EPIC 2024

Electroweak Physics InterseCtions

INFN CAGLIARI

Istituto Nazionale di Fisica Nucleare

Sezione di Cagliari

Simultaneous extraction of the weak radius and the weak mixing angle from EW probes

Nicola Cargioli

nicola.cargioli@ca.infn.it

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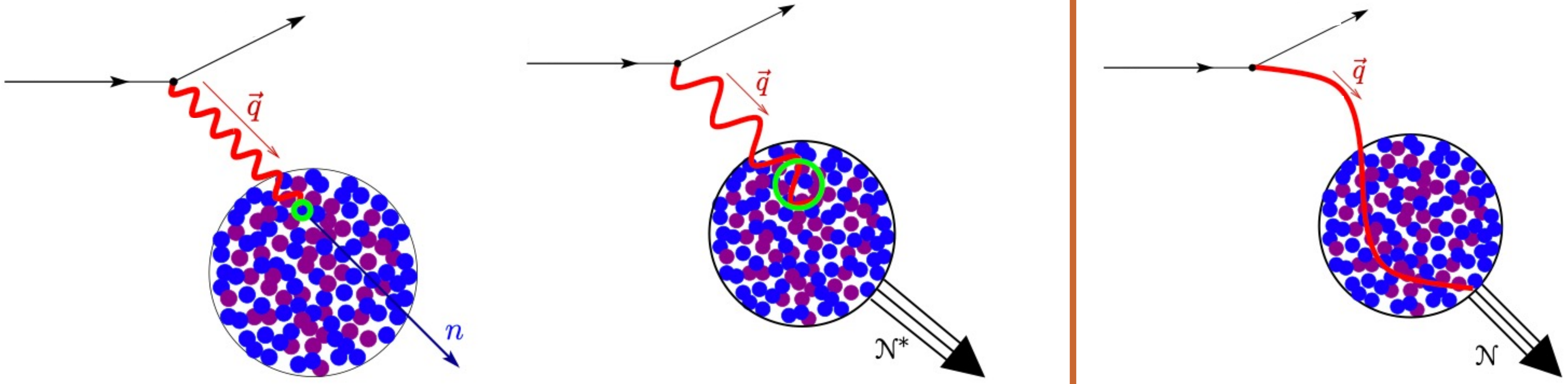
Probing Nuclear Structures

The spatial dimension probed in a scattering experiment depends on the wavelength of the mediator

De Broglie wavelenght: $\lambda = \frac{h}{p}$

The momentum of the mediator is of the order of the momentum transfer $p \sim q$

M. Cadeddu et al., EPL 143 (2023) 3, 34001

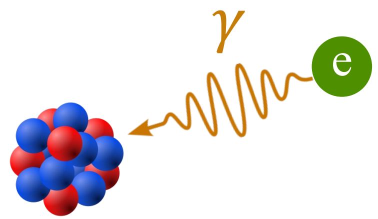


$\lambda_{\text{med}} \ll 2R$ | $\lambda_{\text{med}} \lesssim 2R$ | $\lambda_{\text{med}} \gtrsim 2R$

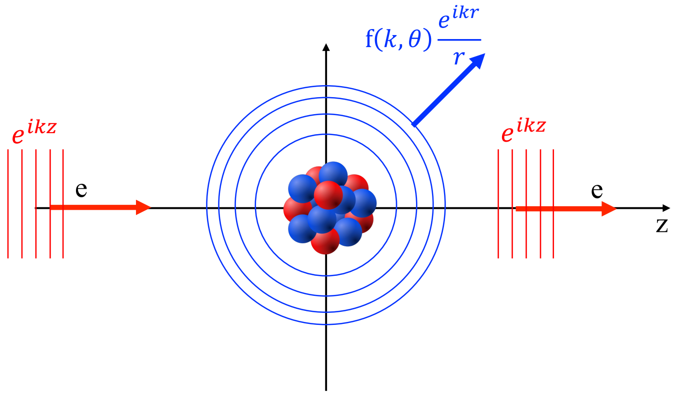
$\lambda \sim \frac{200 \text{ MeV fm}}{q}$ for $q = 20$ MeV $\rightarrow$ $\lambda \cong 10$ fm → **MeV scale neutrinos and MeV-GeV scale electrons**

Probing Nuclear Structures

The dominant process is electromagnetic scattering mediated by the photon

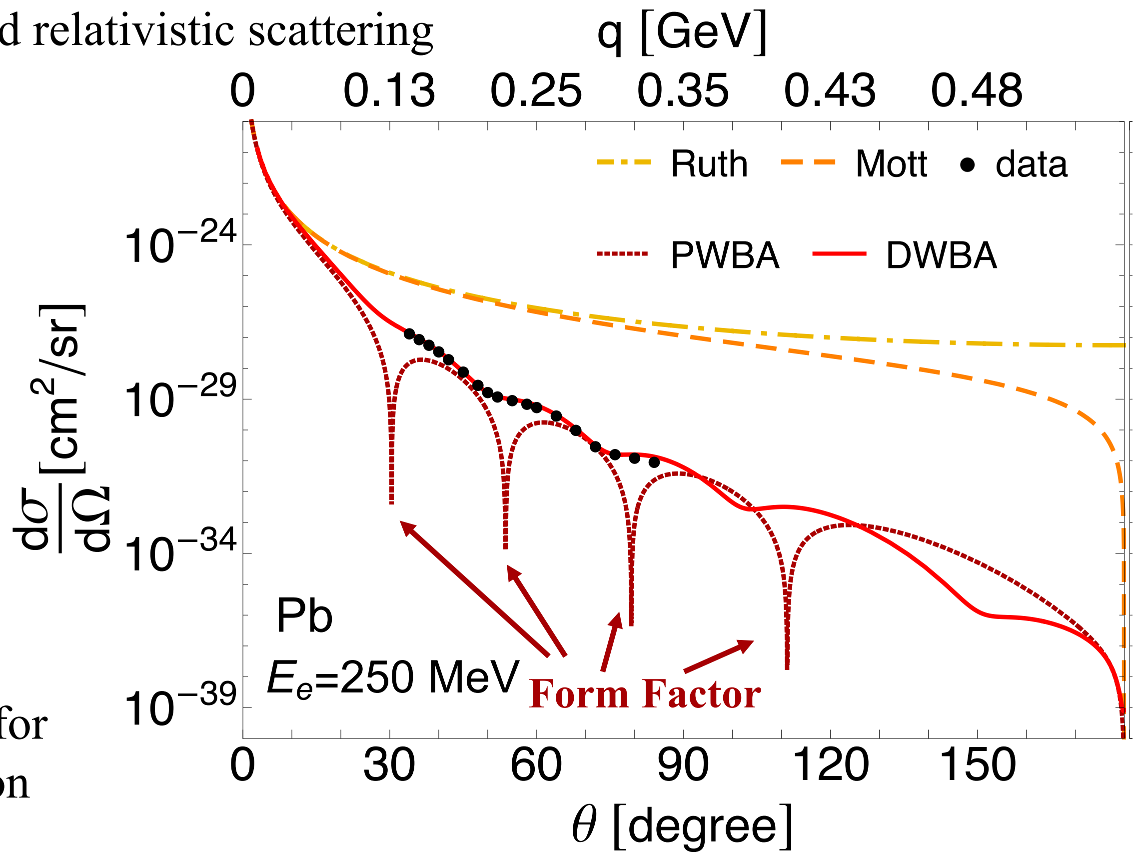


- **Rutherford scattering**: $\left(\frac{d\sigma}{d\Omega}\right)_{\text{Ruth}} \propto \frac{Z\alpha^2}{4E_e^2}\frac{1}{\sin^4\frac{\theta}{2}}$ Point-like nucleus and nonrelativistic scattering
- **Mott Scattering**: $\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \propto \frac{Z\alpha^2}{4E_e^2}\frac{\cos^2\frac{\theta}{2}}{\sin^4\frac{\theta}{2}}$ Point-like nucleus and relativistic scattering
- **PWBA**: $\left(\frac{d\sigma}{d\Omega}\right)_{\text{PWBA}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} |\text{F}_{\text{ch}}(q^2)|^2$
  Extended nucleus and relativistic scattering



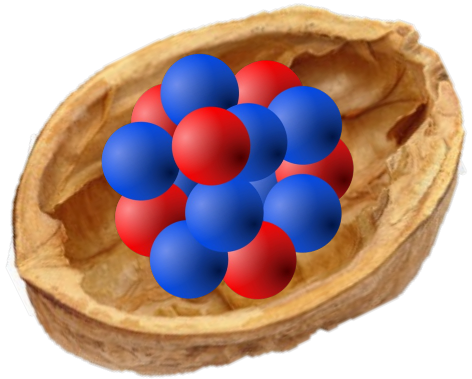
- **DWBA**: Distorted Wave Born Approximation which accounts for the effect of the Coulomb potential on the electron wavefunction

Numerical code to solve the Dirac Equation in a central potential



Only CHARGE and PROTON distributions

Probing Nuclear Structures

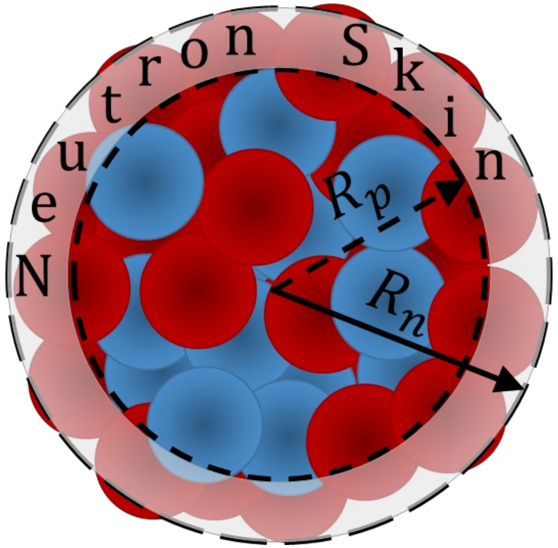


Nucleus: compact object made of nucleons and held up together from the strong force

Distribution of nucleons inside the nucleus: mass, charge, **weak** etc.

In heavy nuclei (N>Z) protons are expected to be distributed over a smaller radius than neutrons: NEUTRON SKIN $\Delta \boldsymbol{R}_{np} = \boldsymbol{R}_n - \boldsymbol{R}_p$

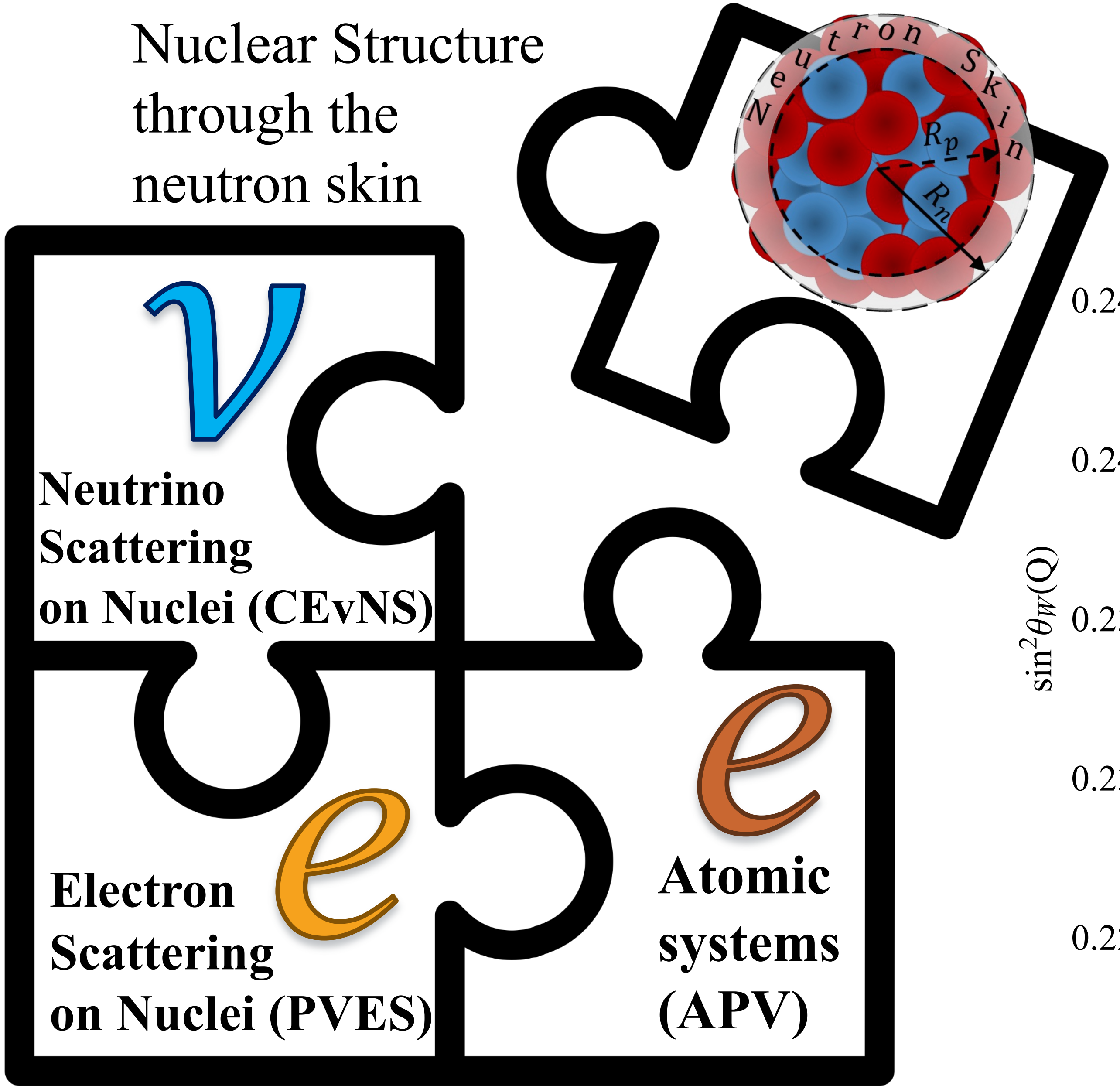
Neutron skin: result of the competition between the Coulomb repulsion, the surface tension and the symmetry energy



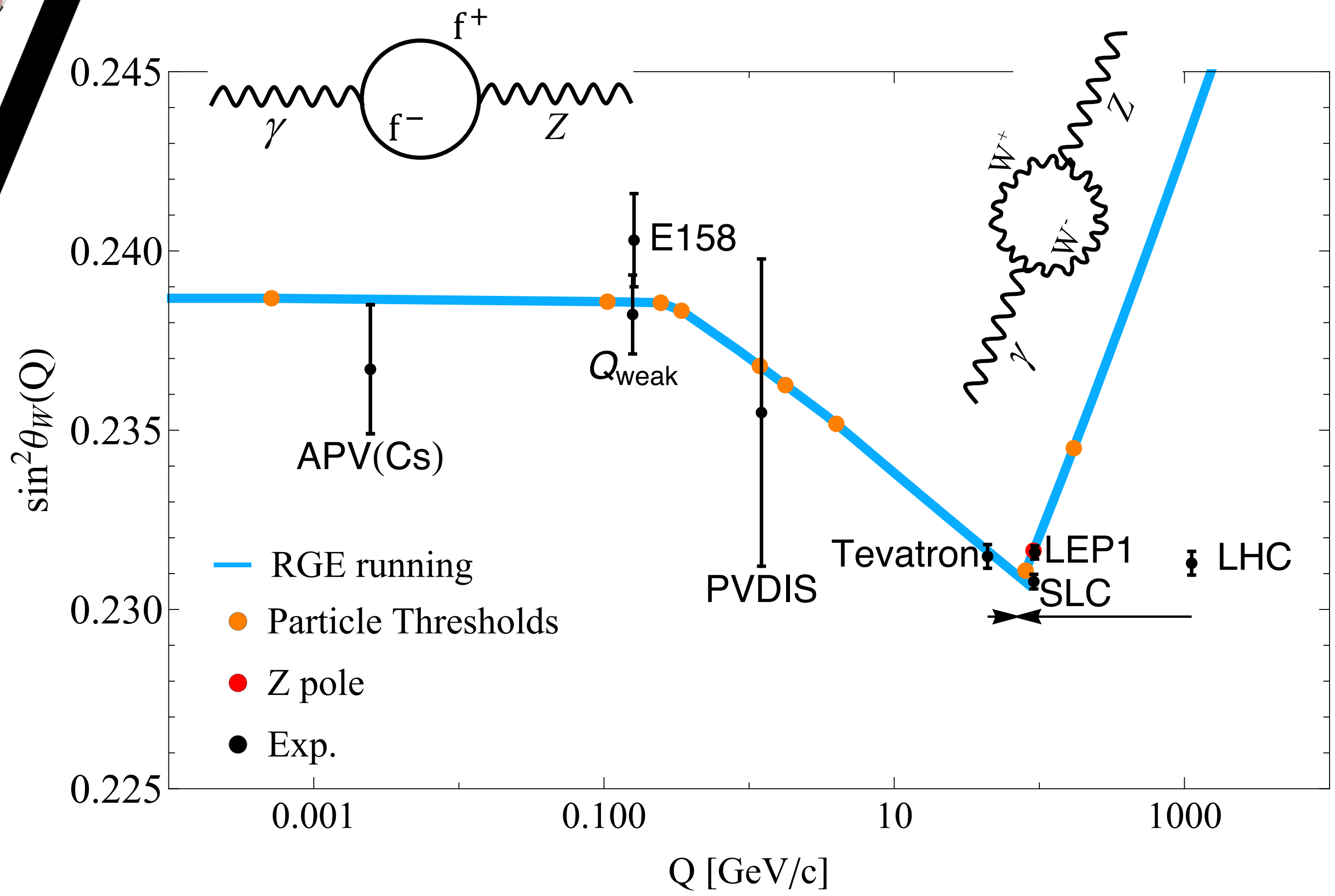
- Surface tension: decreases when the excess neutrons are pushed to the surface
- The neutron skin has implications not only in nuclear theory
- Behaviour of neutron-rich matter such as the one inside the inner core of neutron stars
- EOS of neutron stars: symmetry energy S and slope parameter L (derivative of S wrt density)

Larger neutron skins → Larger L parameters → Larger size of neutron stars

Nuclear Structure through the neutron skin

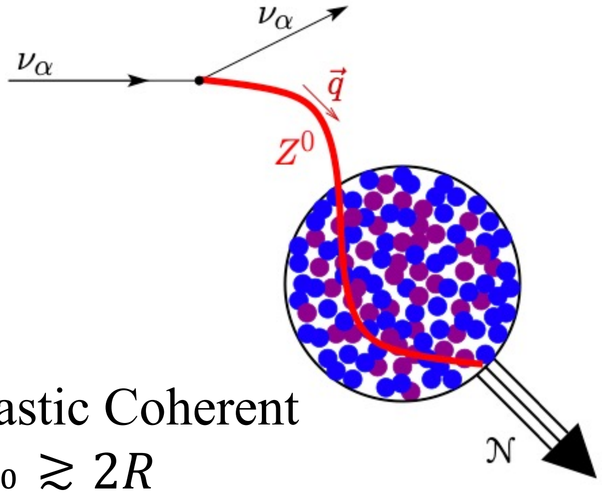


Weak mixing angle: key parameter of the EW theory



The neutrino sector: CEνNS

CEνNS: coherent elastic interaction of the neutrino with the nucleus via a purely NC process



Elastic Coherent
$\lambda_{Z^0} \gtrsim 2R$

$$\frac{d\sigma_{\nu_\ell-\mathcal{N}}(E_\nu, T_{nr})}{dT_{nr}} \cong \frac{G_F^2 m_N}{\pi}\left(1 - \frac{m_N T_{nr}}{2E_\nu^2}\right)\left[Q_W F_W(q^2)\right]^2$$

Nuclear weak charge Q_W (depends on the weak mixing angle)

Weak Form Factor (describes the nuclear structure effects)

$$Q_W F_W(q^2) = g_V^p(\sin^2(\vartheta_W)) Z\, F_Z(|\vec{q}|^2) + g_V^n N\, F_N(|\vec{q}|^2)$$

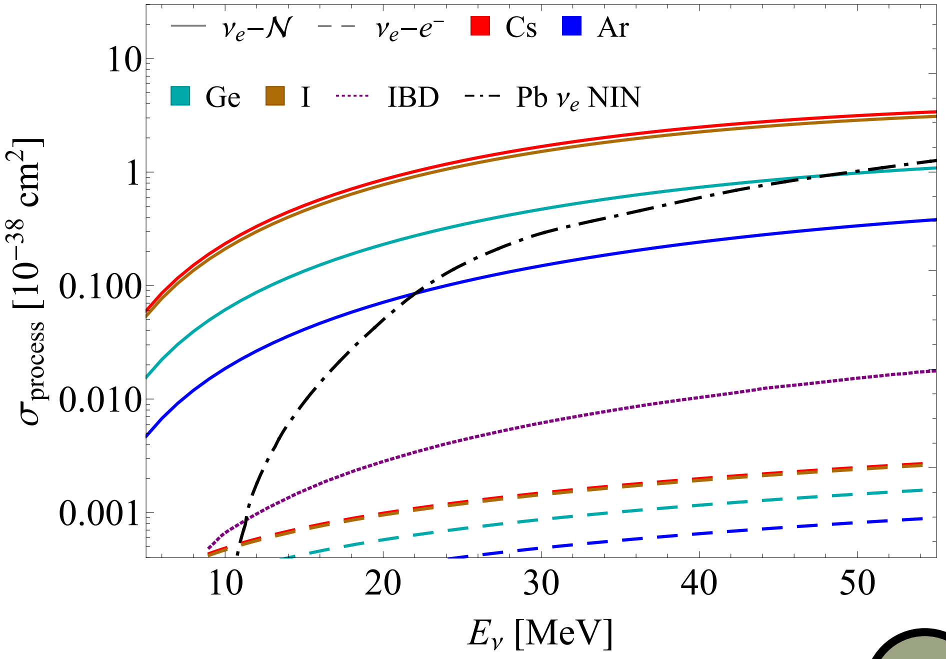
$g_V^p(\nu_e) = 0.0382$

$g_V^p(\nu_\mu) = 0.0300$

$g_V^n = -0.5117$

Neutrinos couple mainly to neutrons! → Neutron nuclear distribution → Weak nuclear distribution

(Large cross section: $\propto N^2$)



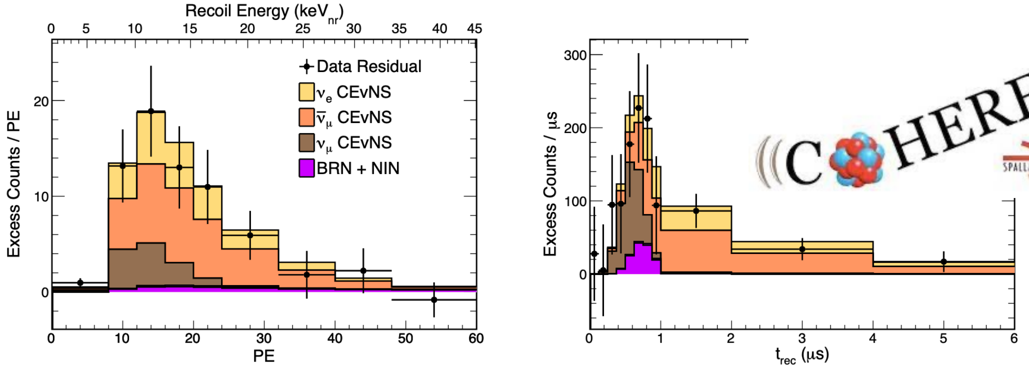
COHERENT experimental program

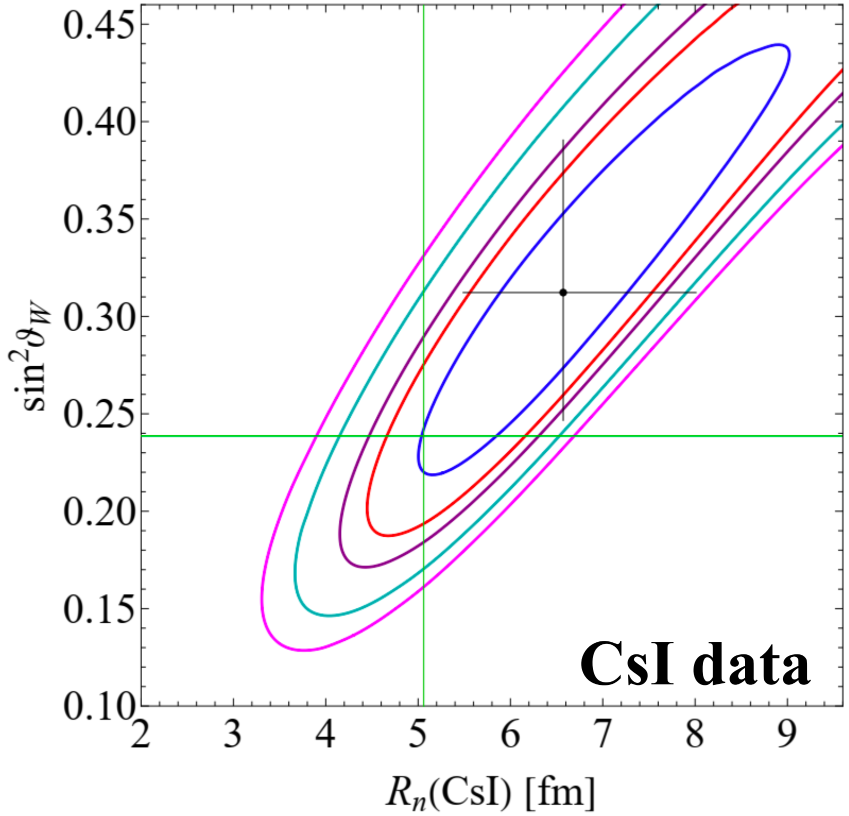
- CsI crystal: D. Akimov et al. Phys.Rev.Lett. 129 (2022) 8,081801
  - 14.6 kg scintillating crystal
  - 19.3 m away from the SNS target
  - $q \sim 50$ MeV
  - $\sim$**11%** on $\sin^2\theta_W$
  - $\sim$**7%** on $R_n(Cs)$ NC et al., Eur.Phys. C 83 (2023) 7,685
  - Future detector $\sim$**0.5%** on $R_n(Cs)$

COHERENT cannot provide (yet) a simultaneous determination of $\sin^2\theta_W$ and $R_n(Cs)$ with competitive precision

Need for a complementary probe to disentangle the two parameters!

- Ar single phase: D. Akimov et al. Phys.Rev.Lett. 126 (2021) 1, 012002
  - 24 kg of atmospheric argon
  - 27.5 m away from the SNS target
  - $q \sim 50$ MeV
  - Worse precision

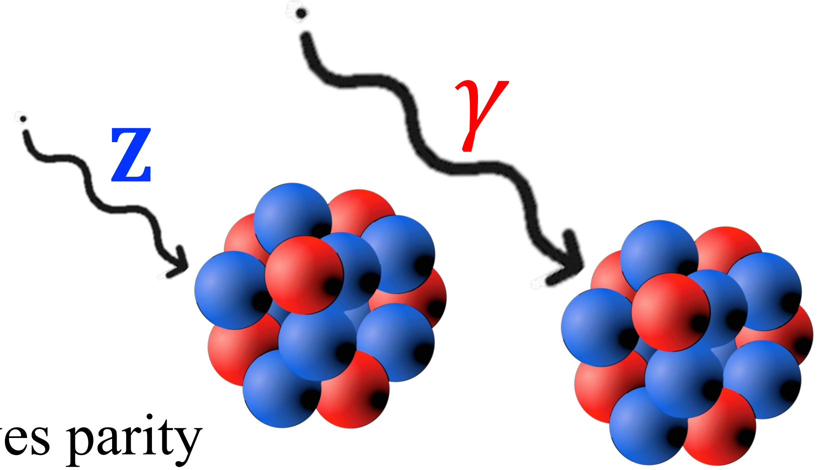




NC et al., Eur.Phys. C 83 (2023) 7,685

Parity Violating Systems

Electrons normally interact with nuclear matter via photon exchange (EM interaction)
But there is also a subdominant weak contribution to the interaction



We need to select the weak part of the interaction :

Parity Violation

- The electromagnetic interaction preserves parity
- The weak interaction violates parity

We need to isolate parity-violating contributions

Atomic transitions forbidden by selection rules (APV)

- For atomic experiments

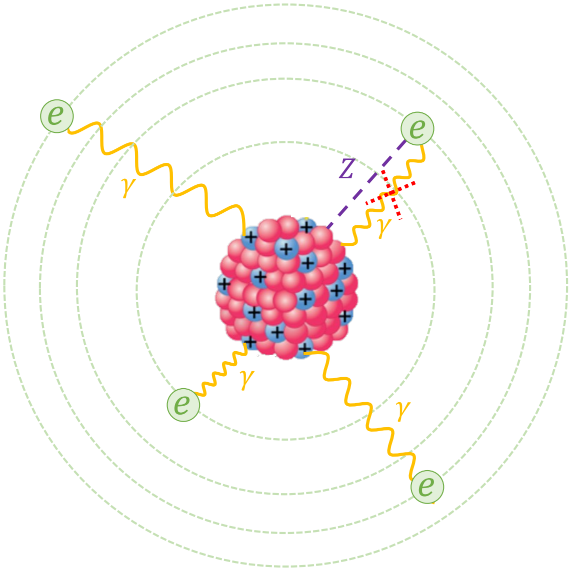
Polarized electron scattering (PVES)

- For scattering experiments

Atomic systems: APV

APV experiments measure the weak mixing angle at very low momentum transfer via electronic transitions which are forbidden by selection rules: they violate parity

We consider the APV measurement on **cesium-133** and on **lead-208**

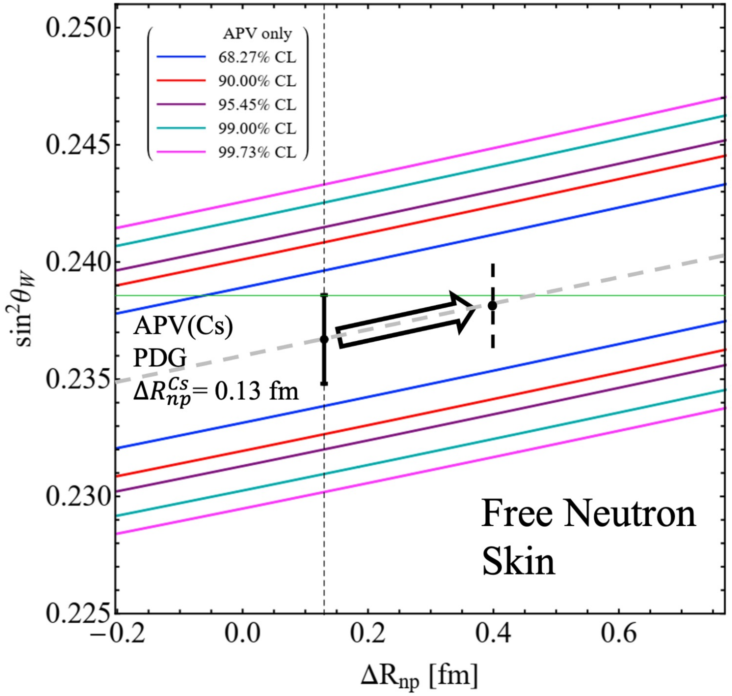


Interaction Hamiltonian	$\hat{h}_{SI} = \frac{G_F}{2\sqrt{2}} Q_W \rho_{wk}(r) \gamma_5$
	Evaluated between the involved atomic states Parity-violating amplitude* E_{PNC}
Nuclear weak charge	$Q_W^{APV}(R_n) = N \left(\frac{\mathrm{Im}\, E_{PNC}(R_n)}{Q_{weak}}\right)_{exp} \left(\frac{Q_{weak}}{N\, \mathrm{Im}\, E_{PNC}(R_n)}\right)_{th} \beta_{exp+th}$

To be compared to the value of the nuclear weak charge calculated in the SM: dependence on $\sin^2(\vartheta_W)$

*There are different atomic calculations available for Cs, we adopt
B.K. Sahoo et al. Phys Rev D 103, L111303 (2021) or
V. Dzuba et al., Phys. Rev. Letter 109, 203003 (2012)

Very sensitive to $\sin^2\theta_W$, not much on $R_n(Cs)$

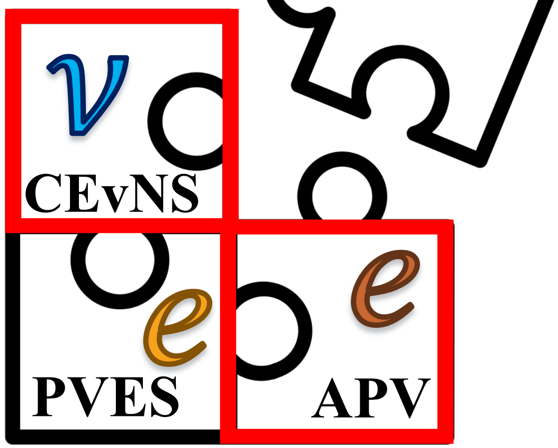


Extremely low momentum transfer $\mathbf{Q_{Cs}\sim 2.4}$ **MeV** and $\mathbf{Q_{Pb}\sim 8}$ **MeV**

Similar, but less precise, measurement on lead-208.
There are two experimental determinations available

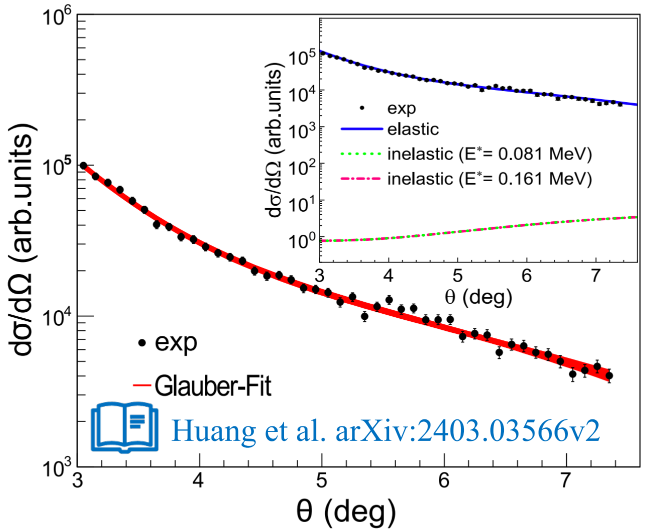
$R_{exp} = -9.80(33)\times10^{-8}$ S.J. Phipp et al. Journal of Physics B 29, 1861 (1996)
$R_{exp} = -9.86(12)\times10^{-8}$ D.M. Meekhof et al. Phys Rev Lett 71,3442 (1993)

CEvNS+APV on Cs

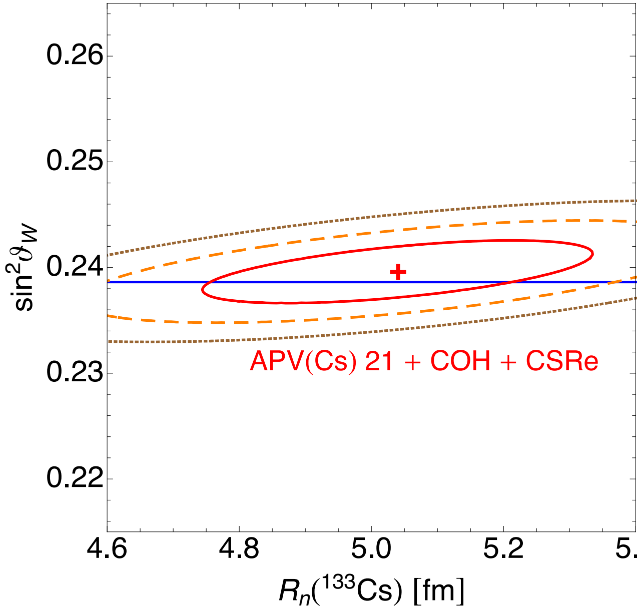


We can combine different probes to exploit different sensitivities to $\sin^2\theta_W$ and $R_n(Cs)$ (different slopes)

New direct measurement of the cesium-133 neutron skin, $\Delta R_{np}(Cs) = 0.12 \pm 0.21$ **fm** available from proton-cesium elastic scattering at the Cooler Storage Ring (CSRe)



Huang et al. arXiv:2403.03566v2



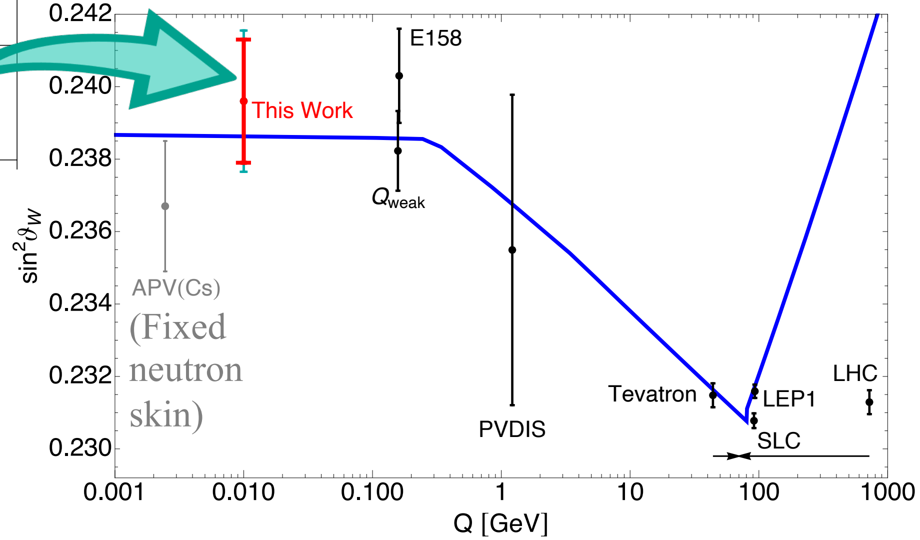
NC et al., Phys. Rev. D 110 (2024) 3, 033005

Meas.	R_n(Cs) [fm]	$\sin^2\vartheta_W$
APV(Cs) 21 + COH + CSRe	$5.04^{+0.19}_{-0.19}$	$0.2396^{+0.0020}_{-0.0019}$

The precision improves significantly by combining the available probes on **Cs**

- **~3.8%** on $R_n(Cs)$
- **~8%** on $\sin^2\theta_W$

See M. Atzori Corona's poster!



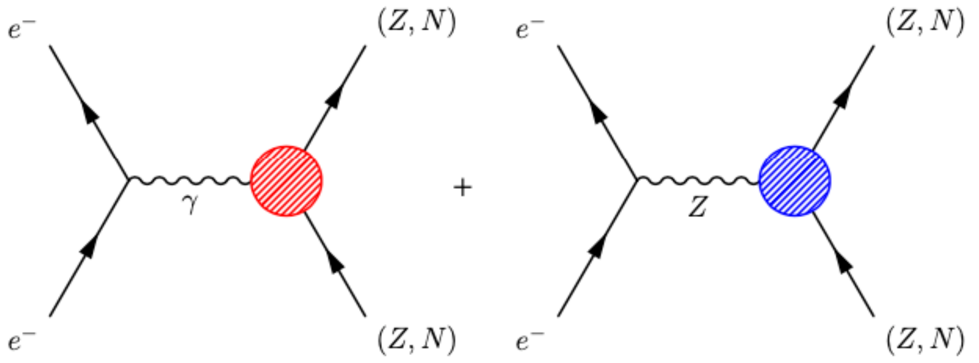
NC et al., Phys. Rev. D 110 (2024) 3, 033005

Electron scattering: PVES

In the case of electron-nucleon scattering:

$$\sigma_{\mathrm{TOT}} \propto |\mathcal{A}_{\mathrm{EM}} + \mathcal{A}_{\mathrm{wk}}|^2 \propto |\mathcal{A}_{\mathrm{EM}}|^2 + \underbrace{|\mathcal{A}_{\mathrm{wk}}|^2}_{\text{negligible}} + 2|\mathcal{A}_{\mathrm{EM}}| \cdot |\mathcal{A}_{\mathrm{wk}}|$$

Electromagnetic Diagram **Weak Diagram**



We can isolate the weak contribution by polarizing the electron beam

- **Parity-violating asymmetry in the case of scattering**

$$A_{\mathrm{pv}} = \frac{\sigma^{\uparrow}_{\mathrm{TOT}} - \sigma^{\downarrow}_{\mathrm{TOT}}}{\sigma^{\uparrow}_{\mathrm{TOT}} + \sigma^{\downarrow}_{\mathrm{TOT}}} \propto \frac{|\mathcal{A}^{\uparrow}_{\mathrm{EM}}| \cdot |\mathcal{A}^{\uparrow}_{\mathrm{wk}}|}{|\mathcal{A}^{\uparrow}_{\mathrm{EM}}|^2} = \frac{|\mathcal{A}^{\uparrow}_{\mathrm{wk}}|}{|\mathcal{A}^{\uparrow}_{\mathrm{EM}}|} \Longrightarrow A_{\mathrm{pv}} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \frac{Q_W}{Z} \frac{F_{\mathrm{wk}}(q^2)}{F_{\mathrm{ch}}(q^2)}$$

Nuclear weak charge (Q_W)

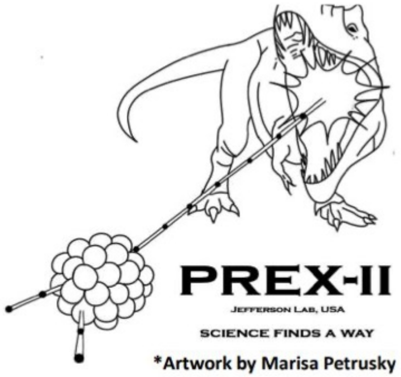
Weak form factor ($F_{\mathrm{wk}}(q^2)$)

Charge form factor ($F_{\mathrm{ch}}(q^2)$) — Known through electromagnetic measurements!

> This definition works in the plane wave Born approximation: we need to account for Coulomb distortions

> Similarly to CEvNS, the nuclear weak charge and the weak form factor enter as a product in the observable

PVES on heavy nuclei

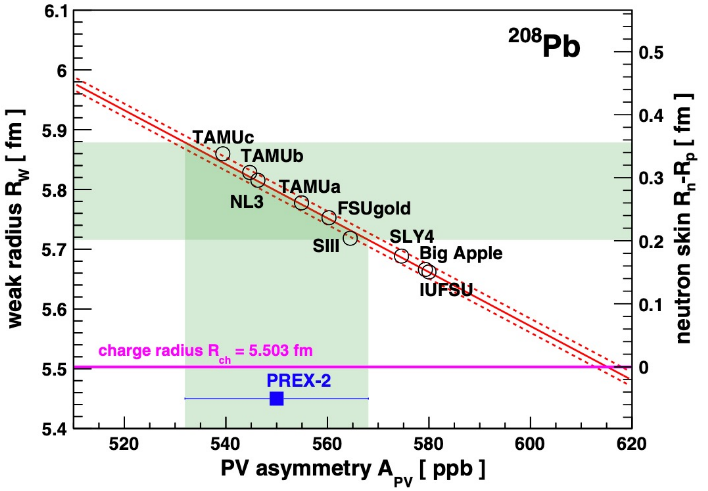


We can consider the PREX measurement of the lead-208 neutron skin

1 GeV polarized electrons scattered at $\theta \sim 5°$ ($q \sim 80$ MeV)

First measurement in 2012, updated one in 2021

S. Abrahamyan et al., Phys. Rev. Lett. 108.112502 (2012)
D. Adhikari et al., Phys. Rev. Lett. 126.172502 (2021)



Measured the neutron skin of lead with unprecedented precision:

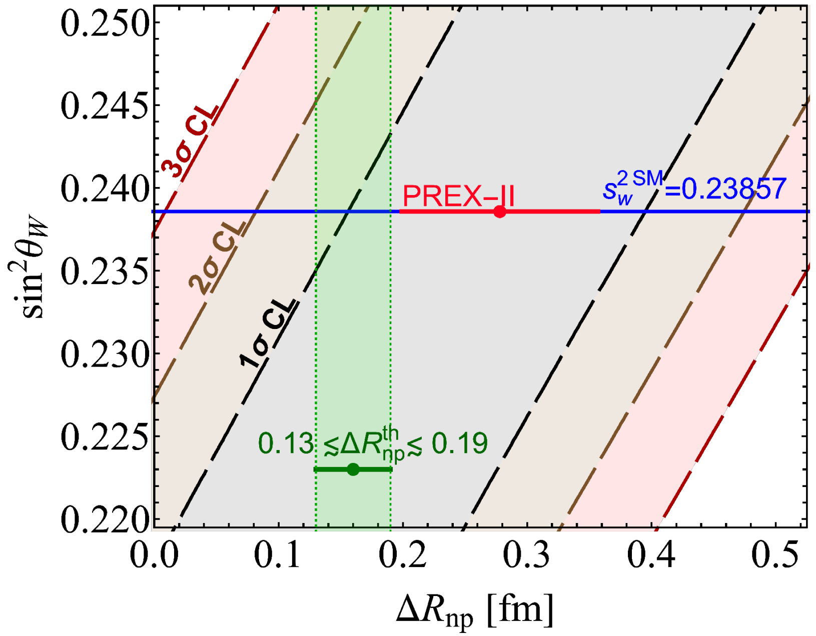
$$\Delta R_{np}(\text{Pb}) = 0.278 \pm 0.078(exp) \pm 0.012\ (th)\ \text{fm}$$

PREX found a rather thick neutron skin compared with EDF predicted values

$$\Delta R_{np}^{th}(\text{Pb}) \approx 0.13 - 0.19\ \text{fm}$$

$$A_{\text{pv}} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \frac{Q_W}{Z} \frac{F_{\text{wk}}(q^2)}{F_{\text{ch}}(q^2)}$$

What is the impact of the weak mixing angle?

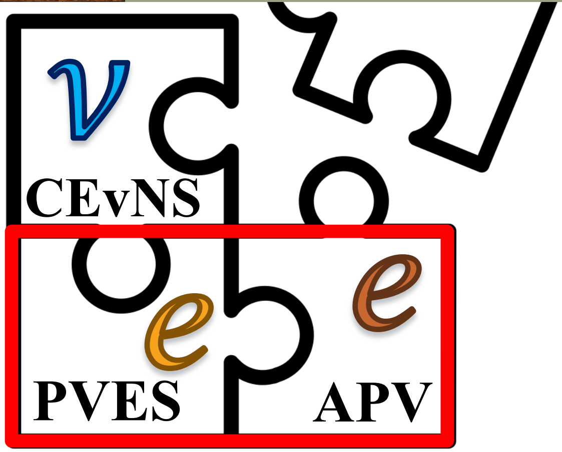


NC et al., Phys.ReV.C 105 (2022) 5, 055503

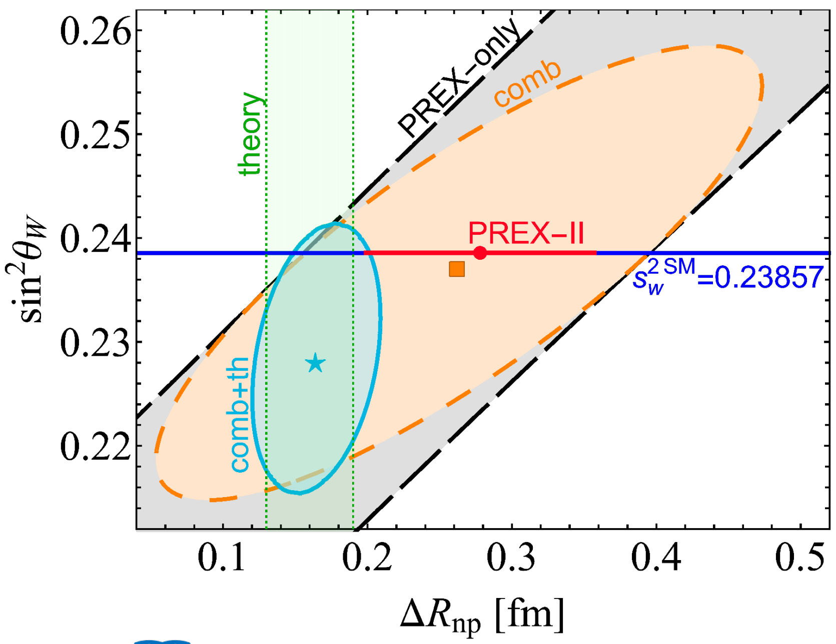
The PREX measurement is degenerate in the plane ΔR_{np}(Pb) vs $\sin^2\theta_W$

Lower values of the weak mixing angle result in larger values of the nuclear weak charge, and thus the fit gives lower neutron skin values

PVES + APV



- PREX alone is degenerate in the plane $\Delta R_{np}(\mathrm{Pb})$ vs $\sin^2\theta_W$
- We exploit the very different dependence on the two free parameters for the different probes: PVES and APV(Pb)
- PVES is sensitive to the neutron skin more than to the weak mixing angle
- APV is sensitive to the weak mixing angle more than to the neutron skin
- It is possible to extract the two with a data-driven approach, but with poorer precision



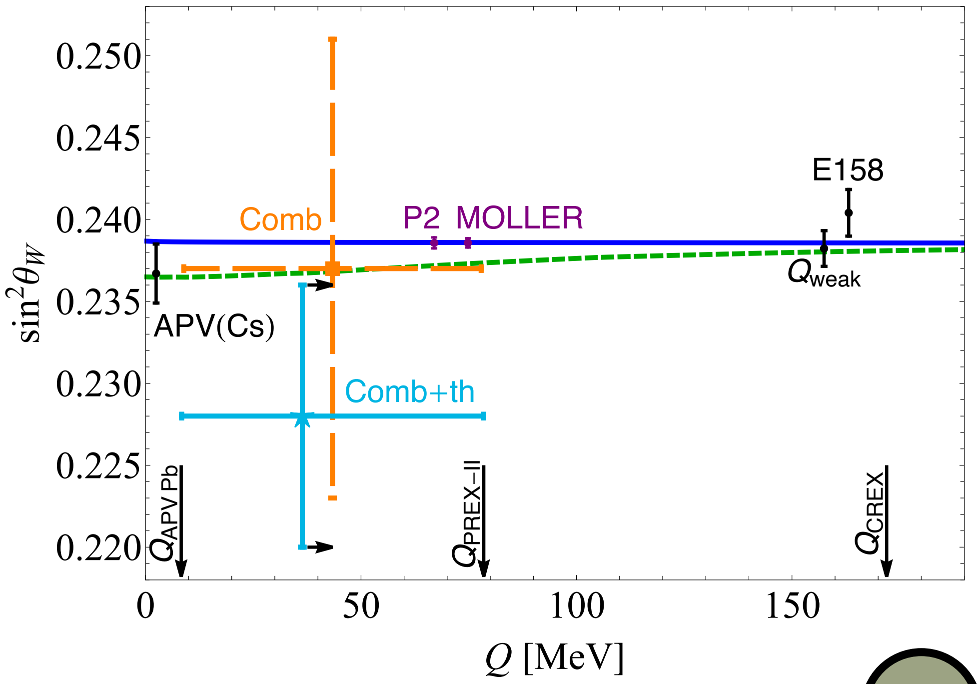
NC et al., Phys.Rev.C 105 (2022) 5, 055503

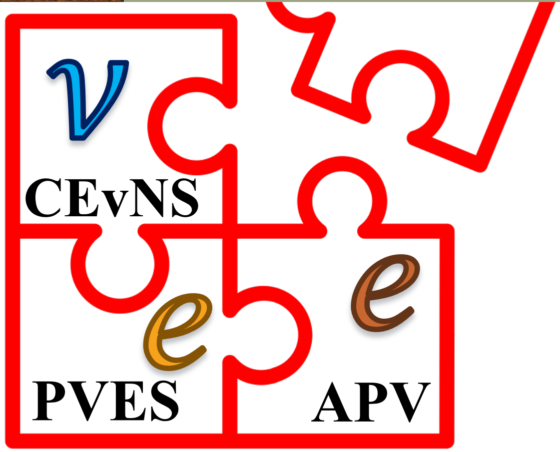
PREX-II+APV(Pb)

$$\Delta R_{np} = 0.262 \pm 0.136 \text{ fm}$$
$$\sin^2\theta_W = 0.237 \pm 0.014$$

PREX-II+APV(Pb)+theory

$$\Delta R_{np} = 0.164 \pm 0.029 \text{ fm}$$
$$\sin^2\theta_W = 0.228 \pm 0.008$$





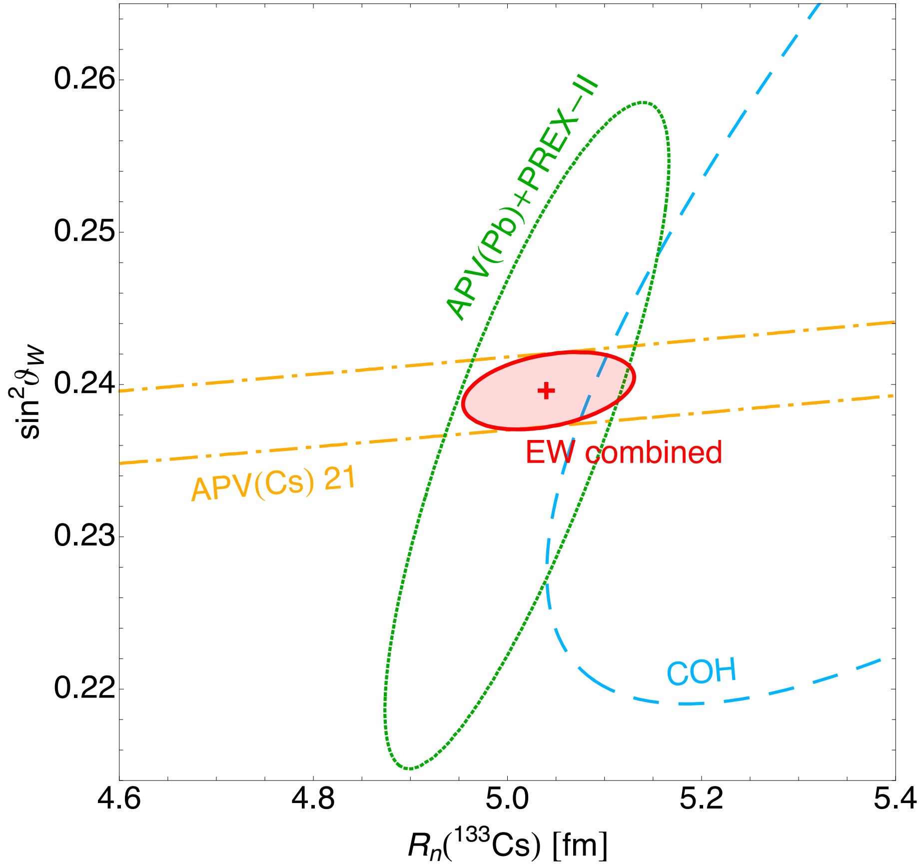
Toward a Global Analysis:

By exploiting a trend in the predictions from mean field models of $\boldsymbol{R_n}$(**Pb**) and $\boldsymbol{R_n}$(**Cs**), we can translate a measurement on lead into a measurement on cesium

Relying on the input from theoretical models

Meas.	R_n(Cs) [fm]	$\sin^2\vartheta_W$
APV(Cs) 21 + COH + CSRe	$5.04^{+0.19}_{-0.19}$	$0.2396^{+0.0020}_{-0.0019}$
APV(Cs) 21 + COH + PREX + APV Pb	$5.041^{+0.058}_{-0.057}$	$0.2396^{+0.0017}_{-0.0017}$

NC et al., Phys. Rev. D 110 (2024) 3, 033005



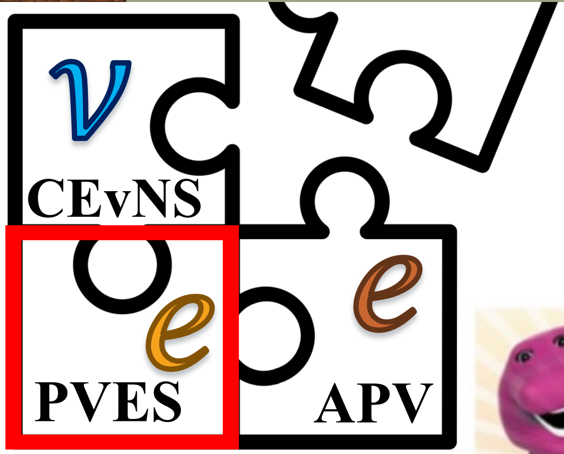
NC et al., Phys. Rev. D 110 (2024) 3, 033005

The precision improves slightly by combining the available probes on **Cs** with the ones on **Pb**

- ∼**1.2%** on $R_n(Cs)$
- ∼**7%** on $\sin^2\theta_W$

The EW combined analysis gives practically the same results of the Cs only fit

PVES + Qweak



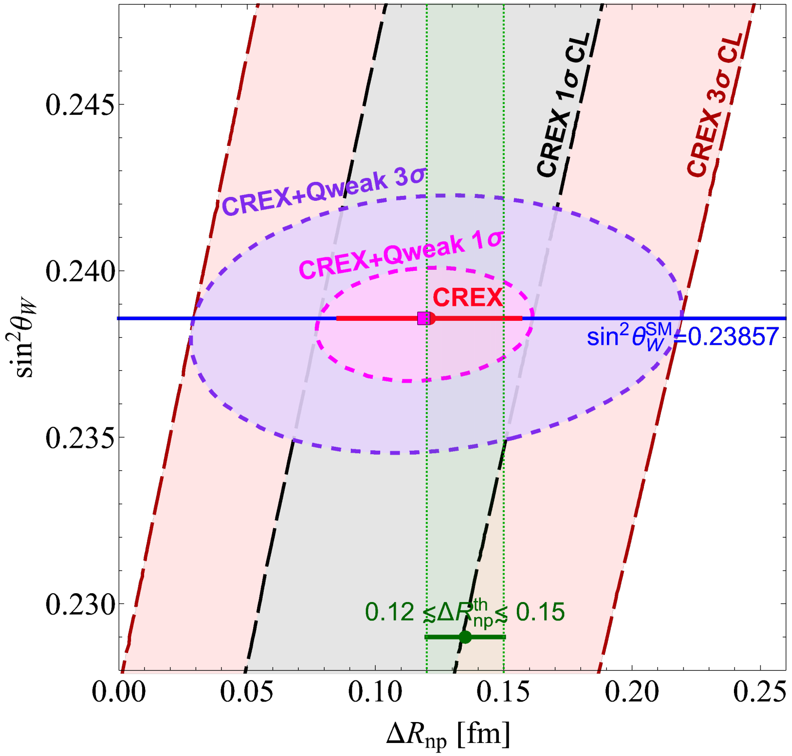
CREX: PVES on calcium-48 D. Adhikari et al., Phys. Rev. Lett. 129.042501(2022)

2.1 GeV polarized electrons on a calcium-48 target scattered at $\theta \sim 5°$ (higher momentum transfer $q \sim 170$ MeV)

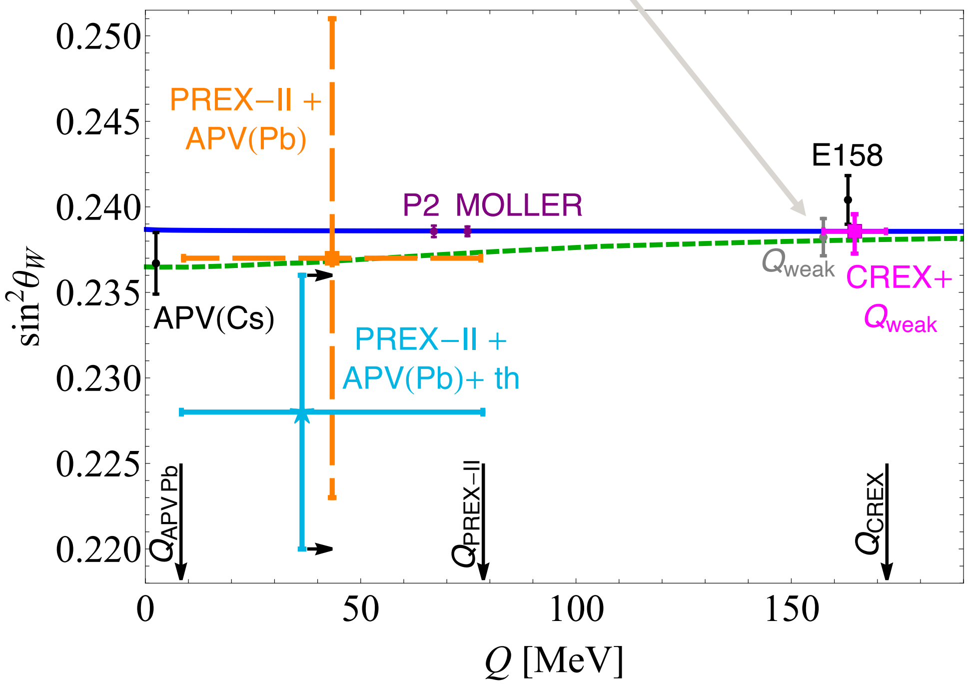
Only one measurement released in 2021

CREX+Qweak

$$\Delta R_{np} = 0.119 \pm 0.028 \text{ fm}$$
$$\sin^2\theta_W = 0.2386 \pm 0.0013$$

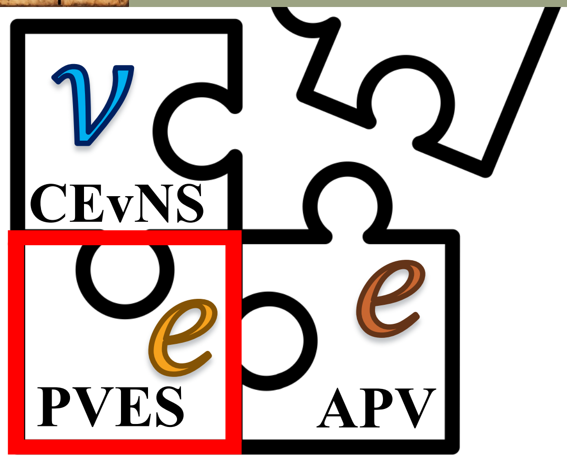


$$Q_p(\sin^2\theta_W) = -2(g_{AV}^{ep}(\sin^2\theta_W))\left(1 - \frac{\alpha}{2\pi}\right)$$



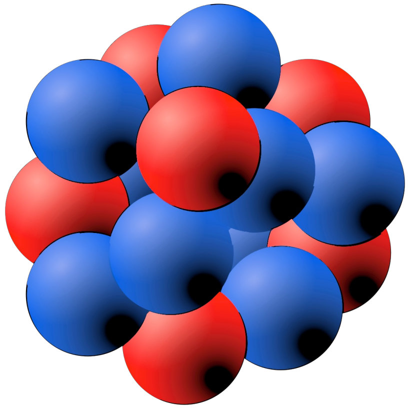
- Qweak sets a horizontal band which breaks the degeneracy of CREX (preserving the precision)
- CREX and PREX point toward different directions!

PVES on light nuclei



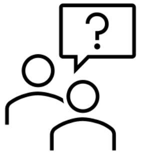
- PVES on heavy nuclei is used to extract information on the neutron skin (i.e. PREX and CREX experiments)
- PVES on light objects, such as the proton or the electrons has been used to measure the weak mixing angle (i.e. Qweak and E158 experiments)

What happens by performing a PVES measurement on a light nucleus?

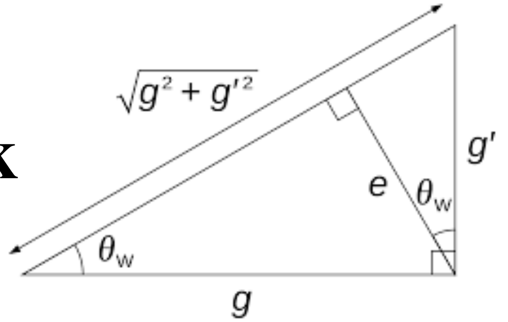


Nuclear Structure test through the neutron skin

OR/AND



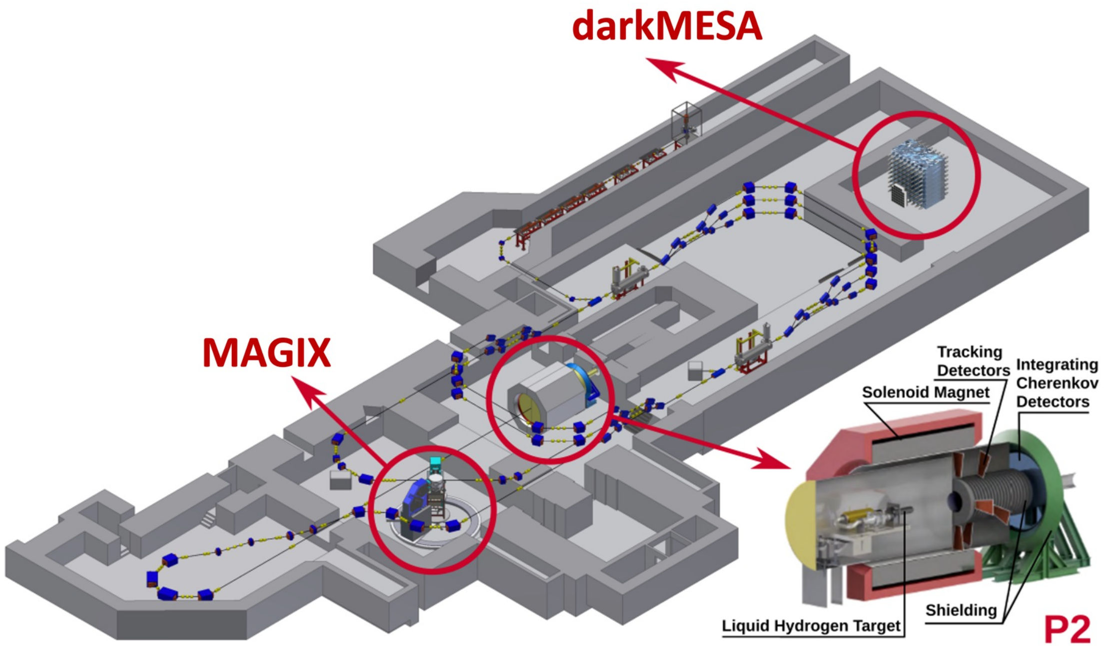
Electroweak test through the weak mixing angle



Using light nuclei, there is no need to reach high electron energies (hundreds of MeV instead of GeV electrons): MESA Facility represent a unique opportunity

MESA facility

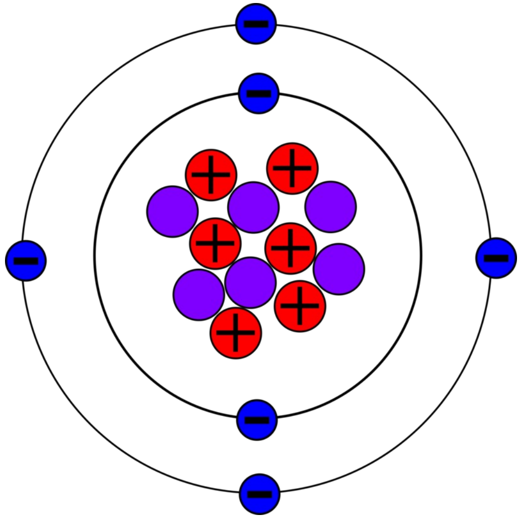
Work in Collaboration with M. Cadeddu, J. Erler, M. Gorchtein, J. Piekarewicz, X. Roca-Maza and H. Spiesberger



D. Becker et al., Eur.Phys.J. A 54, 208 (2018)

- Mainz Energy-recovering Superconductive Accelerator
- MESA facility: **155 MeV** polarized electrons on a carbon-12 target and then collected with the P2 spectrometer
- Two detection systems:
  - forward measurement at $\boldsymbol{\theta} = \mathbf{29°}$ $\left(Q_f^{155} \sim 78\text{ MeV}\right)$
  - backward at $\boldsymbol{\theta} = \mathbf{145°}$ $\left(Q_b^{155} \sim 290\text{ MeV}\right)$

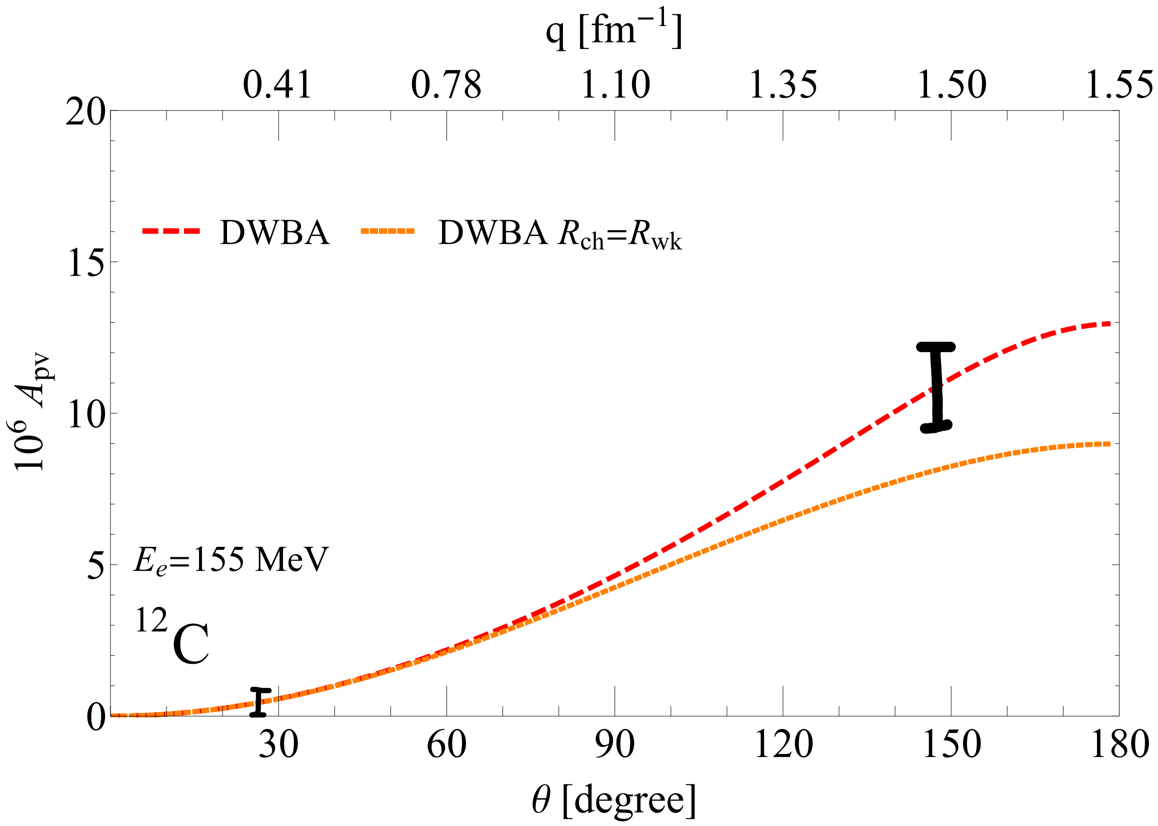
Z=6 **N=6**



- Particular system: much **lighter** than lead and calcium
- The neutron skin is expected to be close to zero and negative
- Coulomb repulsion as dominant effect (**proton skin**)

PVES on C-12

A preliminary study was discussed in a previous publication — O. Koshchii et al., Phys. Rev. C 102, 022501 (2020)

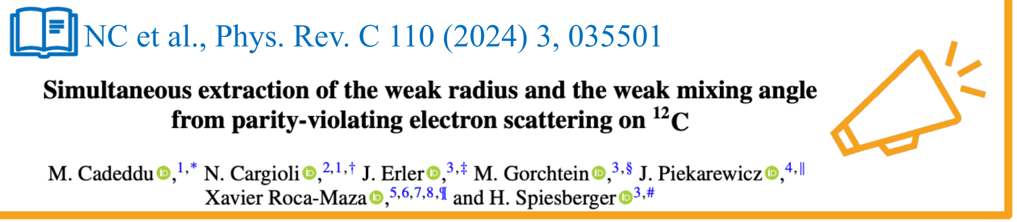


Feasibility study for the **simultaneous** extraction of the weak mixing angle and the weak skin of carbon-12

WEAK SKIN $\Delta R_{wk,skin} = R_{wk} - R_{ch}$

At MESA, the form factor will be measured at two **different energies** within the same experiment

- Forward is more sensitive to the weak mixing angle
- Backward is more sensitive to the weak skin



PHYSICAL REVIEW C **110**, 035501 (2024)

NC et al., Phys. Rev. C 110 (2024) 3, 035501

Simultaneous extraction of the weak radius and the weak mixing angle from parity-violating electron scattering on ^{12}C

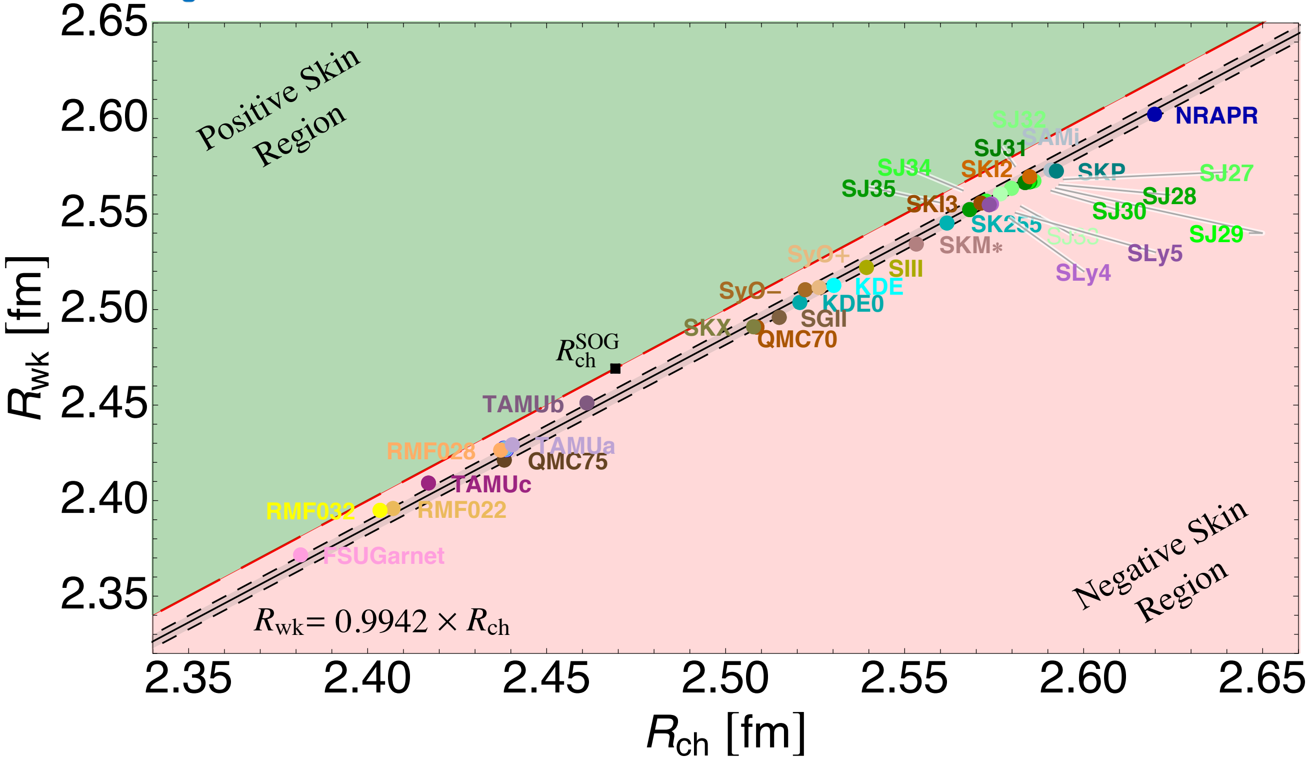
M. Cadeddu[1,*] N. Cargioli[2,1,†] J. Erler[3,‡] M. Gorchtein[3,§] J. Piekarewicz[4,∥] Xavier Roca-Maza[5,6,7,8,¶] and H. Spiesberger[3,#]

What does the theory say about C-12?

- The charge radius of C-12 is known to a certain extent
- $R_{ch}^{SOG} = 2.469(5)$ fm

  H. De Vries et al., At. Data Nucl. Data Tables 36, 495 (1987)
- Mean Field Models:
  - Predict both the weak and charge radius in a consistent way
  - We should not use only part of the information (weak radius) but account also for correlations
  - Predictions for charge and weak radii show a common trend

NC et al., Phys. Rev. C 110 (2024) 3, 035501



A rather large spread in R_{ch} (and R_{wk}) is observed, while the skin remains rather stable!

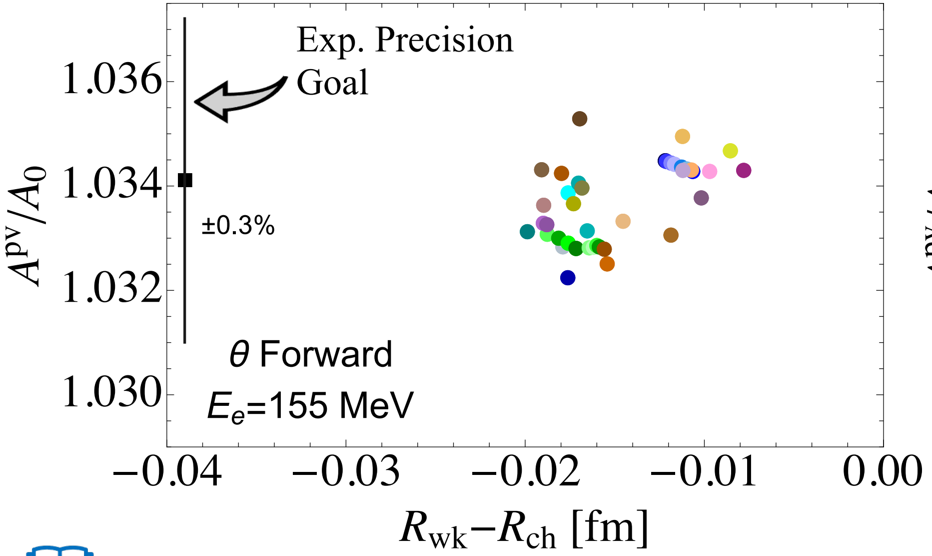
However, the experimental observable is the asymmetry

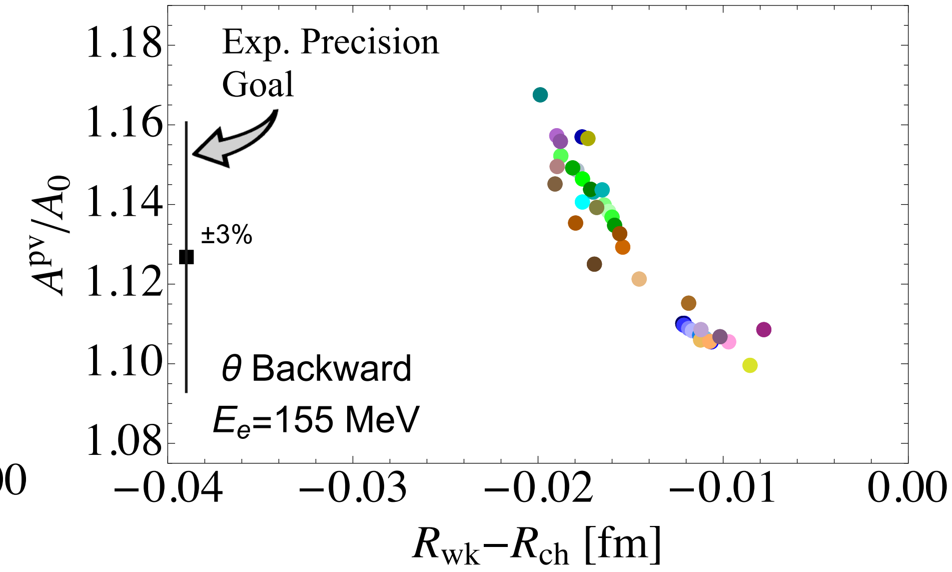
At forward angle:

- The predictions are “randomly”scattered
- The overall vertical spread is small

At Backward angle:

- The predictions are scattered showing a general trend as a function of the weak skin
- The overall vertical spread is non-negligible



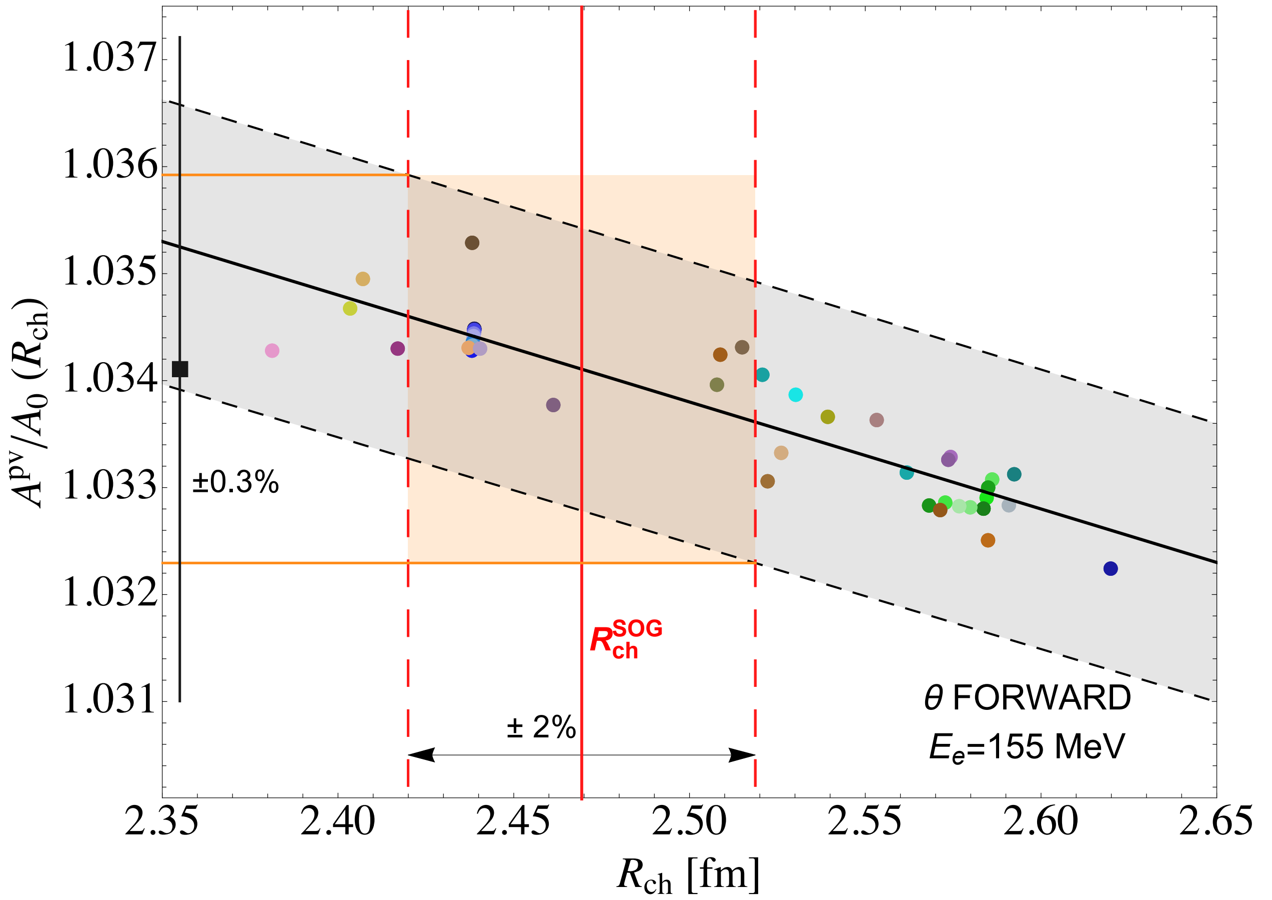


NC et al., Phys. Rev. C 110 (2024) 3, 035501

The Forward measurement is practically independent of the nuclear structure contribution, but how small is the contribution?

- The prediction for the asymmetry at forward angle shows a trend as a function of the charge radius
- We can assume a simple linear function and fit the predictions to obtain a correlation function
- The charge radius is measured
- We can define a confidence region around the measured charge radius to project it toward a range of values for the asymmetries
- The estimated uncertainty due to nuclear structure affecting the forward measurement is ~0.2% (below the precision goal)

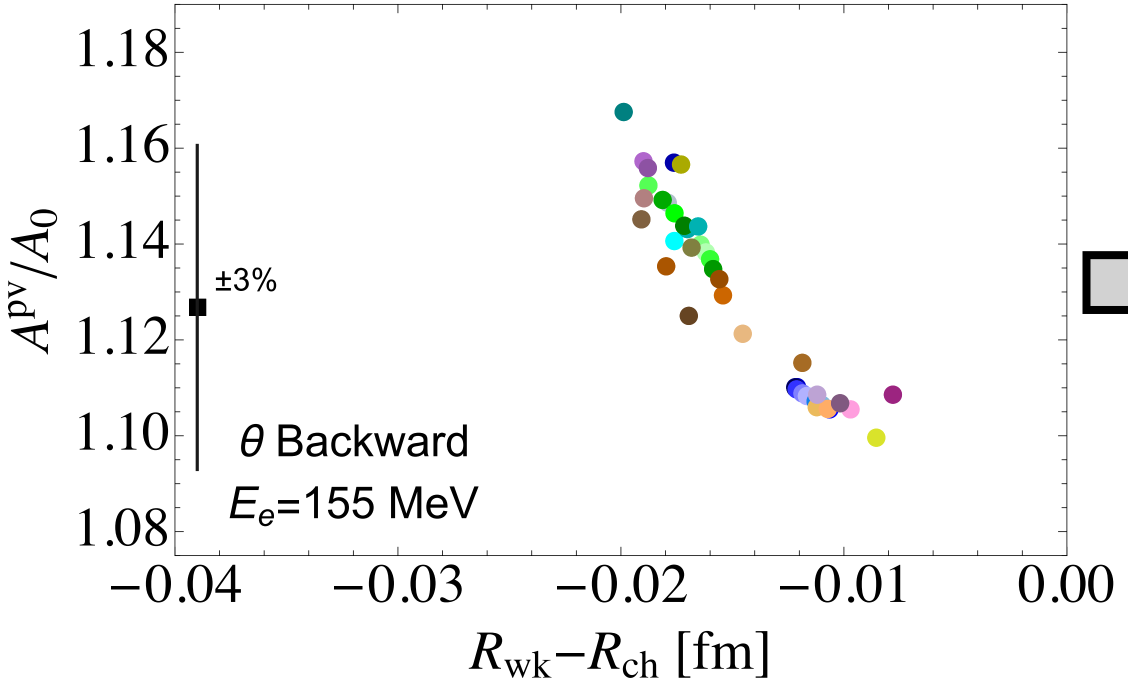
NC et al., Phys. Rev. C 110 (2024) 3, 035501

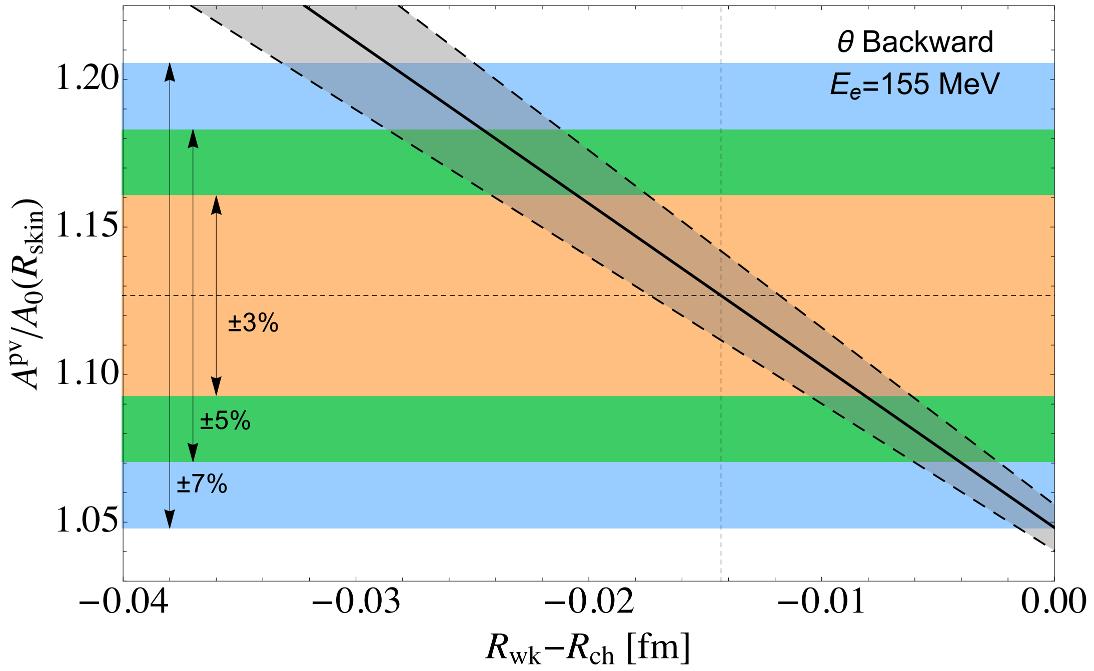


The Backward measurement depends on the nuclear structure contribution

- We fit the prediction using a linear function:
  - $\mathcal{A}_b^{pv}(R_{wskin}) = \mathcal{A}R_{wskin} + \mathcal{B}$

We can use this function to estimate the prediction for the backward asymmetry as a function of the weak skin





NC et al., Phys. Rev. C 110 (2024) 3, 035501

To explore the sensitivity we built the following chi-square function

Forward asymmetry prediction, the dependence on $\sin^2\theta_W$ is explicitly inserted by rescaling the weak charge

Backward asymmetry prediction which depends on both the weak mixing angle and the weak skin

$$\chi^2 = \left(\frac{A_f^{\mathrm{PV,ref}} - \eta_1 A_f^{\mathrm{PV}}(\sin^2\theta_W)}{\epsilon_f}\right)^2 + \left(\frac{A_b^{\mathrm{PV,ref}} - A_b^{\mathrm{PV}}(\eta_2, \sin^2\theta_W, R_{\mathrm{wk}})}{\sigma_b}\right)^2 + \left(\frac{\eta_1 - 1}{\sigma_{\eta_1}}\right)^2 + \eta_2^2,$$

$$A_b^{\mathrm{PV}}(\eta_2, \sin^2\theta_W, R_{\mathrm{wk}}) = \frac{Q_W(\sin^2\theta_W)}{Q_W^{\mathrm{SM}}} \times [(\mathcal{A} + \eta_2\sigma_{\mathcal{A}})R_{\mathrm{wskin}} + \mathcal{B}].$$

Experimental precision goal for the forward measurement

Nuisance parameter introduced to account for the uncertainty due to nuclear structure affecting the forward prediction

Accounts for the experimental precision for the backward measurement and the uncertainty on the intercept $\mathcal{B}$

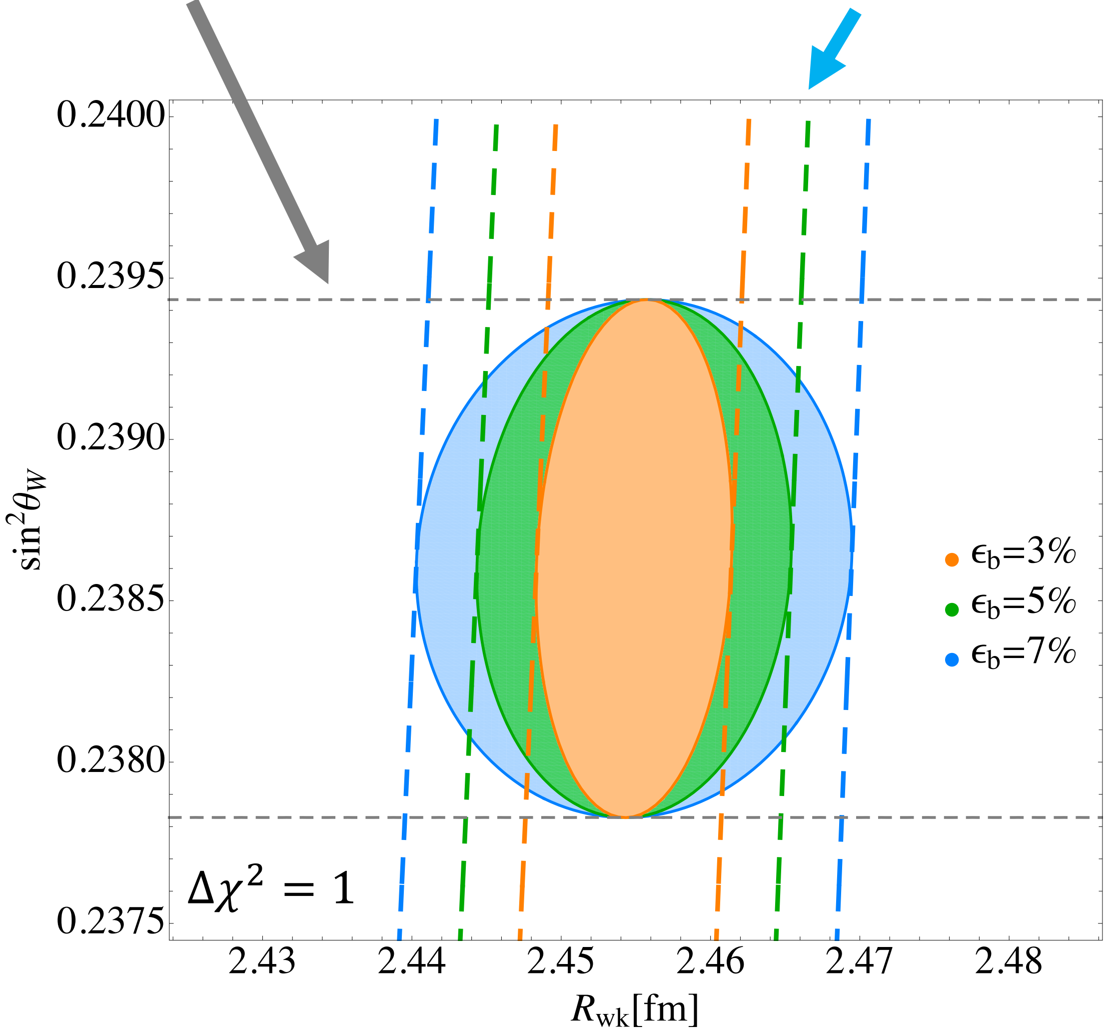
Nuisance parameter relative to the slope of the linear function $\mathcal{A}$ describing the backward prediction

NC et al., Phys. Rev. C 110 (2024) 3, 035501

PVES on C-12

Forward only sensitivity

Backward only sensitivity



NC et al., Phys. Rev. C 110 (2024) 3, 035501

- Forward: Horizontal band, establishes the sensitivity to the **weak mixing angle**
- Backward: Almost vertical band, establishes the sensitivity to the **weak radius** but it is marginally dependent on the weak mixing angle
- We consider different backward precision scenarios

ϵ_f	ϵ_b	R_{wk} [fm]	$\sigma_{R_{wk}}$ [%]	$\sin^2\theta_W$
0.3%	3%	2.455 ± 0.008	0.34%	0.2386 ± 0.0008
0.3%	5%	2.455 ± 0.012	0.48%	0.2386 ± 0.0008
0.3%	7%	2.455 ± 0.016	0.63%	0.2386 ± 0.0008

PVES on C-12

ϵ_f	ϵ_b	$R_{\rm wk}$ [fm]	$\sigma_{R_{\rm wk}}$ [%]	$\sin^2\theta_W$
0.3%	3%	2.455 ± 0.008	0.34%	0.2386 ± 0.0008
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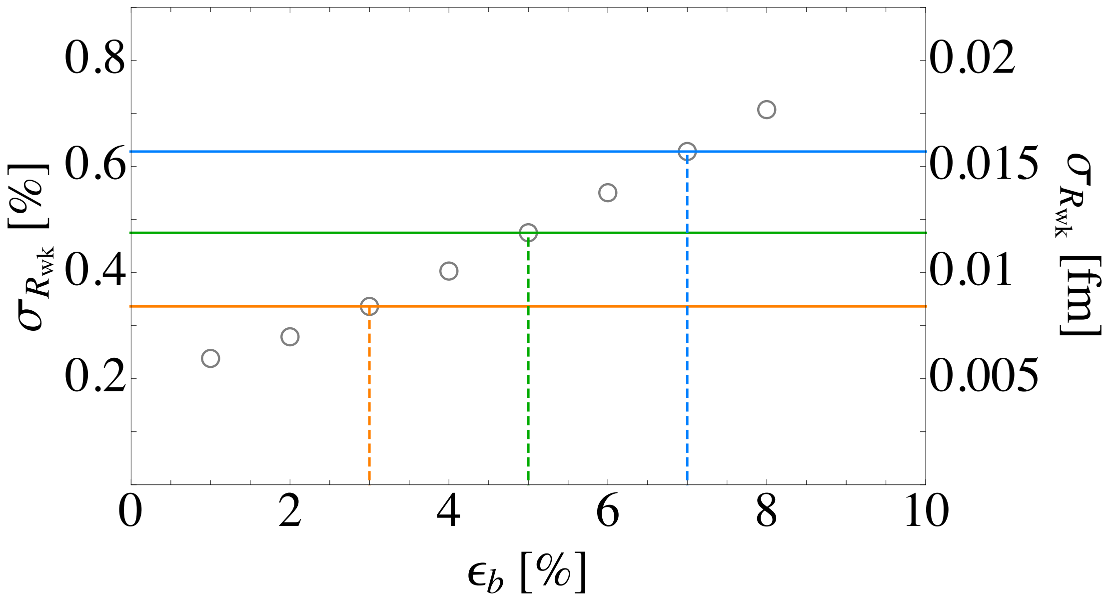
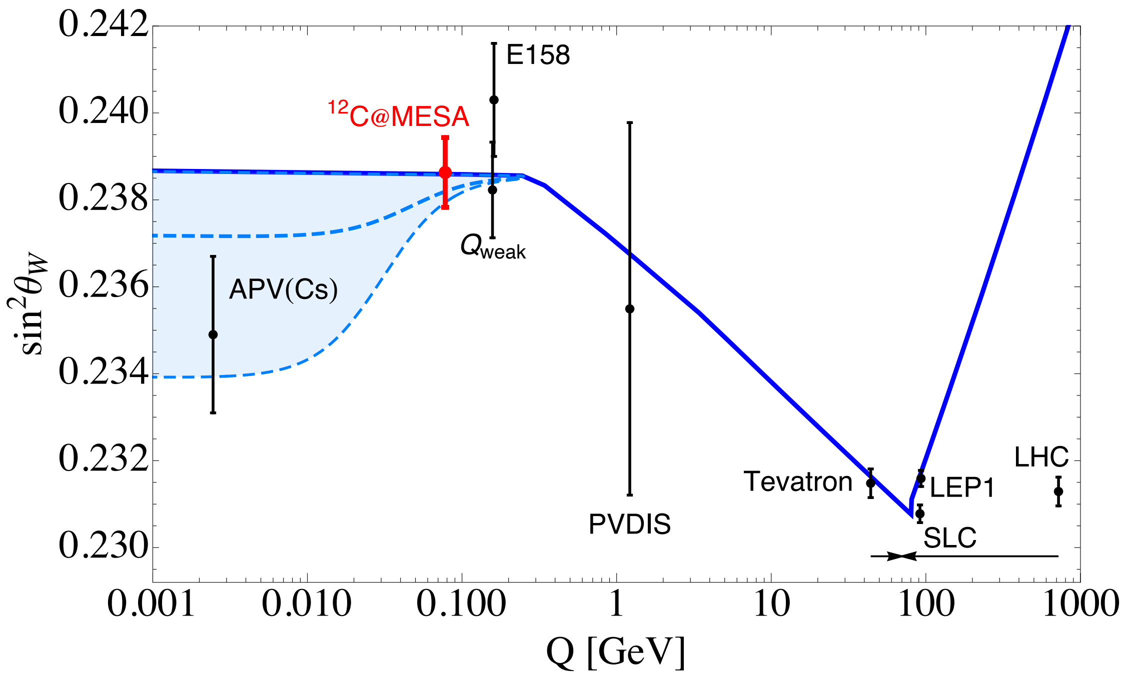
NC et al., Phys. Rev. D 104, L011701 (2021)
H. Davoudiasl et al., Phys. Rev. D 85, 115019 (2012)
H. Davoudiasl et al., Phys. Rev. D 86, 095009 (2012)
H. Davoudiasl et al., Phys. Rev. D 88, 015022 (2013)

It would represent the first electroweak determination of the weak radius and potentially first «proton skin» determination

Unique sensitivity to the weak mixing angle ~0.3% at a crucial momentum transfer: where light new physics could modify the weak mixing angle running



NC et al., Phys. Rev. C 110 (2024) 3, 035501



Beyond C-12

There is intent to extend the study performed on C-12 to different nuclei, in particular to the stable daughter nuclei partecipating in the superallowed nuclear β decay.

B. Ohayon, arXiv:2409.08193v2
C.Y. Seng and M. Gorchtein, Phys. Rev. C 109 (2024) 4, 045501
C.Y. Seng, Phys. Rev. Lett. 130 (2023) 15, 152501
C.Y. Seng and M. Gorchtein, Phys. Lett. B 838 (2023) 137654

Precise measurements of neutron skins → Impact on the extraction of the CKM quark mixing matrix element V_{ud}

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

There is connection between isospin-symmetry breaking corrections to the rates of superallowed nuclear β decay, δ_C and isospin-breaking sensitive combinations of electroweak nuclear radii (experimentally accessible!)

V_{ud} can be extracted from superallowed decays: $$V_{ud}{}^2 = \frac{2984.43s}{\mathcal{F}t(1+\Delta_R^V)}$$

$$\mathrm{ft}(1+\mathrm{RC}+\mathrm{ISB}) = \mathcal{F}\mathrm{t}(1+\Delta_\mathrm{R}^\mathrm{V}) = \mathrm{ft}(1+\delta_\mathrm{R}')(1-\delta_\mathrm{C}+\delta_\mathrm{NS})(1+\Delta_\mathrm{R}^\mathrm{V})$$

- ft: Experiment + Coulomb (theory)
- δ_R': QED (Brems)
- δ_C: Isospin breaking
- δ_NS: Nuclear Structure
- $\Delta_\mathrm{R}^\mathrm{V}$: Universal RC

⇒ $$V_{ud}^{0^+-0^+} = 0.9737\,(1)_{exp,\,nucl}(3)_{NS}(1)_{RC}[3]_{total}$$

The dominant uncertainty is due to nuclear structure

If isospin symmetry were exact

$M_F \to M_0 = \sqrt{2}$

Isospin symmetry is broken in nuclear states, so that in presence of ISB

$M_F^2 = M_0^2(1-\delta_C)$ MacDonald 1958

$\delta_C \sim 0.17\% - 1.6\%$ → Crucial for V_{ud} extraction

Nuclear community embarked on ab-initio δ_C calculations

δ_C can be extracted from nuclear radii: we can build ISB-sensitive combinations of radii

$$\Delta M_B^{(1)} \equiv \frac{1}{2}\left(Z_1 R_{p,1}^2 + Z_{-1} R_{p,-1}^2\right) - Z_0 R_{p,0}^2$$

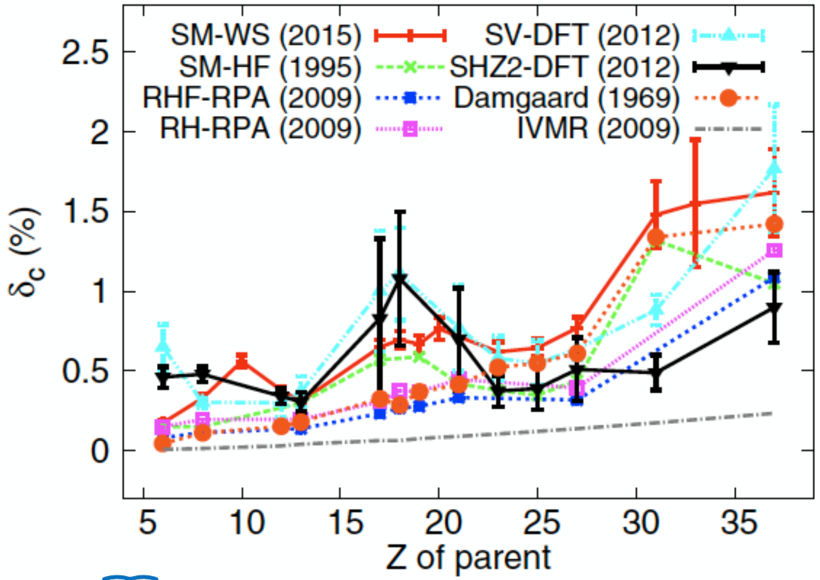
$\Delta M_B^{(1)} = 0$ used for ft-value in isospin limit

$$\Delta M_A^{(1)} \equiv -\langle r_{\mathrm{CW}}^2\rangle + \left(\frac{N_1}{2}\langle r_{n,1}^2\rangle - \frac{Z_1}{2}\langle r_{p,1}^2\rangle\right)$$

Neutron radius: measurable with PV e⁻ scattering!

B. Ohayon, arXiv:2409.08193v2
C.Y. Seng and M. Gorchtein, Phys. Rev. C 109 (2024) 4, 045501
C.Y. Seng, Phys. Rev. Lett. 130 (2023) 15, 152501
C.Y. Seng and M. Gorchtein, Phys. Lett. B 838 (2023) 137654

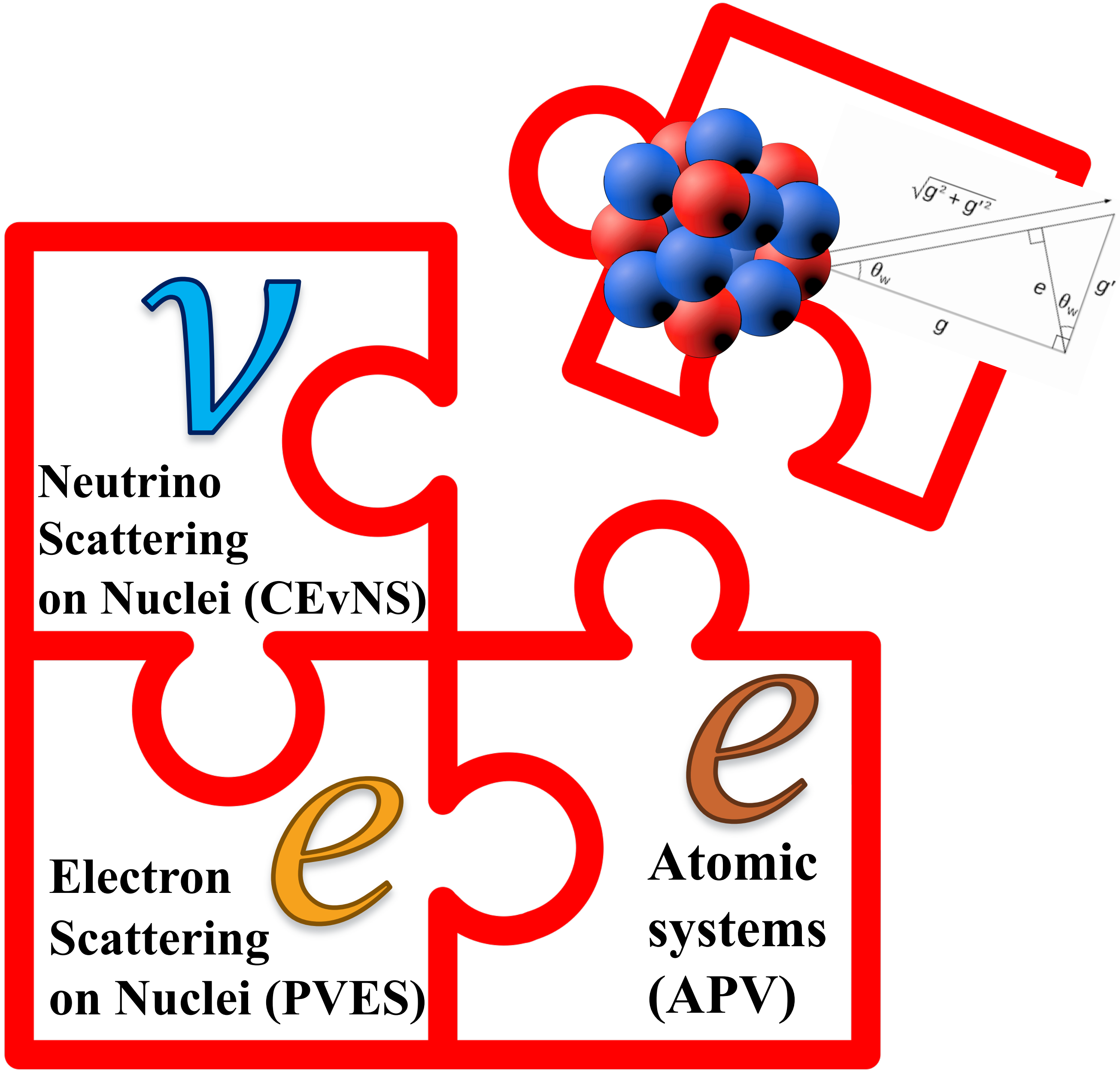
δ_C from shell models, density functionals and random phase approximation theories



L. Xayavong et al., Phys. Rev. C 97 (2018), 024324

The upcoming exp. Facility at Mainz (MESA) can be used to measure the neutron skins of stable daughters (e.g. Mg-26, Ca-42, Fe-54)

Final Remarks



- Electroweak probes represent a **powerful tool** to test the standard model theory and explore the world of nuclear matter
- The **combination** of different probes enhances the sensitivity and allows one to extract **simultaneously** the **weak mixing angle** and the **neutron skin** from available data
- A **light system** such as C-12 can provide interesting information on the weak mixing angle (**world leading precision**) and on nuclear structure in light systems (and **symmetrical** matter)
- Take away message: combine different probes and perform measurements at more energies to gain more sensitivity

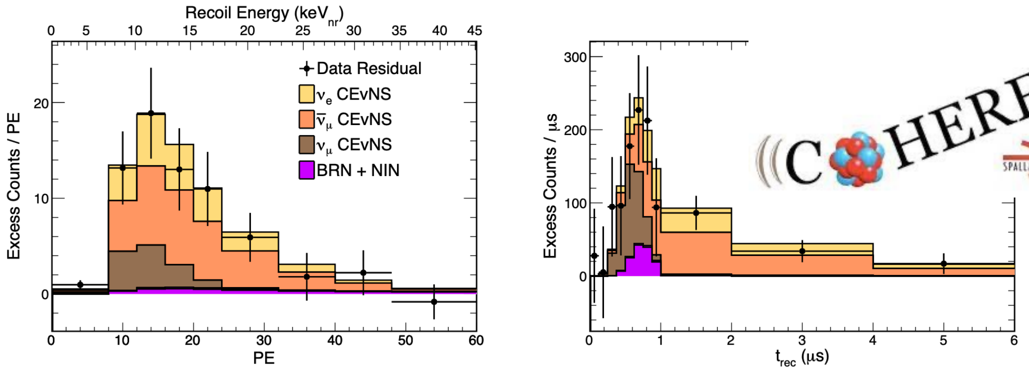
THANK YOU FOR YOUR ATTENTION

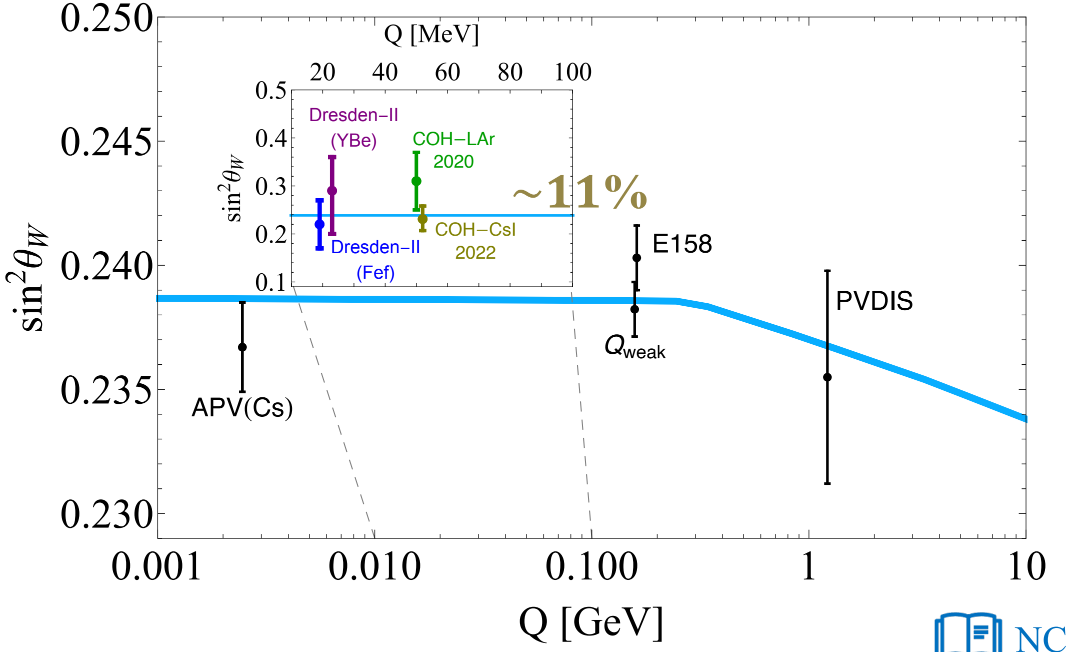
QUESTIONS TIME

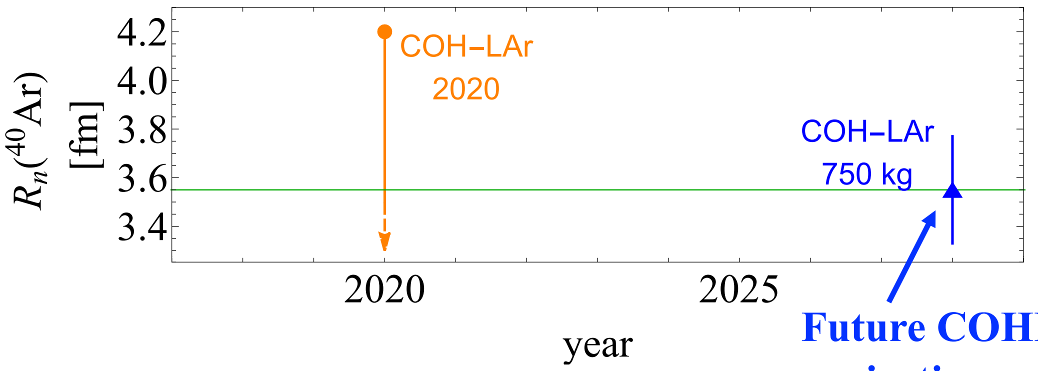
BACK UP SLIDES

COHERENT experimental program

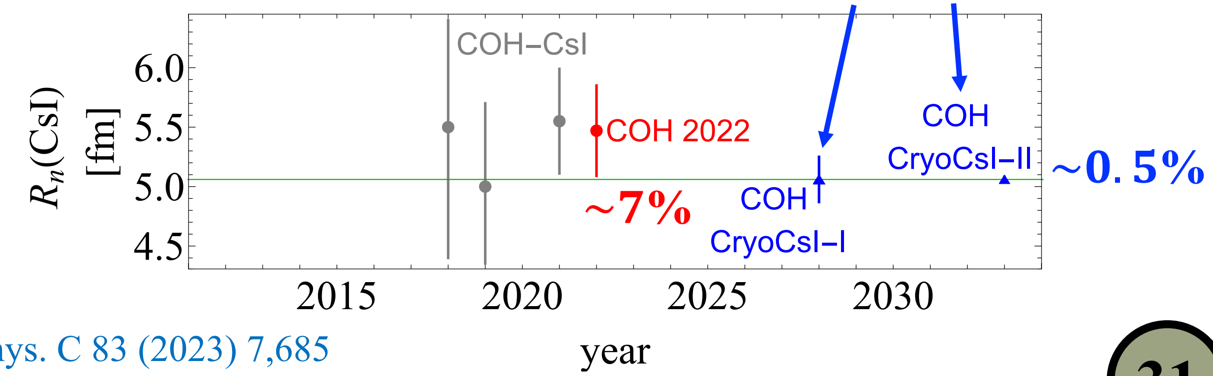
- CsI crystal: D. Akimov et al. **Phys.Rev.Lett**. 129 (2022) 8,081801
  - 14.6 kg scintillating crystal
  - 19.3 m away from the SNS target
  - $q \sim 50$ MeV
- Ar single phase: D. Akimov et al. **Phys.Rev.Lett.** 126 (2021) 1, 012002
  - 24 kg of atmospheric argon
  - 27.5 m away from the SNS target
  - $q \sim 50$ MeV







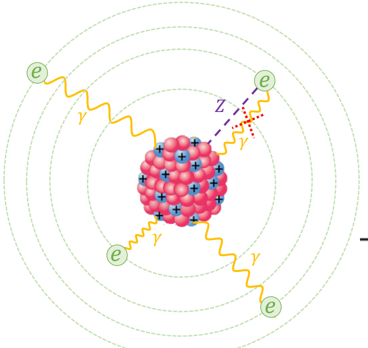
Future COHERENT projections



NC et al., Eur.Phys. C 83 (2023) 7,685

Atomic systems: APV

APV experiments measure the weak mixing angle at very low momentum transfer (few MeVs) via electronic transitions which are forbidden by selection rules: they violate parity

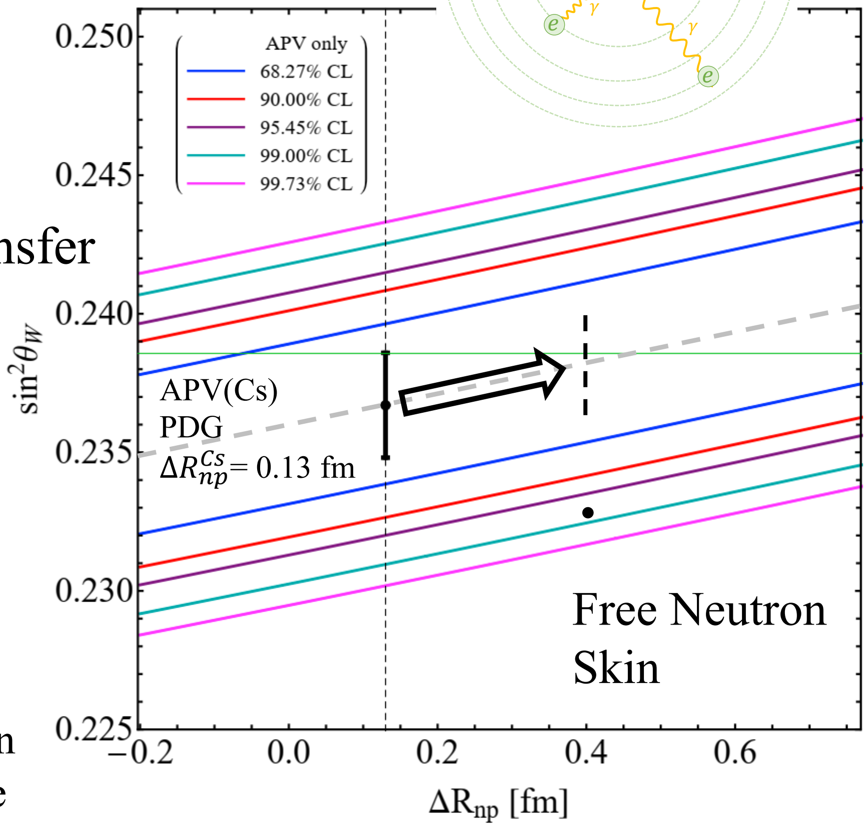


We consider the APV measurement on **cesium-133**

Interaction Hamiltonian	$\hat{h}_{SI} = \frac{G_F}{2\sqrt{2}} Q_W \rho_{wk}(r) \gamma_5$
	↓ involved atomic states: $6S \rightarrow 7S$
Parity-violating amplitude	E_{PNC}
	↓ E_{PNC}: includes the electric-dipole operator
Nuclear weak charge	$Q_W^{APV}(R_n) = N \left(\frac{\text{Im}\, E_{PNC}(R_n)}{Q_{weak}}\right)_{exp} \left(\frac{Q_{weak}}{\text{N Im}\, E_{PNC}(R_n)}\right)_{th} \beta_{exp+th}$

Extremely low momentum transfer **Q~2.4 MeV**

β: tensor transition polarizability: size of the Stark mixing induced electric dipole amplitude



There are different atomic calculations available, we adopt

B.K. Sahoo et al. Phys Rev D 103, L111303 (2021)

Very sensitive to $\sin^2\theta_W$, not much on $R_n(Cs)$

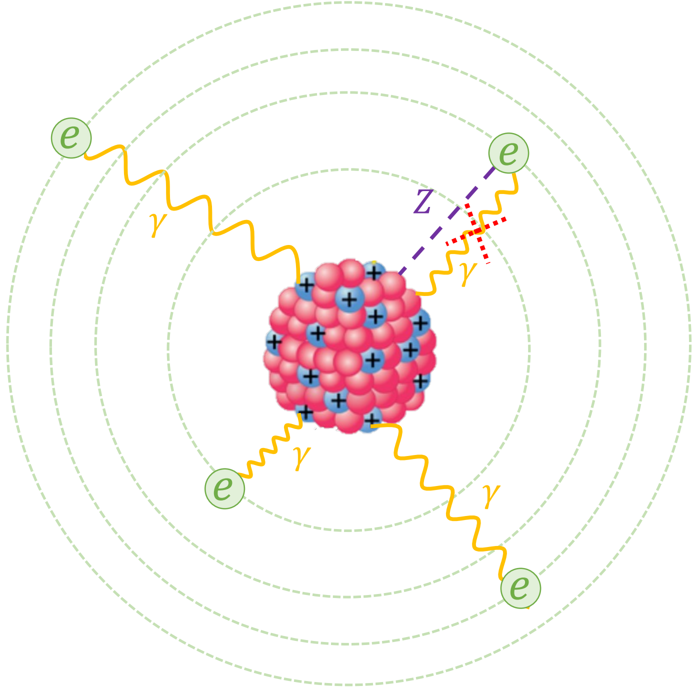
Atomic systems: APV

APV experiments measure the weak mixing angle at very low momentum transfer (few MeVs) via electronic transitions which are forbidden by selection rules: they violate parity

We consider the APV measurement on **lead-208**

Interaction Hamiltonian	$\hat{h}_{SI} = \frac{G_F}{2\sqrt{2}} Q_W \rho_{wk}(r) \gamma_5$
	involved atomic states: $6p^2\ ^3P_0 \rightarrow 6p^2\ ^3P_1$
Parity-violating amplitude	E_{PNC}
	inside the theoretical ratio $R_{th} = \left(\frac{\text{Im}\, E_{PNC}}{M_1}\right)_{th}$
Nuclear weak charge	$Q_W^{APV}(R_n) = -N\, R_{exp} \left(\frac{M_1}{\text{Im}\, E_{PNC}(R_n)}\right)_{th}$

Extremely low momentum transfer **Q~8 MeV**



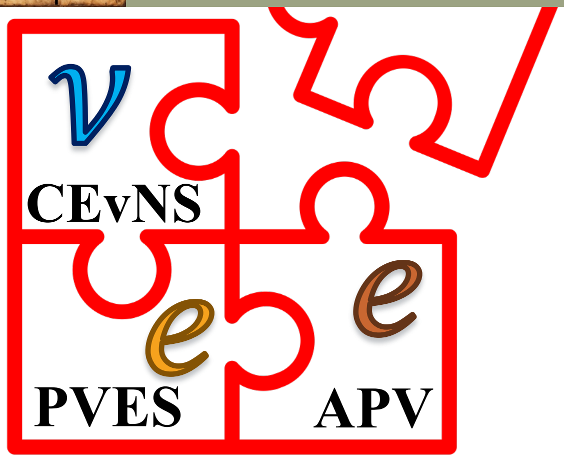
M_1: reduced electric-dipole transition of the magnetic-dipole operator

To be compared to the value of the nuclear weak charge calculated in the SM: dependence on $\sin^2(\vartheta_W)$

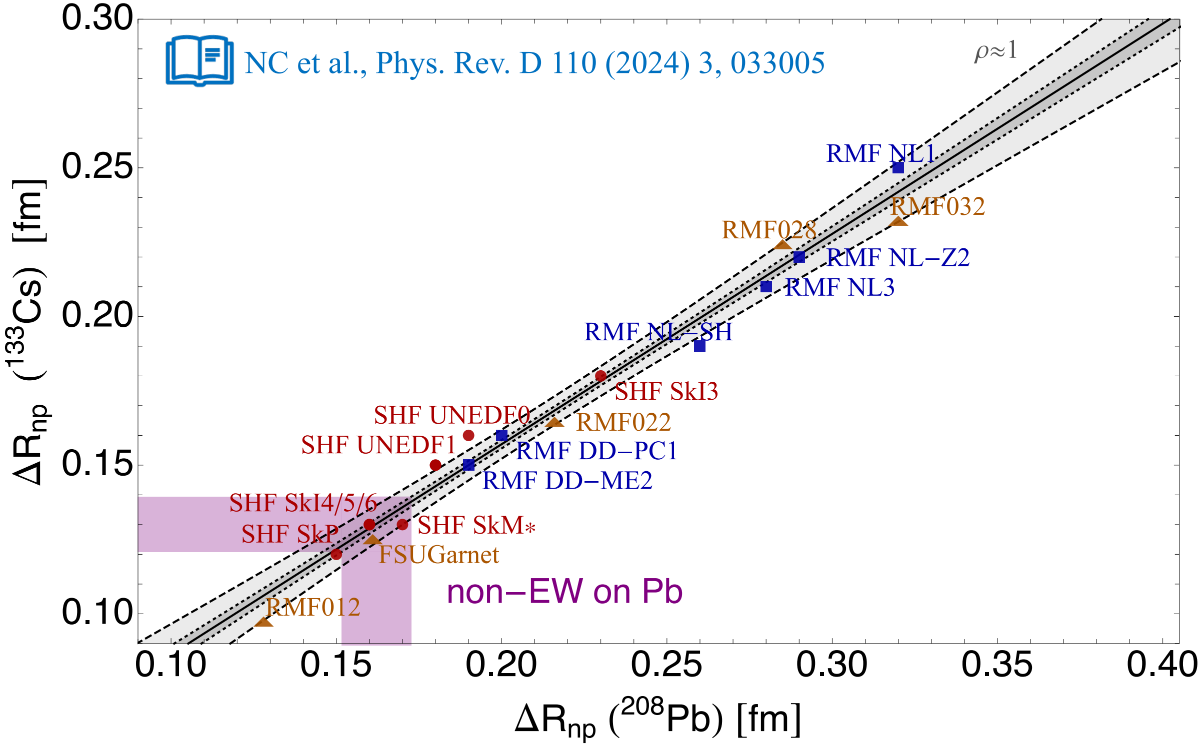
$R_{exp} = -9.80(33) \times 10^{-8}$ S.J. Phipp et al. Journal of Physics B 29, 1861 (1996)

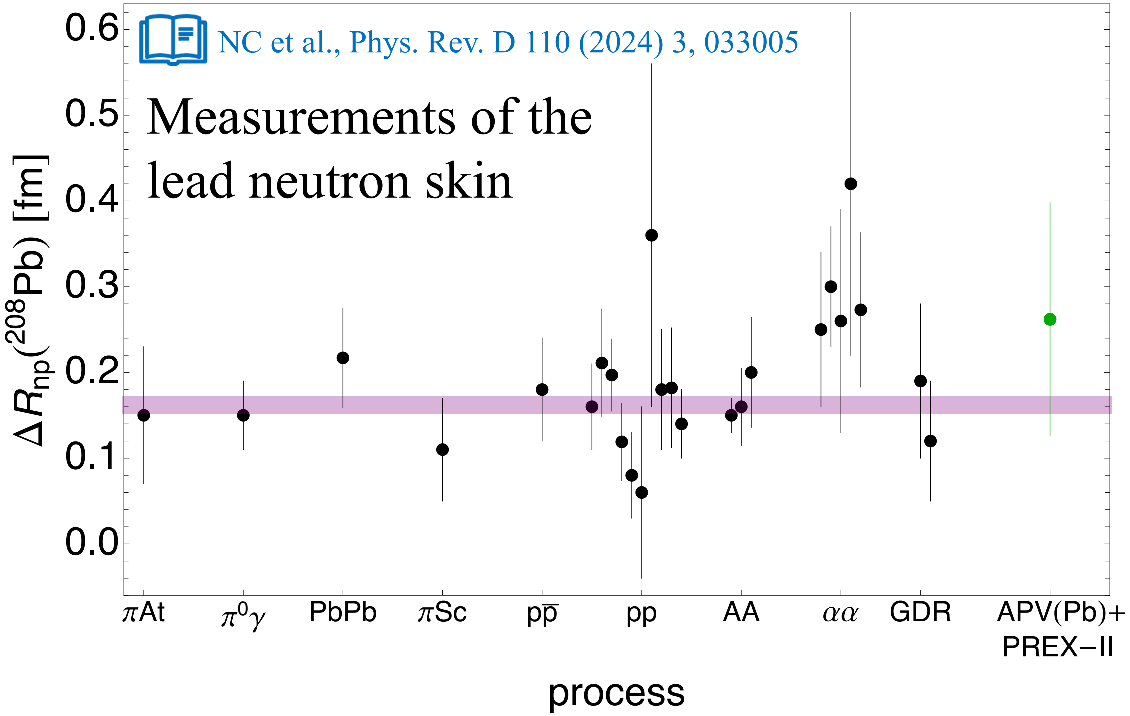
$R_{exp} = -9.86(12) \times 10^{-8}$ D.M. Meekhof et al. Phys Rev Lett 71,3442 (1993)

PVES + APV+ CEvNS



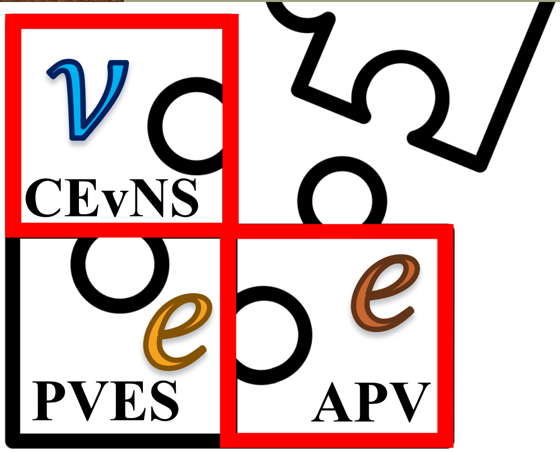
Corelation between the predictions of the lead and cesium neutron skin according to a selection of mean field models

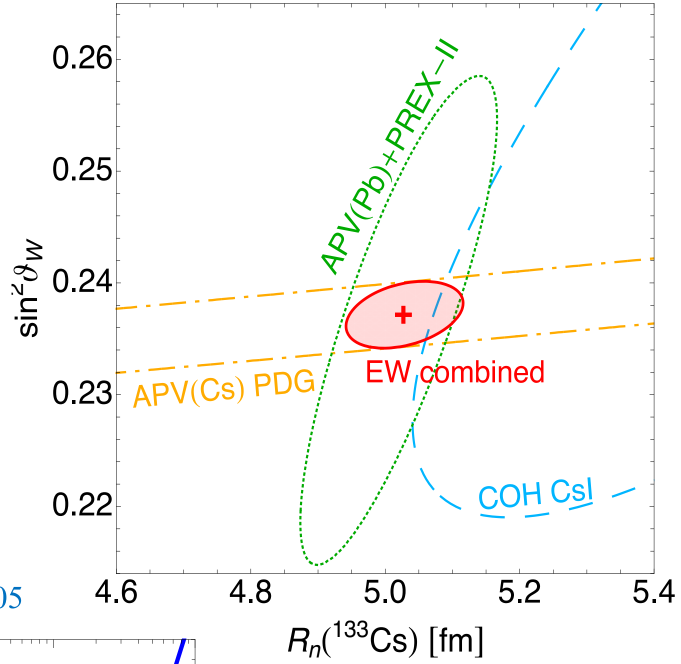




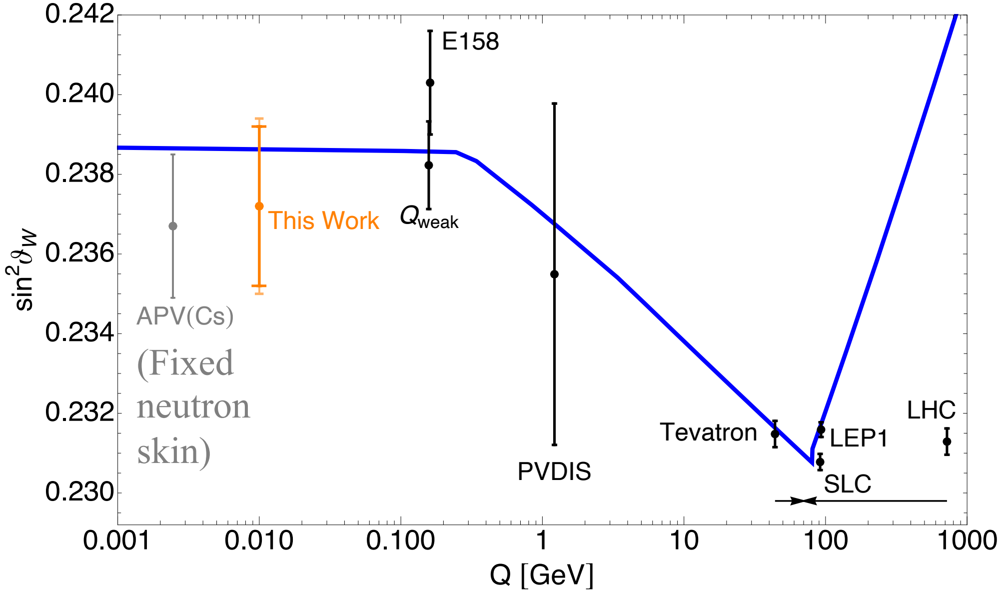
Meas.	R_n(Cs) [fm]	$\sin^2\vartheta_W$
APV(Cs) 21 + COH + CSRe	$5.04^{+0.19}_{-0.19}$	$0.2396^{+0.0020}_{-0.0019}$
APV(Cs) 21 + COH + PREX + APV Pb	$5.041^{+0.058}_{-0.057}$	$0.2396^{+0.0017}_{-0.0017}$
APV(Cs) 21 + COH + PREX + APV Pb + non−EW Pb + CSRe	$4.952^{+0.009}_{-0.009}$	$0.2387^{+0.0016}_{-0.0016}$

CEvNS+APV (PDG) on Cs





NC et al., Phys. Rev. D 110 (2024) 3, 033005



B.K. Sahoo et al. Phys Rev D 103, L111303 (2021)

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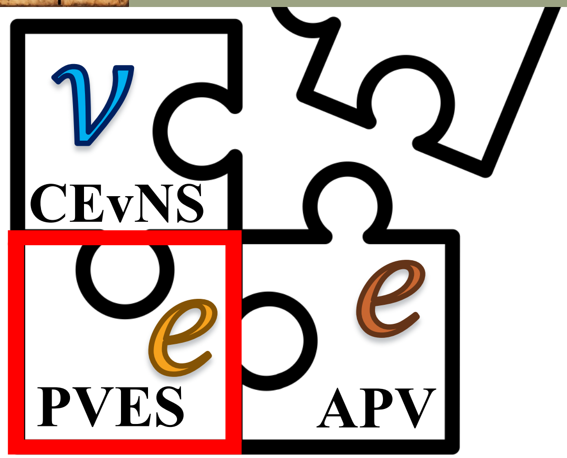
APV(Cs) 21 + COH + PREX + APV Pb	$5.041^{+0.058}_{-0.057}$	$0.2396^{+0.0017}_{-0.0017}$

V. Dzuba et al., Phys. Rev. Letter 109, 203003 (2012)

Meas.	R_n(Cs) [fm]	$\sin^2\vartheta_W$
APV(Cs) PDG + COH + CSRe	$5.04^{+0.19}_{-0.19}$	$0.2372^{+0.0022}_{-0.0022}$
APV(Cs) PDG + COH + PREX + APV Pb	$5.027^{+0.058}_{-0.057}$	$0.2372^{+0.0020}_{-0.0020}$

PVES on Ca-48



We can consider the PREX twin measurement, CREX, performed with a calcium-48 target

2.1 GeV polarized electrons on a calcium-48 target scattered at $\theta \sim 5°$ (higher momentum transfer $q \sim 170$ MeV)

Only one measurement released in 2021

D. Adhikari et al., Phys. Rev. Lett. 129.042501(2022)

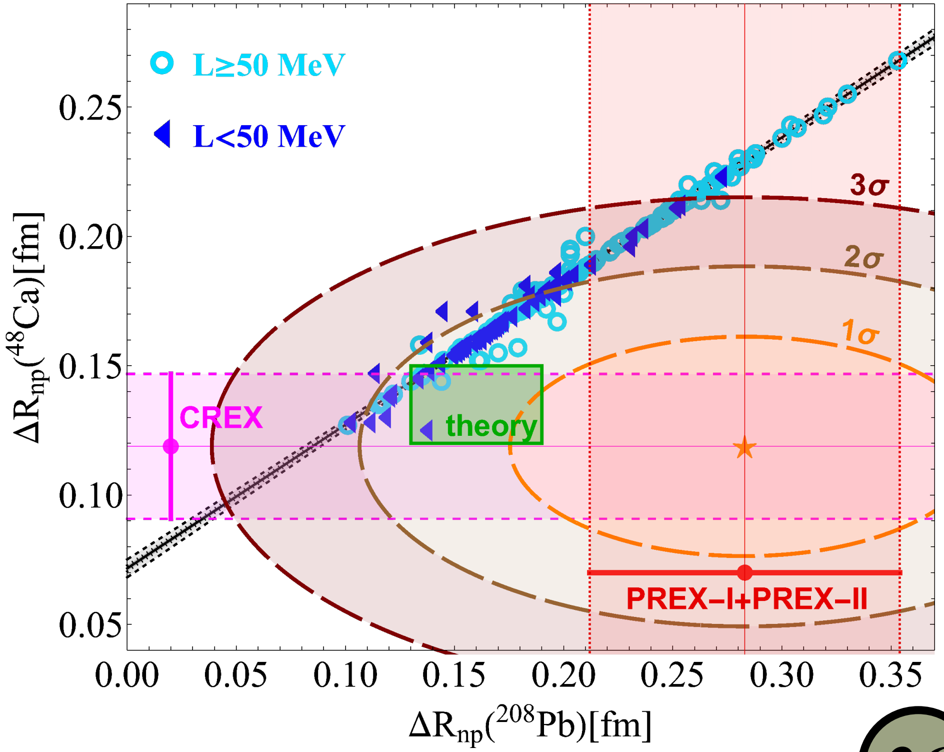
Measured the neutron skin of calcium with unprecedented precision:

$$\Delta R_{np} = 0.121 \pm 0.026(exp) \pm 0.024\ (mod)\ \text{fm}$$
$$\Delta R_{wk} = 0.159 \pm 0.026(exp) \pm 0.023\ (mod)\ \text{fm}$$

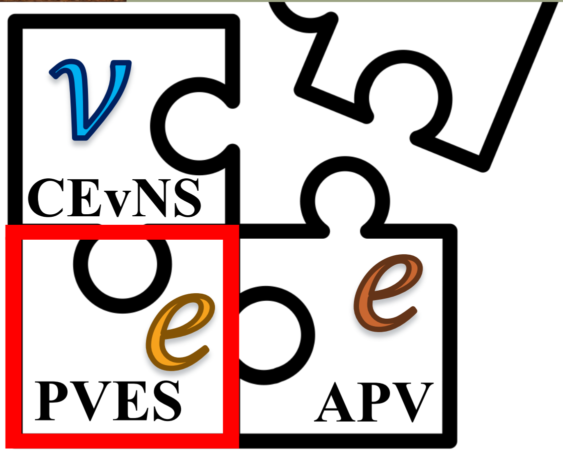
CREX found a neutron skin perfectly compatible with EDF and ab-initio predicted values

$$\Delta R_{np}^{th} \approx 0.12 - 0.15\ \text{fm}$$

We performed the same analysis applied to PREX also for CREX



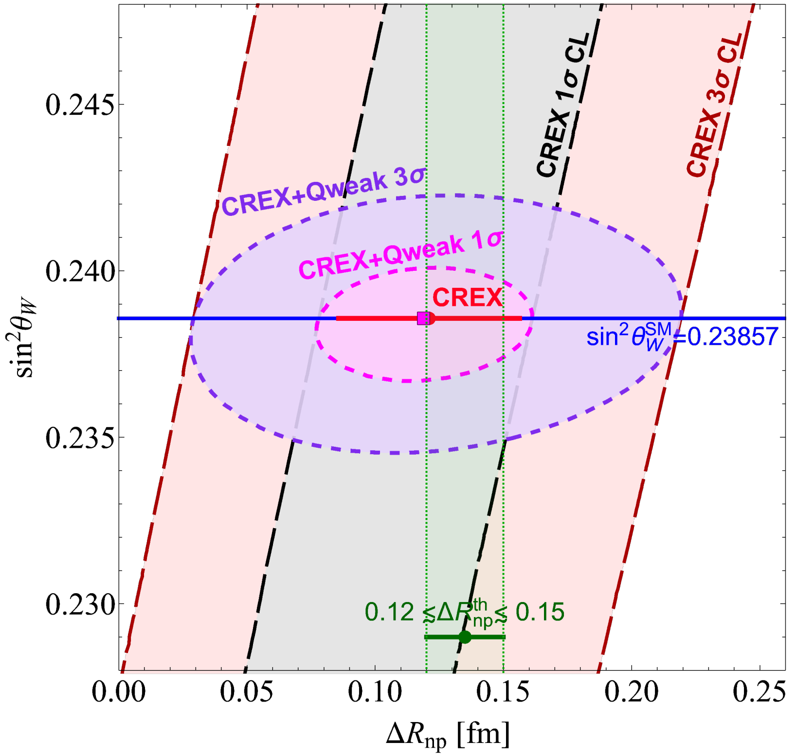
PVES + Qweak



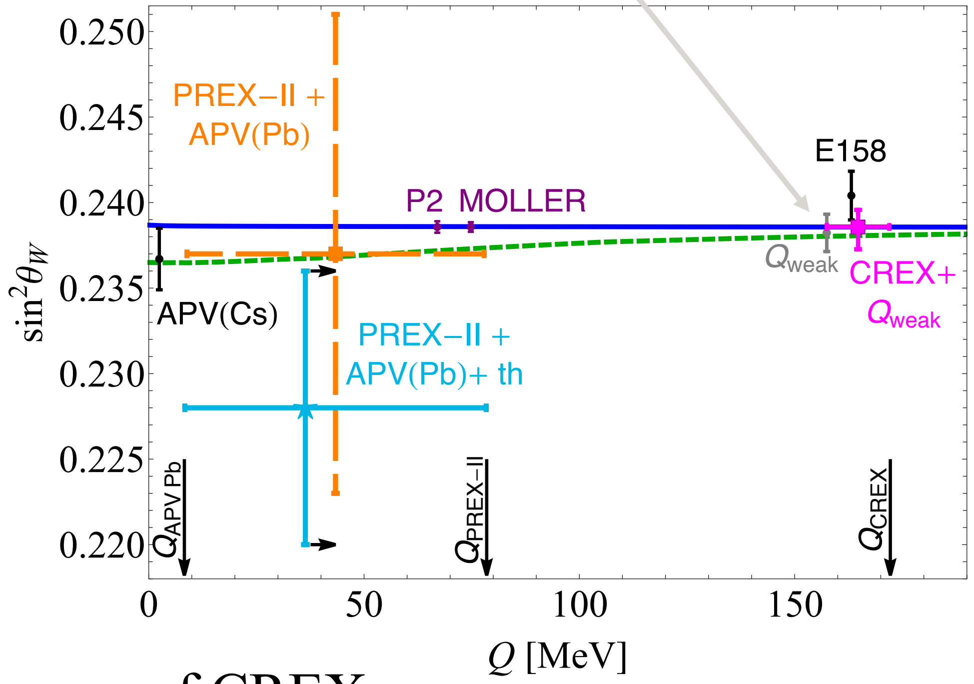
We can use the weak mixing angle measurement from the Qweak measurement of the proton weak charge (no dependence on the neutron skin)

CREX+Qweak

$$\Delta R_{np} = 0.119 \pm 0.028 \text{ fm}$$
$$\sin^2\theta_W = 0.2386 \pm 0.0013$$



$$Q_p(\sin^2\theta_W) = -2(g_{AV}^{ep}(\sin^2\theta_W))\left(1 - \frac{\alpha}{2\pi}\right)$$



- Qweak sets a horizontal band which breaks the degeneracy of CREX
- The precision is preserved
- CREX and PREX point toward different directions!

PVES on C-12

A preliminary study on the possibility to use a pixel-like backward detector

At MESA, the form factor could be measured at more **energies** by using a pixelized detector for the backward measurement

A scan of the form factor in a certain range of momenta could be achievable