MREX: The Mainz neutron Radius EXperiment

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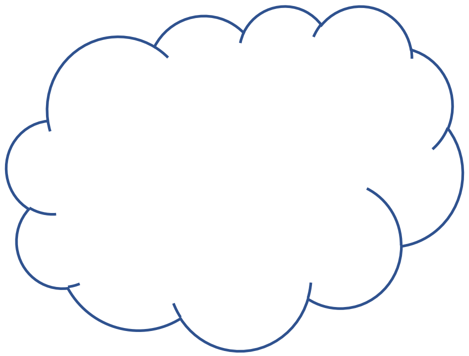
Outline

- Neutron skin and Nuclear Equation of State
- Parity-violating electron scattering
- The Mainz Radius EXperiment (MREX)
  - Experimental setup
  - Simulation framework
  - Systematic uncertainties and measuring time



Neutron skin and EoS

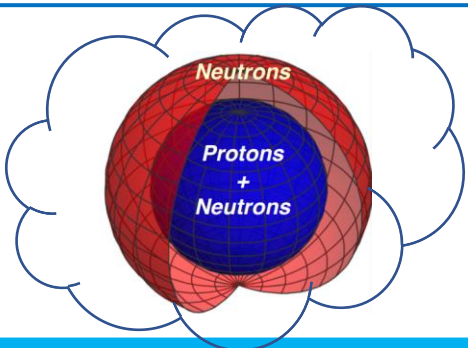
$$\rho(r) = \frac{\rho_0}{1+\exp[(r-C)/a]}$$ — 2pF density distribution

$$\Delta r_{np} = \Delta R_{np} = \langle r^2\rangle_n^{1/2} - \langle r^2\rangle_p^{1/2} = R_n - R_p$$ — NS thickness

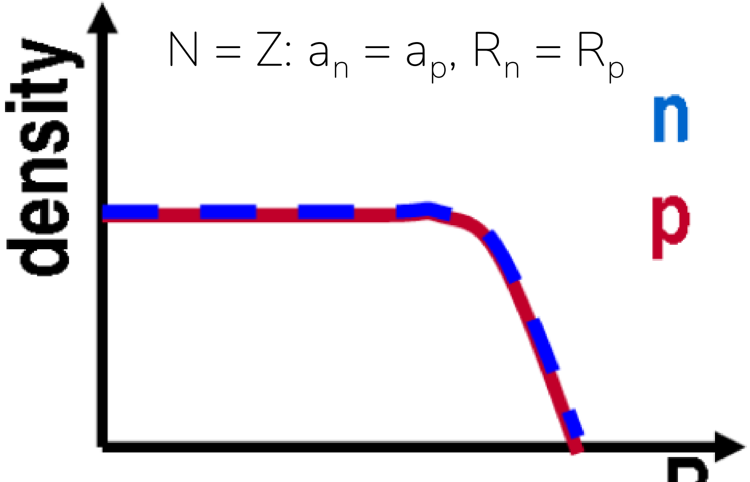
$$\mathcal{E}(\rho,\alpha) = \mathcal{E}_{\text{SNM}}(\rho) + \alpha^2\mathcal{S}(\rho) + \mathcal{O}(\alpha^4),\ \alpha \equiv (\rho_n - \rho_p)/(\rho_n + \rho_p)$$

$$\mathcal{S}(\rho) = J + Lx + \frac{1}{2}K_{\text{sym}}x^2 + \ldots, \quad x = (\rho - \rho_0)/3\rho_0$$

$$L \equiv 3\rho_0 \left(\frac{\partial S}{\partial \rho}\right)\bigg|_{\rho_0}$$ — symmetry energy slope parameter



Symmetry energy ⟷ **Surface tension**



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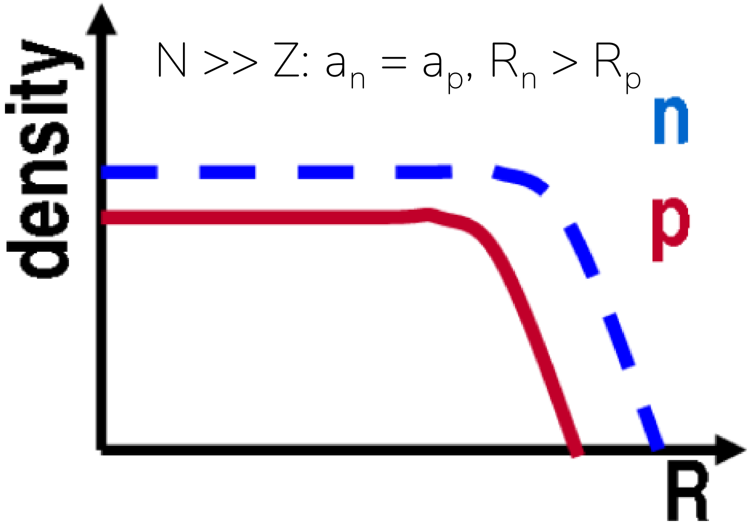
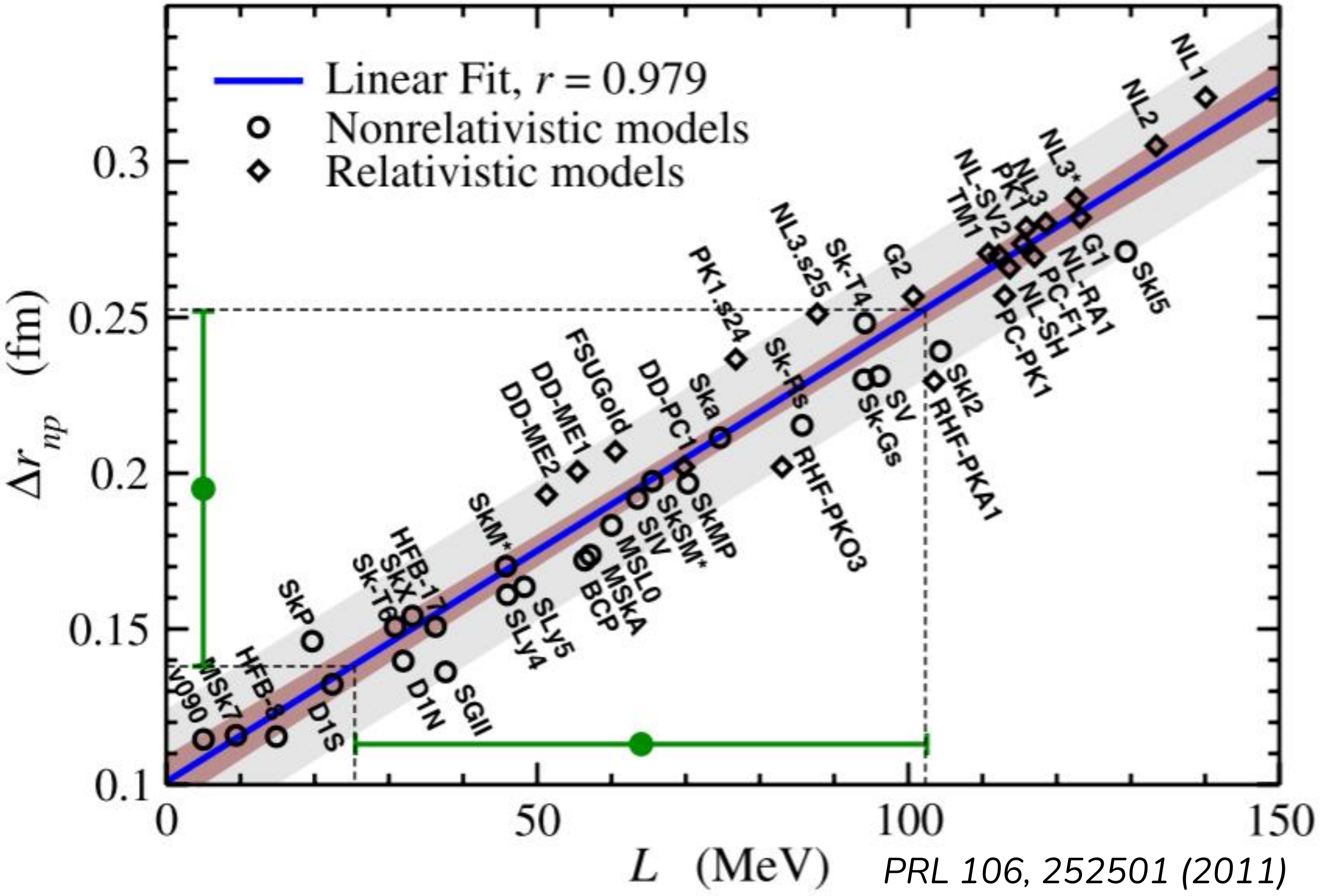


Fig. Schematic representation of neutron and proton density distributions in nuclei

Relation between Δr_{np} and *L*



PRL 106, 252501 (2011)

Fig. Correlation between theoretically predicted neutron skin thickness values in ^{208}Pb and symmetry energy slope

- For ^{208}Pb, many models predict substantially different Δr_{np}
- But there is linear dependence between predicted Δr_{np} and L

“Model-independent” extraction of L from a measurement of neutron skin thickness in ^{208}Pb

Parity-violating electron scattering

- Coupling of the Z^0 boson to neutrons is significantly larger than to protons
- Interference between virtual γ and Z^0 exchange

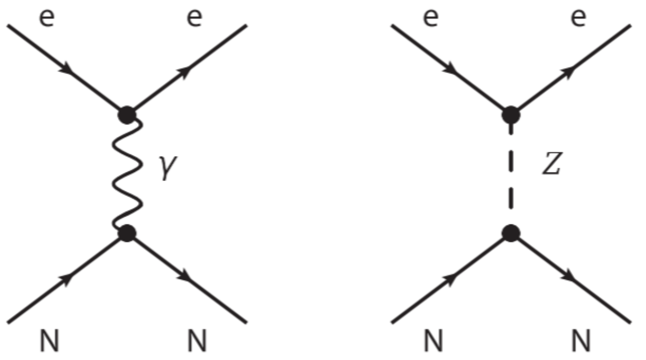


Fig. Electron scattering of nucleus through γ and Z^0 exchange

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

Neutron radius extraction

PREX-II (^{208}Pb): $\Delta r_{np} = 0.28 \pm 0.07$ fm

550±24 seconds in 32 years

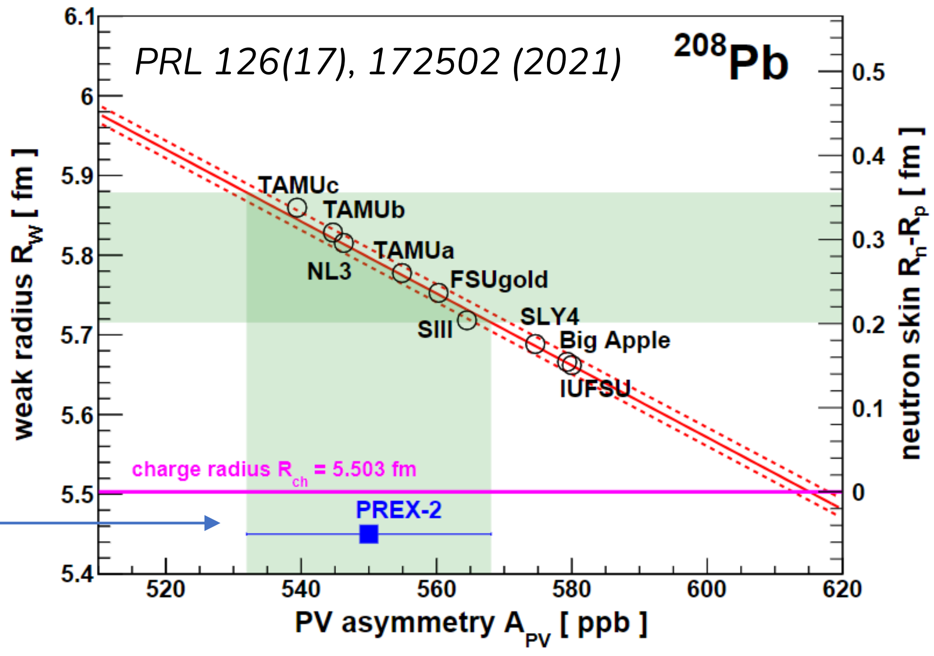
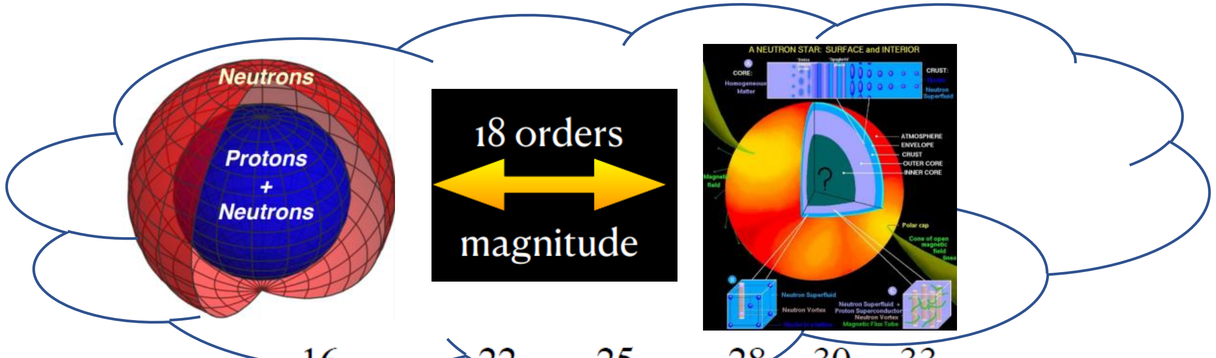


Fig. Correlation between A_{PV}, R_W and Δr_{np} in ^{208}Pb at PREX

Astrophysics connection

- Connection between R_{skin} and $R_\star$ through EoS
- Bound on $\Lambda_\star$ from LIGO-Virgo observation of gravitational wave from a binary neutron star inspiral (GW170817)
- NICER measurement of $R_\star$: X-ray from PSR J0030+0451

Slight tension



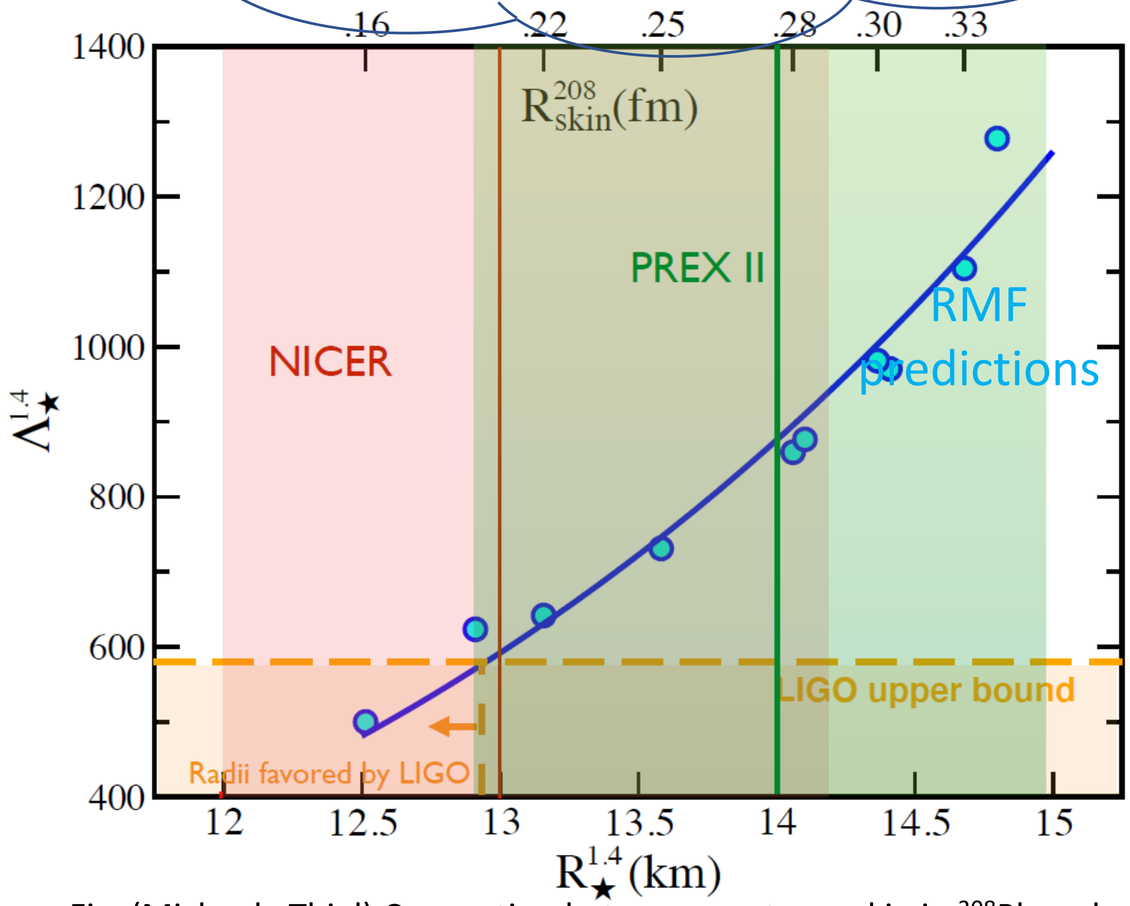
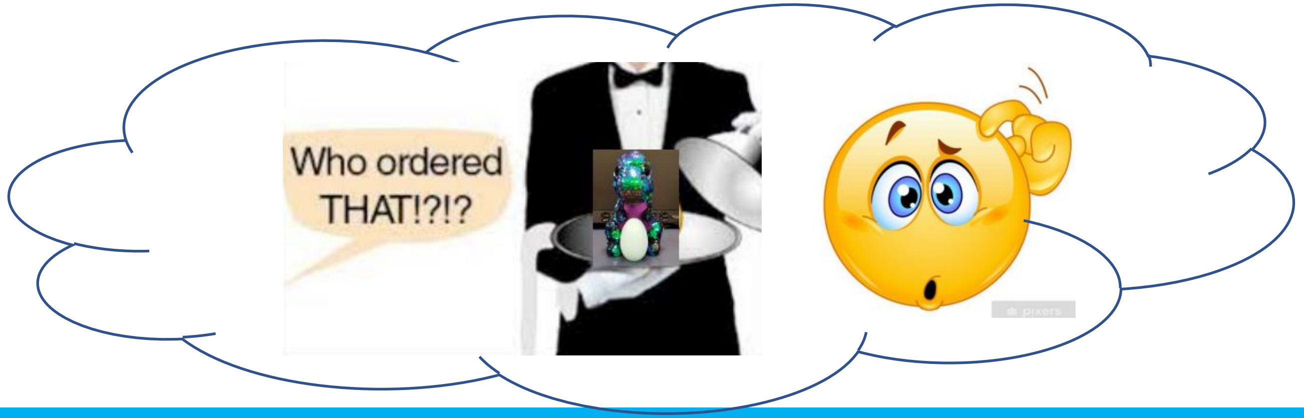


Fig. (Michaela Thiel) Connection between neutrons skin in ^{208}Pb and astrophysical observables

Reasons for MREX

Why PREX is not enough?

- Slight tension with LIGO observation
- Statistical uncertainty must be decreased
- Contradicts CREX (same setup but ^{48}Ca target) in measured *L*



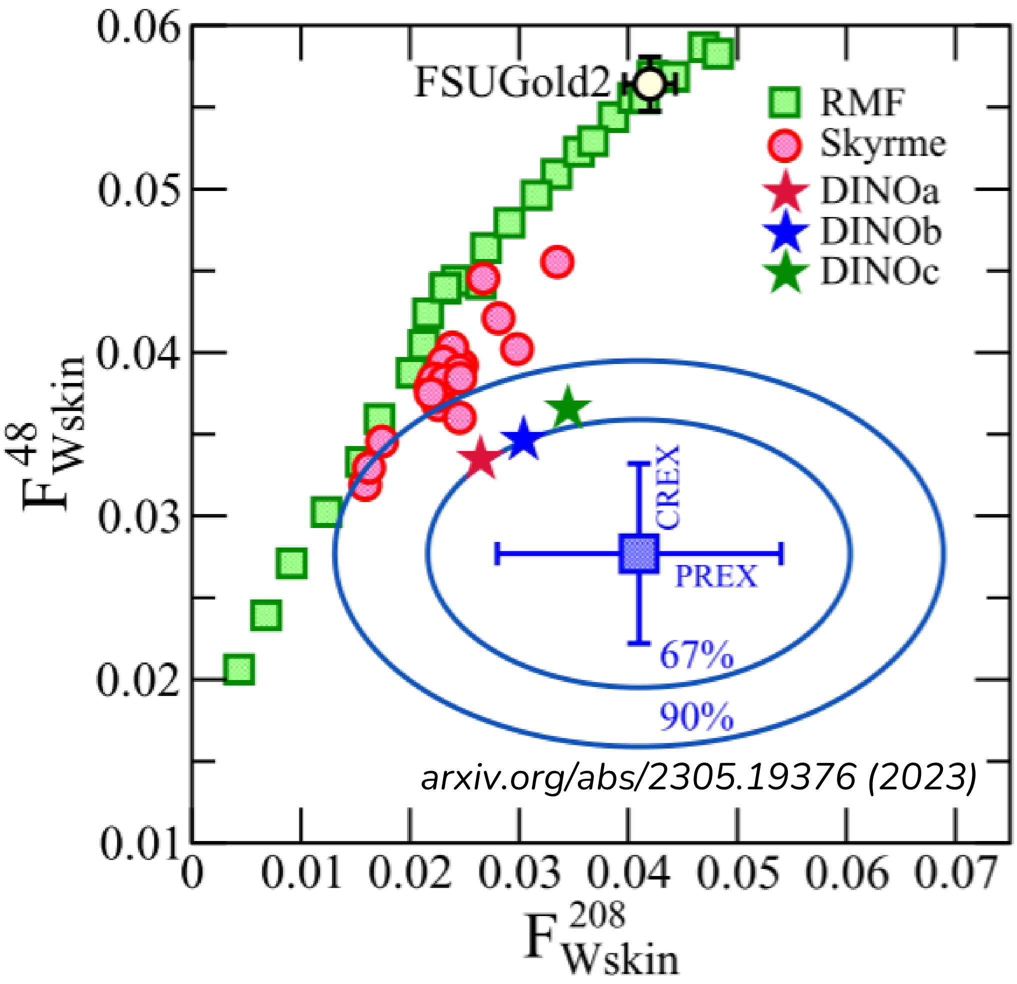


Fig. PREX and CREX results for weak form-factor of ^{208}Pb and ^{48}Ca and theoretical prediction of different models

MESA and P2 Experiment

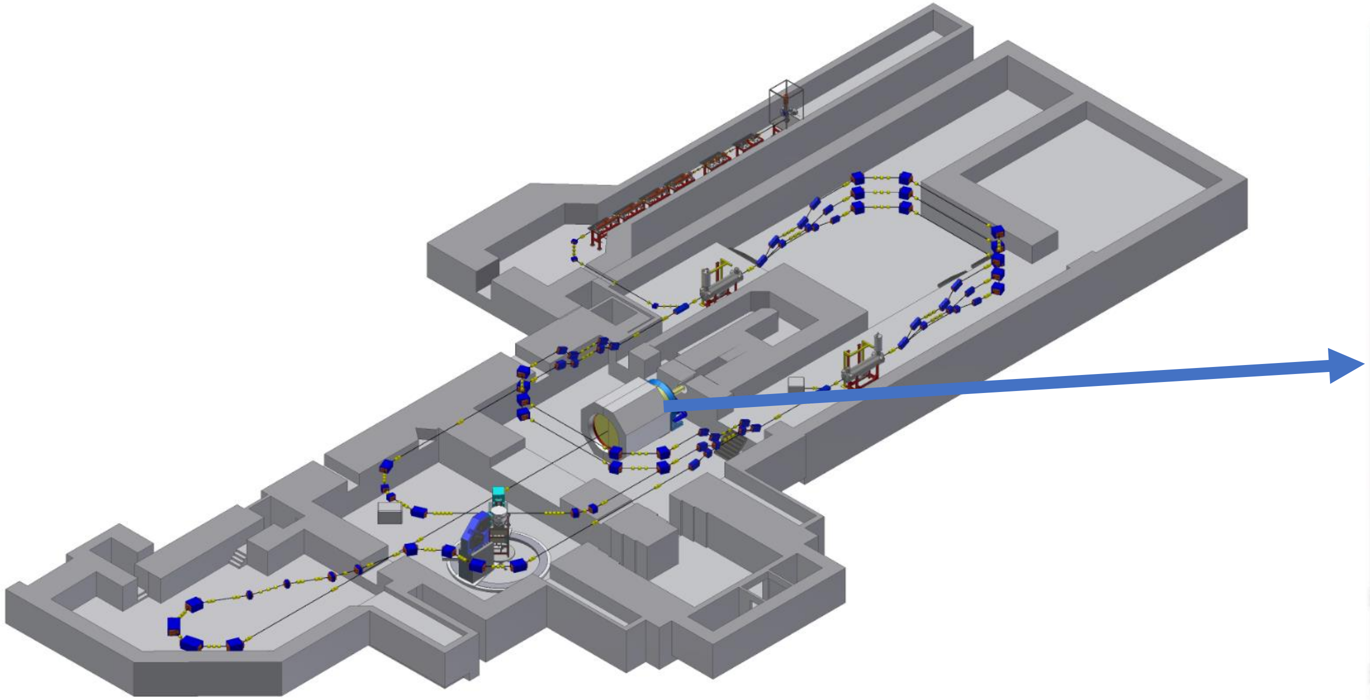


Fig. MESA layout

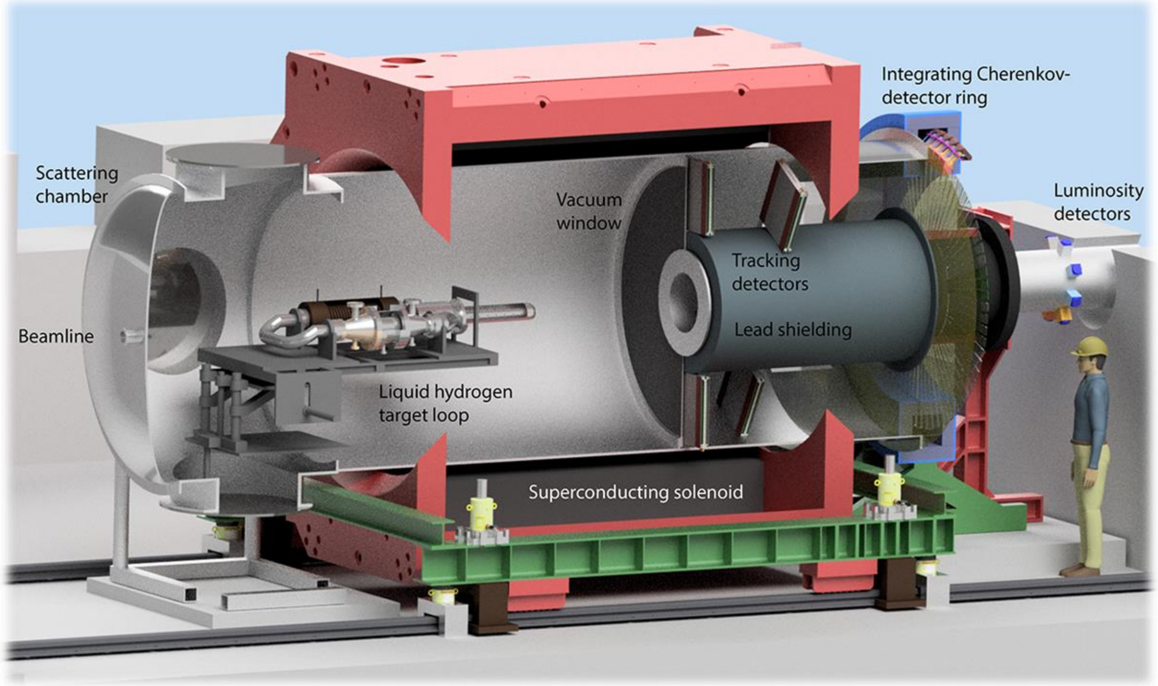


Fig. P2 experiment set-up

- Electron beam with kinetic energy of 55/155 MeV
- 150 μA beam current in polarized mode
- Polarization measurement with <1% accuracy

- High-precision measurement of $\sin^2\theta_W$
- Exchange hydrogen with ^{208}Pb for MREX

Outline for MREX

Average momentum transfer of $Q^2 = 0.0062\ (\mathrm{GeV/c})^2$ to match PREX kinematics and maximize sensitivity to neutron skin

$$Q^2 = -q^2 = -(p - p')^2 = \frac{4EE'}{c^2} \cdot \sin^2\left(\frac{\theta}{2}\right)$$

$$\mathrm{FOM} = \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \times \left(A^{\mathrm{PV}}\right)^2 \times \varepsilon^2 \quad \varepsilon = \frac{\mathrm{d}\ln(A^{\mathrm{PV}})}{\mathrm{d}\ln(R_{\mathrm{n}})} = \frac{R_{\mathrm{n}}}{A^{\mathrm{PV}}}\frac{\delta A^{\mathrm{PV}}}{\delta R_{\mathrm{n}}}$$

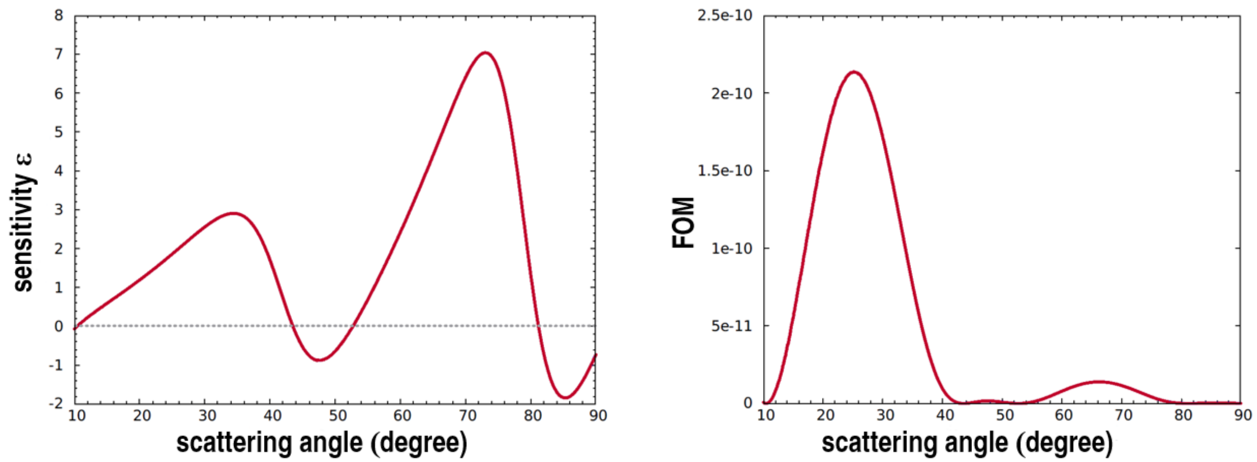
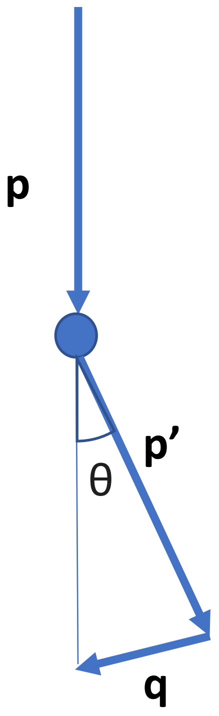


Fig. Theoretical (Chuck Horowitz) predictions for e^--^{208}Pb scattering characteristics at 155 MeV



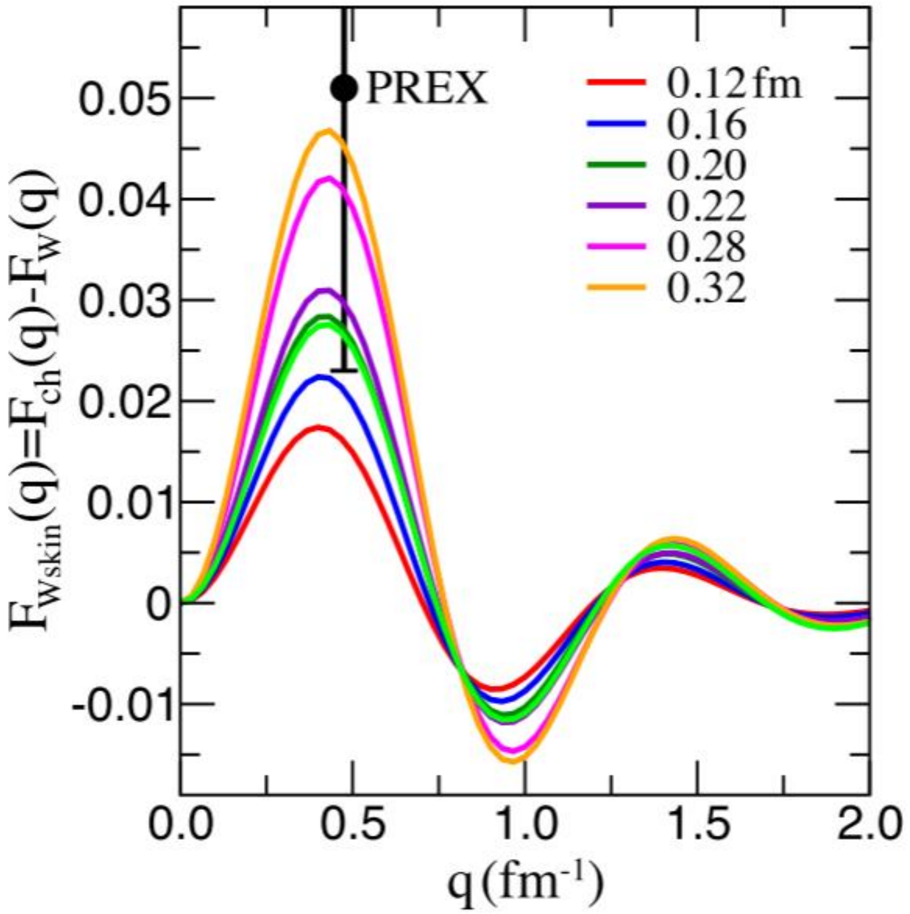


Fig. Theoretical predictions of F_{weak} for nuclei with different NS thickness

Solenoid geometry

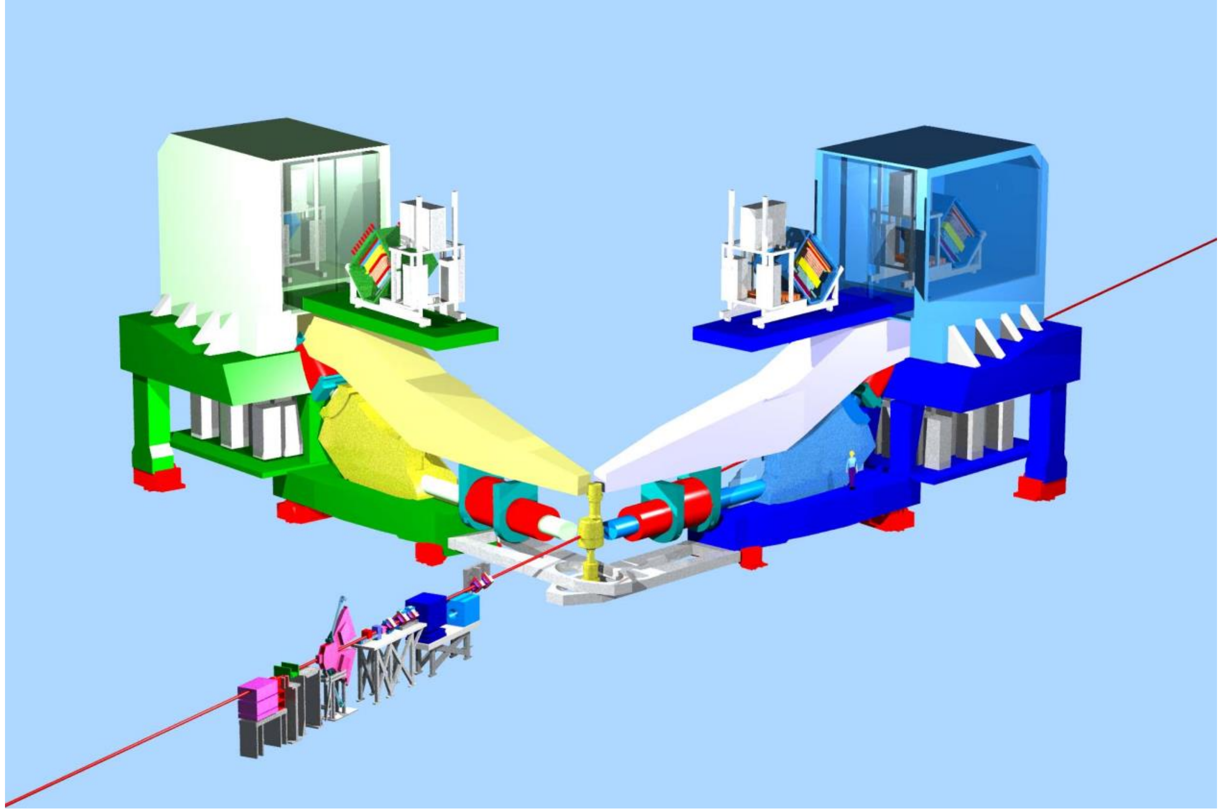


Fig. PREX spectrometer setup

B = 0.70 T, target center @ z = -360 mm

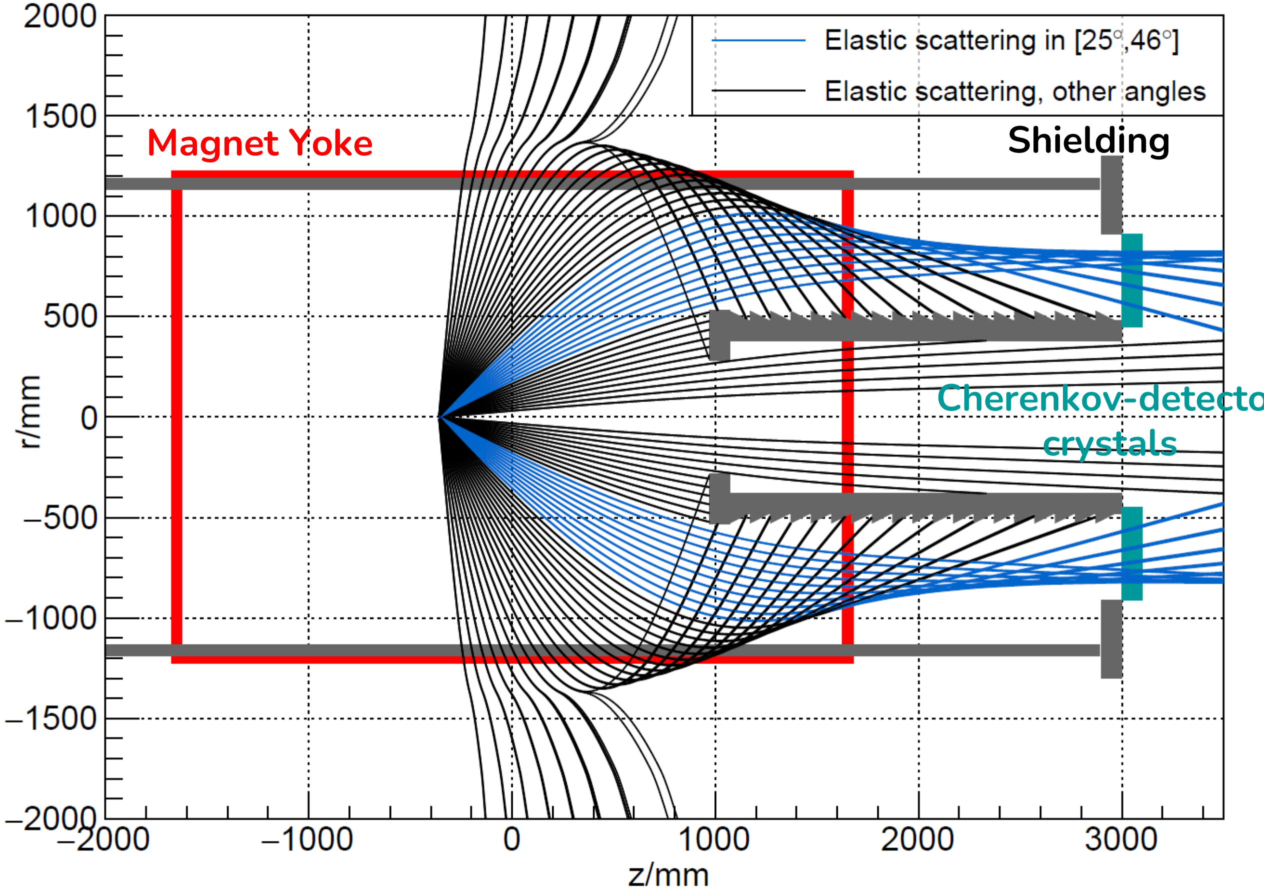


Fig. Tracks of elastically scattered electrons in P2 solenoid

Need to match momentum transfer while maximizing signal from elastic line

Full Monte-Carlo simulation

- Initially created for P2
- Geant4 framework
- Full experimental setup
- Energy deposition
- Secondary particles
- Target background
- Vertex generator
- Scattered electrons generator
- Detector response

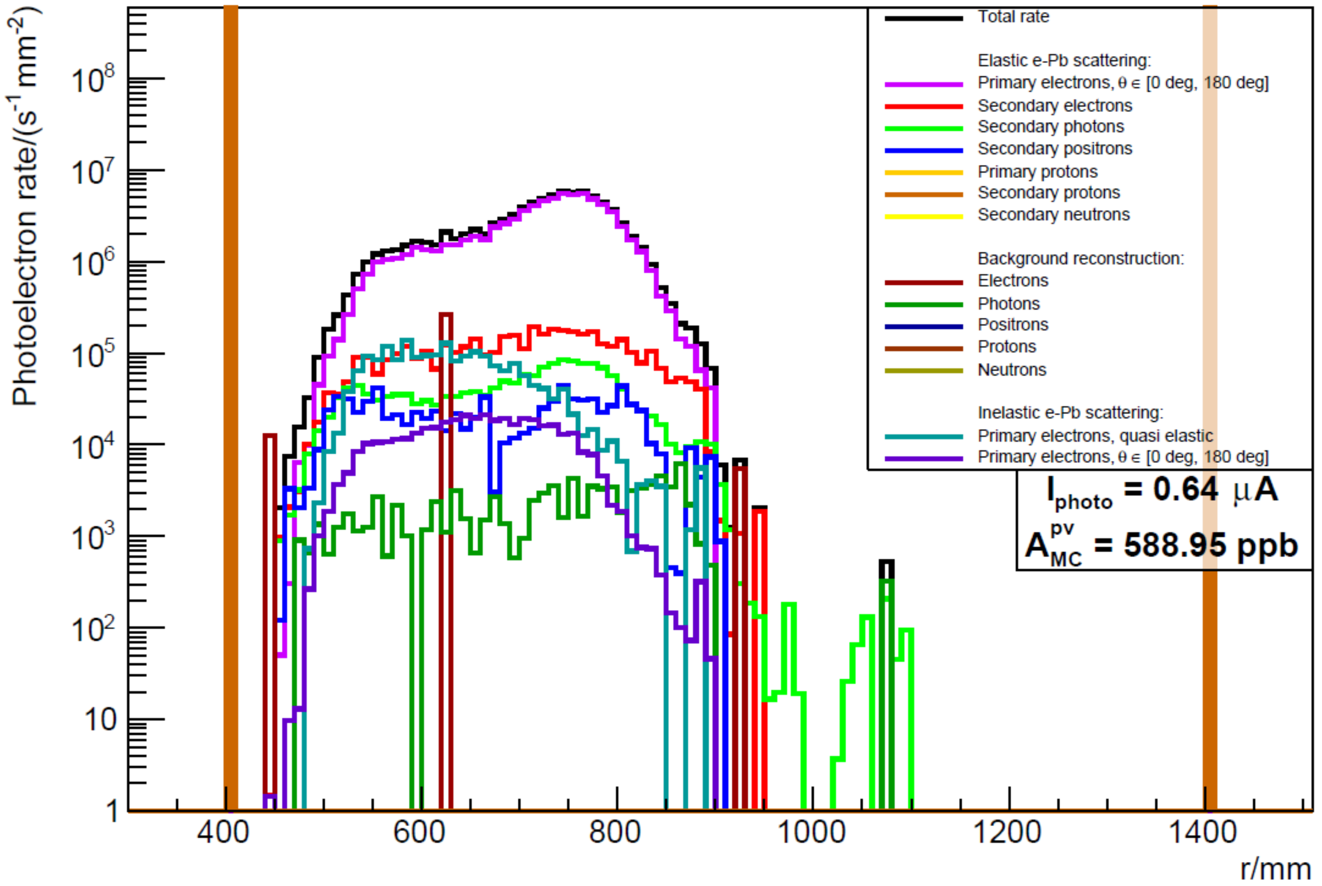


Fig. Radial dependence of the photoelectron rate in Cherenkov detector from different particles

Non-elastic contributions

- Solenoid geometry leads to excitation energy acceptance of around 25 MeV
- Each non-elastic contribution has its own asymmetry
- Target background and secondary produced particles changes the measured asymmetry

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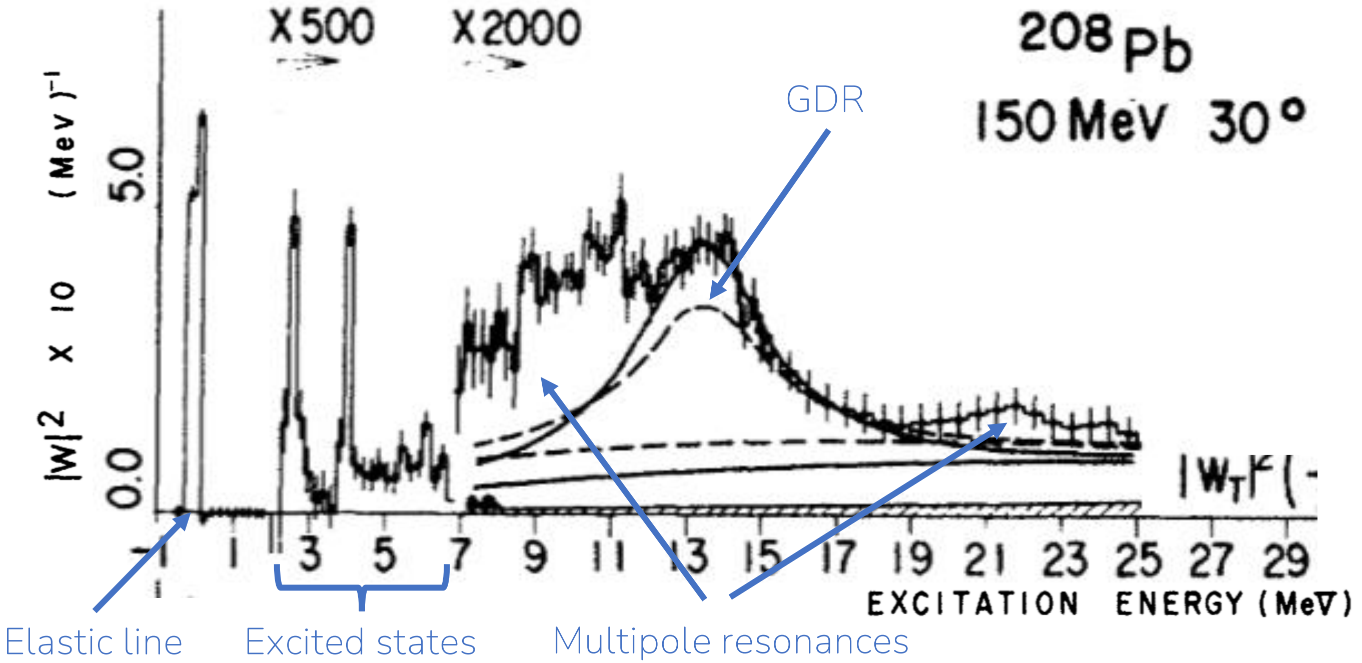


Fig. Spectra of e-^{208}Pb scattering at 150 MeV and 30°

$$A^{meas} = (1 - \sum f_i)A^{el} + \sum f_i A_i, \text{ or}$$

$$A^{el} = \frac{A^{meas} - \sum f_i A_i}{(1 - \sum f_i)}.$$

$$\Delta A_i^f = \frac{A^{meas} - A_i}{(1 - \sum f_i)^2}\Delta f_i,$$

$$\Delta A_i^A = \frac{f_i \Delta A_i}{(1 - \sum f_i)}.$$

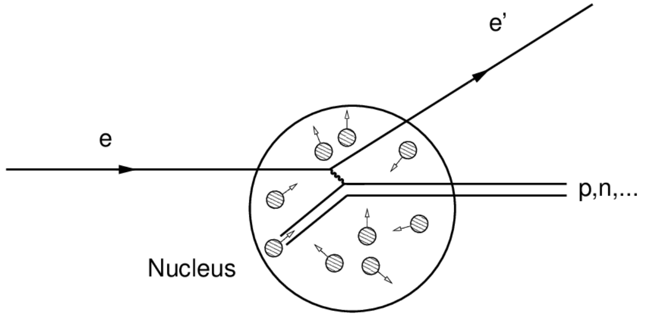
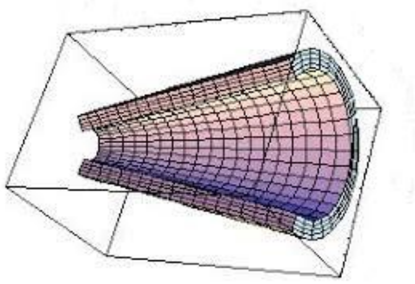


Fig. Quasielastic electron scattering on nucleus

Additional shielding

- Need a way to reduce uncertainty from inelastic contribution
- Moving target backwards can help, but need to stick to the same Q^2

Additional conical shielding next to target



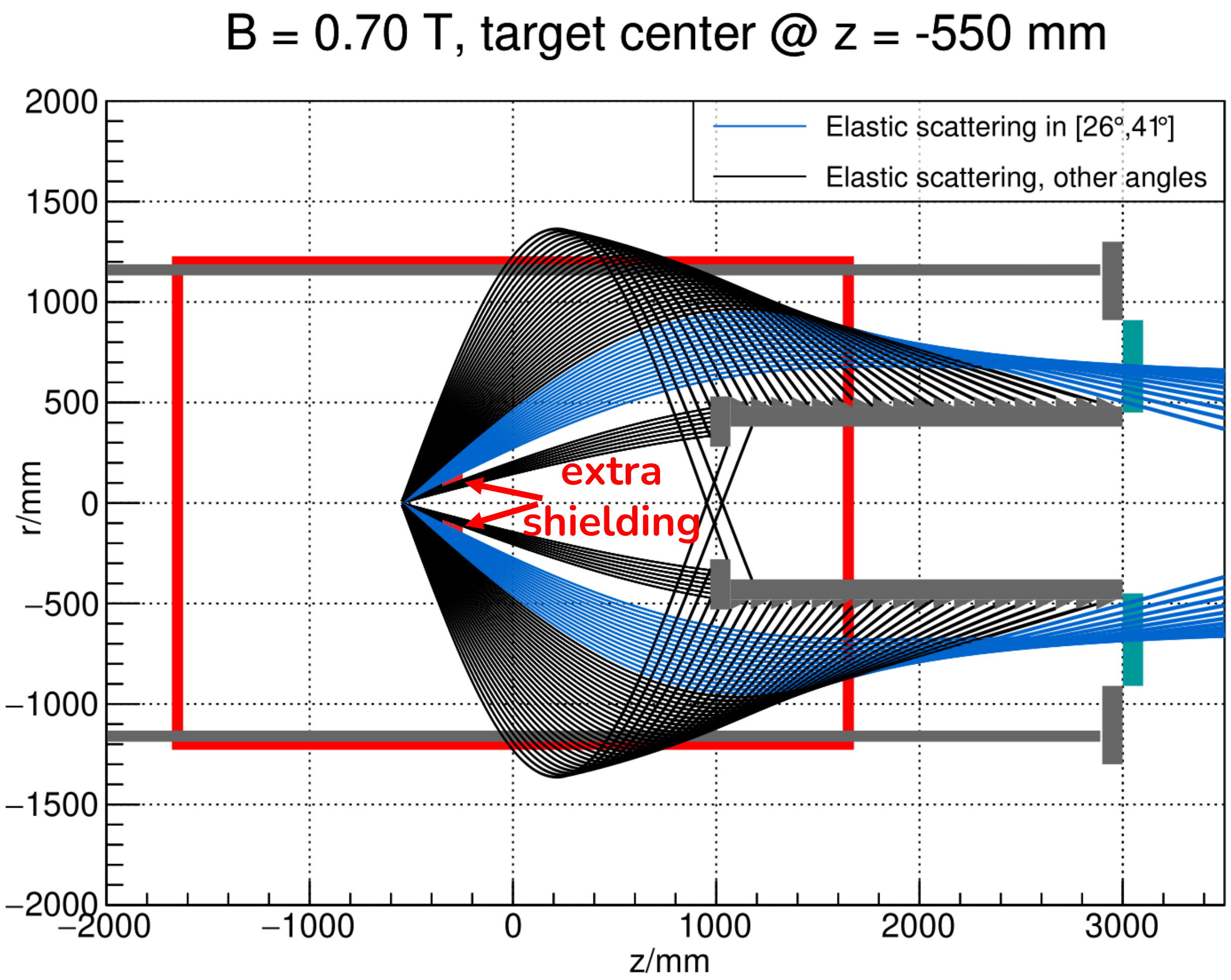


Fig. Tracks of elastically scattered electrons in P2 solenoid with additional shielding

Uncertainty from asymmetry correction

Define uncertainty from different contributions

Contribution i	3^- and 2^+	MR	Other Inel.	QE	TBG	Secondary
ΔA_i	$0.625 \cdot A_{el}$	$0.625 \cdot A_{el}$	$1.5 \cdot A_{el}$	$A_{el} + \lvert A_{QE} \rvert$	0	$\lvert A_{el} - A_{Secondary} \rvert$
$\Delta f_i / f_i$	20%	50%	100%	100%	10%	10%

$$A^{meas} = (1 - \sum f_i) A^{el} + \sum f_i A_i$$

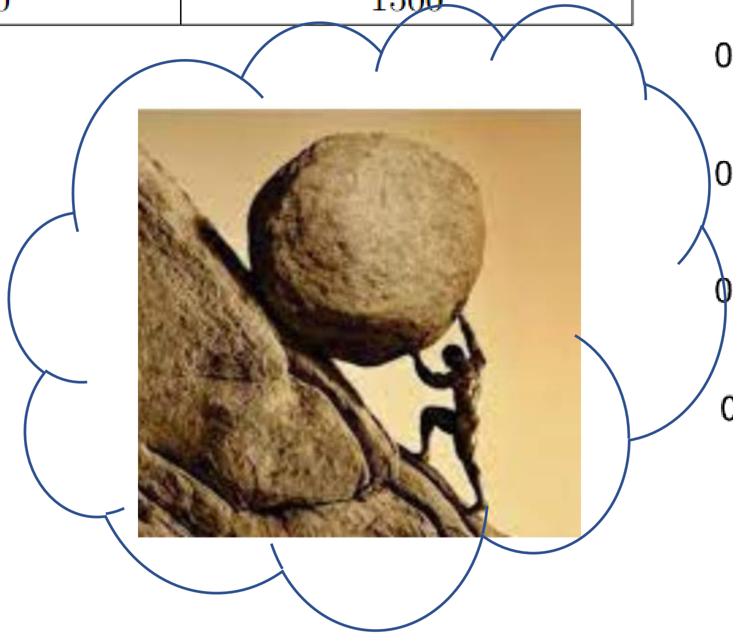
Extract final uncertainty from each contribution

Contribution i	No additional shielding			With additional shielding		
	ΔA_i^f, ppb	ΔA_i^A, ppb	ΔA_i, ppb	ΔA_i^f, ppb	ΔA_i^A, ppb	ΔA_i, ppb
Secondary electrons	0.06	0.51	0.51	0.01	0.05	0.05
Secondary photons	0.07	0.62	0.63	0.04	0.34	0.34
Secondary positrons	0.01	0.04	0.04	0.01	0.05	0.05
Target background	0.08	0.18	0.20	0.06	0.15	0.16
3^- 2.615 MeV	0.10	0.46	0.47	0.07	0.43	0.44
2^+ 4.085 MeV	0.05	0.35	0.36	0.04	0.34	0.34
MR below GDR	0.18	0.52	0.55	0.14	0.49	0.51
Other Inelastic	0.52	0.72	0.88	0.42	0.59	0.73
Quasielastic electrons	1.20	1.34	1.8	0.73	0.80	1.08
Total ΔA_{ne}, ppb		2.31			1.55	

Acceptance and measuring time

Assuming additional 1% systematic uncertainty from beam monitors:

	No additional shielding	With additional shielding
Time for 1% in R_n, h	66	74
Time for 0.6% in R_n, h	390	400
Time for 0.5% in R_n, h	2300	1500



Further work:

- Uncertainty constrain
- Radiation simulation
- Target and shielding development

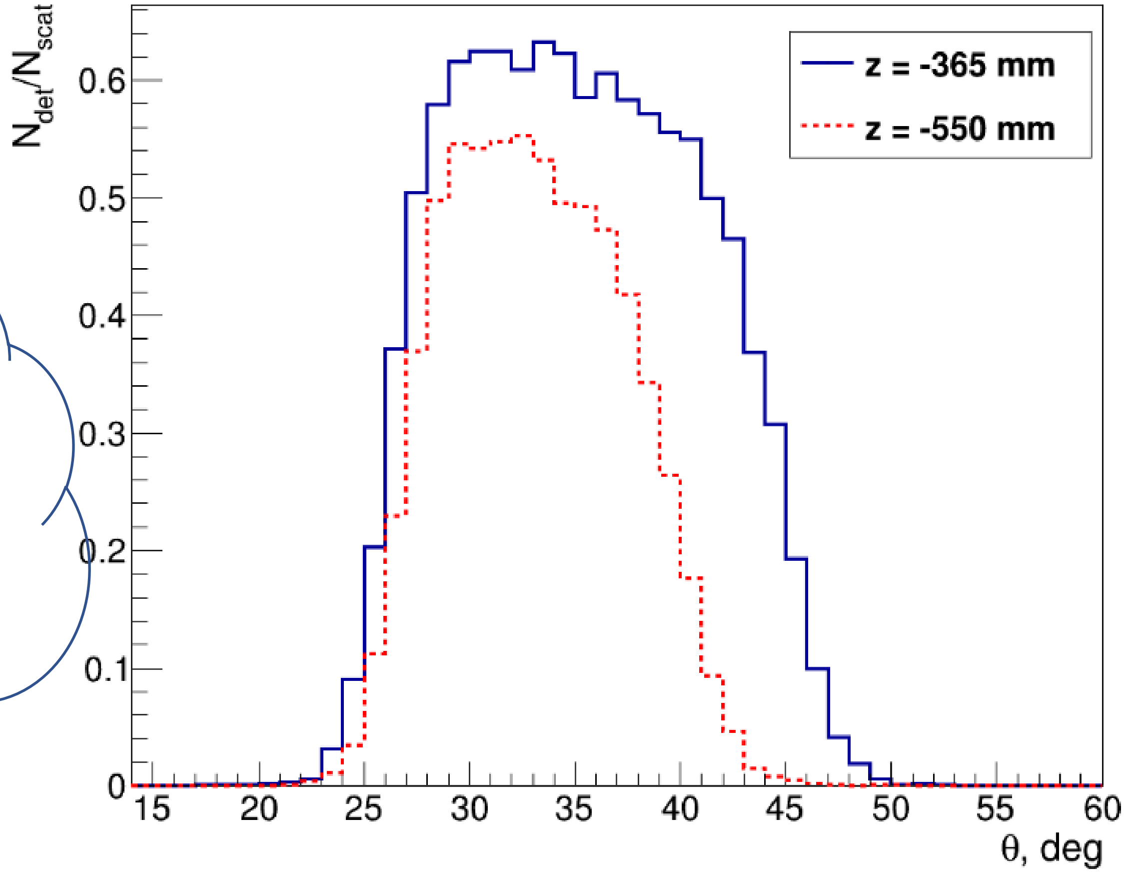


Fig. Fraction of elastically scattered electrons reaching the detector with and without additional shielding

Summary

- Experimental measurement of neutron skins in nuclei allows to constrain Nuclear Equation of State parameterization
- PREX measurement of neutron skin in ^{208}Pb must be cross-checked
- MESA and P2 experimental setup allow for MREX to do that
- Monte-Carlo simulation confirm that MREX can reach necessary neutron radius uncertainty in reasonable measuring time

Thank you for your attention!