The Mainz Radius EXperiment (MREX): neutron skin measurement at MESA

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Outline

- Neutron skin and nuclear equation of state
- Theoretical predictions and experimental measurement of neutron skin
- Mainz Energy-Recovering Superconducting Accelerator and P2 experiment
- The Mainz Radius EXperiment (MREX)

Nucleon density distribution

- Neutrons and protons inside a nucleus are hold by various potentials, resulting in nucleon "droplet"
- Nucleon densities in this droplet are well described by 2-parameter Fermi distribution:

$$\boxed{\rho(r) = \frac{\rho_0}{1 + \exp\left[(r - C)/a\right]}}$$

- Proton density distributions are measured by elastic electron-nucleus scattering experiments

But what about neutrons?

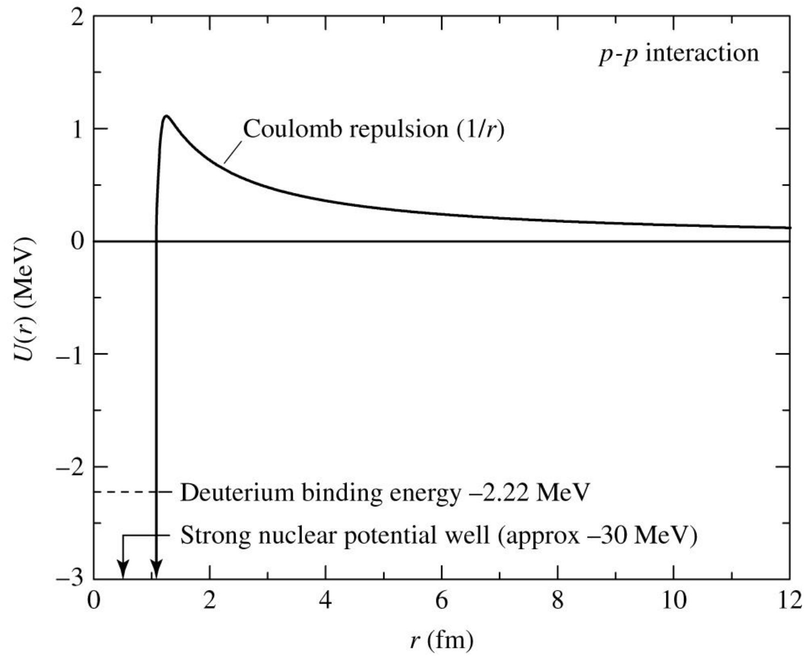

Fig.1 Potential between two interacting protons

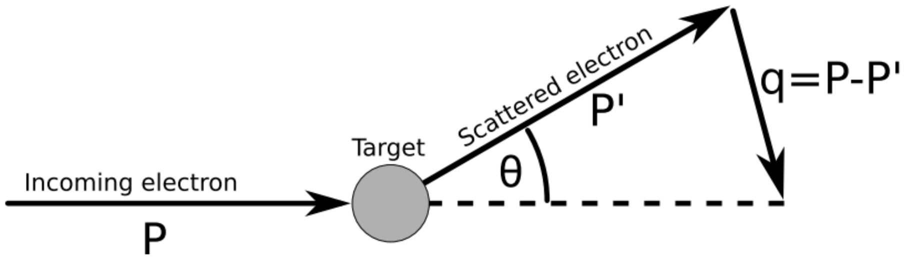

Fig.2 Schematic visualization of electron scattering

Neutron skin

- For symmetrical (N = Z) matter, neutron and proton densities are almost the same.
- In case of heavy neutron rich (N >> Z) nuclei neutrons are pushed out towards the nuclear surface, creating neutron skin
- As a result, root-mean-square radiuses of protons and neutron distributions differ by the value referred to as **neutron skin thickness**:

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

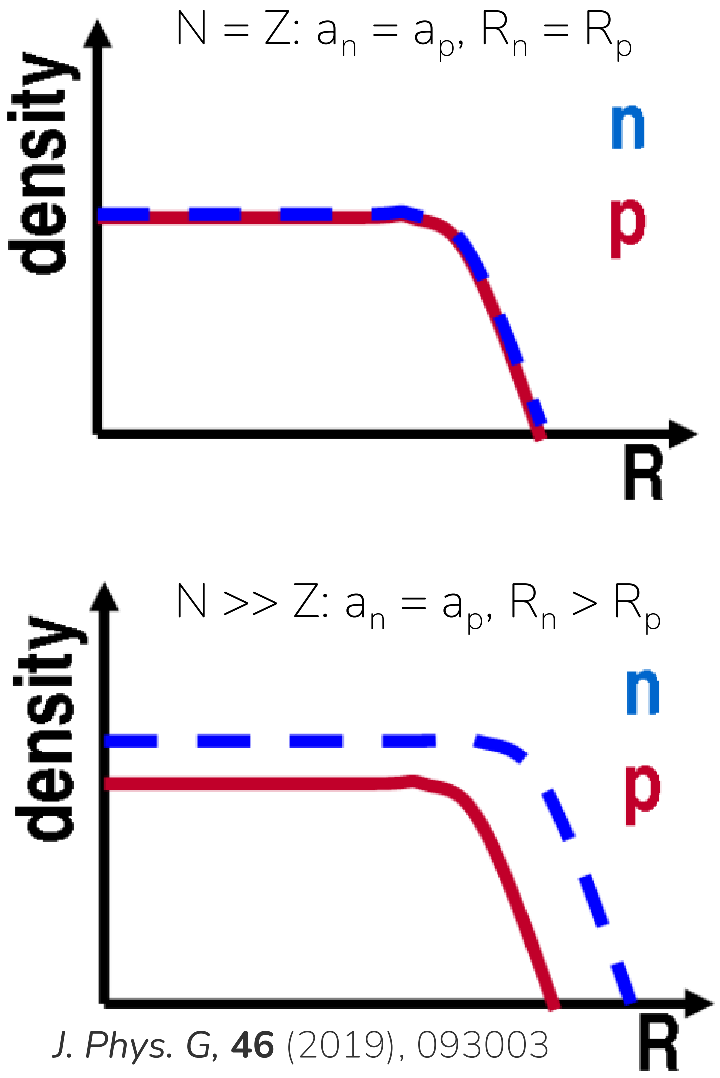

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Fig.3 Schematic representation of neutron and proton density distributions in nuclei

Equation of State

- Equation of state (EOS) - nontrivial relation between thermodynamic variables characterizing a medium
- Necessary for description of any kind of matter
- Nuclear EOS describe the energy per nucleon as a function of the neutron and proton densities
- Plays role in description of early Universe, nucleosynthesis, neutron stars, supernovae, heavy-ion collision and nuclear structure (including **neutron skin**).

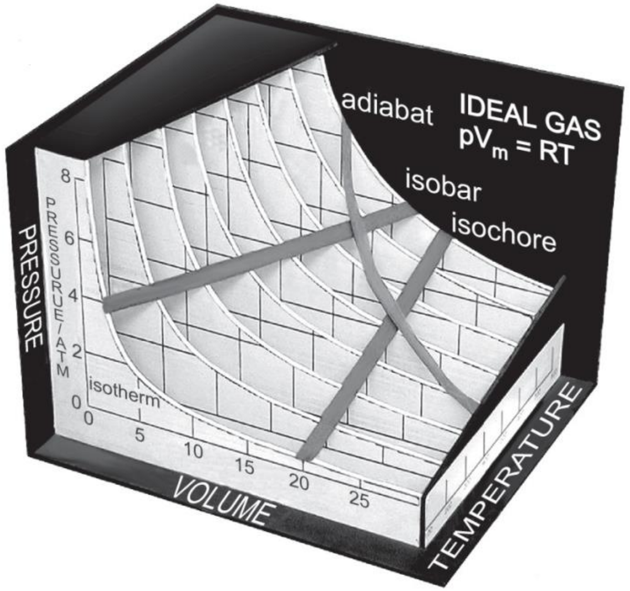

Fig.4 Ideal gas EOS representation

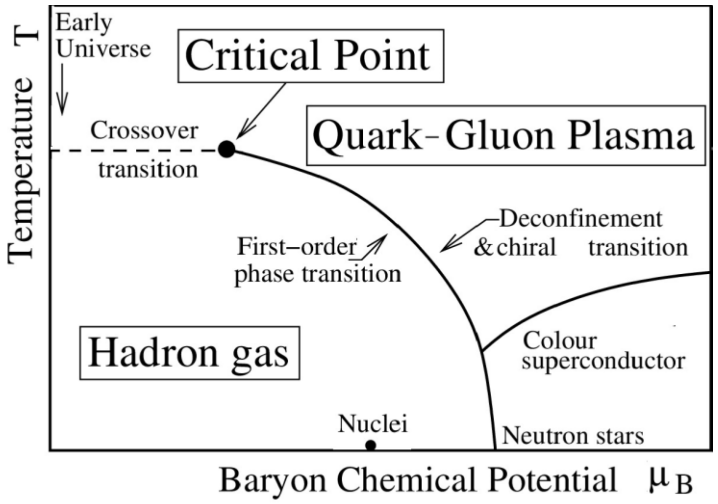

Fig.5 QCD phase diagram

Liquid drop model and nuclear EOS

- Empirical parameterization of nucleus binding energy within Liquid Drop Model (LDM):

$$B(Z,N) = a_{\mathrm{v}}A - a_{\mathrm{s}}A^{2/3} - a_{\mathrm{c}}\frac{Z^2}{A^{1/3}} - a_{\mathrm{a}}\frac{(N-Z)^2}{A} + \dots$$

Binding energy per nucleon   Surface tension   Coulomb repulsion among protons

Pauli exclusion principle + strong isovector interactions that favors symmetric systems

- It is assumed that the drop is incompressible and has constant density: $\rho_0 = \frac{3A}{4\pi R^3} \approx 0.15\ \mathrm{fm}^{-3}$

- To meet EOS definition, one must go to thermodynamic limit, when A->∞, but N:Z remains:

$$\mathcal{E}(\rho_0,\alpha) \equiv -\frac{B(Z,N)}{A} = (\varepsilon_0 + \alpha^2 J)$$

$$\varepsilon_0 = -a_{\mathrm{v}},\ \ J = a_{\mathrm{a}},\ \ \text{and}\ \ \alpha \equiv (\rho_n - \rho_p)/(\rho_n + \rho_p)$$

- This can not describe density fluctuations, so, one must introduce density dependence:

$$\mathcal{E}(\rho,\alpha) = \mathcal{E}_{\mathrm{SNM}}(\rho) + \alpha^2\mathcal{S}(\rho) + \mathcal{O}(\alpha^4)$$

Symmetric nuclear matter: N = Z   Symmetry energy

Symmetry energy and its slope

The nuclear symmetry energy S describes an increase in energy as matter changes from a symmetric configuration of equal numbers of neutrons and protons

Performing a Taylor series expansion around saturation density we get:

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

$$\boxed{L \equiv 3\rho_0 \left(\frac{\partial S}{\partial \rho}\right)\bigg|_{\rho_0}}$$

symmetry energy slope parameter (a measure of the slope of the symmetry energy at saturation)

Thus, neutron skin can be explained as a result of a **balance** between the **symmetry energy**, which is smaller on the nuclear periphery because of lower density, and **surface tension**, which rises towards nuclear surface

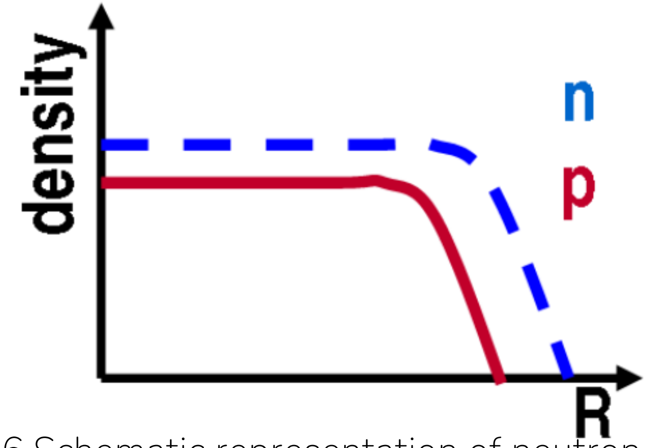

Fig.6 Schematic representation of neutron skin

Relation between Δr_{np} and *L*

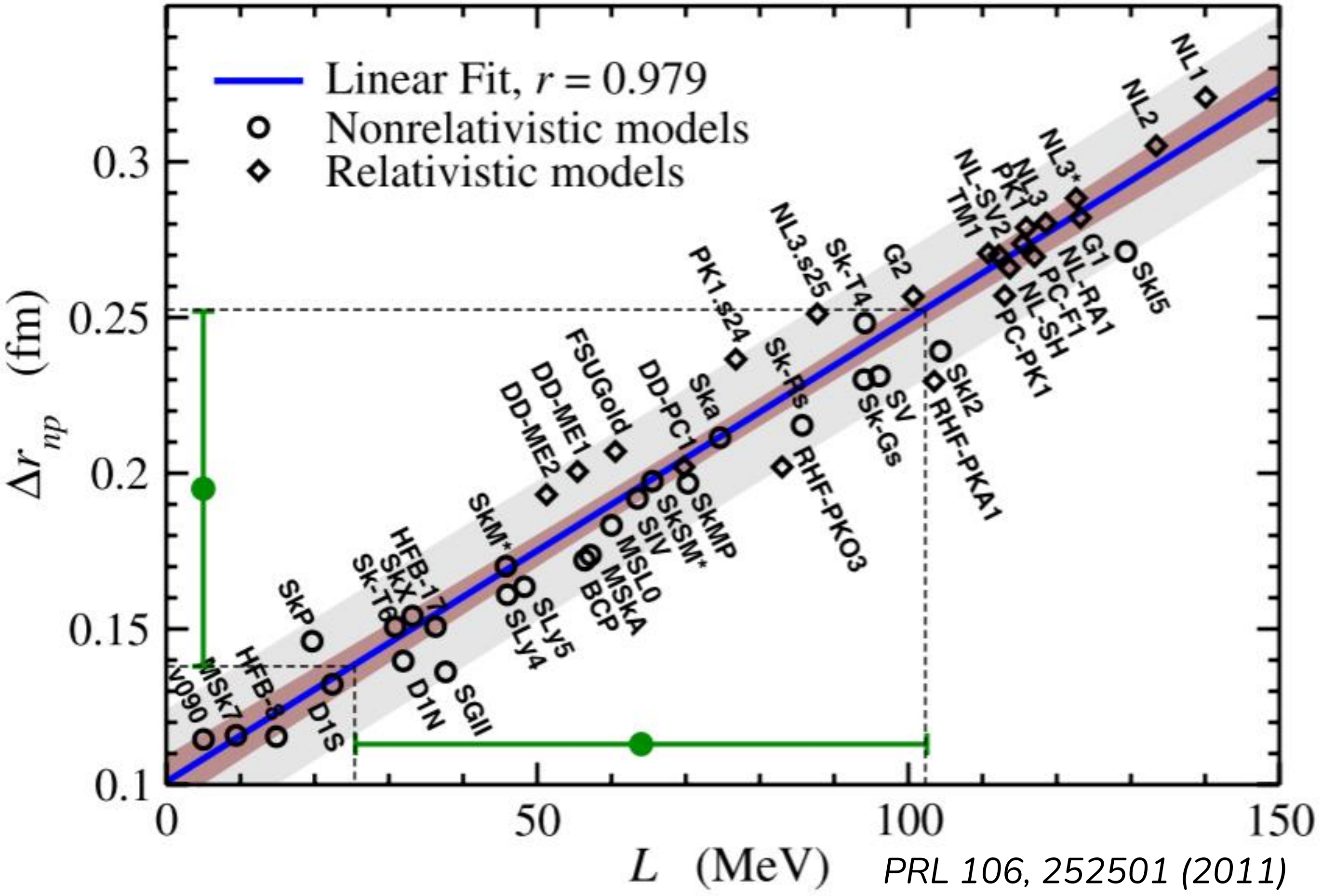

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Fig.7 Correlation between theoretically predicted neutron skin thickness values in ^{208}Pb and symmetry energy slope

- For ^{208}Pb nucleus, many theoretical models predict substantially different neutron skin thickness Δr_{np}
- However, there is clear linear dependence between Δr_{np} and L predicted by these models
- This allows for 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, and right- and left-handed electrons interact with neutrons with different cross-sections.

- This leads to parity-violating asymmetry in electron-nucleus scattering:

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

- PREX experiment used that to determine the neutron skin thickness of ^{208}Pb: $\Delta r_{np} = 0.28 \pm 0.07$ fm

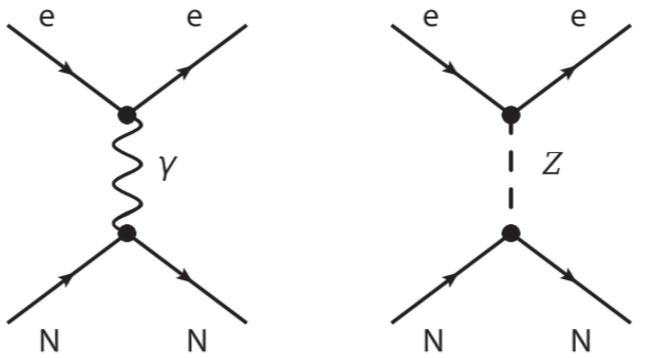


Fig.8 Feynman diagrams for electron scattering of nucleus

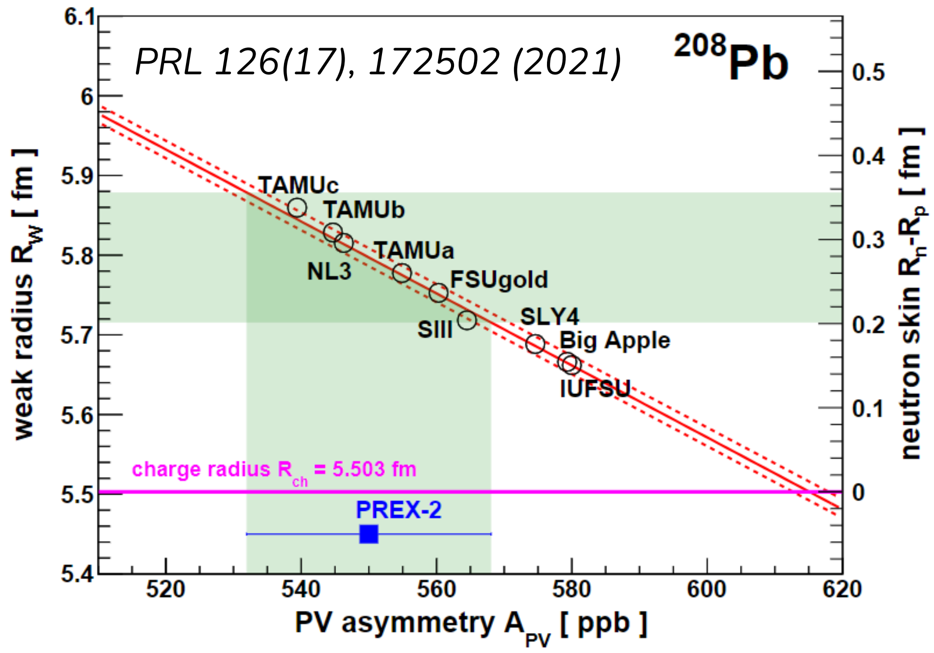


Fig.9 Correlation between A_{PV}, R_W and Δr_{np} in ^{208}Pb at PREX

Motivation for the Mainz Radius EXperiment

MREX is intended to reproduce or confront the PREX measurement. This is necessary because:

- PREX contradict multiple previous measurements of Δr_{np} of ^{208}Pb, obtained through different methodology
- PREX result has substantial statistical uncertainty
- PREX contradict CREX (same setup but ^{48}Ca target) in measured *L*, and no theoretical model reproduce both PREX and CREX results within 1σ

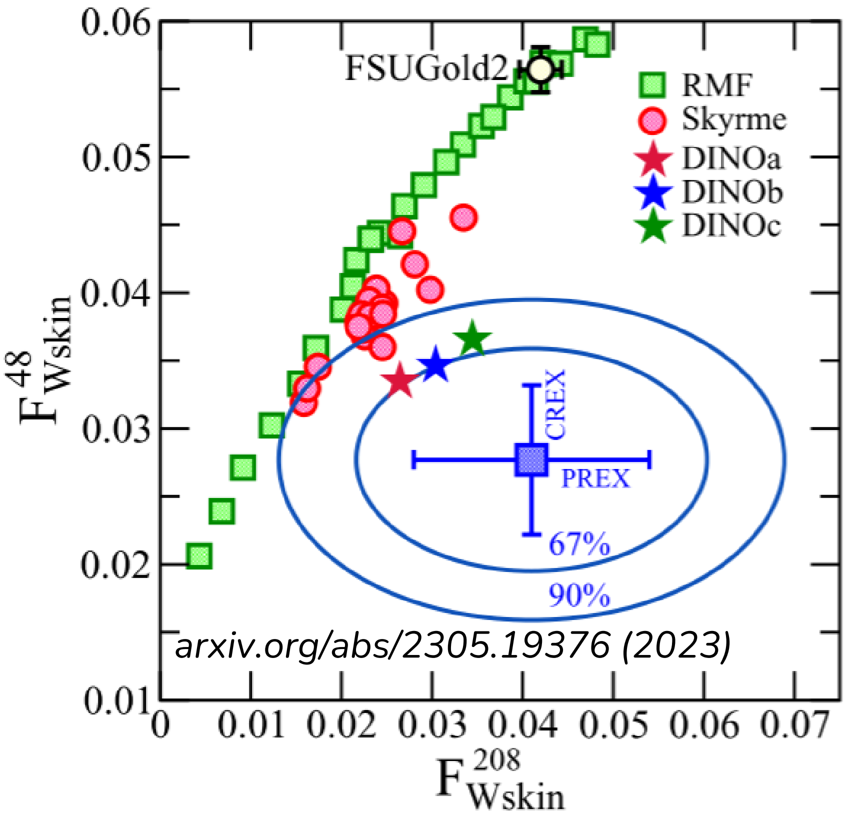


Fig.10 PREX and CREX results for weak form-factor of ^{208}Pb and ^{48}Ca and theoretical prediction of different models

Mainz Energy-Recovering Superconducting Accelerator

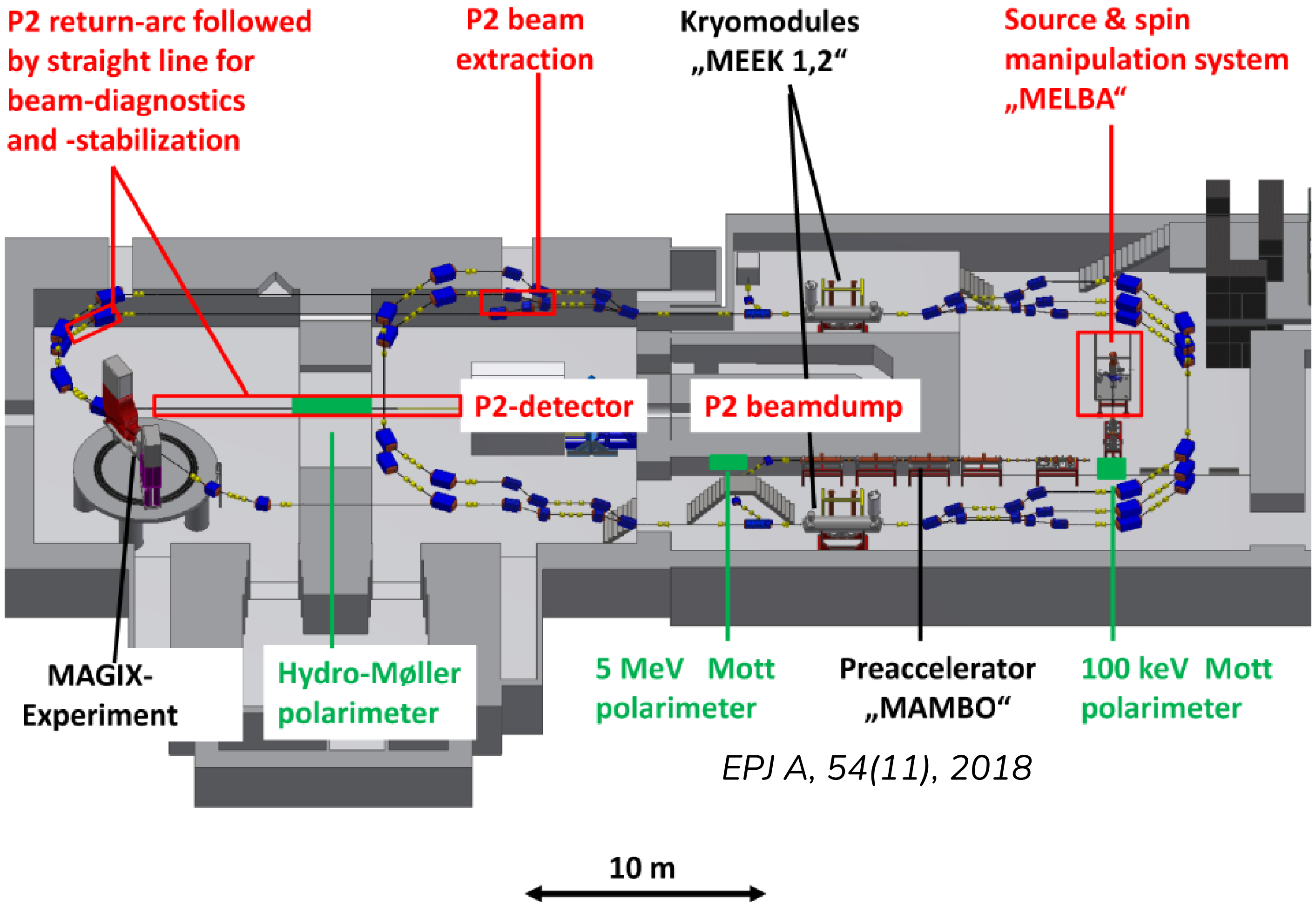


Fig.11 Schematic view of MESA

- Electron beam with kinetic energy of 55 or 155 MeV
- 85% polarization efficiency
- 150 μA beam current
- Polarization measurement with accuracy better than 1%

The P2 experiment

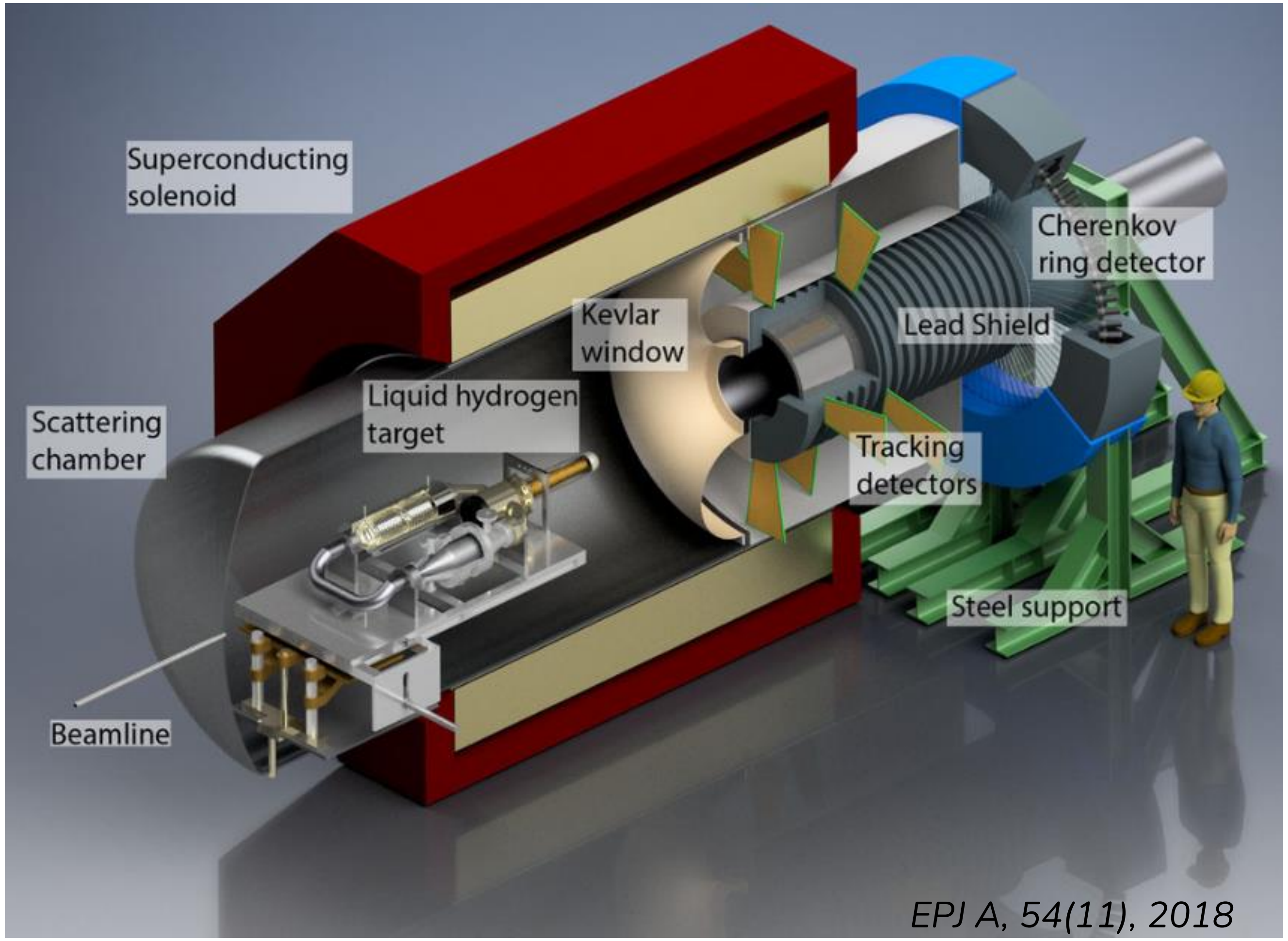


Fig.12 CAD drawing of the P2 detector

- Aimed to measure weak mixing angle $\sin^2\theta_W$ through parity-violating elastic electron scattering on hydrogen
- Uses solenoid spectrometer with tracking detectors and Cherenkov detector
- The same setup but with ^{208}Pb target can be used for neutron skin measurement to confirm/confront PREX results

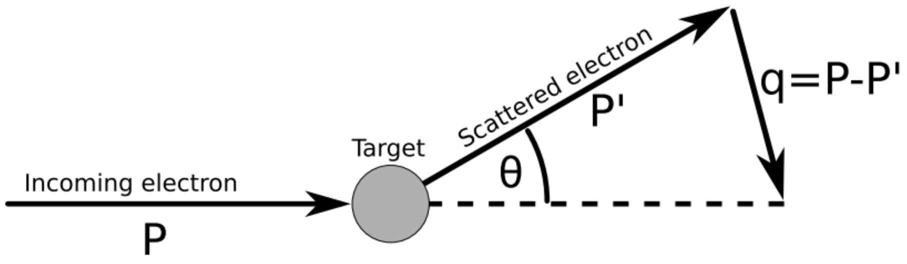
Outline for MREX

- Average momentum transfer $\langle Q^2 \rangle = 0.0062\ \mathrm{GeV}^2$ to match PREX kinematics
- Achieve neutron radius precision $\delta R_n/R_n$ of at least 1%, best case scenario: $\delta R_n/R_n = 0.5\%$
- ^{208}Pb target with thickness of 0.5 mm for balance between rate and radiative losses increase

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

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

$$\varepsilon = \frac{\mathrm{d}\ln(A^{\mathrm{PV}})}{\mathrm{d}\ln(R_{\mathrm{n}})} = \frac{R_{\mathrm{n}}}{A^{\mathrm{PV}}}\frac{\delta A^{\mathrm{PV}}}{\delta R_{\mathrm{n}}}$$



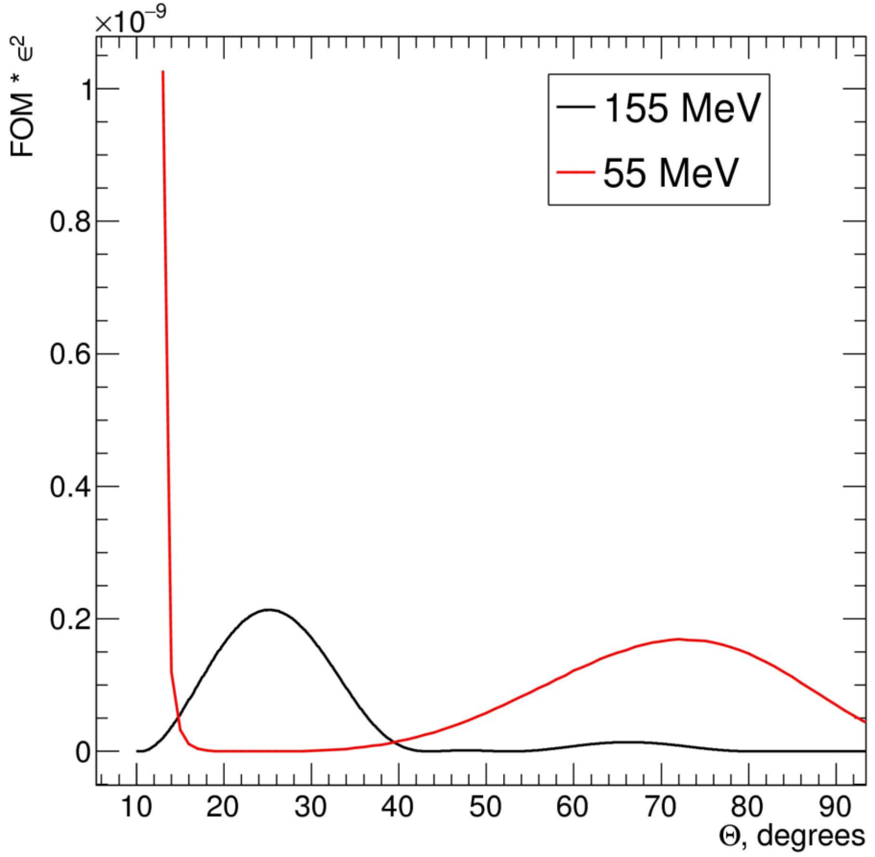


Fig.13 R_n measurement "quality" dependence on scattering angle

MREX achievable uncertainty

- Necessary uncertainty can be achieved at both energies that are possible at MESA

- Desirable Q^2 corresponds to:
  - 29° average scattering angle at 155 MeV – fits uncertainty and detector geometry
  - 91° average scattering angle at 55 MeV – impossible with solenoid geometry

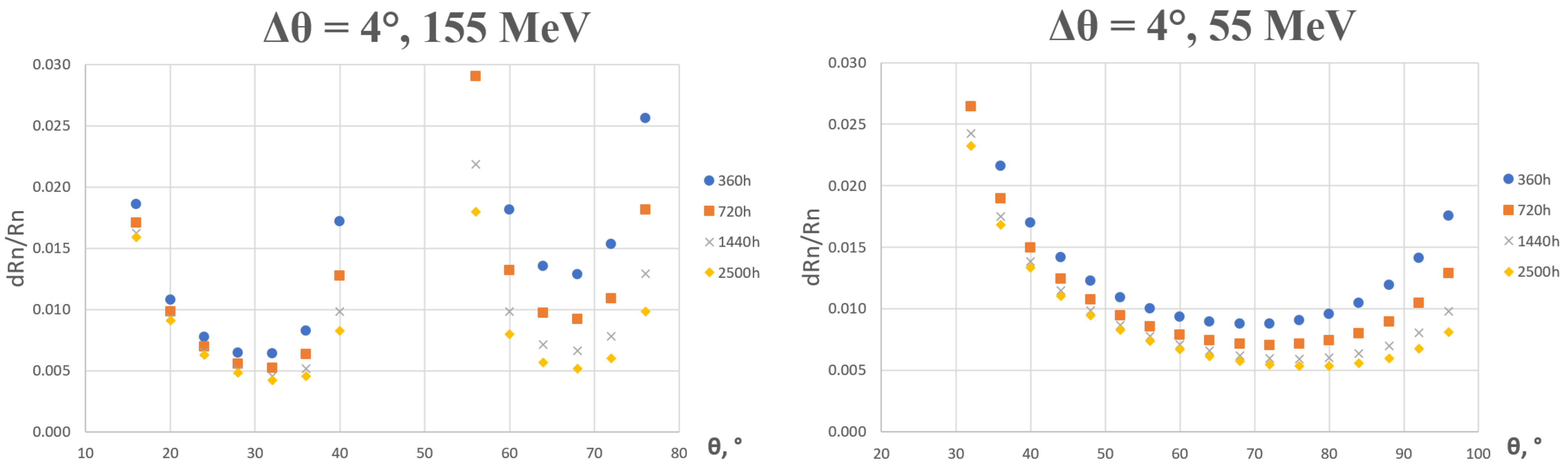


Fig.14 Achievable relative uncertainty of R_n for certain measuring time in case of detection of all electrons with 4° acceptance. 1% systematic uncertainty for A^{PV} assumed

Target position and field strength

Criteria for choosing detector setup:

- Maximizing signal from elastically scattered electrons
- Matching necessary Q^2 value
- Minimizing signal from secondary produced particles
- Minimizing signal from target background
- Decrease influence of inelastic events

Chosen optimal geometry configuration:

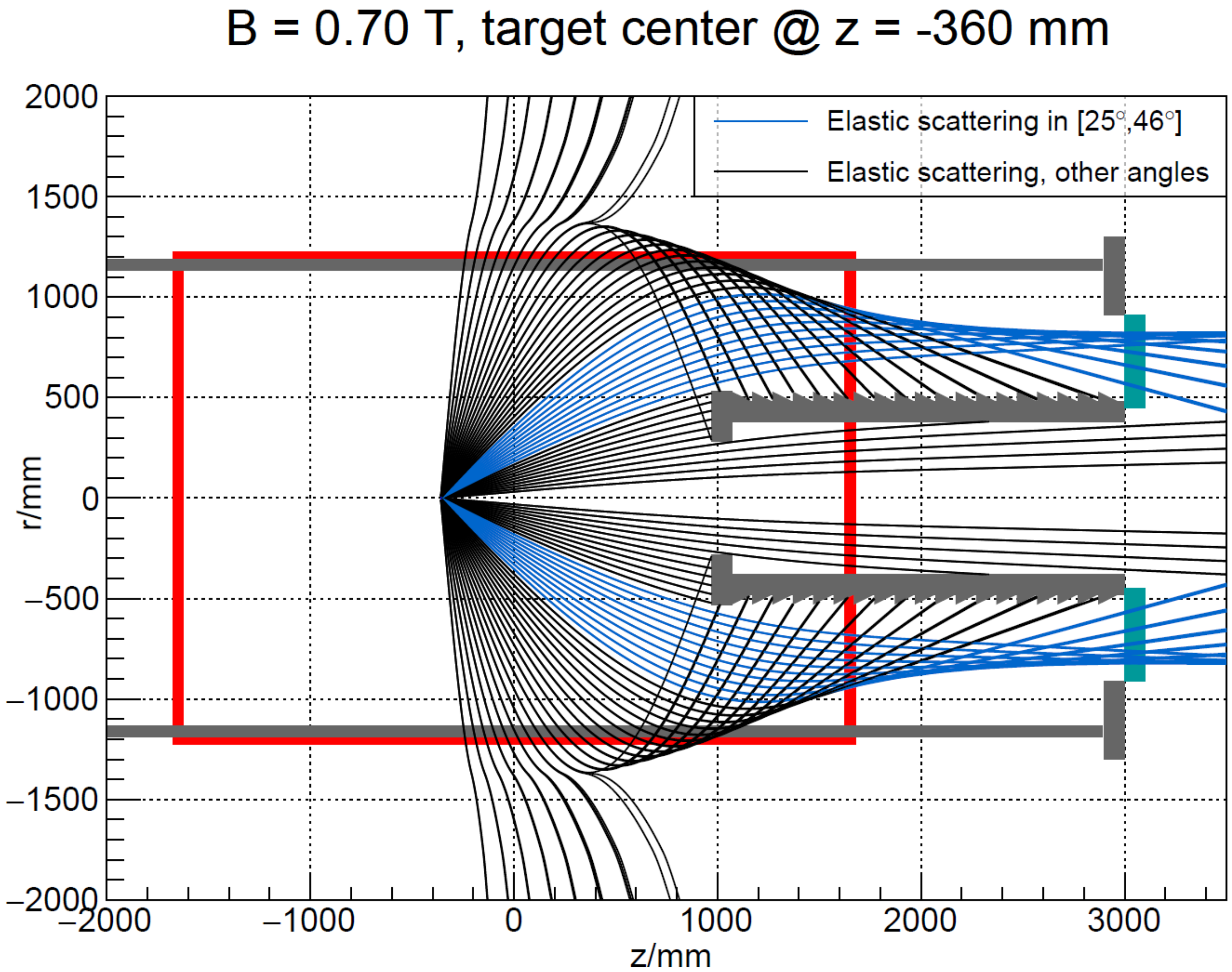


Fig.15 Tracks of elastically scattered electrons in consideration with magnetic field map

Full Monte-Carlo simulation

- P2 simulation framework was modified to be able to produce calculations for MREX
- Geant4 as a base, custom event generator of elastically, inelastically and quasielastically scattered electrons
- Includes detector response function, allowing to account for detection probability of different particles at different momenta

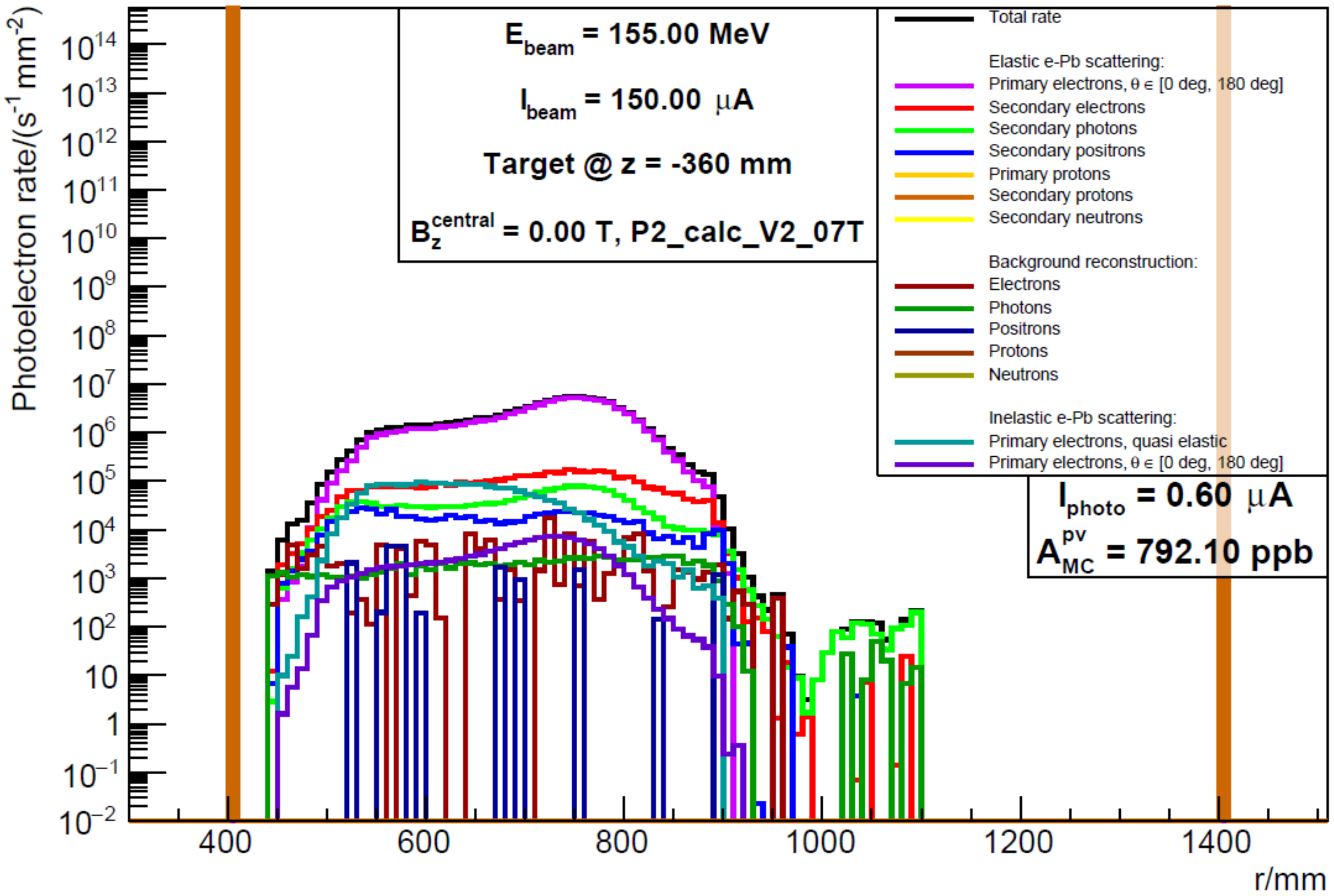


Fig.16 Photoelectron rate distribution in Cherenkov detector from different particles considered in the simulation as a function of the distance r to the beam axis

Acceptance and measuring time

Currently, the measuring times extracted from theoretical predictions and simulated acceptance function, assuming 1% systematic uncertainty for A^{PV}, are:

- 80 hours to reach 1% uncertainty for R_n
- 1000 hours to reach 0.5% uncertainty for R_n

However, further analysis of systematic uncertainties both from theory and experiment is necessary

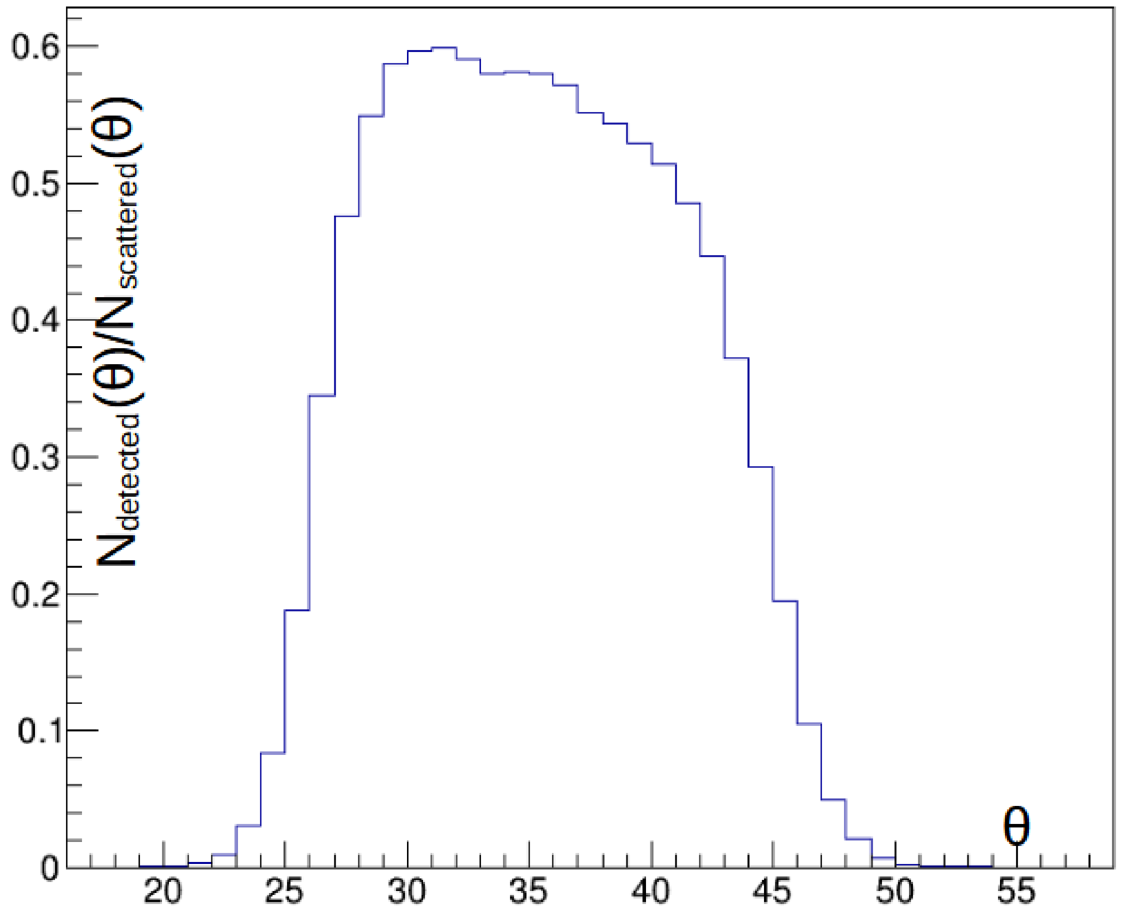


Fig.17 Fraction of scattered electrons reaching the detector as a function of scattering angle

Summary

- Nuclear Equation of State is necessary for descriptions of any nuclear systems, from nuclei to neutron stars.
- Experimental measurement of neutron skins in nuclei allow 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 could reach necessary neutron radius uncertainty in reachable measuring time

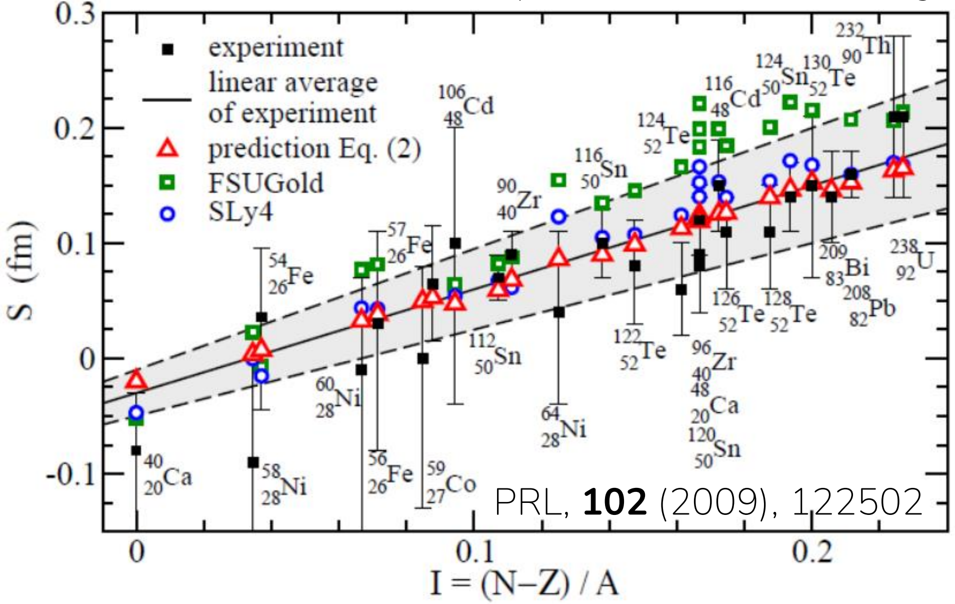
Back-up

Experimental measurements of neutron skin

- Hadronic probes
  - Antiprotonic atoms
  - Proton-nucleus scattering
  - α-nucleus and π-nucleus scattering
- Electric dipole strength function
  - Electric dipole polarizability
  - Pygmy dipole resonances
- Coherent π^0 photoproduction

However, most of these measurements are highly model depended

Fig.5 Neutron skin thickness from antiprotonic atoms and theoretical predictions for wide range of nuclei



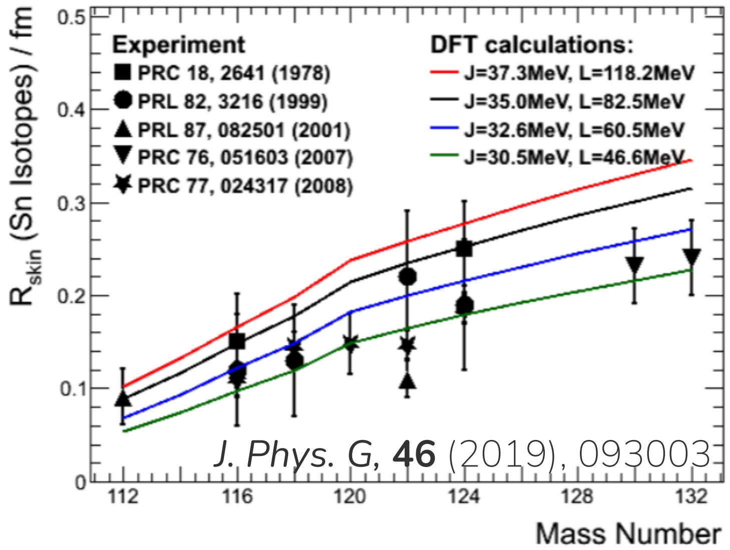


Fig.6 Neutron skin thickness of Sn isotopes from hadronic probes and theory

Symmetry energy and L impact on physics

L defines the properties of any asymmetric baryonic systems with unequal numbers of protons and neutrons (or up and down quarks), as in:

- ❑ Nuclei (e.g. neutron skin, isoscalar monopole resonance, electric dipole polarizability)
- ❑ Neutron stars (e.g. neutron star radii, cooling, gravitational waves from collision)
- ❑ Supernovae (e.g. core collapse supernovae with following neutrino burst)
- ❑ Heavy ion collisions (e.g. nucleon emission, π^{-}/π^{+} ratio, Δ and K production)

Changes in the simulation

- Upgraded to run in batch mode on MOGON cluster for higher statistics
- Updated physics list to include necessary physics
- Revised beam-target interaction model to better describe energy deposition and scattering angles
- Changed target vertex generation algorithm to produce more physical special vertex distribution
- Corrected formfactor in the event generator to better describe experimental data
- Introduced new variables for new plots and observables