# Transverse Electron Polarization in the Neutron Decay

## Direct Search for Scalar and Tensor Couplings in Weak Interaction

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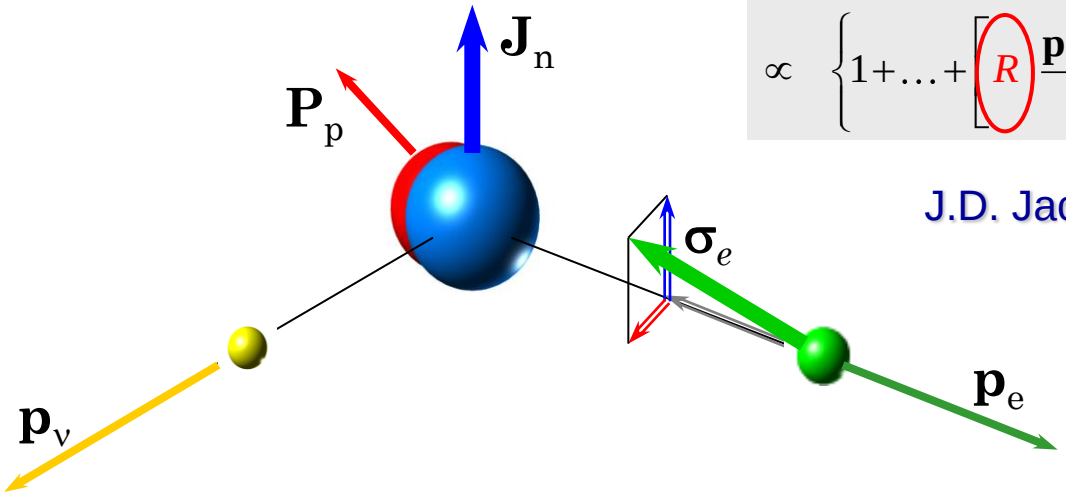
# Electron polarization in β-decay




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

J.D. Jackson et al., Phys. Rev. 106, 517 (1957)

- ***G***-coefficient can be deduced from the longitudinal electron polarization component
- ***N***-coefficient can be deduced from the transverse electron polarization component contained in the plane **parallel** to the parent polarization
- ***R***-coefficient can be obtained from the transverse electron polarization component **perpendicular** to the plane spanned by the neutron polarization and electron momentum

# Electron polarization in $\beta$-decay

- Assuming maximal parity violation $C_V = C'_V = \mathrm{Re}\, C_V = 1,\ C'_A = C_A = \mathrm{Re}\, C_A = \lambda$ and neglecting terms quadratic in $C_S$ and $C_T$ :

$$G = -1 + \frac{\alpha m}{p_e} \cdot \frac{1}{1+3\lambda^2} \cdot \mathrm{Im}\left(\frac{C_S + C'_S}{C_V}\right) + \frac{\alpha m}{p_e} \cdot \frac{\lambda^2}{1+3\lambda^2} \cdot \mathrm{Im}\left(\frac{C_T + C'_T}{C_A}\right)$$

**P**-odd, **T**-even

$$N = \frac{m}{E_e} \cdot \frac{2\lambda(\lambda+1)}{1+3\lambda^2} + \frac{\lambda}{1+3\lambda^2} \cdot \mathrm{Re}\left(\frac{C_S + C'_S}{C_V}\right) + \frac{\lambda(2\lambda+1)}{1+3\lambda^2} \cdot \mathrm{Re}\left(\frac{C_T + C'_T}{C_A}\right)$$

**P**-even, **T**-even

$$R = \frac{\alpha m}{p_e} \cdot \frac{2\lambda(\lambda+1)}{1+3\lambda^2} + \frac{\lambda}{1+3\lambda^2} \cdot \mathrm{Im}\left(\frac{C_S + C'_S}{C_V}\right) + \frac{\lambda(2\lambda+1)}{1+3\lambda^2} \cdot \mathrm{Im}\left(\frac{C_T + C'_T}{C_A}\right)$$

**P**-odd, **T**-odd

- EM contributions are driven by $C_V$ and $C_A$ couplings and scale with the decay asymmetry parameter $A$:

$$N = -\frac{m}{E_e} \cdot A_{SM} - 0.2175 \cdot \mathrm{Re}\left(\frac{C_S + C'_S}{C_V}\right) + 0.3350 \cdot \mathrm{Re}\left(\frac{C_T + C'_T}{C_A}\right)$$

$\approx 0.05$

$$R = -\frac{\alpha m}{p_e} \cdot A_{SM} - 0.2175 \cdot \mathrm{Im}\left(\frac{C_S + C'_S}{C_V}\right) + 0.3350 \cdot \mathrm{Im}\left(\frac{C_T + C'_T}{C_A}\right)$$

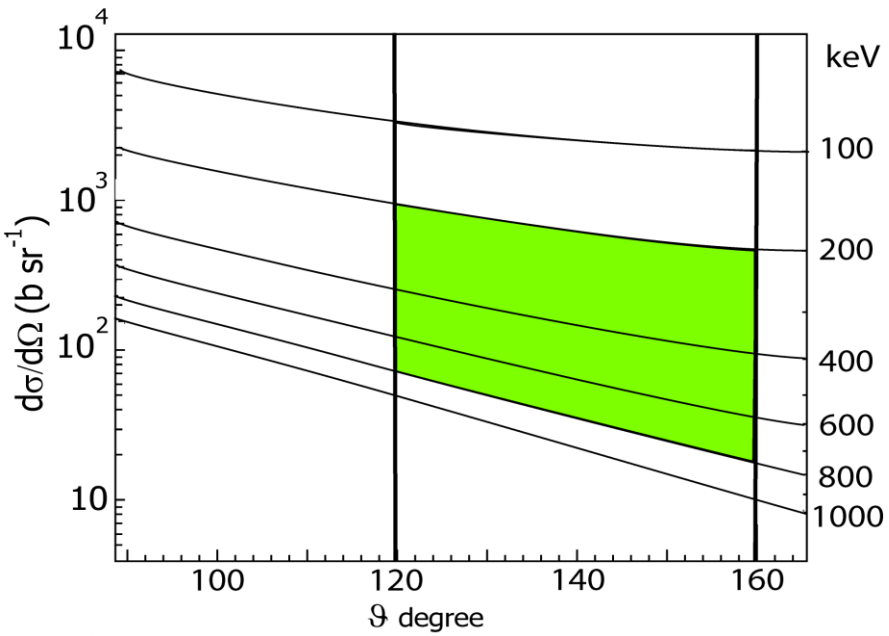
$\approx 0.001$

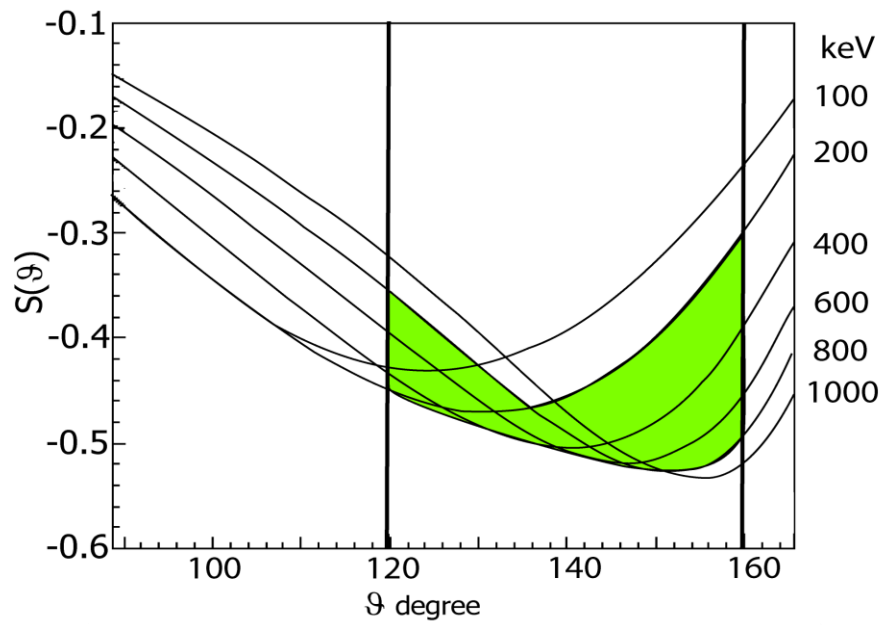
# Scalar and tensor couplings

- SM contributions:
  - Mixing phase $\delta_{CKM}$ gives contribution which is 2nd-order in weak interaction: **$< 10^{-10}$**
  - $\theta$-term contributes through induced NN PVTV interactions: **$< 10^{-9}$**
- Candidate models for scalar couplings (at tree-level):
  - Charged Higgs exchange
  - Slepton exchange (R-parity violating super symmetric models)
  - Vector and scalar leptoquark exchange
- The only candidate model for tree-level tensor contribution (in renormalizable gauge theories) is:
  - Scalar leptoquark exchange

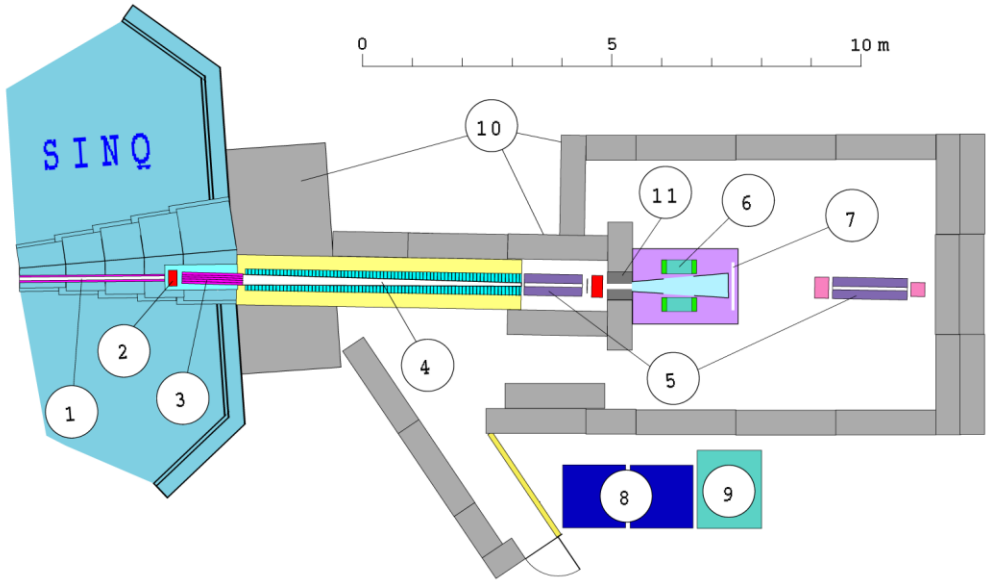
# Mott scattering

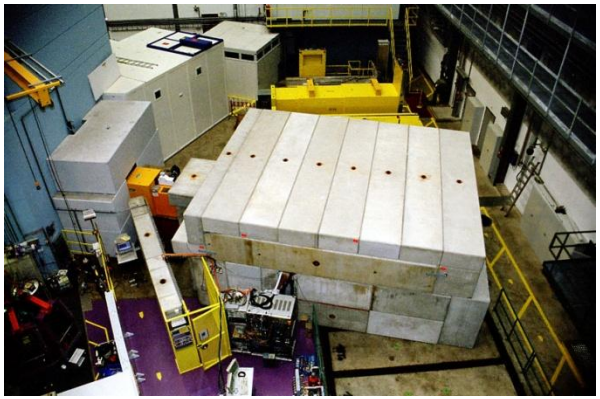
- Mott scattering:
  - Analyzing power caused by spin-orbit force
  - Parity and time reversal conserving (electromagnetic process)
  - Sensitive **exclusively** to the transversal polarization



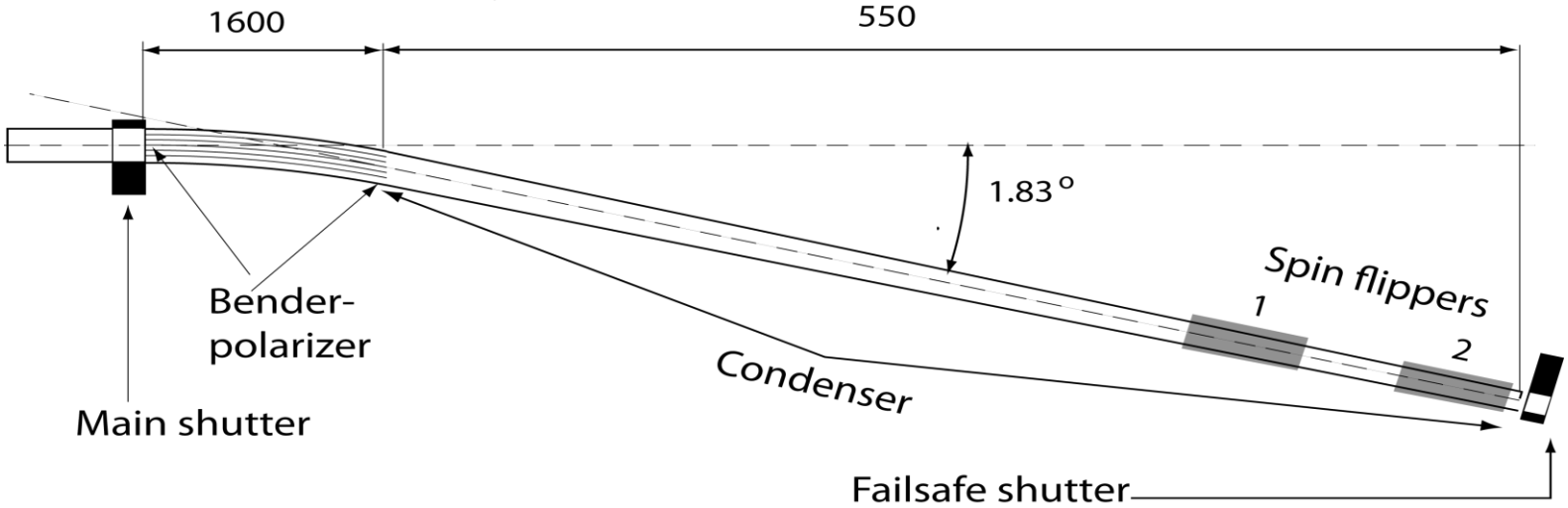



# FUNSPIN – Polarized Cold Neutron Facility at PSI



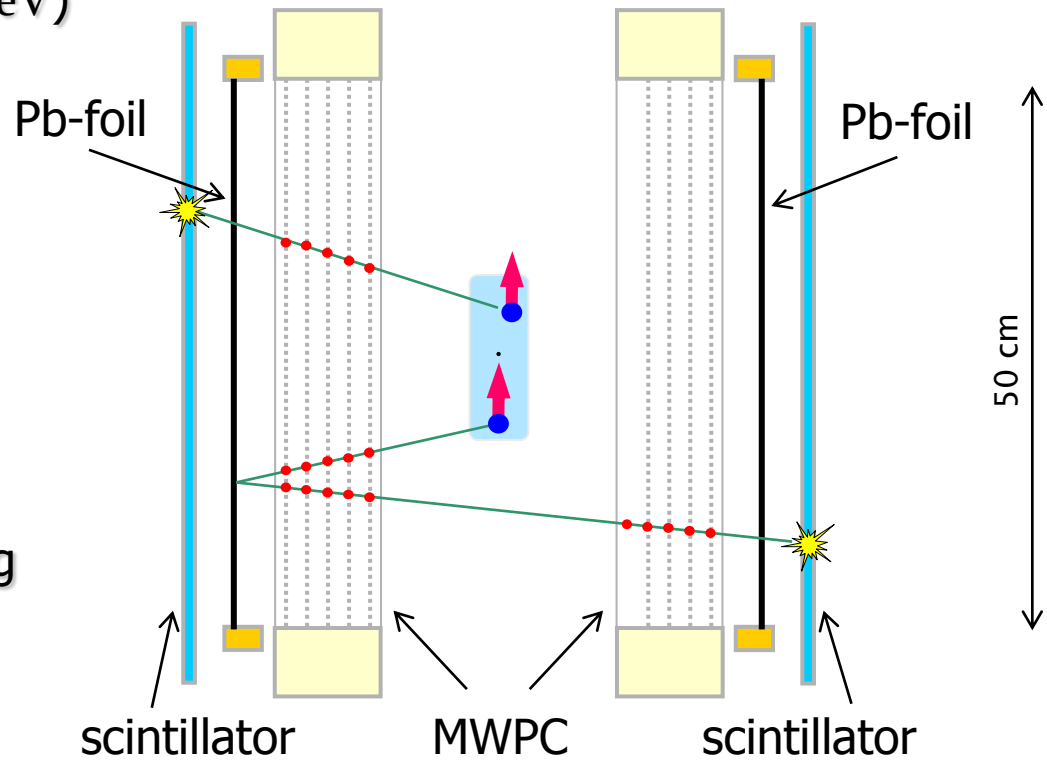
$I_n \approx 10^{10}\,\mathrm{s}^{-1}$ $P_n \approx 80\%$



# Mott polarimeter

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

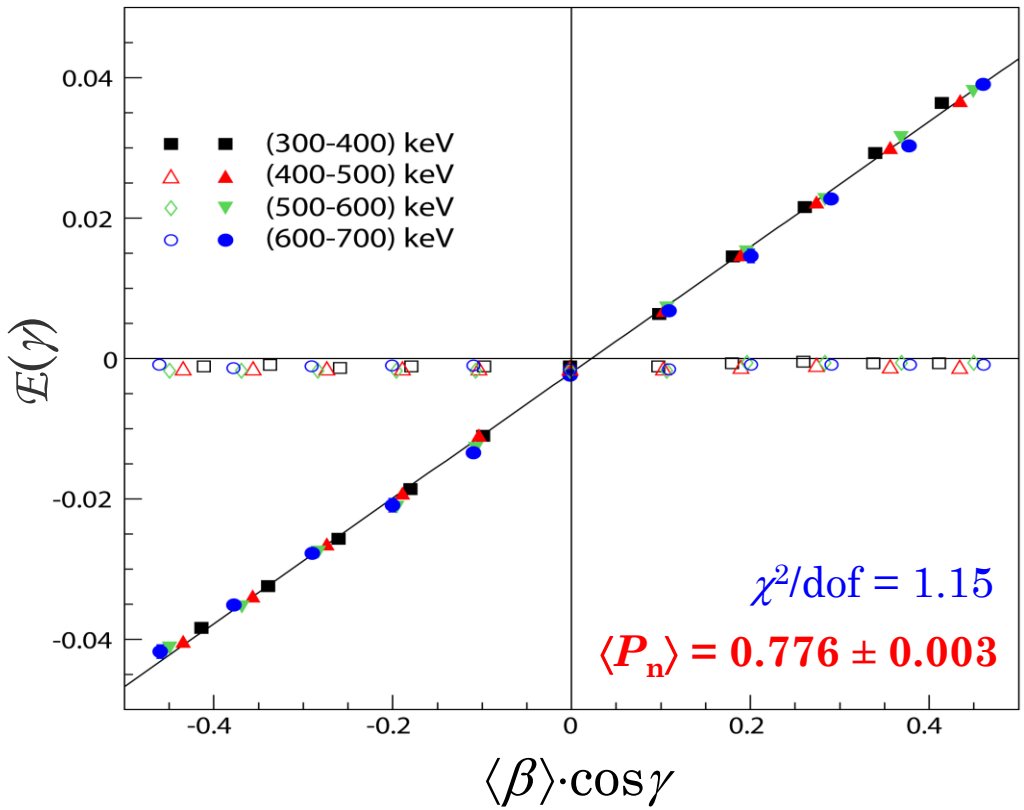
- **Solutions:**
  - Tracking of electrons in low-mass, low-$Z$ MWPCs
  - Identification of Mott-scattering vertex ("V-track")
  - Frequent neutron spin flipping
  - "foil-in" and "foil-out" measurements



# Neutron polarization from decay asymmetry

$$\mathcal{E}(\gamma) \equiv \frac{N(\gamma,+P_n) - N(\gamma,-P_n)}{N(\gamma,+P_n) - N(\gamma,-P_n)} = \langle P_n \rangle A_n \langle \beta \rangle \cos\gamma$$

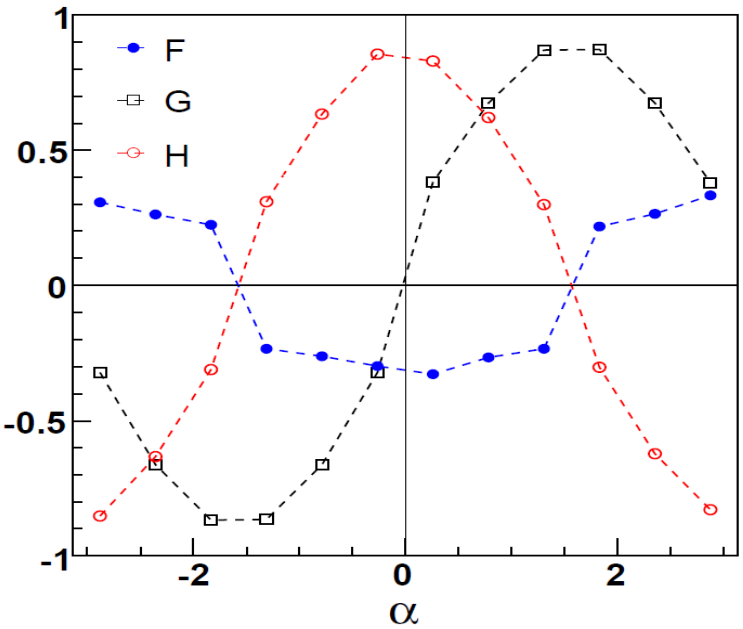
$A_n = -0.1173$

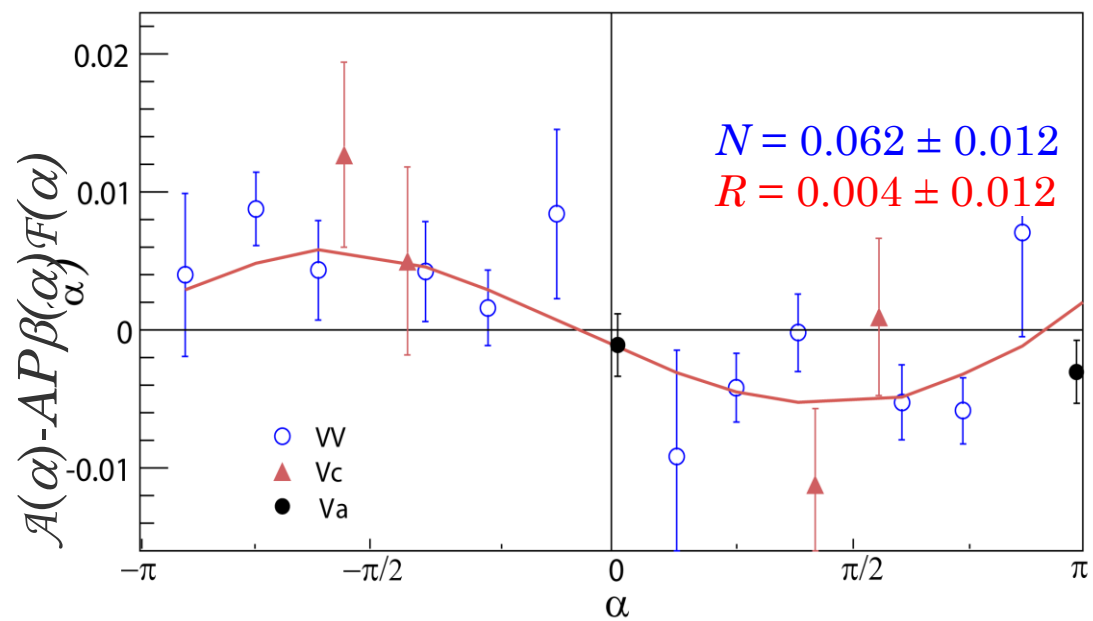



- Average neutron polarization from decay rate asymmetry ("**single-track**" events)
- Averaging super-mirror polarimeter data: $\langle P_n \rangle = 0.87 \pm 0.01$
- Offset in data well understood and corrected for (spin flipper related deadtime)

# Two-parameter fit

$$\mathcal{A}(\alpha) = \frac{n(+P,\alpha) - n(-P,\alpha)}{n(+P,\alpha) + n(-P,\alpha)}$$
$$= \boldsymbol{A} P \beta(\alpha) \mathcal{F}(\alpha) + P\, S(\alpha)\left[\boldsymbol{N}\mathcal{G}(\alpha) + \boldsymbol{R}\beta(\alpha)\mathcal{H}(\alpha)\right] \qquad (2)$$




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

$\hat{n}$ – normal to Mott scattering plane

# Single parameter fit

$$\mathcal{S}(|\alpha|) \equiv \frac{\sqrt{n(+P,+\alpha)n(-P,-\alpha)} - \sqrt{n(+P,-\alpha)n(-P,+\alpha)}}{\sqrt{n(+P,+\alpha)n(-P,-\alpha)} + \sqrt{n(+P,-\alpha)n(-P,+\alpha)}}$$
$$= \boldsymbol{N} \frac{PS\,\mathcal{G}(|\alpha|)}{\beta(|\alpha|)\left(1 - A^2P^2\beta^2(|\alpha|)\mathcal{F}^2(|\alpha|)\right)} \qquad (3)$$

$$\mathcal{U}(|\alpha|) \equiv \frac{\sqrt{n(+P,+\alpha)n(+P,-\alpha)} - \sqrt{n(-P,+\alpha)n(-P,-\alpha)}}{\sqrt{n(+P,+\alpha)n(+P,-\alpha)} + \sqrt{n(-P,+\alpha)n(-P,-\alpha)}}$$
$$= AP\beta(|\alpha|)\mathcal{F}(|\alpha|) + \boldsymbol{R}\,PS(|\alpha|)\mathcal{H}(|\alpha|) \qquad (4)$$

# Final results

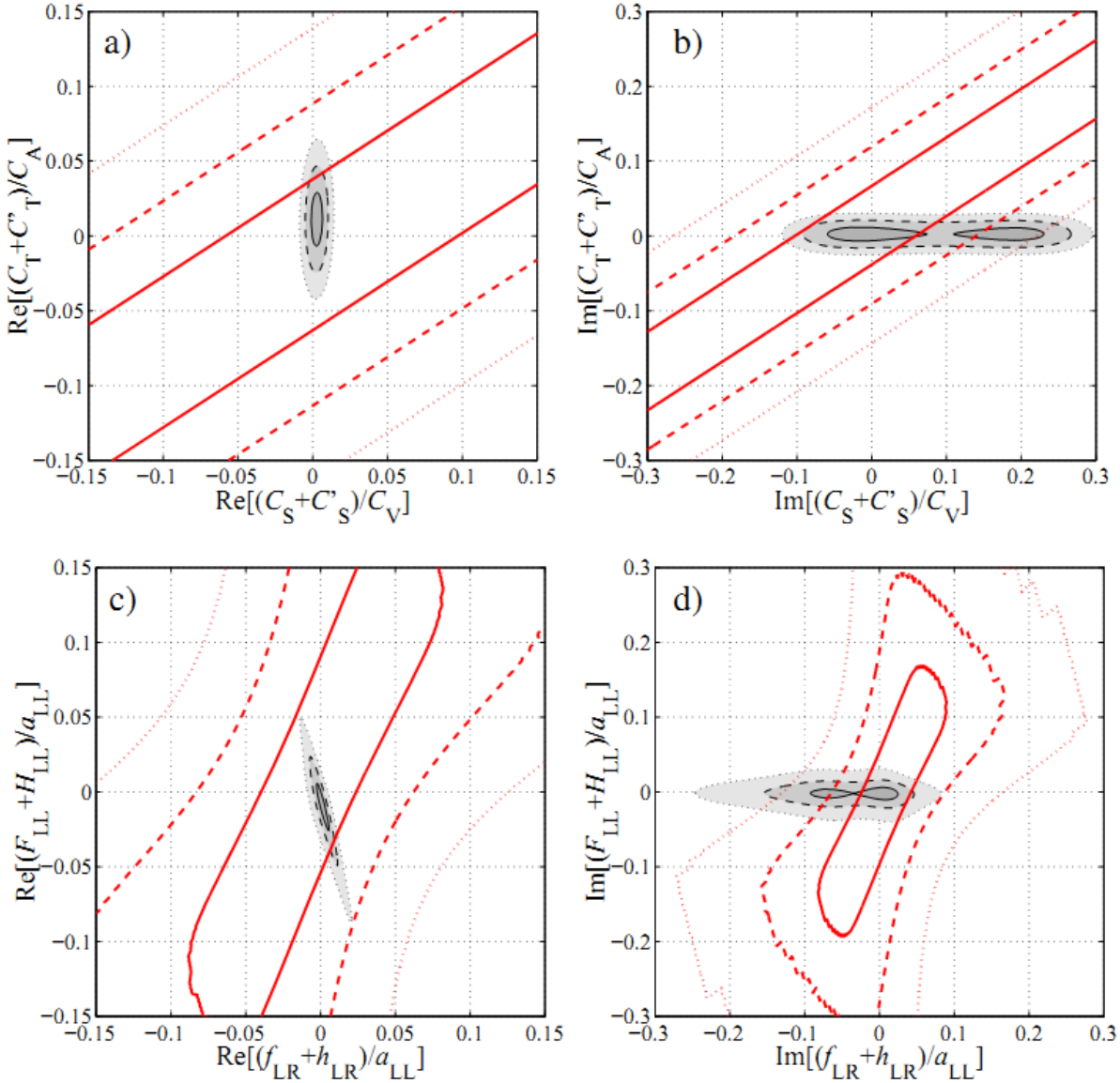
| Run | Sign. | $\sum(n^+ + n^-)$ | $P \times 10^2$ |
|---|---|---|---|
| 2003 | VV | 19000 | $80.3 \pm 1.3 \pm 1.6$ |
| 2004 | VV | 74000 | $44.2 \pm 0.4 \pm 1.5$ |
| 2006 | VV | 312000 | $80.0 \pm 1.0 \pm 1.5$ |
| 2006 | V | 111000 | $80.0 \pm 1.0 \pm 1.5$ |
| 2007 | VV | 1747000 | $77.4 \pm 0.2 \pm 0.7$ |
| 2007 | V | 711000 | $77.4 \pm 0.2 \pm 0.7$ |
| Total | | 2974000 | |

| Run | Sign. | $N \times 10^3$ (Eq. 2) | $N \times 10^3$ (Eq. 3) | $R \times 10^3$ (Eq. 2) | $R \times 10^3$ (Eq. 4) |
|---|---|---|---|---|---|
| 2003 | VV | $89 \pm 92 \pm 31$ | $139 \pm 124 \pm 27$ | $-90 \pm 137 \pm 42$ | $-55 \pm 152 \pm 42$ |
| 2004 | VV | $74 \pm 80 \pm 17$ | $171 \pm 103 \pm 15$ | $-14 \pm 131 \pm 30$ | $-58 \pm 146 \pm 30$ |
| 2006 | VV | $94 \pm 35 \pm 10$ | $97 \pm 35 \pm 10$ | $-13 \pm 48 \pm 10$ | $-36 \pm 48 \pm 12$ |
| 2006 | V | $44 \pm 109 \pm 23$ | $53 \pm 117 \pm 23$ | $-50 \pm 55 \pm 21$ | |
| 2007 | VV | $59 \pm 13 \pm 5$ | $63 \pm 14 \pm 5$ | $13 \pm 18 \pm 6$ | $-5 \pm 18 \pm 6$ |
| 2007 | V | $51 \pm 32 \pm 14$ | $52 \pm 33 \pm 5$ | $9 \pm 20 \pm 13$ | |
| Total | | $62 \pm 12 \pm 4$ | $67 \pm 11 \pm 4$ | $4 \pm 12 \pm 5$ | $-10 \pm 17 \pm 5$ |

$N_{SM} = (68 \pm 1) \times 10^3$

$R_{SM} = 0.5 \times 10^3$

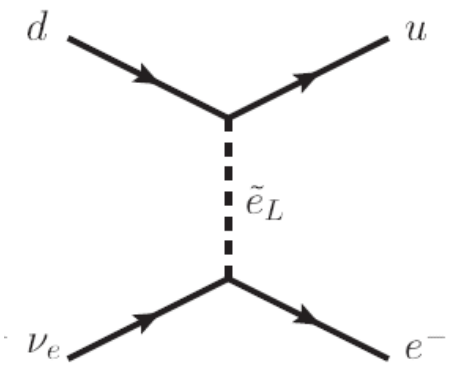
# Limits on $S$ and $T$ contributions



# RPV MSSM contributions to n-decay

*R*-parity violating super-symmetric contributions to the neutron beta decay
Nodoka Yamanaka *et al* 2010 *J. Phys. G: Nucl. Part. Phys.* **37** 055104

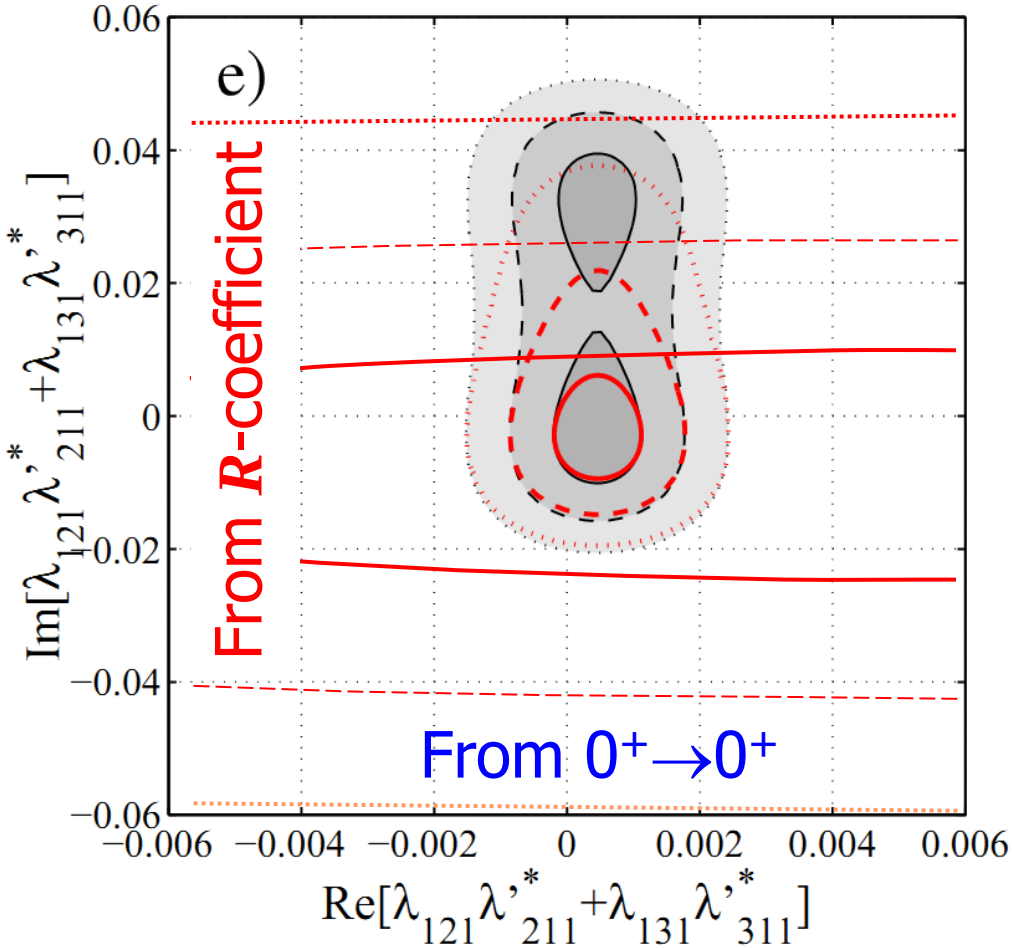
$$R = (-1)^{2j+3B+L}.$$




$$C_S = g_S \sum_{i=2,3} \frac{\lambda_{1i1}\lambda'^*_{i11}}{4m^2_{\tilde{e}_{Li}}}$$

$$g_S = \frac{M_n - M_p}{m_d - m_u} = 0.49 \pm 0.17$$

$$m_{\tilde{e}_L} = 100\ \text{GeV}$$



# What next?

# Transverse electron polarization

$$\omega(E_e, \Omega_e, \Omega_{\bar{\nu}}) \quad \propto$$

$$1 + \boldsymbol{a}\frac{\mathbf{p}_e \cdot \mathbf{p}_{\bar{\nu}}}{E_e E_{\bar{\nu}}} + \boldsymbol{b}\frac{m_e}{E_e} + \frac{\langle \mathbf{J} \rangle}{J} \cdot \left[ \boldsymbol{A}\frac{\mathbf{p}_e}{E_e} + \boldsymbol{B}\frac{\mathbf{p}_{\bar{\nu}}}{E_{\bar{\nu}}} + \boldsymbol{D}\frac{\mathbf{p}_e \times \mathbf{p}_{\bar{\nu}}}{E_e E_{\bar{\nu}}} \right]$$

$$+ \quad \hat{\boldsymbol{\sigma}}_\perp \cdot \left[ \boldsymbol{H}\frac{\mathbf{p}_{\bar{\nu}}}{E_{\bar{\nu}}} + \boldsymbol{L}\frac{\mathbf{p}_e \times \mathbf{p}_{\bar{\nu}}}{E_e E_{\bar{\nu}}} + \boldsymbol{N}\frac{\langle \mathbf{J} \rangle}{J} + \boldsymbol{R}\frac{\langle \mathbf{J} \rangle \times \mathbf{p}_e}{J\, E_e} \right.$$

$$\left. + \boldsymbol{S}\frac{\langle \mathbf{J} \rangle}{J}\frac{\mathbf{p}_e \cdot \mathbf{p}_{\bar{\nu}}}{E_e E_{\bar{\nu}}} + \boldsymbol{U}\mathbf{p}_{\bar{\nu}}\frac{\langle \mathbf{J} \rangle \cdot \mathbf{p}_e}{J\, E_e E_{\bar{\nu}}} + \boldsymbol{V}\frac{\mathbf{p}_{\bar{\nu}} \times \langle \mathbf{J} \rangle}{J\, E_{\bar{\nu}}} \right]$$

$$X = X_{\mathrm{SM}} + X_{\mathrm{FSI}} + c_{\mathrm{Re}S}\,\Re(\mathfrak{S}) + c_{\mathrm{Re}T}\,\Re(\mathfrak{T}) + c_{\mathrm{Im}S}\,\Im(\mathfrak{S}) + c_{\mathrm{Im}T}\,\Im(\mathfrak{T})$$

# Sensitivity factors for scalar and tensor couplings

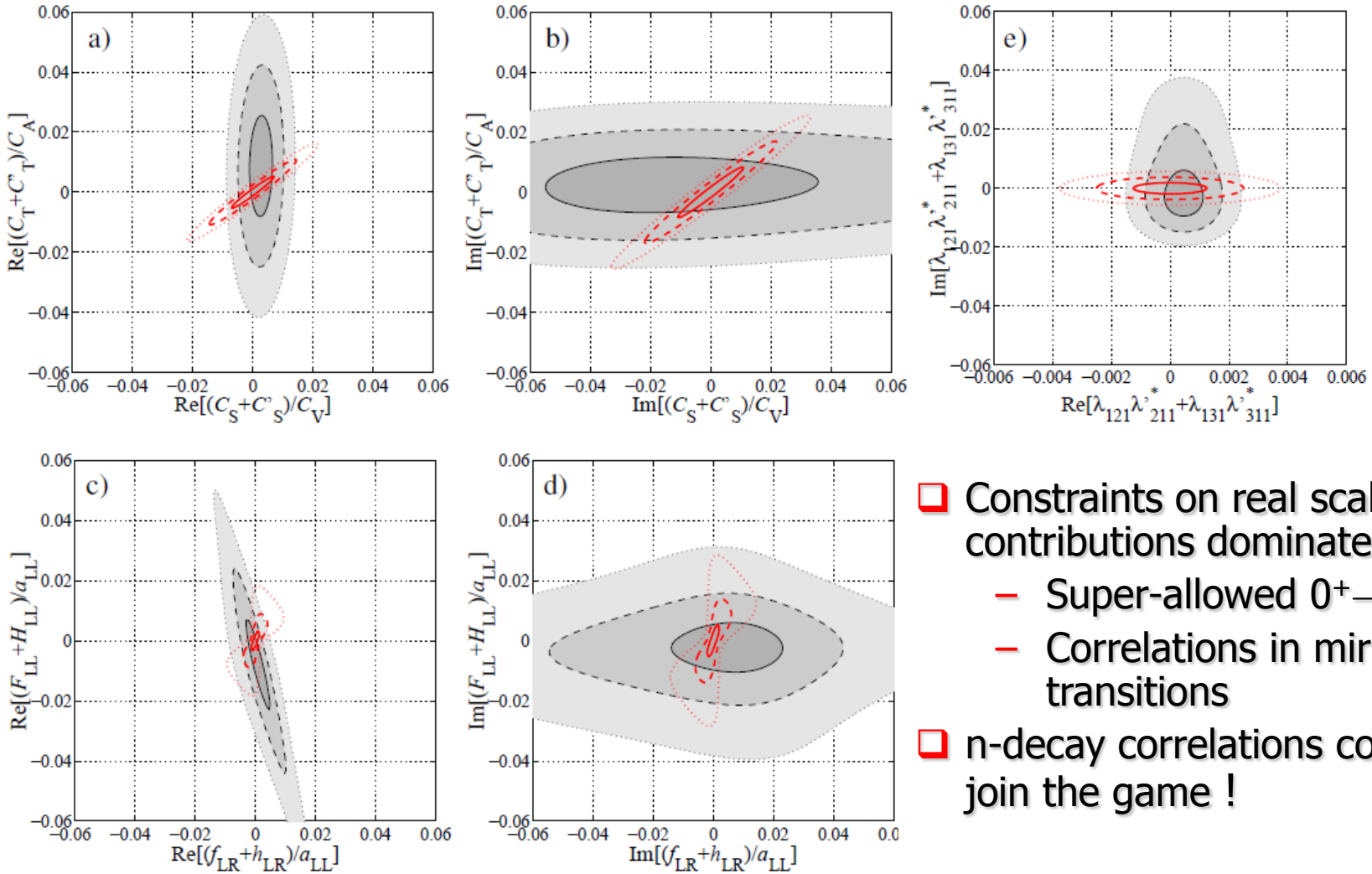
| | SM (λ) | FSI (λ)@ | Re$\mathcal{S}$ | Re$\mathcal{T}$ | Im$\mathcal{S}$ | Im$\mathcal{T}$ |
|---|---|---|---|---|---|---|
| ***a*** | –0.104793 | 0 | –0.171405† | 0.171405† | –0.000727 | +0.001171 |
| ***b*** | 0 | 0 | +0.171405 | +0.828595 | 0 | 0 |
| ***A*** | –0.117233 | 0 | 0 | 0 | –0.000923 | +0.00142 |
| ***B*** | +0.987560 | 0 | –0.126422 | +0.194539 | 0 | 0 |
| ***D*** | 0 | 0 | 0 | 0 | +0.000923 | –0.000923 |
| ***H*** | 0 | +0.060888 | –0.171405 | +0.276198 | 0 | 0 |
| ***L*** | 0 | –0.000444 | 0 | 0 | +0.171405 | –0.276198 |
| ***N*** | 0 | +0.068116 | –0.217582 | +0.334815 | 0 | 0 |
| ***R*** | 0 | +0.000497 | 0 | 0 | –0.217582 | +0.334815 |
| ***S*** | 0 | –0.001845 | +0.217582 | –0.217582 | 0 | 0 |
| ***U*** | 0 | 0 | –0.217582 | +0.217582 | 0 | 0 |
| ***V*** | 0 | 0 | 0 | 0 | –0.217582 | +0.217582 |

* Kinematical factor averaged over $E_k$ = (200,783) keV

† $(|C_S|^2+|C'_S|^2)/2$ instead of Re$\mathcal{S}$ and $(|C_T|^2+|C'_T|^2)/2$ instead of Re$\mathcal{T}$, respectively

@ 1st order, static field, point charge, no recoil

# Impact of *H*, *L*, *N*, *R*, *S*, *U*, *V* measurement with anticipated accuracy of $5\times10^{-4}$



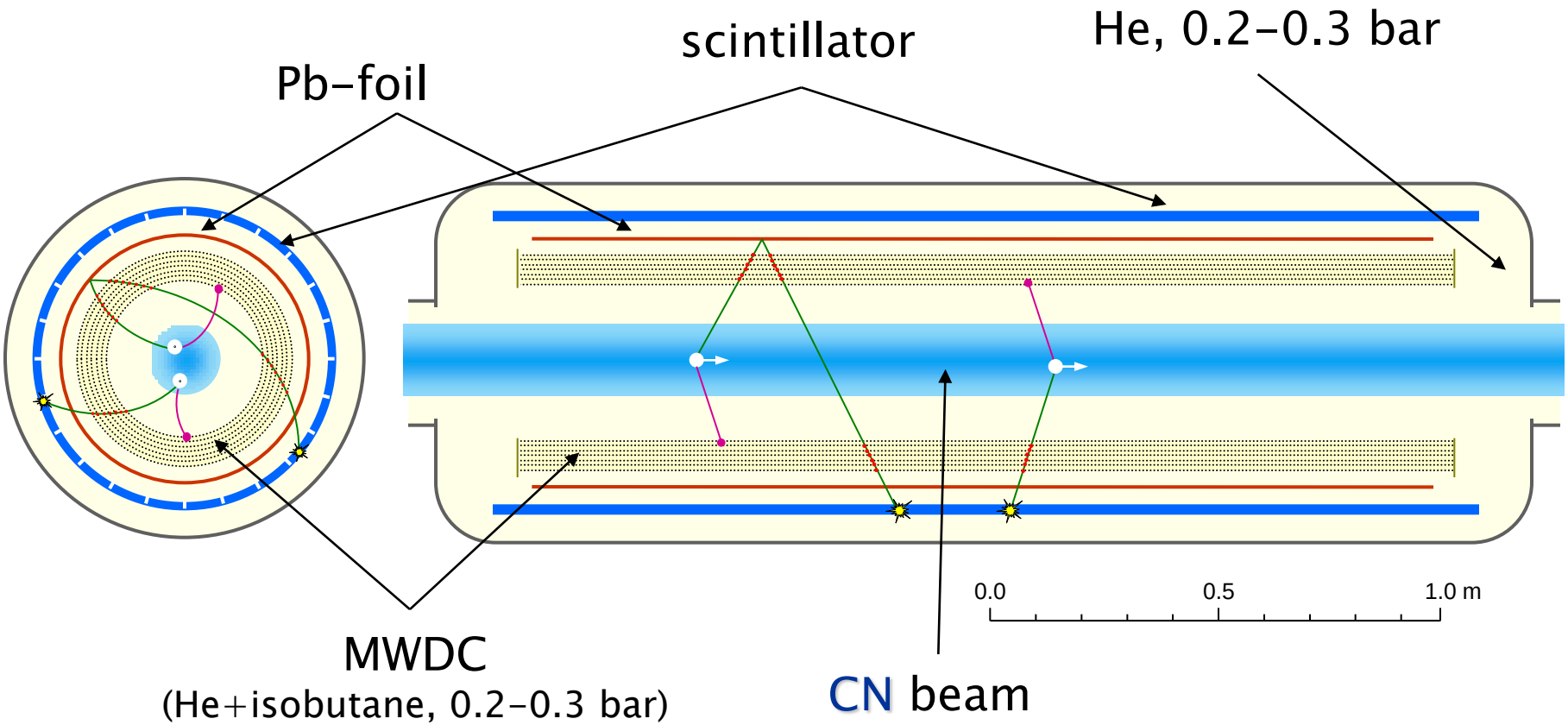

- Constraints on real scalar contributions dominated by:
  - Super-allowed $0^+\rightarrow0^+$
  - Correlations in mirror transitions
- n-decay correlations could join the game !

# $2^{nd}$-generation experiment with CN beam

- General features of the experimental setup:
  - Axial polarimeter geometry (instead of planar)
    - 2.5 m long beam acceptance
  - Multi Wire Drift Chambers (instead of MWPC):
    - Hexagonal cell geometry
    - $x$-,$y$-coordinates from drift time ($\Delta x = \Delta y = 0.5$ mm)
    - $z$-coordinate from charge division ($\Delta z = 1.0$ mm)
    - Reduced pressure (0.2-0.3 bar) **WORKS !**

      K. Lojek at al., NIMA 611 (2009) 284
  - Additional background suppression and higher polarization:
    - 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)
- Expected sensitivity for all coefficients: **$5 \times 10^{-4}$**

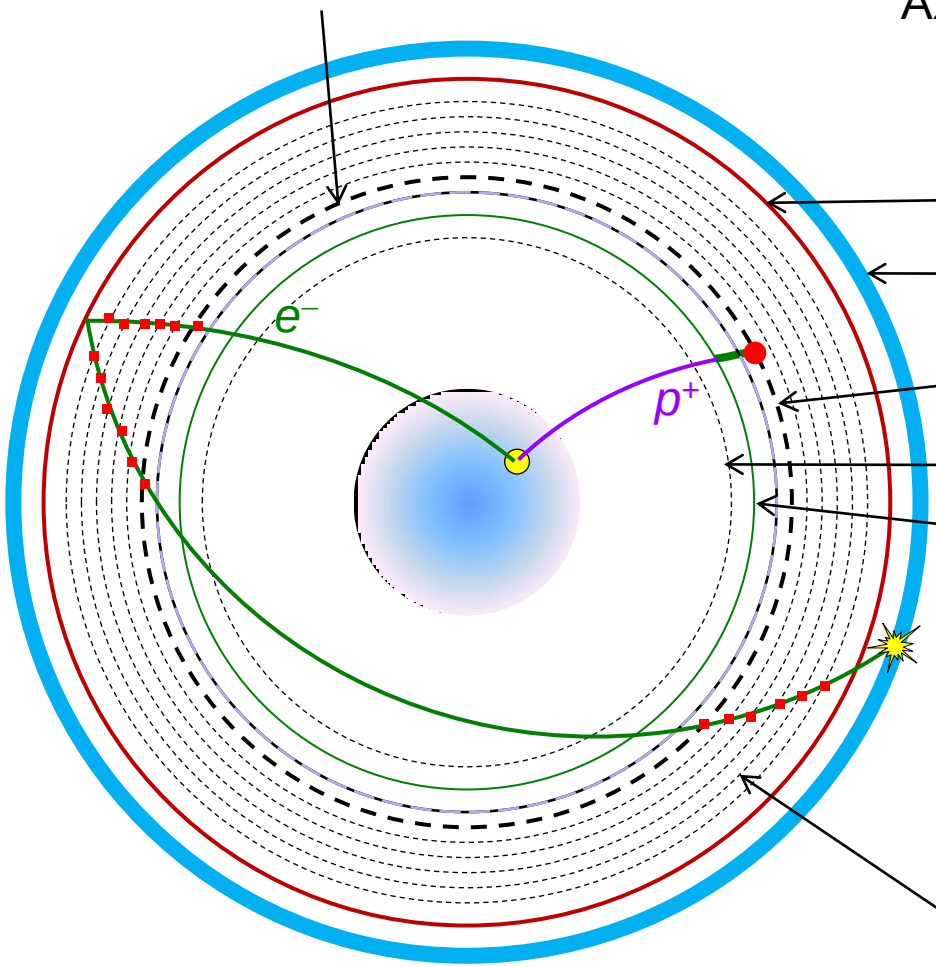
# 2nd-generation experiment with CN beam



# With detection of electrons and recoil protons...

Grounded vacuum window: 6 μm Mylar, reinforced with Kevlar fibers

Longitudinal neutron polarization, Axial guiding field B = 0.1÷0.5 mT




Mott scattering foil

Plastic scintillator

MWPC, 1 layer

Grounded grid

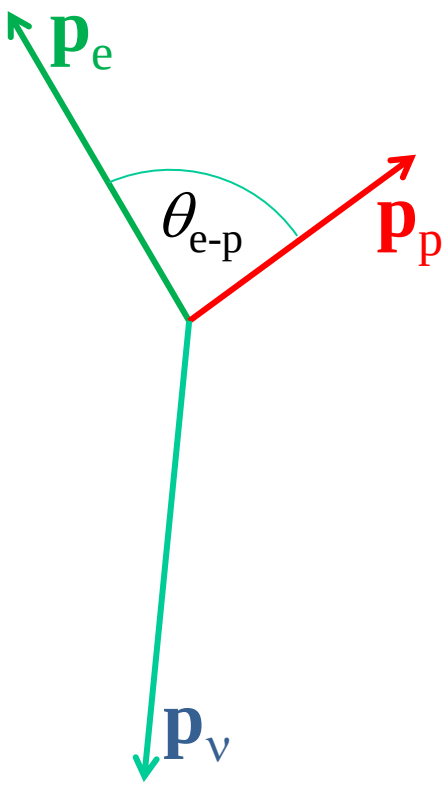
**p-e conversion foil**

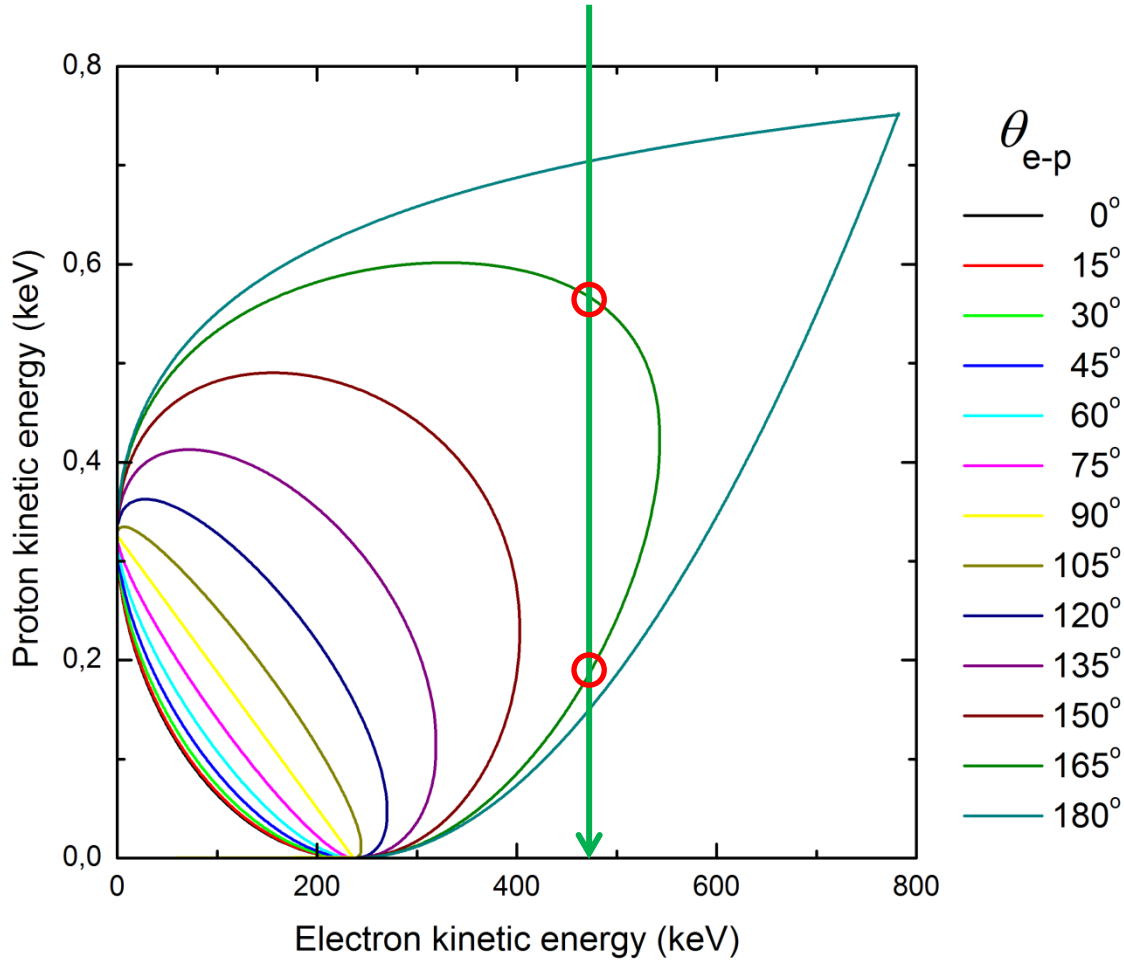
LiF (20nm) + Al (10nm) + 6F6F(100nm), -25 kV

[S. Hoedl et al., J. Appl. Phys. 99, 084904 (2006)]

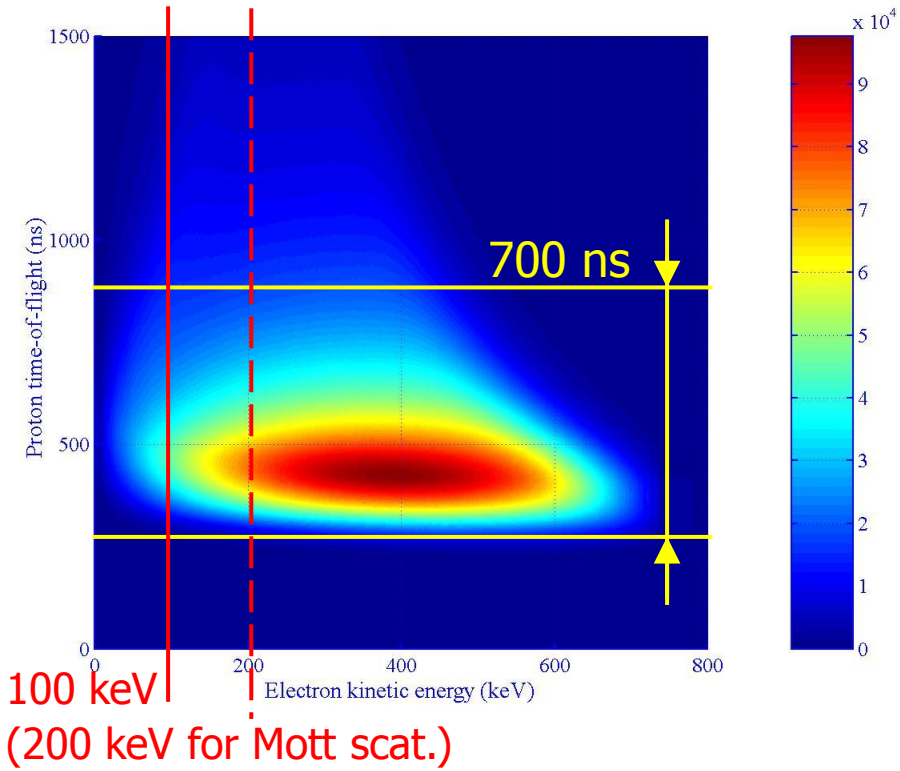
MWDC, hexagonal, 5 layers

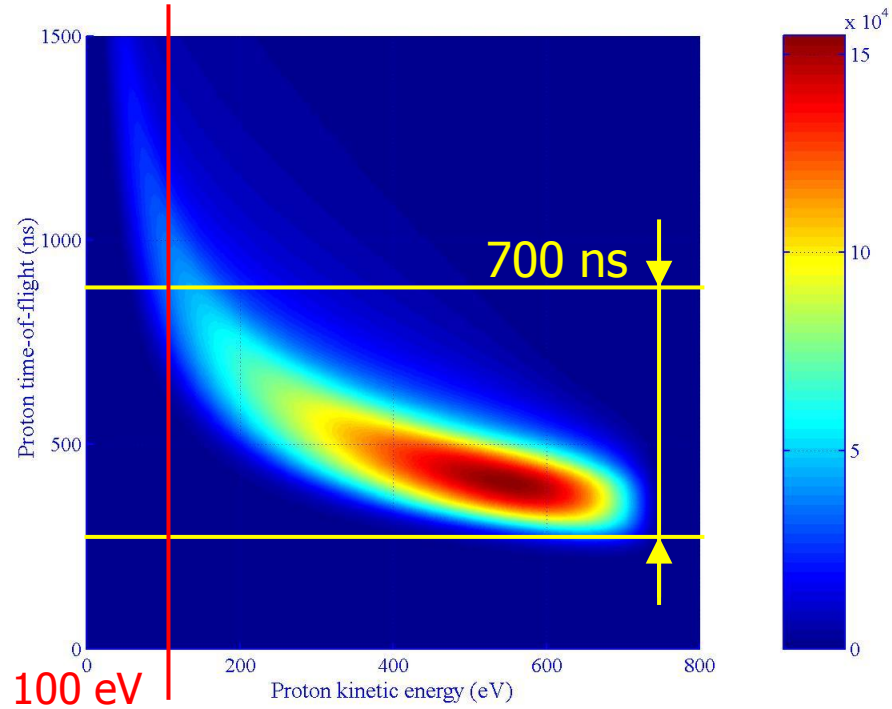
# Electron-proton kinematics



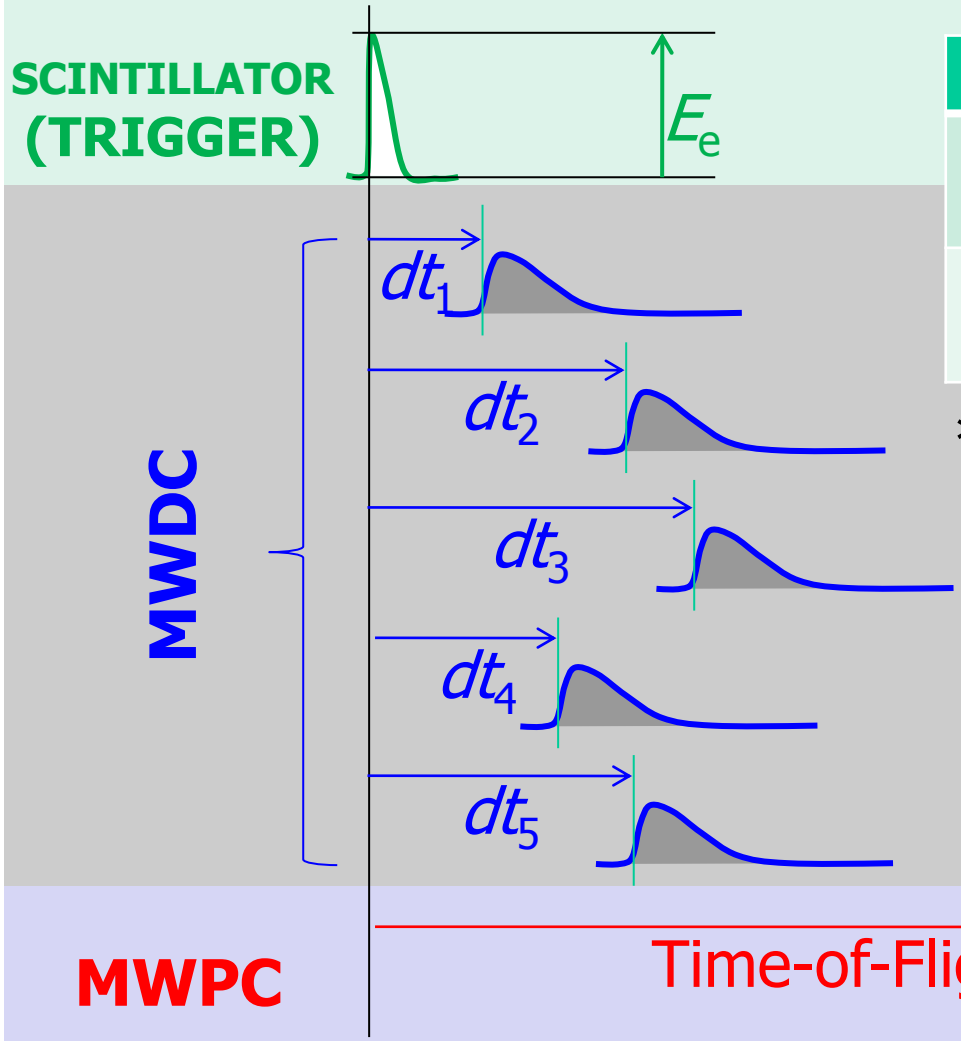
# Electron-proton kinematics




- Measured electron energy, reconstructed proton flight path and measured proton time-of-flight **must match !**
- Constraints from 3-body kinematics will considerably **reduce coincidence time**
- With **$10^5$** decays per second: single rate (per wire) **< 1 kHz**

# DAQ




| Quantity | Exp. Information |
|---|---|
| Electron momentum | Scintillation light & electron track* |
| Proton momentum | Time-of-flight & hit position |

* Electron track reconstructed with drift times ($x$, $y$) and charge division ($z$)

1 μs

# Conclusions

- **Within 3 months long data taking:**
  - **$3\times10^8$** Mott scattered electrons (***N, R***)
  - **$10^8$** protons in coincidence with Mott scattered electrons (***H, L, S, U, V***)
  - **$10^{12}$** single electrons (***A***)
  - **$3\times10^{11}$** e-p coincidences (***a, B, D***)
- **Advantages:**
  - Complete set of competitive constrains for scalar and tensor contributions from neutron decay alone
  - In further perspective, ***a, b, A, B, D*** correlations with different systematic effects
  - Systematic study of FSI effects in neutron decay
- **Theory challenges:**
  - Recoil order and electromagnetic corrections for electron spin related correlation coefficients on (at least) $10^{-4}$ accuracy level [V. Gudkow et al., PRC 73 035501 (2006); J.L. Garcia-Luna et al., J. Phys. G: Nucl. Part. Phys. 32 (2006) 333–344]
  - Deeper analysis of electron spin related correlation coefficients (e.g. LRSM)
- **Experimental challenges:**
  - Intensive, parallel and highly polarized CN beam (with well known phase space)
  - p-e conversion foil (2 $m^2$ !) [S. Hoedl et al., J. Appl. Phys. 99, 084904 (2006)]
  - Vacuum window (3 $m^2$ !)
  - Low pressure MWDC
- **Possible locations:**
  - NIST, ILL, …

# Backup slides

# Guidelines:

Measurements of the transverse electron polarization in n-decay provide **direct**, i.e. first-order access to the exotic **scalar** and **tensor** coupling constants

In order to simultaneously access **REAL** and **IMAGINARY** parts of the exotic couplings - measure **both** components of the transverse polarization of electrons emitted in neutron decay

# Systematic errors (2007)

- Decay origin "from/off beam" (mm): $x_{1max}$, $y_{1max}$, $z_{1max}$
- Electron energy "from/off neutron decay" (keV): $E_{Lmin}$, $E_{Lmax}$, $E_{Hmin}$, $E_{Hmax}$
- Mott vertex position (mm): $X_{min}$, $X_{max}$, $Y_{max}$, $Z_{max}$

Background subtraction related

Decay asymmetry correction

| Source | $\delta N \times 10^4$ | $\delta R \times 10^4$ |
|---|---|---|
| $x_{1_{max}} \in (80, 95)$ | 20 | 17 |
| $z_{1_{max}} \in (240, 250)$ | 16 | 9 |
| $y_{1_{max}} \in (100, 120)$ | 26 | 25 |
| $E_{L_{min}} \in (200, 260)$ | 13 | 11 |
| $E_{L_{max}} \in (580, 660)$ | 18 | 15 |
| $E_{H_{min}} \in (780, 860)$ | 5 | 4 |
| $E_{H_{max}} \in (1400, 1900)$ | 7 | 16 |
| $X_{min} \in (190, 210)$ | 11 | 18 |
| $X_{max} \in (245, 265)$ | 15 | 18 |
| $Y, Z_{max} \in (210, 230)$ | 19 | 23 |
| term $PA\overline{\beta\mathcal{F}}$ | 6 | 30 |
| effective Sherman function $\bar{S}$ | 13 | 4 |
| guiding field misalignment | 3 | 7 |
| dead time variations | 9 | 0.5 |
| Total | 54 | 61 |

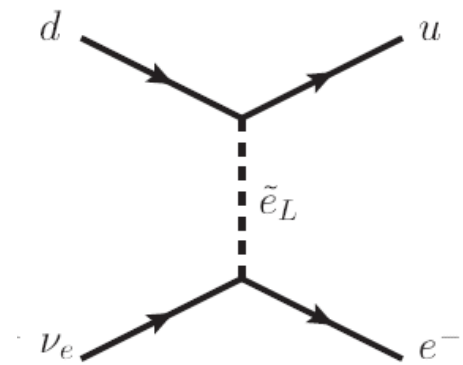
# RPV MSSM contributions to n-decay

*R*-parity violating super-symmetric contributions to the neutron beta decay
Nodoka Yamanaka *et al* 2010 *J. Phys. G: Nucl. Part. Phys.* **37** 055104

$$R = (-1)^{2j+3B+L}.$$

$$\mathcal{M}_{\tilde{e}_L} = \sum_{i=2,3} \frac{(\lambda_{1i1} - \lambda_{i11})\lambda'^{*}_{i11}}{8m^2_{\tilde{e}_{Li}}} \bar{u}\,(1+\gamma_5)\,d \cdot \bar{e}\,(1-\gamma_5)\,\nu_e$$

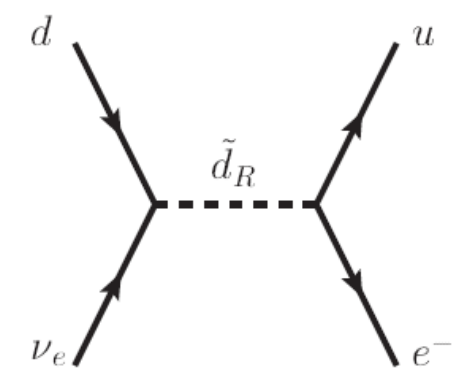
$$= \sum_{i=2,3} \frac{\lambda_{1i1}\lambda'^{*}_{i11}}{4m^2_{\tilde{e}_{Li}}} \bar{u}(1+\gamma_5)d \cdot \bar{e}(1-\gamma_5)\nu_e \ ,$$



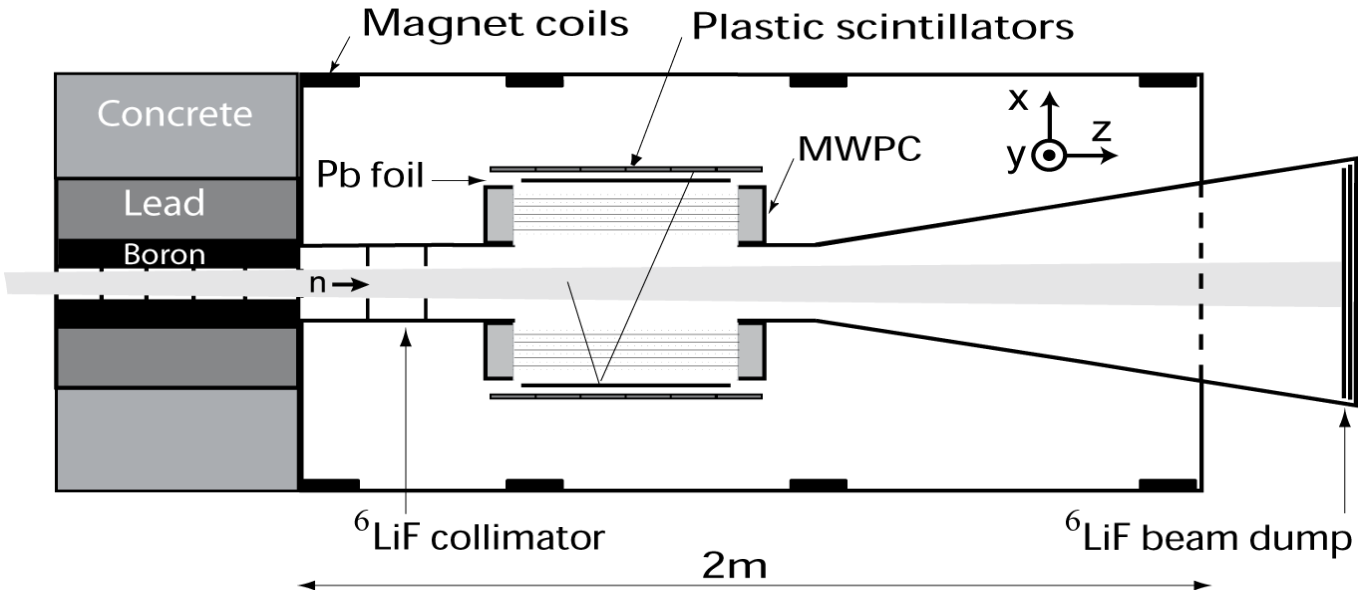

$$\mathcal{M}_{\tilde{d}_R} = \sum_{i=1,2,3} \frac{|\lambda'_{11i}|^2}{4m^2_{\tilde{d}_{Ri}}} \bar{\nu}^c_e(1-\gamma_5)d \cdot \bar{u}(1+\gamma_5)e^c$$

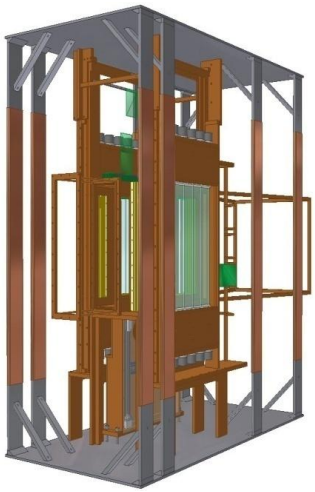
$$= \sum_{i=1,2,3} \frac{|\lambda'_{11i}|^2}{8m^2_{\tilde{d}_{Ri}}} \bar{u}\gamma^\mu(1-\gamma_5)d \cdot \bar{\nu}^c_e\gamma_\mu(1+\gamma_5)e^c$$

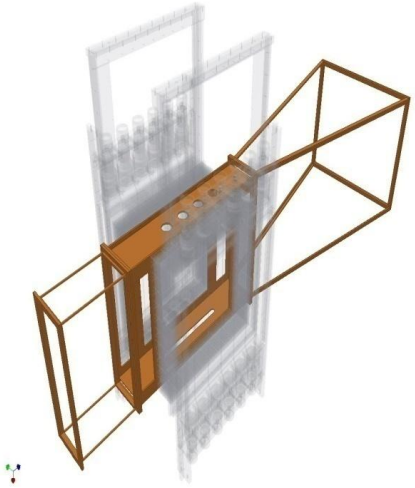
$$= \sum_{i=1,2,3} \frac{|\lambda'_{11i}|^2}{8m^2_{\tilde{d}_{Ri}}} \bar{u}\gamma^\mu(1-\gamma_5)d \cdot \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \ .$$

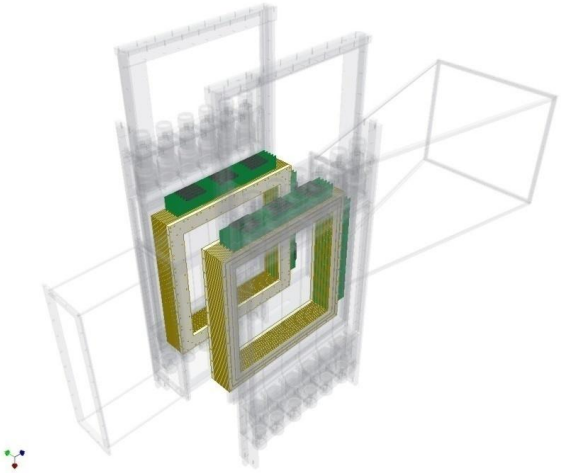


# Experimental setup

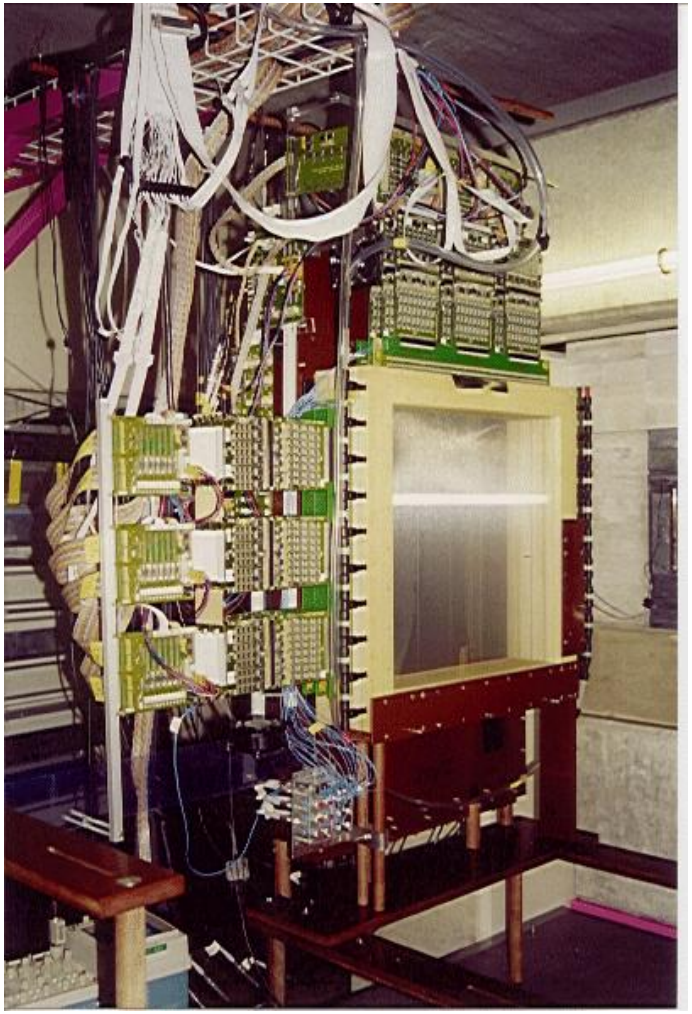


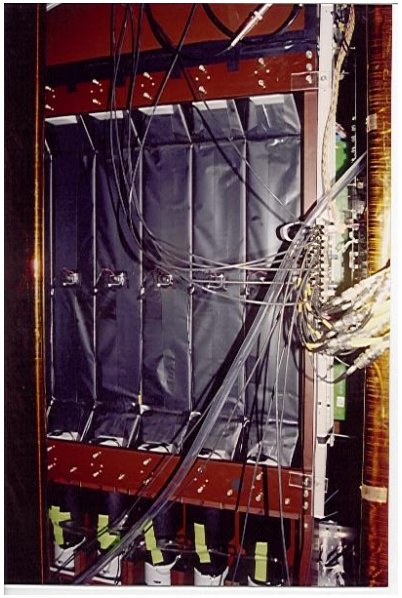



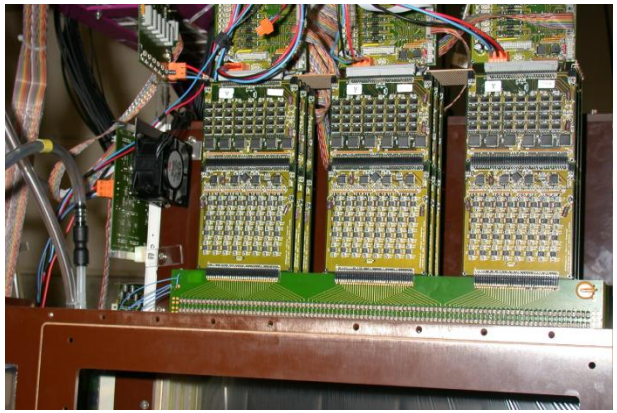


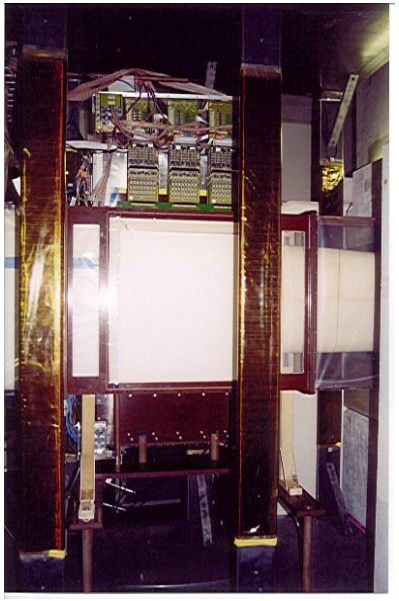


# MWPCs, scintillators and electronics





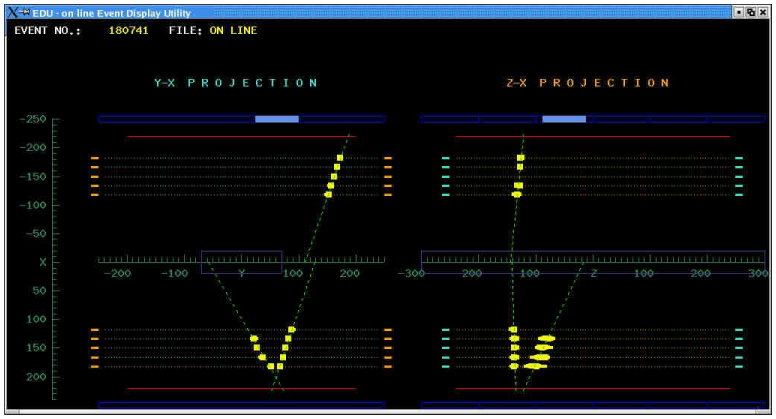




# "V-track" events – on-line display

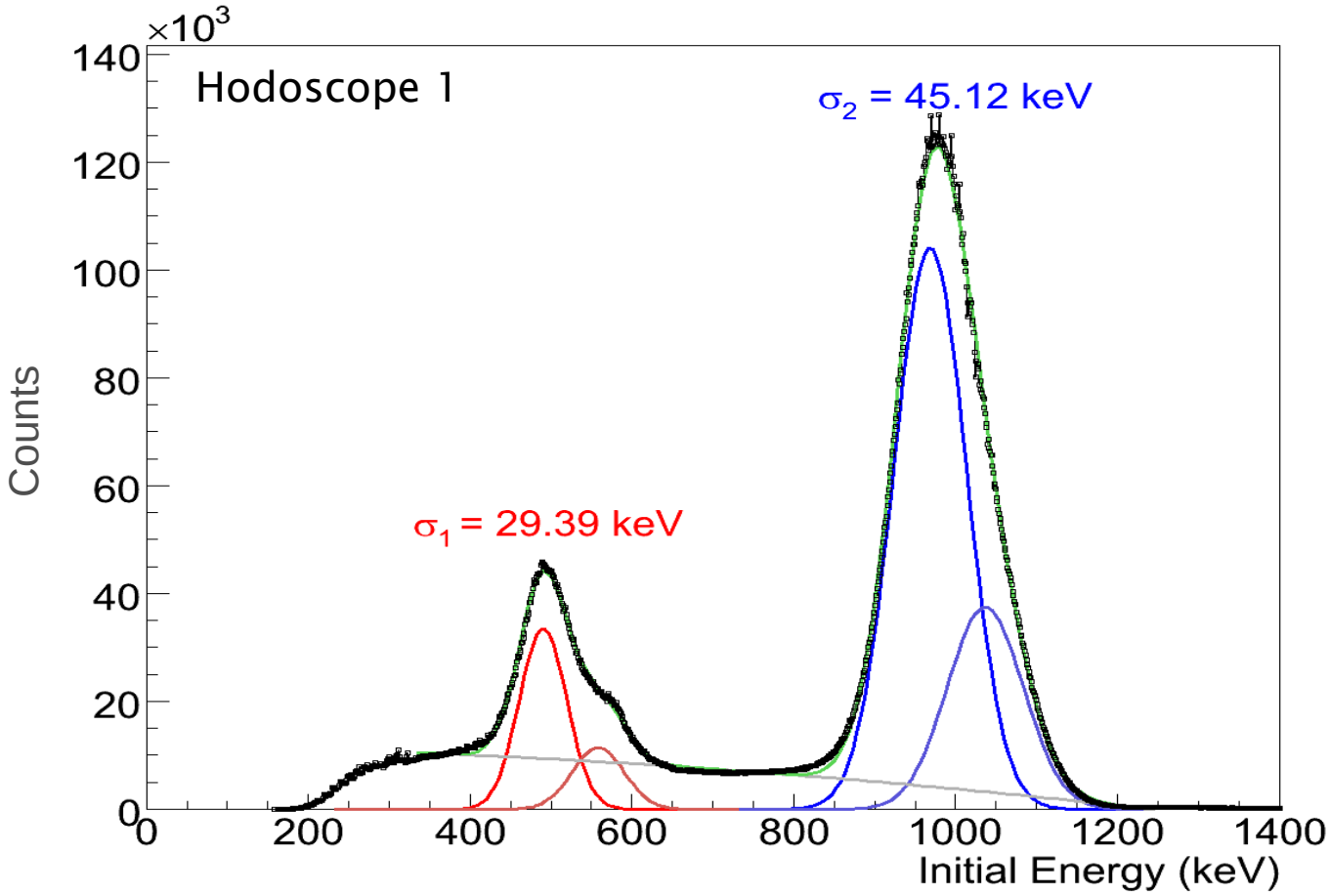




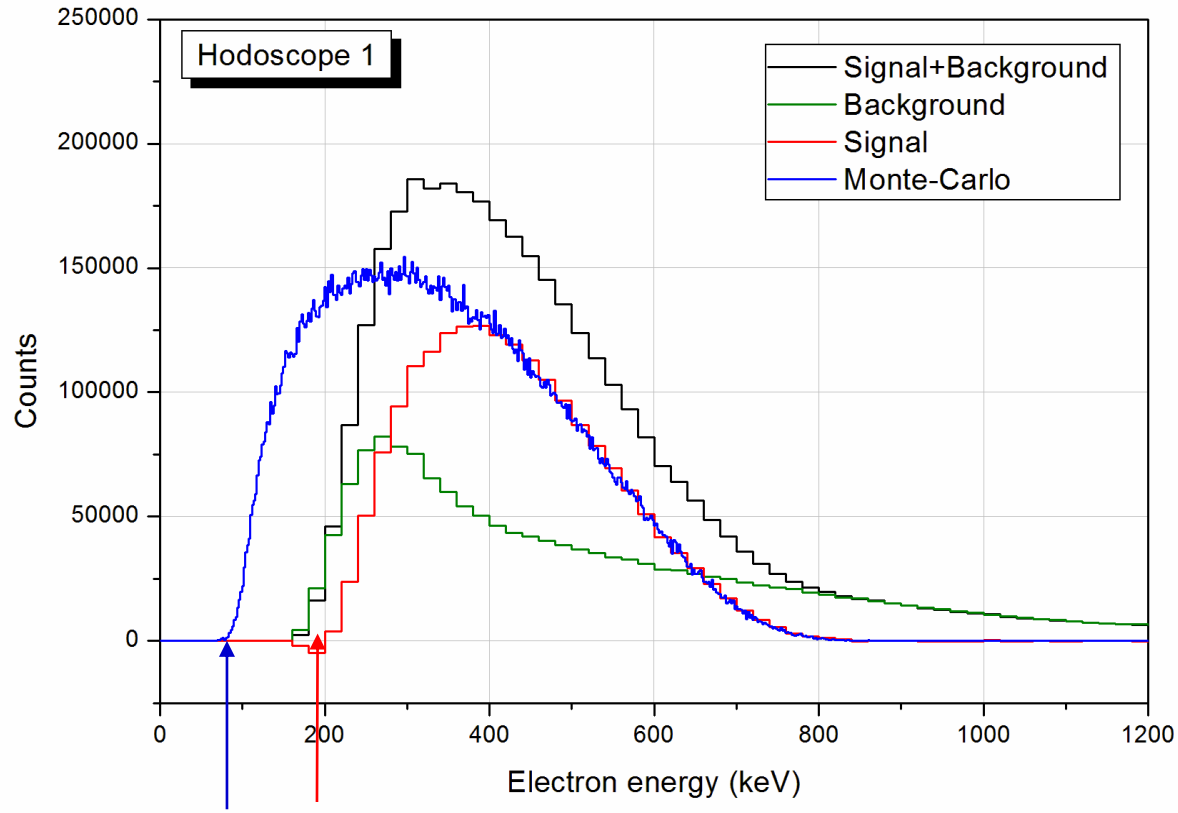



# Energy resolution

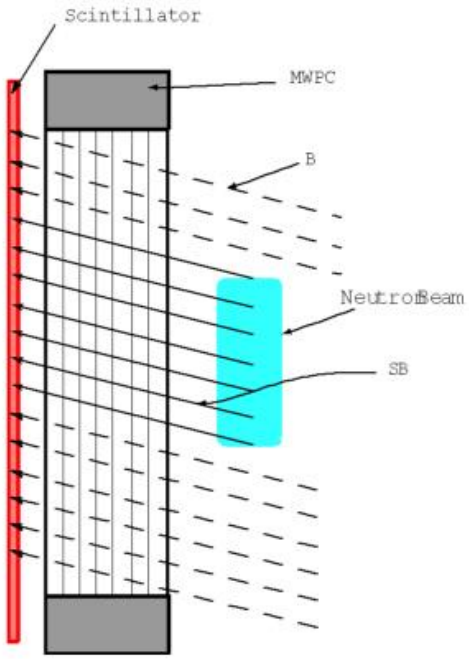
- Conversion electrons from $^{207}Bi$



# Background subtraction




Absorption threshold Electronic threshold




## ❑ Observation:

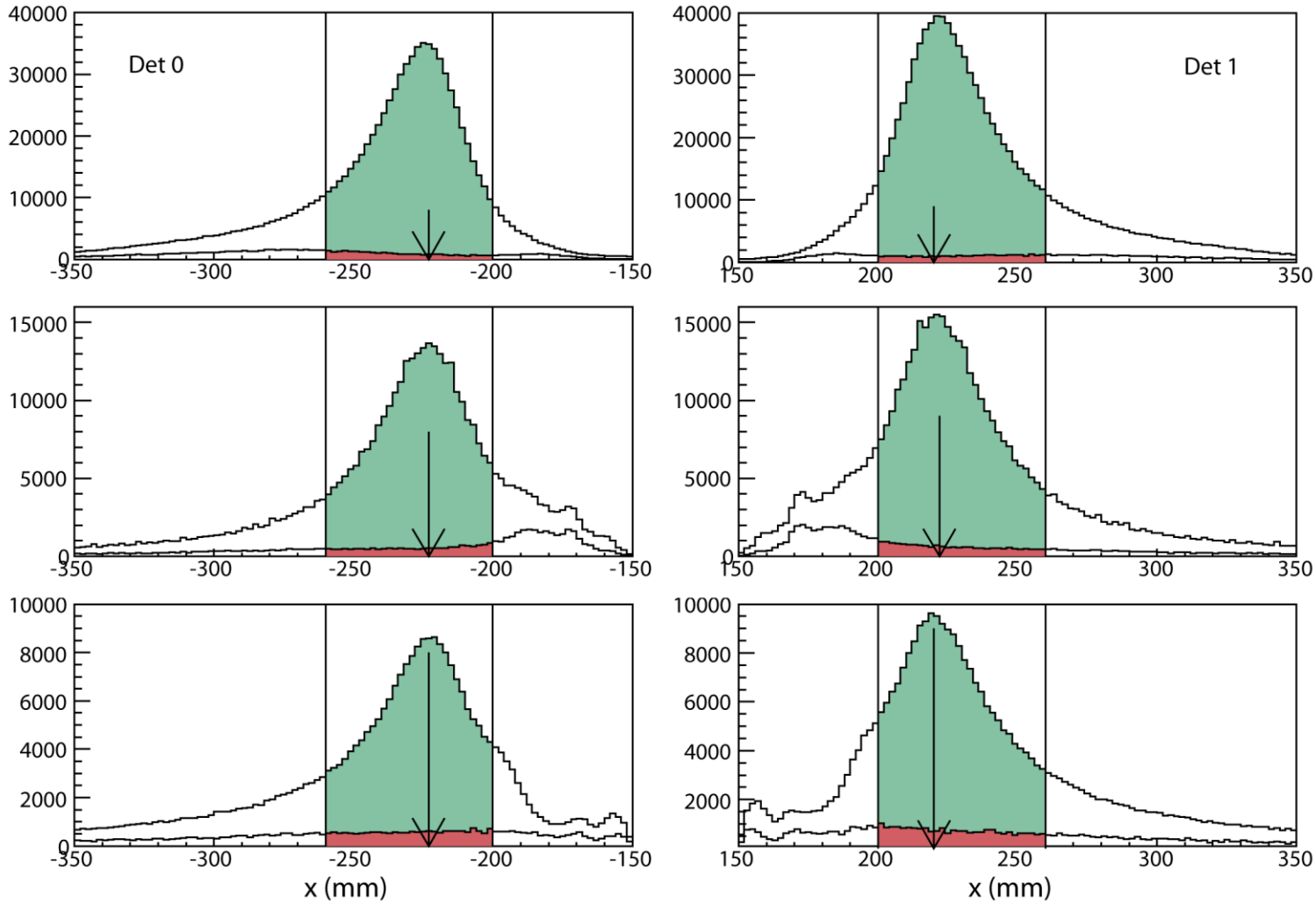
Spectral distribution of background depends weakly on the electron origin

# Mott scattering vertex distribution

Coinciding vertices in V and H projections

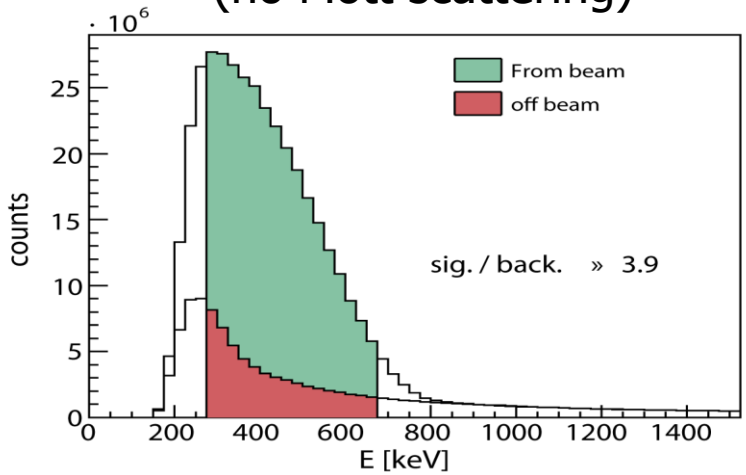
Vertex in V projection only

Vertex in H projection only

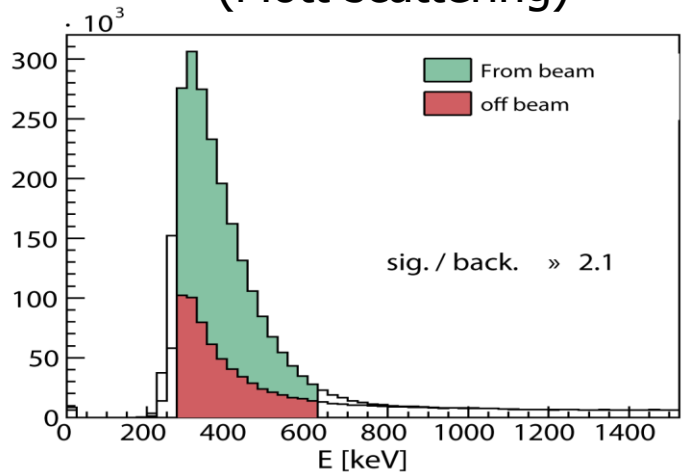


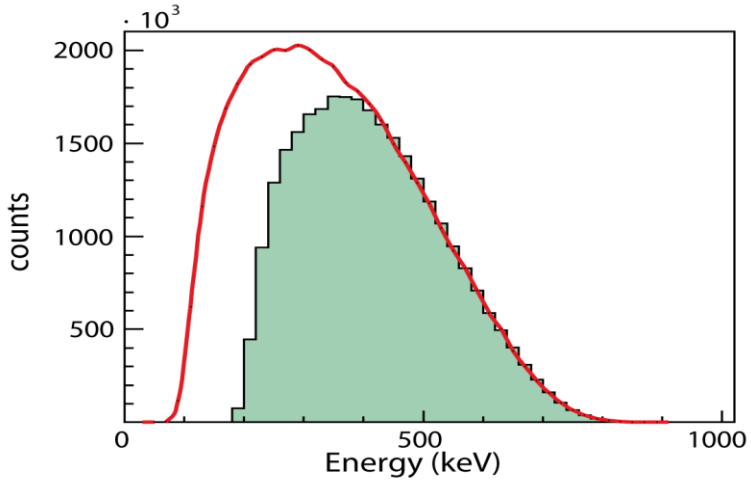
# Electron energy distribution

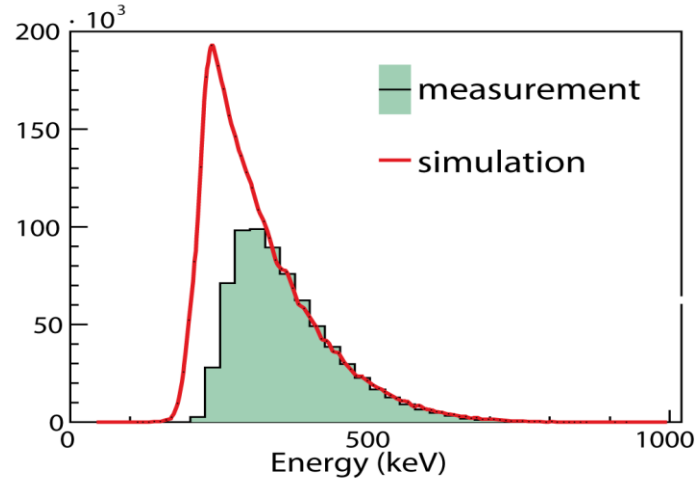
Single-track events
(no Mott scattering)



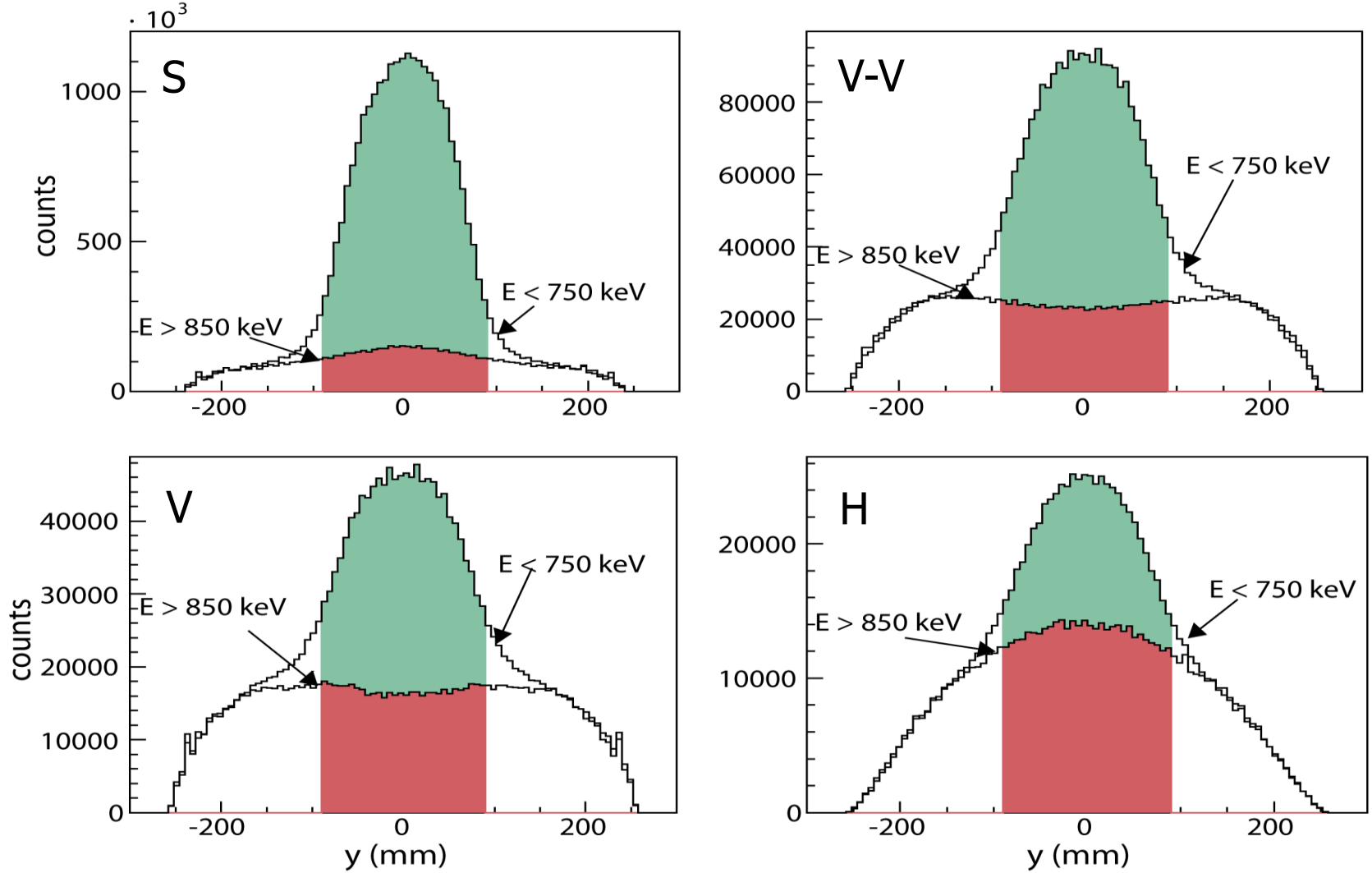

Double V-track events
(Mott scattering)



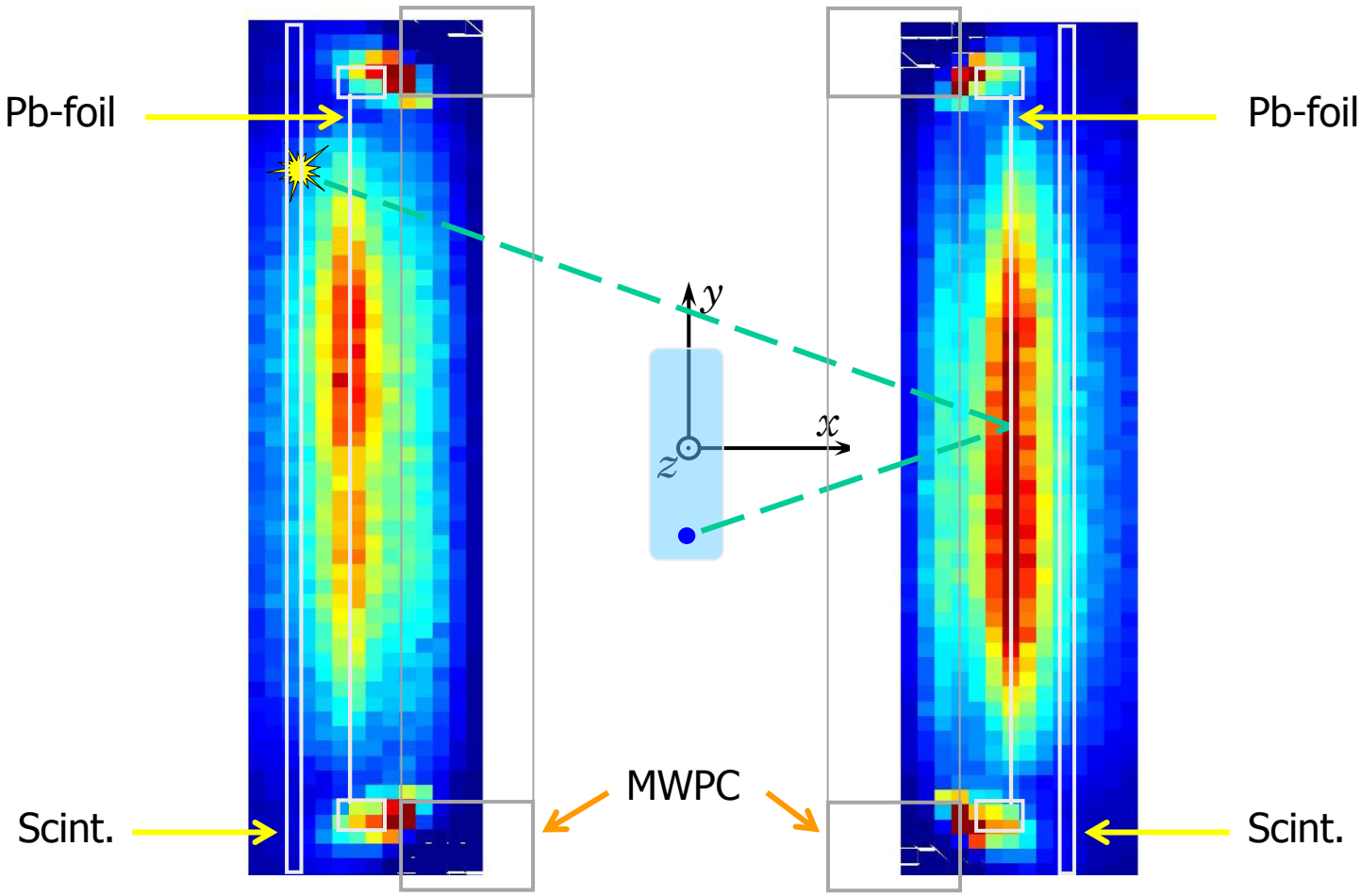



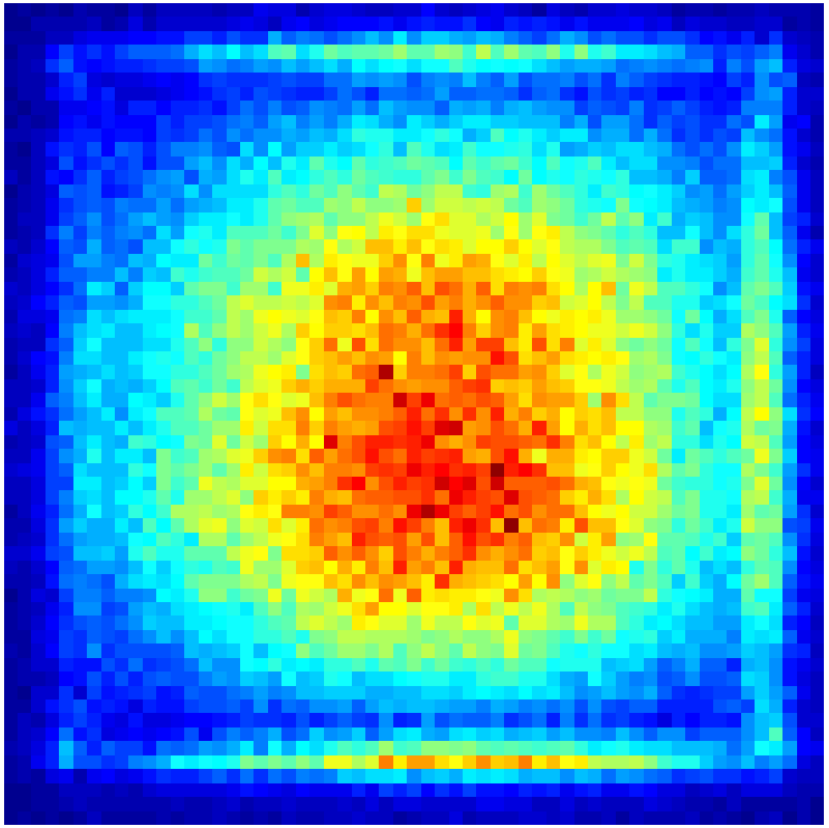
# Neutron beam "tomography"

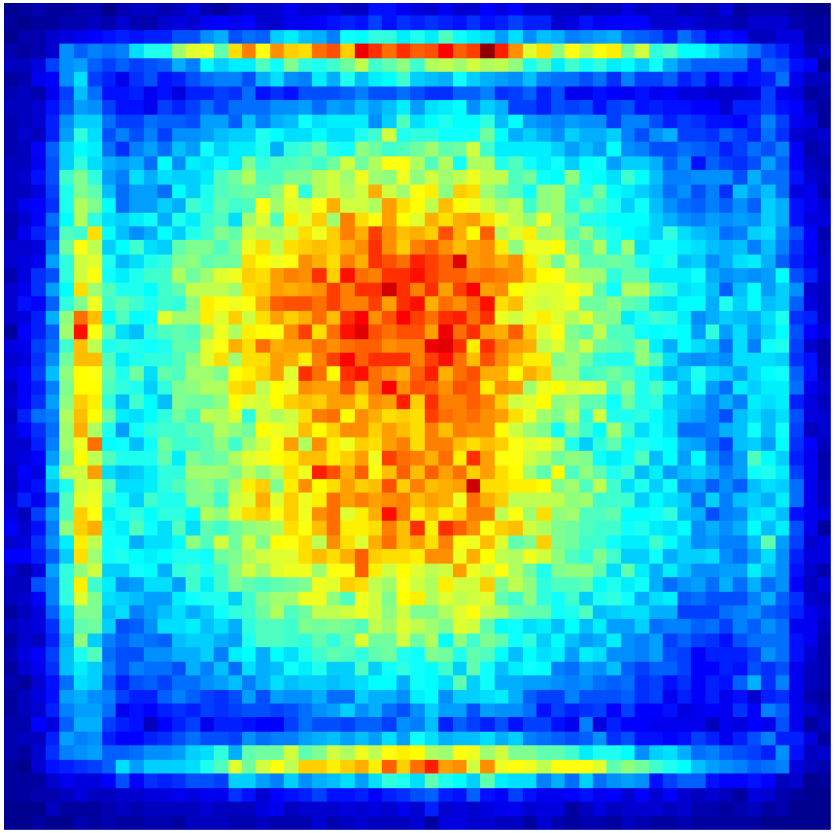


# Projection of vertices onto XY-plane



# Projection of vertices onto Pb-foil planes





# 2nd-generation experiment with CN beam

- Statistics

| | Item | Gain factor |
|---|---|---|
| 1. | Beam intensity | 10 |
| 2. | Beam fiducial volume | 5 |
| 3. | Detector acceptance | 10 |
| 4. | Beam polarization | 1.2 |
| 5 | Analyzing power | 1.3 |
| | **Total** | **780** |

- Systematical uncertainty

| | Item | Reduction factor |
|---|---|---|
| 1. | Background subtraction | 10 |
| 2. | Average neutron polarization | 5 |
| 3. | Analyzing power | 3 |

# Reconstruction of momenta

Actual position of the decay vertex is not known

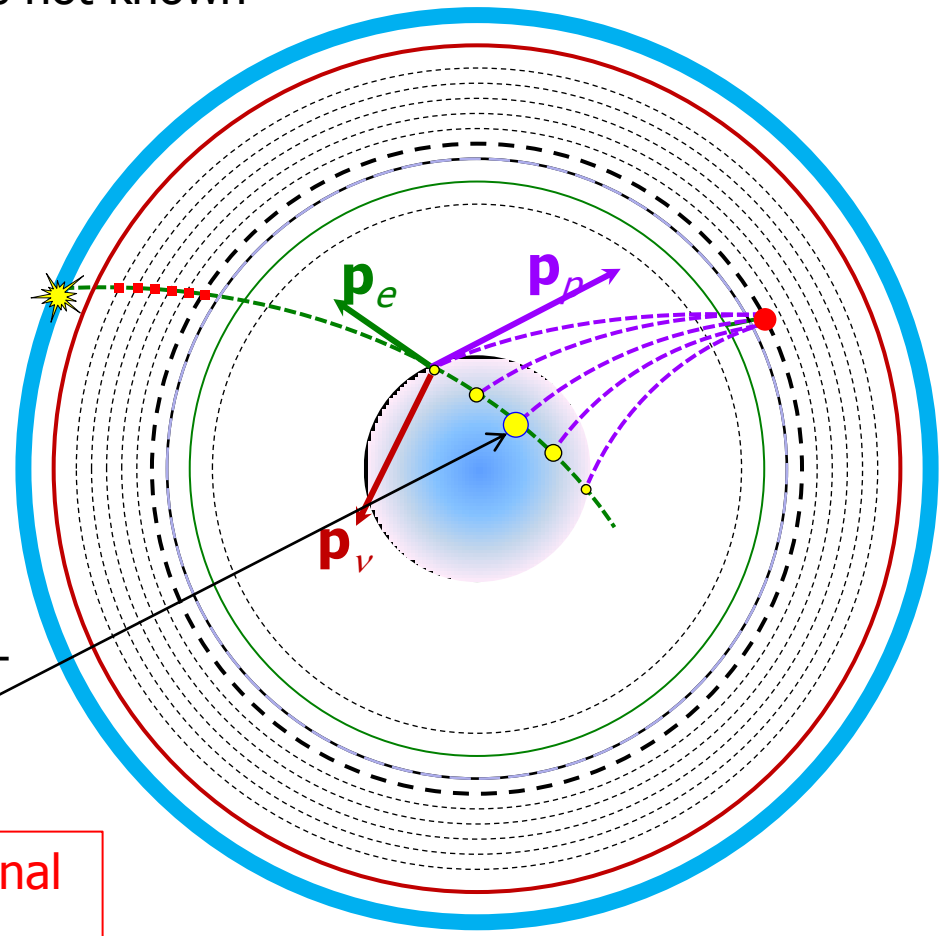
**But:**

It **must be located** on the electron trajectory segment coincident with the beam

Neutron decay density distribution in the beam **is known**

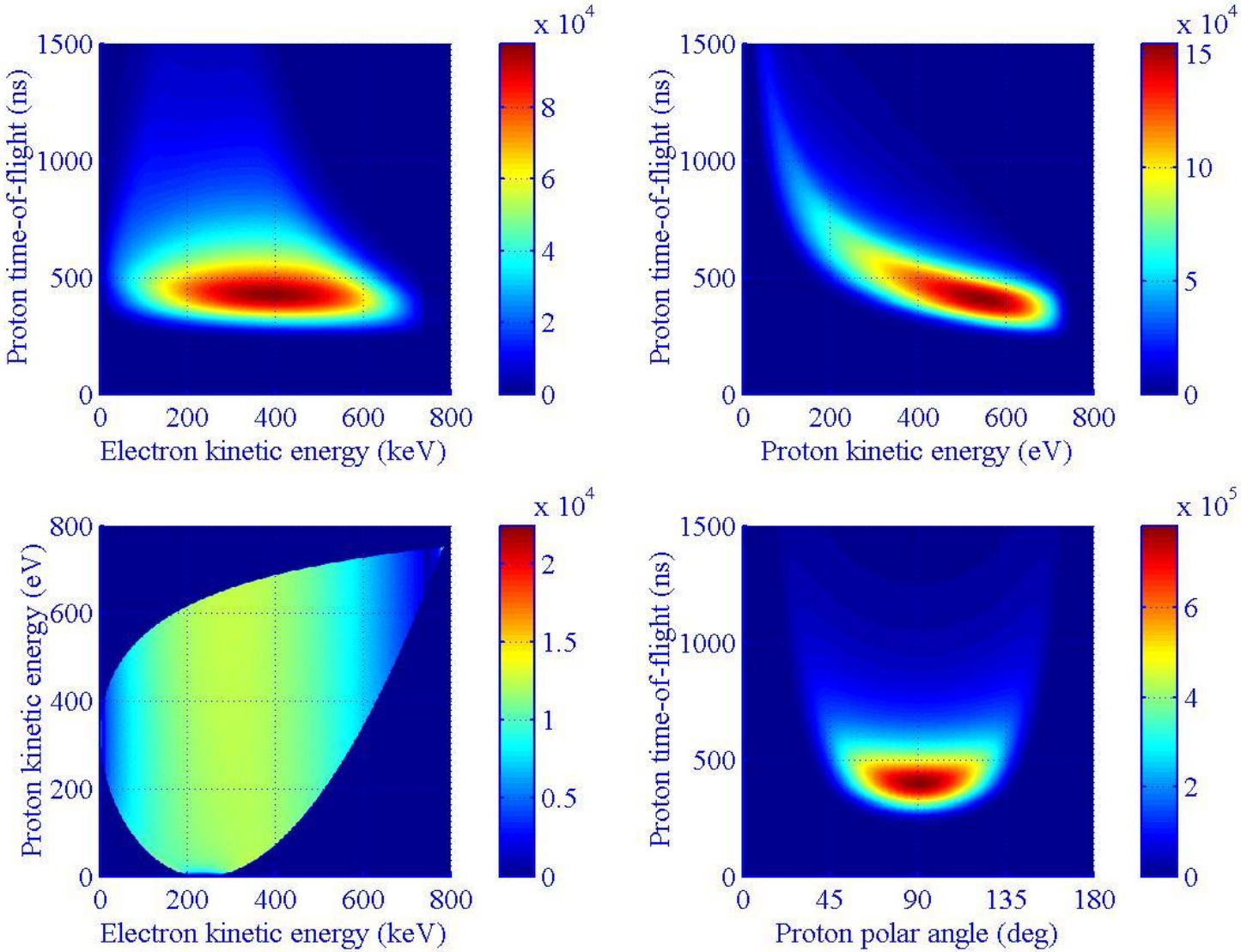
**Finally:**

In extraction of correlation coefficients we sum over momenta – ambiguity in vertex position is not essential

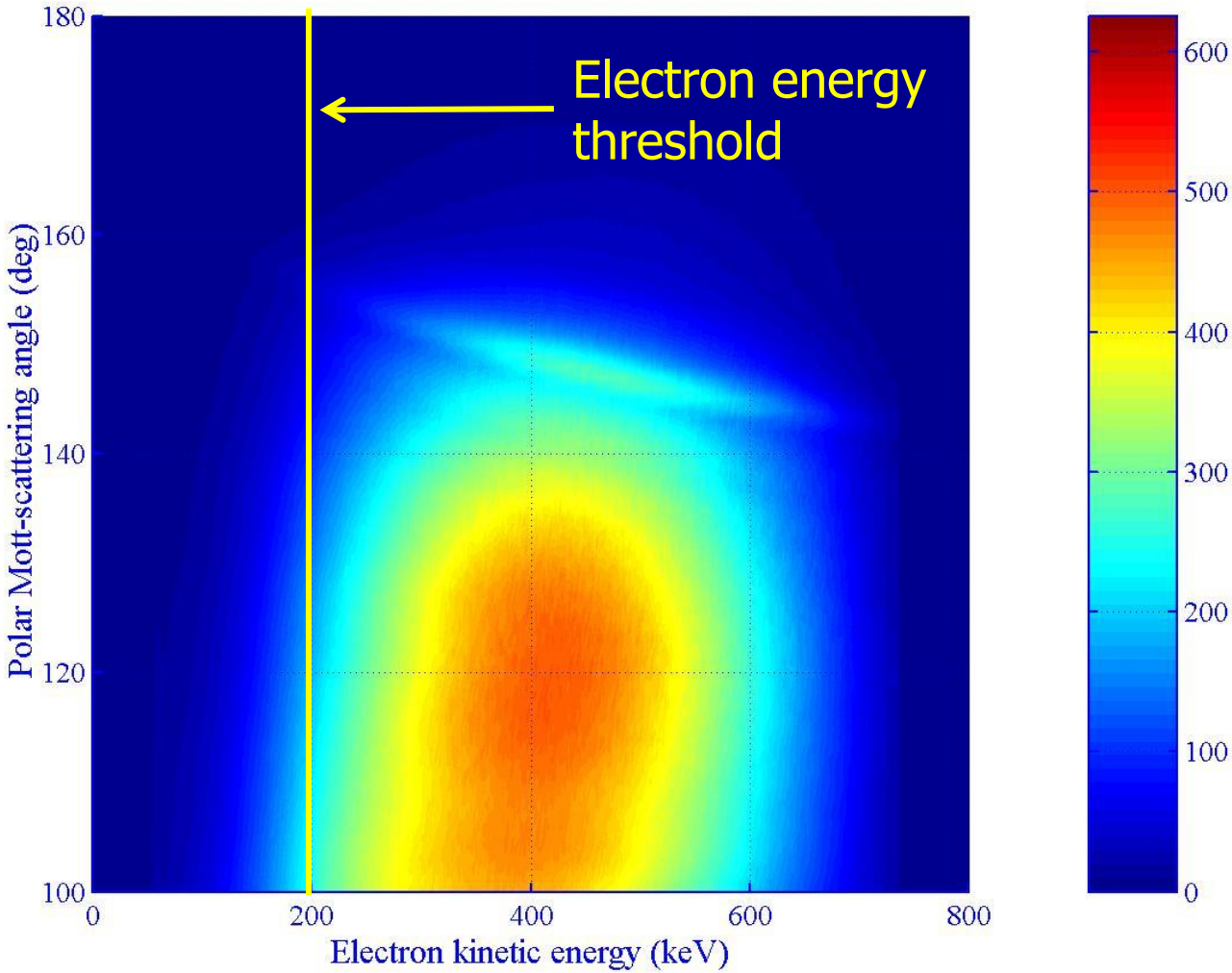



assigned weight is proportional to the decay density

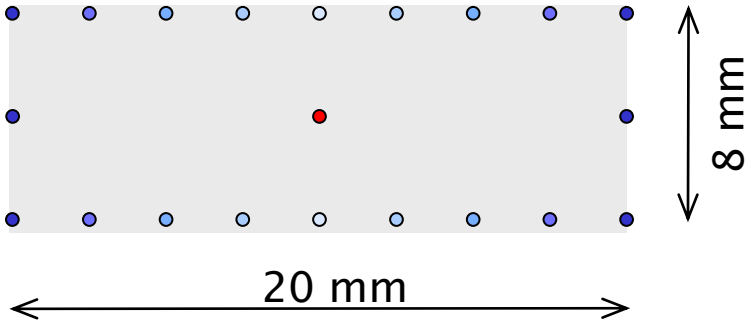
# Electron-proton kinematics

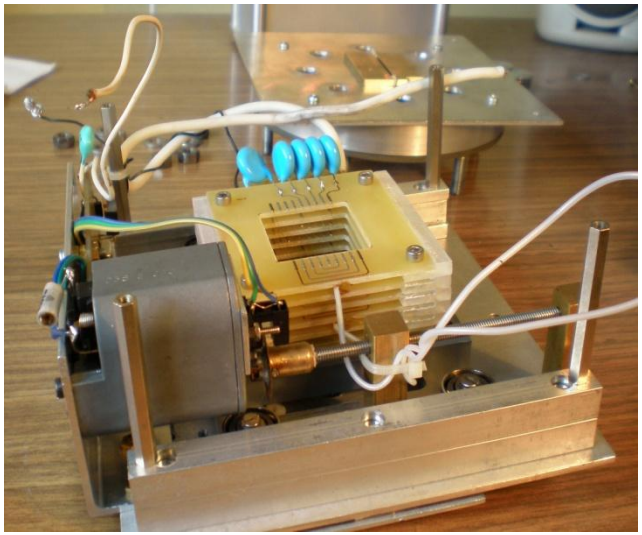


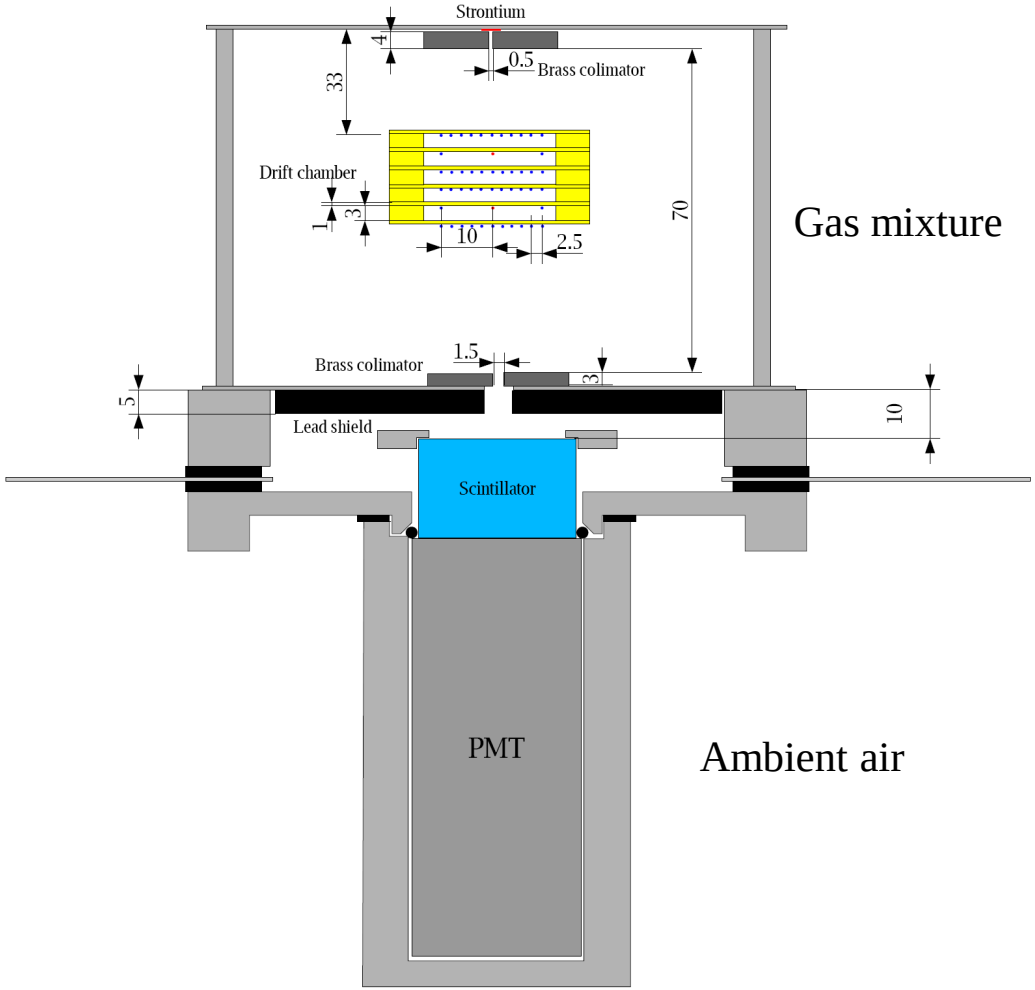
# Figure-of-Merit for Mott scattering



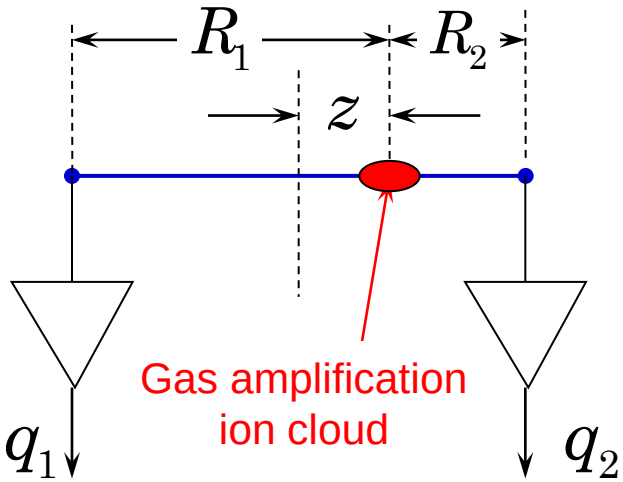
# MWDC operation in lowered gas pressure



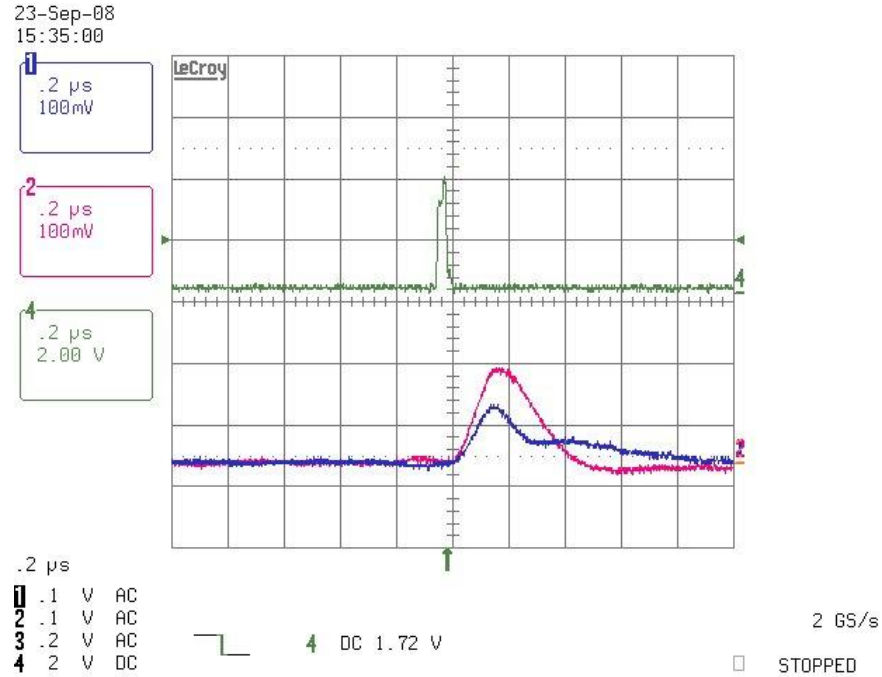



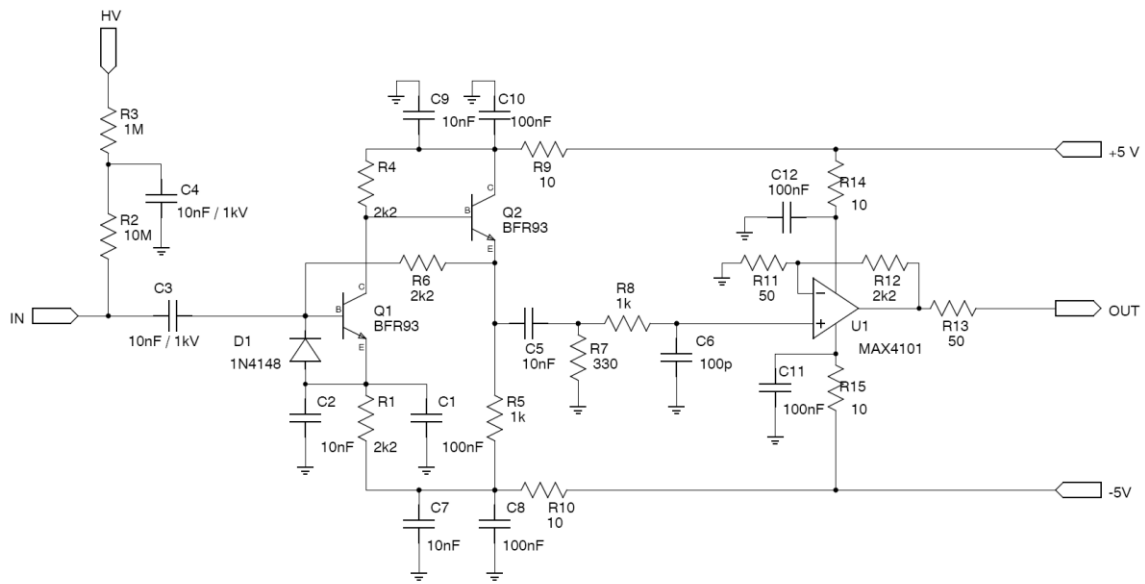


# Current preamplifier (for readout from both wire ends)




$$z = \frac{q_1 - q_2}{q_1 + q_2} \approx \frac{R_2 - R_1}{R_2 + R_1}$$



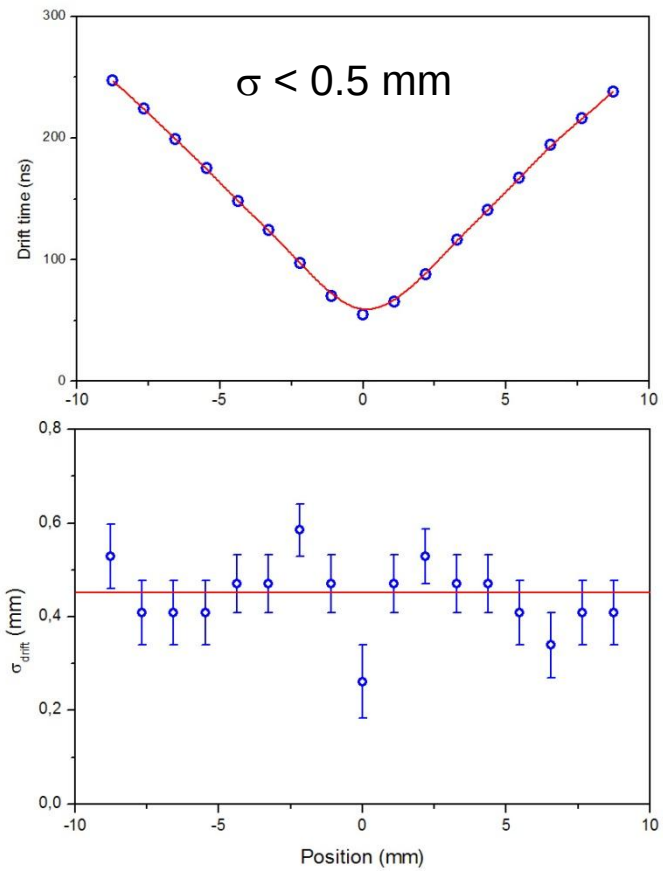



# Achieved performance

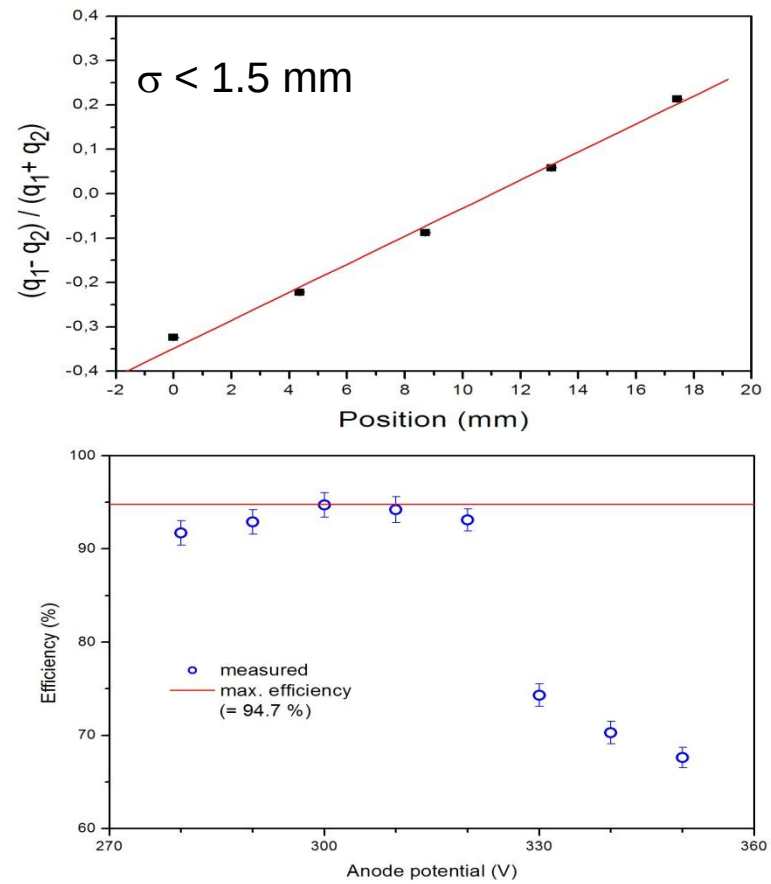
Gas mixture: $\mathrm{He}$ $(90\%)$ + isobutane $(10\%)$, $P = 300$ $\mathrm{mbar}$

Wire resistance = 3 Ohm; Preamplifier input impedance = 10 Ohm

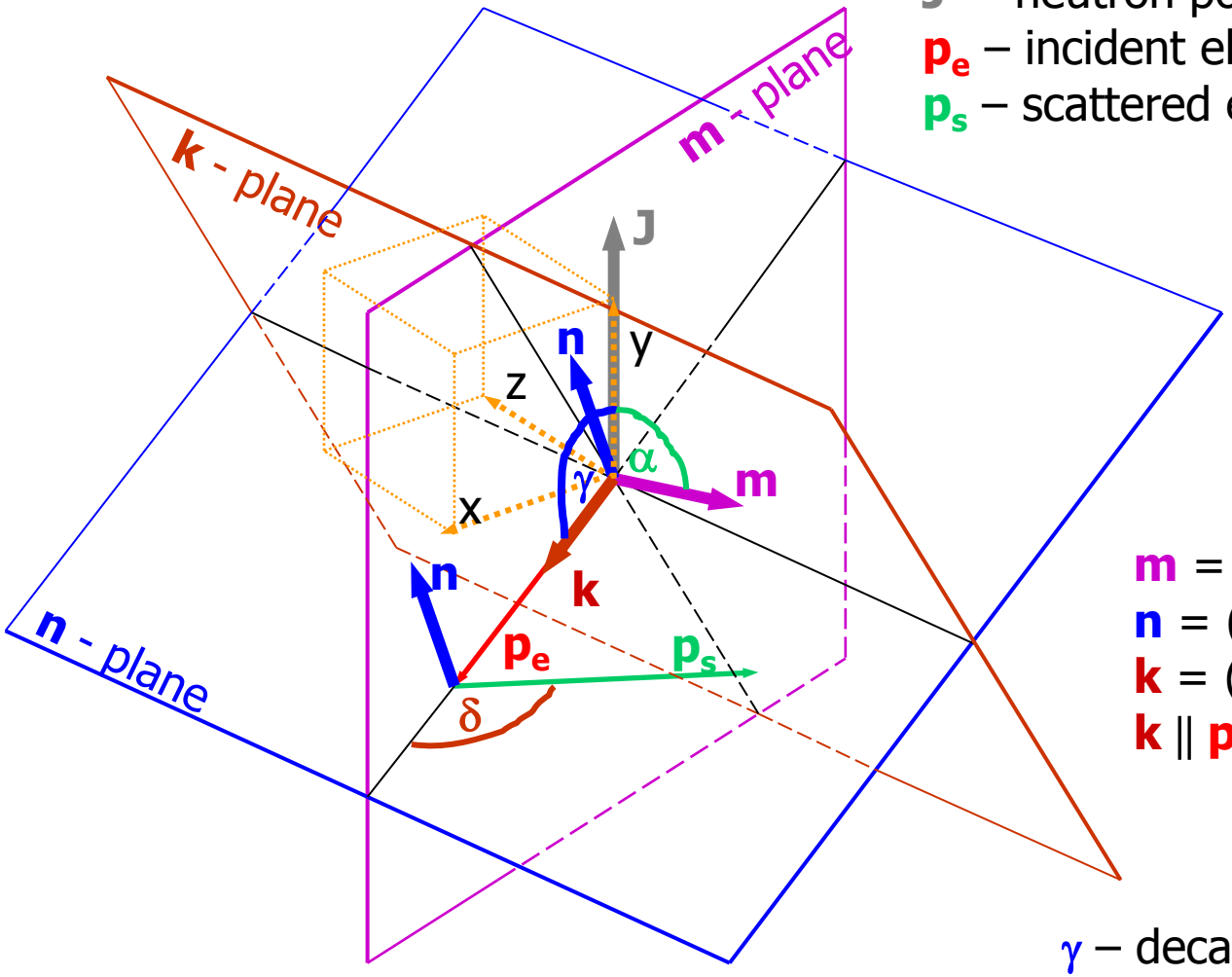
From drift time




From charge division



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




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

$\gamma$ – decay angle
$\delta$ – Mott scattering angle
$\alpha$ – event projection angle

(x,y,z) – LAB frame