*a*SPECT: Measurements of Correlation Coefficients in Neutron Decay

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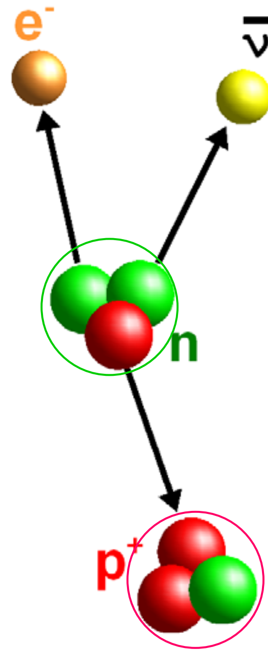
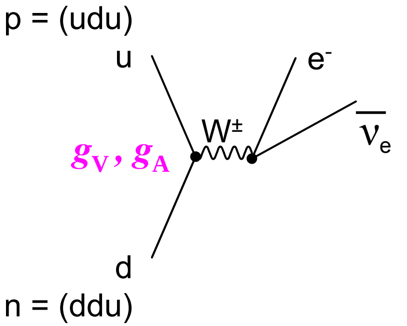
- Contributions to the Standard Model
  - Neutron Beta Decay Correlations
  - The Neutron Decay Spectrometer *a*SPECT
- Searches for physics beyond the Standard Model
  - Scalar and Tensor Currents
  - The Proton Asymmetry and Right-handed Currents



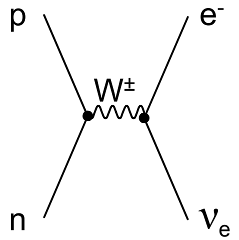
Coupling Constants of the Weak Interaction

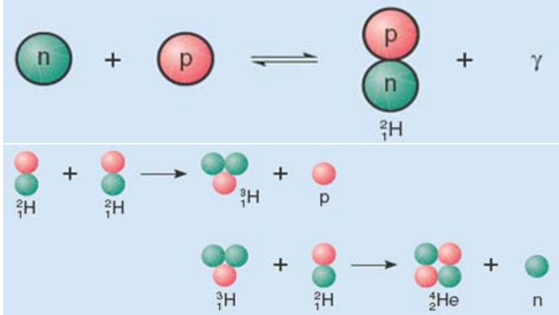
Neutron Decay



$$n \rightarrow p + e^- + \overline{\nu}_e$$

Primordial Nucleosynthesis

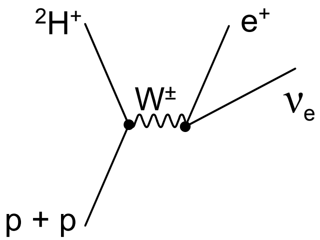




$$n + \nu_e \leftrightarrow p + e^-$$

Start of Big Bang Nucleosynthesis,
Primordial ^{4}He abundance

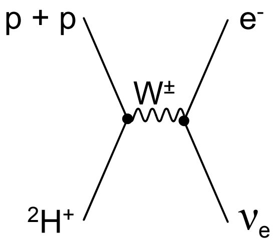
Solar cycle

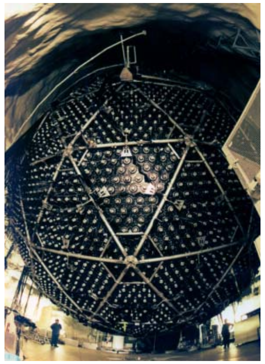


$$p + p \rightarrow {}^2H^+ + e^+ + \nu_e$$

Start of Solar Cycle,
determines amount of Solar Neutrinos

Neutrino Detection (SNO, CC)



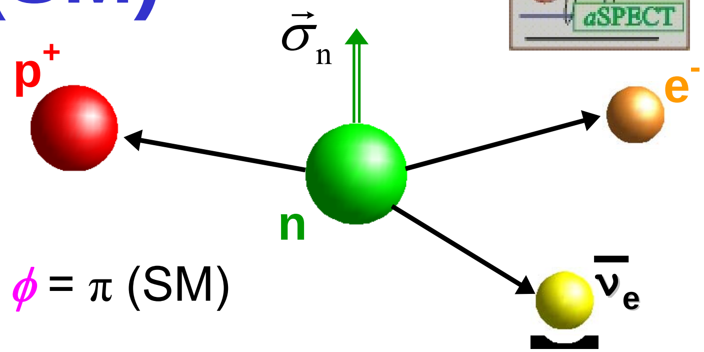


$$\nu_e + {}^2H^+ \rightarrow p + p + e^-$$

Fermi-Transitions $g_V = G_F \cdot V_{ud}$

Gamow-Teller-Transitions $g_A = G_F \cdot V_{ud} \cdot \lambda$

Neutron Decay Parameters (SM)



$$H_{\rm weak} = G_{\rm F} V_{\rm ud} \langle n | \gamma^{\mu} - \lambda \gamma^{\mu}\gamma^{5} | p \rangle \langle \nu_e | \gamma_{\mu} - \gamma_{\mu}\gamma_5 | e^- \rangle$$

Coupling constant ratio $\lambda = |g_{\rm A}/g_{\rm V}|e^{i\phi}$, where phase $\phi = \pi$ (SM)

Jackson et al., PR **106**, 517 (1957)

$$dW \propto \underbrace{G_{\rm F}^2 V_{\rm ud}^{\ 2}\left(1+3|\lambda|^2\right)}\cdot\left\{1 + a\frac{\vec{p}_{\rm e}\cdot\vec{p}_{\nu}}{E_{\rm e}E_{\nu}} + b\frac{m_{\rm e}}{E_{\rm e}} + \vec{\sigma}_{\rm n}\cdot\left(A\frac{\vec{p}_{\rm e}}{E_{\rm e}} + B\frac{\vec{p}_{\nu}}{E_{\nu}} + D\frac{\vec{p}_{\rm e}\times\vec{p}_{\nu}}{E_{\rm e}E_{\nu}}\right)\right\}$$

Neutron lifetime — Neutrino-Electron Correlation — Beta-Asymmetry

$$\tau_{\rm n}^{\ -1} \propto G_{\rm F}^2 V_{\rm ud}^{\ 2}\left(1+3|\lambda|^2\right)$$

$$a = \frac{1-|\lambda|^2}{1+3|\lambda|^2}$$

$$A = -2\frac{|\lambda|^2 + |\lambda|\cos\phi}{1+3|\lambda|^2}$$

λ can be extracted from either a or A $\Rightarrow$ over-determined problem

Possible Tests of the Standard Model

- Search for Right-handed Currents
  - W_R?
- Search for Scalar and Tensor Interactions
  - Leptoquarks? Charged Higgs Bosons?
- Search for Supersymmetric Particles
  - (Loop corrections to Beta Decay change Coupling Constants)
- Test of the Unitarity of the CKM-Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{td} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$|V_{ud}|^2 = \frac{(4908.7 \pm 1.9)\,\mathrm{s}}{\tau_n (1 + 3\lambda^2)}$$

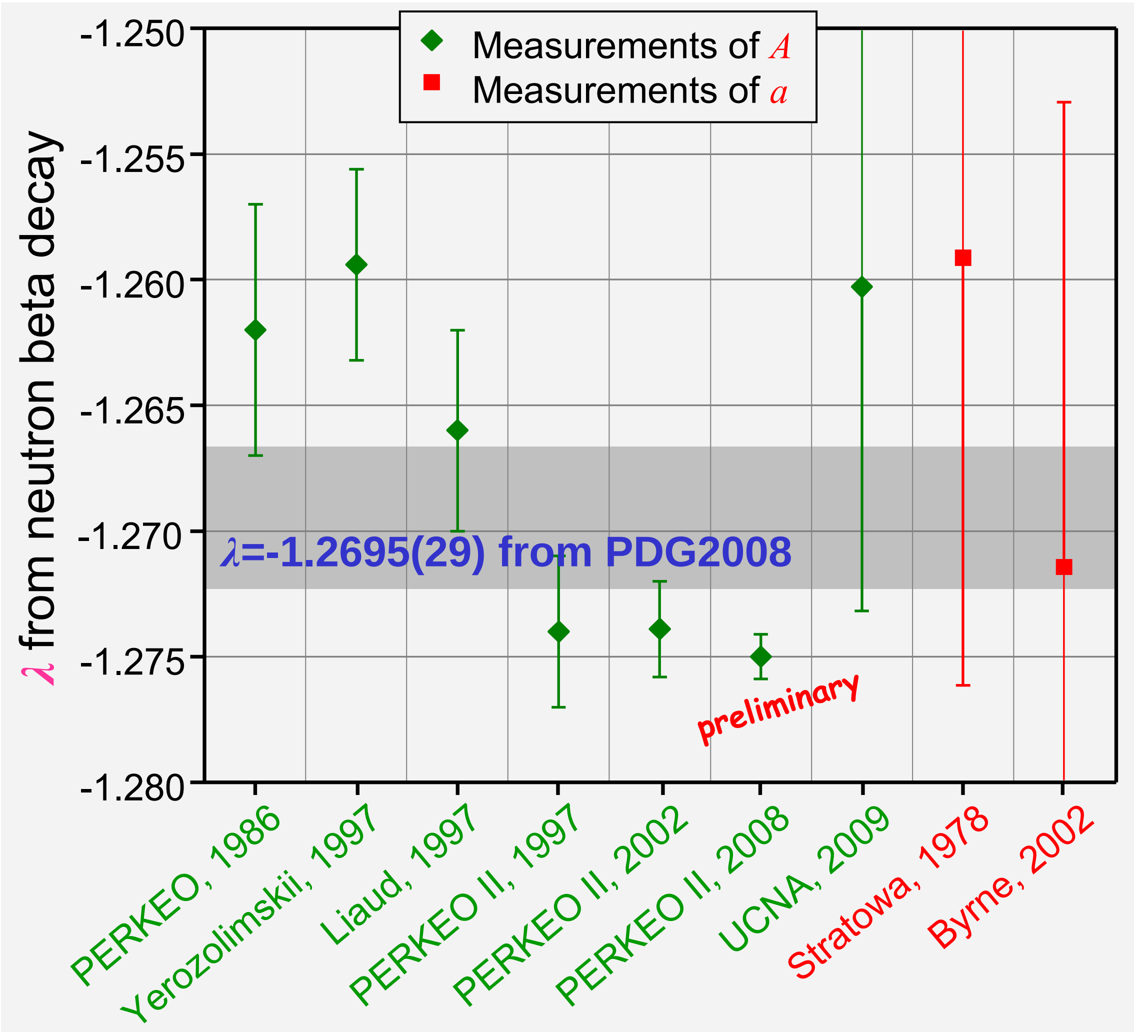
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

$0^+ \rightarrow 0^+$ decays

Kaon decays

B/ D mesons

Determination of $\lambda = g_A / g_V$ from n decay



- PERKEO II is the systematically cleanest experiment
- Still the disagreement with older measurements is not explained
- A measurement of a is independent of possible unknown errors in A; systematics are entirely different

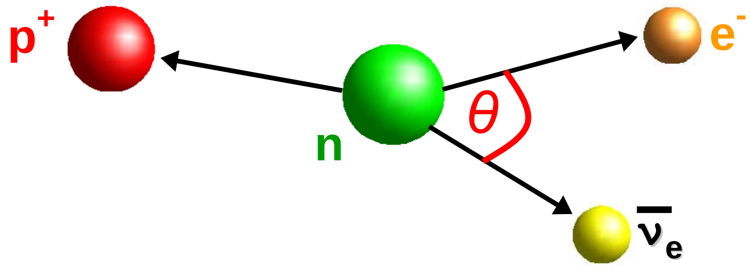
Present best experiments have $\Delta a/a$ ~ 5 %

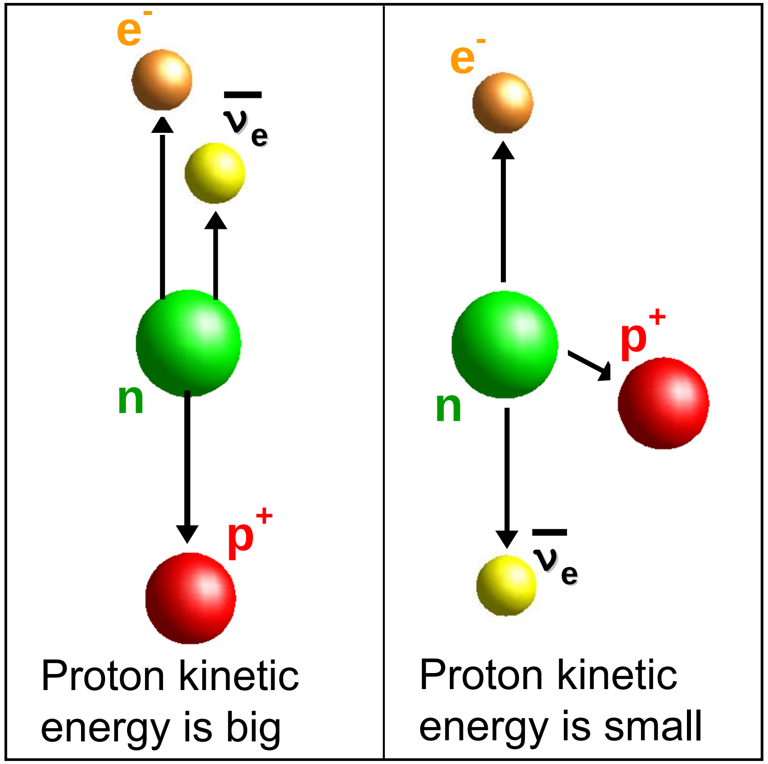
Aim of aSPECT is $\Delta a/a$ ~ 0.3% ≙

The Neutrino-Electron Correlation *a*
and the Proton Spectrum in Neutron Decay

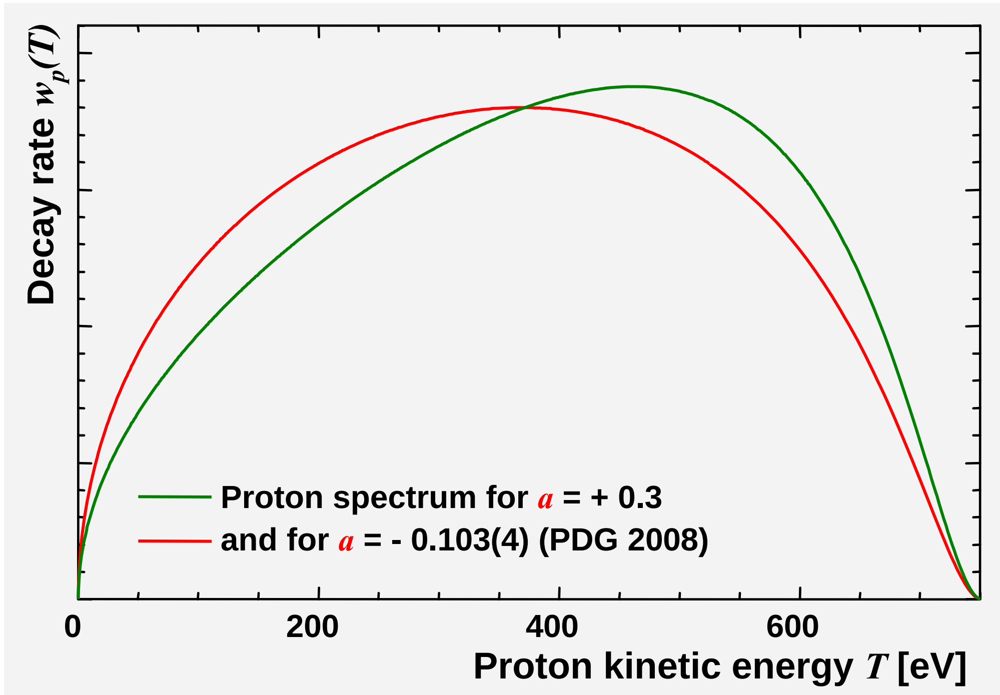
The Correlation coefficient *a*

$$dW \propto \left(1 + a\frac{v_e}{c}\cos\left(\vec{p}_e, \vec{p}_\nu\right)\right)$$

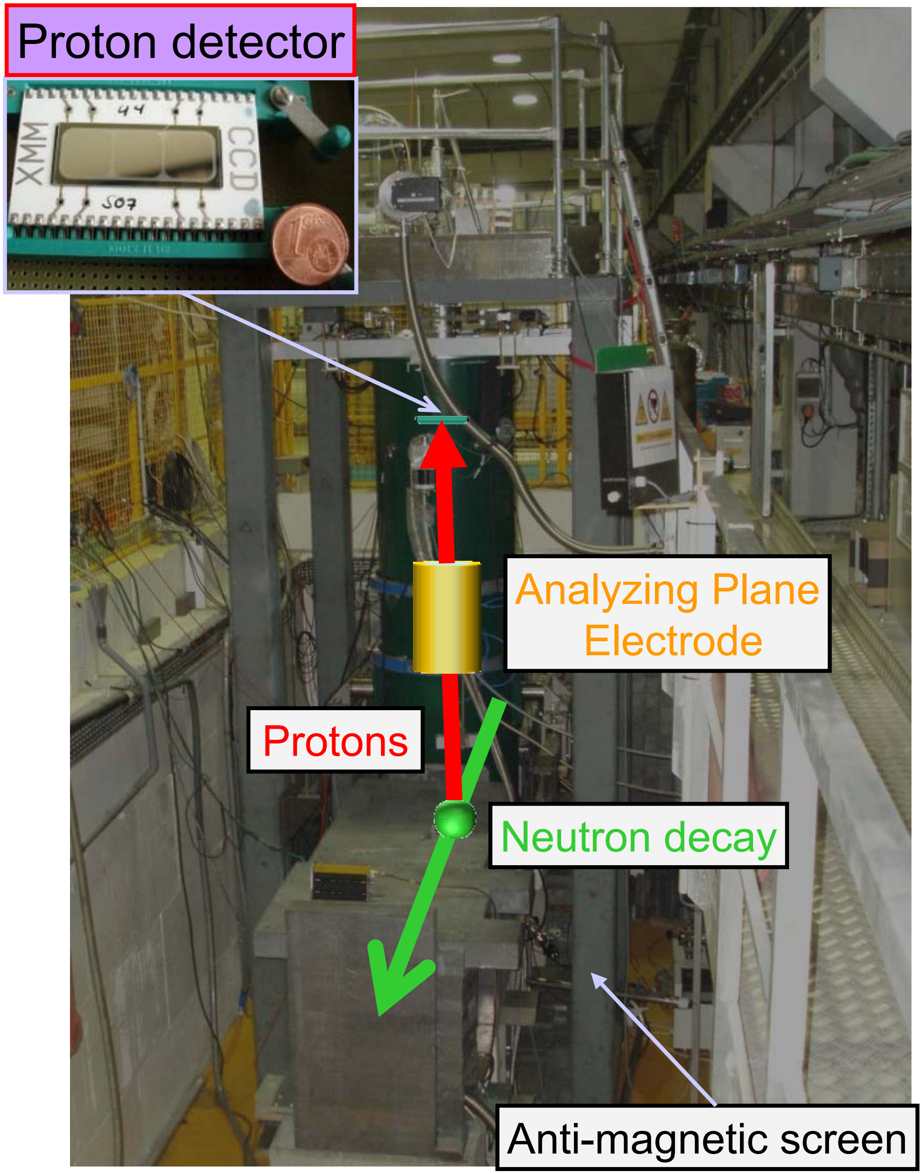


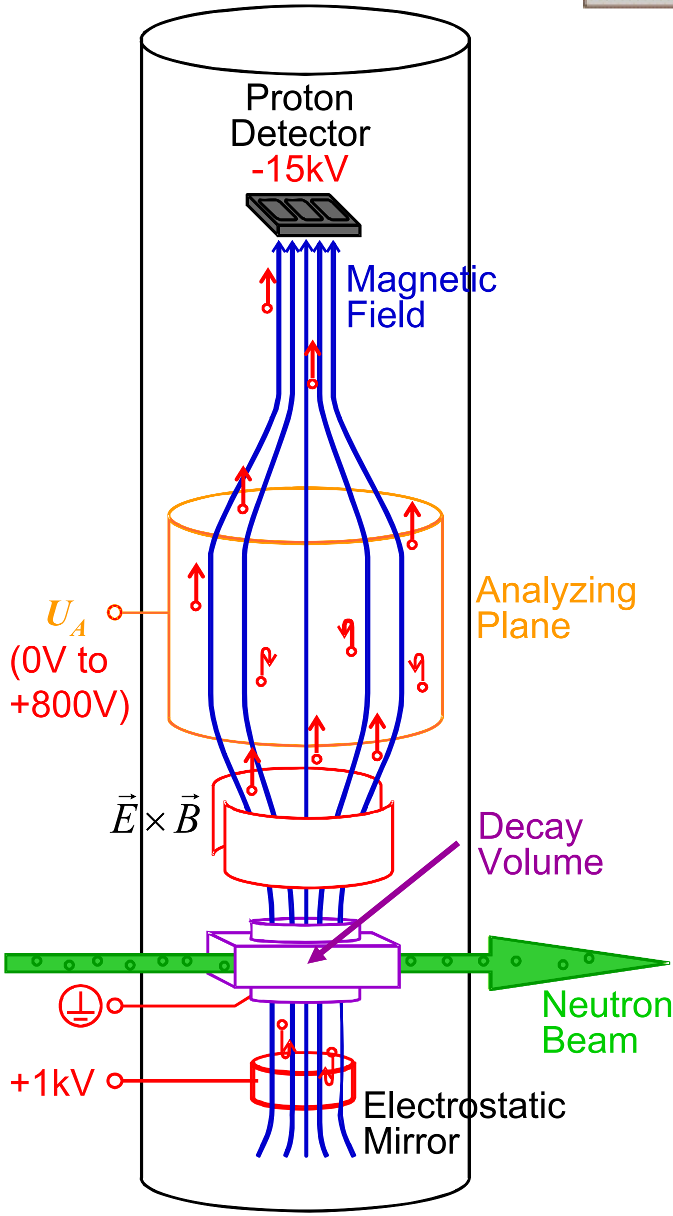


Sensitivity of the Proton Spectrum to *a*

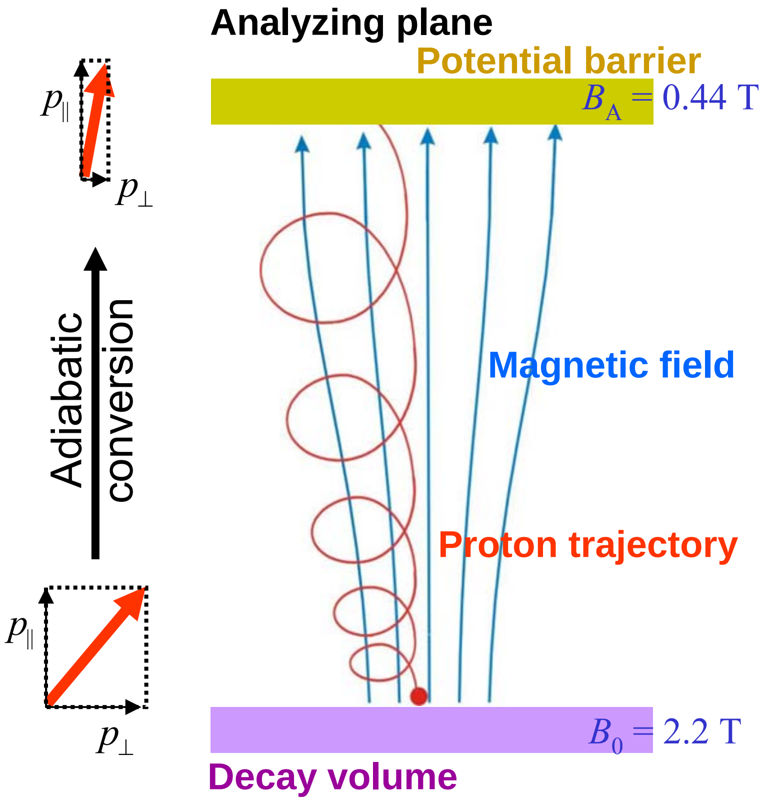


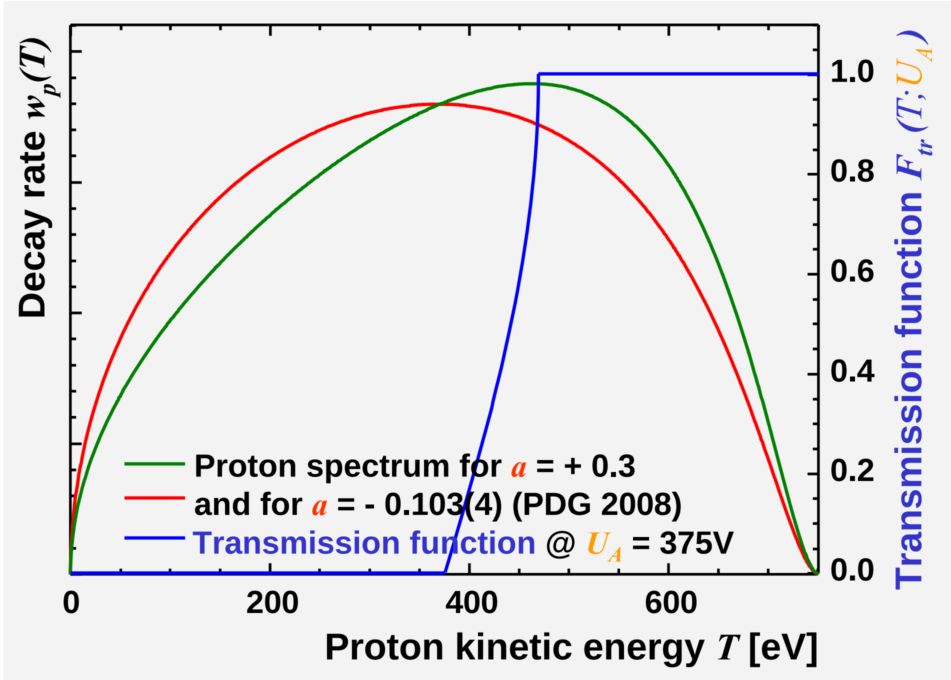
Setup of *a*SPECT at PF1b/ ILL and Spectrometer sketch





Principle of a Retardation spectrometer



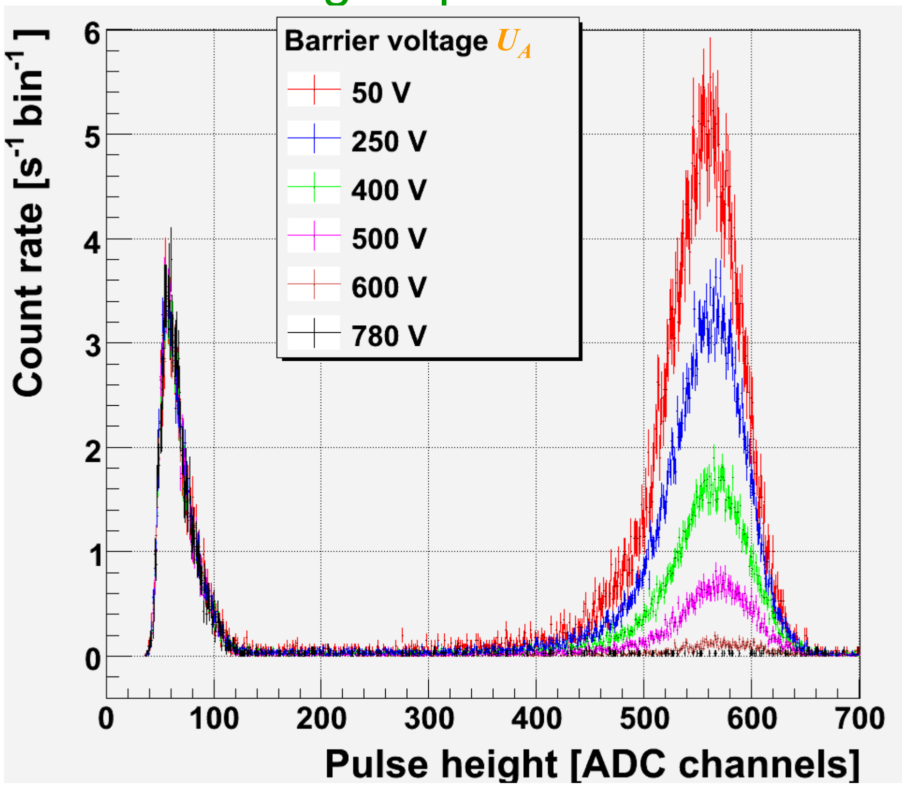


Transmission function $F_{tr}(T;U_A)$ in the adiabatic limit

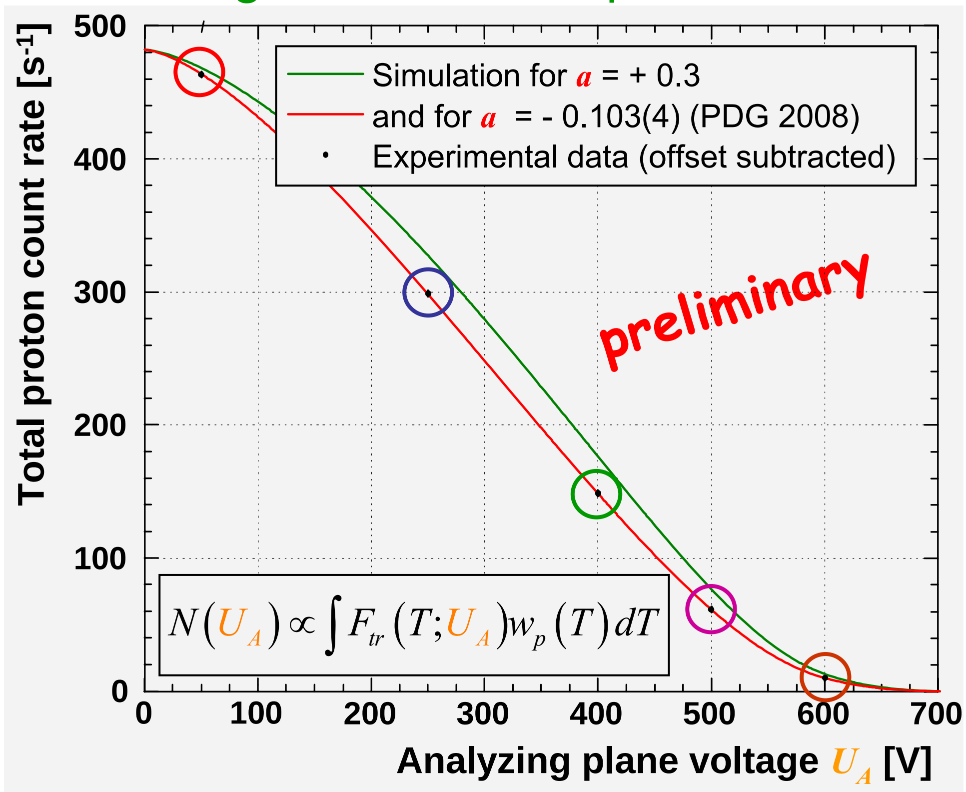
$$F_{\mathrm{tr}}(T;U_\mathrm{A}) = \begin{cases} 0 & ; \quad T < eU_\mathrm{A} \\ 1 - \sqrt{1 - B_0/B_\mathrm{A}\left(1 - eU_\mathrm{A}/T\right)} & ; \quad \text{otherwise} \\ 1 & ; \quad T > eU_\mathrm{A}/\left(1 - B_\mathrm{A}/B_0\right) \end{cases}$$

First results of 2008 beam time at ILL

Pulse height spectrum



Integrated Proton Spectrum

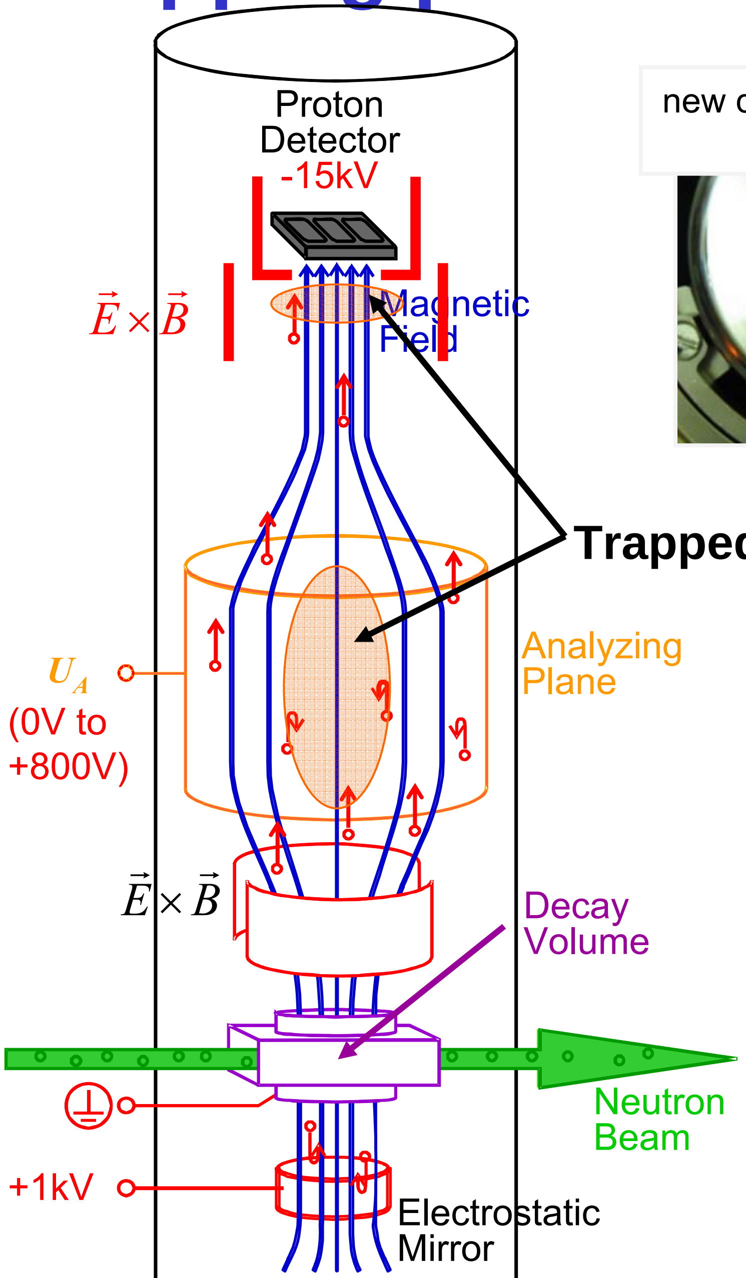


- About 470 events per second at U_A = 50 V (on one detector pad)
- Statistical sensitivity to a about 2 % per 24 h measurement time
- Background more stable

M. Simson *et al.*, Proceedings of the IWPPSN, Nucl. Instr. and Meth. A 611, 203 (2009), arXiv:0811.3851

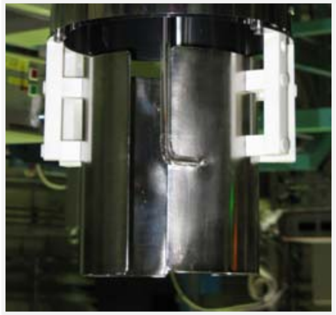
G. Konrad *et al.*, Proceedings of the PANIC08, Nucl. Phys. A 827, 529c (2009)

Trapping problems reduced



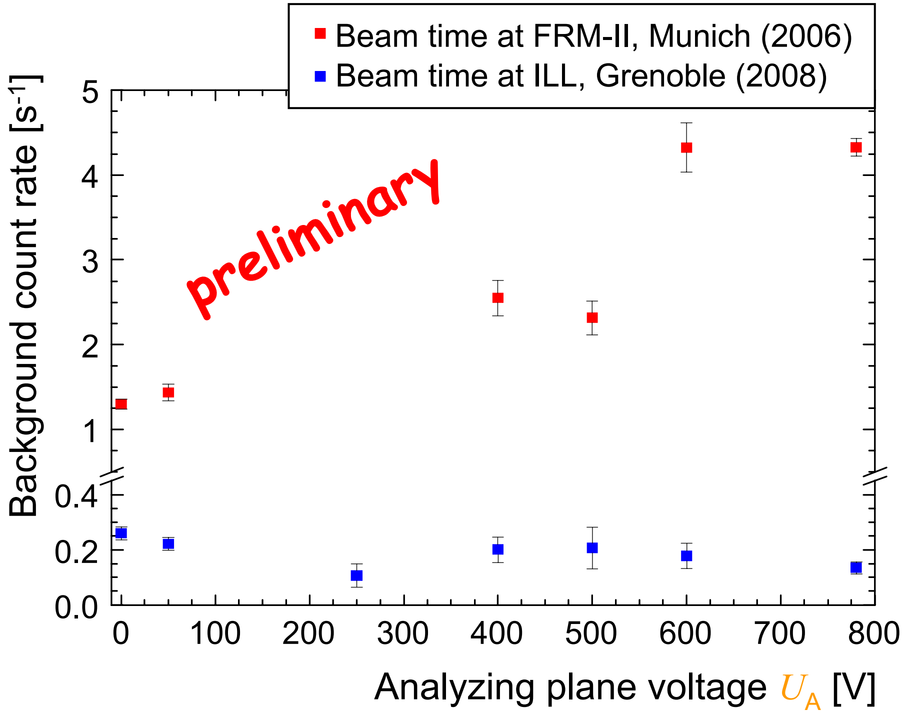
new detector -HV electrode,
SDD detector

new *ExB* electrode



Internal getter pumps

Measurements without neutron beam



Improvements and Outlook

Present status of *a*SPECT: $(\Delta a/a)_{stat}$ = 2 % per day

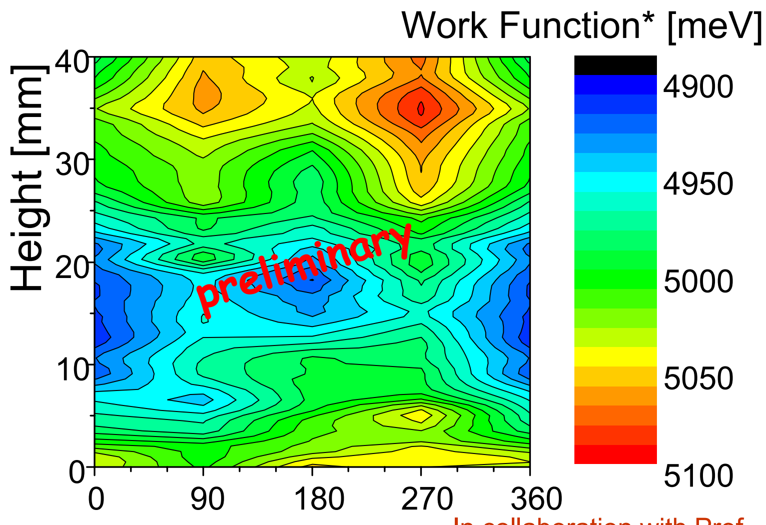
Final aim (0.3%) requires: $(\Delta B/B)_0$, $(\Delta B/B)_A < 10^{-4}$ and ΔU < 10 mV

1.) Online NMR

- Proof of principle with ^3He
- Accuracy better than 10^{-4}
- Field ratio stable in time

2.) Surface Voltage

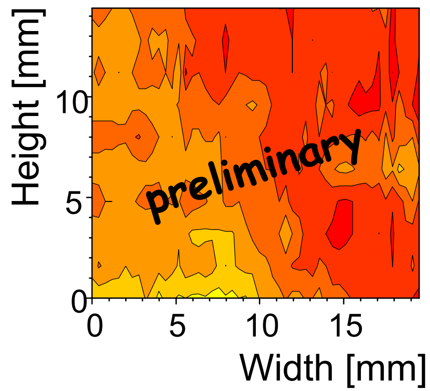
*a*SPECT electrode



In collaboration with Prof. I. Baikie, KP Technologies

Test sample

- better polishing
- better coating



*) arbitrary offset added

Possible solution: Other surface coatings, calibration

General Beta Decay Hamiltonian

$$H_{\text{if}} = \frac{2G_{\text{F}}V_{\text{ud}}}{\sqrt{2}} \sum_{j\in\{\text{V,A,S,T}\}} L_j \langle p|\Gamma_j|n\rangle \langle e^-|\underbrace{\Gamma_j \frac{1-\gamma_5}{2}}_{\text{Left-handed neutrino}}|\nu_e\rangle + R_j \langle p|\Gamma_j|n\rangle \langle e^-|\underbrace{\Gamma_j \frac{1+\gamma_5}{2}}_{\text{Right-handed neutrino}}|\nu_e\rangle$$

with operators: $\Gamma_{\text{V}} = \gamma_\mu$; $\Gamma_{\text{A}} = i\gamma_\mu\gamma_5$; $\Gamma_{\text{S}} = 1$; $\Gamma_{\text{T}} = \frac{i[\gamma_\mu, \gamma_\nu]}{2\sqrt{2}}$

Standard Model: $L_{\text{V}} = 1$; $L_{\text{A}} = \lambda$; $L_{\text{S}} = L_{\text{T}} = R_V = R_{\text{A}} = R_{\text{S}} = R_{\text{T}} = 0$

Neutron lifetime: $\tau_{\text{n}} \propto \left(\underbrace{|L_{\text{V}}|^2 + 3|L_{\text{A}}|^2}_{\text{Standard Model: } 1+3\lambda^2} + \underbrace{|L_{\text{S}}|^2 + 3|L_{\text{T}}|^2 + |R_{\text{V}}|^2 + 3|R_{\text{A}}|^2 + |R_{\text{S}}|^2 + 3|R_{\text{T}}|^2}_{\text{Standard Model: } 0} \right)$

Neutrino Electron Correlation: $a = \frac{|L_{\text{V}}|^2 - |L_{\text{A}}|^2 - |L_{\text{S}}|^2 + |L_{\text{T}}|^2 + |R_{\text{V}}|^2 - |R_{\text{A}}|^2 - |R_{\text{S}}|^2 + |R_{\text{T}}|^2}{|L_{\text{V}}|^2 + 3|L_{\text{A}}|^2 + |L_{\text{S}}|^2 + 3|L_{\text{T}}|^2 + |R_{\text{V}}|^2 + 3|R_{\text{A}}|^2 + |R_{\text{S}}|^2 + 3|R_{\text{T}}|^2}$

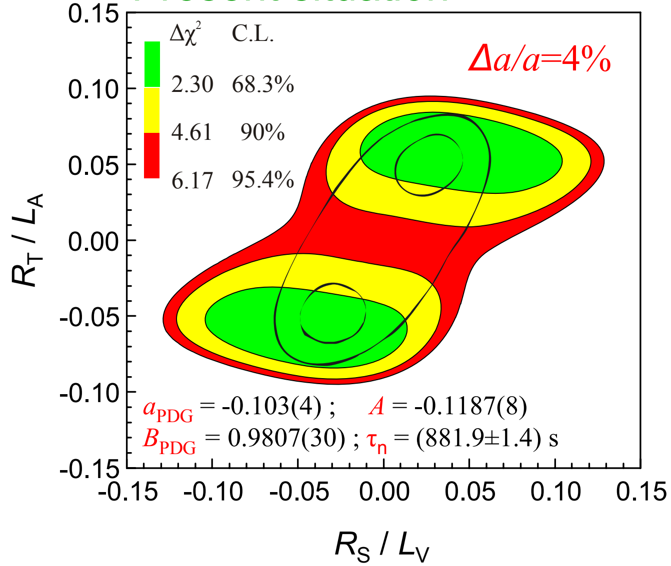
Beta Asymmetry: $A = \frac{2\,\text{Re}\left(-|L_{\text{A}}|^2 - L_{\text{V}}L_{\text{A}}^* + |L_{\text{T}}|^2 + L_{\text{S}}L_{\text{T}}^* + |R_{\text{A}}|^2 + R_{\text{V}}R_{\text{A}}^* - |R_{\text{T}}|^2 - R_{\text{S}}R_{\text{T}}^*\right)}{|L_{\text{V}}|^2 + 3|L_{\text{A}}|^2 + |L_{\text{S}}|^2 + 3|L_{\text{T}}|^2 + |R_{\text{V}}|^2 + 3|R_{\text{A}}|^2 + |R_{\text{S}}|^2 + 3|R_{\text{T}}|^2}$

Glück *et al.*, NPA 593, 125 (1995), Jackson, PR 106, 517 (1957)

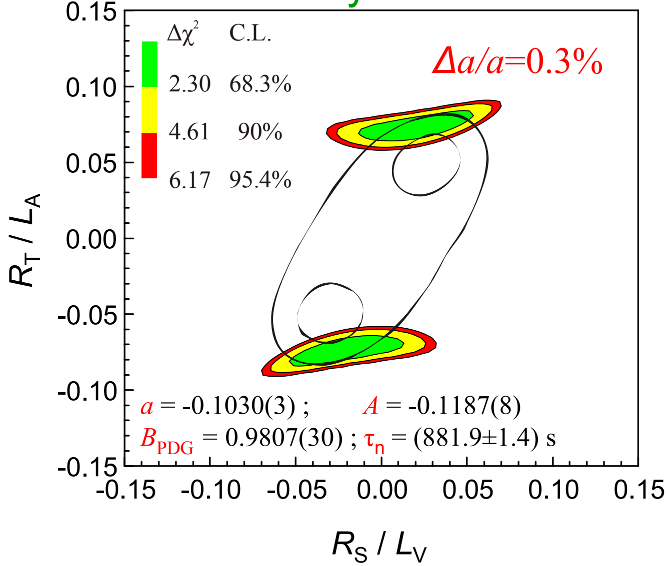
Search for right-handed scalar and tensor currents

- Time reversal invariance assumed
- Limits are worse then for left-handed S-T currents. Only quadratic sensitivity of observables.
- Shown are limits from n decay (own average for A and τ_n). The black lines correspond to 1σ, 2σ from N. Severijns *et al.*, RMP78, 991 (2006)
- Limits on scalar part can best be improved with B (or "artificial" correlation C).

Present situation



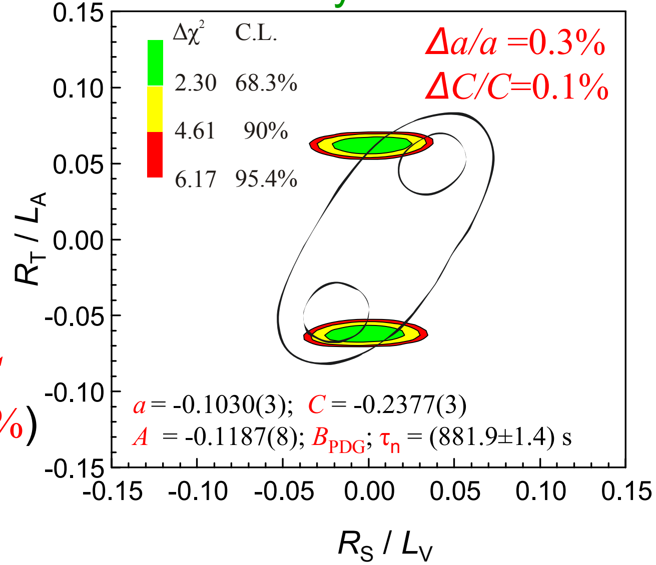
Personal toy model



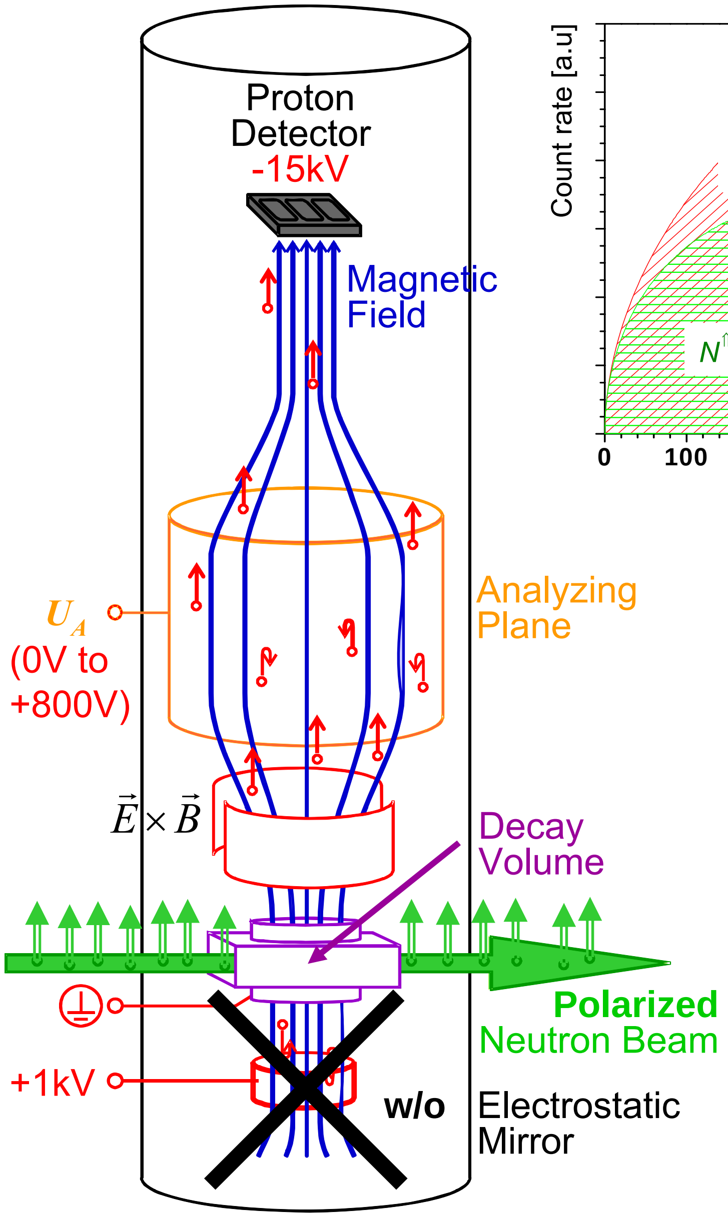
Left: Improved precision in only a

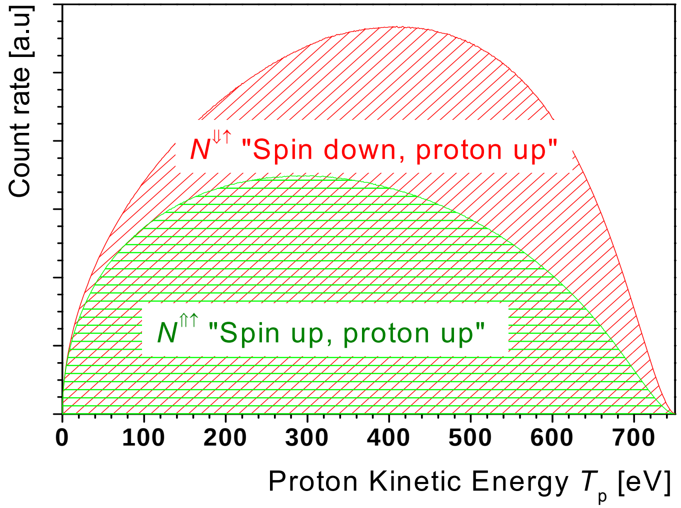
Right: Improved precision in a and C (at present $\Delta C/C$=1%)

Personal toy model



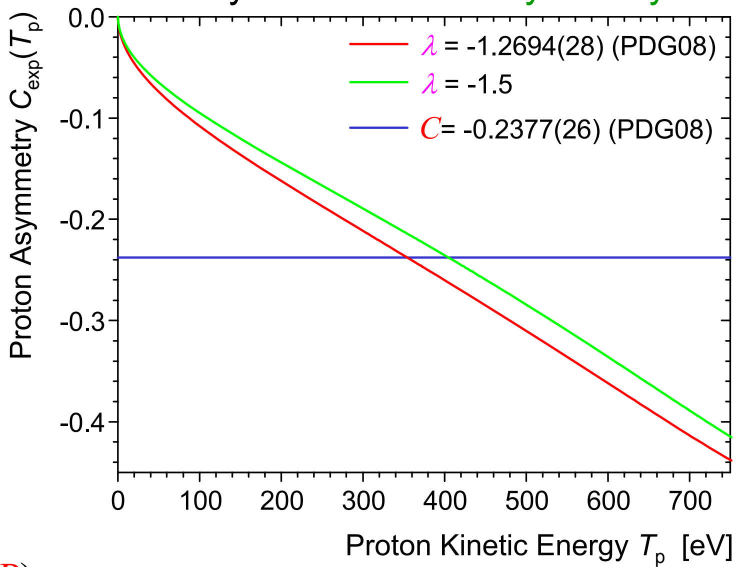
The Proton Asymmetry C





$$C_{exp} = \frac{N^{\Uparrow\uparrow} - N^{\Downarrow\uparrow}}{N^{\Uparrow\uparrow} + N^{\Downarrow\uparrow}}$$

Sensitivity of the Proton Asymmetry to λ



Standard Model

$$C = \int C_{exp}\left(T_p\right) dT_p$$
$$= -0.27484(A+B)$$
$$= -0.2377(26)$$

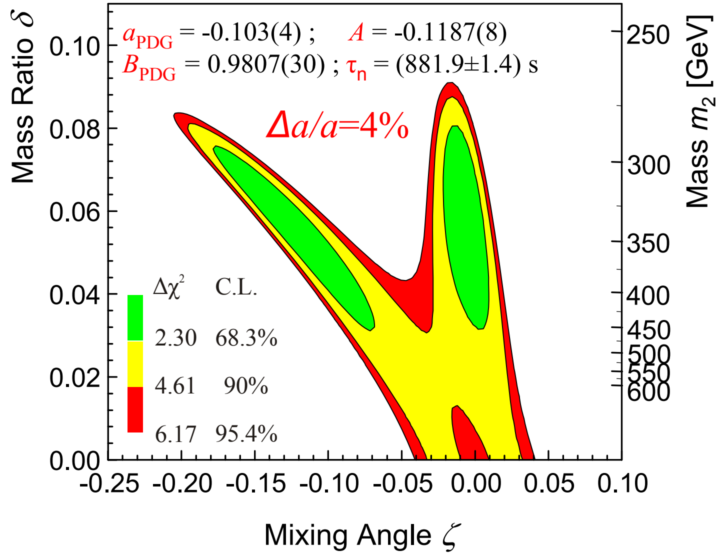
M. Schumann *et. al*, PRL100, 151801 (2008)

Search for Right-handed Currents

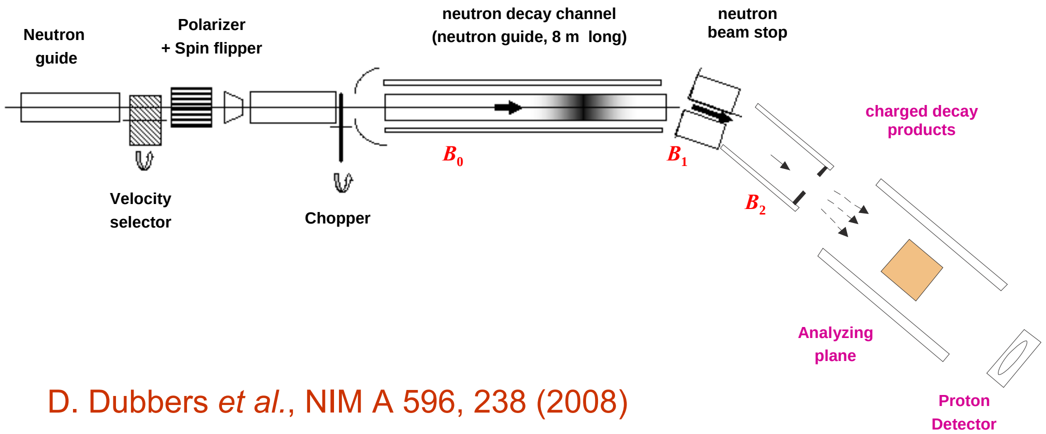
$$W_1 = \cos\zeta W_L + \sin\zeta W_R, \qquad W_2 = -\sin\zeta W_L + \cos\zeta W_R$$

- Manifest left-right symmetric model with further parameters $\delta = m_1^2 / m_2^2$ and $\lambda' = g'_A / g'_V$
- Shown are limits only from neutron decay (own average for A and τ_n)
- Complementary to High-energy limits (in more general models)

Present situation

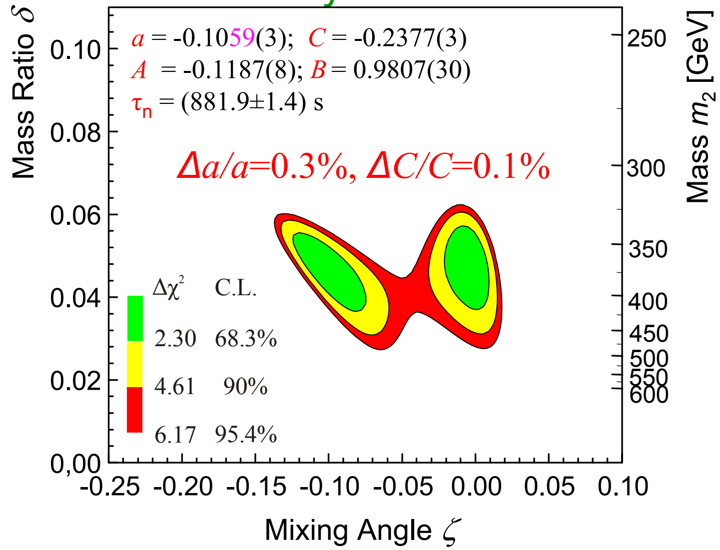


- The PERC project (at ILL or FRM-II): Increase count rates by a factor 100 compared to best experiments.



D. Dubbers *et al.*, NIM A 596, 238 (2008)

Personal toy model



Summary

- *a*SPECT
  - From our last measurement we expect a new value for *a* well below the present literature value of 5%
  - A statistical accuracy of $\Delta a/a$ ~ 0.3% can be obtained within one further beam time at ILL
  - Our final goal is $\Delta C/C$ ~ 0.1%

- Neutron particle physics
  - Rich experimental program with the study of neutron decay correlations
  - New physics might be found with precision measurements. Maybe soon!

The *a*SPECT collaboration

- Present collaborators

F. Ayala Guardia[1], S. Baeßler[2], M. Borg[1], F. Glück[3], W. Heil[1], I. Konorov[4], K.K.H. Leung[4,5], R. Muñoz Horta[1], B. Ostrick[1], M. Simson[4,5], Y. Sobolev[1], T. Soldner[4,5], H.-F. Wirth[6], O. Zimmer[4,5], G. K.[1]

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- Thanks to our past collaborators

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Thank you for your interest!