Monte Carlo Simulation Studies for the BRAND Experiment

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for the BRAND Collaboration

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The BRAND experiment[1] uses polarized cold neutrons to probe physics beyond the Standard Model. It intends to measure **11 beta decay correlation coefficients** simultaneously, including **7 (H, L, N, R, S, U, V)** accessible via **transverse electron polarization** measured with **Mott scattering**[2]. Neutron beta decay events are identified by reconstructing full **three-body kinematics**.

$$d\Gamma \sim 1 + a\frac{\mathbf{p}_e}{E_e}\cdot\frac{\mathbf{p}_{\bar\nu}}{E_{\bar\nu}} + b\frac{m_e}{E_e} + \frac{\langle\mathbf{J}\rangle}{J}\cdot\left[A\frac{\mathbf{p}_e}{E_e} + B\frac{\mathbf{p}_{\bar\nu}}{E_{\bar\nu}} + D\frac{\mathbf{p}_e}{E_e}\times\frac{\mathbf{p}_{\bar\nu}}{E_{\bar\nu}}\right]$$
$$+\sigma_\perp\cdot\left[H\frac{\mathbf{p}_{\bar\nu}}{E_{\bar\nu}} + L\frac{\mathbf{p}_e}{E_e}\times\frac{\mathbf{p}_{\bar\nu}}{E_{\bar\nu}} + N\frac{\langle\mathbf{J}\rangle}{J} + R\frac{\langle\mathbf{J}\rangle}{J}\times\frac{\mathbf{p}_e}{E_e}\right]$$
$$+\sigma_\perp\cdot\left[S\frac{\langle\mathbf{J}\rangle}{J}\frac{\mathbf{p}_e}{E_e}\cdot\frac{\mathbf{p}_{\bar\nu}}{E_{\bar\nu}} + U\frac{\mathbf{p}_{\bar\nu}}{E_{\bar\nu}}\frac{\langle\mathbf{J}\rangle}{J}\cdot\frac{\mathbf{p}_e}{E_e} + V\frac{\mathbf{p}_{\bar\nu}}{E_{\bar\nu}}\times\frac{\langle\mathbf{J}\rangle}{J}\right]$$

Electron transverse polarization

NEVER MEASURED BEFORE !!!

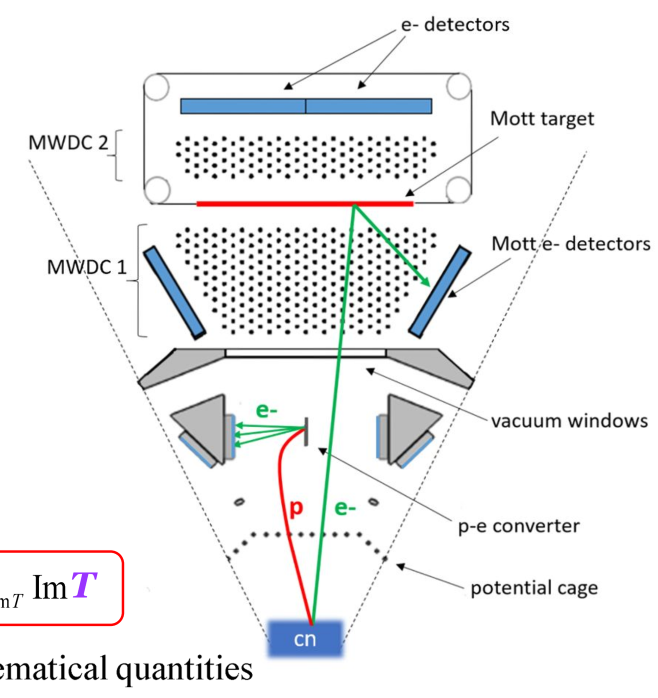
$\mathbf{p}_e$ - electron momentum
$\mathbf{p}_\nu$ - neutrino momentum
$\mathbf{J}$ - neutron spin projection

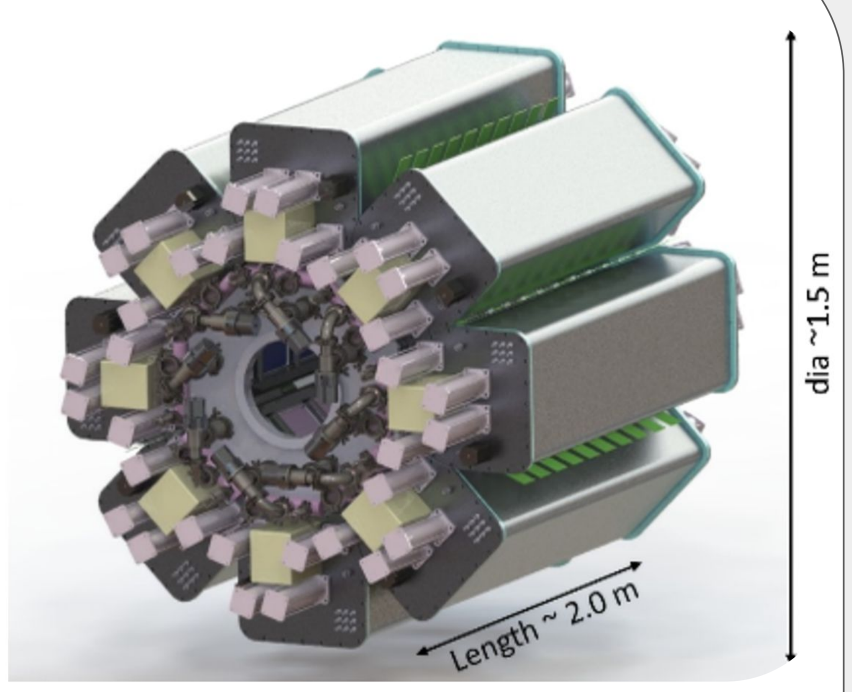
- All correlation coefficients can be expressed as **combinations** of real and imaginary parts of exotic (scalar and tensor) couplings:

$$S = \frac{C_S + C_S'}{C_V}, \quad T = \frac{C_T + C_T'}{C_A}$$

$$X = X_{V\text{-}A} + X_{FSI} + c_{\mathrm{Re}S}\,\mathrm{Re}S + c_{\mathrm{Re}T}\,\mathrm{Re}T + c_{\mathrm{Im}S}\,\mathrm{Im}S + c_{\mathrm{Im}T}\,\mathrm{Im}T$$

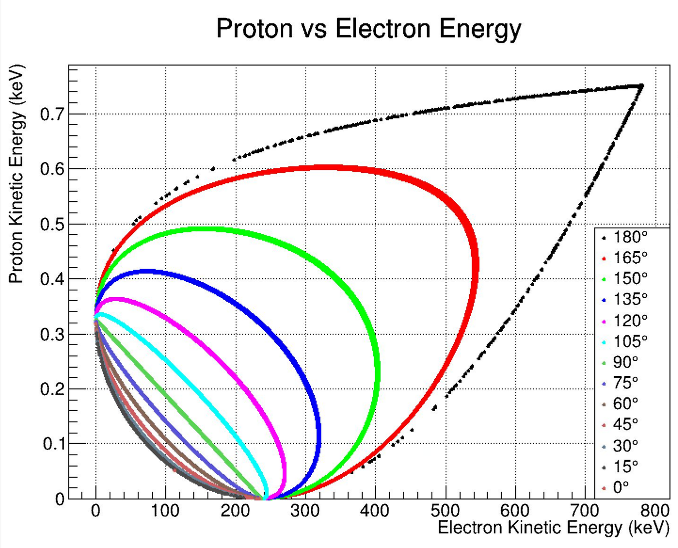
$c_{\mathrm{Re}S}, c_{\mathrm{Re}T}, c_{\mathrm{Im}S}, c_{\mathrm{Im}T}$ – functions of $\lambda = C_A/C_V$ and kinematical quantities

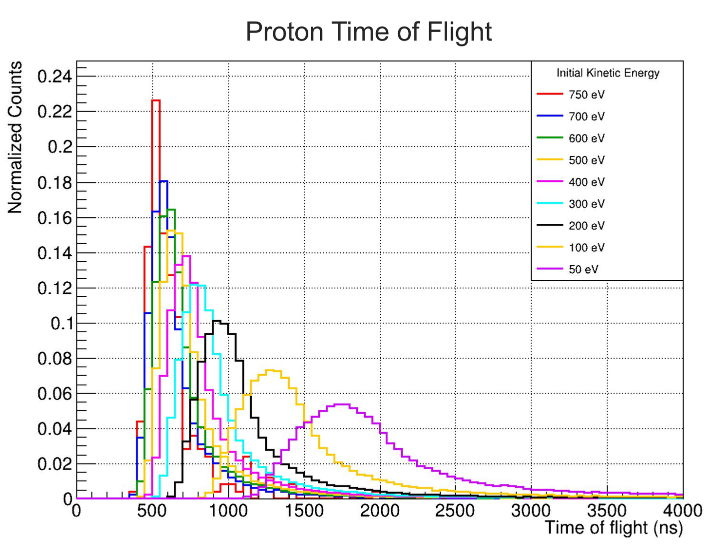




Methodology

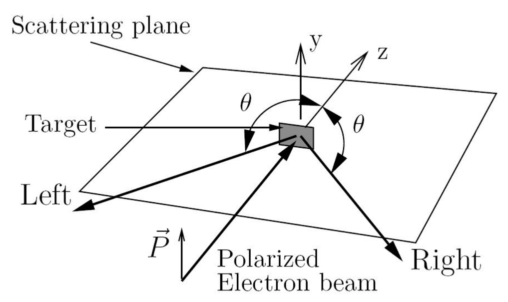
- Electron Detection System: Multi-Wire Drift Chambers for tracking; Plastic scintillators for energy measurement and trigger.
- Proton Detection System: Proton-electron conversion using LiF; Time-of-Flight and hit position are extracted.
- Electron momentum vector is reconstructed from the incoming electron track and deposited energy in plastic scintillator.
- Proton momentum vector is reconstructed using time-of-flight and hit position respecting the three-body kinematics.





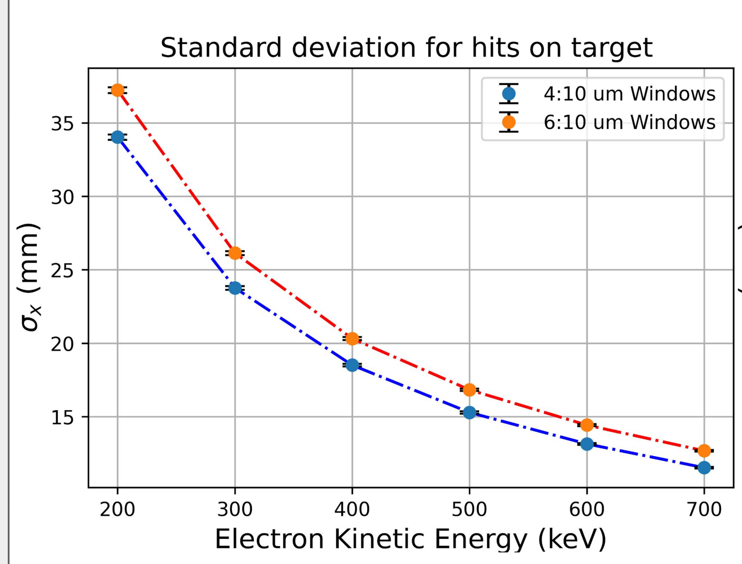
- **Transverse Electron Polarization:** From Mott scattering asymmetry, analyzing power is calculated using pre-tabulated (MC + ELSEPA) effective Sherman function $S_{eff}(E,\theta)$.

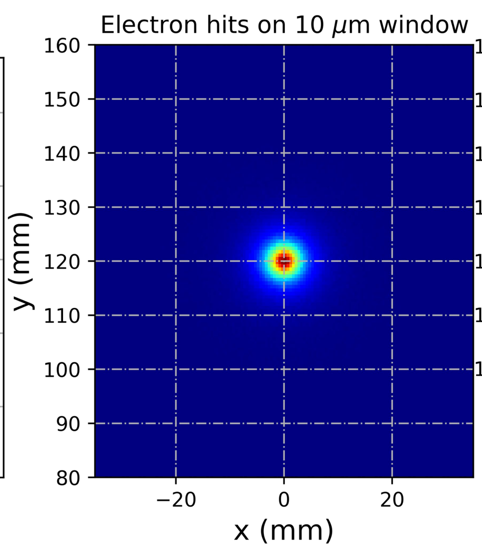
$$\vec{P}\cdot\vec{n} = \frac{A}{S_{\mathrm{eff}}(E,\theta)}, \quad A = \frac{N_L - N_R}{N_L + N_R}$$

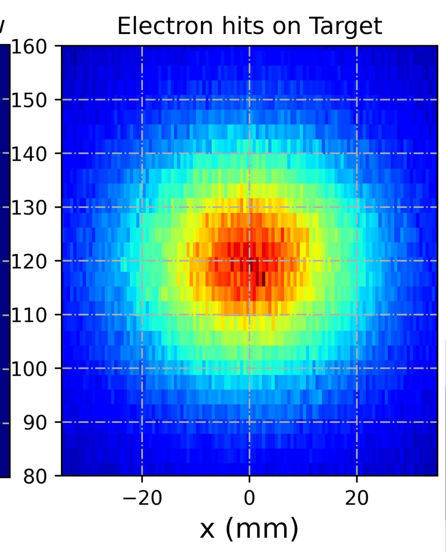


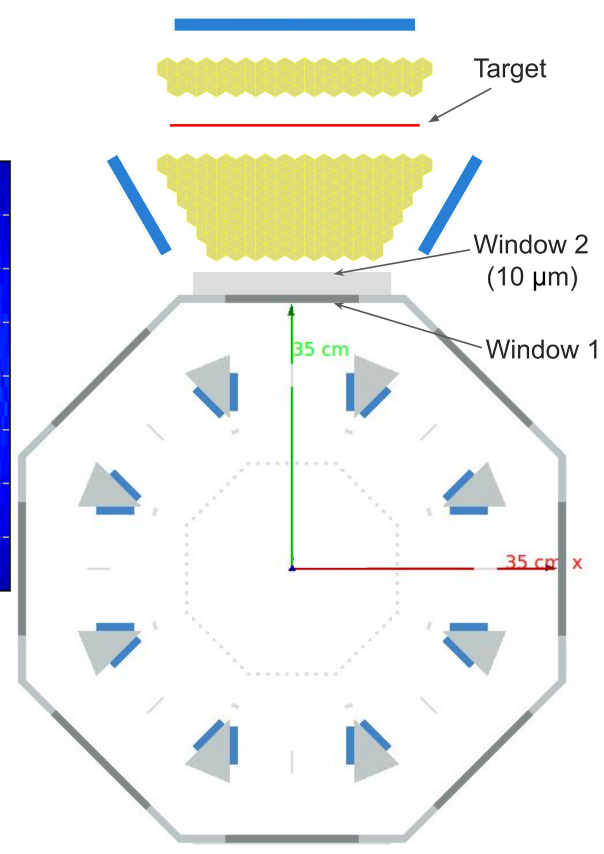
MC Simulation Setup for the BRAND-II

- First experimental run will utilize two Mott polarimeters.
- With the simulation setup in Geant4, effects of multiple scattering in vacuum windows, deflections due to electric field for proton acceleration are studied.
- Sample examples are shown below:

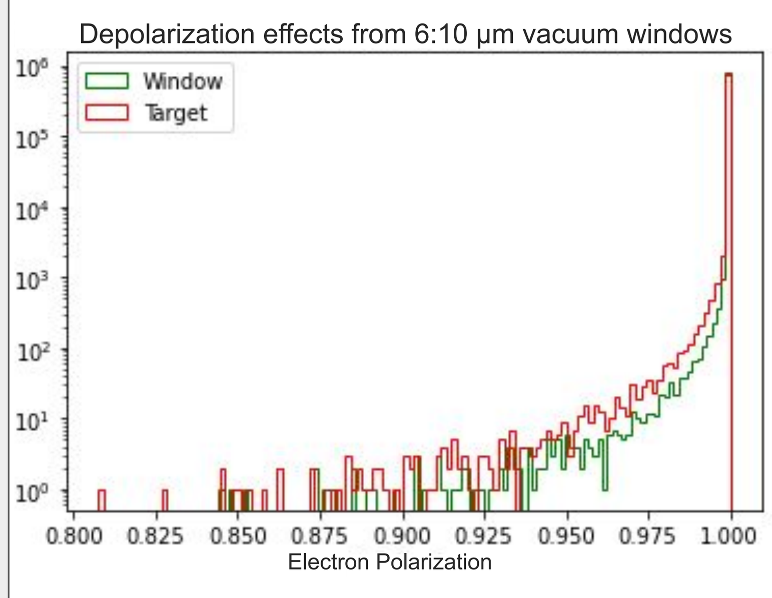


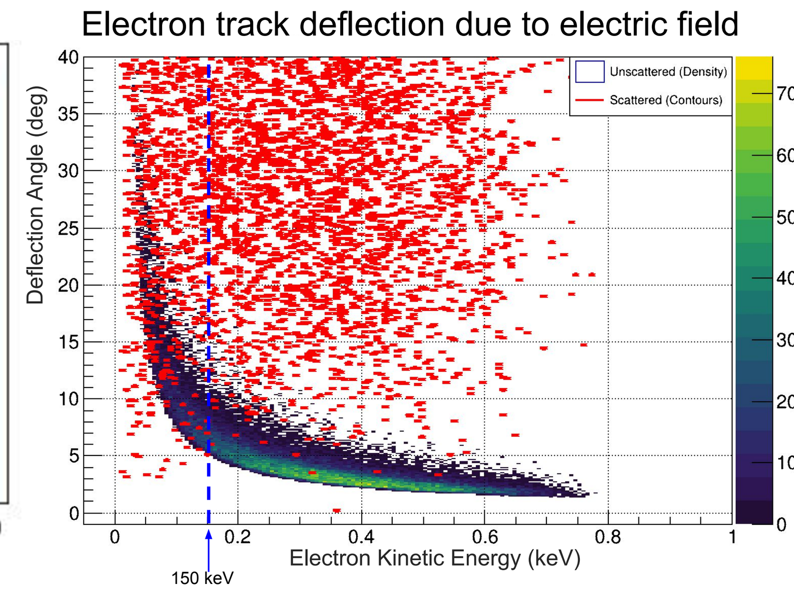






- Depolarization of electrons in the vacuum windows found to be negligible:





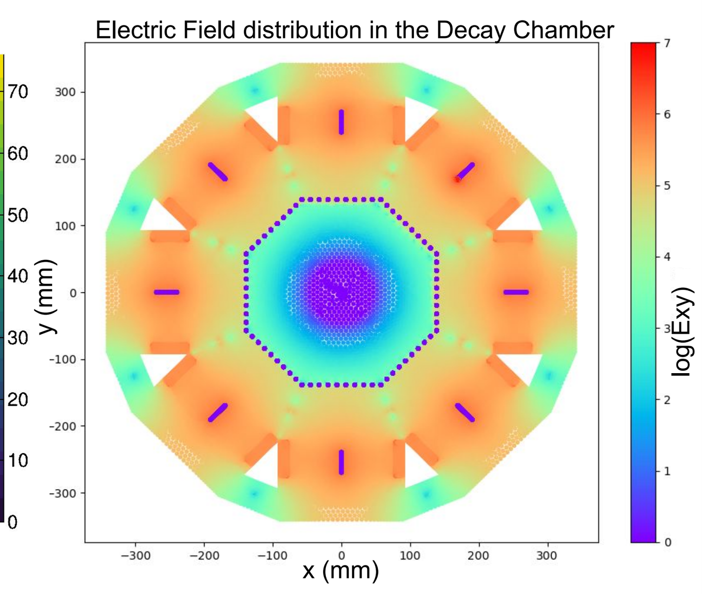
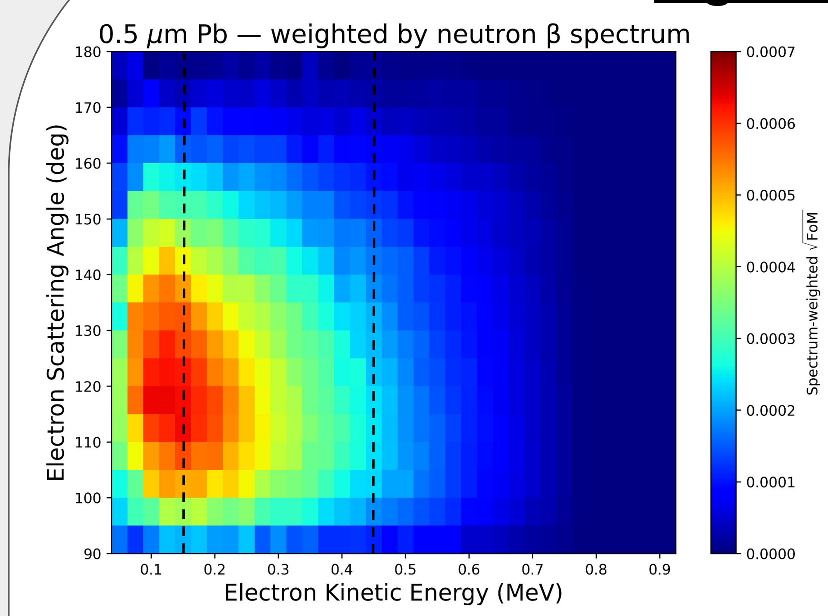
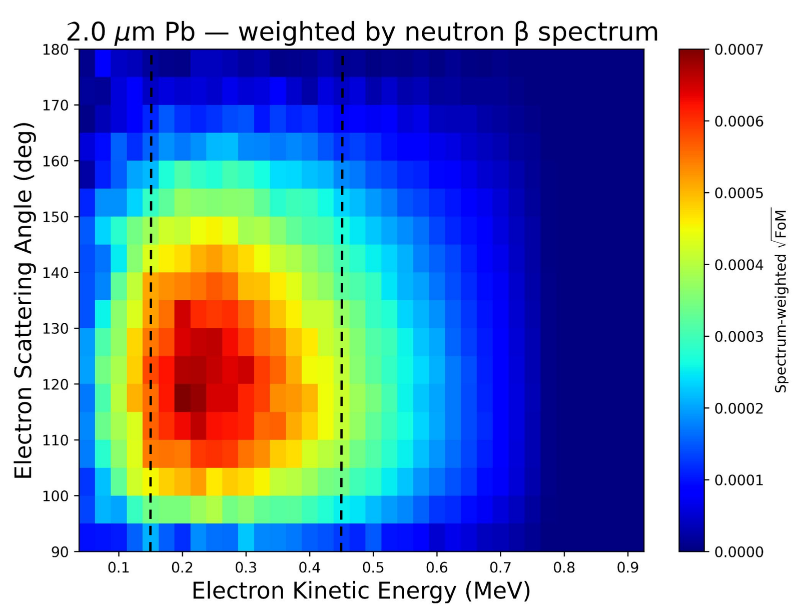
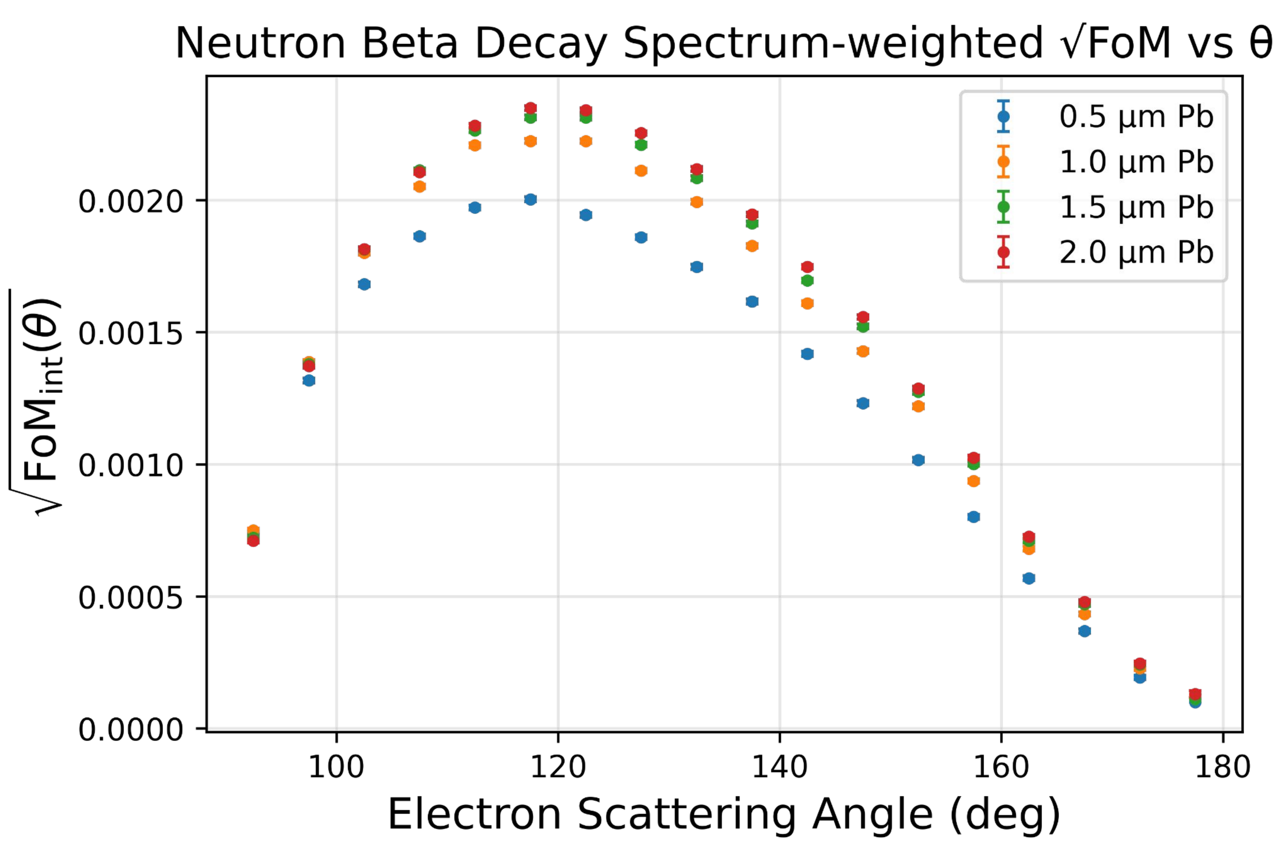


Figure of Merit (FoM) for Mott Polarimetry







$$w(E) \propto F(Z,E)p(E)E_{tot}(E)(E_0 - E)^2$$

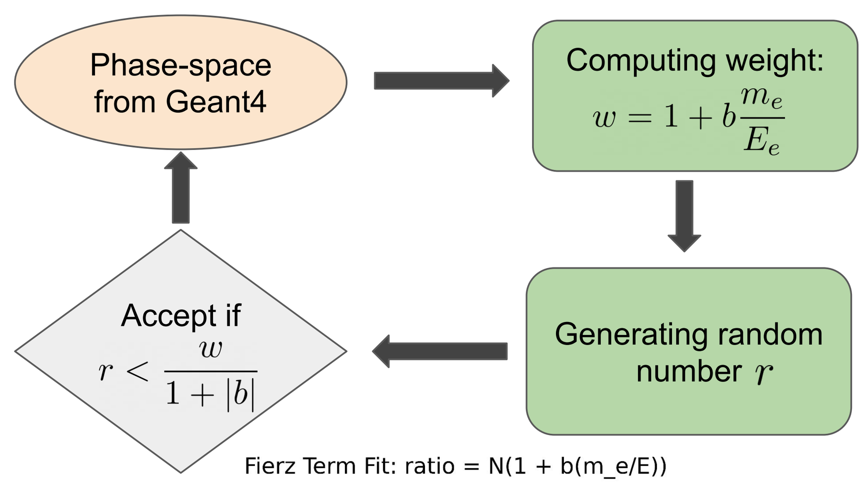
$$FoM(E,\theta) = \left(\frac{N_{Det}}{N_{in}}\right) * S_{eff}^2(E,\theta) * w(E)$$

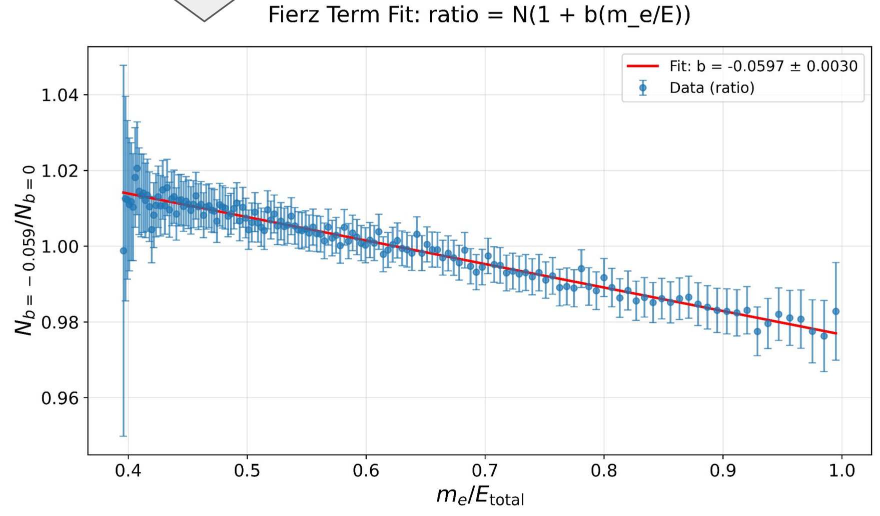
$$FoM_{int}(\theta) = \int dE\; w(E)\; FoM(E,\theta)$$

- Figure of merit obtained using MC methods (Geant4+ELSEPA) are used to optimize the Mott target thickness.
- For lead as a target material, the optimum thickness is found to be 1.5 μm to 2.0 μm
- The figure of merit has broad maximum for electron energies from 150 keV to 450 keV and the back-scattering angles from 100° to 150°.

Current Status

- **Fine-tuning** neutron decay model in Geant4 to include more correlations of interest.
- As a first step, Fierz term was introduced on the top of already existing neutron decay model using acceptance-rejection sampling.





Acknowledgement

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References:
[1] K. Bodek, Acta Phys. Pol. B. 47, 349 (2016).
[2] Mott N. F., Proc. R. Soc. Lond., A124425–442 (1929).

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