LORENTZ INVARIANCE VIOLATION IN NEUTRON DECAY

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Lorentz Invariance

- *Symmetries of space-time, Lorentz and CPT – roots of understanding universe*
- *Unification of Standard Model (Particle Physics) and General Relativity (both conserve Lorentz and CPT) – major goal for theory*
- *Direct experiments – far from reach because of high energy relevant for unification*
- *Hope in possible Lorentz and CPT violation – traces are expected at lower energies*
- *Effective Field Theory approach: Standard Model Extension (SME)*
  - *D. Colladay and V. A. Kostelecky, Phys. Rev. D 55, 6760 (1997)*
  - *D. Colladay and V. A. Kostelecky, Phys. Rev. D 58, 116002 (1998)*
- *Advanced studies on LIV effects due to electromagnetic and strong interactions – stringent empirical constraints exist*

LIV in beta decay

- *Unexplored domain – papers concentrate on:*
  - *^{3}H decay spectrum anomaly (dispersion relation)*
  - *Double beta decay*
- *Weak interaction can contribute to LIV and unique signals with virtually no "SM background" can be detected:*
  - *J.P. Noordmans, H.W. Wilschut, R.G.E. Timmermans, Phys. Rev. C 87, 055502 (2013)*
- *Tests of Rotational Invariance were attempted for forbidden transitions – daily modulation of decay rate:*
  - *^{90}Y [(R. Newman, PRD 14, 1 (1976)];*
    ^{137}Cs, ^{99}Tc [J.D. Ullman, PRD 17, 1750 (1978)]
    – no modulation found at a level of 10^{-5} – 10^{-6}
  - *reinterpreted by J.P. Noordmans, et al., Phys. Rev. Lett. 111, 171601 (2013) – stringent limits on certain parameter combinations deduced*
  - *^{60}Co, ^{137}Cs [Yu.A. Baurov et al., Mod. Phys. Lett. A16 (2001) 2089]*
    ^{90}Sr [E. Novikov, at al., arXiv:hep-ex/0002057v1]
    – report signal at a level of 10^{-5}

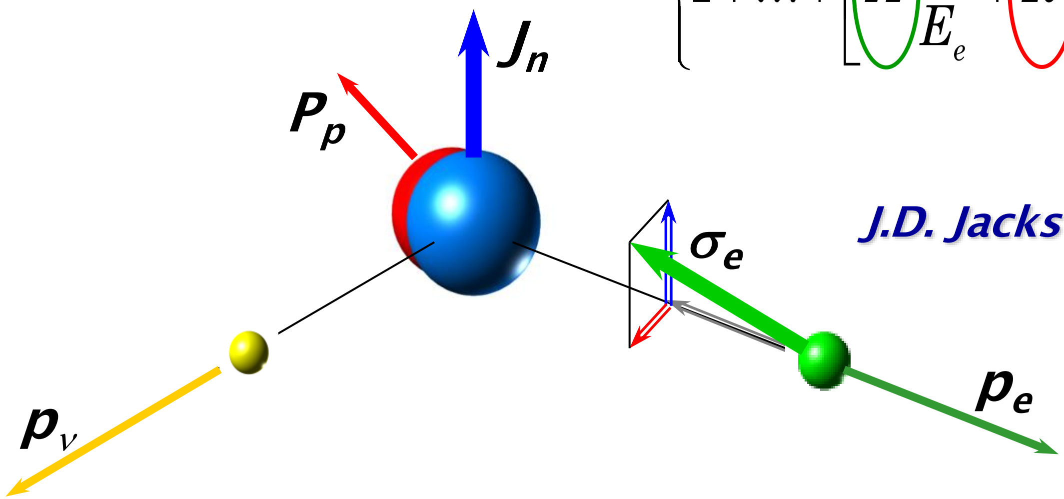
LIV in beta decay

- *Inspired by Gerco Ondervater and Rob Timmermans (KVI, Groningen) we performed purely phenomenological LIV analysis of data collected in the neutron decay experiment (originally searching for Time Reversal Violation in weak interactions) – results published in:*
  - *A. Kozela et al., CPT and Lorentz Symmetry 5, 174, (2011)*
- *Meanwhile, SME parametrization for allowed beta decays became available:*
  - *J.P. Noordmans, H.W. Wilschut, R.G.E. Timmermans, Phys. Rev. C 87, 055502 (2013)*
- *Goal for the present work: interpretation of neutron decay asymmetry in terms of SME parameters*

TRV, transverse electron polarization, electron asymmetry

$$\omega(\langle \mathbf{J}_\mathrm{n} \rangle \sigma \,|\, E_\mathrm{e} \Omega_\mathrm{e}) \cdot dE_\mathrm{e} d\Omega_\mathrm{e}$$

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

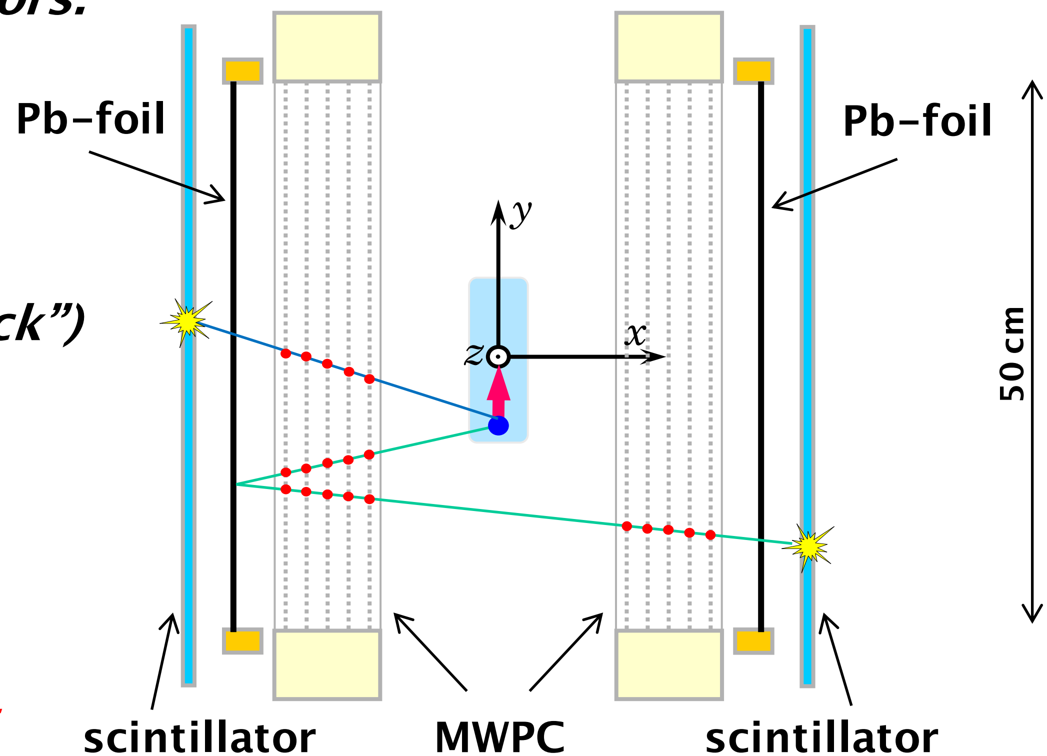


J.D. Jackson et al., Phys. Rev. 106, 517 (1957)

- ***Neutron decay asymmetry parameter A was measured at PSI as a reference for R and N correlation coefficients:***
  - *A. Kozela et al., Phys. Rev. Lett. 102, 172301 (2009).*
  - *A. Kozela et al., Phys. Rev. C 85, 045501 (2012).*

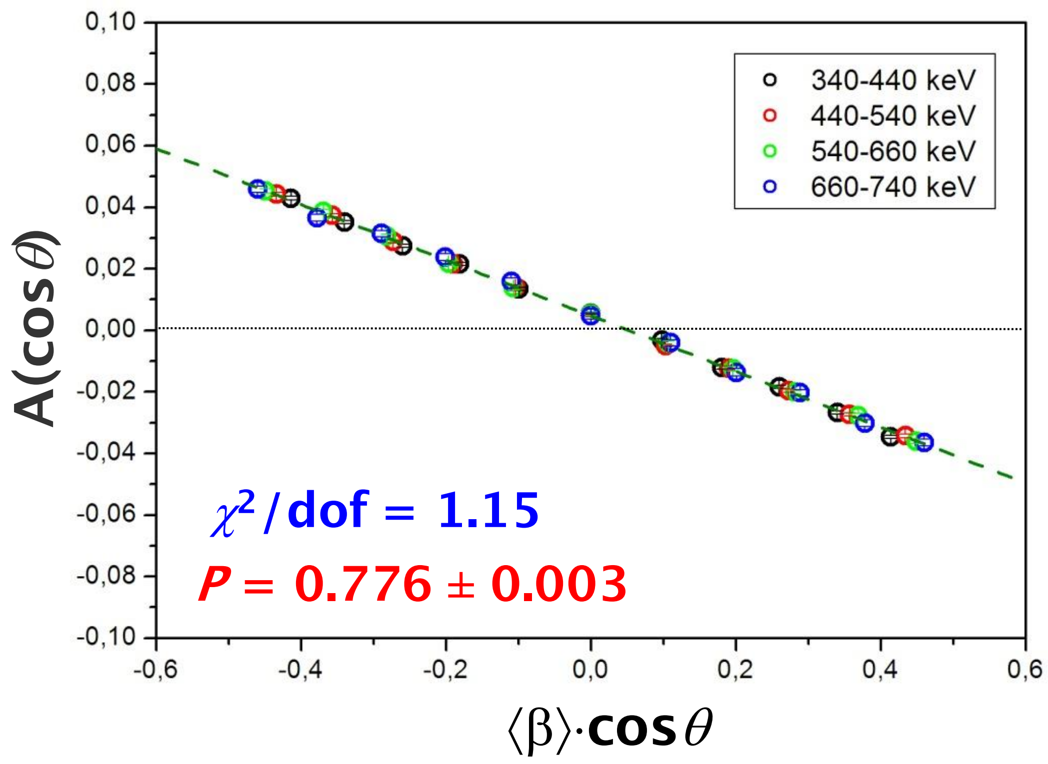
Transverse electron polarization, Mott scattering

- **Difficulties:**
  - *Weak decay source in presence of high background (neutron capture).*
  - *Depolarization of electrons due to multiple Coulomb scattering in Mott target and detectors.*
- **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"*
  - *Average neutron polarization from decay rate asymmetry ("single-track" events)*



Neutron polarization from decay asymmetry

$$\mathcal{A}(\cos\theta) \equiv \frac{W(\gamma,+P)-W(\gamma,-P)}{W(\gamma,+P)-W(\gamma,-P)} = P A_n \langle\beta\rangle \cos\theta$$



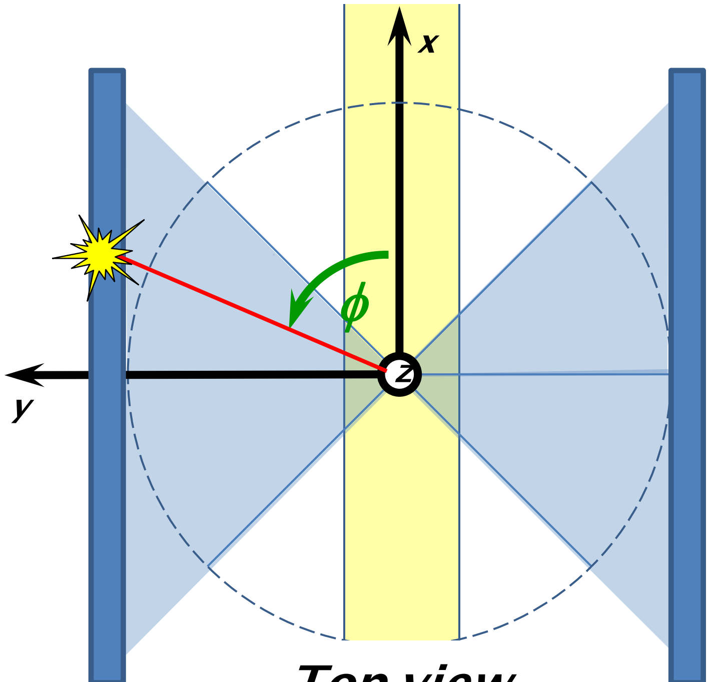
Sidereal modulation ?

Average neutron polarization from decay rate asymmetry ("single-track" events) –

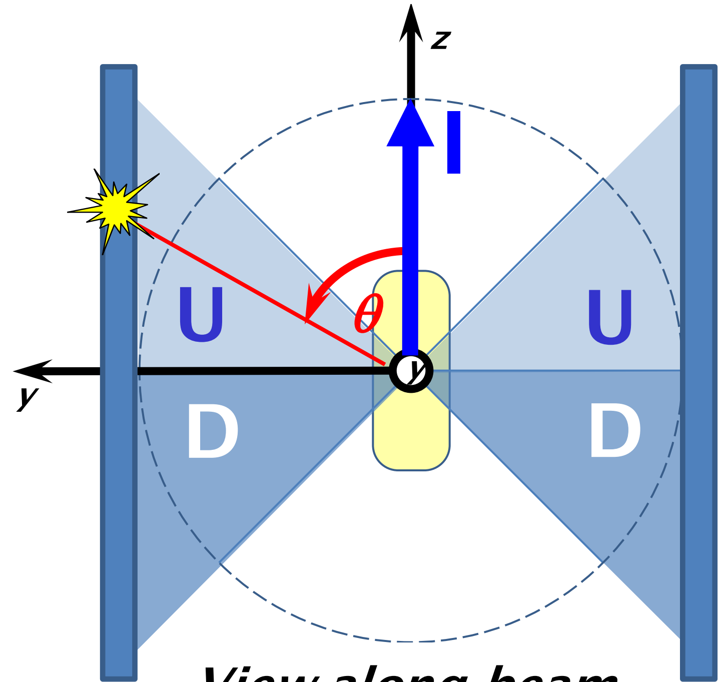
3×10^8 events with fully reconstructed momenta

Grouping of counts

- ***Spin states:***
  - ***"+" – spin UPWARDS, +P***
  - ***"–" – spin DOWNWARDS, -P***
- ***Virtual detector acceptance (integration of events):***
  - ***UPPER ("U"):*** $\pi/4 \le \theta \le 2\pi/4;\ \pi/4 \le \phi \le 3\pi/4,\ 5\pi/4 \le \phi \le 7\pi/4$
  - ***LOWER ("D"):*** $\pi/2 \le \theta \le 3\pi/4;\ \pi/4 \le \phi \le 3\pi/4,\ 5\pi/4 \le \phi \le 7\pi/4$



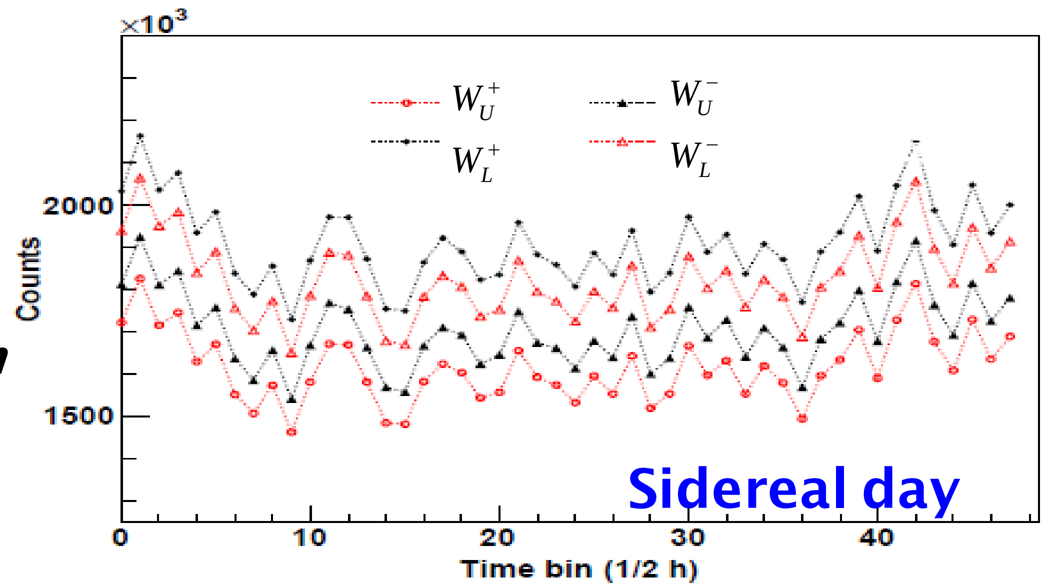
Top view



View along beam

Time series of detector counts

- Time stamps (every second) present in raw data stream
  - Relative accuracy: <1 μs
  - Absolute synchronization to GMT: ±2 s
- Gross bins: 1/48 of Sidereal day
- On border crossings, counts belonging to 1 s long fine bins were split proportionally between neighboring bins
- Measurements performed in subsequent (sidereal) days were folded together
- Instrumental effects:
  - Bin-to-bin fluctuation (correlated)
  - Correlated slow drifts



Parametrization

- *Explicit LIV introduced in the W-boson propagator [J.P. Noordmans, H.W. Wilschut, R.G.E. Timmermans, Phys. Rev. C 87, 055502 (2013)]*

$$\left\langle W^{\mu+}(p) W^{\nu-}(-p) \right\rangle = \frac{-i\left(g^{\mu\nu} + \chi^{\mu\nu}\right)}{M_W^2}$$

$g^{\mu\nu}$ – *Minkowski metric*
$\chi^{\mu\nu}$ – *general LIV tensor (complex, traceless)*

- *Matrix element for allowed β decay*

$$\left|\mathcal{M}\right|^2 = \left| C_V \left\langle 1 \right\rangle J_{\mp}^0 - C_A \left\langle \boldsymbol{\sigma} \right\rangle \right|^2 \cdot \mathbf{J}_{\mp}$$

- *Lepton current with LIV at nucleus center*

$$J_-^\rho = \left(g^{\rho\sigma} + \chi^{\rho\sigma}\right) \bar{\psi}_{e-}(0) \gamma_\sigma \left(1 - \gamma^5\right) \psi_{\bar{\nu}}(0)$$

$$J_+^\rho = \left(g^{\rho\sigma} + \chi^{\rho\sigma *}\right) \bar{\psi}_{\nu}(0) \gamma_\sigma \left(1 - \gamma^5\right) \psi_{e+}(0)$$

Parametrization

- *Differential β-decay rate*

$$dW = \frac{\delta\left(E_e + E_\nu - E_0\right)}{\left(2\pi\right)^5 2E_e 2E_\nu} \sum_{\nu\,\text{spin}} \left|\mathcal{M}\right|^2 d^3p\, d^3k$$

- *Differential rate for polarized neutron decay (measured momentum of outgoing electrons)*

$$dW = dW^0 \left\{1 - 0.21\chi_r^{00} + \left[0.34\chi_r^{0l} + 0.55\left(\chi_r^{l0} + \tilde{\chi}_i^l\right)\right]\frac{p^l}{E_e}\right.$$
$$\left. + \frac{\langle m \rangle}{j}\hat{\mathbf{i}}^k \left[0.43\left(\chi_r^{k0} + \chi_r^{0k}\right) - 0.55\tilde{\chi}_i^k - \left(0.12 - 0.99\chi_r^{00}\right)\frac{p^k}{E_e} - 0.99\left(\chi_r^{lk} - \chi_i^{s0}\varepsilon^{ksl}\right)\frac{p^l}{E_e}\right]\right\}$$

$C_A/C_V = -1.27$ axial vector-to-vector coupling constant ratio
($A = -0.12$ - SM decay electron asymmetry parameter)

Parametrization

- ***For integrated (over detector solid angle) rates substitute:***
  - ***Electron velocity*** $\frac{p^i}{E_e} \to \beta^K \mathcal{F}_i^K, \quad i = x, y, z, \quad K = U, D, L, R$
  - ***Neutron polarization*** $\frac{\langle m \rangle}{j} \hat{\mathbf{I}}^i \to P_i, \quad P_z = P, \quad P_x = P_y = 0$

- ***Kinematical form-factors:***

$$\mathcal{F}_i^K(t) = \int_{\Omega_K} d\Omega\, \hat{\mathrm{p}}^i \rho(\Omega, t) \Big/ \int_{\Omega_K} d\Omega\, \rho(\Omega, t) \qquad K = U, L$$

$$\beta^K(t) = \int_{\Omega_K} d\Omega\, (\mathrm{p}/\mathrm{E})\, \rho(\Omega, t) \Big/ \int_{\Omega_K} d\Omega\, \rho(\Omega, t)$$

$\rho(\Omega, t)$ – ***detector efficiency***

Instrumental effects

- *Detected rate depends on the efficiency function $\rho(\theta,\phi,t)$*
- *$\rho(\theta,\phi,t)$ changes in time due to variations of ambient temperature, pressure etc.*
- *Spin flipping efficiency is <100% (ε = 0.005)*
- *Spin flipping causes additional (small) efficiency modulation (η = 0.0012)*
- *Total efficiencies of LOWER and UPPER detector hemispheres differ slightly (λ = 0.05)*
- ***NO** sidereal modulation is expected in neutron polarization **P** (strong and EM interactions)*

- *Substitutions into integrated count rates:*

$$W_U^{0\pm} \to (1+\lambda)(1\pm\eta)W^0, \quad W_D^{0\pm} \to (1-\lambda)(1\pm\eta)W^0, \quad P^{\pm} \to \pm(1\pm\varepsilon)P$$

Observables

- ***Two observables appear to be useful for extraction of selected χ terms***

$$\mathcal{E}(t)=\frac{\sqrt{W_U^+(t)W_D^+(t)}-\sqrt{W_U^-(t)W_D^-(t)}}{\sqrt{W_U^+(t)W_D^+(t)}+\sqrt{W_U^-(t)W_D^-(t)}},\quad \mathcal{R}(t)=\frac{\sqrt{W_U^+(t)W_U^-(t)}-\sqrt{W_D^+(t)W_D^-(t)}}{\sqrt{W_U^+(t)W_U^-(t)}+\sqrt{W_D^+(t)W_D^-(t)}}$$

- ***W^0 and $\rho_{av}(t)$ – cancel out***
- ***$\chi^{\mu\nu}$, λ, η, ε and $\delta\langle\beta\mathcal{F}_i^K\rangle$ – small parameters***

$$\beta\mathcal{F}_i^U(t)=+\left\langle\beta^{UD}\mathcal{F}_i^{UD}\right\rangle+\delta\left(\beta^{UD}\mathcal{F}_i^{UD}(t)\right);\qquad \beta\mathcal{F}_i^D(t)=-\left\langle\beta^{UD}\mathcal{F}_i^{UD}\right\rangle+\delta\left(\beta^{UD}\mathcal{F}_i^{UD}(t)\right)$$

- ***Taylor expansion (1st order) around mean values with:***

$$\lambda=0.05,\quad \eta=0.0012,\quad \varepsilon=0.005,\quad P=0.78,$$

$$\left\langle\beta^{UD}\mathcal{F}_x^{UD}\right\rangle=-0.01294,\quad \left\langle\beta^{UD}\mathcal{F}_y^{UD}\right\rangle=-0.00745,\quad \left\langle\beta^{UD}\mathcal{F}_z^{UD}\right\rangle=+0.27548,$$

$$\delta\left(\beta^{UD}\mathcal{F}_x^{UD}\right)=-0.00549,\quad \delta\left(\beta^{UD}\mathcal{F}_y^{UD}\right)=+0.01478,\quad \delta\left(\beta^{UD}\mathcal{F}_z^{UD}\right)=+0.01681$$

- ***2nd order corrections smaller by two orders of magnitude***

Observables

- ***Resulting dependence on $\chi^{\mu\nu}$ in LAB (neglected terms with coefficients <10⁻³):***

$$\mathcal{E}(t) = -0.01a_z + 0.78b_0, \qquad \mathcal{R}(t) = 0.05 - 0.01a_x - 0.01a_y + 0.28a_z + 0.02b_0$$

$$a_x = 0.55\left(\chi_r^{x0} + \chi_i^{yz} - \chi_i^{zy}\right), \quad a_y = 0.55\left(\chi_r^{y0} + \chi_i^{zx} - \chi_i^{xz}\right), \quad a_z = 0.55\left(\chi_r^{z0} + \chi_i^{xy} - \chi_i^{yx}\right),$$

$$b_0 = 0.43\left(\chi_r^{z0} - \chi_r^{0z}\right) - 0.55\left(\chi_i^{xy} - \chi_i^{yx}\right)$$

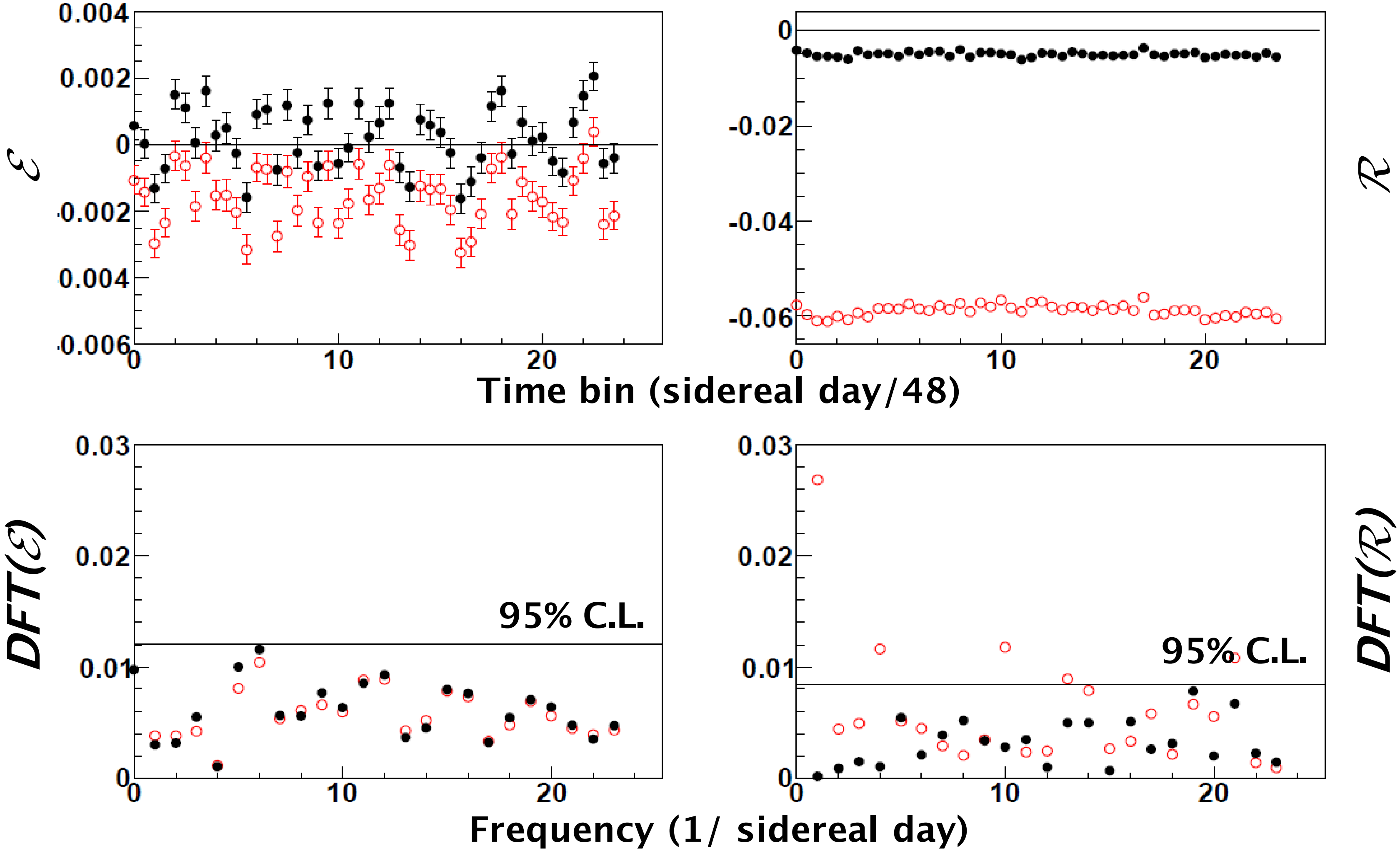
- ***Transforming to Sun-centered reference frame:***

$$\mathcal{E}(t) = -0.23X_r^{TZ} + 0.23X_r^{ZT} + \left[-0.31\left(X_i^{YZ} - X_i^{ZY}\right) + 0.25\left(X_r^{XT} - X_r^{TX}\right)\right]\cos(\Omega t)$$
$$+\left[+0.31\left(X_i^{XZ} - X_i^{ZX}\right) + 0.25\left(X_r^{YT} - X_r^{TY}\right)\right]\sin(\Omega t)$$

$$\mathcal{R}(t) = 0.05 - 0.01X_r^{TZ} + 0.12X_r^{ZT}\left[+0.10\left(X_i^{YZ} - X_i^{ZY}\right) - 0.01X_r^{TX} + 0.12X_r^{XT}\right]\cos(\Omega t)$$
$$+\left[-0.10\left(X_i^{XZ} - X_i^{ZX}\right) - 0.01X_r^{TX} + 0.12X_r^{XT}\right]\sin(\Omega t)$$

Ω – sidereal day ($23^h 56^m 04^s$), latitude of PSI – 47.52°

Isolation of instrumental effects



o – raw data, • – after instrumental corrections

Limits on sidereal modulations

- ***Frequentists confidence level analysis: probability distribution of a given signal hypothesis:***
  (A – modulation amplitude, Φ – modulation phase)

$$\chi^2_{sig} = \frac{1}{N}\sum\left[\frac{r_i - A\sin\left(\Omega t_i + \Phi\right)}{\Delta r_i}\right]^2$$

compared with prob. distr. of null hypothesis (A=0,Φ)

- ***Confidence level of a given hypothesis (A,Φ)***

$$L\left(A,\Phi\right) = \int_{-\infty}^{\chi^2_{data}} q_{sig}\left(\chi^2\right) d\chi^2$$

- ***Probability distributions q(A,Φ) from MC***

Results

- *Only time dependent terms can be constrained*
- *Phase of the sidereal day with respect to Sun-centered reference frame was not controlled – amplitudes of sin(Ωt) and cos(Ωt) set equal:*

$$C_E = S_E = A = 3.2\times10^{-3}, \quad C_R = S_R = A = 1.9\times10^{-3} \quad (95\%\,\mathrm{CL})$$

$$\left|-0.31\left(X_i^{YZ} - X_i^{ZY}\right) + 0.25\left(X_r^{XT} - X_r^{TX}\right)\right| < C_E = 3.2\times10^{-3}$$

$$\left|+0.31\left(X_i^{XZ} - X_i^{ZX}\right) + 0.25\left(X_r^{YT} - X_r^{TY}\right)\right| < S_E = 3.2\times10^{-3}$$

$$\left|+0.10\left(X_i^{YZ} - X_i^{ZY}\right) - 0.01 X_r^{TX} + 0.12 X_r^{XT}\right| < C_R = 1.9\times10^{-3}$$

$$\left|-0.10\left(X_i^{XZ} - X_i^{ZX}\right) - 0.01 X_r^{TX} + 0.12 X_r^{XT}\right| < S_R = 1.9\times10^{-3}$$

$$\left|+0.62 X_r^{XT} - 0.28 X_r^{TX}\right| < C_E + 3C_R$$

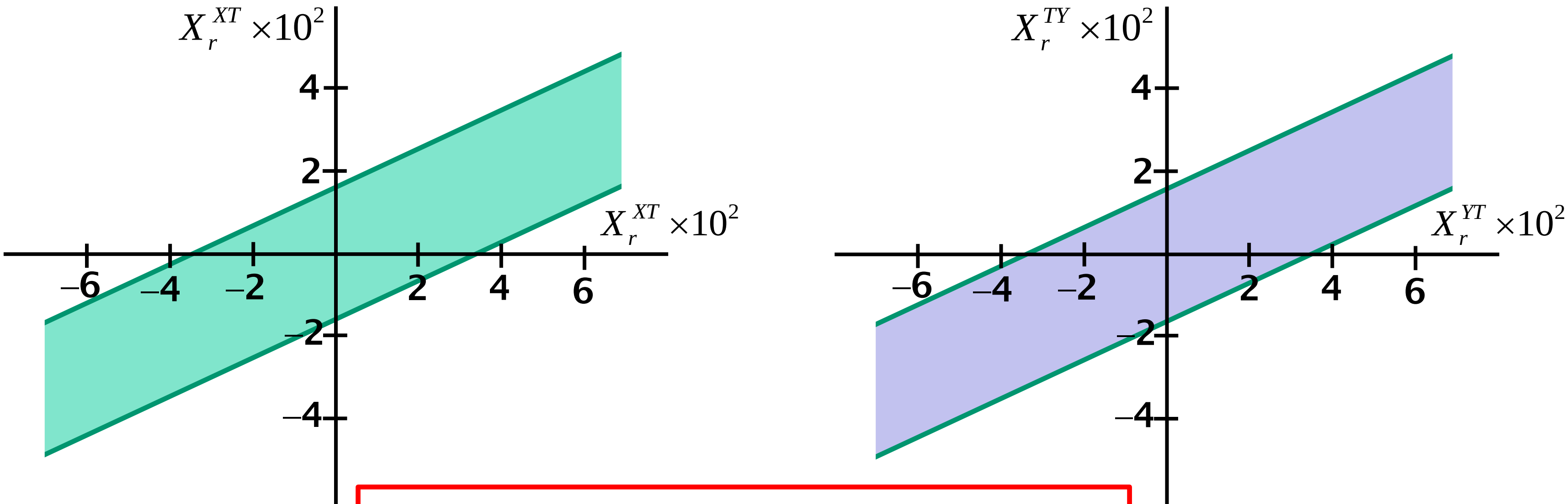
$$\left|+0.62 X_r^{YT} - 0.28 X_r^{TY}\right| < S_E + 3S_R$$

$$\left|+0.62 X_r^{XT} - 0.28 X_r^{TX}\right| < 0.9\times10^{-2}$$

$$\left|+0.62 X_r^{YT} - 0.28 X_r^{TY}\right| < 0.9\times10^{-2}$$

Results

- *Allowed values of X_r^{TX}, X_r^{XT}, X_r^{TY}, X_r^{YT}*



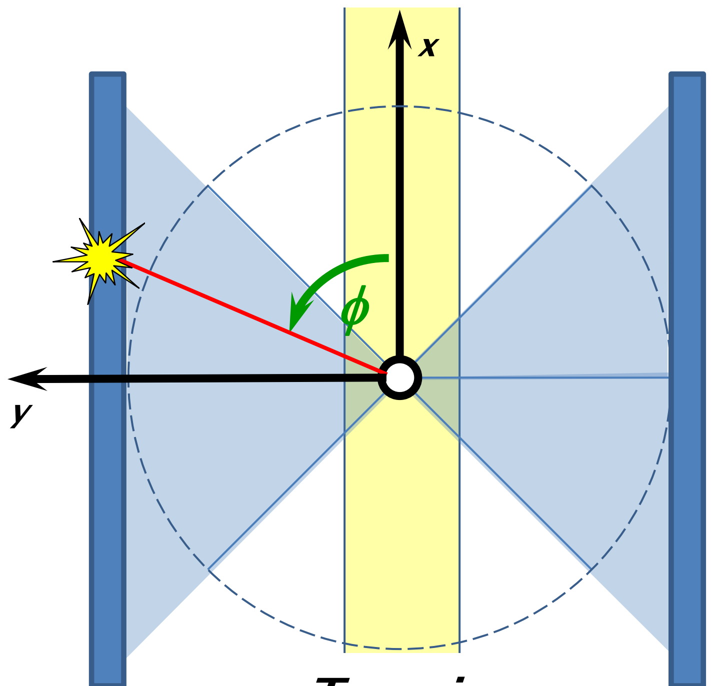
$$\left| +0.62 X_r^{XT} - 0.28 X_r^{TX} \right| < 0.9 \times 10^{-2}$$

$$\left| +0.62 X_r^{YT} - 0.28 X_r^{TY} \right| < 0.9 \times 10^{-2}$$

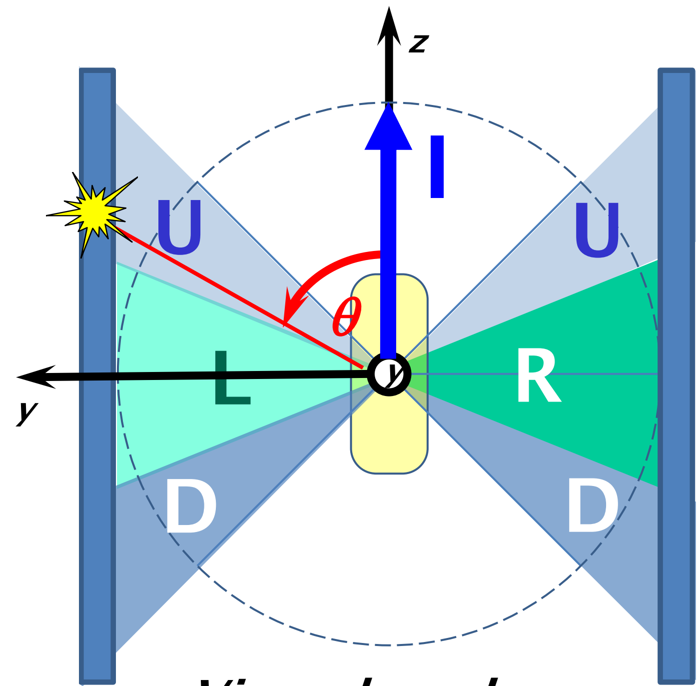
- ***Drawback**: $\mathcal{E}(t)$ and $\mathcal{R}(t)$ are not independent – derived from the same event set $\Rightarrow$ **limits could be biased***

New grouping of counts

- ***Virtual detector acceptance (integration of events):***
  - ***UPPER ("U"):*** $2\pi/8 \le \theta \le 3\pi/8;\ \pi/4 \le \phi \le 3\pi/4,\ 5\pi/4 \le \phi \le 7\pi/4$
  - ***LOWER ("D"):*** $5\pi/8 \le \theta \le 6\pi/8;\ \pi/4 \le \phi \le 3\pi/4,\ 5\pi/4 \le \phi \le 7\pi/4$
  - ***LEFT ("L"):*** $3\pi/8 \le \theta \le 5\pi/8;\ \pi/4 \le \phi \le 3\pi/4$
  - ***RIGHT ("R"):*** $3\pi/8 \le \theta \le 5\pi/8;\ 5\pi/4 \le \phi \le 7\pi/4$



Top view



View along beam

Observables

- *Two observables constructed from independent event groups*

$$\mathcal{E}(t)=\frac{\sqrt{W_L^+(t)W_R^+(t)}-\sqrt{W_L^-(t)W_R^-(t)}}{\sqrt{W_L^+(t)W_R^+(t)}+\sqrt{W_L^-(t)W_R^-(t)}},\quad \mathcal{R}(t)=\frac{\sqrt{W_U^+(t)W_U^-(t)}-\sqrt{W_D^+(t)W_D^-(t)}}{\sqrt{W_U^+(t)W_U^-(t)}+\sqrt{W_D^+(t)W_D^-(t)}}$$

$$\beta^K\mathcal{F}_i^K(t)=+\left\langle\beta^{KM}\mathcal{F}_i^{KM}\right\rangle+\delta\left(\beta^{KM}\mathcal{F}_i^{KM}(t)\right);\qquad K=U,L$$

$$\beta^M\mathcal{F}_i^M(t)=-\left\langle\beta^{KM}\mathcal{F}_i^{KM}\right\rangle+\delta\left(\beta^{KM}\mathcal{F}_i^{KM}(t)\right);\qquad M=D,R$$

- *Taylor expansion (1st order) around mean values with:*
  - $\lambda=0.05,\quad \eta=0.0012,\quad \varepsilon=0.005,\quad P=0.78$ ***and***
  - $\mathcal{E}(t)$: $\left\langle\beta^{LR}\mathcal{F}_x^{LR}\right\rangle=-0.01541,\quad \left\langle\beta^{LR}\mathcal{F}_y^{LR}\right\rangle=+0.76243,\quad \left\langle\beta^{LR}\mathcal{F}_z^{LR}\right\rangle=-0.03845,$
    $\delta\left(\beta^{LR}\mathcal{F}_x^{LR}\right)=-0.00630,\quad \delta\left(\beta^{LR}\mathcal{F}_y^{LR}\right)=+0.00610,\quad \delta\left(\beta^{LR}\mathcal{F}_z^{LR}\right)=+0.00109$
  - $\mathcal{R}(t)$: $\left\langle\beta^{UD}\mathcal{F}_x^{UD}\right\rangle=-0.01926,\quad \left\langle\beta^{UD}\mathcal{F}_y^{UD}\right\rangle=-0.01746,\quad \left\langle\beta^{UD}\mathcal{F}_z^{UD}\right\rangle=+0.40972,$
    $\delta\left(\beta^{UD}\mathcal{F}_x^{UD}\right)=-0.00273,\quad \delta\left(\beta^{UD}\mathcal{F}_y^{UD}\right)=+0.00755,\quad \delta\left(\beta^{UD}\mathcal{F}_z^{UD}\right)=-0.00043$

Final results

- *Only time dependent terms can be constrained*
- *Phase of the sidereal day with respect to Sun-centered reference frame was not controlled – amplitudes of sin(Ωt) and cos(Ωt) set equal:*

$$C_E = S_E = A = 3.0\times10^{-3},\quad C_R = S_R = A = 3.7\times10^{-3}\quad (95\%\ \mathrm{CL})$$

$$\left|-0.32\left(X_i^{YZ} - X_i^{ZY}\right) + 0.25\left(X_r^{XT} - X_r^{TX}\right)\right| < C_E = 3.7\times10^{-3}$$

$$\left|+0.32\left(X_i^{XZ} - X_i^{ZX}\right) + 0.25\left(X_r^{YT} - X_r^{TY}\right)\right| < S_E = 3.7\times10^{-3}$$

$$\left|+0.15\left(X_i^{YZ} - X_i^{ZY}\right) + 0.17 X_r^{XT}\right| < C_R = 3.0\times10^{-3}$$

$$\left|-0.15\left(X_i^{XZ} - X_i^{ZX}\right) + 0.17 X_r^{YT}\right| < S_R = 3.0\times10^{-3}$$

$$\left|+0.61 X_r^{XT} - 0.25 X_r^{TX}\right| < C_E + 2.13 C_R$$

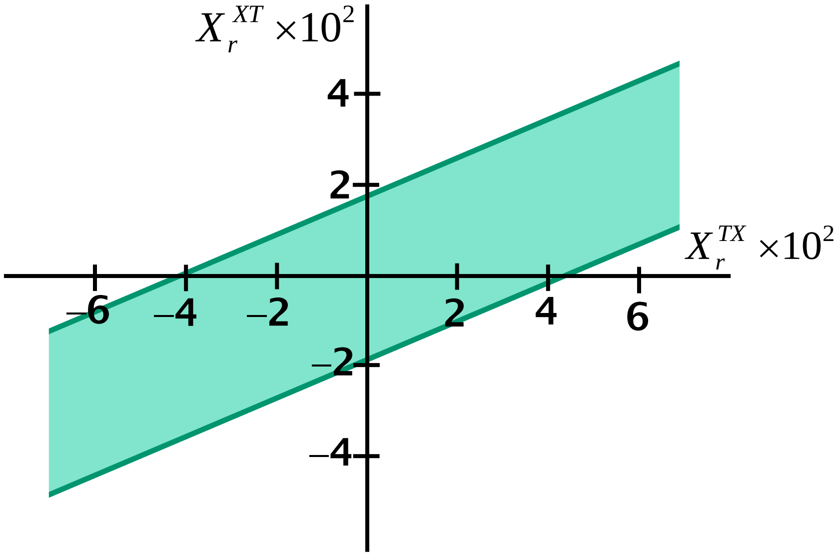
$$\left|+0.61 X_r^{YT} - 0.25 X_r^{TY}\right| < S_E + 2.13 S_R$$

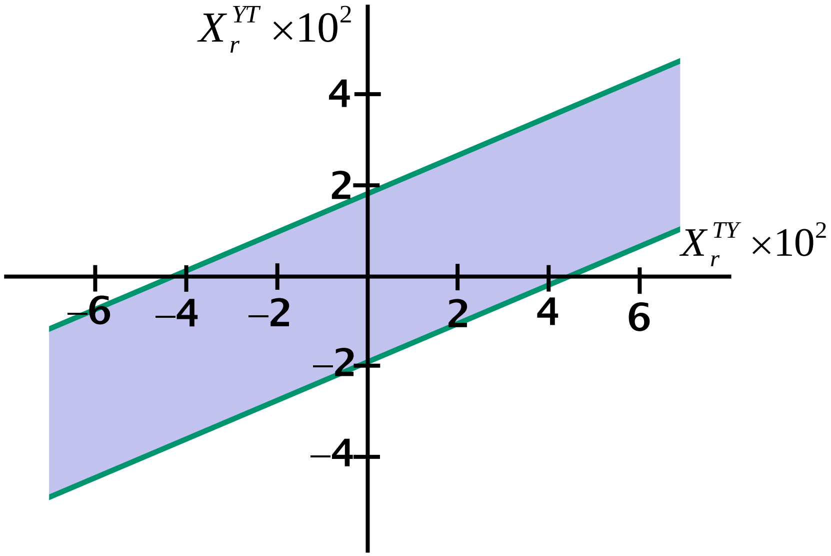
$$\left|+0.61 X_r^{XT} - 0.25 X_r^{TX}\right| < 1.1\times10^{-2}$$

$$\left|+0.61 X_r^{YT} - 0.25 X_r^{TY}\right| < 1.1\times10^{-2}$$

Final results

- *Allowed values of X_r^{TX}, X_r^{XT}, X_r^{TY}, X_r^{YT}*





$$\left| +0.61 X_r^{XT} - 0.25 X_r^{TX} \right| < 1.1 \times 10^{-2}$$

$$\left| +0.61 X_r^{YT} - 0.25 X_r^{TY} \right| < 1.1 \times 10^{-2}$$

Conclusions and outlook

- *Very few tests of Lorentz Invariance in weak interactions exist*
- *Old experiments reporting LIV signal in beta decay remain unconfirmed*
- *Preferable forbidden transitions – offer higher sensitivity*
- *Reinterpretation of old experiments:*
  - ^{90}Y *[R. Newman, PRD 14, 1 (1976)];*
  - ^{137}Cs, ^{99}Tc *[J.D. Ullman, PRD 17, 1750 (1978)]*

J.P. Noordmans, et al., Phys. Rev. Lett. 111, 171601 (2013)

$$\chi^{\mu\nu} = -k_{\phi\phi}^{\mu\nu} - ik_{\phi W}^{\mu\nu}/2g$$

$$-5 \times 10^{-9} < (k_{\phi\phi}^{S})^{ZT}, (k_{\phi\phi}^{A})^{YX}, (k_{\phi W})^{YX} < 1 \times 10^{-8},$$
$$-1 \times 10^{-6} < (k_{\phi\phi}^{S})^{ZZ} < 4 \times 10^{-7},$$
$$-1 \times 10^{-6} < (k_{\phi\phi}^{S})^{TT} < 3 \times 10^{-6},$$
$$|(k_{\phi\phi}^{S})^{XX}|, |(k_{\phi\phi}^{S})^{YY}| < 1 \times 10^{-6},$$
$$|(k_{\phi\phi}^{S})^{XT}|, |(k_{\phi\phi}^{S})^{YT}|, |(k_{\phi\phi}^{A})^{XZ}|, |(k_{\phi\phi}^{A})^{YZ}|, |(k_{\phi W})^{XZ}|, |(k_{\phi W})^{YZ}| < 2 \times 10^{-8},$$
$$|(k_{\phi\phi}^{S})^{XY}|, |(k_{\phi\phi}^{S})^{XZ}|, |(k_{\phi\phi}^{S})^{YZ}| < 5 \times 10^{-7}.$$

Conclusions and outlook (cont.)

- ***Dedicated new experiments: e.g. S.E. Müller et al., Phys. Rev. D 88, 071901(R) – decay rate asymmetry of spin polarized ^{20}Na nuclei – deduced constrains***

Coefficient	Value	95% C.L. interval
$\xi_2 N^1$	$(-12 \pm 9) \times 10^{-4}$	$[-29, +6] \times 10^{-4}$
$\xi_2 N^2$	$(-3 \pm 8) \times 10^{-4}$	$[-19, +14] \times 10^{-4}$
$\tilde{X}_i^1$	$2(k_{\phi\phi}^A)^{32} + \frac{1}{g}(k_{\phi W})^{32}$	$[-9, +2] \times 10^{-3}$
$\tilde{X}_i^2$	$2(k_{\phi\phi}^A)^{13} + \frac{1}{g}(k_{\phi W})^{13}$	$[-6, +4] \times 10^{-3}$

- ***Constraints for 32 weak interaction SME parameters needed !***
- ***Non-dedicated ongoing and new beta decay experiments are important !***
  - ***Search for sidereal modulations (SME parameters related to rotational invariance)***
  - ***Time stamping of data,***

Conclusions and outlook (cont.)

- ***Allowed transition selection***

  J.P. Noordmans, et al., Phys. Rev. C 87, 055502 (2013):

		χ_r^{00}	χ_r^{0l}	χ_r^{ml}	χ_i^{0l}	χ_i^{ml}	χ_i^{00}	χ_r^{l0}	χ_i^{l0}	Comments
t		X								
w_1	$\hat{k}$		F			GT		GT		$\chi_i^{(ml)}$ not accessible.
w_2	$\hat{I}$		M			GT			M	If $\chi_r^{[\mu\nu]} = 0$, χ_r^{0k} cancels χ_r^{k0}. $\chi_i^{(ml)}$ not accessible.
w_3	$\hat{p}$		F			GT		GT		$\chi_i^{(ml)}$ not accessible.
T_1	$\hat{I}^*$			GT						Vanishes for $j = \frac{1}{2}$
T_2	$\hat{I}, \hat{k}$	GT		GT	M				GT	
T_3	$\hat{p}, \hat{k}$	X		GT	F				GT	$\chi_r^{[ml]}$ not accessible.
T_4	$\hat{p}, \hat{I}$	GT		GT	M				GT	
S_1	$\hat{I}^*, \hat{k}$					GT		GT		Vanishes for $j = \frac{1}{2}$
S_2	$\hat{p}, \hat{k}$					GT		GT		Vanishes for $j = \frac{1}{2}$
S_3	$\hat{p}, \hat{I}, \hat{k}$		M			GT	M	GT		
R	$\hat{p}, \hat{I}^*, \hat{k}$			GT					GT	Vanishes for $j = \frac{1}{2}$

- ***LIV relevant directions:***
  - *Parent spin*
  - *Electron momentum*
  - *Neutrino (recoil) momentum*

Conclusions and outlook (cont.)

- *Neutron beta decay correlation experiments: PERC, Nab, abBA, aSPECT, aCORN, emiT, UCNA/UCNB, etc. should look for LIV*
- *Given parametrization of LIV signal and detector capable to reconstruct momenta, we propose a method to eliminate fake instrumental effects in a controlled way*
- *BRAND – proposal of an experiment to measure (simultaneously) 11 correlation coefficients in neutron decay – 5 never attempted before [K. Bodek, et al., Physics Procedia 17 (2011) 30–39]*

$$\omega(E_e,\Omega_e,\Omega_{\bar\nu}) \propto 1 + \boxed{a}\frac{\mathbf{p}_e\cdot\mathbf{p}_{\bar\nu}}{E_eE_{\bar\nu}} + b\frac{m_e}{E_e} + \frac{\langle\mathbf{J}\rangle}{J}\cdot\left[\boxed{A}\frac{\mathbf{p}_e}{E_e} + \boxed{B}\frac{\mathbf{p}_{\bar\nu}}{E_{\bar\nu}} + \boxed{D}\frac{\mathbf{p}_e\times\mathbf{p}_{\bar\nu}}{E_eE_{\bar\nu}}\right]$$

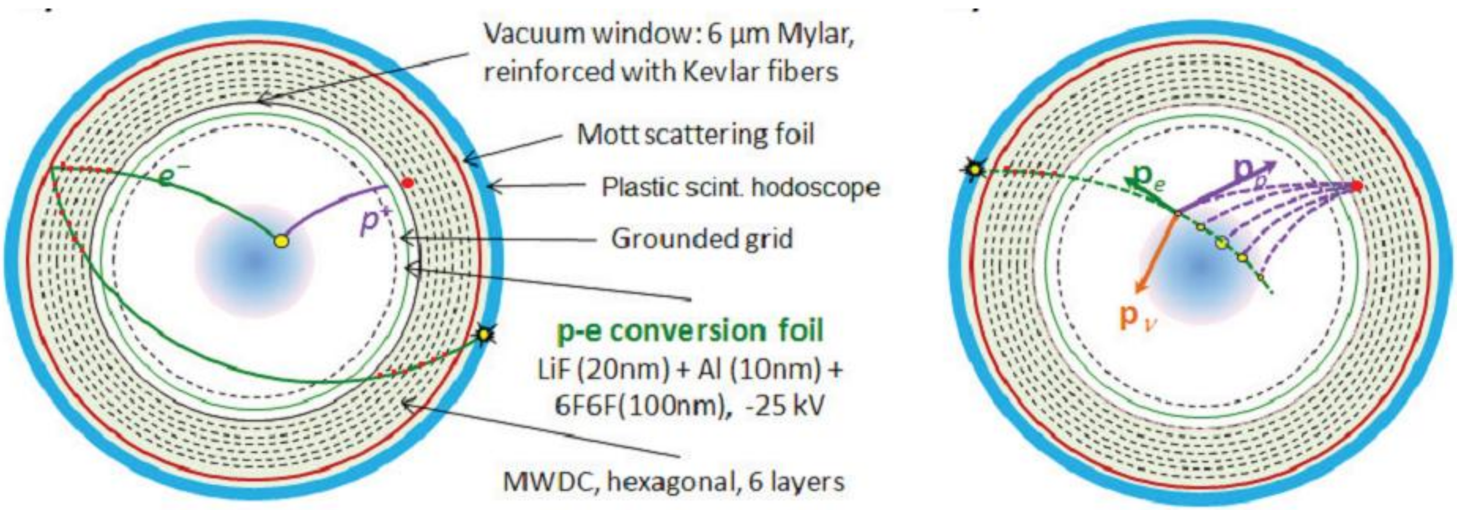
$$+ \sigma_\perp\cdot\left[\boxed{H}\frac{\mathbf{p}_{\bar\nu}}{E_{\bar\nu}} + \boxed{L}\frac{\mathbf{p}_e\times\mathbf{p}_{\bar\nu}}{E_eE_{\bar\nu}} + \boxed{N}\frac{\langle\mathbf{J}\rangle}{J} + \boxed{R}\frac{\langle\mathbf{J}\rangle\times\mathbf{p}_e}{J\,E_e} + \boxed{S}\frac{\langle\mathbf{J}\rangle}{J}\frac{\mathbf{p}_e\cdot\mathbf{p}_{\bar\nu}}{E_eE_{\bar\nu}} + \boxed{U}\mathbf{p}_{\bar\nu}\frac{\langle\mathbf{J}\rangle\cdot\mathbf{p}_e}{J\,E_eE_{\bar\nu}} + \boxed{V}\frac{\mathbf{p}_{\bar\nu}\times\langle\mathbf{J}\rangle}{J\,E_{\bar\nu}}\right]$$

- *Devoted mainly to scalar and tensor couplings but …*

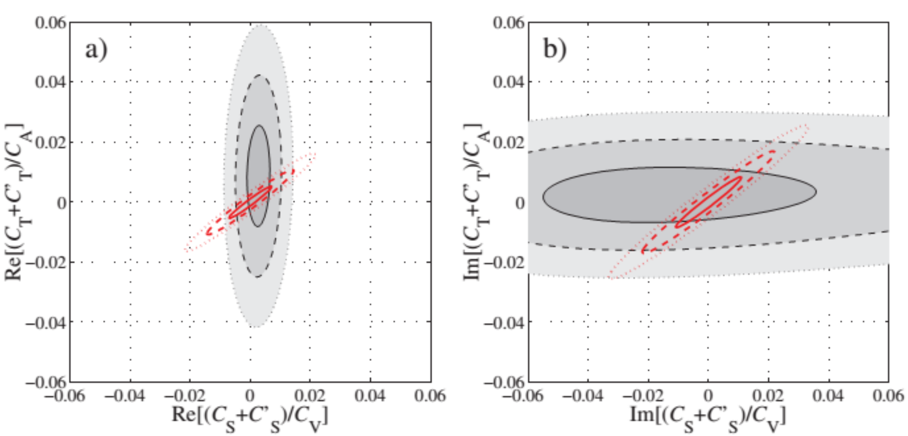
… would also look for LIV !

Conclusions and outlook (cont.)

- *Scheme of BRAND*



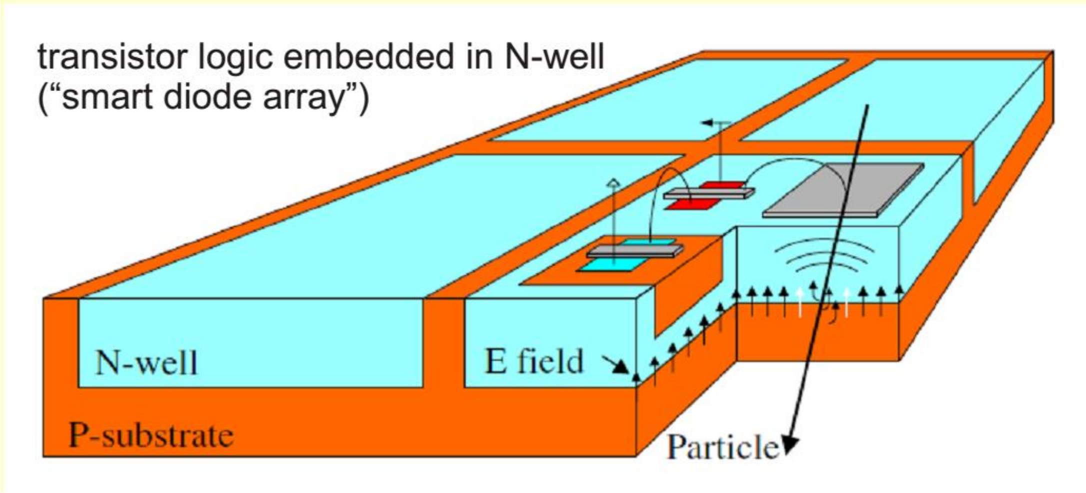
Longitudinal neutron polarization; axial guiding field $B = 0.1 \div 0.5$ mT



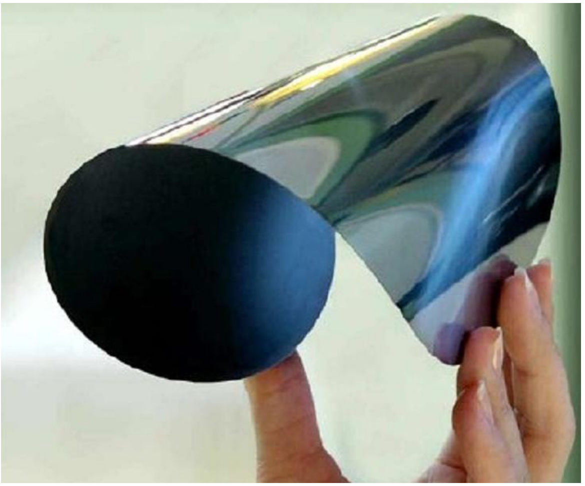
- ***Difficulties:***
  - *Vacuum window (~2 m²)*
  - *2 m long, parallel CN beam*
  - *p-e conversion foil (~2 m²)*
  - *Low pressure (~100 mbar) MWDC*

Conclusions and outlook (cont.)

- ***Progress in Si-pixel detectors:***
  - *HV-MAPS [I. Peric, P. Fischer et al., NIM A 582 (2007) 876]*
  - *High position resolution (pixels 20×20 μm²)*
  - *Thickness 35 μm – can be thinned down to 25 μm (I. Peric, priv. comm.)*
  - *Small R/O bandwidth (active sensors), triggerless, LVDS link integrated*
  - *Low power dissipation – 7 μW/pixel*
  - *Low production costs (standard HV-CMOS process, 60-80 V) – 75 k€/m²*
  - *Mu3e Collaboration at PSI follows this track*

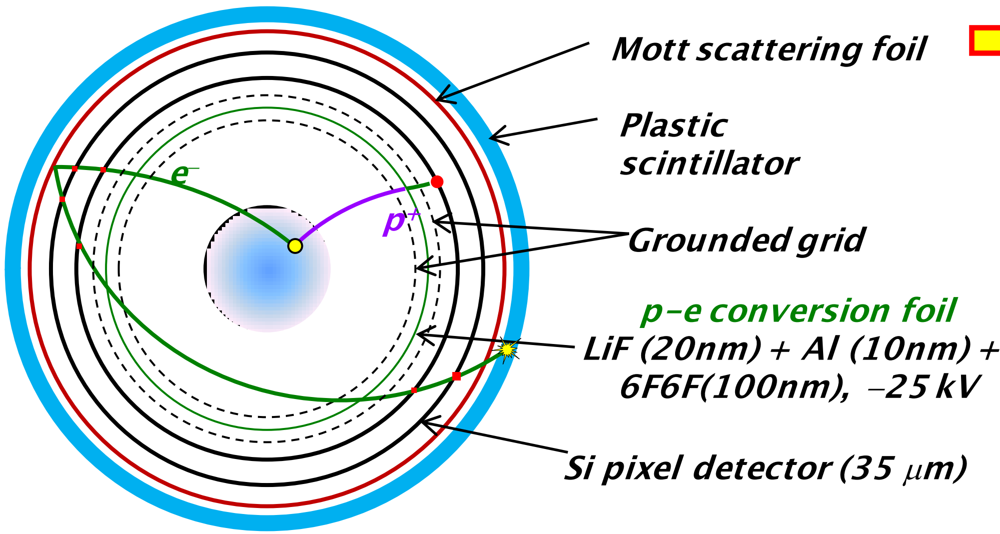


50 μm thick Si wafer



Conclusions and outlook (cont.)

- *Idea: replace MWDC with two layers of HV-MAPS*



All four intrinsic difficulties of BRAND setup – relaxed

- *Anticipated dimensions:*
  - Length: ~30÷50 cm
  - Outer diameter: ~30 cm
  - Pixel det. diam.: ~15÷20 cm
- *Feasible electron energy threshold:*
  - 150 keV for direct electrons
  - 250 keV for Mott scattered electrons
- *Within 6 months of data taking:*
  - 10^{12} direct electrons (A coefficient)
  - 3×10^{11} e–p coincidences (a, B, D coefficients)

Could improve current limits from neutron decay by at least two orders and constrain new SME parameter combinations

K. Bodek[1], A. Kozela[2], G. Ban[4], A. Białek[2#], P. Gorel[4,3,1#], K. Kirch[3,7], St. Kistryn[1], M. Kuźniak[1,3*], O. Naviliat-Cuncic[4,8], N. Severijns[5], E. Stephan[6] and J. Zejma[1]

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(*) Presently at Queen's University, Kingston, Canada

Backup slides

FUNSPIN – Polarized Cold Neutron Facility at PSI

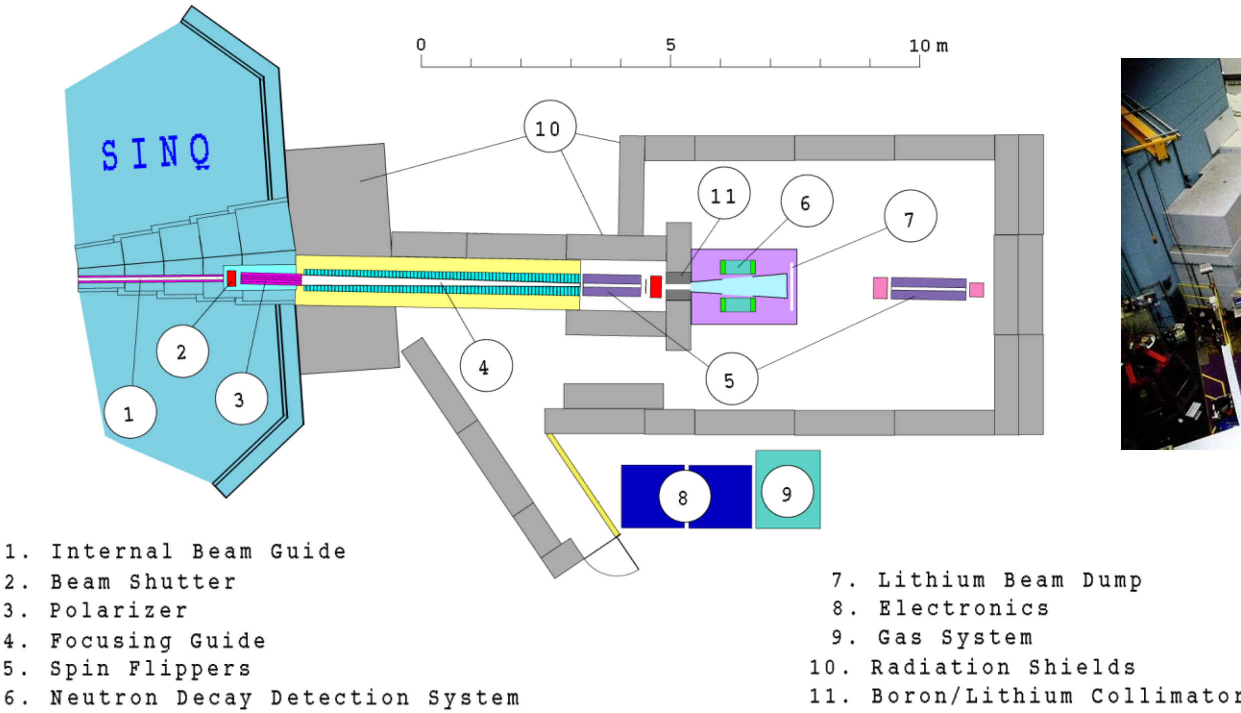
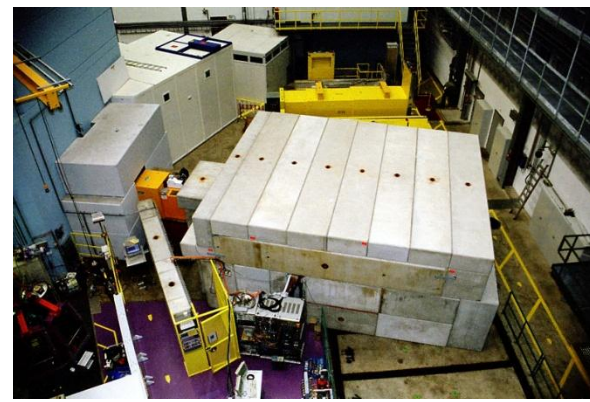


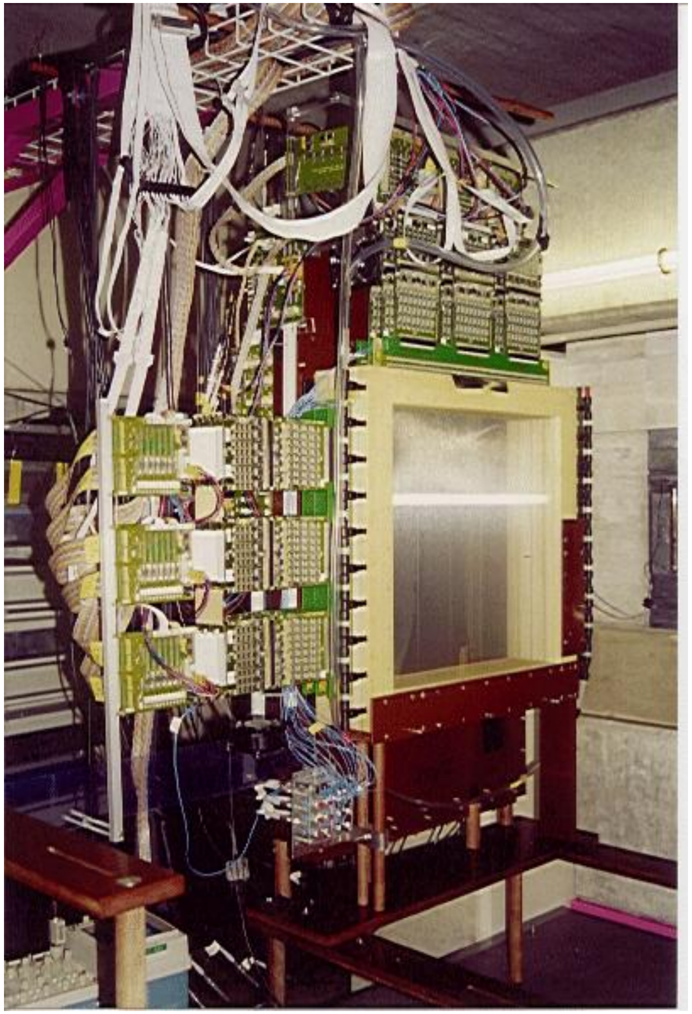
Figure 4: Layout of the Polarized Cold Neutron Facility at PSI.

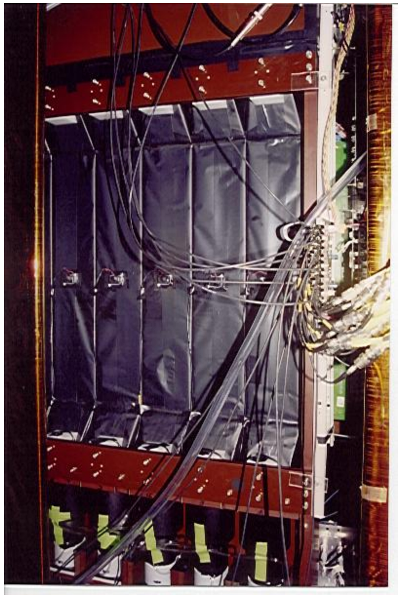


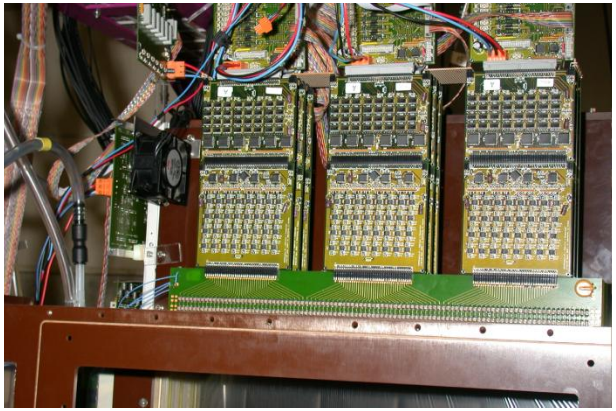
$$I_n \simeq 10^{10}\,\mathrm{s}^{-1}$$

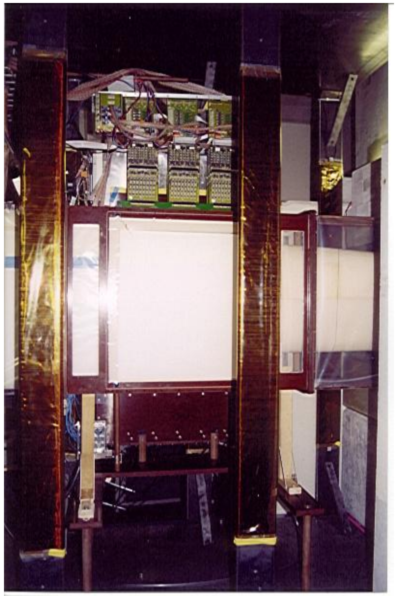
$$P_n \simeq 80\%$$

MWPCs, scintillators and electronics

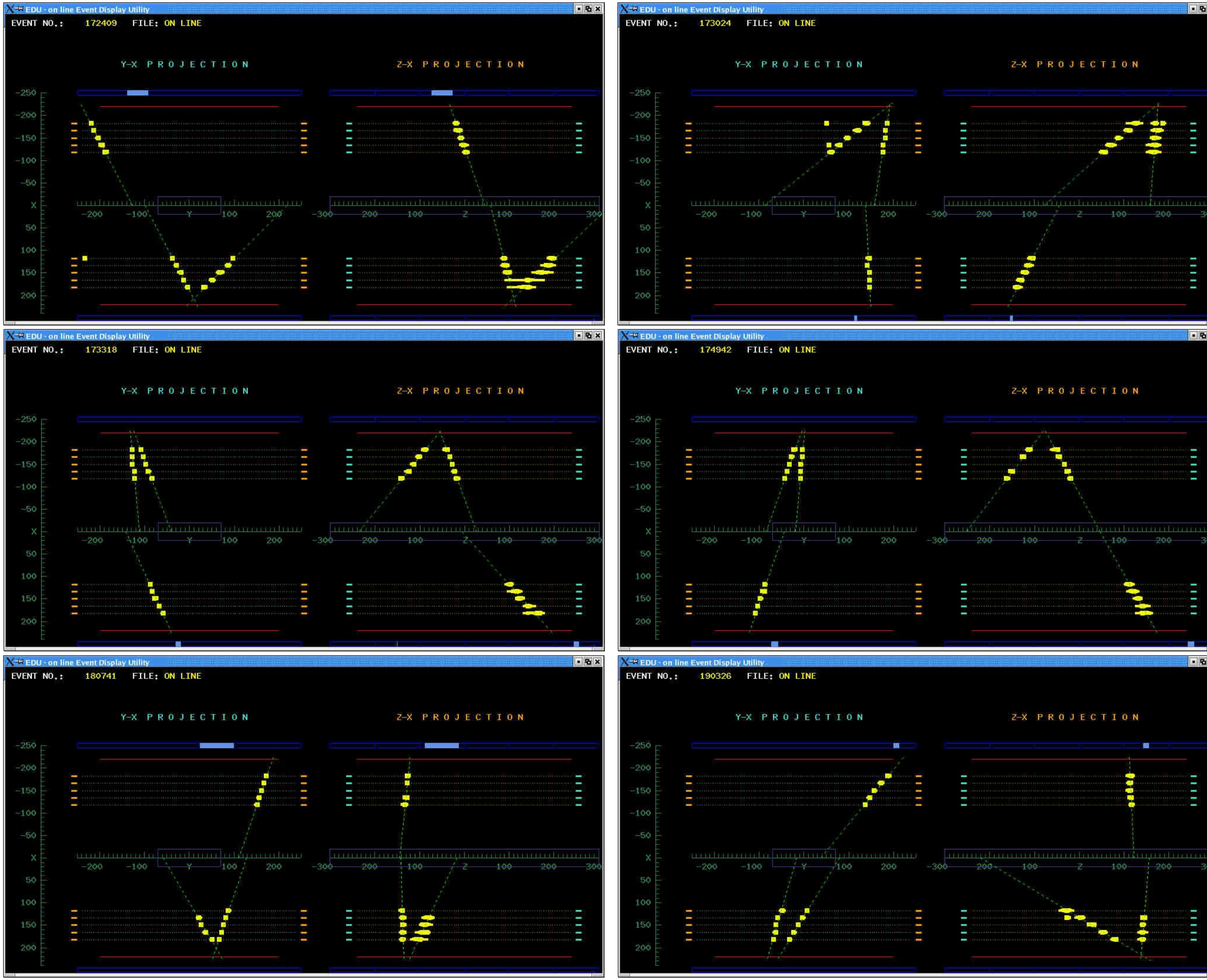








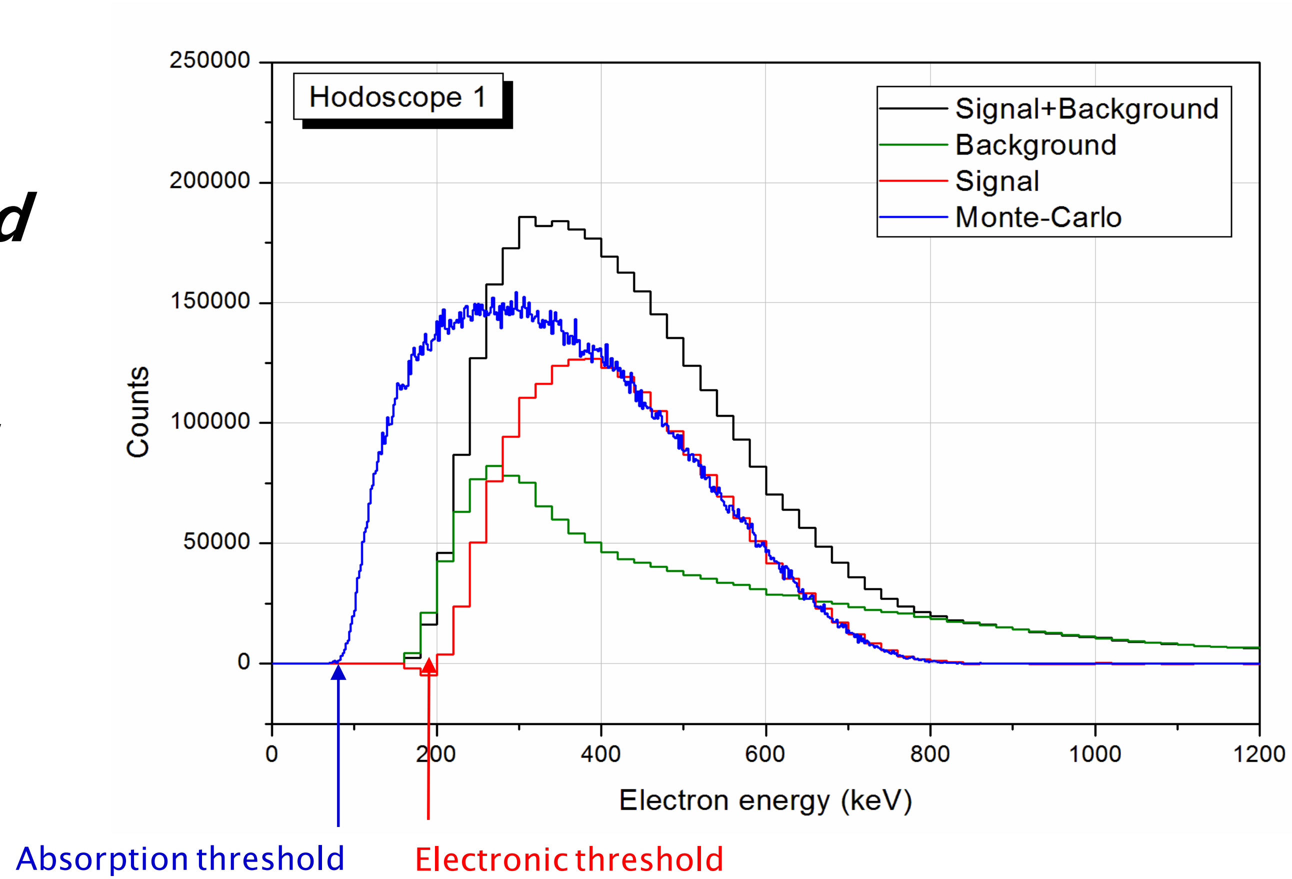
"V-track" events - on-line display



Electron energy spectrum

- ***3×10⁸ reconstructed momenta of decay electrons***

- ***Background measured and subtracted***



Energy calibration

- ***Conversion electrons from ^{207}Bi***