Search for Time Reversal Violating Effects in the Neutron Decay

A Measurement of the Transverse Polarization of Electrons from the Decay of Polarized Neutrons

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*) Theory support

T–odd correlations in β–decay

- Angular distribution contains in the lowest order 4 T–odd observables:

$$\omega(\langle \mathbf{J}_\mathrm{n}\rangle | E_\mathrm{e}\Omega_\mathrm{e}\Omega_\nu)\cdot dE_\mathrm{e}d\Omega_\mathrm{e}d\Omega_\nu \quad \propto \quad \left[1+\ldots+D\frac{(\mathbf{p}_\mathrm{e}\times\mathbf{p}_\nu)\cdot\langle \mathbf{J}_\mathrm{n}\rangle}{E_e E_\nu}+\ldots\right]\cdot dE_\mathrm{e}d\Omega_\mathrm{e}d\Omega_\nu$$

$$\omega(\langle \mathbf{J}_\mathrm{n}\rangle \sigma | E_\mathrm{e}\Omega_\mathrm{e})\cdot dE_\mathrm{e}d\Omega_\mathrm{e} \quad \propto \quad \left[1+\ldots+R\frac{(\mathbf{p}_\mathrm{e}\times\sigma)\cdot\langle \mathbf{J}_\mathrm{n}\rangle}{E_e}+\ldots\right]\cdot dE_\mathrm{e}d\Omega_\mathrm{e}$$

$$\omega(\sigma | E_\mathrm{e}\Omega_\mathrm{e}\Omega_\nu)\cdot dE_\mathrm{e}d\Omega_\mathrm{e}d\Omega_\nu \quad \propto \quad \left[1+\ldots+L\frac{\sigma\cdot(\mathbf{p}_\mathrm{e}\times\mathbf{p}_\nu)}{E_e E_\nu}+\ldots\right]\cdot dE_\mathrm{e}d\Omega_\mathrm{e}d\Omega_\nu$$

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

D, L : T–odd, P–even $\qquad$ R, V : T–odd, P–odd

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

T–odd 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

The 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 !
- Using the formula of D.J. Jackson et al., Phys. Rev. **106**, 517 (1957)

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

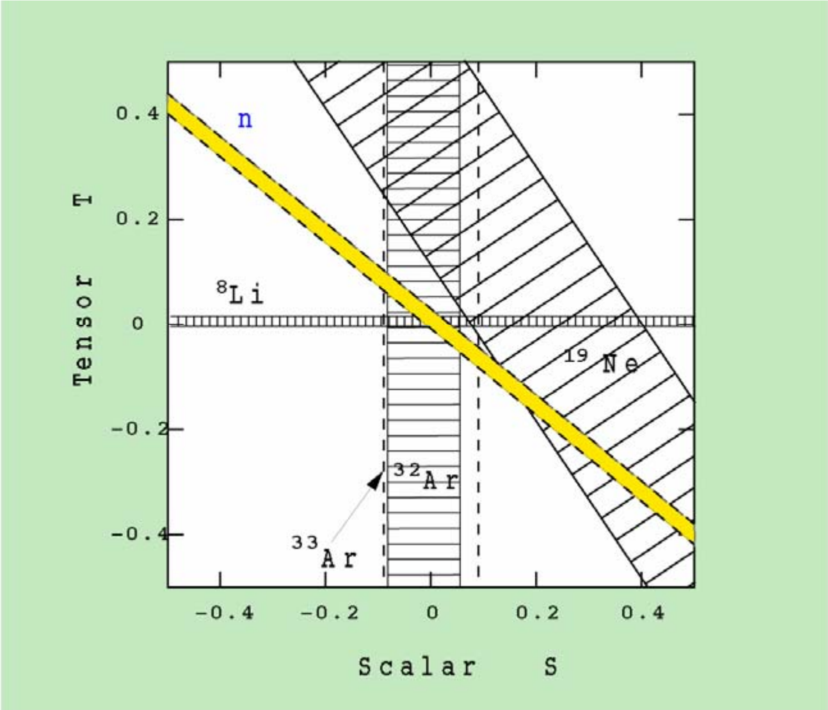
and defining:

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

- One obtains finally:

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

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



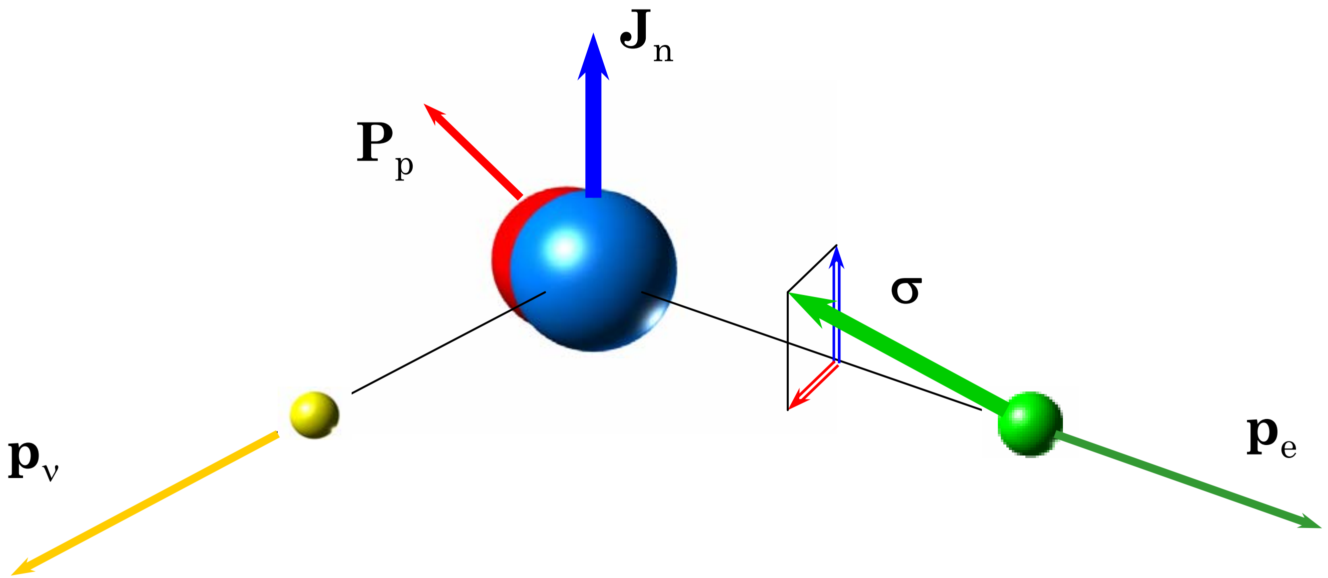
$$S = Im\left[(C_S + C'_S)/C_A\right],$$
$$T = Im\left[(C_T + C'_T)/C_A\right]$$

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 $S, T = 0$.

Transverse electron polarization

- R coefficient can be obtained from the transverse electron polarization

$$\omega(\langle \mathbf{J}_\mathrm{n} \rangle \sigma \,|\, E_\mathrm{e} \Omega_\mathrm{e}) \cdot dE_\mathrm{e} d\Omega_\mathrm{e} \propto \left[1 + \ldots + R \frac{(\mathbf{p}_\mathrm{e} \times \sigma) \cdot \langle \mathbf{J}_\mathrm{n} \rangle}{E_e} + N \sigma \cdot \langle \mathbf{J}_\mathrm{n} \rangle + \ldots \right] \cdot dE_\mathrm{e} d\Omega_\mathrm{e}$$



The N–correlation

- Can be determined from the transverse electron polarization component contained in the plane of lepton momentum and parent polarization:

$$N = \langle \vec{\sigma}_{T1} \rangle / \sin\theta_e,$$

- Conserves *T* and *P*, not measured for β–decay yet

$$\begin{aligned} N \cdot \xi \;=\;& 2 \cdot |M_{GT}|^2 \frac{1}{I+1} \cdot \mathrm{Re}[\frac{1}{2}\frac{m}{E}(|C_T|^2 + |C_A|^2 + |C'_T|^2 \\ &+ |C'_A|^2) + (C_T C_A^* + C'_T C'^*_A)] \\ &+ 2 \cdot M_F M_{GT} \sqrt{\frac{I}{I+1}} \cdot \mathrm{Re}[(C_S C_A^* + C_V C_T{}^* + C'_S C'^*_A \\ &+ C'_V C'_T{}^*) + \frac{m}{E}(C_S C_T{}^* + C_V C_A^* + C'_S C'_T{}^* + C'_V C'^*_A)] \end{aligned}$$

The N–correlation in neutron decay

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

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

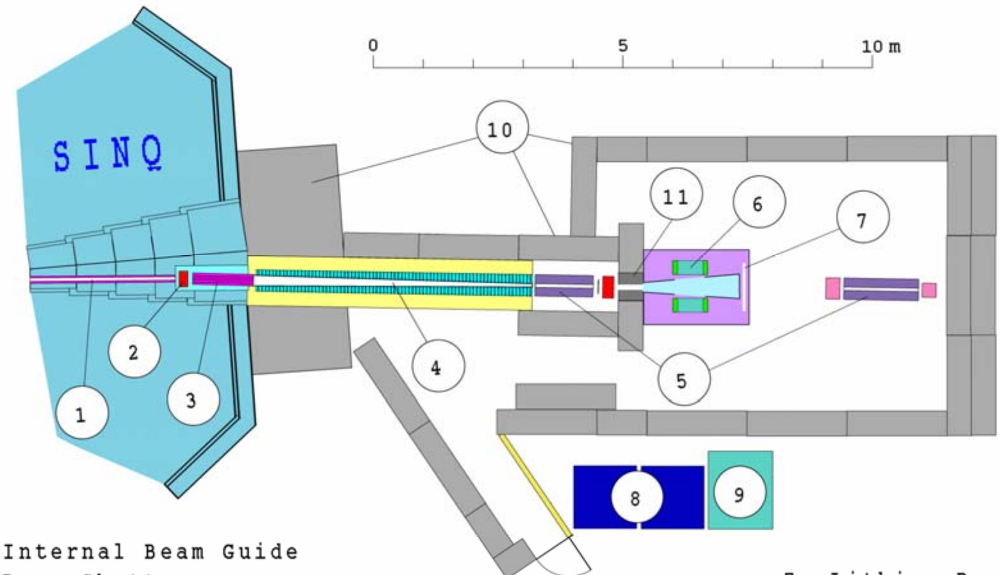
$$N_{\mathrm{SM}}^{n} \square\ 5 \times 10^{-2} \square\ 10 \cdot \Delta R_n (\text{anticipated})$$

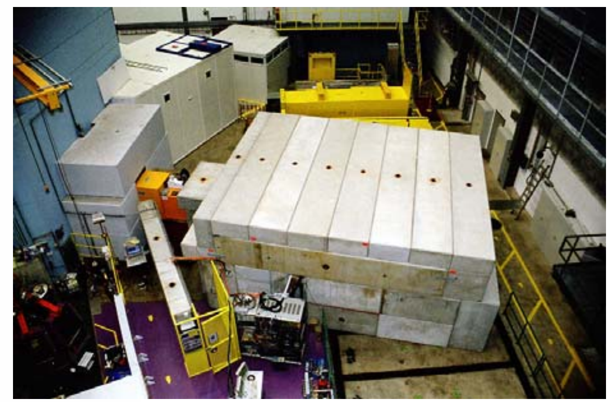
- Self calibration tool for R–correlation measurement.
- Excellent cross check for systematic effects in R–correlation.

Conclusion:

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

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

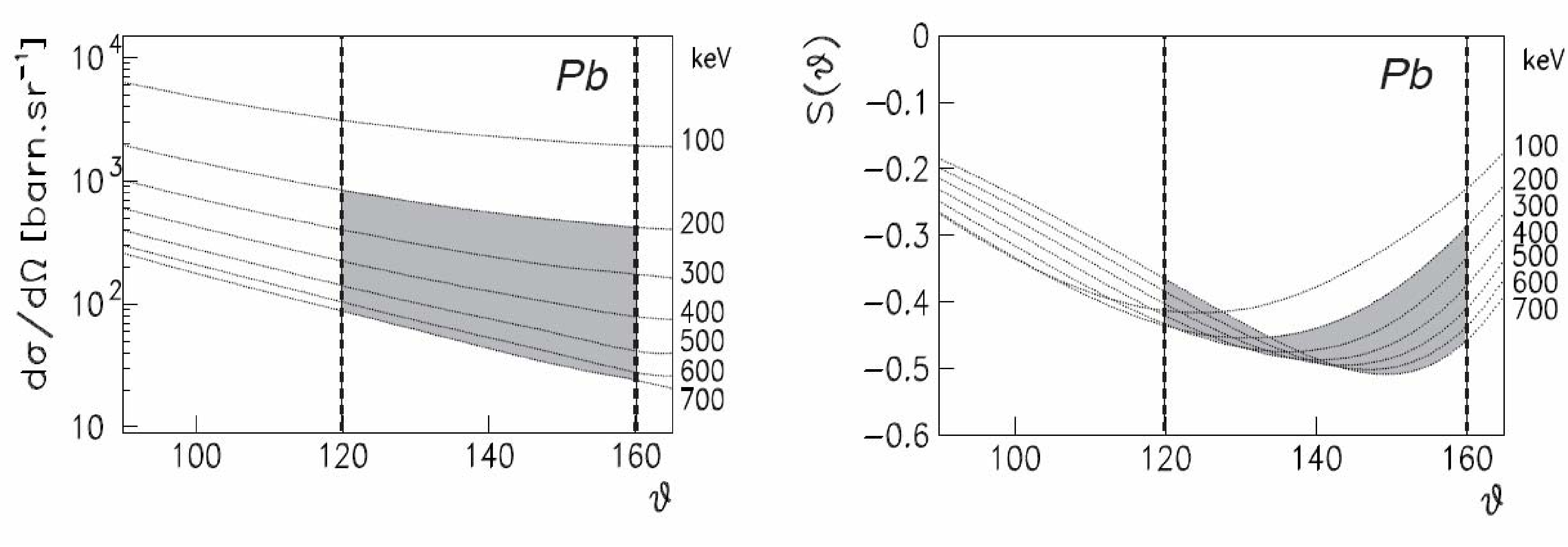
$I_n \approx 10^{10} s^{-1}$

$P_n \approx 90\%$

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

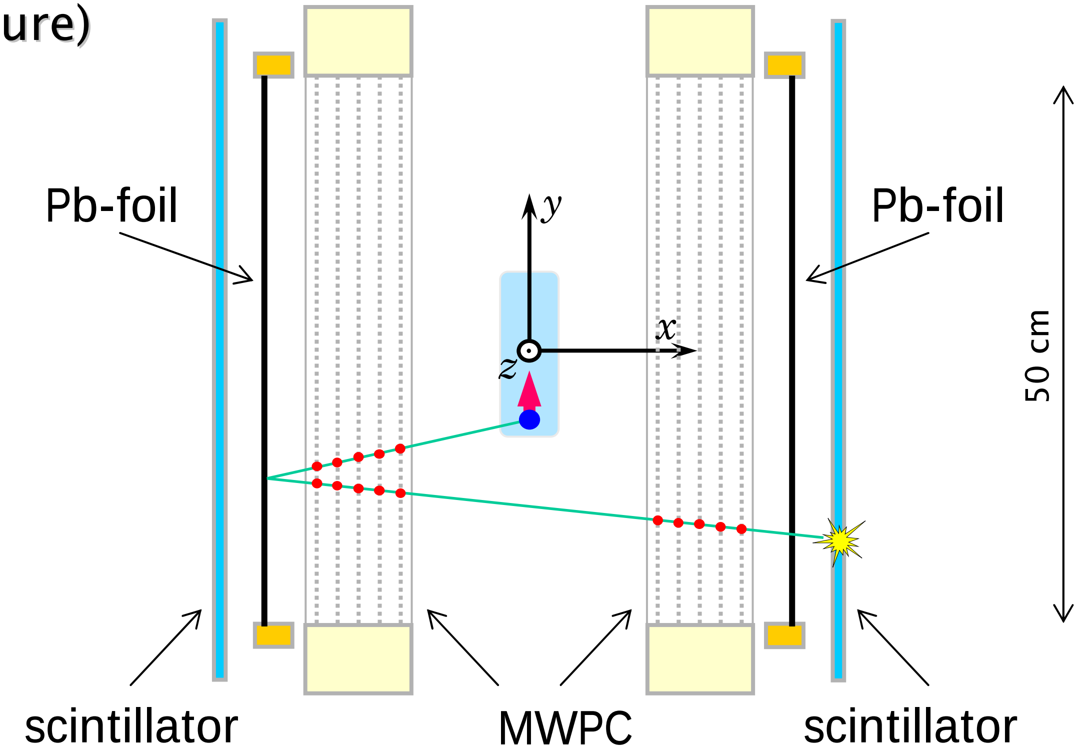
Mott scattering

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



Mott polarimeter

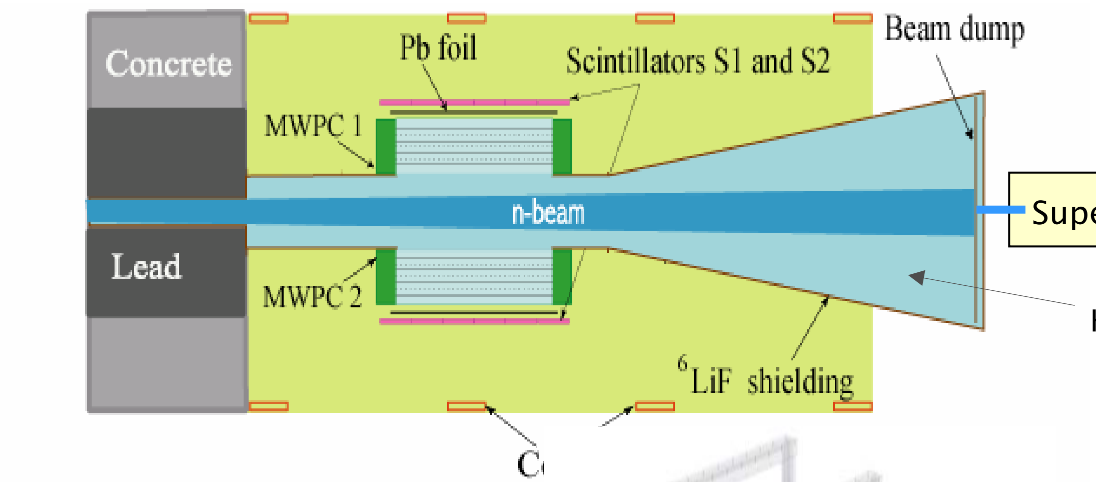
- **Challenges:**
  - Weak and diffuse decay source
  - Electron depolarization in multiple Coulomb scattering
  - Low energy electrons (<783 keV)
  - High background (n–capture)

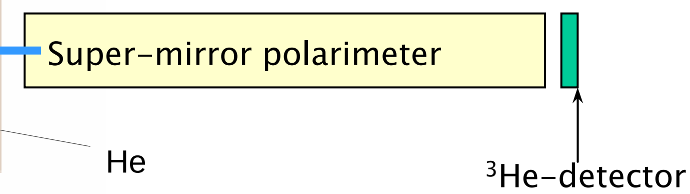


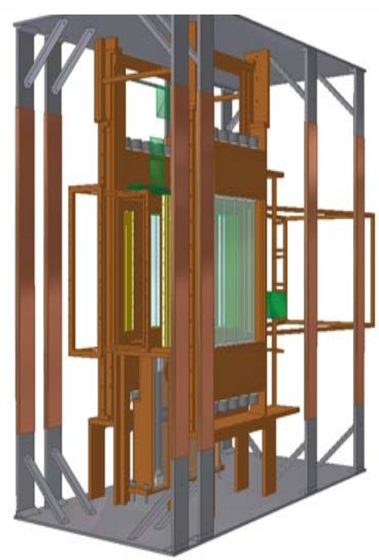
- **Solutions:**
  - Tracking of electrons in low–mass, low–Z MWPCs
  - Identification of Mott–scattering vertex
  - Frequent neutron spin flipping
  - "foil–in" and "foil–out" measurements

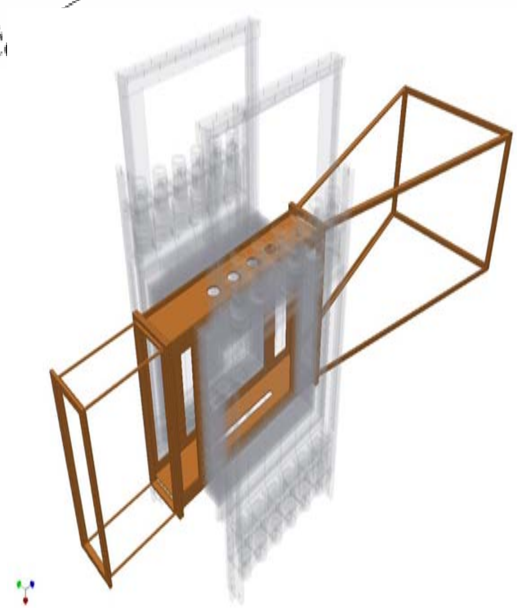
Experimental setup

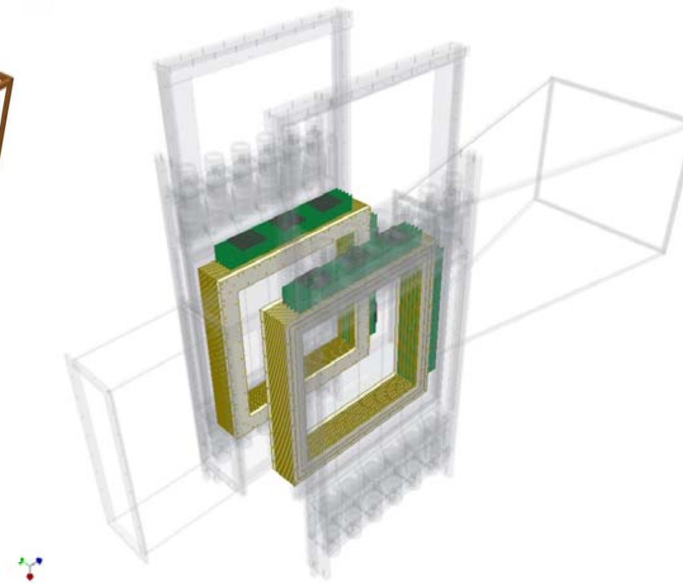
Analyzing power $\langle S_{\mathrm{Mott}} \rangle \approx 0.2$



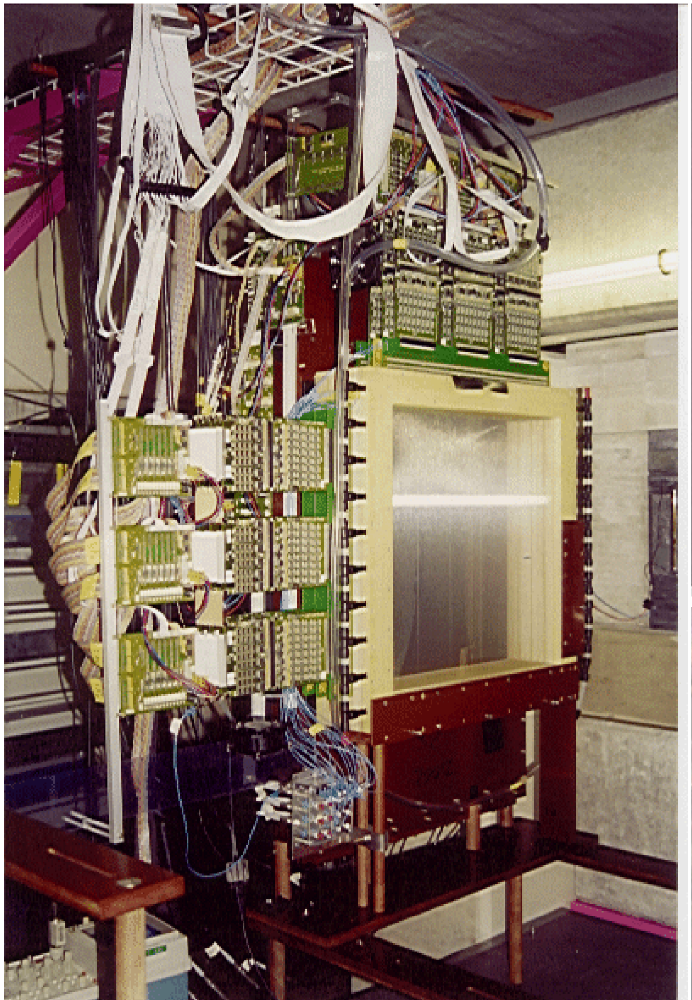


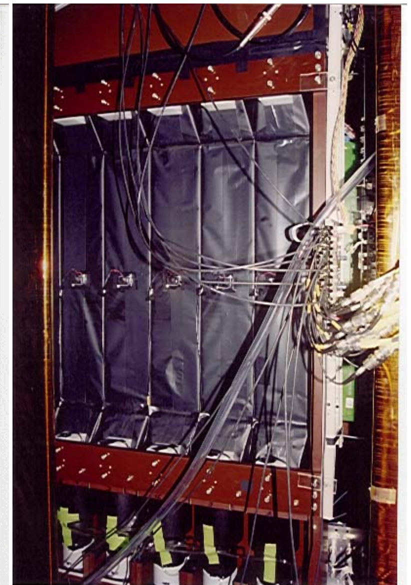


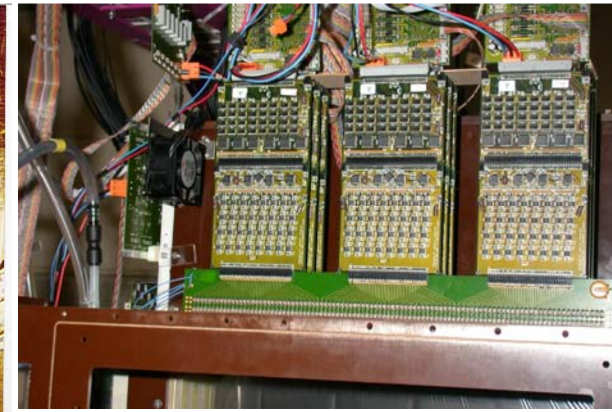




MWPCs, scintillators and electronics



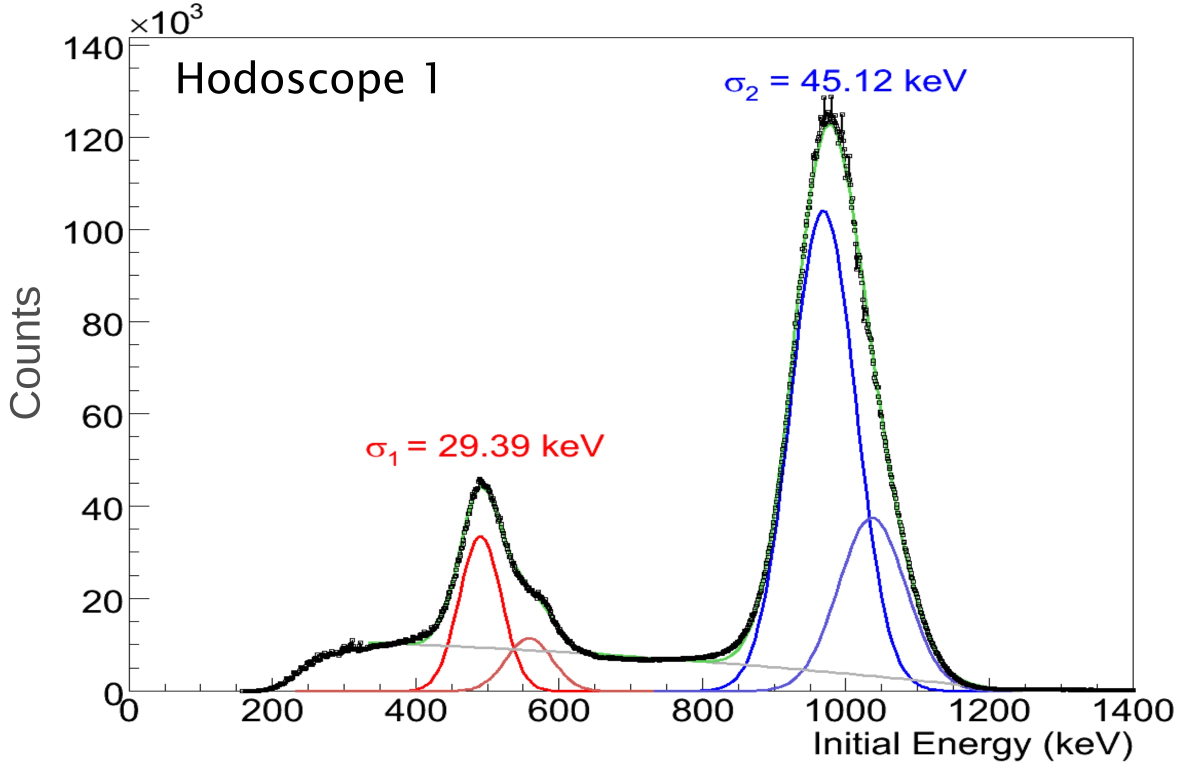




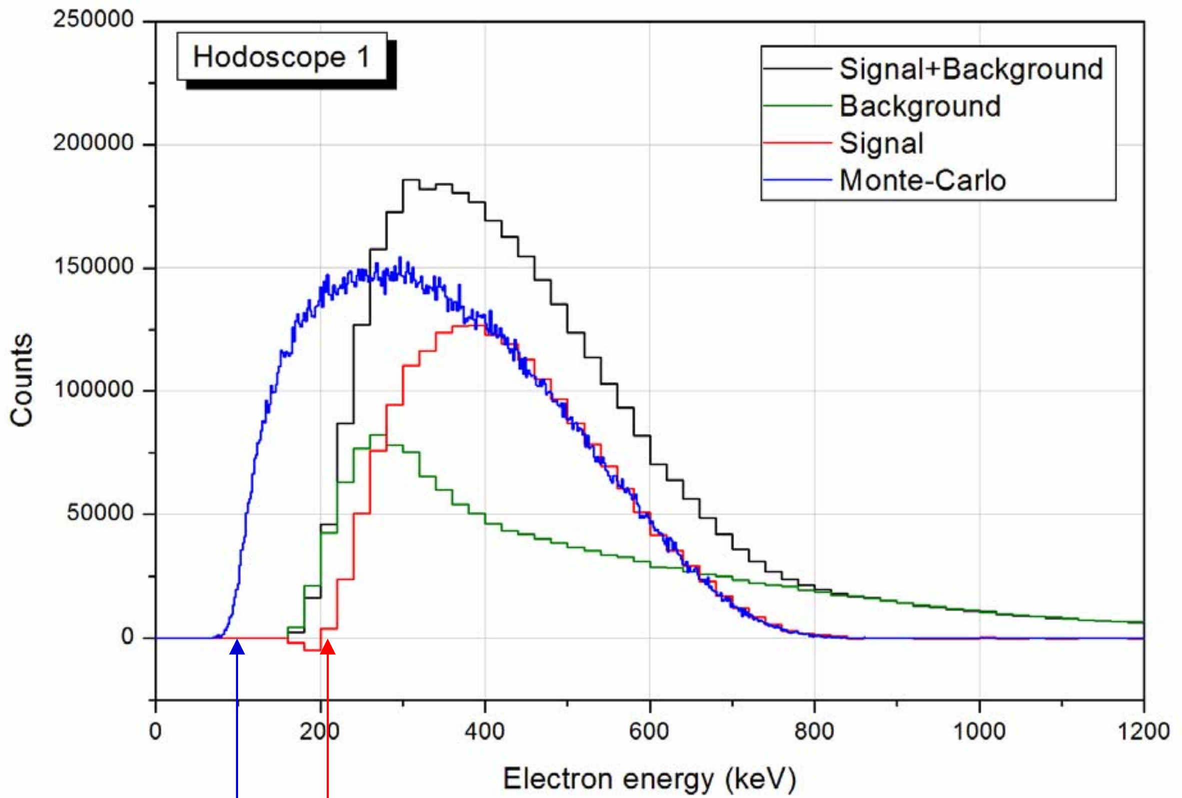
“Single–track events”

Energy calibration

- Conversion electrons from ^{207}Bi



β–energy distribution – background subtraction

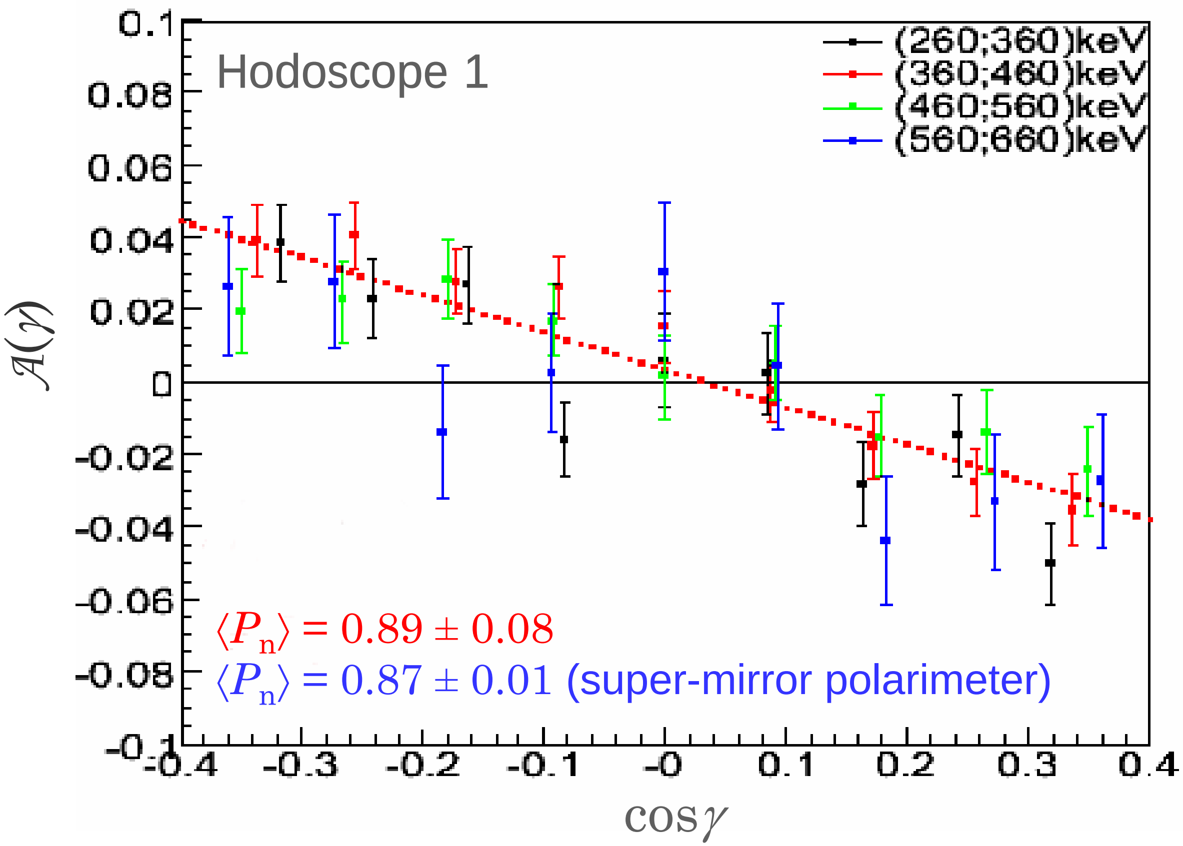


Absorption threshold

Electronic threshold

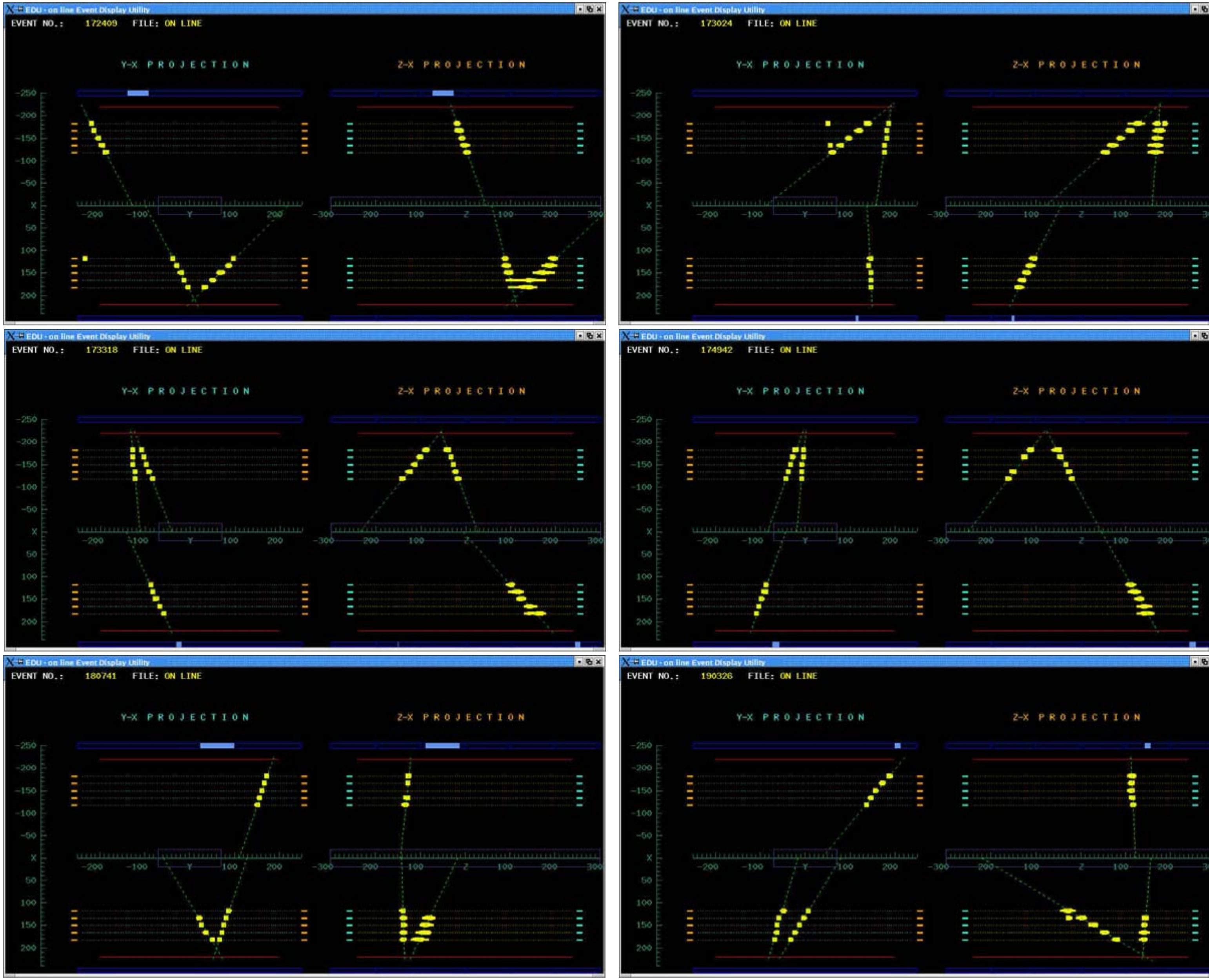
Decay asymmetry

$$\mathcal{A}(\gamma) \equiv \frac{\omega(\gamma,+P_{\mathrm{n}}) - \omega(\gamma,-P_{\mathrm{n}})}{\omega(\gamma,+P_{\mathrm{n}}) - \omega(\gamma,-P_{\mathrm{n}})} = P_{\mathrm{n}} A_{\mathrm{n}} \cdot \beta \cos\gamma$$

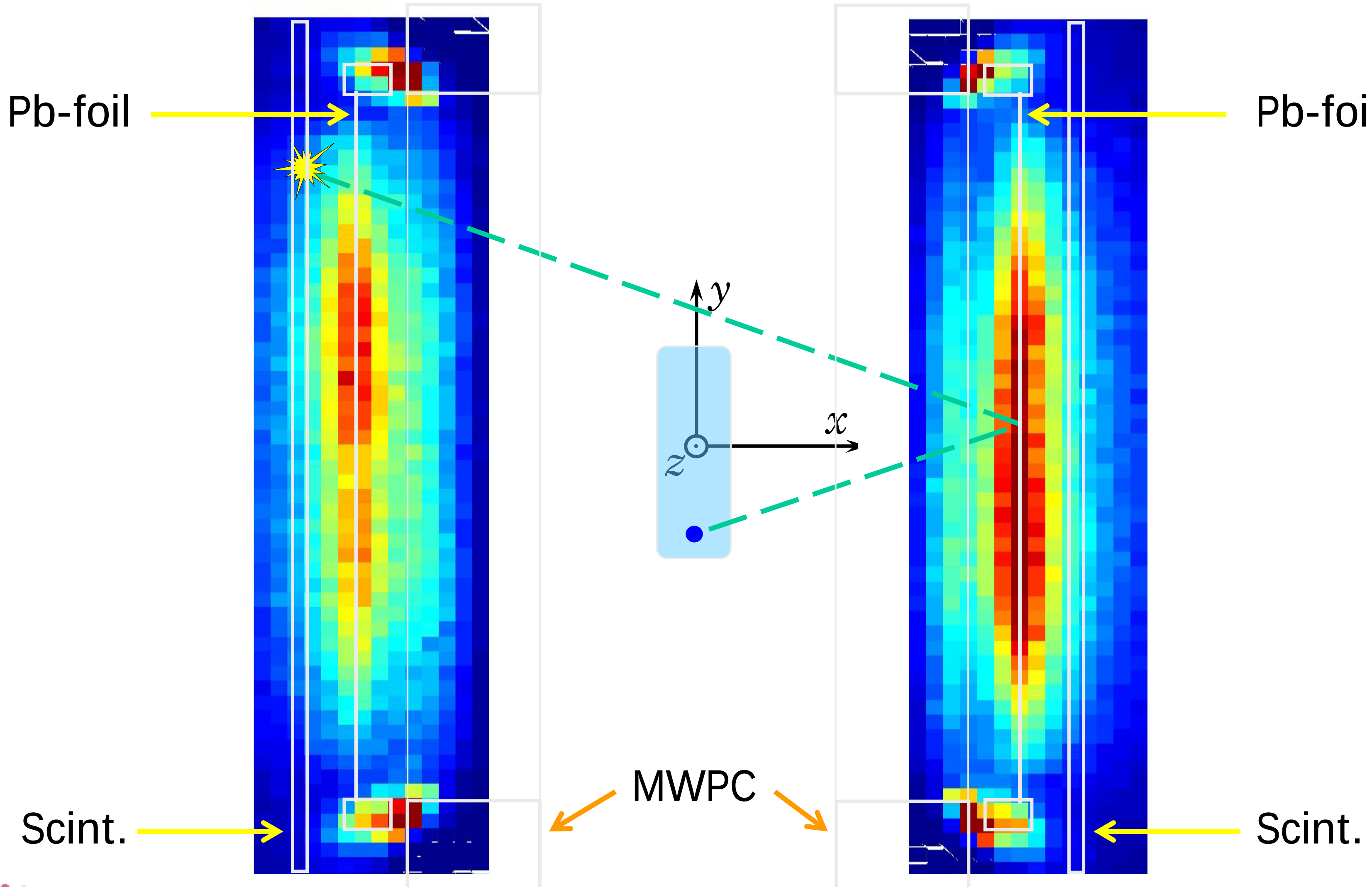


“V–tracks”: Mott scattering events

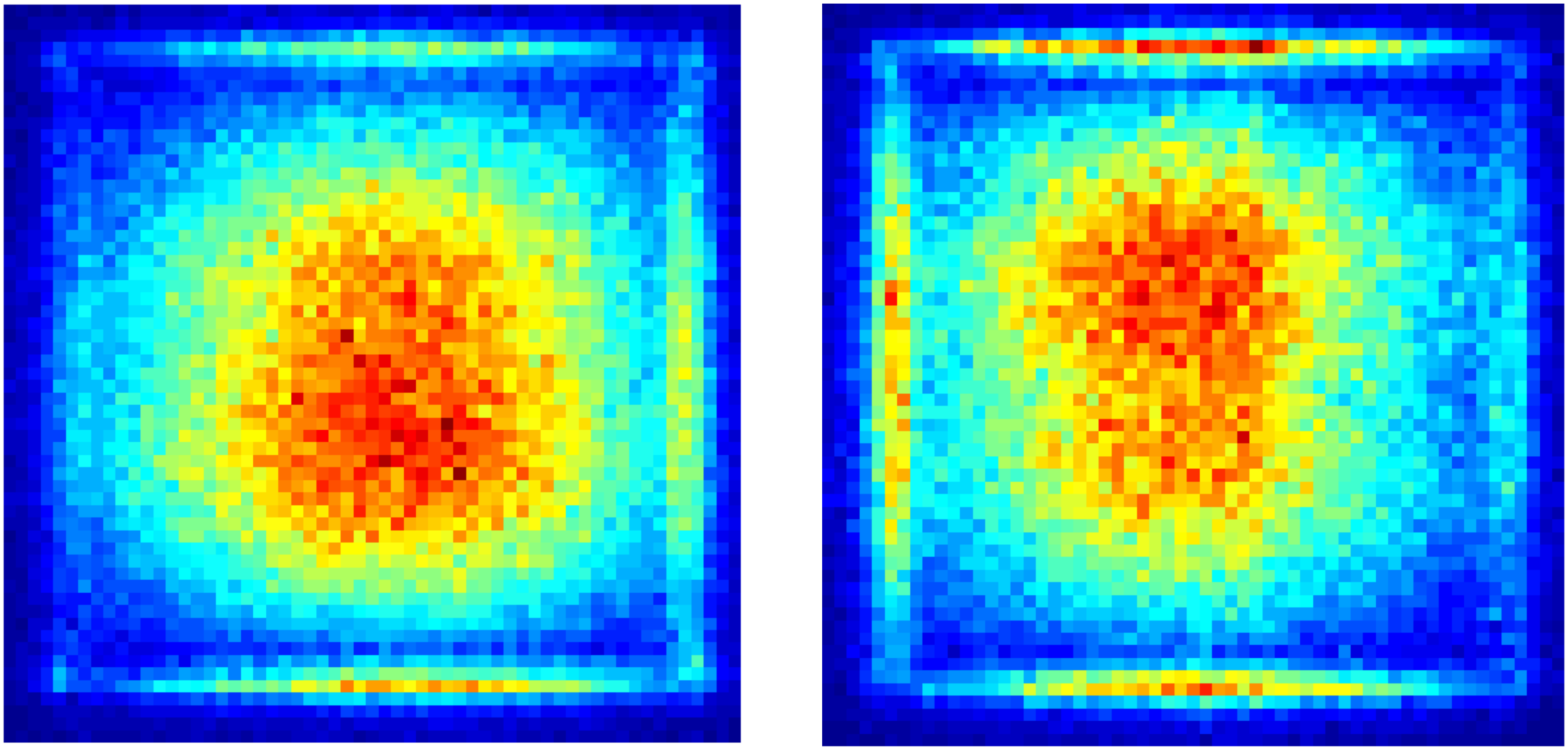
“V-track” events – on-line display



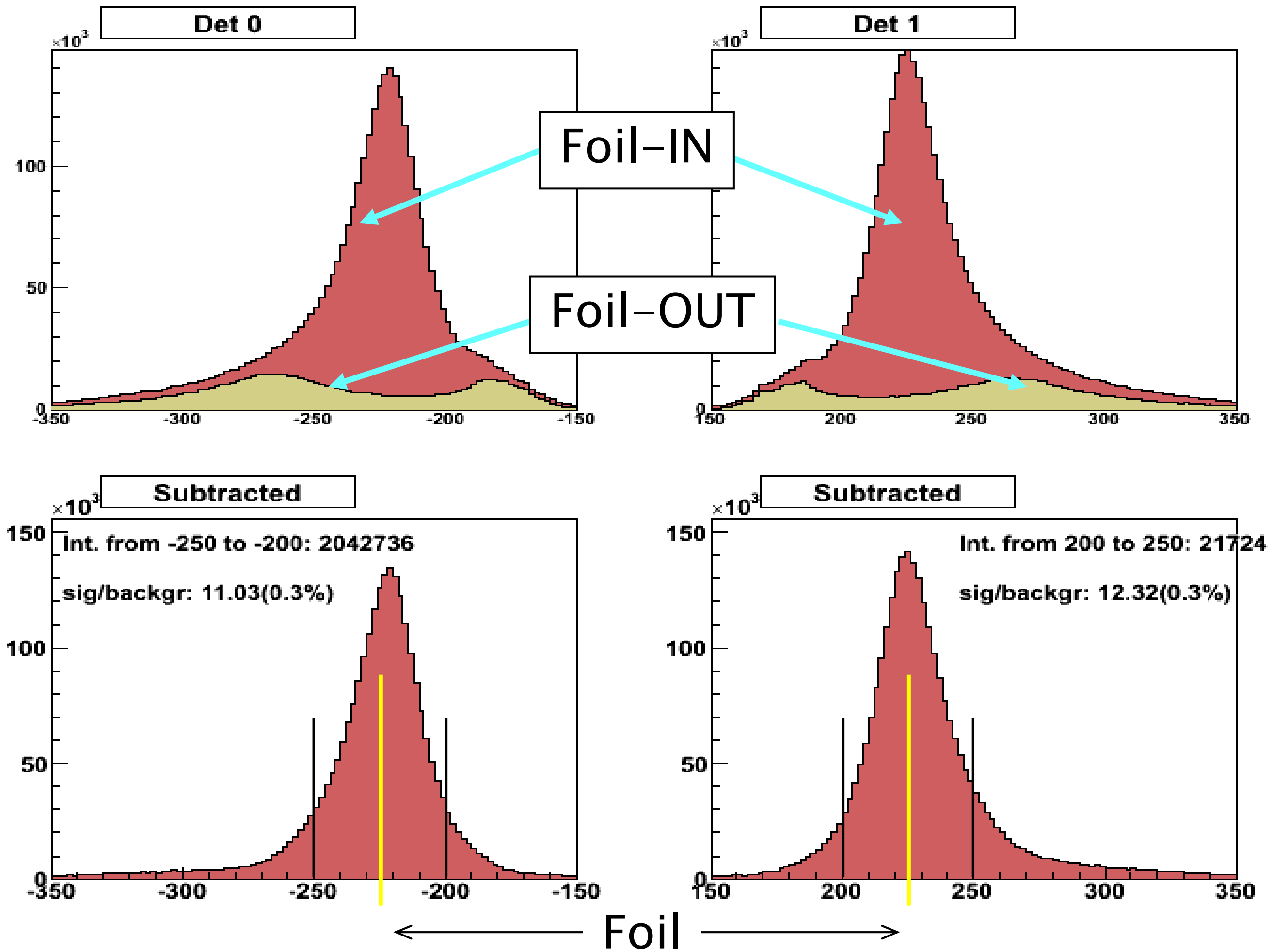
Projection of vertices onto XY–plane



Projection of vertices onto Pb–foil planes

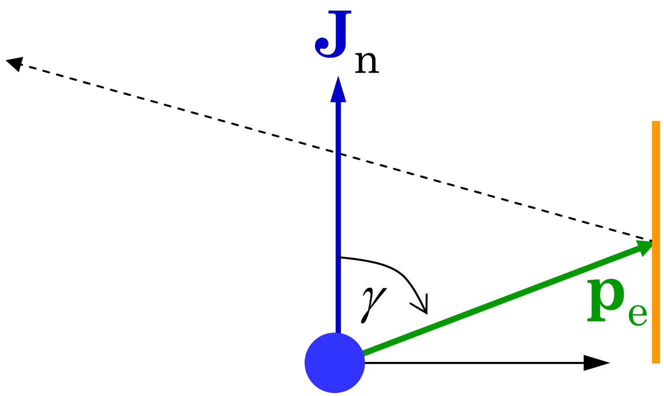


Mott scattering vertex distribution



“Short–arm” asymmetry

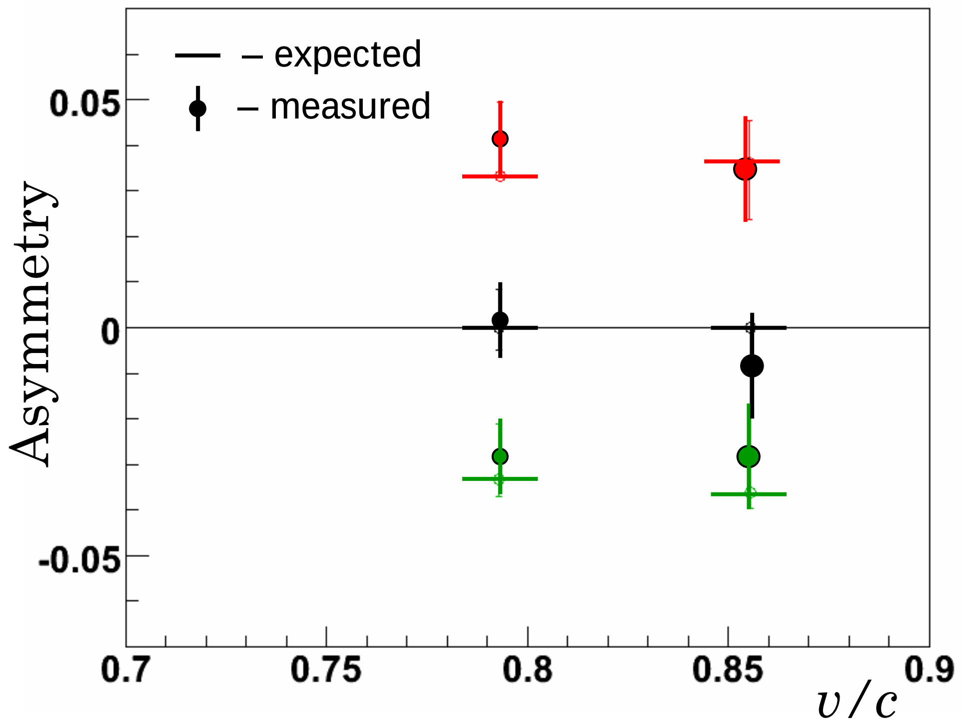
- “Short–arm” of a V–track must reveal UP–DOWN asymmetry (β–decay)



$-0.6 \leq \cos\gamma \leq -0.2$

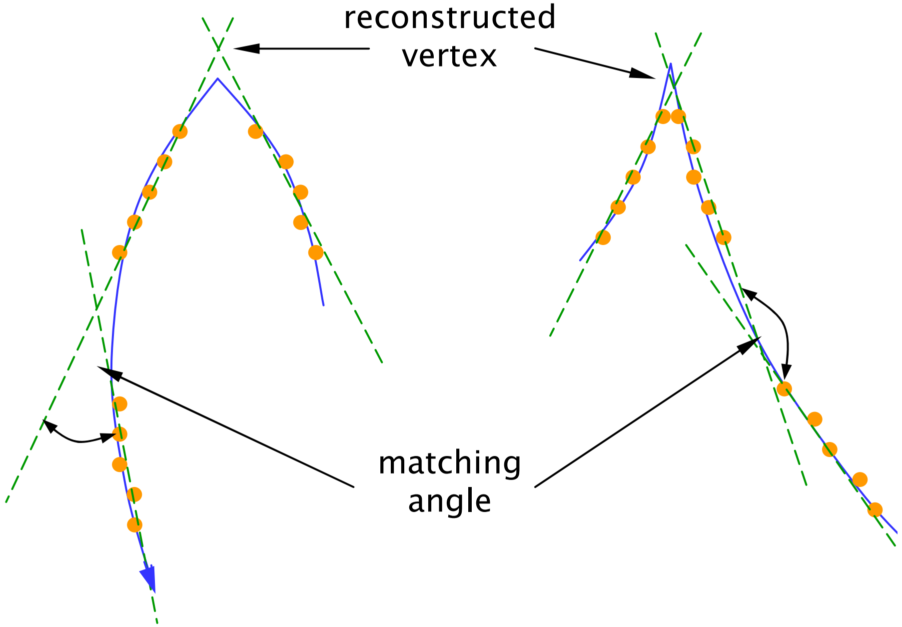
$-0.2 \leq \cos\gamma \leq +0.2$

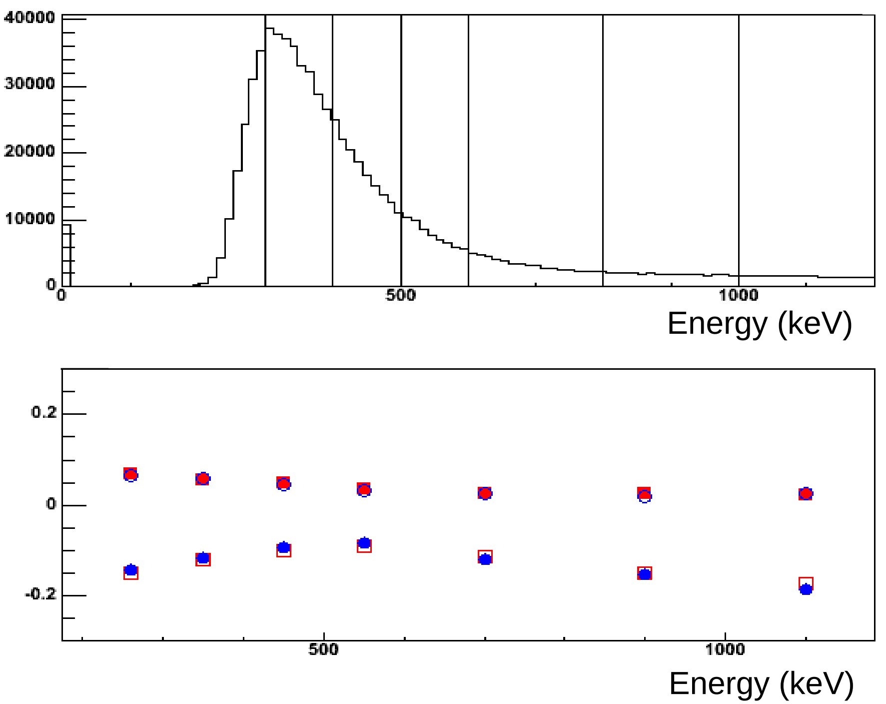
$+0.2 \leq \cos\gamma \leq +0.6$



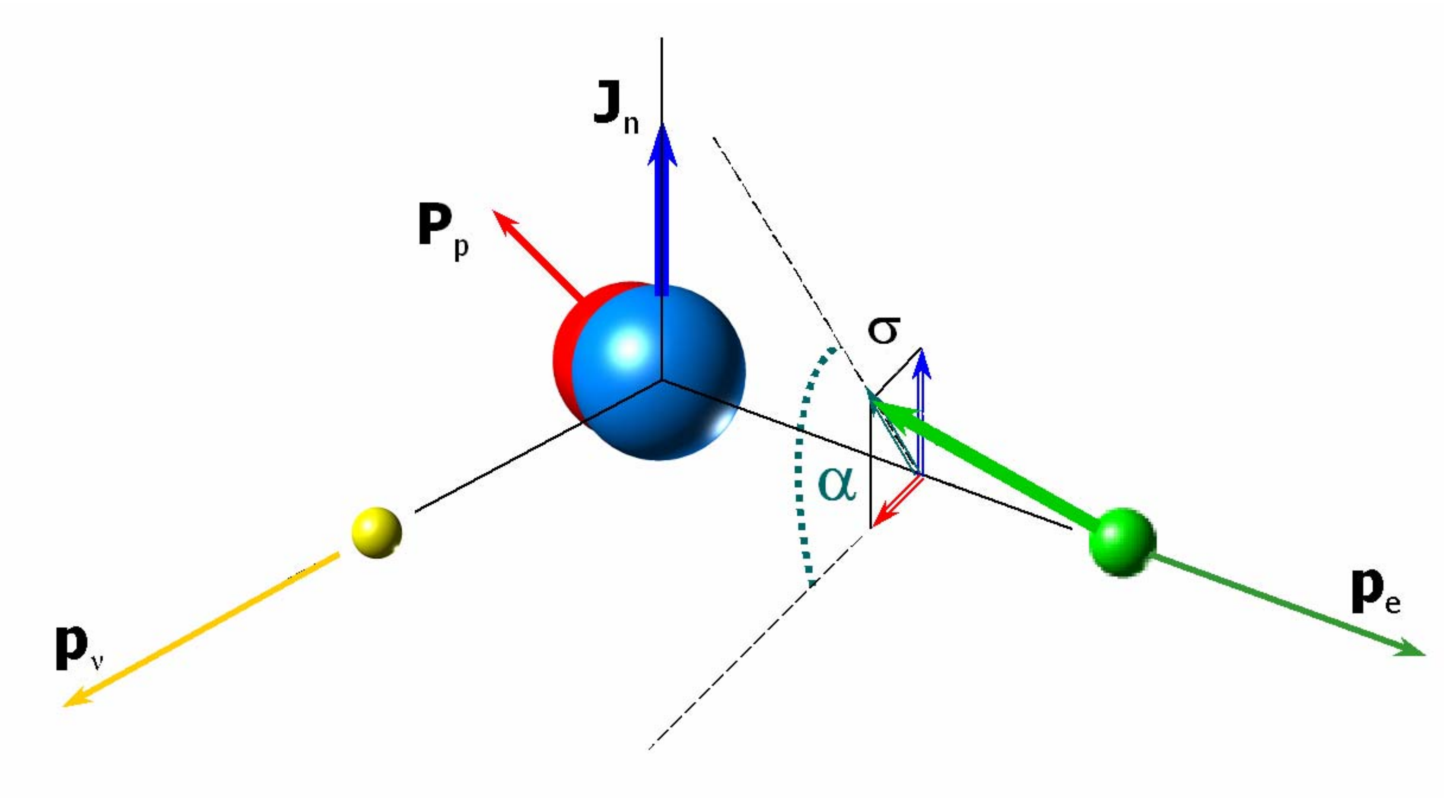
Influence of magnetic field on V–tracks

- Bending of electron tracks in the magnetic field of about $0.5\ \mathrm{mT}$ can be traced back in the matching of track segments





Projection of V−track events onto α



Electron transverse polarization

- **Mott scattering asymmetry:**
  - Efficiency and acceptance are complicated and unknown functions but they do not change with neutron spin flip

$$\bar{X}(\alpha) = \frac{\bar{\omega}(P,\alpha) - \bar{\omega}(-P,\alpha)}{\bar{\omega}(P,\alpha) + \bar{\omega}(-P,\alpha)}$$

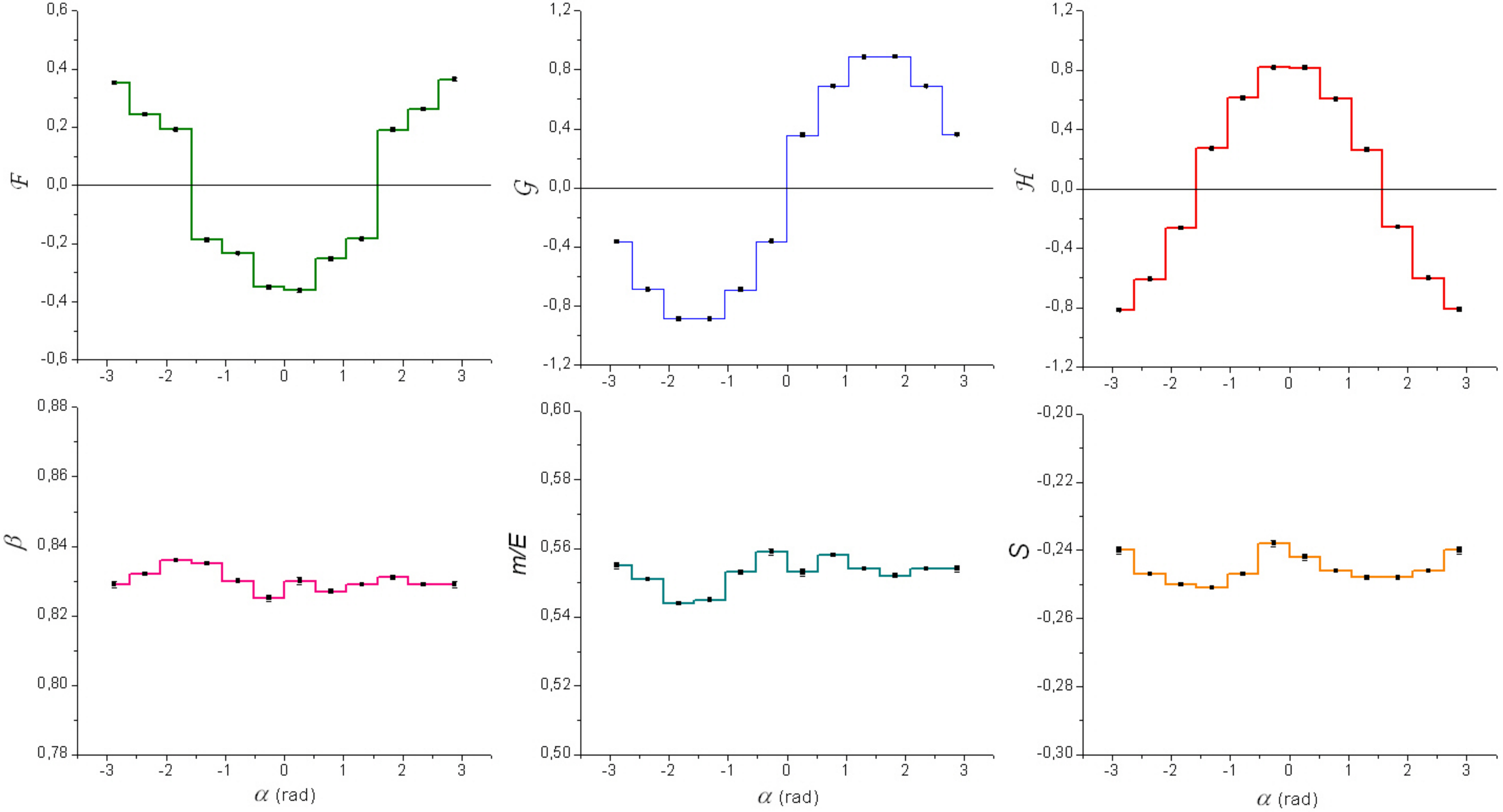
$$= AP\bar{\beta}\bar{\mathcal{F}}(\alpha) + P\bar{\beta}\,\bar{S}(\alpha)\left[N'\bar{\mathcal{G}}(\alpha) + R\bar{\mathcal{H}}(\alpha)\right]$$

$$N' \equiv N/\beta$$

$$\bar{\mathcal{F}}(\alpha) = \left\langle \hat{J}\cdot\hat{p}_e \right\rangle, \quad \bar{\mathcal{G}}(\alpha) = \left\langle \hat{n}\cdot\hat{J} \right\rangle, \quad \bar{\mathcal{H}}(\alpha) = \left\langle \hat{n}\cdot\left(\hat{J}\times\hat{p}_e\right)\right\rangle$$

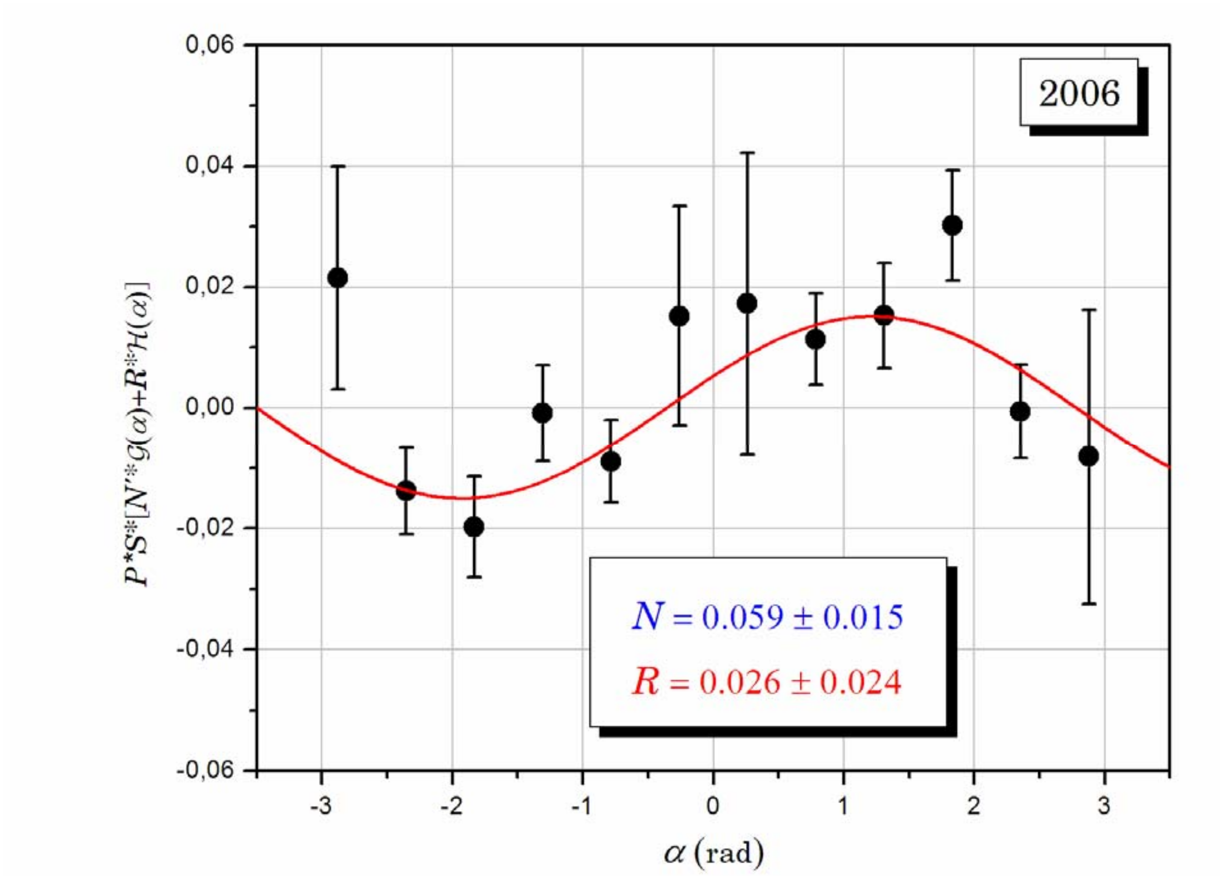
  - Average values of the geometry factors $\bar{\mathcal{F}}(\alpha), \bar{\mathcal{G}}(\alpha), \bar{\mathcal{H}}(\alpha), \bar{\beta}(\alpha)$ are calculated event-by-event from reconstructed momenta and are known to a high precision
  - Asymmetry parameter A is taken from another, high precision, dedicated experiment

Geometrical factors



Electron transverse polarization

PRELIMINARY



$N_{SM} = 0.066$
$R_{SM} = 0.0$

Electron transverse polarization

- **Super-ratio:**
  - Makes use of geometrical symmetry of the detecting system
  - Correction due to decay asymmetry suppressed by an order of magnitude (~0.1 → ~0.01)
  - Only N parameter can be extracted

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

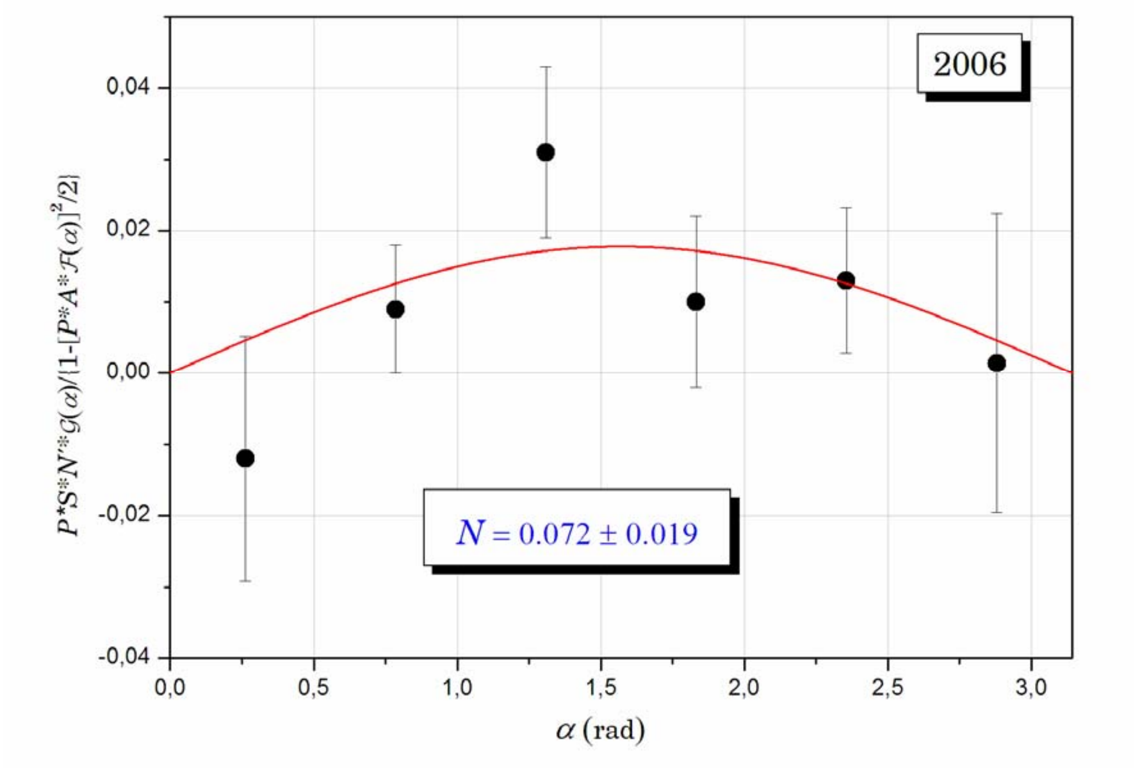
$$\bar{S}(-\alpha) \square \bar{S}(\alpha), \qquad \bar{\beta}(-\alpha) \square \bar{\beta}(\alpha)$$

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

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

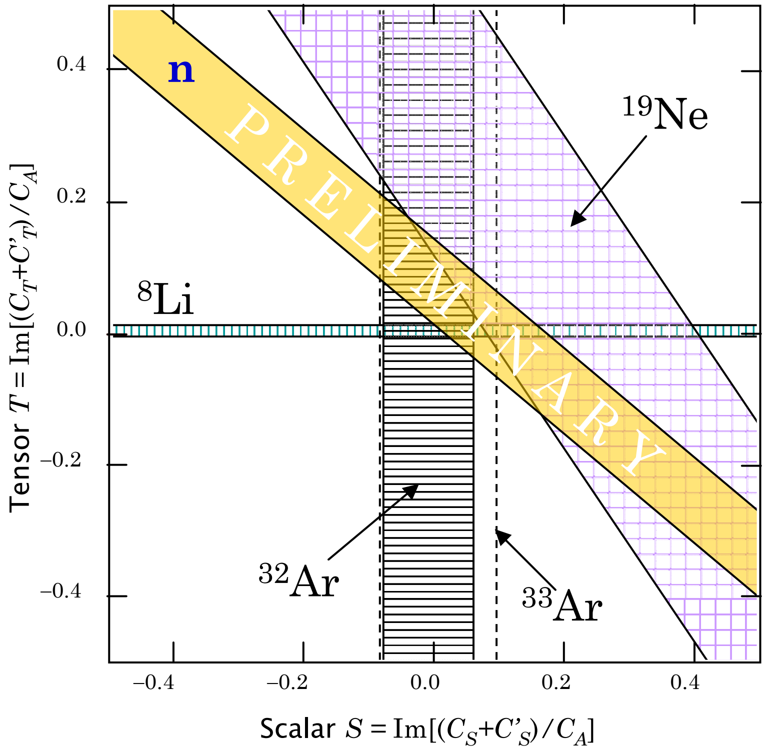
Electron transverse polarization (from "super-ratio")

PRELIMINARY



$N_{SM} = 0.066$

Limits on S and T coupling constants



Conclusions

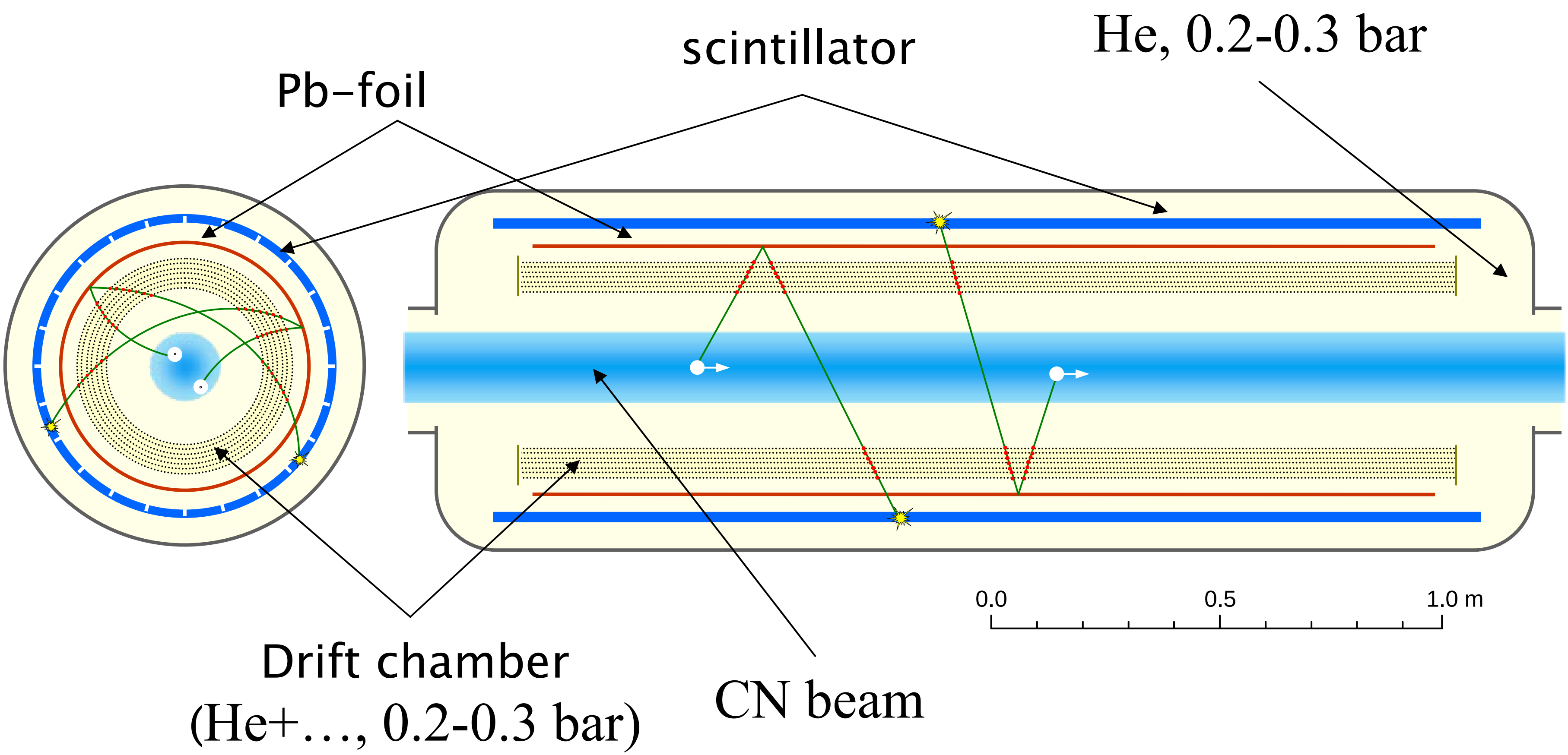
- Collected data are sufficient for $\Delta R = 0.010 \div 0.015$
- Assessment of systematic effects – in progress
- Total experimental uncertainty is dominated by statistics
- Final data taking scheduled for 2007 (4 months)
- The anticipated accuracy $\Delta R = 0.005$ should be reached (if nothing unexpected happens!)

What next?

2^{nd}-generation experiment

- Feasible sensitivity: $\Delta R = 5\times10^{-4}$
- Needed 10^8 reconstructed V-track events
- General features of the experimental setup:
  - Axial polarimeter geometry
    - 2.5 m long beam acceptance
  - Drift chambers:
    - Hexagonal cell geometry
    - x-,y-coordinates from drift time
    - z-coordinate from charge division
    - Reduced pressure (0.2-0.3 bar) both in the beam line and in the drift chambers (promising tests underway)
  - Additional background suppression:
    - pulsed beam (?)
    - ^{3}He spin filter (?)
- Overall gain factor in the rate of reconstructed V-track events: 20 – 30 (as compared to the present setup)

2^{nd}–generation experiment



Questions

- Final State Interaction ?
- Direct vs. indirect constrains ?
- Sensitivity to particular models ?

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}

- Jackson's formula [Nucl. Phys. 4 (1957) 206]:
  - "Allowed approximation"
  - Electron wave function for point like Coulomb potential
  - $\Rightarrow$ Theoretical uncertainty: $\Delta R_{FSI}/R_{FSI} \approx 10\ \%$
  - $\Rightarrow \Delta R_{FSI}(\text{neutron}) \approx 10^{-4}$
- Vogel & Werner [NP 404 (1983) 345] corrected for:
  - 2^{nd}–forbidden term
  - Higher terms in the lepton function expansion
  - Radiative effects
  - Finite nuclear size
  - Electron screening effect
  - $\Rightarrow$ Theoretical uncertainty: $\Delta R_{FSI}/R_{FSI} \approx 1\ \%$
  - $\Rightarrow \Delta R_{FSI}(\text{neutron}) \approx 10^{-5}$

- Specific case for neutron decay:
  - Corrections for proton charge distribution are small (small energy release); can be calculated (A. Czarnecki) with improved proton charge radius (from muonic hydrogen Lamb shift – PSI project)
  - No uncertainty due to atomic screening
  - $\Rightarrow$ Expected theoretical uncertainty: $\Delta R_{\mathrm{FSI}}/R_{\mathrm{FSI}} \approx 0.5\ \%$
  - $\Rightarrow \Delta R_{\mathrm{FSI}}(\mathrm{neutron}) \approx 5\times10^{-6}$

"*Discovery potential*" or "*exclusion power*" (4 standard deviations) of the *R*–parameter in the free neutron decay with present FSI theory is: $R_{\mathrm{n}} \approx 2\times10^{-5}$

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

Indirect bounds for $\mathrm{Im}(C_{S,T}+C'_{S,T})$

- Khriplovich & Lamoreaux (1997), P. Herczeg (2001):
  - Indirect, stringent bounds on T-odd, P-even interactions are obtained from atomic EDM searches:

$$\mathrm{Im}\left(C_{S,T} + C'_{S,T}\right) \leq 10^{-4}$$

- Linear combination of $\mathrm{Im}(C_S+C'_S)$ and $\mathrm{Im}(C_T+C'_T)$:
  - Different than in the R–correlation
  - Weaker bounds on $\mathrm{Im}(C_S+C'_S)$ than on $\mathrm{Im}(C_T+C'_T)$
  - Model uncertainty may be large

Should the indirect limits from atomic EDMs be viewed as *complementary* rather than *competitive* to the direct ones from R–correlation ?

Sensitivity to particular models

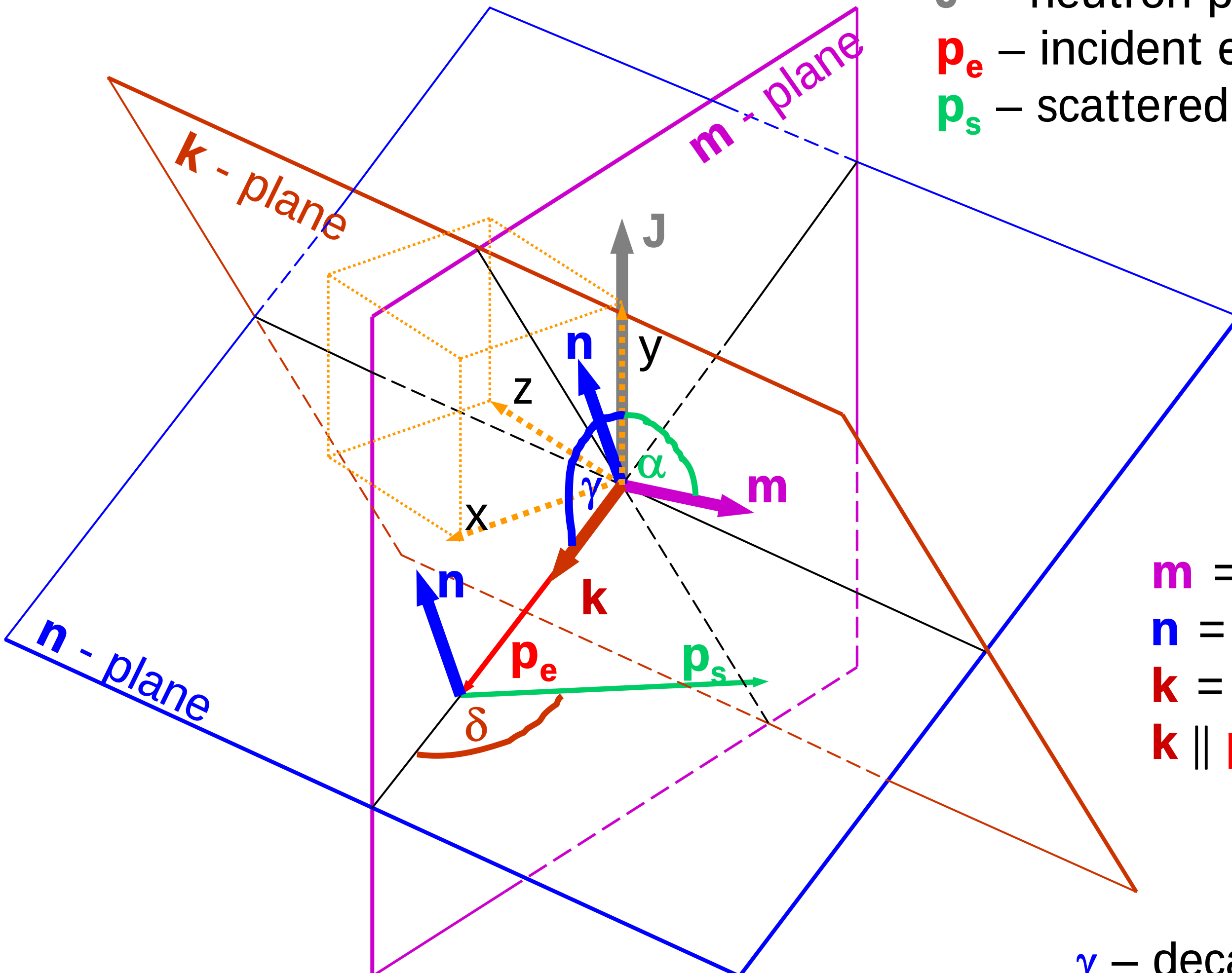
Contrary to D–coefficient, R–coefficient lacks of a particular model scenario where it could outperform other methods

Is the above statement true ?

Suggestions from theory are welcomed !

Backup slides

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

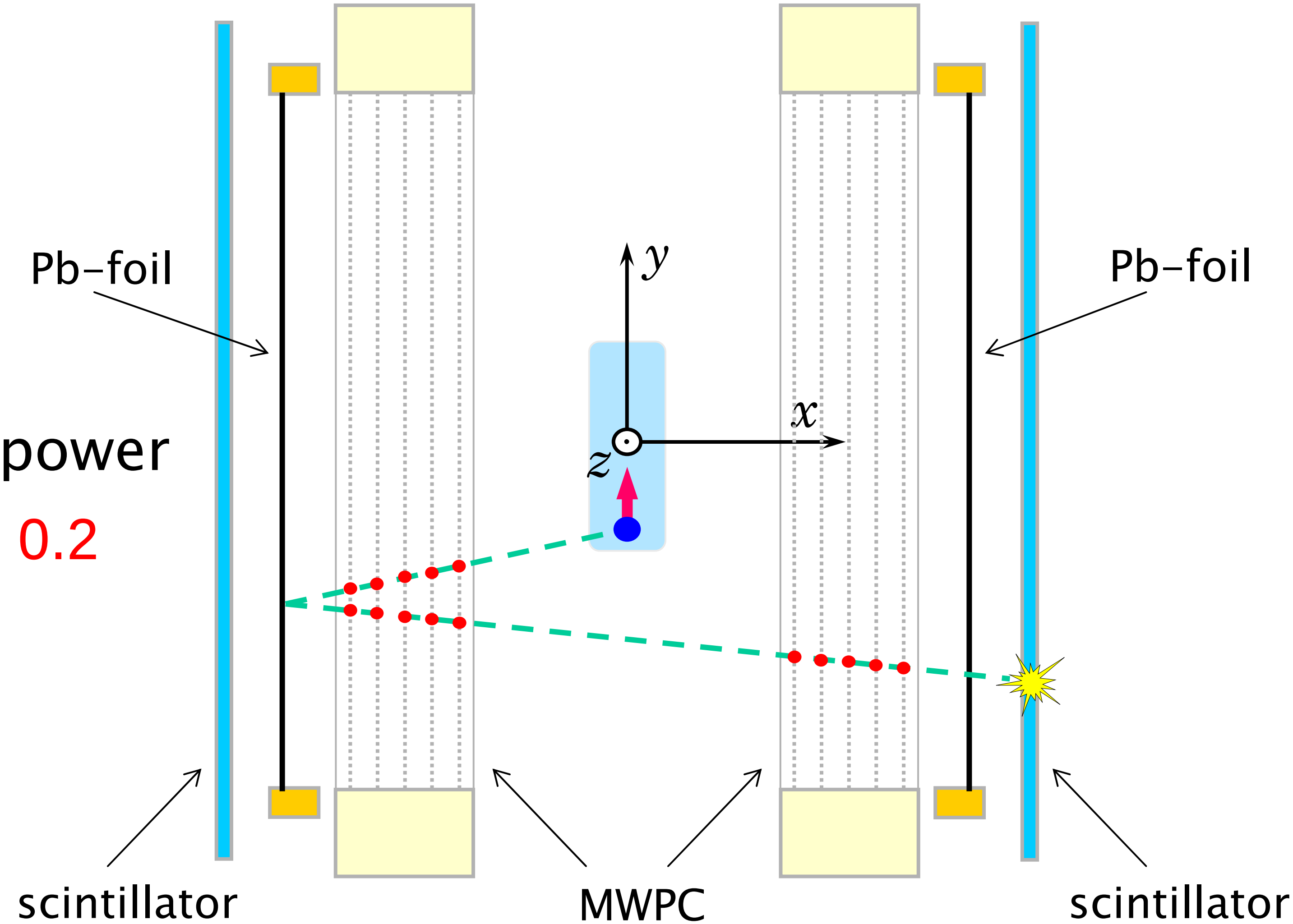


$\mathbf{m} = (\mathbf{J}\times\mathbf{p_e})/|\mathbf{J}\times\mathbf{p_e}|$
$\mathbf{n} = (\mathbf{p_e}\times\mathbf{p_s})/|\mathbf{p_e}\times\mathbf{p_s}|$
$\mathbf{k} = (\mathbf{m}\times\mathbf{n})/|\mathbf{m}\times\mathbf{n}|$
$\mathbf{k} \parallel \mathbf{p_e}$

(x,y,z) – LAB frame

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

Mott polarimeter



Analyzing power

$\langle S_{\text{Mott}} \rangle \approx 0.2$