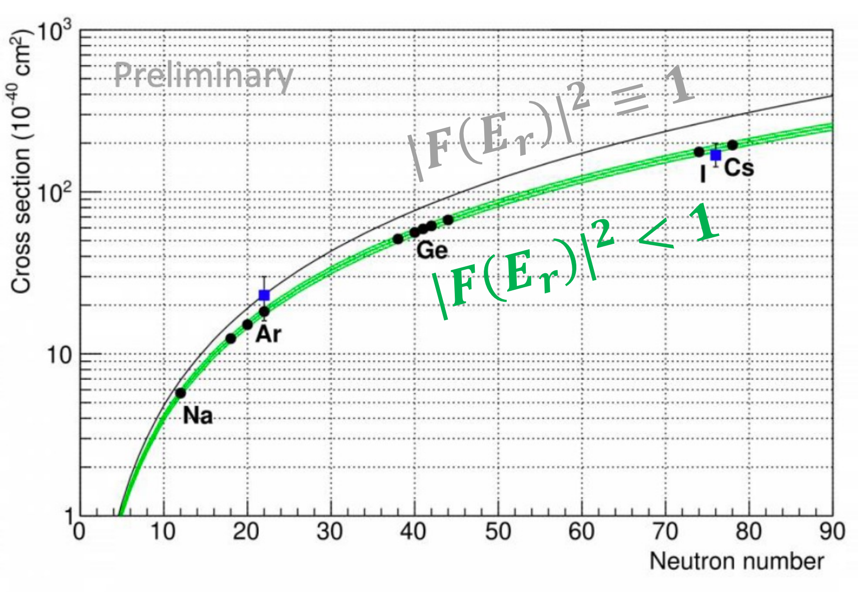
COHERENT experiment

- 2020 results using 24 kg of atmosphering Ar (CENNS-10 detector)
- Test of the dependence on N^2

>3σ CEνNS detection significance



COHERENT, PRL 126, 012002 (2021)



Pershey, talk @Magnificent CEνNS '20

Observed cross section consistent with the N^2 dependence

CENNS-10 is still taking data and an upgrade to a 750 kg detector

CEνNS cross section

Neutrino energy

Mass of the nucleus

SM vector proton coupling

New ν interactions

SM vector neutron coupling

New ν properties

$$\frac{d\sigma^{CE\nu NS}(E_\nu, E_r)}{dE_r} \cong \frac{G_F^2\, m_N}{\pi}\left(1-\frac{m_N E_r}{2E_\nu^2}\right)\left[g_V^p\left(\sin^2(\vartheta_W)\right) Z\, F_Z(|\vec{q}|^2) + g_V^n\, N\, F_N(|\vec{q}|^2)\right]^2 + \dots$$

Nuclear recoil energy

Weinberg angle

Proton Form Factor

Neutron Form Factor

EW precision

Nuclear physics

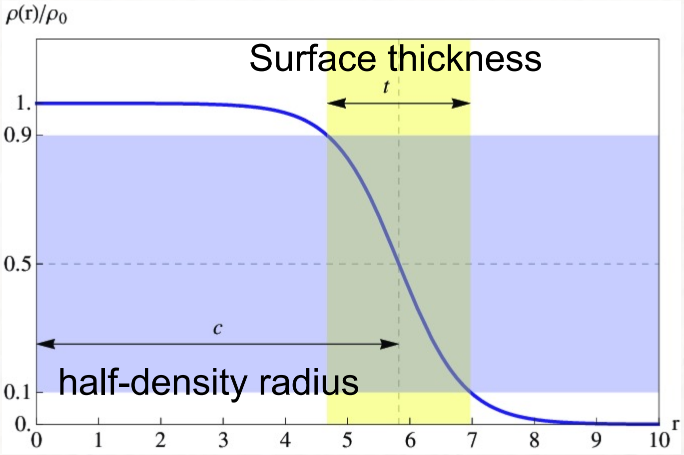
Nuclear Structure

- The analogy with electron and x-ray diffraction is very close and it is merely necessary to replace the electron cloud of an atom by the proton cloud of a nucleus
- Born approximation: to obtain the actual scattering for a finite nucleus it is necessary to multiply the point charge scattering cross section by the square of the form factor
- Unfortunately for medium and heavy nuclei this procedure fails:
- As is well known, the first Born approximation is equivalent to consider both the incident and diffracted waves as a plane waves.
- The waves are distorted by the intese nuclear electromagnetic field, so that they can no longer be considered plane waves: DISTORTED WAVER BORN APPROXIMAPTON (DWBA)
- By considering the PWBA two principal types of errors are committed: the PWBA puts true zeros into the form factors, whereas the accurate calculations show minima rather than zeros; Radii determined from PWBA are generally larger than the exact calculations.

Nuclear Structure

- The charge radii of nuclei have been studied with muonic spectroscopy and the data were fitted with two-parameters Fermi (2pF) density distributions of the form

$$\rho_{2pF}(r,c,a) = \frac{\rho_0}{1+e^{(r-c)/a}}$$



- The **half-density radius c** is related to the root-mean square (rms) radius

$$R_{rms} \equiv \sqrt{\langle r^2 \rangle} \equiv \sqrt{\frac{\int r^2 \rho(\mathrm{r})\, d^3 r}{\int \rho(\mathrm{r})\, d^3 r}} = \sqrt{\frac{\int r^2 \rho(\mathrm{r})\, d^3 r}{Ze}} \rightarrow$$

$$R_{rms}^{2pF} \equiv \sqrt{\langle r^2 \rangle} = \sqrt{\frac{3}{5}\, c^2 + \frac{7}{5}(\pi\, a)^2}$$

- The **a** parameter, called **diffuseness**, is related to the **surface thickness t**:

$$t = 4\, a\, \ln 3 \cong 4.40\, a$$

- In principle a three-parameters Fermi density distributions could be employed, adding the w parameter which allows for a **dip or a bump** in the central region

$$\rho_{3pF}(r,c,a,w) = \left(1 + w\frac{r^2}{c^2}\right)\rho_{2pF}$$

Nuclear Structure

Charge radii of Cesium & Iodine: surface thickness fixed to t=2.3 fm (i.e. a=0.5234 fm)

TABLE IIIA. Muonic $2p \rightarrow 1s$ Transition Energies and Barrett Radii for $Z < 60$ and $Z > 77$

See page 194 for Explanation of Tables

Isotope	$E_{exp.}$ [keV]	$E_{theo.}$ [keV]	NPol [keV]	c [fm]	$\langle r^2 \rangle^{1/2}_{model}$ [fm]	α [1/fm]	k	C_z [am/keV]	$R^{\mu}_{k\alpha}$ [fm]	Ref.
^{133}Cs	3840.702	3840.670	1.531			0.1193	2.2296	-2.759	6.1459	[Kl88]
Cesium	39			5.6710	4.804				(1;13)	
	3902.636	3902.656	1.289	1		0.1182	2.2274	-2.710	6.1464	
	31								(1;11)	
^{127}J	3667.361	3667.466	0.532			0.1166	2.2229	-2.969	6.0762	[Kl88]
Iodine	35			5.5931	4.749				(1;5)	
	3723.742	3723.650	1.454	1		0.1155	2.2209	-2.919	6.0768	
	33								(1;13)	

G. Fricke et al., Atom. Data Nucl. Data Tabl. **60**, 177 (1995)

In a 2pF one can retrieve in a model-dependent way the rms charge radius

$$R_{ch}^{rms} \equiv \langle r^2 \rangle^{1/2}_{model} = \sqrt{\frac{3}{5}\,c^2 + \frac{7}{5}\left(\pi\,\frac{t_{fixed}}{4\,\ln 3}\right)^2}$$

$R_{ch}^{Cs} = 4.804$ fm (Cesium charge rms radius)

$R_{ch}^{I} = 4.749$ fm (Iodine charge rms radius)

Nuclear Structure

Once the charge radius is determined, it is necessary to translate such quantity into the proton radius, taking into account **finite size** of both **protons** and **neutrons** plus **other corrections**

$$R_{ch}^2 = \boxed{R_{\text{point}}^2 + \langle r_{\text{p}}^2 \rangle} + \frac{N}{Z}\langle r_{\text{n}}^2 \rangle + \frac{3}{4M^2} + \langle r^2 \rangle_{SO}$$

Charge radius

Point-proton radius

Mean squared charge radius of a single proton
$\langle r_{\text{p}}^2 \rangle = 0.7071\ \text{fm}^2$

Mean squared charge radius of a single neutron
$\langle r_{\text{n}}^2 \rangle = -0.1161\ \text{fm}^2$

Relativistic Darwin-Foldy correction
$\sim 0.033\ \text{fm}^2$

Spin-orbit correction
$\sim 0.09\ \text{fm}^2$ for ^{48}Ca

$\sim 0.028\ \text{fm}^2$ for ^{208}Pb

Spin-independent Spin-independent

G. Hagen et al. *Nature Physics* **12**, 186–190 (2016), Arxiv: 1509.07169

M. Cadeddu et al. PRD 102, 015030 (2020), Arxiv: 2005.01645

$$R_p^{\text{rms}} = \sqrt{R_{\text{point}}^2 + \langle r_{\text{p}}^2 \rangle}$$

$$= \sqrt{R_{ch}^2 - \left(\frac{N}{Z}\langle r_{\text{n}}^2 \rangle + \frac{3}{4M^2} + \langle r^2 \rangle_{SO}\right)}$$

RMS proton distribution radius

Results

Assuming to know the SM prediction at low energy $\sin^2\hat{\theta}_W(0) = 0.23857(5)$

The weak charge for APV with the neutron skin contribution reads $\widetilde{Q}_W \equiv Z q_p (1 - 4\sin^2\vartheta_W) - N q_n$

This coupling depends on the integrals $q_{p,n} = 4\pi \int_0^\infty \rho_{p,n}(r) f(r) r^2 \mathrm{d}r$

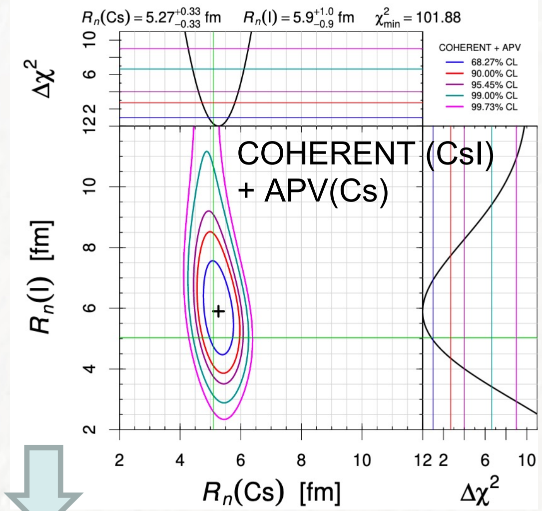
where **ρ(r)** are the proton and neutron densities in the nucleus and f(r) is the matrix element of the electron axial current between the atomic $s_{1/2}$ and $p_{1/2}$ wave functions inside the nucleus normalized to f(0)=1.

$$f(r) = 1 - 2\int_0^r \frac{V(r')}{r'^2} \int_0^{r'} V(r'') r''^2 \mathrm{d}r'' \mathrm{d}r' + \left(\frac{1}{r}\int_0^r V(r') r'^2 \mathrm{d}r'\right)^2,$$

where V(r) represents the radial electric potential determined uniquely by the charge distributon $\boldsymbol{\rho_c(r)}$ of the nucleus.

$$V(r) = 4\pi Z\alpha \left[\frac{1}{r}\int_0^r \rho_c(r') r'^2 \mathrm{d}r' + \int_r^\infty \rho_c(r') r' \mathrm{d}r'\right]$$

We performed the calculations considering charge, proton and neutron distribution densities that correspond to the form factors in CEvNS cross section using both Helm and 2pF parametrization.



Cadeddu et al., arXiv:2102.06153

$\Delta R_{np}(^{127}\mathrm{I}) = R_n - R_p = 1.1^{+1.0}_{-0.9}$ fm

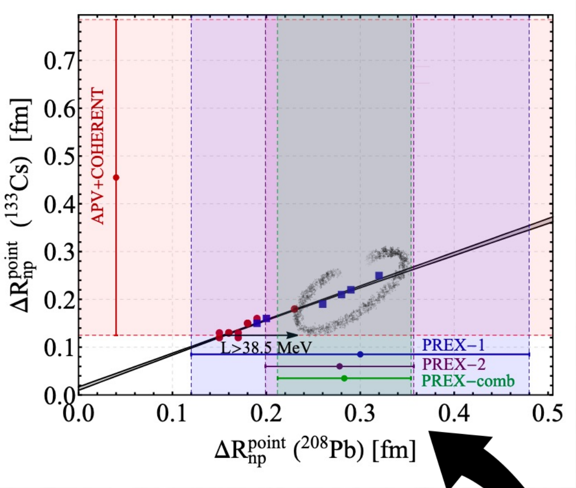
$\boldsymbol{\Delta R_{np}(^{133}\mathrm{Cs}) = R_n - R_p = 0.45^{+0.33}_{-0.33}}$ **fm**

Contribution of Cs and I disentangled!!

Results

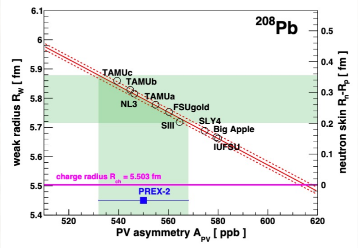
Strong linear correlation between the neutron skin of Cs and Pb among different nuclear model predictions

Cadeddu et al., arXiv:2102.06153



$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{G_F Q^2 |Q_W|}{4\sqrt{2}\pi\alpha Z} \frac{F_W(Q^2)}{F_{ch}(Q^2)}$$

PREX: parity-violating asymmetry APV in the elastic scattering of longitudinally polarized electrons on ^{208}Pb

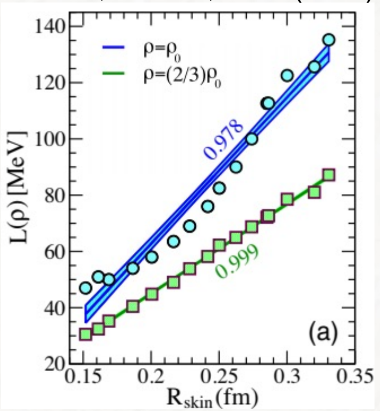


PREX, PRL 126, 172502 (2021)

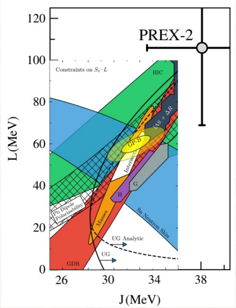
Important complementarity of R_n with the astrophysical sector

- ΔR_{np} is the result of the **competition between the Coulomb repulsion, the surface tension**, that decreases when the excess neutrons are pushed to the surface, and **the symmetry energy**.
- The slope parameter, L, is the derivative of the symmetry energy wrt density at saturation
- Theoretical calculations show a strong linear correlation between ΔR_{np} and L, namely **larger neutron skins translate into larger values of L**

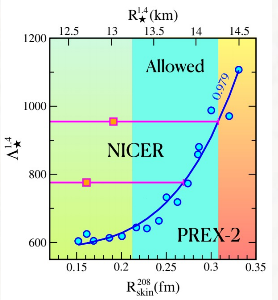
Reed at al., PRL 126, 172503 (2021)
Horowitz et al., PRL 86, 5647 (2001)



COHERENT and APV result **L> 38.5 MeV**



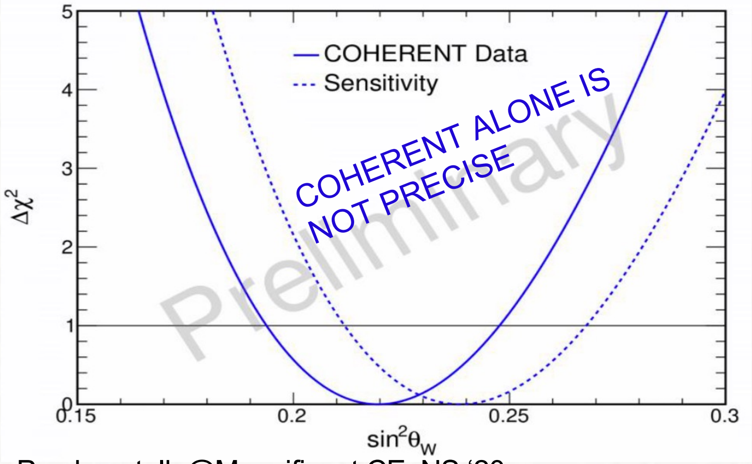
Given that L is proportional to the pressure of pure neutron matter at saturation density, larger values of ΔR_{np} imply a **larger size of neutron stars**



Results

Both CEvNS data on CsI and APV on Cs **depend on R_n** and **$\sin^2(\vartheta_W)$**: strong interplay between nuclear physics and weak interactions. Try to exploit **correlations** in both measurements!

The dependece of the weak charge on the Weinberg angle allows CEvNS to measure it

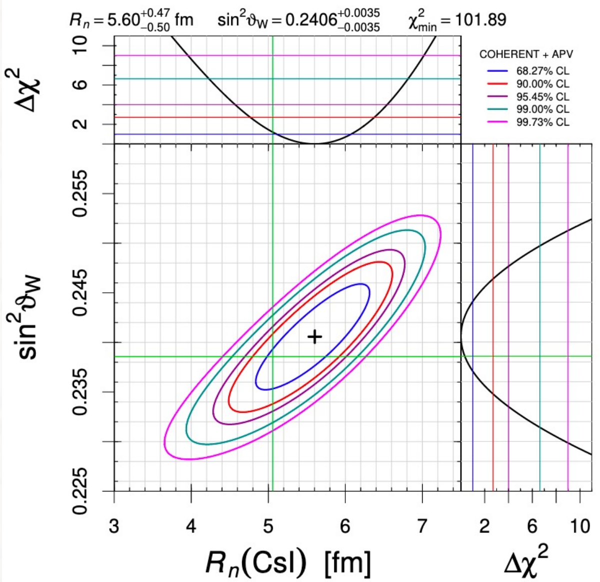


Pershey, talk @Magnificent CEνNS '20

$$\sin^2(\vartheta_W) = 0.220^{+0.028}_{-0.027}$$

Measurement not currently competitive due to the suppression of the proton contribution

Cadeddu et al, arXiv:2102.06153



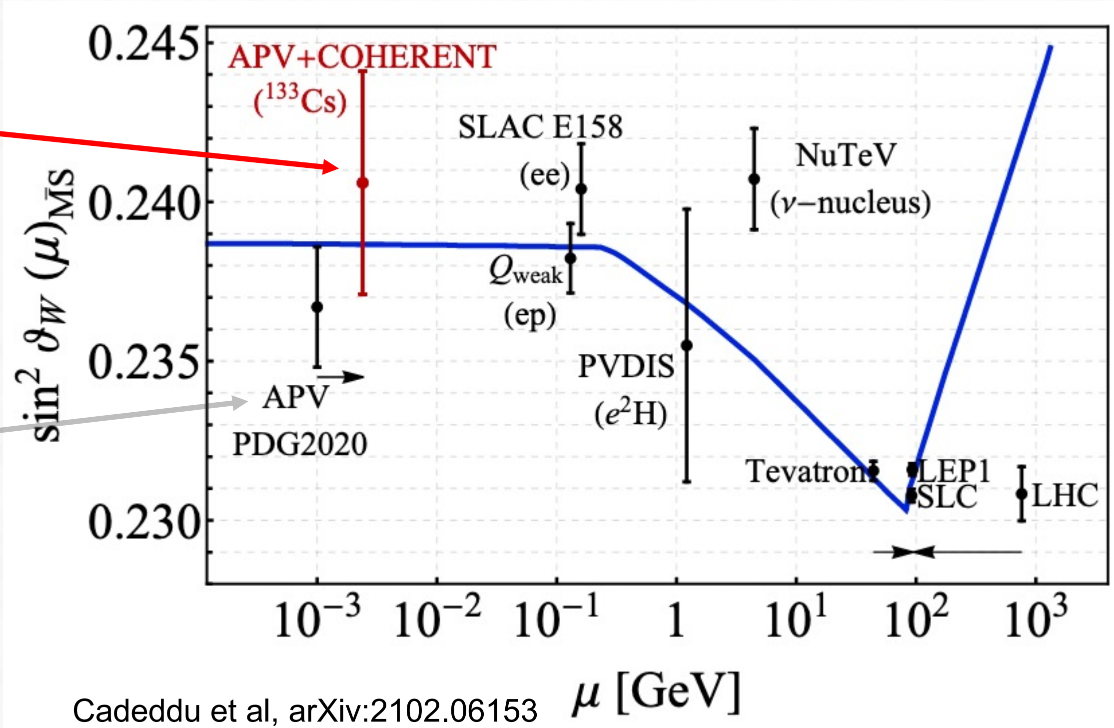
CEvNS is helpful in combination with APV measurement on ^{133}Cs in order to provide experimental constrain on R_n and $\sin^2(\vartheta_W)$ simultaneously

Data driven result!

Results

COHERENT+APV 1-D-marginalization on $\sin^2(\vartheta_W)$

$$\sin^2(\vartheta_W) = 0.2406^{+0.0035}_{-0.0035}$$



Cadeddu et al, arXiv:2102.06153

Here the value of $R_n(^{133}Cs)$ was **extrapolated** from hadronic experiments using antriprotonic atoms, known to be affected by considerable **model dependencies**.