PARITY-VIOLATING ELECTRON SCATTERING FROM CARBON-12

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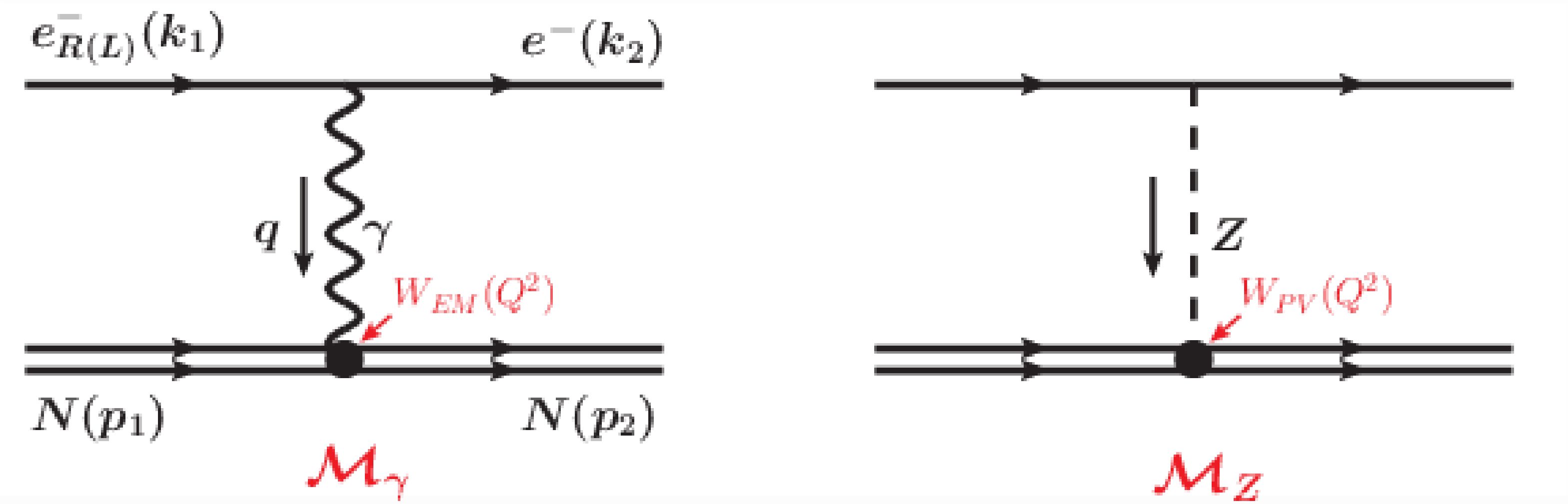
INTRODUCTION TO PV ASYMMETRY

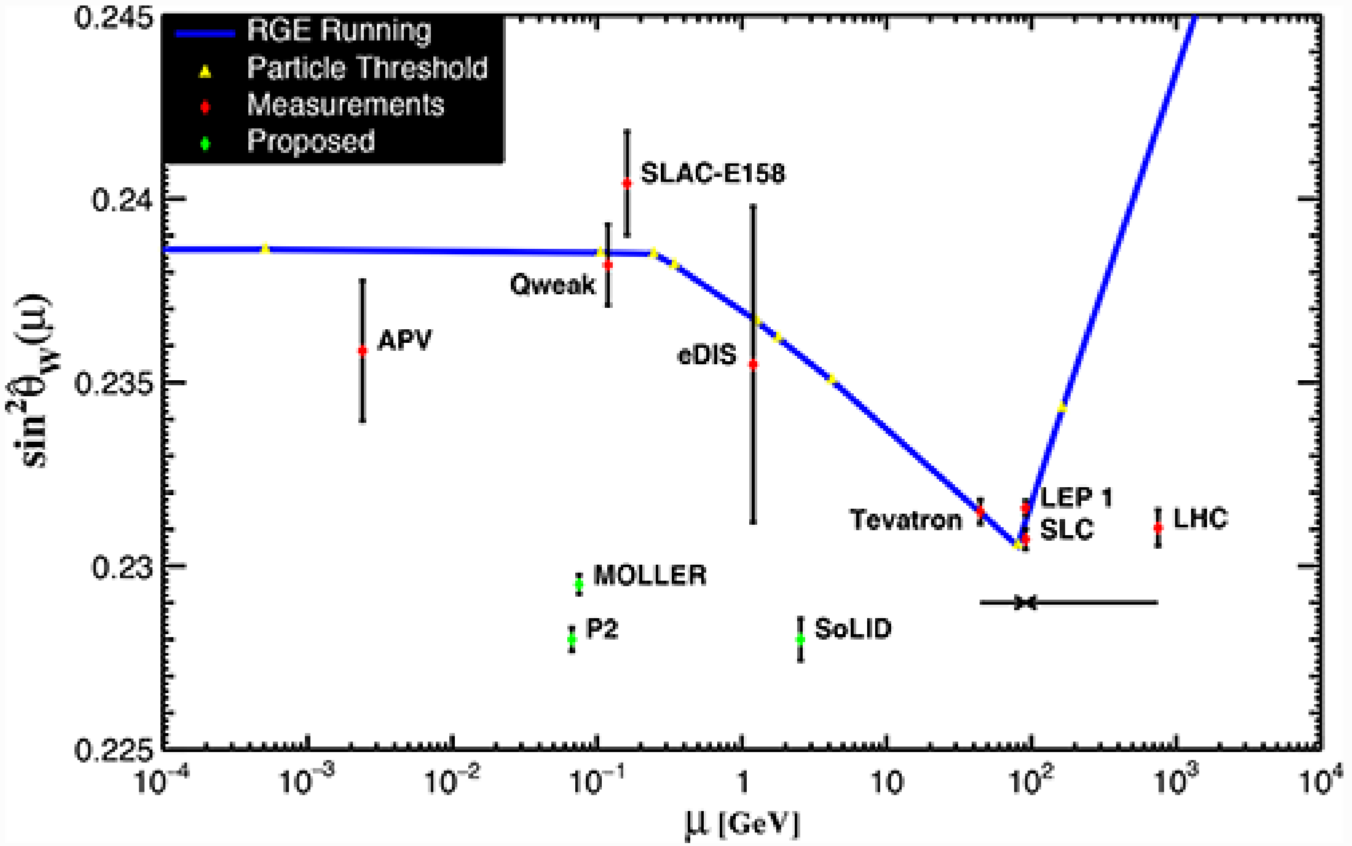


$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{|M_\gamma + M_Z^R|^2 - |M_\gamma + M_Z^L|^2}{|M_\gamma + M_Z^R|^2 + |M_\gamma + M_Z^L|^2} \approx \frac{(M_Z^R - M_Z^L)M_\gamma^*}{|M_\gamma|^2} = -\frac{G_F}{\sqrt{2}}\frac{Q^2}{4\pi\alpha_{EM}}\frac{W_{PV}}{W_{EM}}$$

Weak charge of the nucleus (Z protons, N neutrons):

$$\frac{Q_W}{Z} = \lim_{Q^2 \to 0} \frac{W_{PV}(Q^2)}{W_{EM}(Q^2)}\Bigg|_{E_{beam}=0}$$

WEAK CHARGE AS A PRECISION TEST OF THE SM



[PDG, 2018]

Tree level: $Q_W = Z\left(1-4\sin^2\theta_W\right)-N$

WEAK CHARGES

- Nucleus:

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

- Proton: The weak charge is highly sensitive to BSM physics.

$$Q_W^p \approx 1-4\sin^2\theta_W \approx 0.08 \;\Rightarrow\; \Delta\sin^2\theta_W \big/ \sin^2\theta_W \approx 0.09\,\Delta Q_W^p \big/ Q_W^p$$

- ^{12}C: Theoretically easy to handle, reduced beam time requirements.

$$Q_W^{^{12}C} \approx -24\sin^2\theta_W \;\Rightarrow\; \Delta\sin^2\theta_W \big/ \sin^2\theta_W = \Delta Q_W^{^{12}C} \big/ Q_W^{^{12}C}$$

- Neutron: Weak interactions probe mainly neutrons inside the nucleus.

$$Q_W^n \approx -1$$

NEUTRON SKIN

PV asymmetry: $A_{PV} = A_0 W_{PV} / W_{EM}$

Response functions:

$$W_{EM}(Q^2) = \int d^3 r \rho_{ch}(\vec{r}) e^{i\vec{q}\cdot\vec{r}} = Z\left(1 - \frac{Q^2}{6} R_{ch}^2 + \ldots\right)$$

$$W_{PV}(Q^2) = \int d^3 r \rho_W(\vec{r}) e^{i\vec{q}\cdot\vec{r}} = Q_W\left(1 - \frac{Q^2}{6} R_W^2 + \ldots\right)$$

RMS radii:

$$R_{ch} = \left(\frac{4\pi}{Z}\int dr\ r^4 \rho_{ch}(r)\right)^{1/2} \qquad R_W = \left(\frac{4\pi}{Q_W}\int dr\ r^4 \rho_W(r)\right)^{1/2}$$

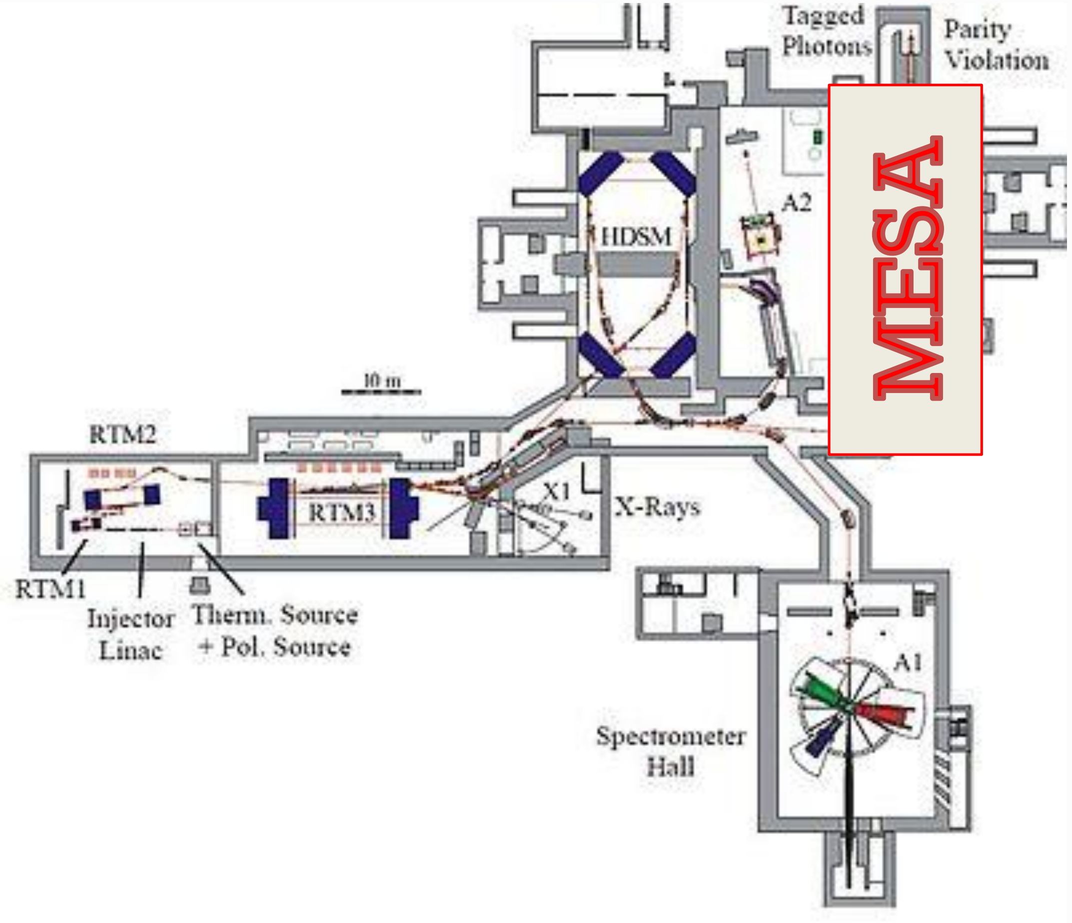
Weak skin: $\Delta R_W = R_W - R_{ch}$

Neutron skin: $\Delta R_{np} = R_n - R_p$

PV asymmetry measurements provide a relatively clean way in accessing neutron density distributions.

[Donnelly, Dubach, Sick, NPA, 1989]

C-12 @ MESA

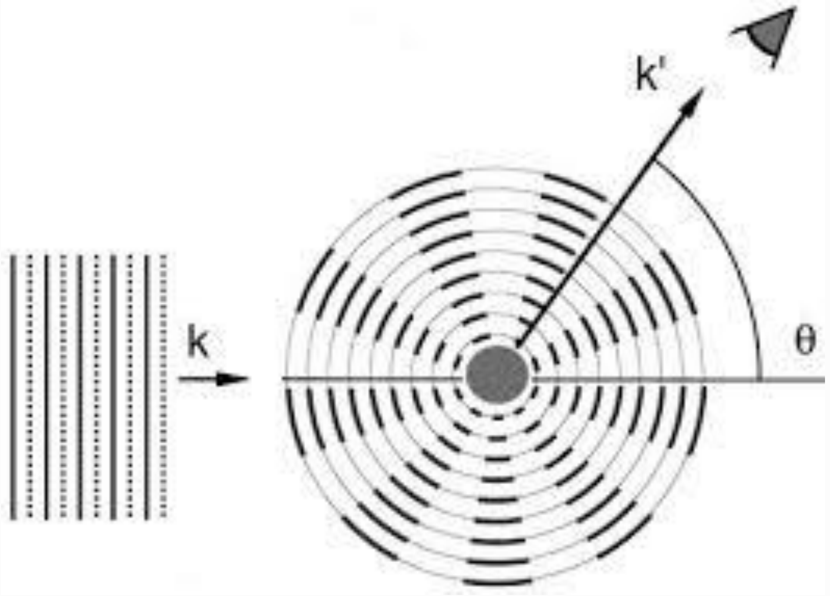


[https://www.kernphysik.uni-mainz.de]

Mainz Energy-recovery Superconducting Accelerator

- ^{12}C measurement
  - Electron beam energy E=155 MeV (150 μA)
  - Polarization > 85%
  - High runtime (more than 4000 h/year)
  - Interesting physics case if uncertainty ~ 0.3%
  - German-Mexican collaboration grant: theory predictions within the SM

ELECTRON-NUCLEUS SCATTERING USING PARTIAL WAVES



[www.tcm.phy.cam.ac.uk]

- The Dirac equation:

$$\left[-i\vec{\alpha}\cdot\vec{\nabla}+\beta m_e+V(\vec{r})\right]\psi=E\psi$$

- Identify interaction potential, e.g.:

$$rV_{EM}(r)=-4\pi\alpha_{EM}\left(\int_0^r dr'r'^2\rho_{ch}(r')+r\int_r^\infty dr'r'\rho_{ch}(r')\right)$$

- Solve the Dirac equation. We use ELSEPA code by Salvat et al.

$$\psi\sim\sum_{\kappa,m}\psi_{\kappa,m}$$

[Salvat, Jablonski, Powell, Comp. Phys. Com., 2004]

- Study asymptotic behavior of the solution
- Determine scattering amplitudes and XS

COULOMB DISTORTION AND PV ASYMMETRY

Massless electron scattering:

$$\left[-i\vec{\alpha}\cdot\vec{\nabla}+V_{R(L)}(r)\right]\psi_{R(L)}=E\psi_{R(L)}$$

$$V_{R(L)}(r)=V_{EM}(r)\mp V_{PV}(r)$$ [Horowitz, PRC, 1998]

EM potential: $$V_{EM}(r)=-4\pi\alpha_{EM}\left(\frac{1}{r}\int_0^r dr'r'^2\rho_{ch}(r')+\int_r^\infty dr'r'\rho_{ch}(r')\right)$$

Weak potential: $$V_{PV}(r)=-\frac{G_F}{2\sqrt{2}}\rho_W(r)$$

Charge and weak charge density distributions are the crucial input for determinations of PV asymmetry in Coulomb distortion approach!

MODELS FOR EM CHARGE DISTRIBUTION

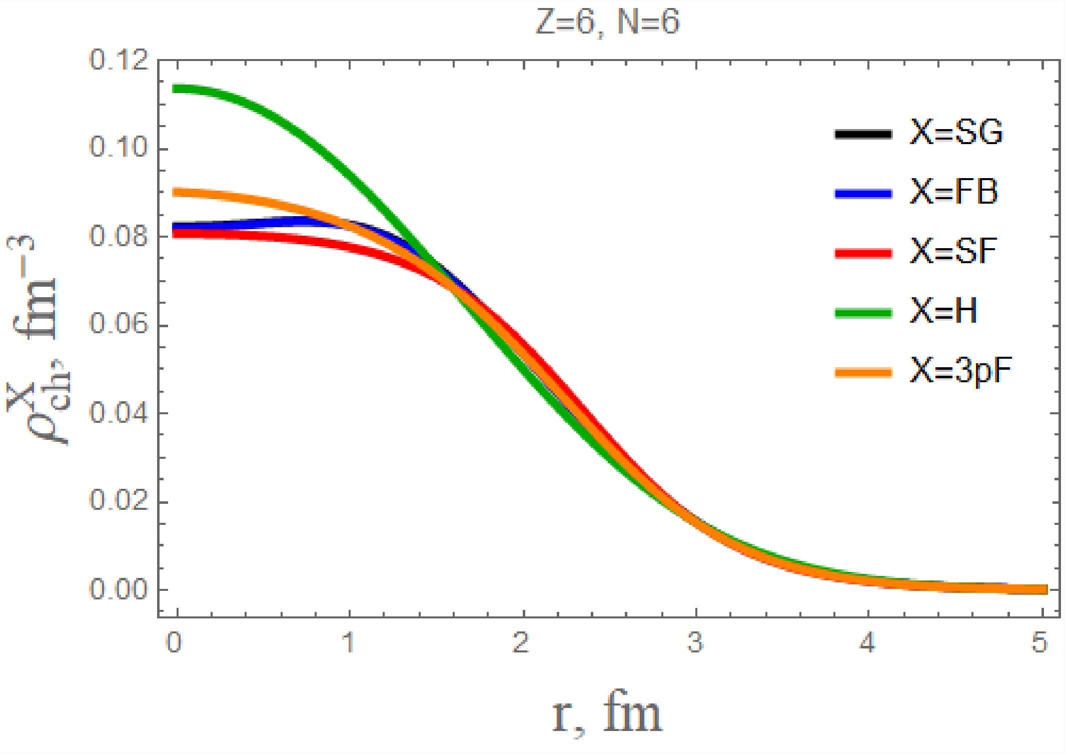
- Parametrizations providing the best description of experimental data
  - Sum of Gaussians (SG)
  - Fourier-Bessel (FB)

[H. de Vries et al., ADNDT, 1987]

- Other parametrizations
  - 2p Symmetrized Fermi (SF)
  - 2p Helm (H)
  - 3p Fermi (3pF)

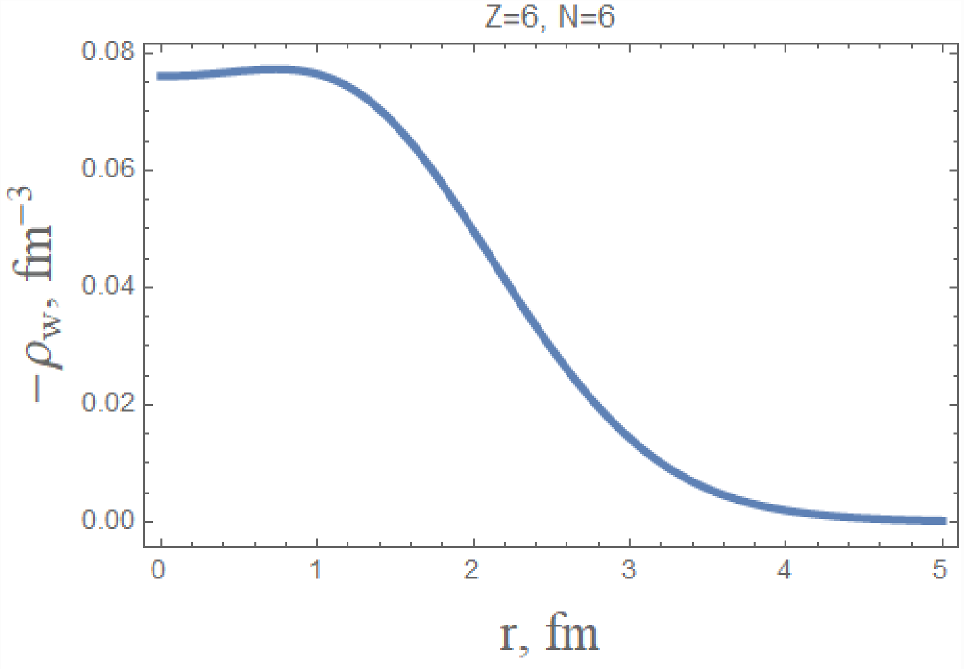
[J. Piekarewicz et al., PRC, 2016]

[C. de Jager et al., ADNDT, 1974]



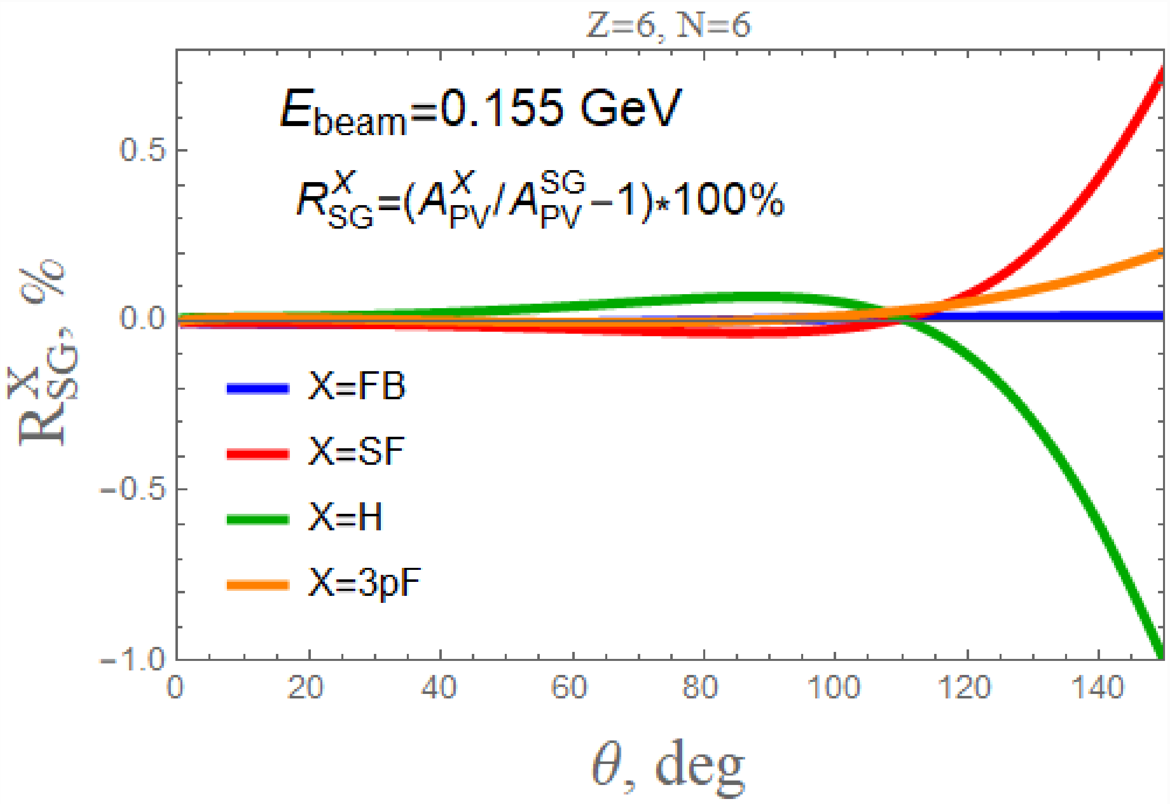
WEAK-CHARGE DISTRIBUTION WITH NO SKIN

$$\rho_w(r) = \rho_{ch}(r)\frac{Q_W}{Z}$$



- This parametrization assumes that the weak density has the same spatial distribution as the charge density and preserves the normalization on the weak charge.
- Assumes no difference in distribution of protons and neutrons within the nucleus or, equivalently, it generates no weak (neutron) skin.

UNCERTAINTY DUE TO EM CHARGE DISTRIBUTION



At forward angles none of the tested parametrizations bring significant uncertainty. At backward angles the uncertainty increases.

WEAK-CHARGE DISTRIBUTION WITH SKIN

$$A_{PV}^{PW} \approx -\frac{G_F}{\sqrt{2}}\frac{Q^2}{4\pi\alpha}\frac{Q_W}{Z}\left(1-\frac{Q^2}{3}\Delta R_W R_{ch}\right)$$

$$\Delta R_W \equiv R_W - R_{ch}$$

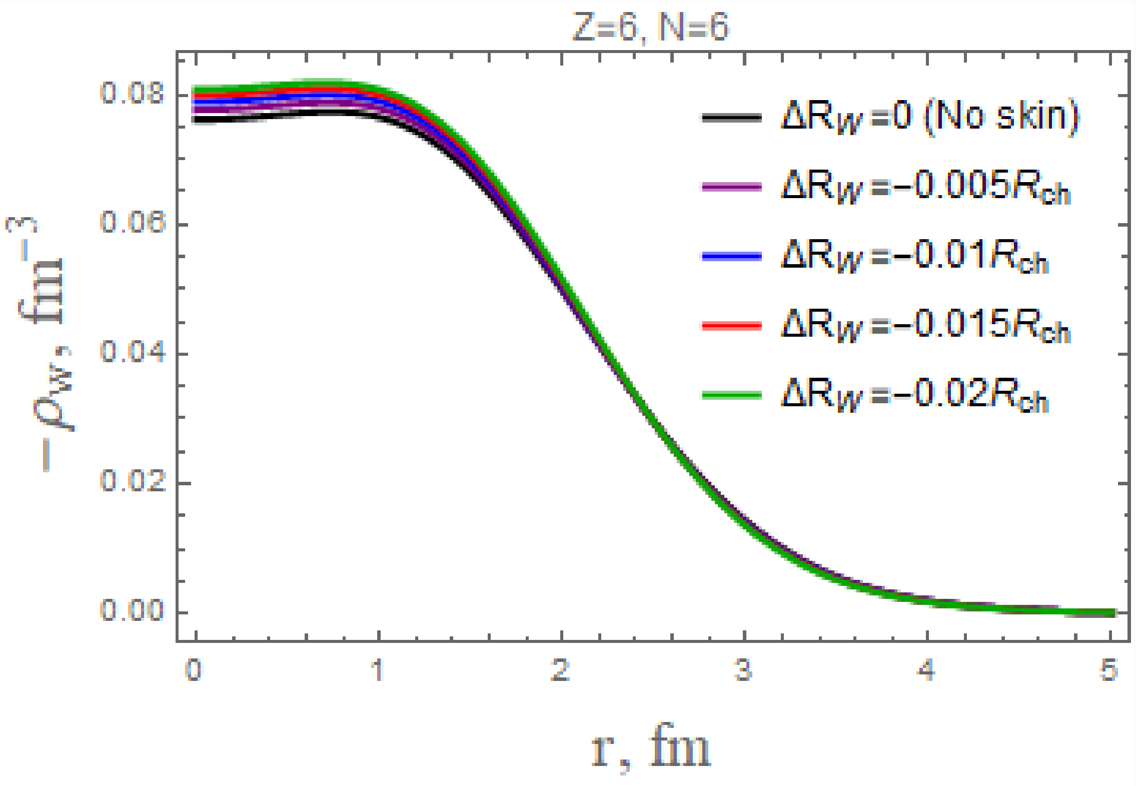
Model the weak skin using 2p symmetrized Fermi model:

$$\rho_w(r) = \rho_{ch}(r)\frac{Q_W}{Z} + \left(\rho_2(r) - \rho_1(r)\right)\frac{Q_W}{Z}$$

with:

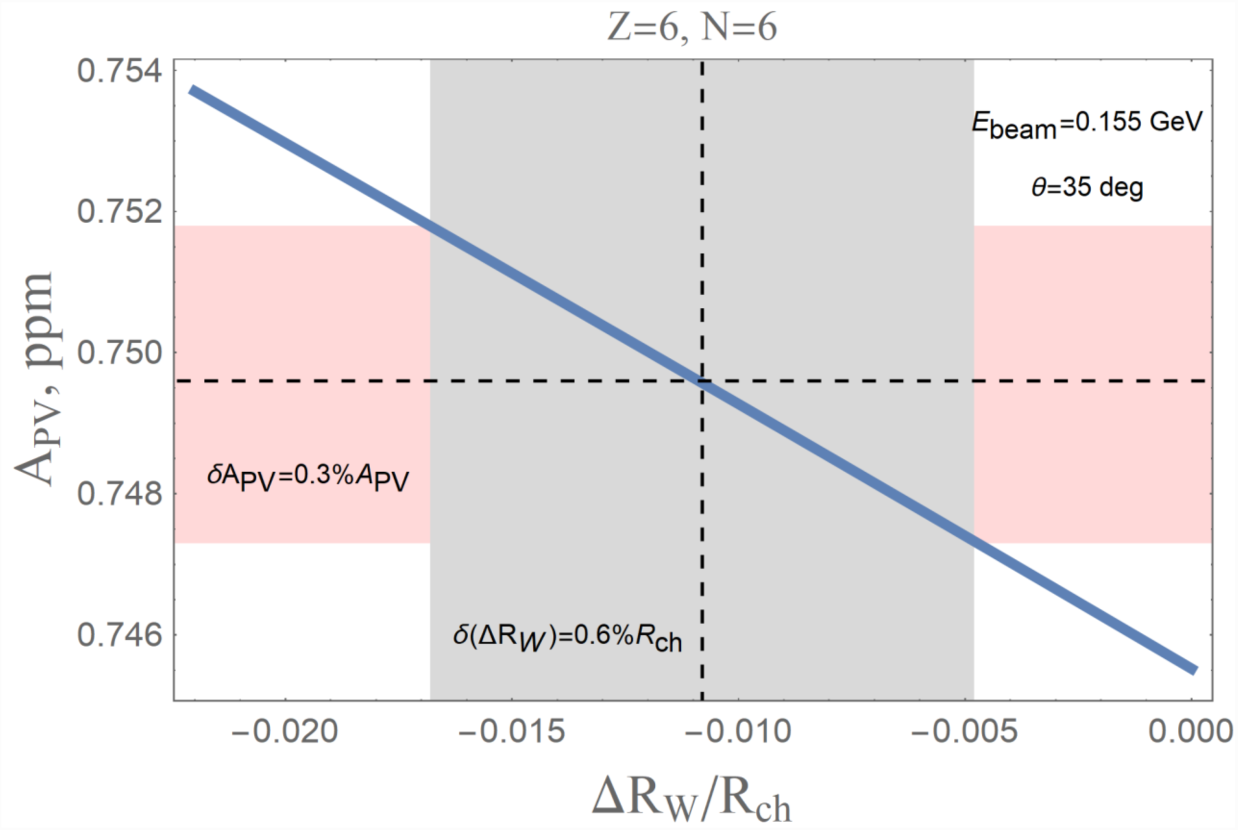
$$\rho_{1(2)}(r) = \rho_{01(02)}\frac{\sinh\left(c_{1(2)}/a_{1(2)}\right)}{\cosh\left(r/a_{1(2)}\right) + \cosh\left(c_{1(2)}/a_{1(2)}\right)}$$

$$\int d^3r\left(\rho_2(r) - \rho_1(r)\right) = 0$$



Can generate non-zero skin by varying parameter(s) $c_1(c_2)$ at fixed $a_1(a_2)$.

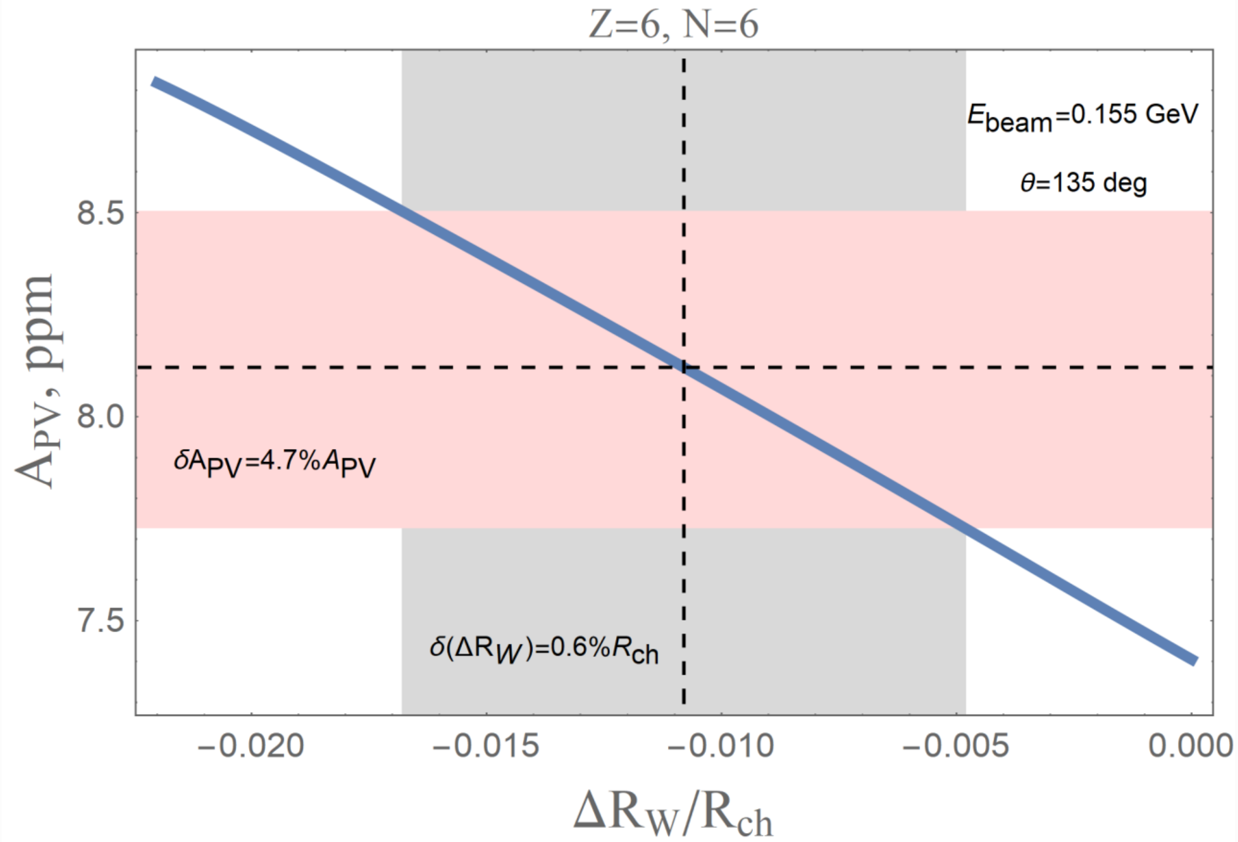
UNCERTAINTY DUE TO WEAK SKIN



$$\Delta R_W \equiv R_W - R_{ch}$$

- MF models suggest that the weak skin of C-12 can be known to 0.6% of R_{ch}. However, p-scattering and ab initio models predict 0 neutron skin for C-12.
- Not to depend on models, we can determine experimentally the weak skin of C-12 to 0.6% by measuring A_{pv}.
- Backward kinematics is favorable for measurement of the skin with A_{pv}.

BACKWARD MEASUREMENT



- The backward measurement would be much more sensitive to the weak skin than the forward measurement.
- Can be implemented in a relatively simple manner at MESA using the experimental setup designed for the forward measurement.
- Downside: the backward measurement may be affected by higher moments of the weak density.

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CONCLUSIONS

- Implemented Coulomb distortion formalism to provide PV asymmetry predictions.
- Studied effects of various nuclear charge distribution parametrizations on PV asymmetries.
- Parametrized weak skin using 2p symmetrized Fermi model. Observed considerable effect of the weak skin on extraction of the weak mixing angle.
- Showed enhancement of the weak skin contribution in backward kinematics. This enhancement can be used to experimentally measure the weak skin of C-12 at MESA.