Search for Time Reversal Violation in Neutron Decay

A Measurement of the Transverse Polarization of Electrons

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Angular correlations in β–decay

Angular distribution contain 4 T–odd observables (lowest order):

$$\omega(\langle \mathbf{J}_n \rangle | E_e \Omega_e \Omega_\nu) \cdot dE_e d\Omega_e d\Omega_\nu \propto \left[1 + \ldots + D \frac{(\mathbf{p}_e \times \mathbf{p}_\nu) \cdot \langle \mathbf{J}_n \rangle}{E_e E_\nu} + \ldots \right] \cdot dE_e d\Omega_e d\Omega_\nu$$

$$\omega(\langle \mathbf{J}_n \rangle \boldsymbol{\sigma} | E_\nu \Omega_\nu) \cdot dE_\nu d\Omega_\nu \propto \left[1 + \ldots + V \frac{(\mathbf{p}_\nu \times \boldsymbol{\sigma}) \cdot \langle \mathbf{J}_n \rangle}{E_\nu} + \ldots \right] \cdot dE_\nu d\Omega_\nu$$

$$\omega(\boldsymbol{\sigma} | E_e \Omega_e \Omega_\nu) \cdot dE_e d\Omega_e d\Omega_\nu \propto \left[1 + \ldots + L \frac{\boldsymbol{\sigma} \cdot (\mathbf{p}_e \times \mathbf{p}_\nu)}{E_e E_\nu} + \ldots \right] \cdot dE_e d\Omega_e d\Omega_\nu$$

$$\omega(\langle \mathbf{J}_n \rangle \boldsymbol{\sigma} | E_e \Omega_e) \cdot dE_e d\Omega_e \propto \left[1 + \ldots + R \frac{(\mathbf{p}_e \times \boldsymbol{\sigma}) \cdot \langle \mathbf{J}_n \rangle}{E_e} + \ldots \right] \cdot dE_e d\Omega_e$$

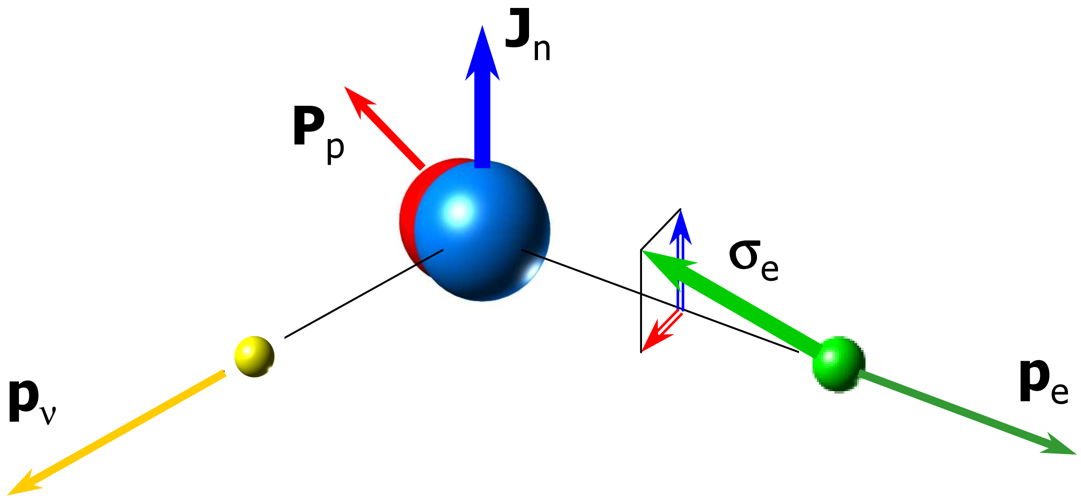
T–invariance holds $\Rightarrow$ D, R, V, L = 0 !!!

Angular correlations in β–decay

$$\omega(\langle \mathbf{J}_n \rangle \boldsymbol{\sigma} | E_e \Omega_e) \cdot dE_e d\Omega_e \propto \left[1 + \ldots + R \frac{(\mathbf{p}_e \times \boldsymbol{\sigma}) \cdot \langle \mathbf{J}_n \rangle}{E_e} + N \boldsymbol{\sigma} \cdot \langle \mathbf{J}_n \rangle + \ldots \right] \cdot dE_e d\Omega_e$$

R–coefficient can be deduced from transversal polarization of electrons emitted from polarized nuclei (or neutrons)

D :	T–odd	P–even
R :	T–odd	P–odd
V :	T–odd	P–odd
L :	T–odd	P–even
N :	T–even	P–even



Angular correlations in β–decay

D and ***R*** are sensitive to distinct aspects of T–violation:

$$D \cdot \xi = M_F M_{GT} \sqrt{\frac{I}{I+1}}\, 2\,\mathrm{Im}\left(C_S C_T^{*} - C_V C_A^{*} + C_S^{'} C_T^{'*} - C_V^{'} C_A^{'*} \right) + D_{\mathrm{FSI}}$$

$$R \cdot \xi = \left| M_{GT} \right|^2 \frac{1}{I+1}\, 2\,\mathrm{Im}\left(C_T C_A^{'*} + C_T^{'} C_A^{*} \right)$$

$$+ M_F M_{GT} \sqrt{\frac{I}{I+1}}\, 2\,\mathrm{Im}\left(C_S C_A^{'*} + C_S^{'} C_A^{*} - C_V C_T^{'*} - C_V^{'} C_T^{*} \right) + R_{\mathrm{FSI}}$$

$$\xi = \left| M_F \right|^2 \left(\left| C_S \right|^2 + \left| C_V \right|^2 + \left| C_S^{'} \right|^2 + \left| C_V^{'} \right|^2 \right) + \left| M_{GT} \right|^2 \left(\left| C_T \right|^2 + \left| C_A \right|^2 + \left| C_T^{'} \right|^2 + \left| C_A^{'} \right|^2 \right)$$

D is primarily sensitive to the relative phase between *V* and *A* couplings.

R is sensitive to the linear combination of imaginary parts of scalar and tensor couplings.

T-violation in β-decay

- T-violation in β-decay may arise from:
  - o semileptonic interaction ($d \rightarrow u e^- \nu_e$)
  - o nonleptonic interactions
- SM-contributions for ***D***- and ***R***-correlations:
  - o Mixing phase δ_{CKM} gives contribution which is 2nd order in weak interactions:

    $< 10^{-10}$
  - o θ -term contributes through induced NN PVTV interactions:

    $< 10^{-9}$
- Candidate models for scalar contributions (at tree-level) are:
  - o Charged Higgs exchange
  - o Slepton exchange (R-parity violating super symmetric models)
  - o Leptoquark exchange
- The only candidate model for tree-level tensor contribution is:
  - o Spin-zero leptoquark exchange.

Measurements of triple correlations in β–decay provide direct, i.e. first–order access to the T–violating part of the weak interaction coupling constants

R–correlation in neutron decay

- Transverse electron polarization component contained in the plane perpendicular to the parent polarization.
- Not measured for the decay of free neutron yet !
- Inserting specific matrix elements

$$R = \frac{\mathrm{Im}\left[\left(C_V^* + 2C_A^*\right)\left(C_T + C_T'\right) + C_A^*\left(C_S + C_S'\right)\right]}{\left|C_V\right|^2 + 3\left|C_A\right|^2}$$

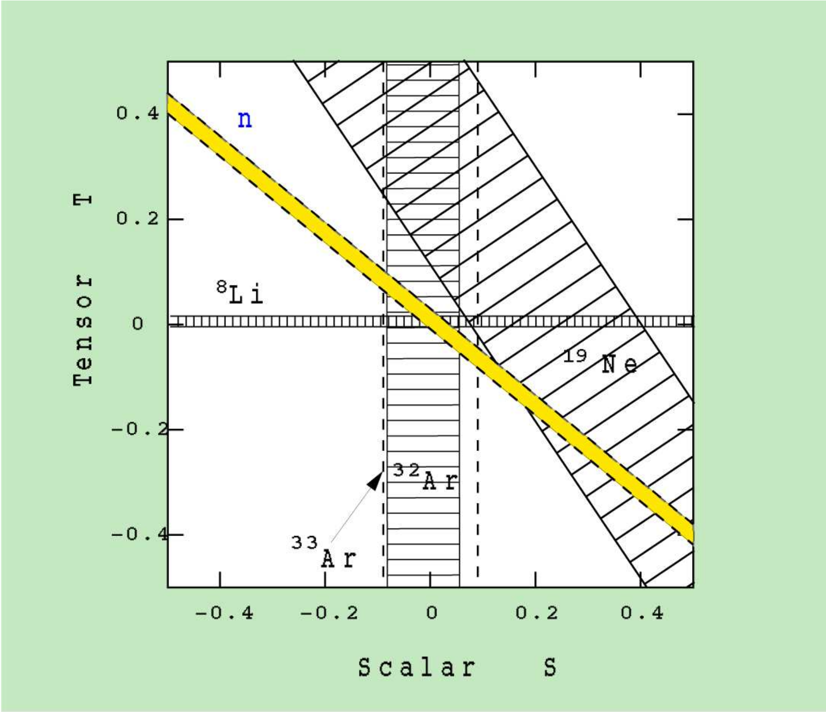
and defining:

$$S \equiv \mathrm{Im}\left(\frac{C_S + C_S'}{C_A}\right); \quad T \equiv \mathrm{Im}\left(\frac{C_T + C_T'}{C_A}\right)$$

- one obtains finally:

$$R = 0.28 \cdot S + 0.33 \cdot T$$

Anticipated accuracy of the present experiment: ΔR (neutron) ≈ 5×10^{-3}



$$S = Im\left[(C_S + C'_S)/C_A\right],$$
$$T = Im\left[(C_T + C'_T)/C_A\right]$$

Figure 1: Results from the experiments testing time reversal symmetry in the scalar and tensor weak interaction. The bands indicate $\pm1\sigma$ limits. Constraints from the study of the R-correlation in the free neutron decay with an accuracy of ±0.005 are attached. This prediction is arbitrarily fixed at $S, T = 0$.

N–correlation

- Can be deduced from the transverse electron polarization component contained in the plane parallel to the parent polarization.
- Scales with the decay asymmetry A ($\lambda \equiv C_A / C_V$):

$$N_{SM}^{n} = -\frac{m}{E} A_{SM} = \frac{m}{E} \frac{2\left(\lambda^2 + \lambda\right)}{1 + 3\lambda^2} \approx +0.1173 \frac{m}{E}$$

$$N_{SM}^{n} \simeq 5 \times 10^{-2} \simeq 10 \cdot \Delta R_n \,(\text{anticipated})$$

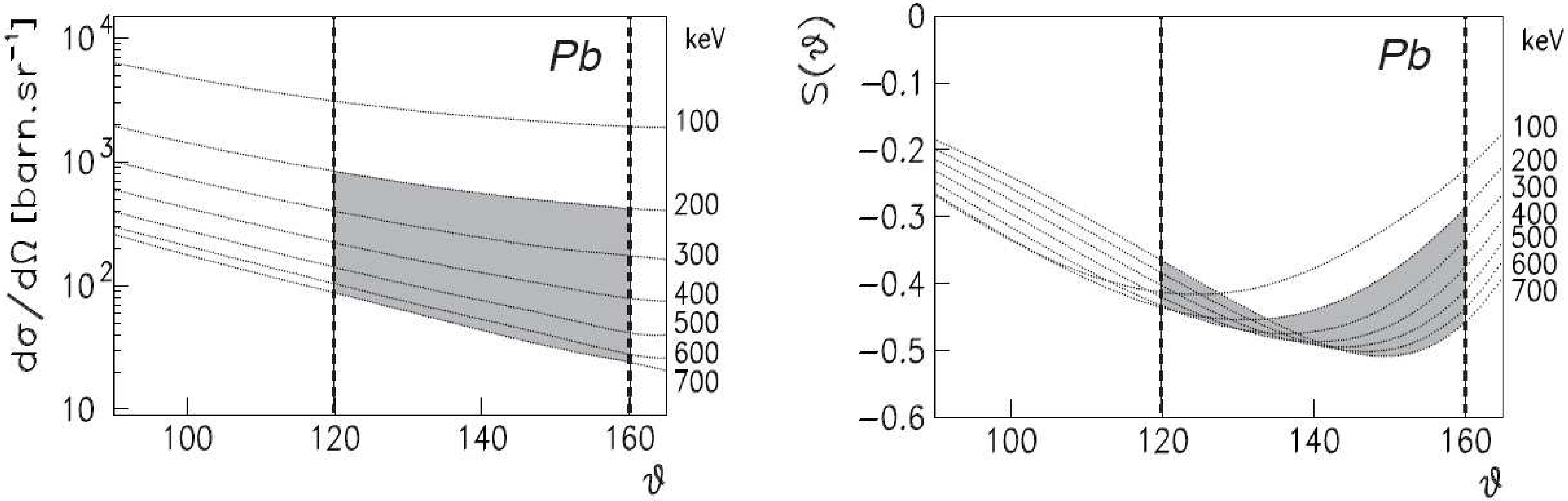
- Self calibration tool for R–correlation measurement.
- Excellent cross check for systematic effects in R–correlation.

Conclusion:

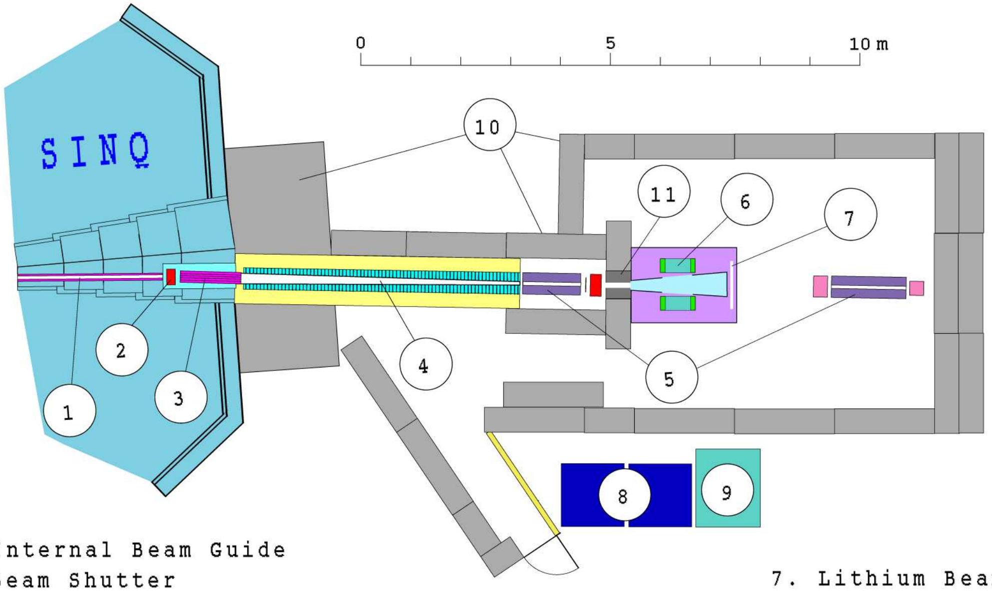
Simultaneously measure both components of the transverse polarization of electrons emitted in neutron decay

Mott polarimetry

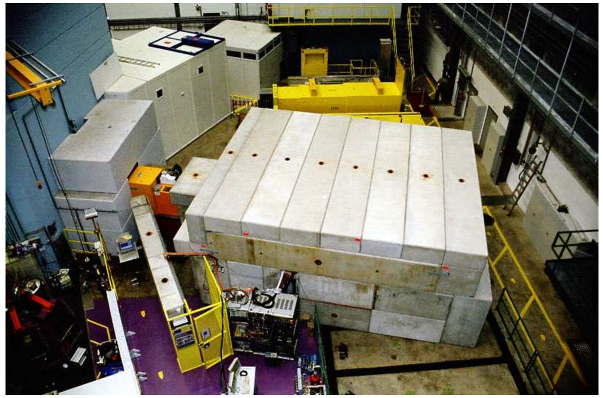
- Mott scattering:
  - Analyzing power caused by spin-orbit force
  - Parity and time reversal conserving (electromagnetic process)
  - Sensitive exclusively to the transversal polarization



FUNSPIN – Polarized Cold Neutron Facility at PSI



1. Internal Beam Guide
2. Beam Shutter
3. Polarizer
4. Focusing Guide
5. Spin Flippers
6. Neutron Decay Detection System
7. Lithium Beam Dump
8. Electronics
9. Gas System
10. Radiation Shields
11. Boron/Lithium Collimator



$$I_n \simeq 10^{10}\,\mathrm{s}^{-1}$$

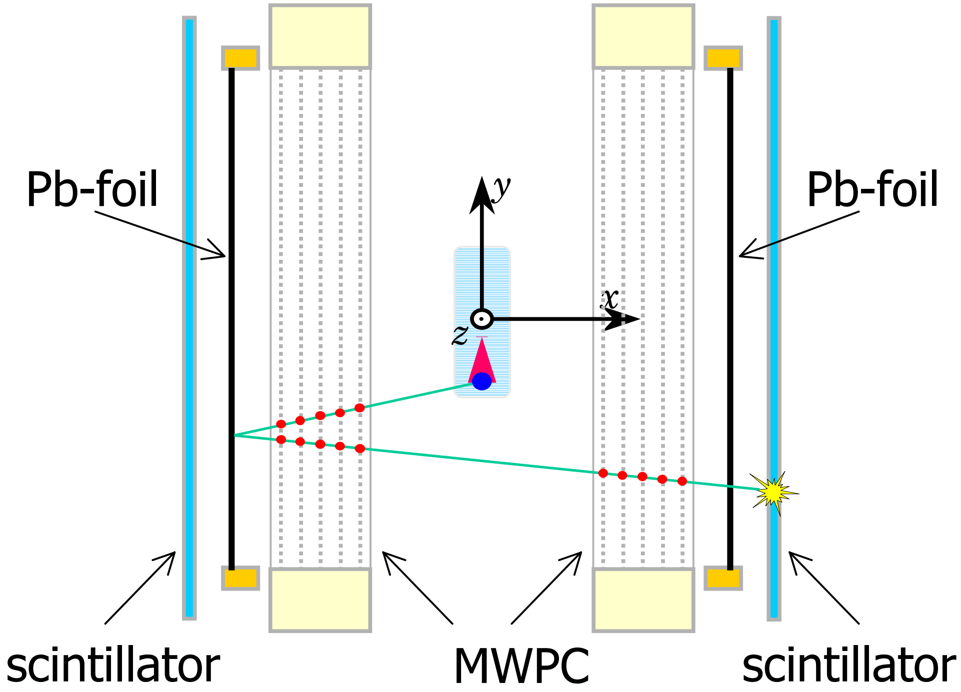
$$P_n \simeq 90\%$$

Figure 4: Layout of the Polarized Cold Neutron Facility at PSI.

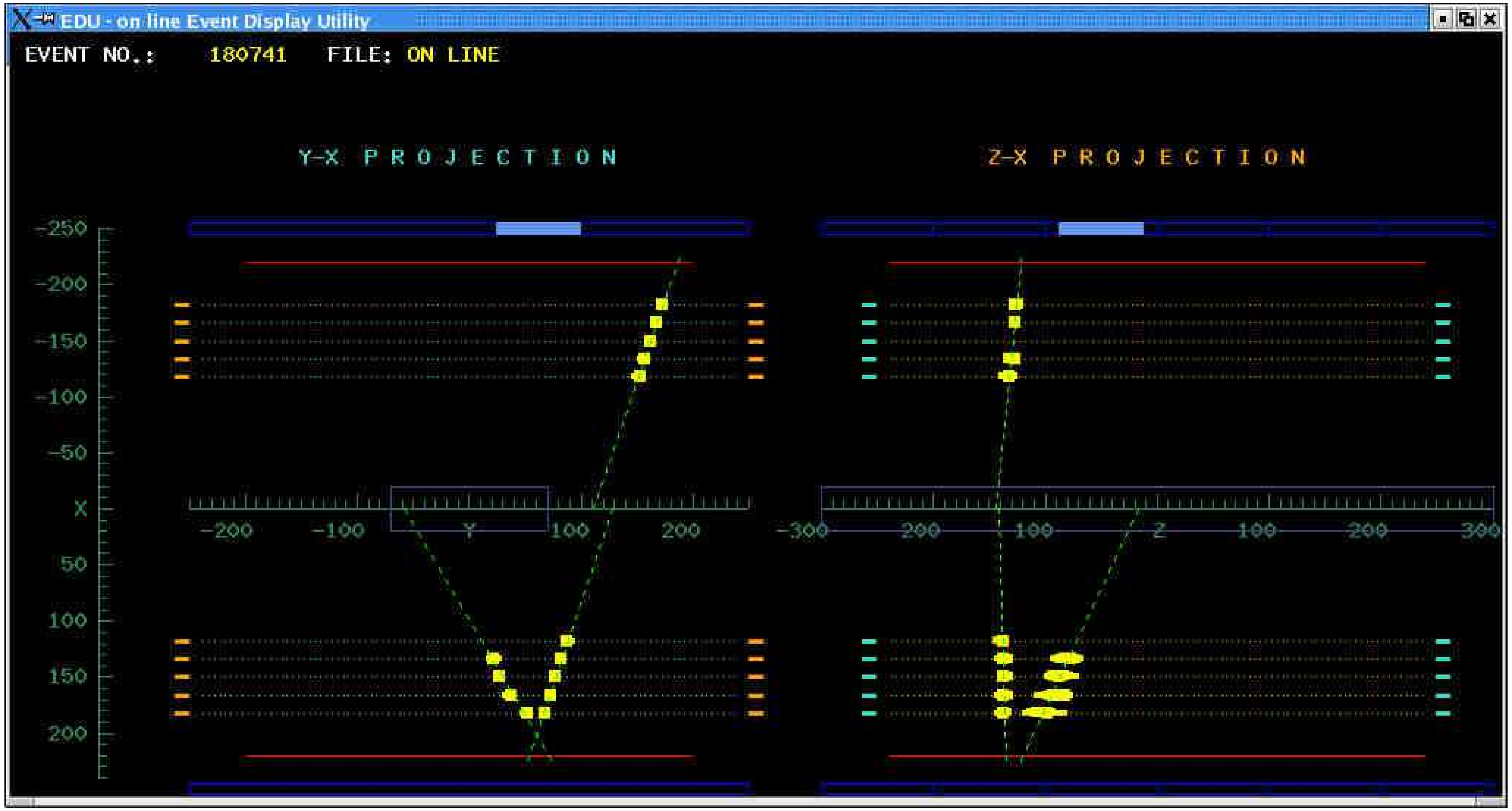
Mott polarimeter

- Challenges:
  - Weak and diffuse decay source
  - Electron depolarization in multiple Coulomb scatterings
  - Low energy electrons (<783 keV)
  - High background (n-capture)

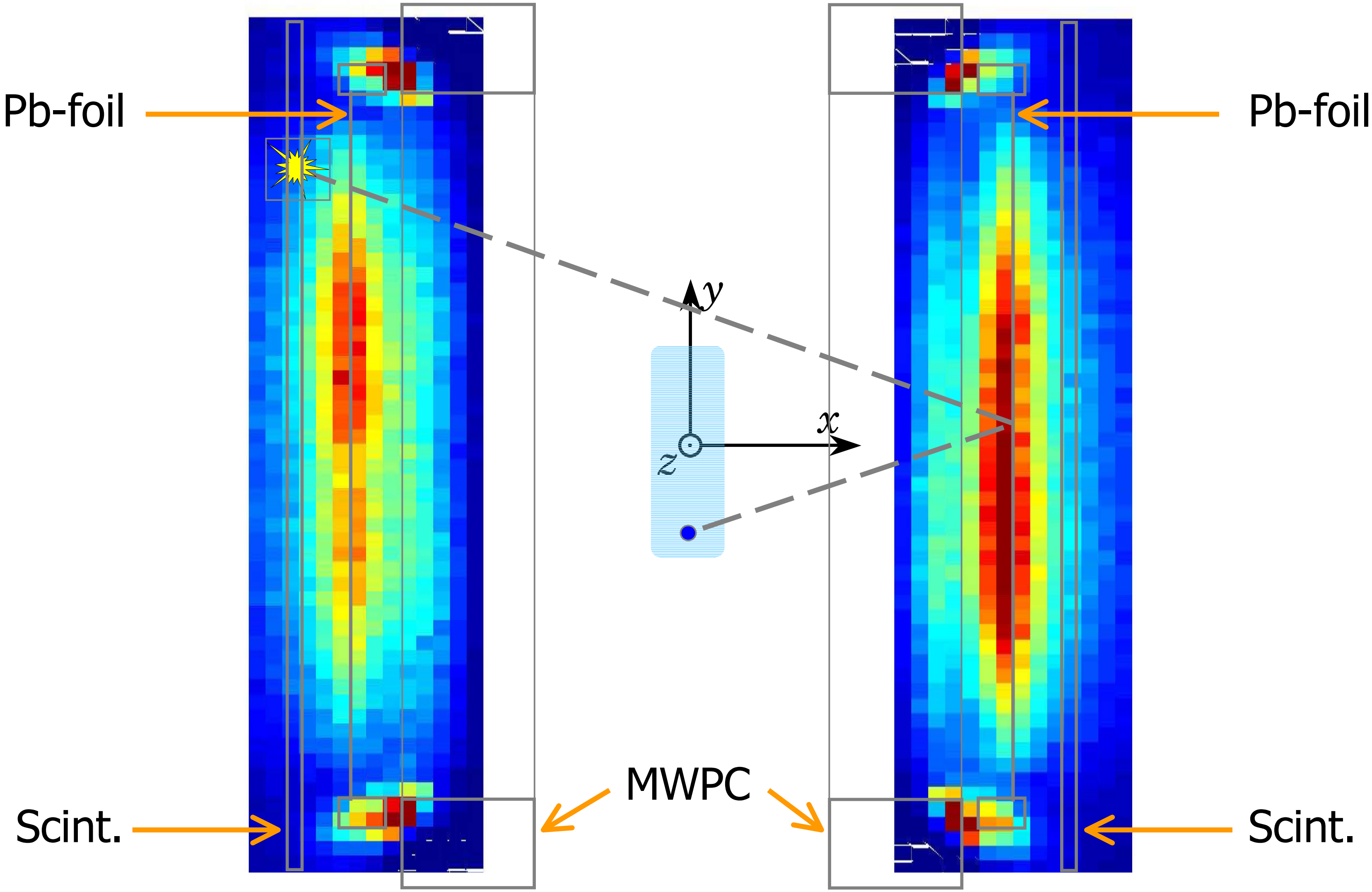
- Solutions:
  - Tracking of electrons in low-mass, low-Z MWPCs
  - Identification of Mott-scattering vertex.
  - Frequent neutron spin flipping.
  - “foil-in” and “foil-out” measurements.



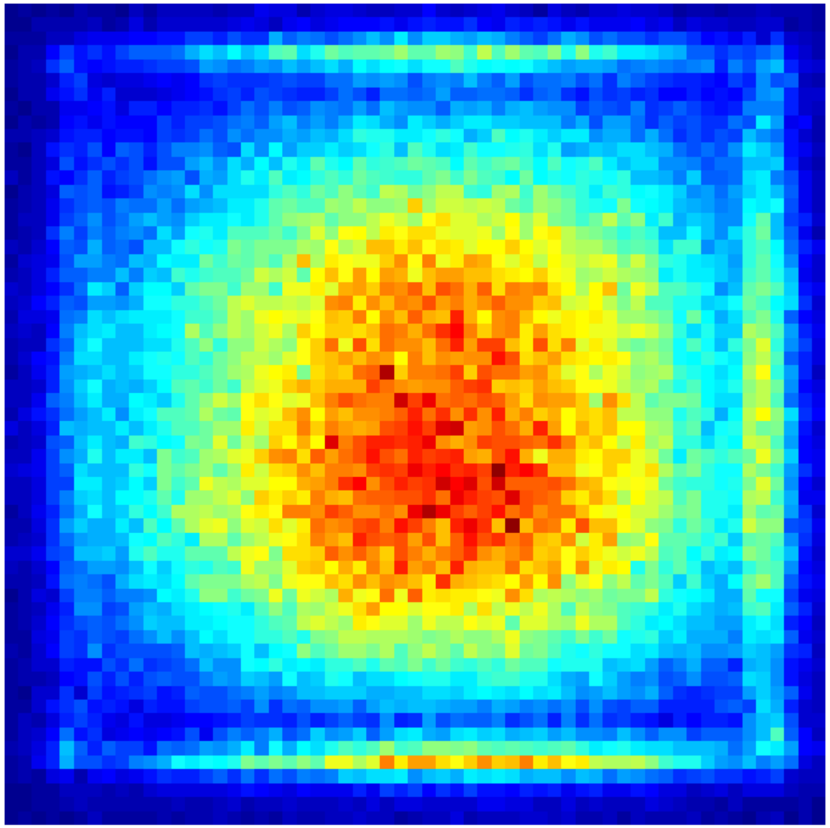
Mott-scattering: “V-track” events

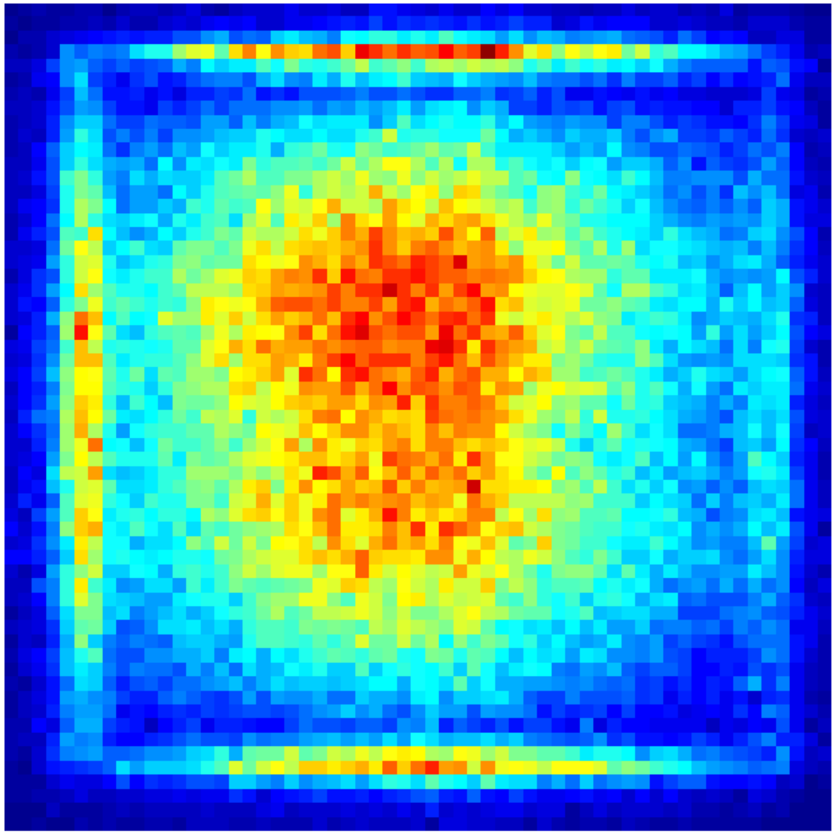


Projection of vertices onto XY–plane

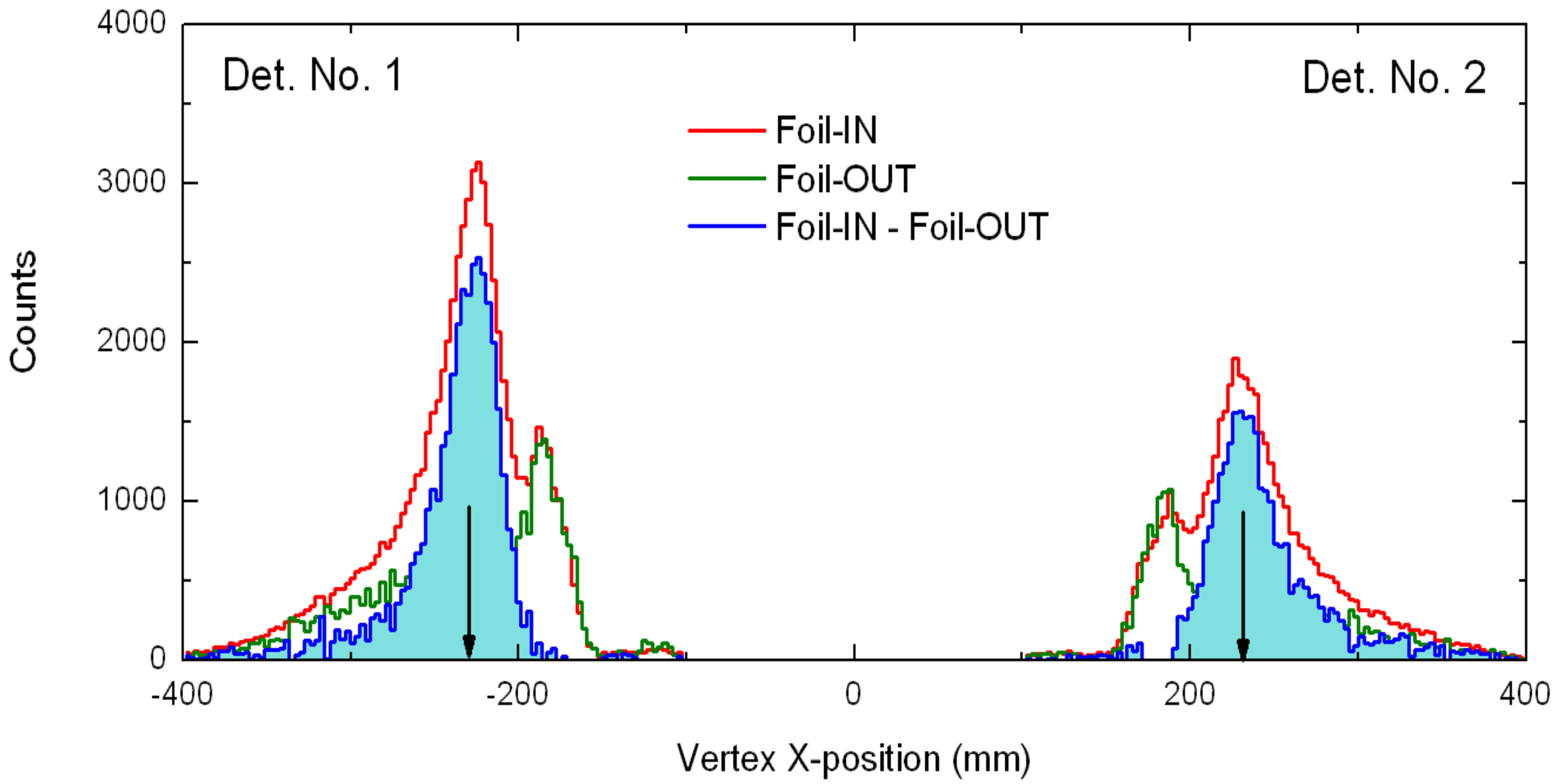


Projection of the Mott-scattering vertices onto Pb-foil planes



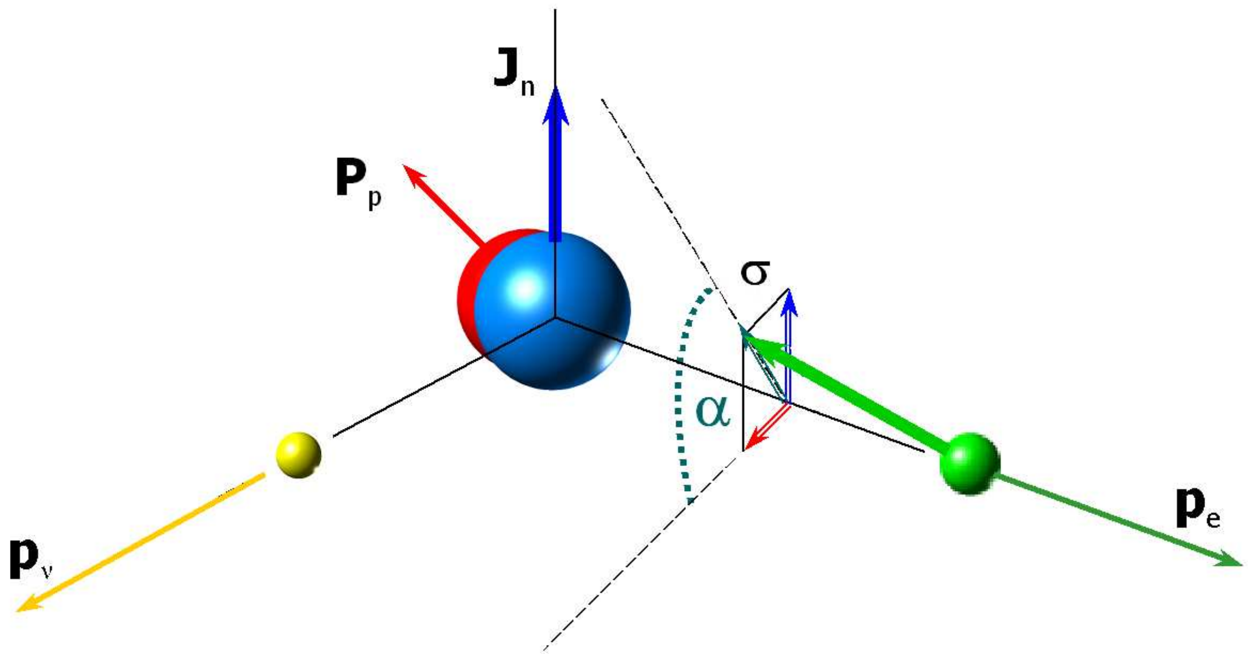


Projection of vertices onto X-axis



Data analysis

- Idea:
  - Express event rate distributions as functions of the azimuthal angle α making use of reconstructed (event-by-event) angles.
  - Finite geometry and unknown efficiency-acceptance will be absorbed in the "experimental factors" evaluated with high precision.



Data analysis

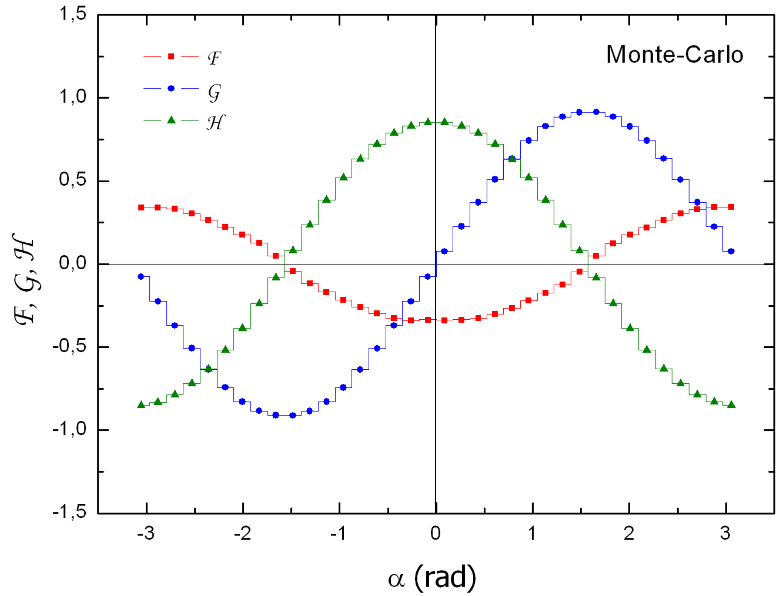
- Scenario I:
  - Efficiency and acceptance do not change with neutron spin flip

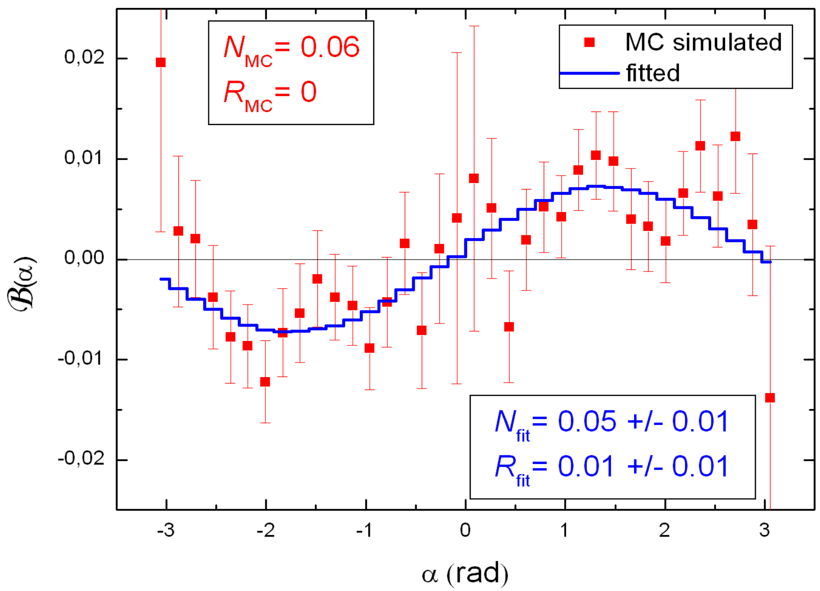
$$\bar{\mathcal{A}}(\alpha) = \frac{\bar{\omega}(P,\alpha) - \bar{\omega}(-P,\alpha)}{\bar{\omega}(P,\alpha) + \bar{\omega}(-P,\alpha)}$$
$$= P\bar{\beta}(\alpha)\left\{A\bar{\mathcal{F}}(\alpha) + \bar{S}(\alpha)\left[N'\bar{\mathcal{G}}(\alpha) + R\bar{\mathcal{H}}(\alpha)\right]\right\}$$
$$N' \equiv N/\beta, \quad \beta \equiv v/c,$$
$$\bar{\mathcal{F}}(\alpha) \equiv \left\langle \hat{J}\cdot\hat{p}_e \right\rangle, \quad \bar{\mathcal{G}}(\alpha) \equiv \left\langle \hat{n}\cdot\hat{J} \right\rangle, \quad \bar{\mathcal{H}}(\alpha) \equiv \left\langle \hat{n}\cdot\left(\hat{J}\times\hat{p}_e\right)\right\rangle,$$
$$\bar{S}(\alpha) \equiv \left\langle S(\alpha)\right\rangle, \qquad \bar{\beta}(\alpha) \equiv \left\langle S(\alpha)\right\rangle$$

  - Asymmetry parameter *A* for correction is taken from another, high precision, dedicated experiment

$$\bar{\mathcal{B}}(\alpha) = \bar{\mathcal{A}}(\alpha) - PA\bar{\beta}(\alpha)\bar{\mathcal{F}}(\alpha)$$
$$= P\bar{\beta}(\alpha)\bar{S}(\alpha)\left[N'\bar{\mathcal{G}}(\alpha) + R\bar{\mathcal{H}}(\alpha)\right]$$

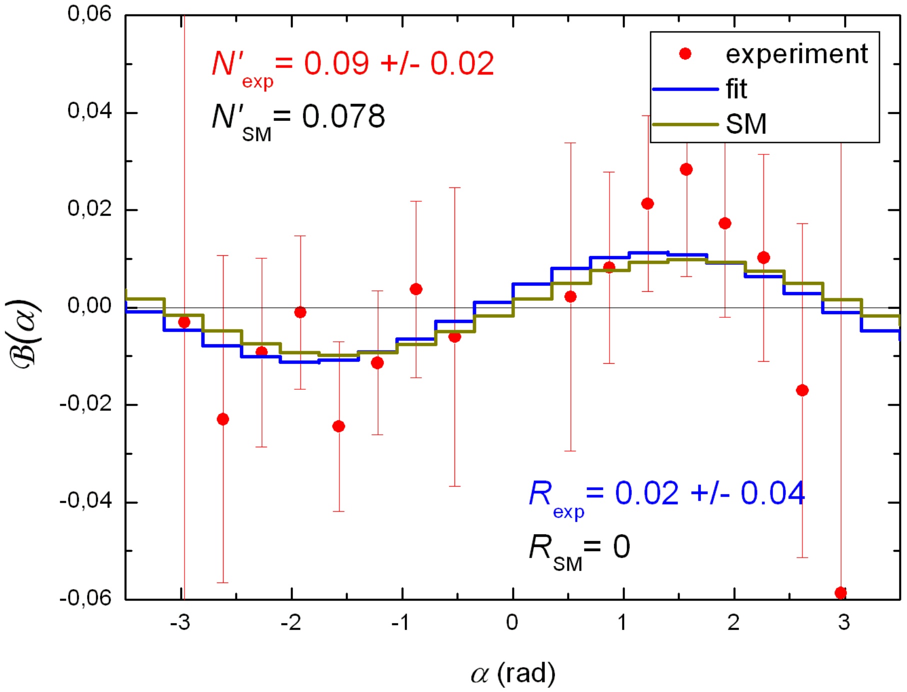
Monte-Carlo simulation



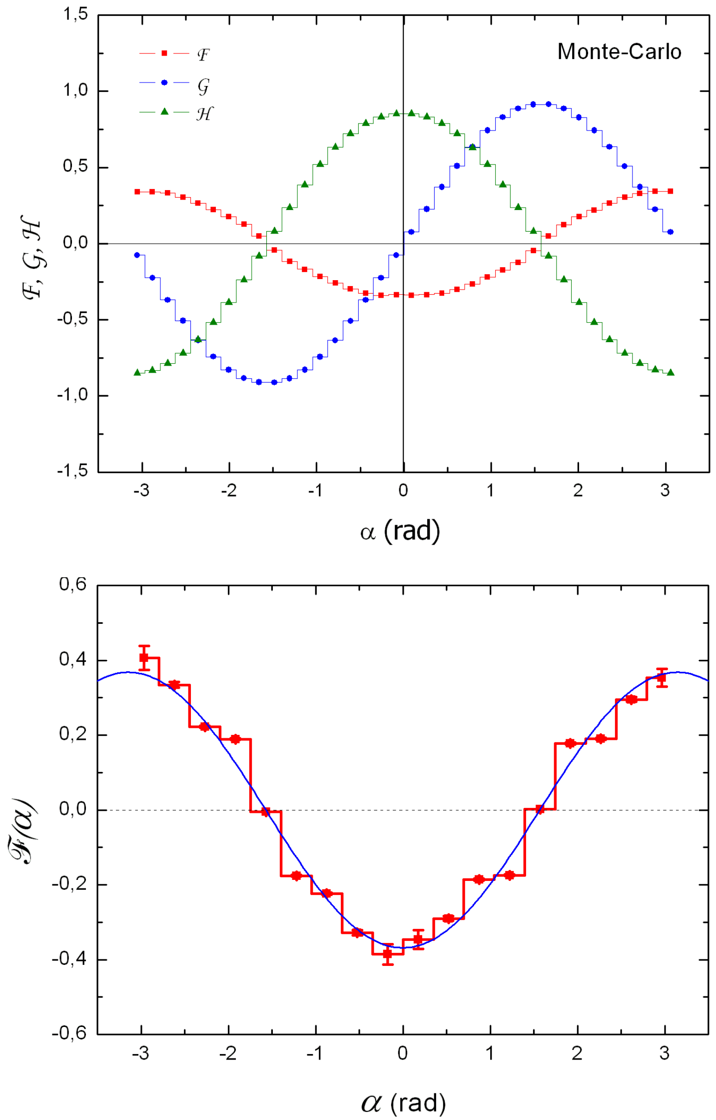


Experiment

- First phase of data taking – completed
- Analyzed:
  - ~40'000 events (~10% of full data set)
  - Analysis of systematic effects still in progress
  - PRELIMINARY RESULT:



Experimental geometry factors



Data analysis

- Scenario II:
  - Make use of symmetry of the detecting system:

$$\bar{\mathcal{F}}(-\alpha) \simeq \bar{\mathcal{F}}(\alpha), \quad \bar{\mathcal{G}}(-\alpha) \simeq -\bar{\mathcal{G}}(\alpha), \quad \bar{\mathcal{H}}(-\alpha) \simeq \bar{\mathcal{H}}(\alpha)$$

$$\bar{S}(-\alpha) \simeq \bar{S}(\alpha), \qquad \bar{\beta}(-\alpha) \simeq \bar{\beta}(\alpha)$$

  - Calculate "super-ratio":

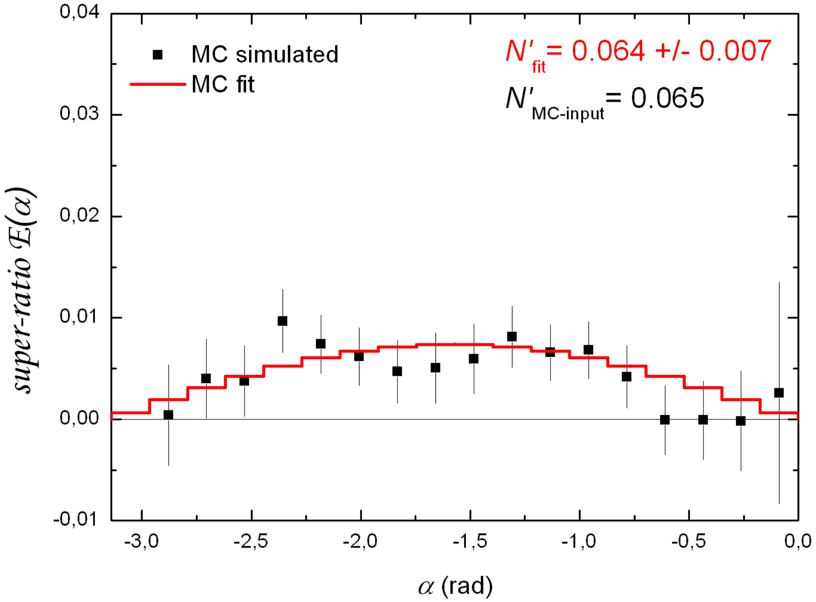
$$\bar{\mathcal{E}}(\alpha) = \frac{\bar{r}(\alpha) - 1}{\bar{r}(\alpha) + 1}, \quad \bar{r}(\alpha) \equiv \sqrt{\frac{\bar{\varpi}^{+}(\alpha)\bar{\varpi}^{-}(-\alpha)}{\bar{\varpi}^{+}(-\alpha)\bar{\varpi}^{-}(\alpha)}}$$

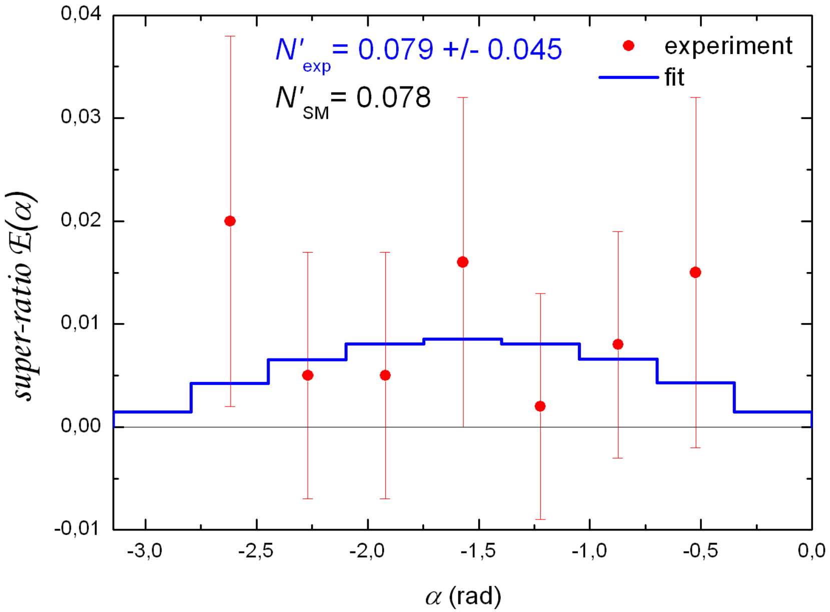
  - Now the correction is of the order $\propto \left[PA\bar{\beta}(\alpha)\bar{\mathcal{F}}(\alpha) \right]^2 < 0.01$

$$\bar{\mathcal{E}}(\alpha) \simeq \frac{N \cdot P\bar{S}(\alpha)\bar{\mathcal{G}}(\alpha)}{1 - \left[PA\bar{\beta}(\alpha)\bar{\mathcal{F}}(\alpha) \right]^2}$$

Data analysis

- Scenario II:
  - PRELIMINARY RESULT:



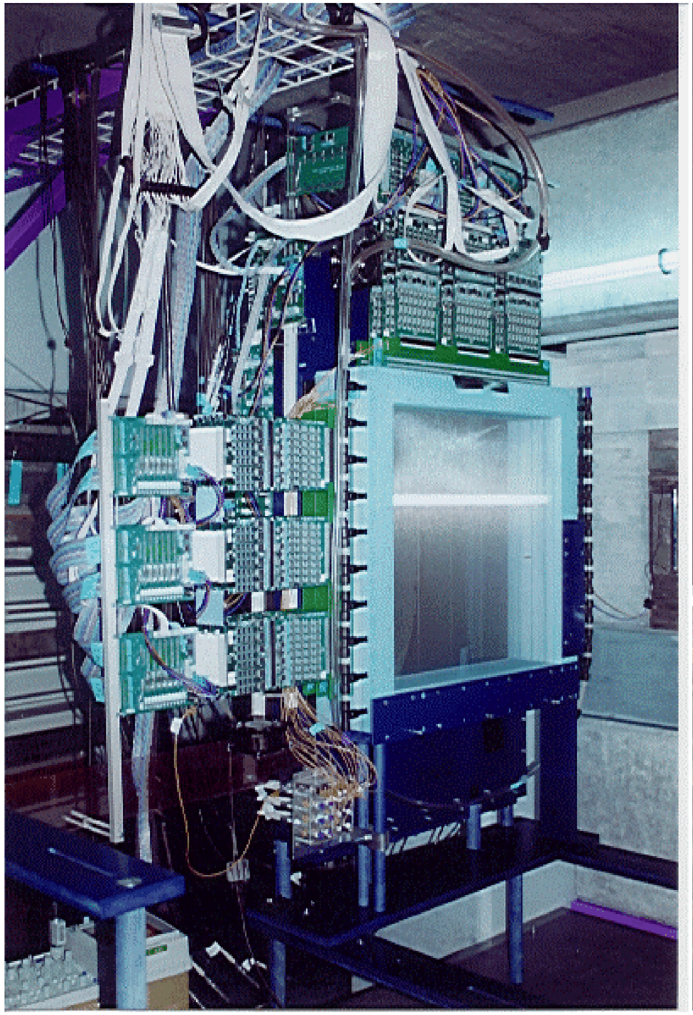


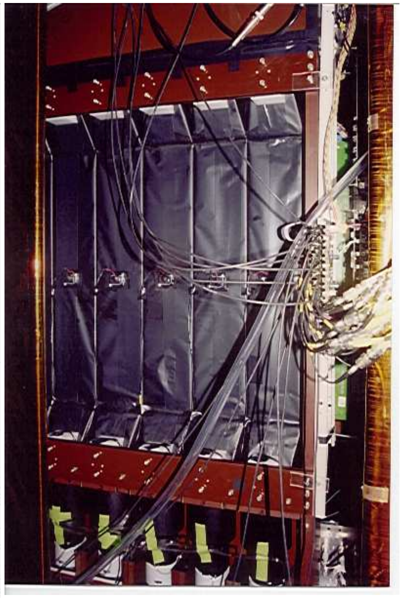
$$\bar{\mathcal{E}}(\alpha) \simeq \frac{N \cdot P\bar{S}(\alpha)\bar{\mathcal{G}}(\alpha)}{1-\left[PA\bar{\beta}(\alpha)\bar{\mathcal{F}}(\alpha)\right]^2}$$

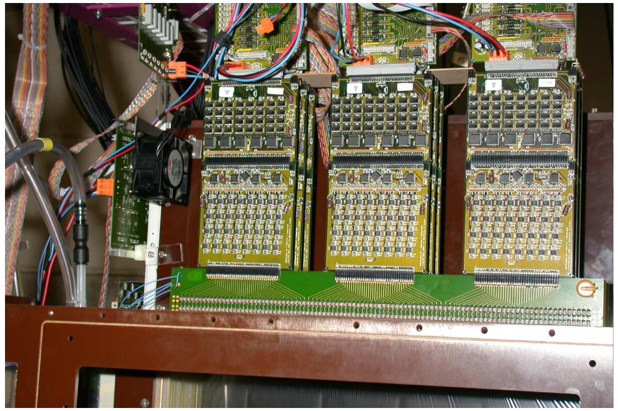
Conclusions

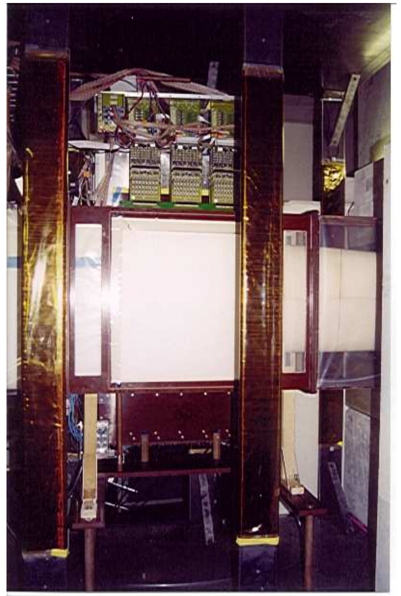
- $N \neq 0 \Rightarrow$ transversal polarization of electrons from β–decay experimentally confirmed (for the first time !)
- Mott–polarimeter has expected effective analyzing power (~18%)
- Size and sign of measured N–parameter agree with expectations !
- Errors are dominated by statistics
- Analysis of full data set (~500'000 events) – in progress
- Plans: Collect ~1'000'000 events in 2006

MWPCs, scintillators and electronics

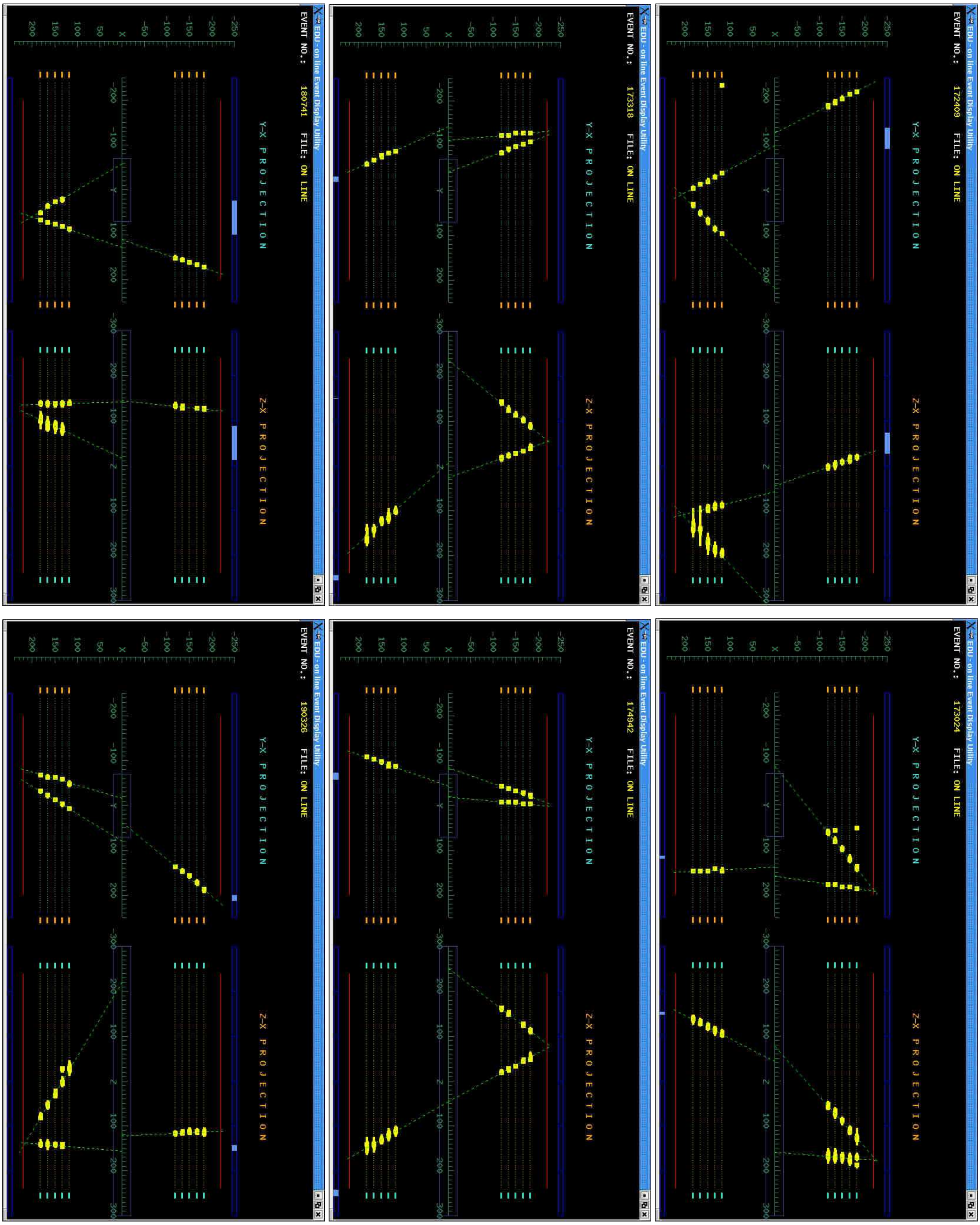




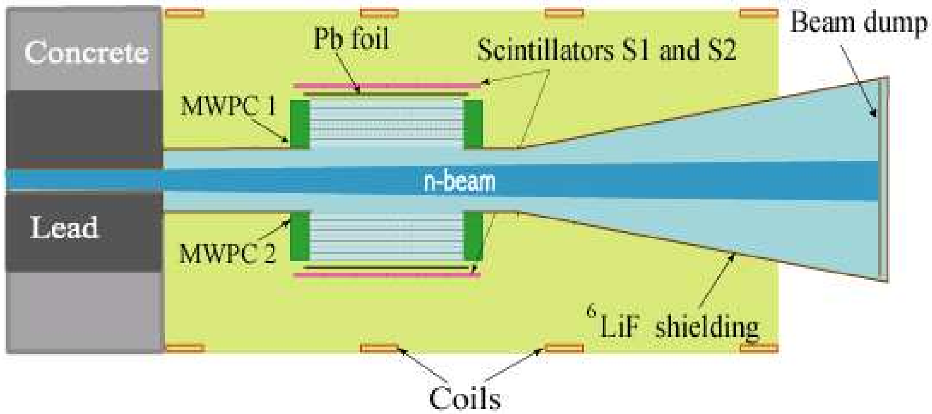


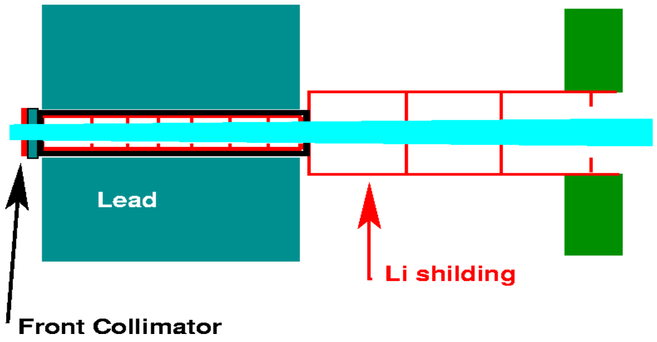


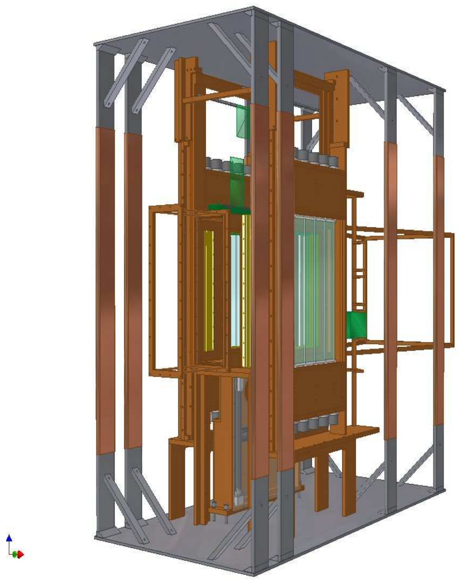
“V-track” events – on-line display

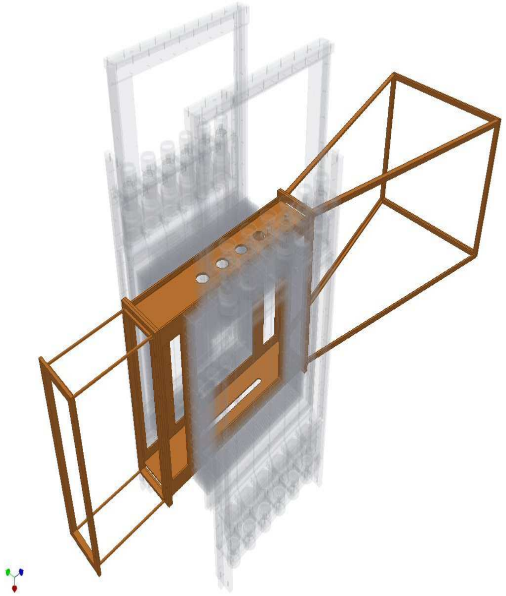


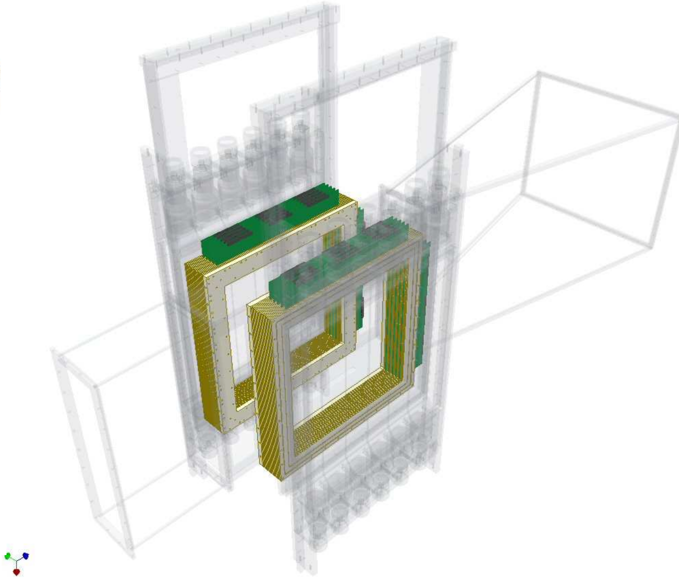
Experimental setup





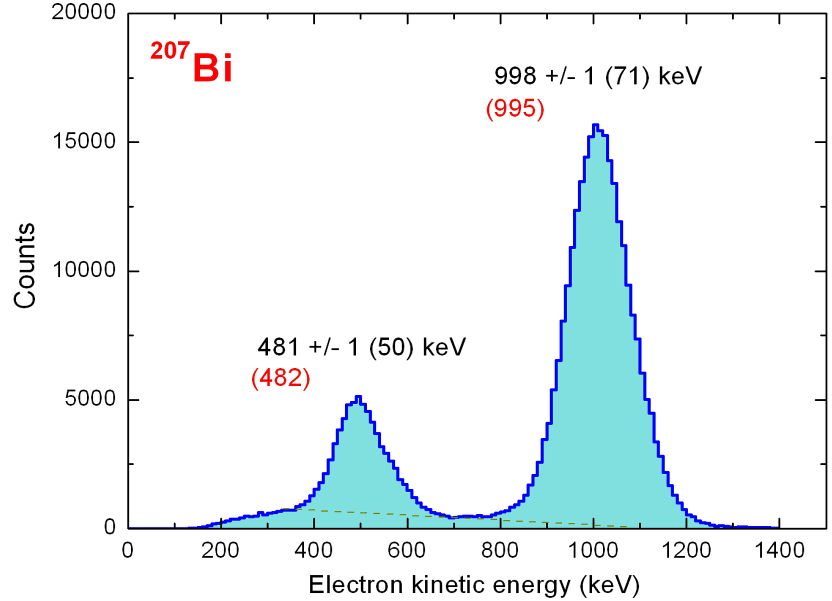




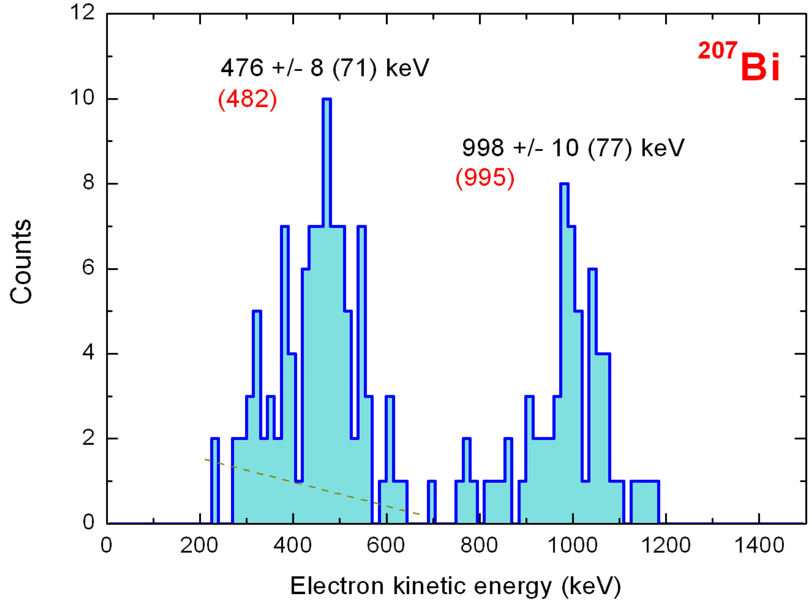


Energy calibration

Single track events

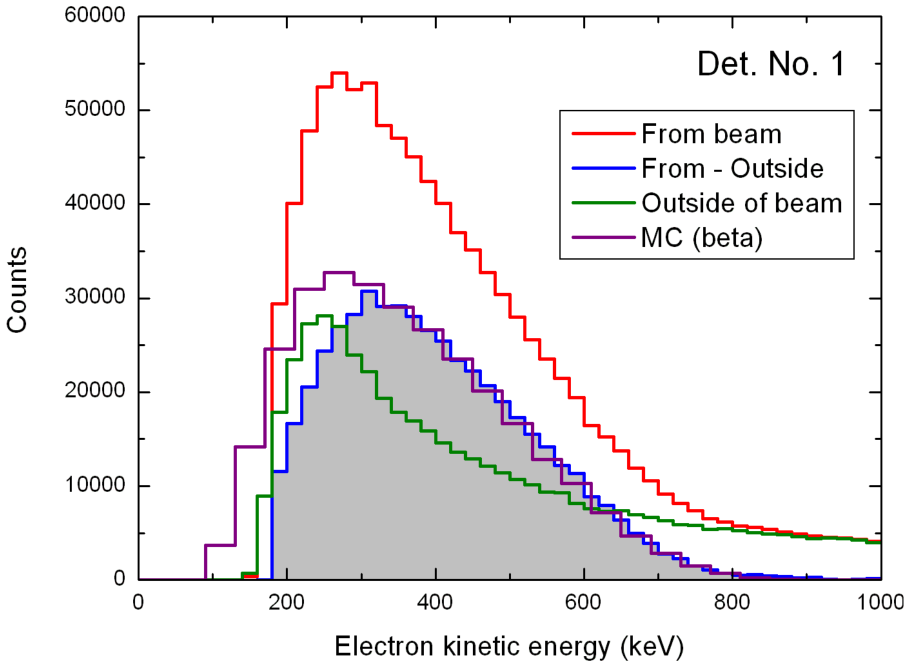


V-track events

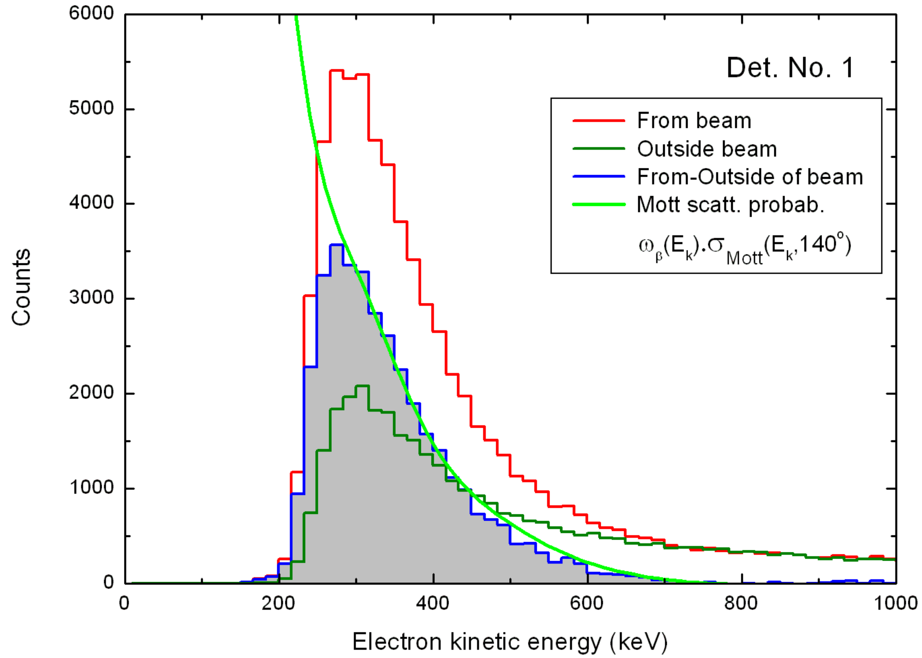


Energy distribution

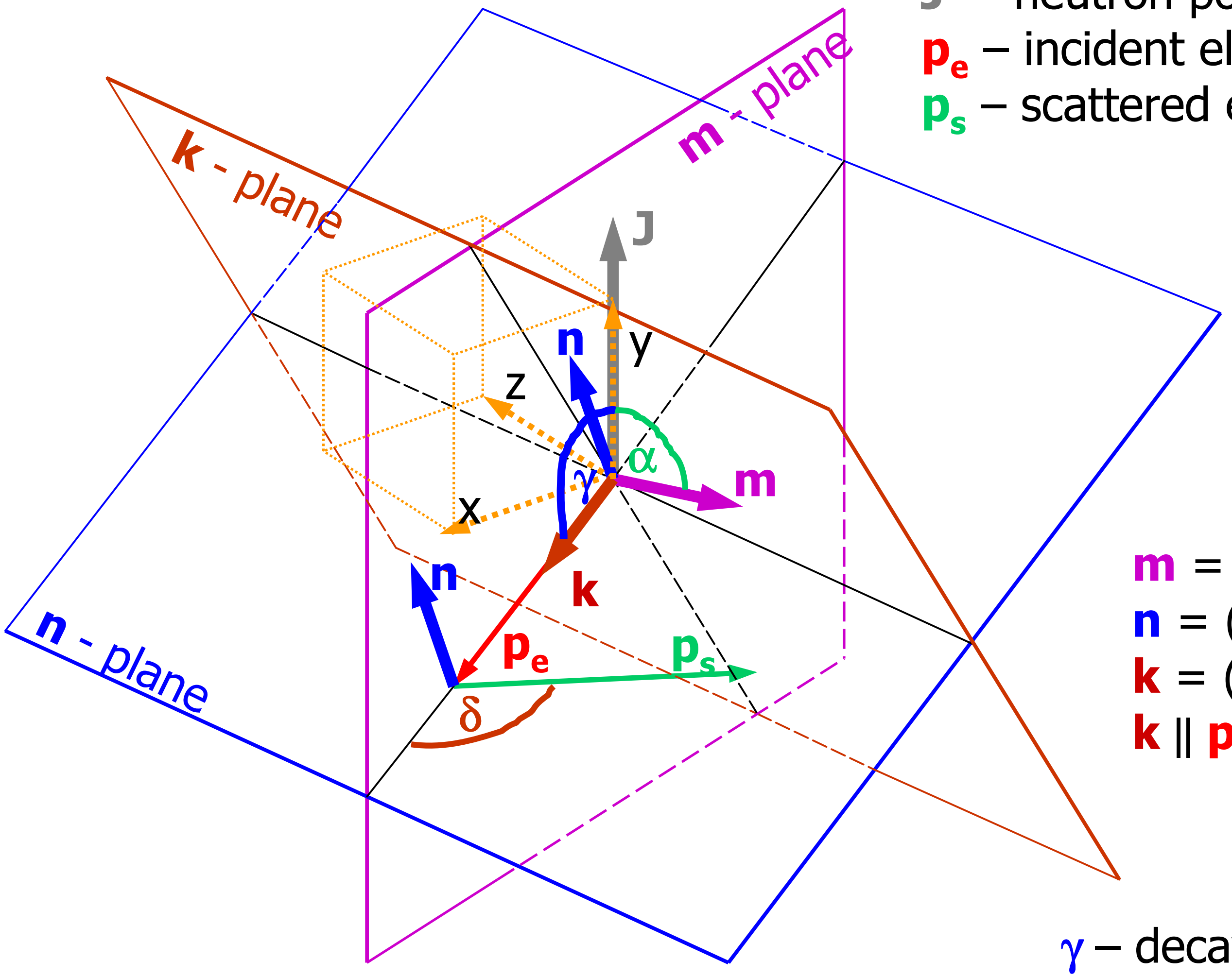
Single-track events



V-track events



J – neutron polarization
$\mathbf{p_e}$ – incident electron momentum
$\mathbf{p_s}$ – scattered electron momentum



$\mathbf{m} = (\mathbf{J}\times\mathbf{p_e})/|\mathbf{J}\times\mathbf{p_e}|$
$\mathbf{n} = (\mathbf{p_e}\times\mathbf{p_s})/|\mathbf{p_e}\times\mathbf{p_s}|$
$\mathbf{k} = (\mathbf{m}\times\mathbf{n})/|\mathbf{m}\times\mathbf{n}|$
$\mathbf{k} \parallel \mathbf{p_e}$

(x,y,z) – LAB frame

γ – decay angle
δ – Mott scattering angle
α – event projection angle

1-st order FSI contribution

$$R_{\mathrm{FSI}} \cdot \xi = 2 \cdot \frac{\alpha Z m}{p} \cdot [\, |M_{GT}|^2 \frac{1}{I+1} \cdot \mathrm{Re}(C_T C'^*_T - C_A C'^*_A) + M_F M_{GT} \sqrt{\frac{I}{I+1}} \cdot \mathrm{Re}(C_S C'^*_T + C'_S C^*_T - C_V C'^*_A - C'_V C^*_A)\,]$$

In the SM:

$C_V = C'_V = \mathrm{Re}C_V = 1,\ C_A = C'_A = \mathrm{Re}C_A = -1.26,$

$|C_S|, |C'_S|, |C_T|, |C'_T| = 0:$

$$R_{\mathrm{FSI,SM}} = \frac{\alpha Z m}{p} \cdot A_{\mathrm{SM}}.$$

For neutron decay, $A = -0.1173(13)$

$$R^n_{\mathrm{SM}} \approx 0.001$$

Theoretical uncertainty of R_{FSI}

- Vogel & Werner [NP 404 (1983) 345] corrected for:
  $\Rightarrow \Delta R_{\mathrm{FSI}}(\mathrm{neutron}) \approx 10^{-5}$
- A. Czarnecki: with new theory input parameters, one can reach
  $\Rightarrow \Delta R_{\mathrm{FSI}}(\mathrm{neutron}) \approx 5\times10^{-6}$

"Discovery potential" or *"exclusion power"* (4 standard deviations) of the R–parameter in the free neutron decay with present FSI theory is:

$$R_n \approx 2\times10^{-5}$$

$$\mathrm{Im}(C_S+C'_S) + 1.2\times\mathrm{Im}(C_T+C'_T) \approx 10^{-4}$$