

Parity-Violating Asymmetry for ^{208}Pb

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- Introduction
- Parity-violating asymmetry
- Nuclear structure models
- Symmetry energy at saturation density
- Results for ^{208}Pb
- Predictions for ^{48}Ca

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Purpose

Our goal is present and discuss numerical predictions for the neutron density distribution of ^{208}Pb and compare the results with the experimental data obtained from different reactions

Theoretical background

- Relativistic and non-relativistic mean-field models for the nuclear structure
- Parity-violating asymmetry parameter for elastic electron scattering is computed at the kinematics of the PREX experiment and is obtained averaging the theoretical results over the experimental acceptance function
- Theoretical predictions of the neutron skin thickness are obtained from mean field models

Osaka measurement - Phys. Rev. C, **82**, 044611 (2010)

- Cross sections and analyzing power for polarized proton elastic scattering
- Measurement of neutron density distribution and neutron skin thickness

PREX measurement - Phys. Rev. Lett. **108**, 112502 (2012)

- Parity-violating asymmetry A_{pV} from ^{208}Pb
- Information about the difference between the radii of the neutron and proton distributions $R_n - R_p$
- First electroweak observation of the neutron skin

Mainz measurement - Phys. Rev. Lett. **112**, 242502 (2014)

- Coherent pion photoproduction from ^{208}Pb
- Information on the size and shape of the neutron skin

Dirac equation

$$[\boldsymbol{\alpha} \cdot \mathbf{p} + U_{\pm}(r)]\Psi_{\pm} = E\Psi_{\pm}$$

Total potential:

$$U(r)_{\pm} = V(r) \pm \gamma_5 A(r)$$

Axial potential:

$$A(r) = \frac{G_F}{2\sqrt{2}} \rho_W(r)$$

Weak charge density

$$\rho_W(r) = \int d\mathbf{r}' G_E(|\mathbf{r} - \mathbf{r}'|) \times \left[-\rho_n(r') + (1 - 4\sin^2\Theta_W)\rho_p(r') \right]$$

Electric form factor:

$$G_E(r) \approx \frac{\Lambda^3}{8\pi} e^{-\Lambda r} \quad \Lambda = 4.27 \text{ fm}^{-1}$$

Parity-violating asymmetry in Born approximation

$$A_{PV} = \frac{G_F Q^2}{4\sqrt{2} \pi \alpha} \left[4 \sin^2 \Theta_W - 1 + \frac{F_n(q)}{F_p(q)} \right]$$

Relativistic models

- Nonlinear RMF model (NL)
- Density-dependent RMF model (DD)
- Nonlinear point-coupling RMF model (PC)
- Density-dependent point-coupling RMF model (DDPC)

Non-relativistic models

- Skyrme interaction (SIII, SKM*, SLY4, SLY5)
- Gogny interaction (D1S)

Approximations

- Mean field description
- Spherical symmetry
- No-sea approximation (relativistic models)

Nuclei are described as a system of Dirac nucleons interacting by the exchange of mesons and the electromagnetic field

Nonlinear RMF model

- Lagrangian: $\mathcal{L} = \mathcal{L}_N + \mathcal{L}_m + \mathcal{L}_{int}$
- \mathcal{L}_m includes terms like: $\omega_\mu \omega^\mu, (\omega_\mu \omega^\mu)^2, \dots$
- \mathcal{L}_{int} contains the interaction terms between nucleons and mesons

Density-dependent RMF model

- Lagrangian: $\mathcal{L} = \mathcal{L}_N + \mathcal{L}_m + \mathcal{L}_{int}$
- \mathcal{L}_{int} contains the interaction terms between nucleons and mesons with density-dependent coupling constants
- $g_i(\rho) = g_i(\rho_{sat}) f_i(x)$ for $i = \sigma, \omega, \rho, \quad x = \rho / \rho_{sat}$
- $\rho_{sat} = 0.152 \text{ fm}^{-3}$ denotes the nucleon density at saturation in symmetric nuclear matter

The point-coupling models are defined by a Lagrangian density that only consists of nucleon fields

Nonlinear point-coupling RMF model

- Lagrangian: $\mathcal{L} = \mathcal{L}_{free} + \mathcal{L}_{4f} + \mathcal{L}_{hot} + \mathcal{L}_{der}$
- \mathcal{L}_{4f} includes 4-fermion terms: $(\bar{\psi}\gamma_{\mu}\psi)(\bar{\psi}\gamma^{\mu}\psi)$
- \mathcal{L}_{hot} includes higher order terms: $[(\bar{\psi}\gamma_{\mu}\psi)(\bar{\psi}\gamma^{\mu}\psi)]^2$
- \mathcal{L}_{der} includes derivative terms: $(\partial_{\nu}\bar{\psi}\gamma_{\mu}\psi)(\partial^{\nu}\bar{\psi}\gamma^{\mu}\psi)$

Density-dependent point-coupling RMF model

- Lagrangian: $\mathcal{L} = \mathcal{L}_{free} + \mathcal{L}_{4f} + \mathcal{L}_{der}$
- \mathcal{L}_{4f} includes 4-fermion terms: $(\bar{\psi}\gamma_{\mu}\psi)(\bar{\psi}\gamma^{\mu}\psi)$
- \mathcal{L}_{der} represents derivatives in the nucleon scalar density
- Coupling constants are density-dependent

Skyrme interaction

- Interaction: $V = \sum_{i<j} V(ij) + \sum_{i<j<k} V(ijk)$
- Short-range expansion for the two-body interaction:

$$V(1,2) = V_0\delta(\mathbf{r}_1 - \mathbf{r}_2) + V_1 \left[\delta(\mathbf{r}_1 - \mathbf{r}_2)\hat{\mathbf{k}}^2 + \hat{\mathbf{k}}^2\delta(\mathbf{r}_1 - \mathbf{r}_2) \right] \\ + V_2\hat{\mathbf{k}}\delta(\mathbf{r}_1 - \mathbf{r}_2)\hat{\mathbf{k}} + iW_0(\boldsymbol{\sigma}^{(1)} + \boldsymbol{\sigma}^{(2)})\hat{\mathbf{k}} \times \delta(\mathbf{r}_1 - \mathbf{r}_2)\hat{\mathbf{k}}$$

- Zero-range force for three-body interaction:

$$V(1,2,3) = V_3\delta(\mathbf{r}_1 - \mathbf{r}_2)\delta(\mathbf{r}_2 - \mathbf{r}_3)$$

Gogny interaction

- Zero-range forces of Skyrme interaction might not be able to simulate the long range parts of the realistic effective interaction
- V_0 , V_1 and V_2 of Skyrme force are replaced by a sum of two Gaussians with spin-isospin exchange mixtures

EOS of isospin asymmetric nuclear matter

$$E(\rho, \alpha) = E(\rho, \alpha = 0) + E_{\text{sym}}(\rho) \alpha^2 + O(\alpha^4)$$

Nuclear symmetry energy and isospin asymmetry:

$$E_{\text{sym}}(\rho) = \frac{1}{2} \left. \frac{\partial^2 E(\rho, \alpha)}{\partial \alpha^2} \right|_{\alpha=0} \quad \alpha = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

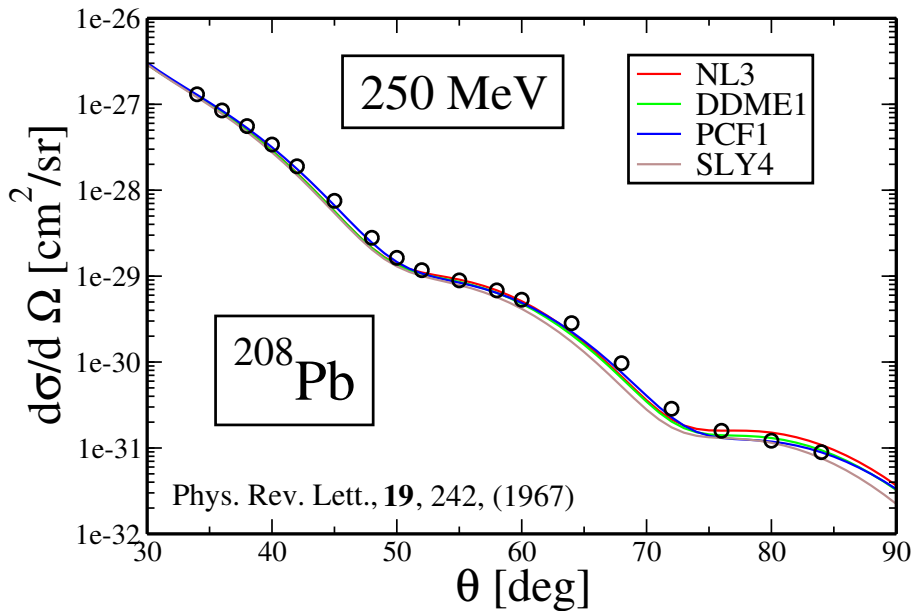
Nuclear symmetry energy at saturation density

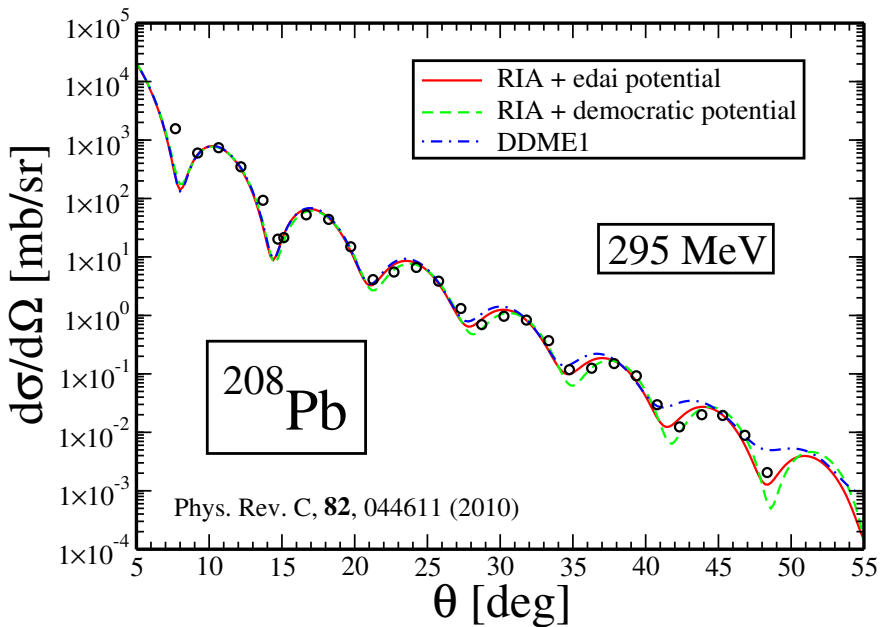
$$E_{\text{sym}}(\rho) \simeq E_{\text{sym}}(\rho_0) + \frac{L}{3} \left(\frac{\rho - \rho_0}{\rho} \right) + \frac{K_{\text{sym}}}{18} \left(\frac{\rho - \rho_0}{\rho} \right)^2$$

Parameters of expansion:

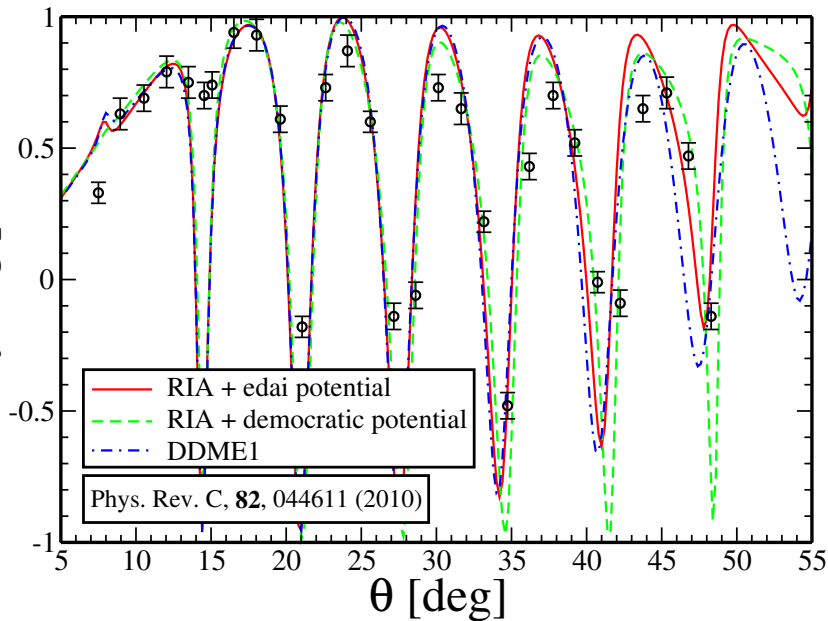
$$L = 3\rho_0 \left. \frac{\partial E_{\text{sym}}(\rho)}{\partial \rho} \right|_{\rho=\rho_0} \quad K_{\text{sym}} = 9\rho_0^2 \left. \frac{\partial^2 E_{\text{sym}}(\rho)}{\partial \rho^2} \right|_{\rho=\rho_0}$$

Elastic Scattering off ^{208}Pb

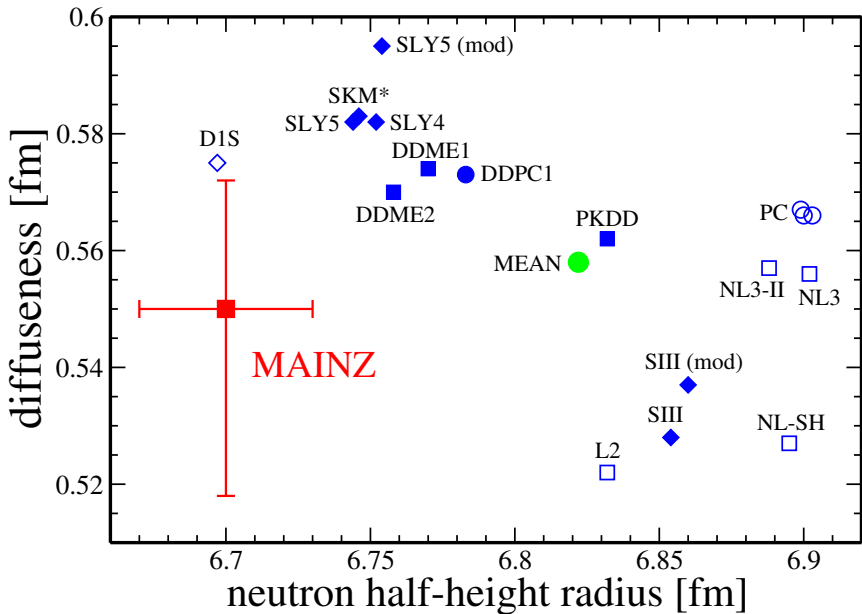


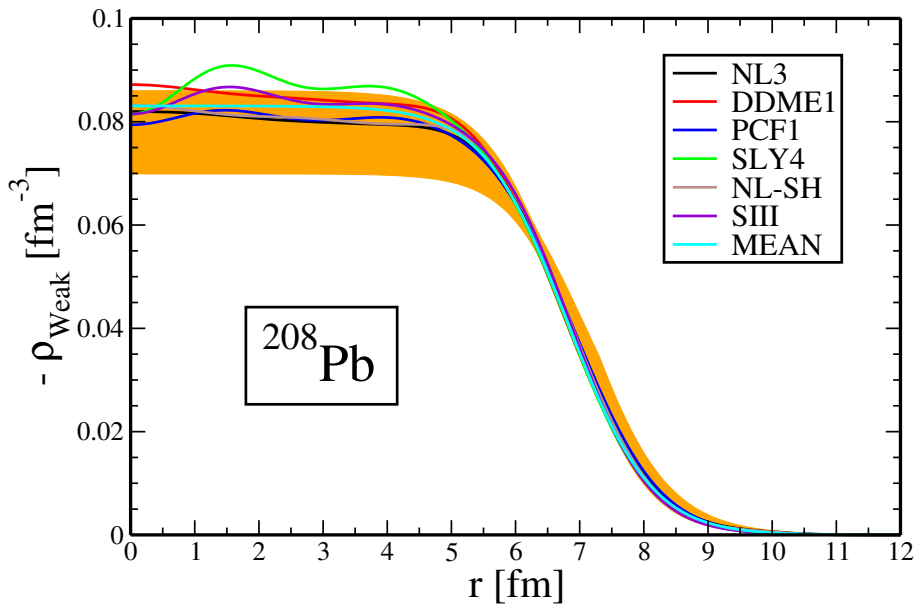


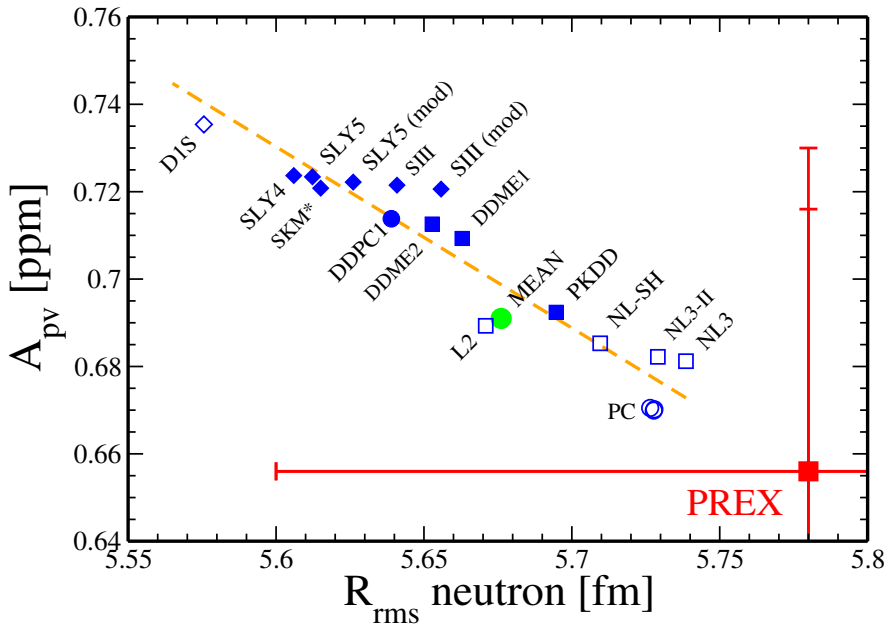
analyzing power

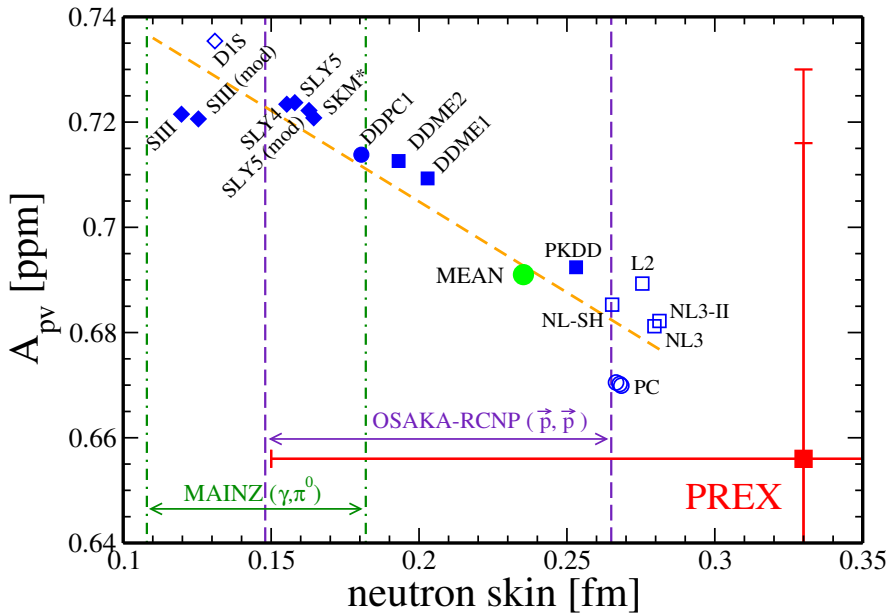


Results for ^{208}Pb

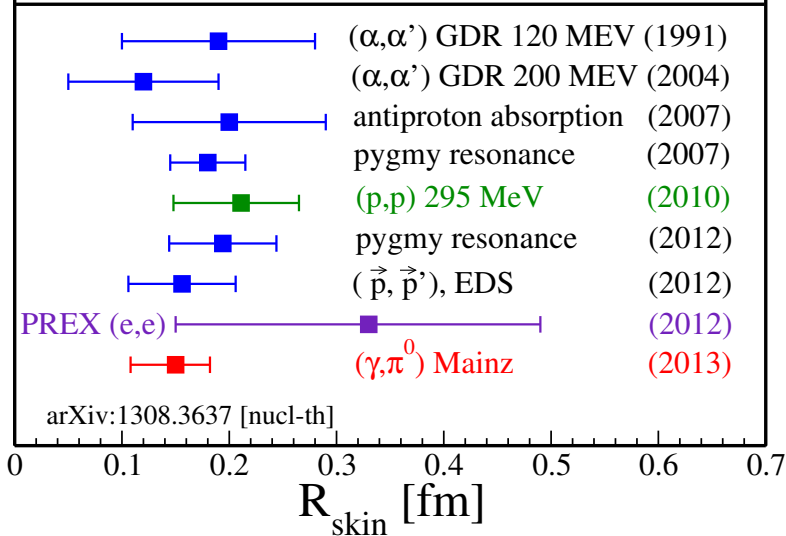


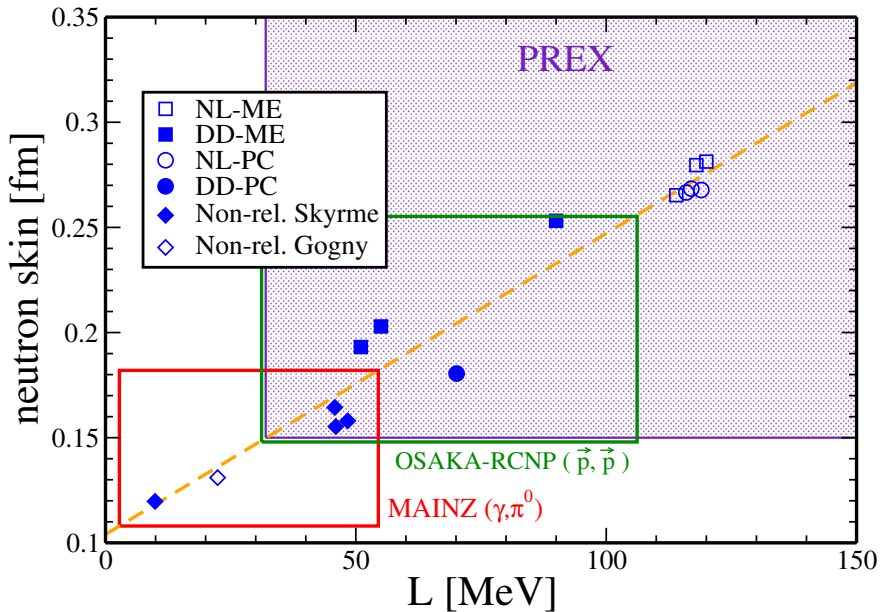


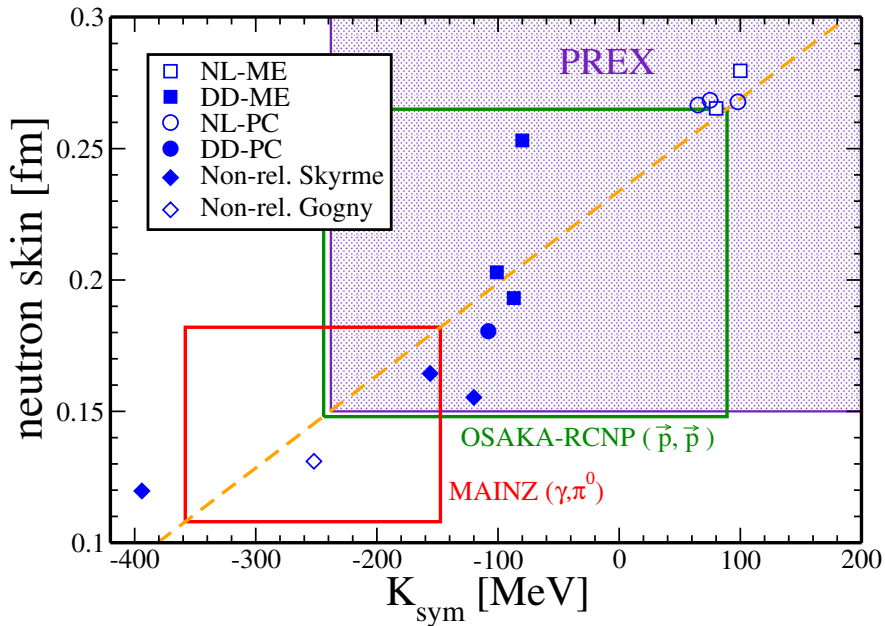




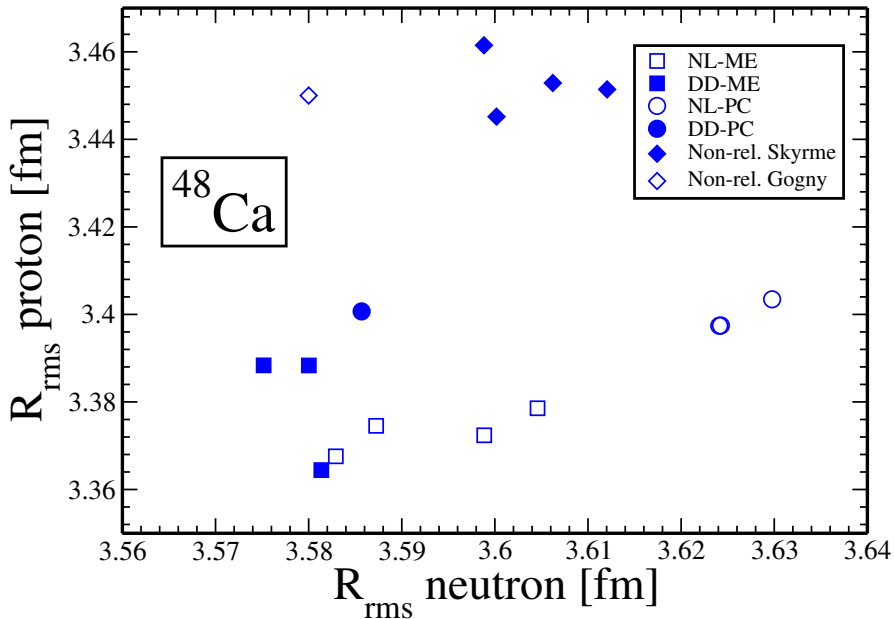
Measured values of neutron skin thicknesses of ^{208}Pb

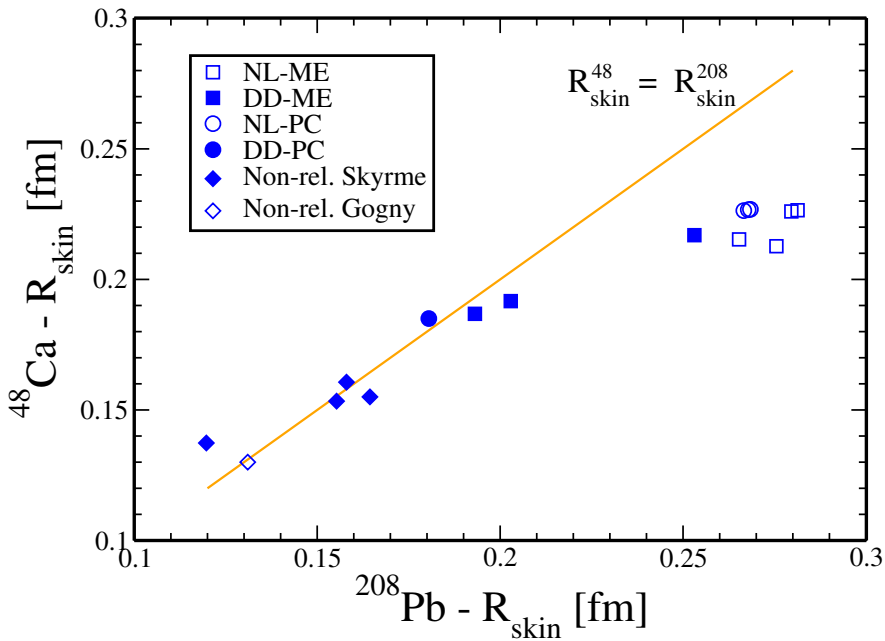


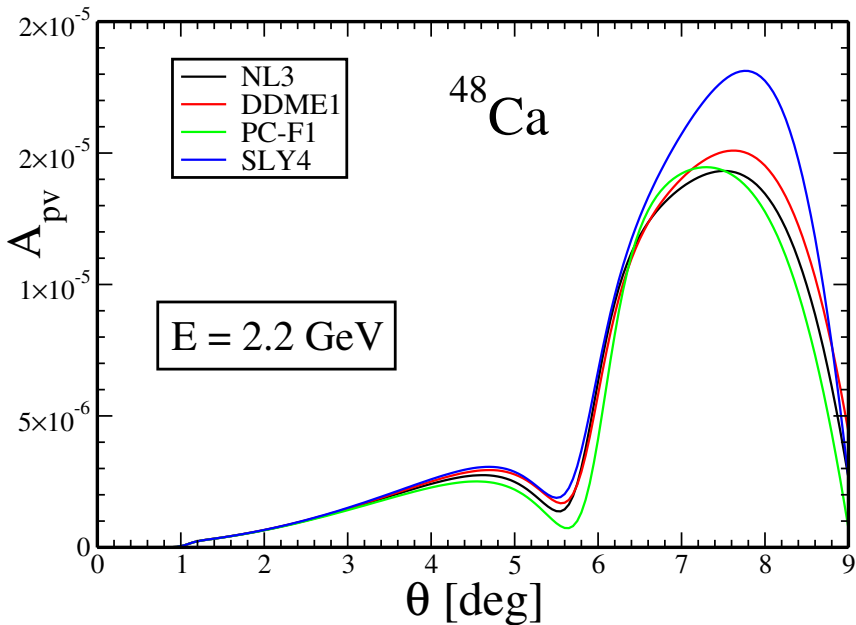


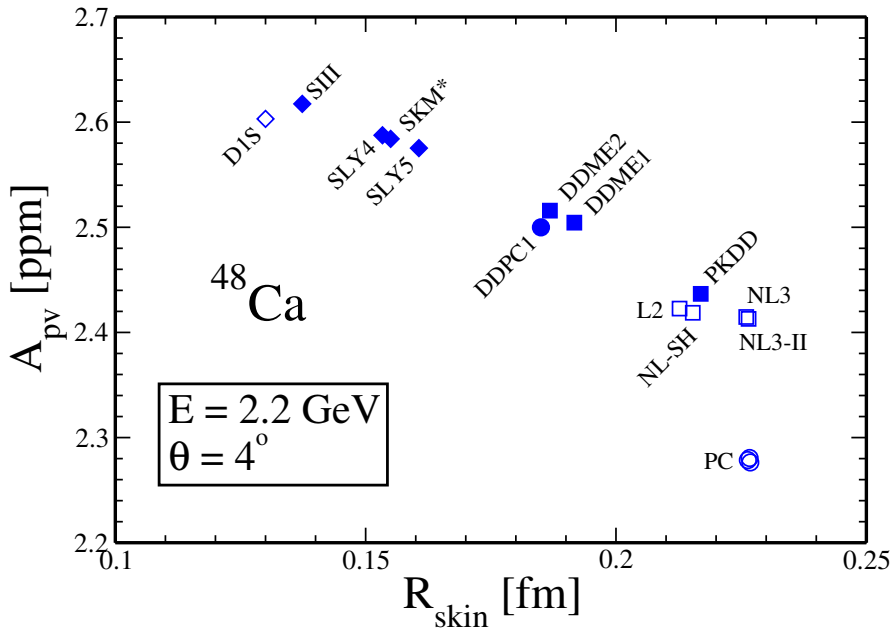


Predictions for ^{48}Ca









- Determination of neutron distribution in nuclei
- Great experimental and theoretical efforts have been devoted to achieve this goal
- Parity-violating electron scattering is an accurate and model-independent tool for probing neutron properties
- More information on nuclear structure
- More stringent constraints of the range of variation of nuclear matter expansion parameters

Backup Slides

- Two-parameter distribution

$$\rho(r) = \rho_0 \frac{\sinh(R/a)}{\cosh(R/a) + \cosh(r/a)}$$

$$\rho_0 = \frac{3}{4\pi R^3} \left[1 + \left(\frac{\pi a}{R} \right)^2 \right]^{-1}$$

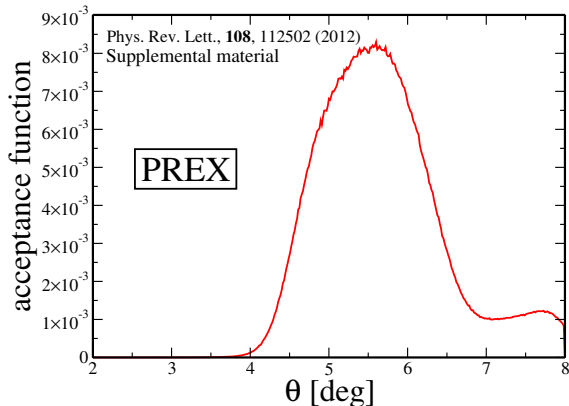
- Properties

$$\int d^3r \rho(r) = 1$$

- Asymmetry parameter

$$\langle A_{PV} \rangle = \frac{\int d\theta \sin \theta A_{PV}(\theta) \frac{d\sigma}{d\Omega} \epsilon(\theta)}{\int d\theta \sin \theta \frac{d\sigma}{d\Omega} \epsilon(\theta)}$$

- Acceptance function



	Slope	Intercept	Chi-Square
$R_{\text{rms}} - A_{\text{pv}}$	-4.133×10^{-1}	3.045	1.07×10^{-3}
$R_{\text{skin}} - A_{\text{pv}}$	-3.426×10^{-1}	7.738×10^{-1}	1.39×10^{-3}
$L - R_{\text{skin}}$	$+1.455 \times 10^{-3}$	1.019×10^{-1}	1.15×10^{-2}
$K_{\text{sym}} - R_{\text{skin}}$	$+3.494 \times 10^{-4}$	2.363×10^{-1}	2.67×10^{-2}