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Neutron decay parameters *a, b*
Status and prospects

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INTERNATIONAL SOLVAY INSTITUTES BRUSSELS

Solvay Workshop on
Beta-Decay Weak Interaction Studies in the Era of the LHC

Université Libre de Bruxelles
3–5 September 2014

Thanks for contributions from:
S. Baeßler, M. Beck, F. Wietfeldt, A. Young

Outline

- Neutron beta-decay within the Standard Model
  - Status of the electron-antineutrino correlation *a*
  - Future prospects for *a*
- Searches for new physics beyond the Standard Model
  - Prospects for scalar and tensor type interactions
  - Future prospects for the Fierz interference term *b*
- Summary and Outlook

Neutron decay parameters in the SM

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

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{2(2\pi)^5} \overbrace{G_F^2 |V_{ud}|^2 \left(1+3|\lambda|^2\right)}^{\propto \tau_n^{-1}} p_e E_e (E_0 - E_e)^2 \times \left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \frac{\langle\vec{\sigma}_n\rangle}{\vec{\sigma}_n} \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right)\right]$$

- 3 unknown parameters

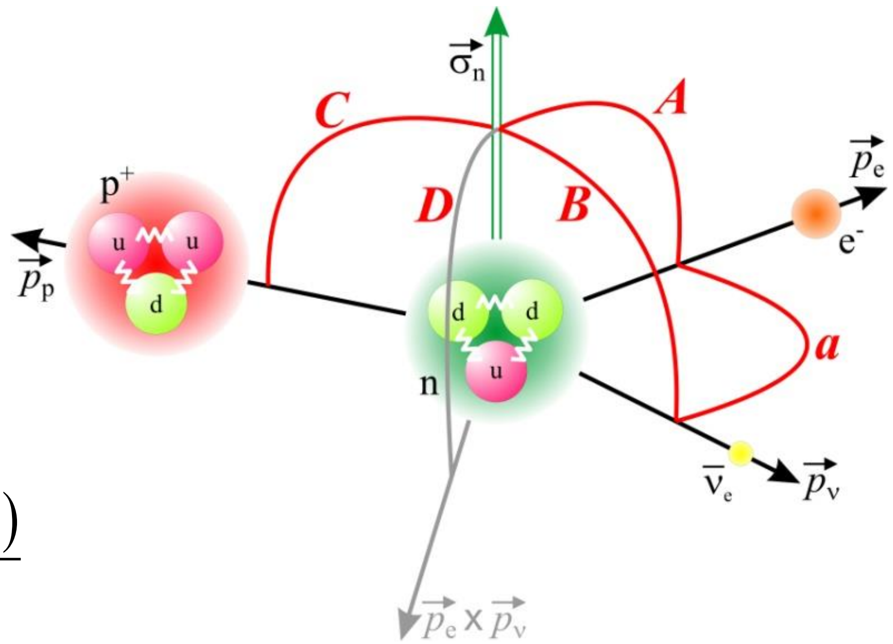
  G_F, V_{ud}, $\lambda = g_A/g_V$

  ↑ μ decay $\qquad g_V = G_F V_{ud}$

- 20 or more observables

  τ_n, a, b, A, B, C, D, …

$$a = \frac{1-|\lambda|^2}{1+3|\lambda|^2} \qquad A = -2\frac{|\lambda|^2 + \mathrm{Re}(\lambda)}{1+3|\lambda|^2}$$



Current status of the parameter *a*

J. Beringer *et al.* (Particle Data Group), PR **D86**, 010001 (2012) and 2013 partial update for the 2014 edition (URL: http://pdg.lbl.gov)

e-$\overline{\nu}_e$ ANGULAR CORRELATION COEFFICIENT a

For a review of past experiments and plans for future measurements of the a parameter, see WIETFELDT 05. In the Standard Model, a is related to $\lambda \equiv g_A/g_V$ by $a = (1 - \lambda^2) / (1 + 3\lambda^2)$; this assumes that g_A and g_V are real.

VALUE	DOCUMENT ID		TECN	COMMENT
-0.103 ± 0.004	**OUR AVERAGE**			
-0.1054 ± 0.0055	BYRNE	02	SPEC	Proton recoil spectrum
-0.1017 ± 0.0051	STRATOWA	78	CNTR	Proton recoil spectrum
-0.091 ± 0.039	GRIGOREV	68	SPEC	Proton recoil spectrum

PHYSICAL REVIEW D VOLUME 18, NUMBER 11 1 DECEMBER 1978

Ratio $|g_A/g_V|$ derived from the proton spectrum in free-neutron decay

Chr. Stratowa, R. Dobrozemsky, and P. Weinzierl

Physics Institute, Research Center Seibersdorf, Österreichische Studiengesellschaft für Atomenergie m.b.H., Lenaugasse 10, A-1082 Vienna, Austria

(Received 11 July 1978)

The electron-neutrino angular-correlation coefficient was determined by measuring the shape of the proton recoil spectrum from free-neutron decay. The protons leaving a highly evacuated tangential reactor beam tube were analyzed by a spherical condenser spectrometer and counted in an ion-electron converter detector. The design of the apparatus, the possible disturbing influences, and the measures to reduce their effects are discussed. The remaining corrections were either calculated or determined by auxiliary measurements and applied to the spect... $a = -0.1017 \pm 0.0051$ ...are considered and included in the final results. We obtained ...9 ± 0.017.

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **28** (2002) 1325–1349 PII: S0954-3899(02)32083-8

Determination of the electron–antineutrino angular correlation coefficient a_0 and the parameter $|\lambda| = |G_A/G_V|$ in free neutron β-decay from measurements of the integrated energy spectrum of recoil protons stored in an ion trap

J Byrne[1], P G Dawber[1,5], M G D van der Grinten[1,6], C G Habeck[1,7], F Shaikh[1], J A Spain[1], R D Scott[2], C A Baker[3], K Green[3] and O Zimmer[4,8]

[1] School of Chemistry, Physics and Environmental Science, University of Sussex, Brighton BN1 9QH, UK
[2] Scottish Universities Research and Reactor Centre, East Kilbride, Glasgow G75 0QU, UK
[3] Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK
[4] Institut Laue-Langevin, BP 156, 38042 Grenoble Cedex 9, France

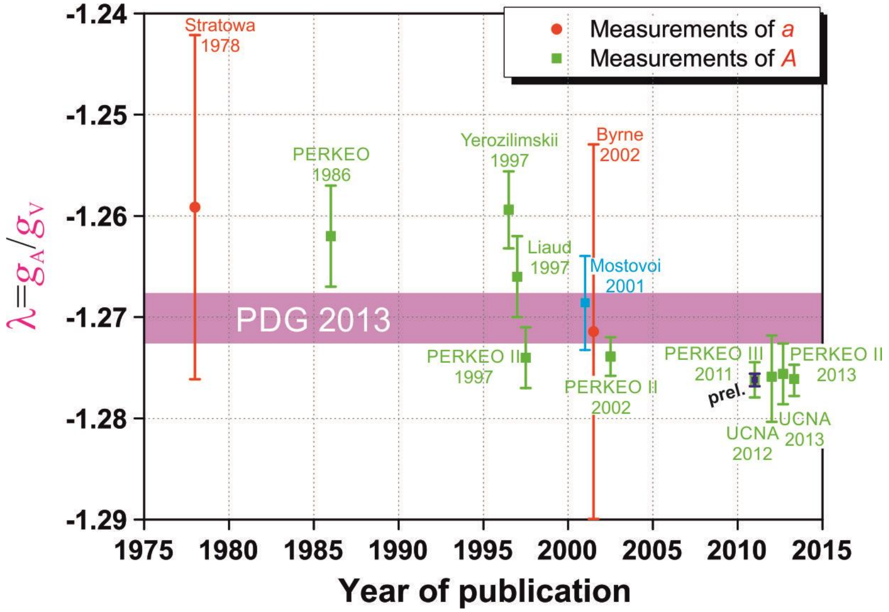
Received 19 December 2001, in final form 18 March 2002
Published 22 April 2002
Online at stacks.iop.org/JPhysG/28/1325

Abstract

Recoil protons from the β-decay of unpolarized neutrons are stored in a cryogenic ion trap formed by the superposition of an axisymmetric electrostatic field on a coaxial magnetic field, which varies uniformly in space between regions of high (~4.30 T) and low (~0.61 T) homogeneous field. Protons generated in the high field region are adiabatically focused onto a 'mirror' electrode in the low field region. The integrated energy spectrum is determined by counting the number of stored protons as a function of mirror potential. Violation of the exact adiabatic conditions is corrected for by carrying out alternat... differ by a factor of 2. The results: $a_0 = -0.1054 \pm 0.0055$, ...0.018 are in agreement with previou...

Reasons to measure *a* more precisely

Determination of $\lambda = g_A/g_V$



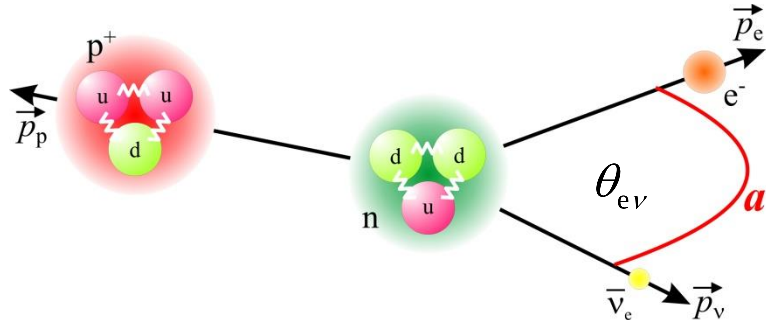
- determines λ, with similar sensitivity as A, but without requiring neutron polarimetry
- helps test CKM unitarity
- improves tests of self-consistency of the SM:

	current	*predicted*
	$F_1 = 1 + A - B - a = 0.0047(51)$	$F_1 = 0$
	$F_2 = aB - A - A^2 = 0.0028(40)$	$F_2 = 0$

- helps improve limits on new physics beyond the SM …

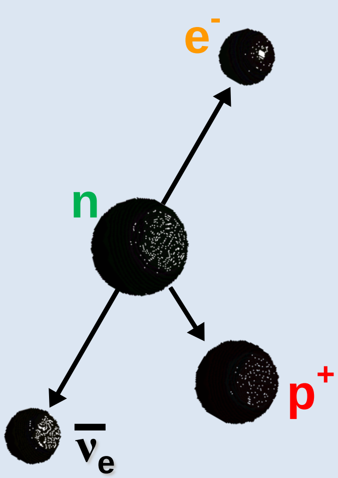
Determination of the parameter *a*

$$\frac{d^2\Gamma}{dE_e\, d\theta_{e\nu}} \propto \left(1 + a\frac{v_e}{c}\cos\theta_{e\nu}\right)$$



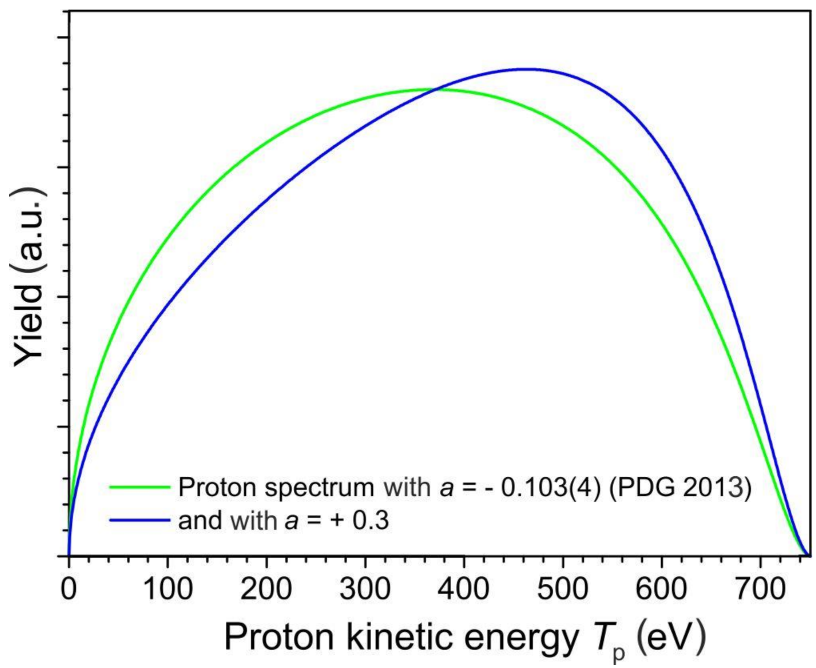
$\cos\theta_{e\nu} = -1$

a < 0



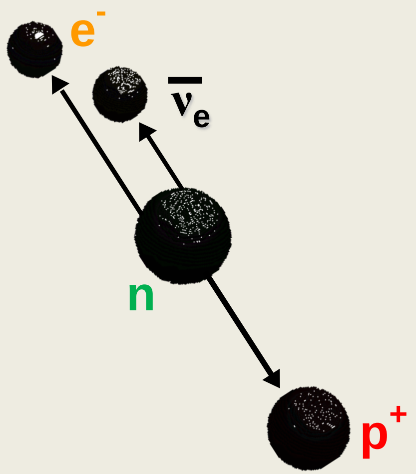
T_p small

Recoil energy spectrum



$\cos\theta_{e\nu} = +1$

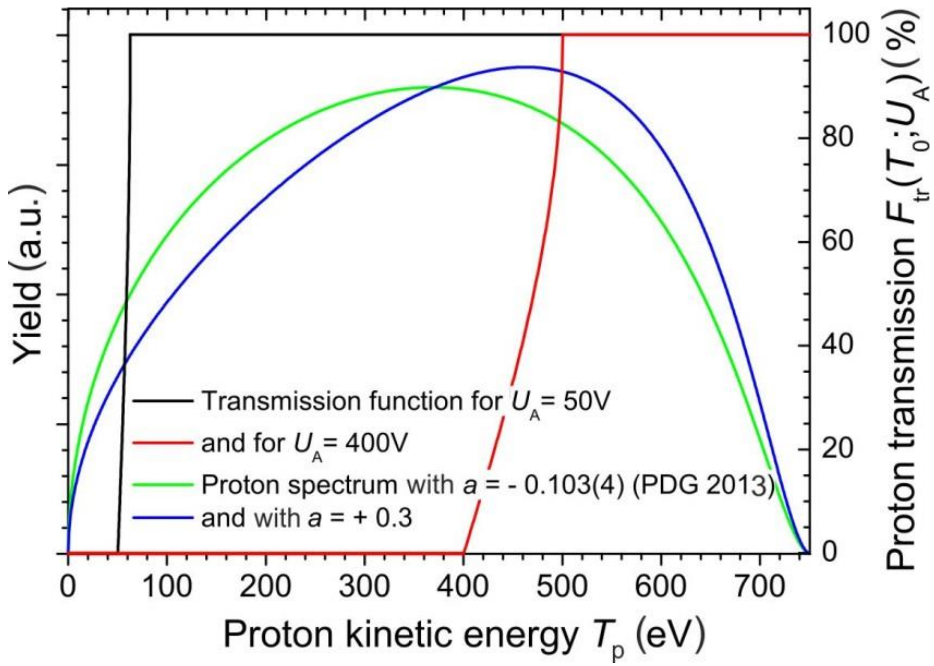
a > 0

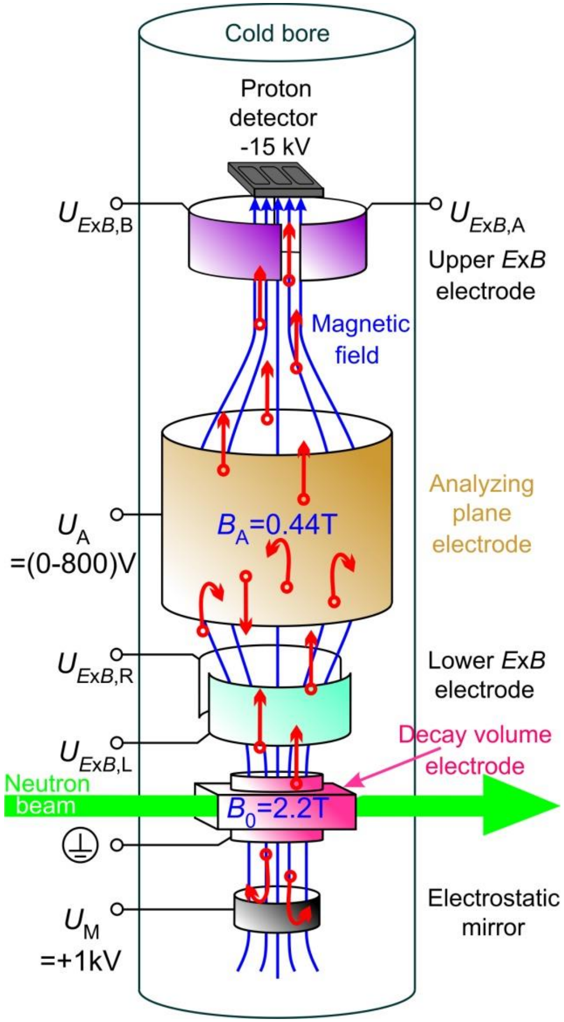


T_p large

The retardation spectrometer *a*SPECT

Proton transmission function





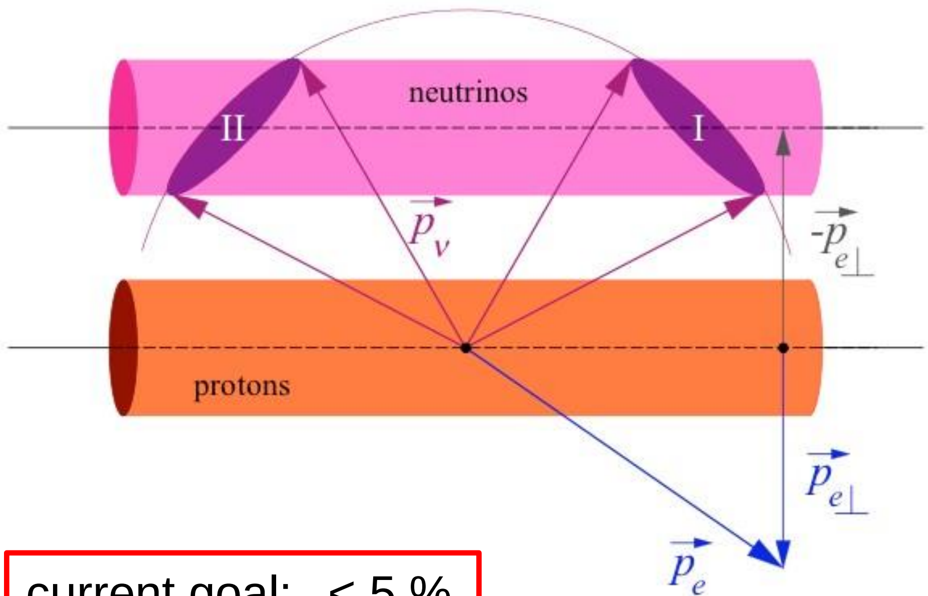
current goal: < 3 %
design goal: 0.3 %

F. Glück *et al.*, EPJ A **23**, 135 (2005)
S. Baeßler, G. K. *et al.*, EPJ A **38**, 17 (2008)
G. Konrad *et al.*, NP A **827**, 529c (2009)

A new approach to *a*: aCORN @ NIST

Measurement principle

B. Yerozolimsky *et al.*, arXiv:nucl-ex/0401014, 2004



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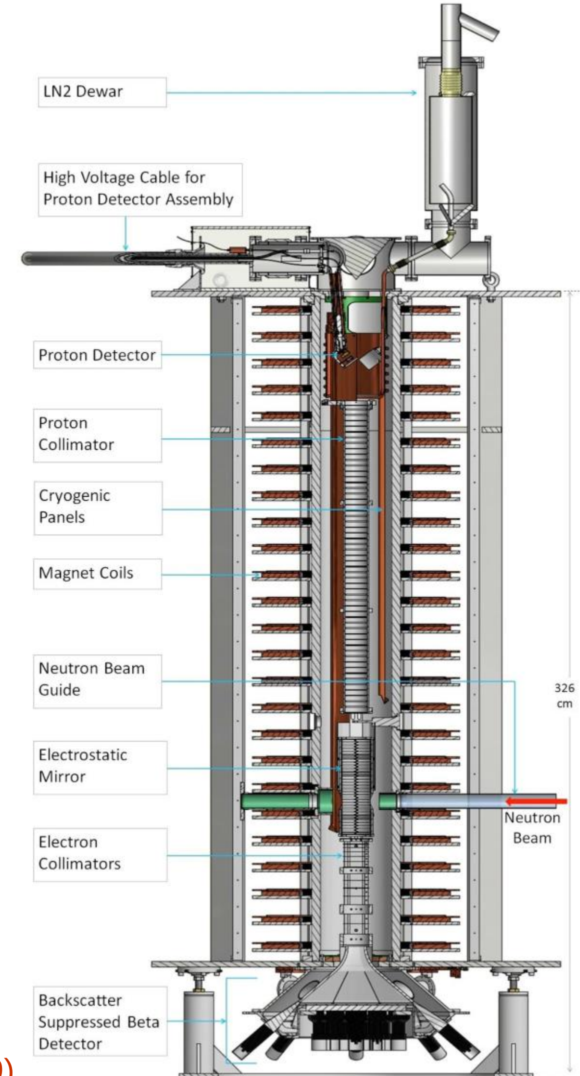
design goal: 0.5 %

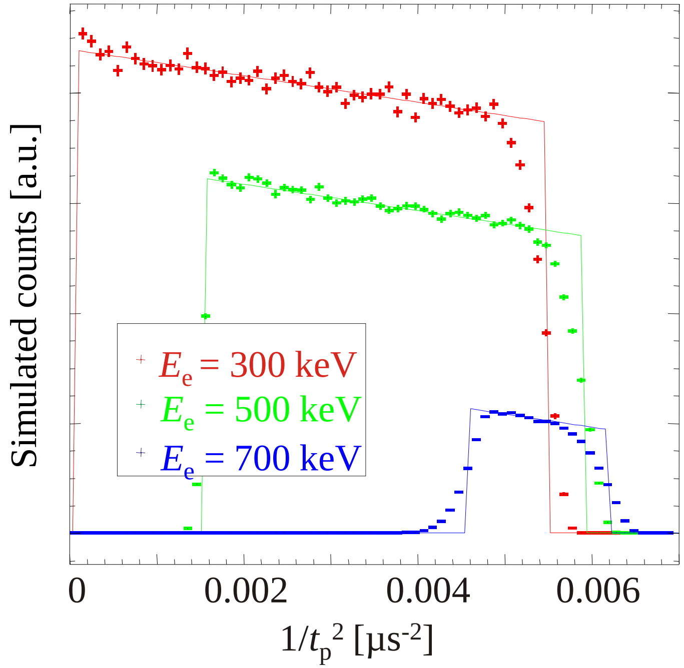


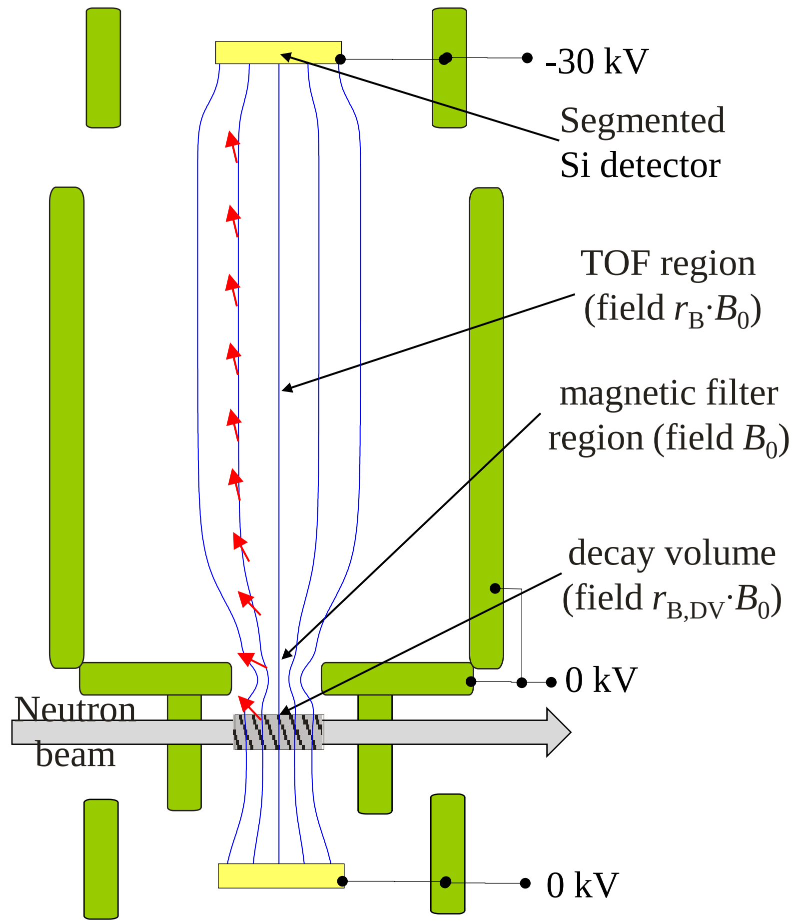
F.E. Wietfeldt *et al.*, NIM A **538**, 574 (2005), NIM A **545**, 181 (2005), NIM A **611**, 207 (2009)

Tulane University · Indiana University · DePauw University · Hamilton · NIST · Harvard

Future prospects for *a*: Nab @ SNS

Proton $1/t_p^2$ histograms

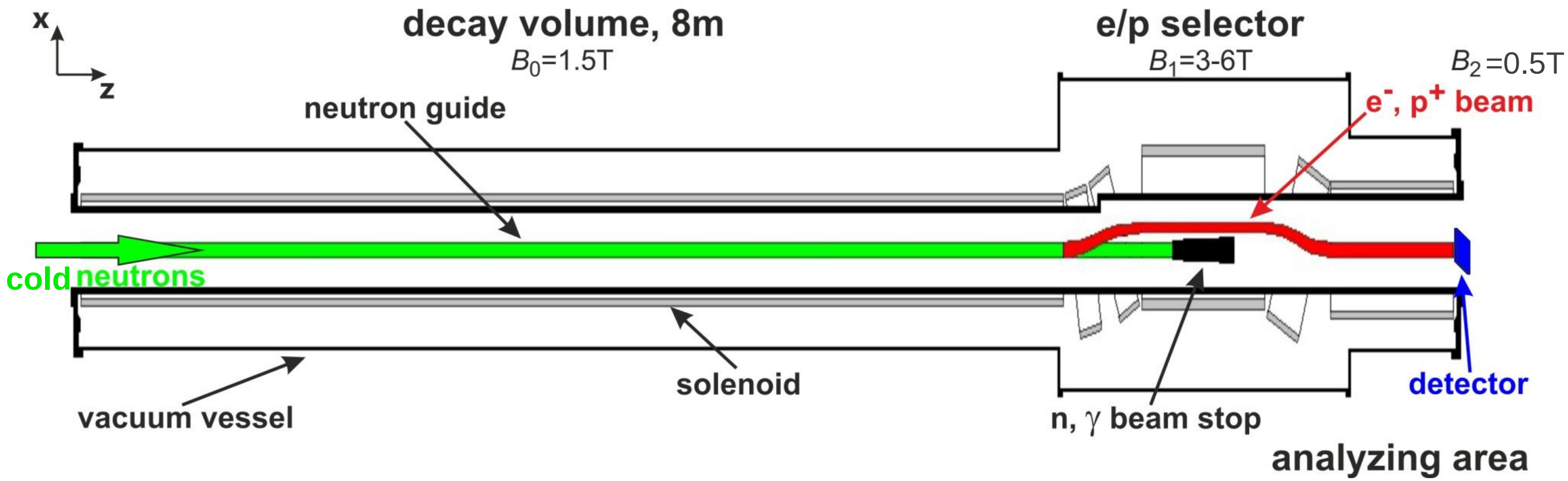




design goal: 0.1 %

D. Počanić *et al.*, NIM A **611**, 211 (2009)
S. Baeßler *et al.*, arXiv:1209.4663v1 [nucl-ex], 2012
A. Salas-Bacci *et al.*, NIM A **735**, 408 (2014)

Future prospects for *a*: PERC @ FRM II



Sensitivity:
- improved by up to 2 orders of magnitude
- high phase space density

Systematics:
- $\leq 10^{-4}$ (for e^-)
- precise cuts in $d\Omega_e$, $d\Omega_p$: $\frac{\sin\theta_1}{\sin\theta_0} = \sqrt{\frac{B_1}{B_0}}$

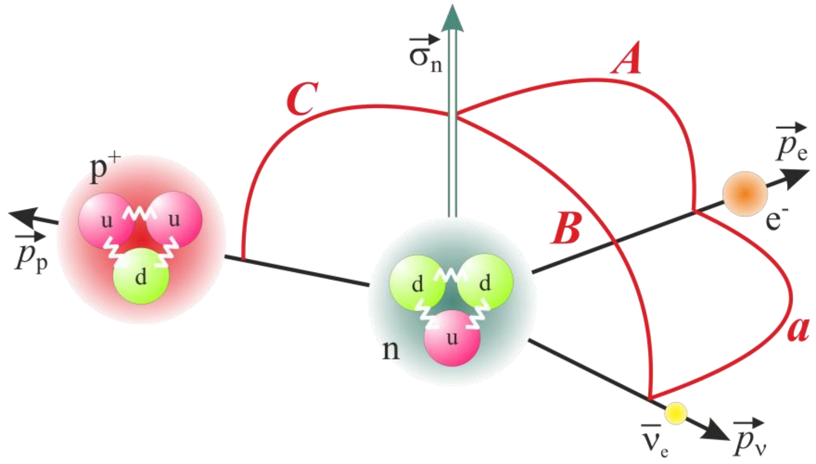
Versatility: $a, b, A, B, C, f_2, \ldots$

D. Dubbers *et al.*, NIM A **596** (2008) 238 and arXiv:0709.4440
G. Konrad *et al.* , J. Phys.: Conf. Ser. **340** (2012) 012048

ATOMINSTITUT   Uni Heidelberg   JOHANNES GUTENBERG UNIVERSITÄT MAINZ   NEUTRONS FOR SCIENCE   FRM II Forschungs-Neutronenquelle Heinz Maier-Leibnitz   TECHNISCHE UNIVERSITÄT MÜNCHEN

Detection systems for PERC

goal for a : < 0.1 %



Observable	Correlations	Measurement principle	Examples
β and **p momenta**	a, b, A	Magnetic spectrometer PLUS position sensitive detectors	
β energy	A, B, b, f_2, g_2 radiative corrections	β energy sensitive detectors such as scintillation OR silicon detectors	PERKEO I-III UCNA
p energy	a, C	Retardation spectrometer PLUS p detector	*a*SPECT
p velocity	a, C	Wien filter PLUS position sensitive detector	
p TOF	a	p beam pulsed by electric gate voltage PLUS p detector	

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Neutron decay parameters

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

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{2(2\pi)^5} G_F^2 |V_{ud}|^2 p_e E_e (E_0 - E_e)^2 \times \xi \left[1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \frac{\langle \vec{\sigma}_n \rangle}{\sigma_n} \cdot \left(A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right]$$

- 10 unknown parameters

  G_F, V_{ud}, C_j, C_j', $j = V, A, S, T$

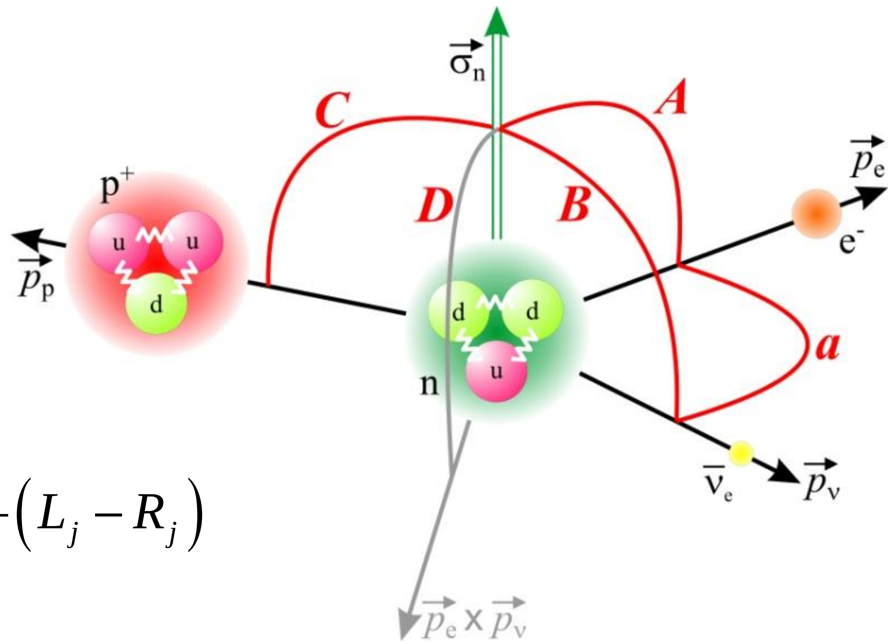
- 20 or more observables

  τ_n, a, b, A, B, C, D, …

- Coupling constants L_j to left-handed and R_j to right-handed neutrinos

$$C_j = \frac{G_F V_{ud}}{\sqrt{2}} (L_j + R_j) \qquad C_j' = \frac{G_F V_{ud}}{\sqrt{2}} (L_j - R_j)$$

F. Glück *et al.*, NP A **593**, 125 (1995)



Neutron decay parameters

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

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{2(2\pi)^5} G_F^2 |V_{ud}|^2 p_e E_e (E_0 - E_e)^2$$
$$\times \xi \left[1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \frac{\langle \vec{\sigma}_n \rangle}{\vec{\sigma}_n} \cdot \left(A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right]$$

- 10 unknown parameters: G_F, V_{ud}, L_j, R_j, $j = V, A, S, T$
- 20 or more observables: τ_n, a, b, A, B, C, D, …

$$\xi a = |L_V|^2 - |L_A|^2 - |L_S|^2 + |L_T|^2 + |R_V|^2 - |R_A|^2 - |R_S|^2 + |R_T|^2$$

$$\xi A = -2\Re\left(|L_A|^2 + L_V L_A^* - |L_T|^2 - L_S L_T^* - |R_A|^2 - R_V R_A^* + |R_T|^2 + R_S R_T^* \right)$$

$$\xi b = 2\Re\left(L_S L_V^* + 3 L_A L_T^* + R_S R_V^* + 3 R_A R_T^* \right)$$

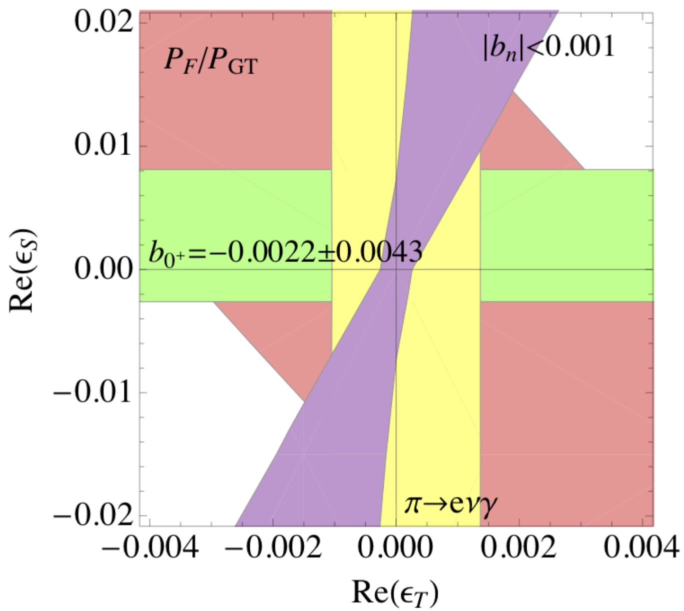
yet unmeasured

$$\xi = |L_V|^2 + 3|L_A|^2 + |L_S|^2 + 3|L_T|^2 + |R_V|^2 + 3|R_A|^2 + |R_S|^2 + 3|R_T|^2$$

F. Glück *et al.*, NP A **593**, 125 (1995)

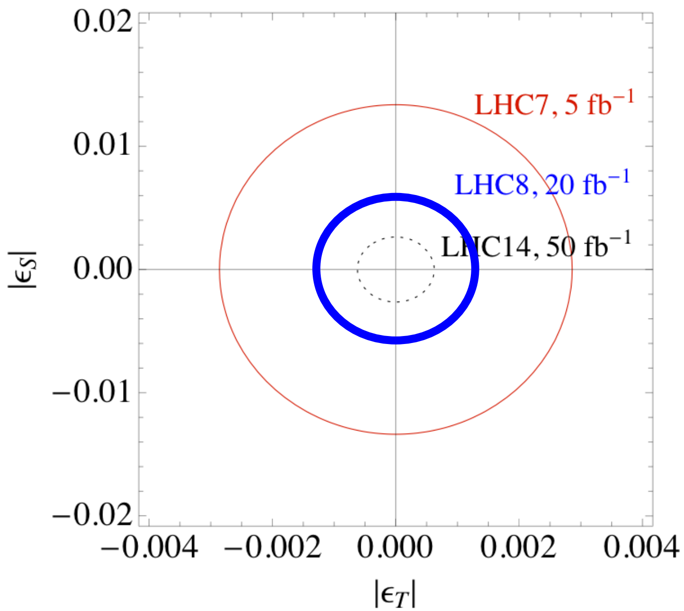
b at 10^{-3} level precision

$O(1) \cdot L_S / L_V$



$O(1) \cdot L_T / L_A$

LHC limits

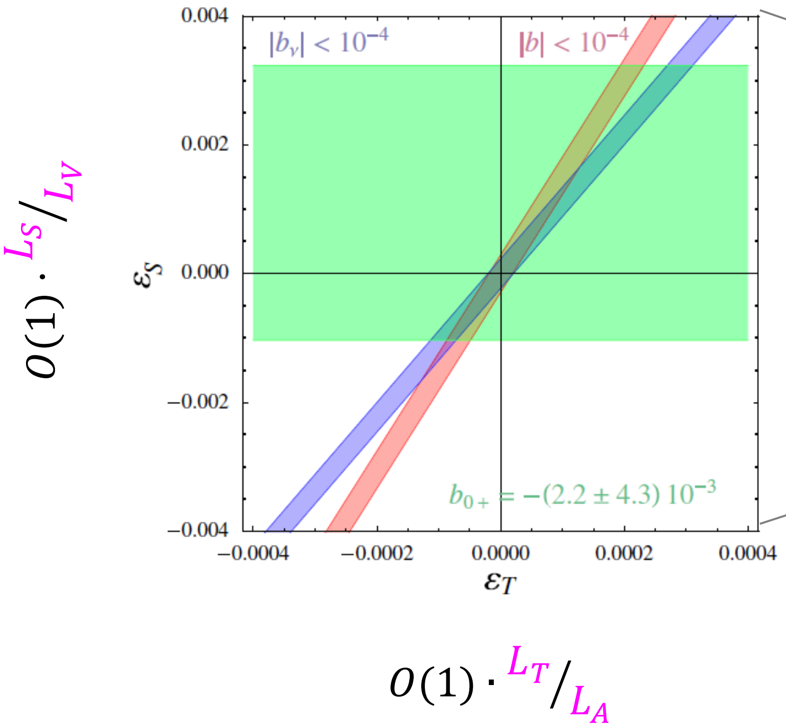


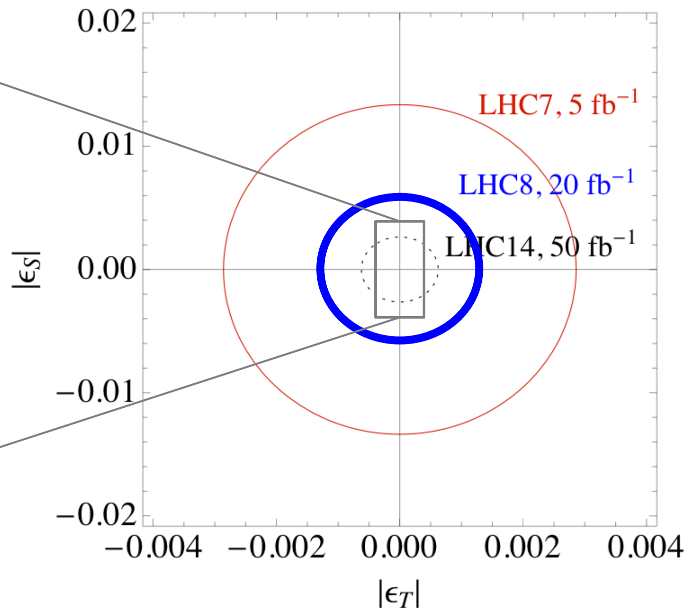
CMS search for $pp \to e + \nu + X$

M. González-Alonso, O. Naviliat-Cuncic, NPAC-13-03; arXiv:1304.1759
see also: G. Konrad *et al.,* in: Proc. 5th BEYOND 2010, World Scientific, 660, 2011, arXiv: 1007.3027v2 (2010)

b at 10^{-4} level precision

LHC limits



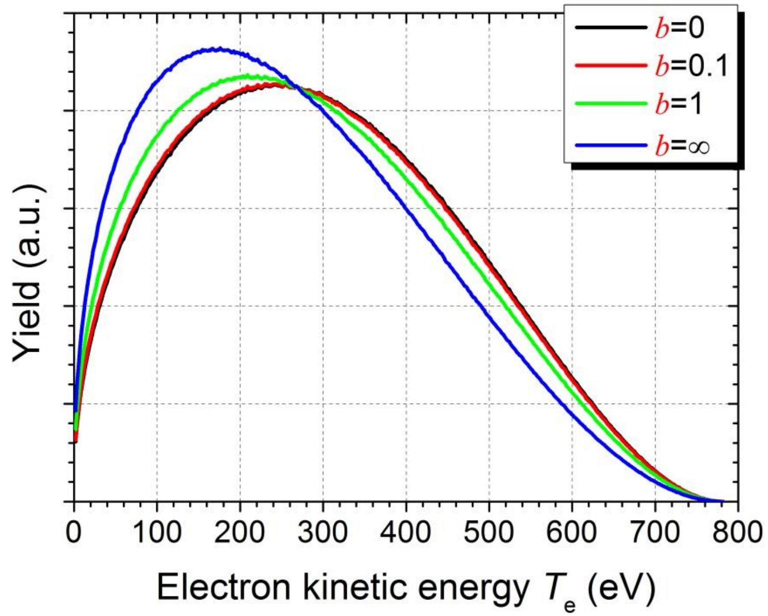


CMS search for $pp \to e + \nu + X$

T. Bhattacharya *et al.*, PR D**85**,054512 (2012)
M. González-Alonso, O. Naviliat-Cuncic, NPAC-13-03; arXiv:1304.1759

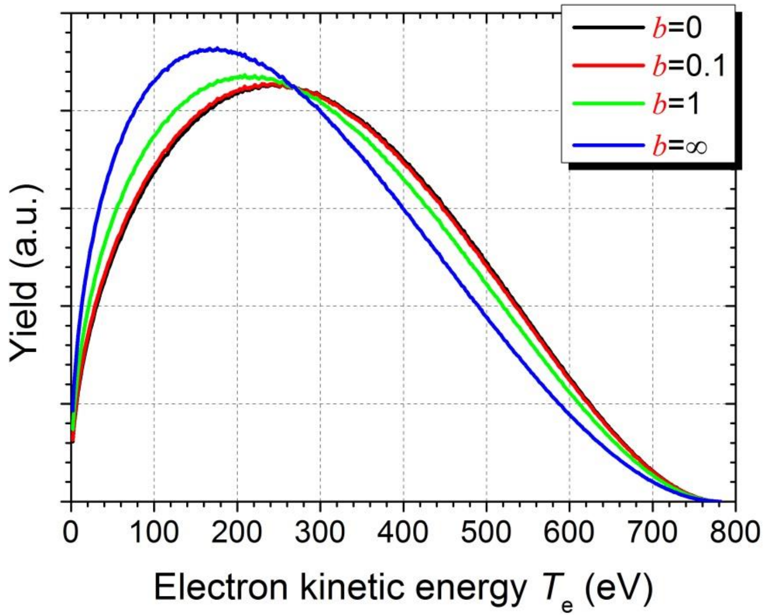
Determination of the Fierz term *b*

Electron energy spectrum



Future prospects for *b*: Nab @ SNS

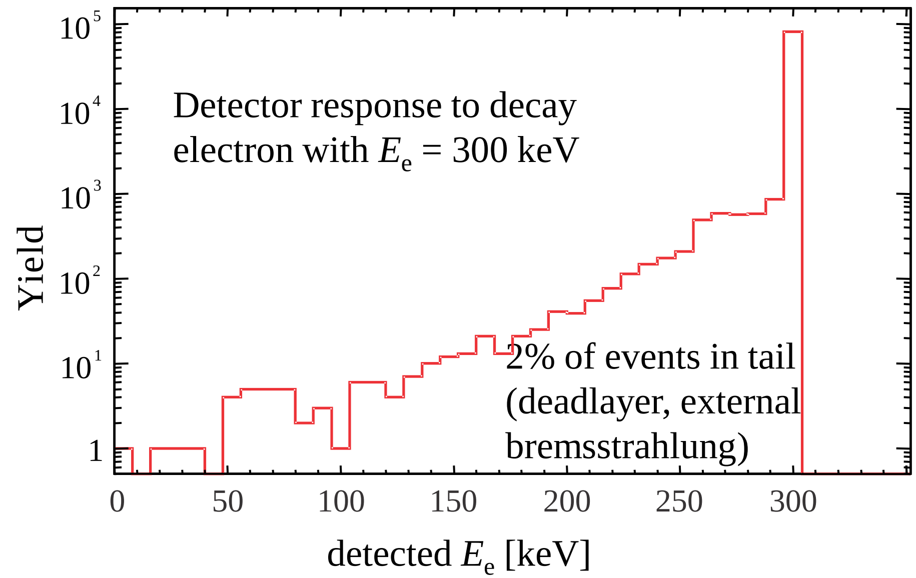
Electron energy spectrum



design goal: 0.003

Systematic uncertainties

- Electron energy determination:

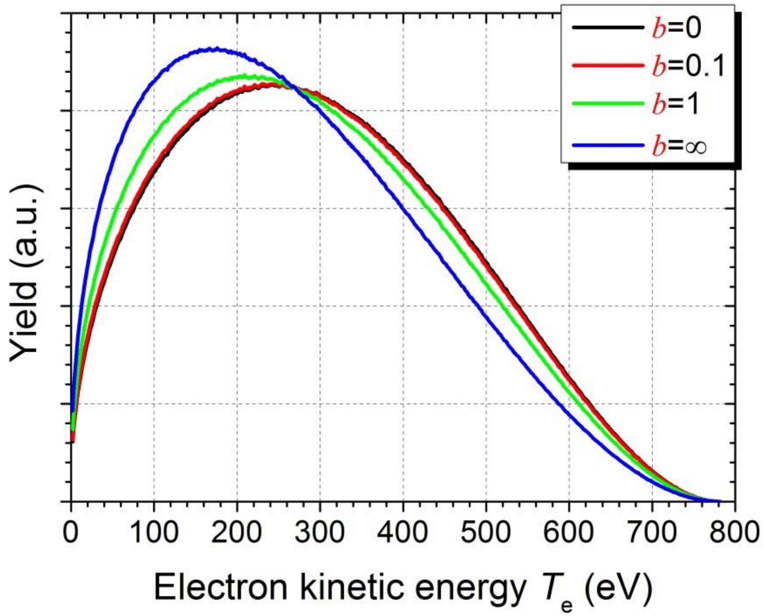


- Background

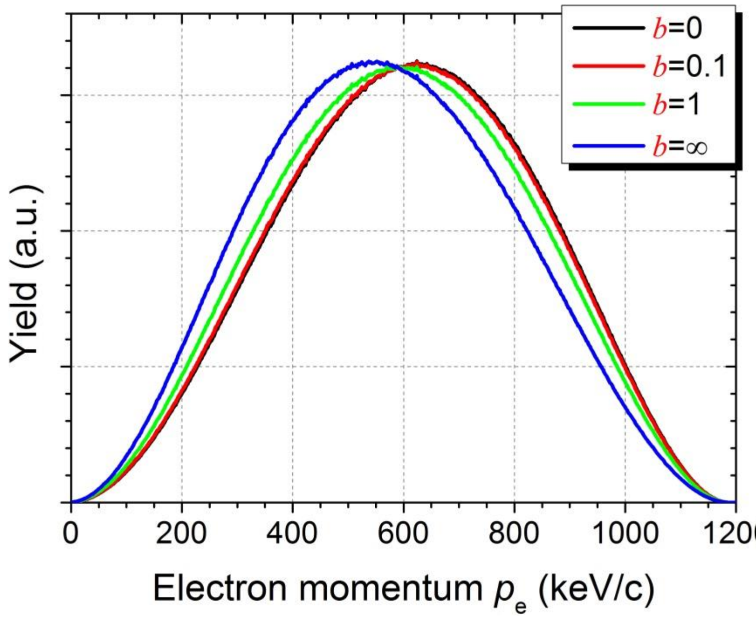
D. Počanić *et al.*, NIM A **611**, 211 (2009)
S. Baeßler *et al.*, arXiv:1209.4663v1 [nucl-ex], 2012

Future prospects for *b*: PERC @ FRM II

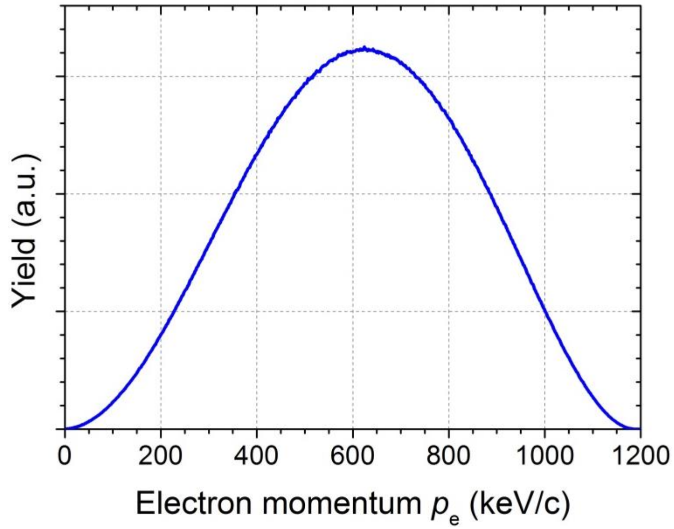
Electron energy spectrum

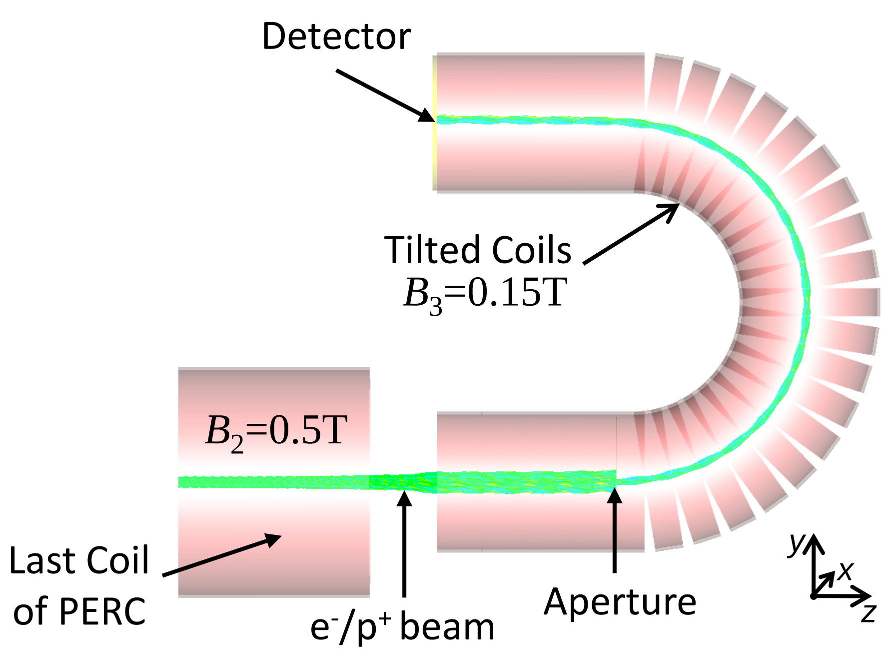


Electron momentum spectrum



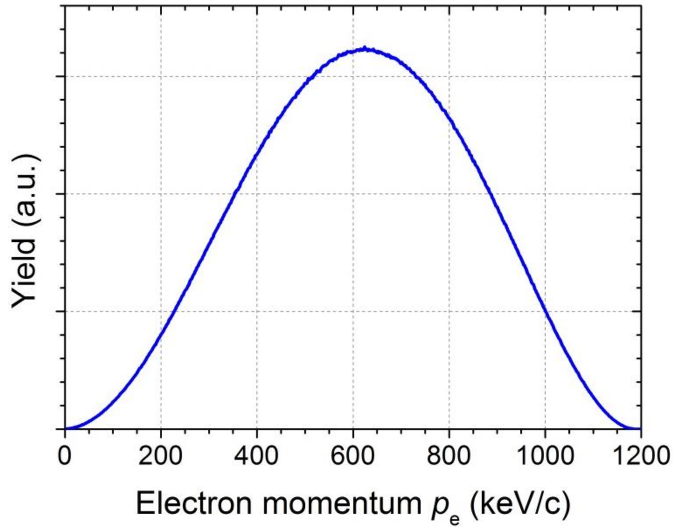
Novel **R×B** drift momentum spectrometer

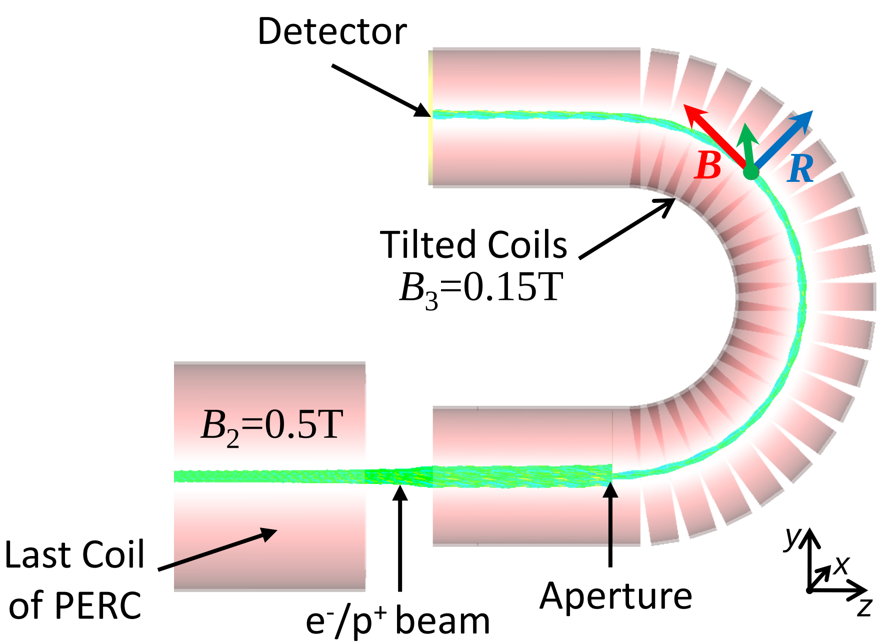




X. Wang, H.A., G.K., NIM A **701** (2013), 254; arXiv:1209.6595

Novel **R×B** drift momentum spectrometer

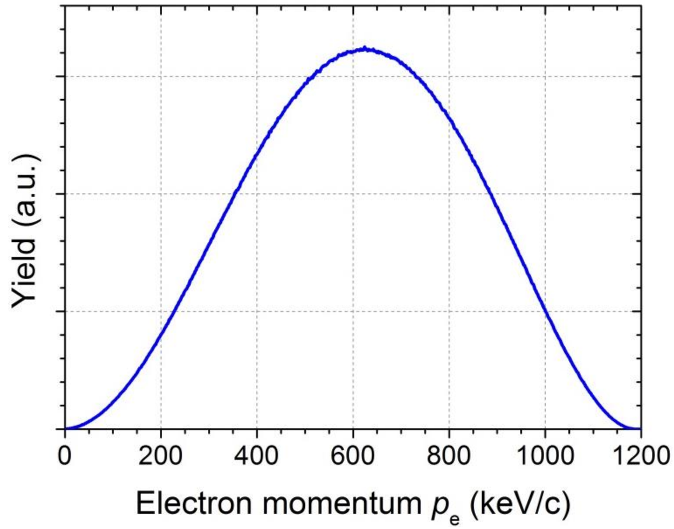


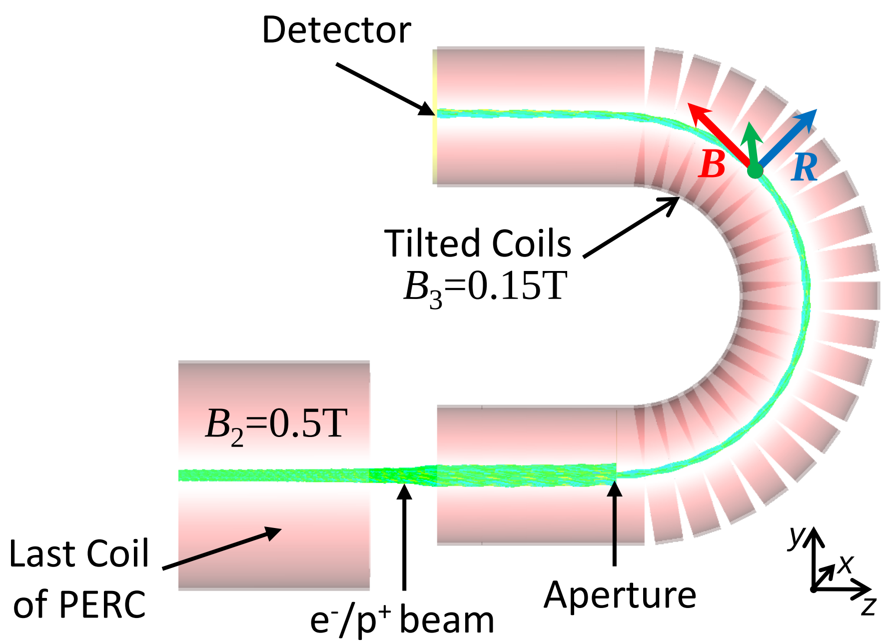


$$\mathbf{v}_\mathbf{d} \propto \frac{\boldsymbol{R}\times\boldsymbol{B}}{qR^2B^2}$$

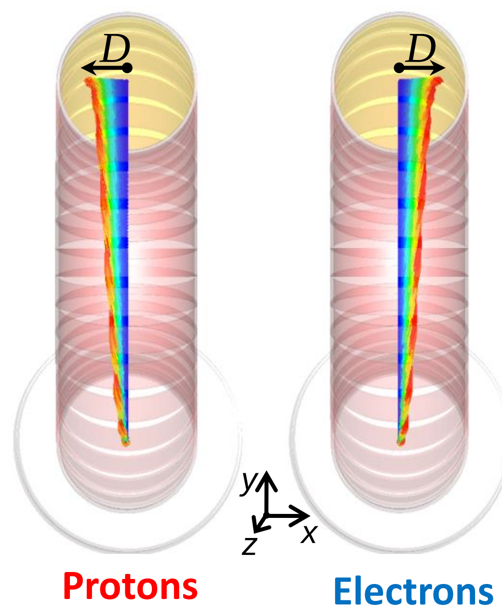
X. Wang, H.A., G.K., NIM A **701** (2013), 254; arXiv:1209.6595

Novel **R×B** drift momentum spectrometer

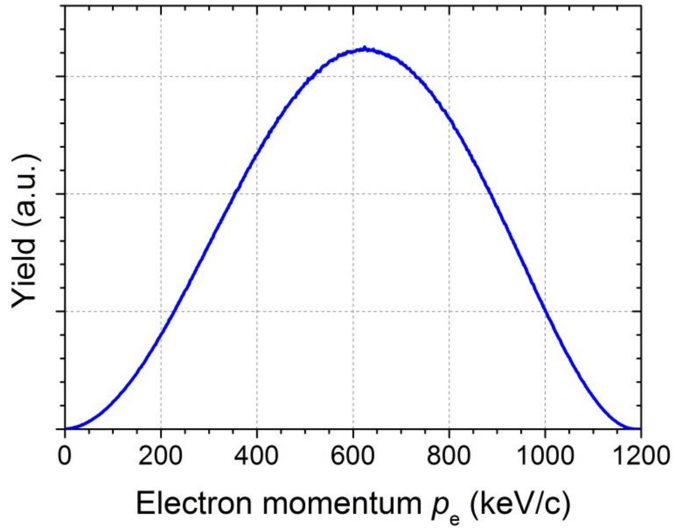


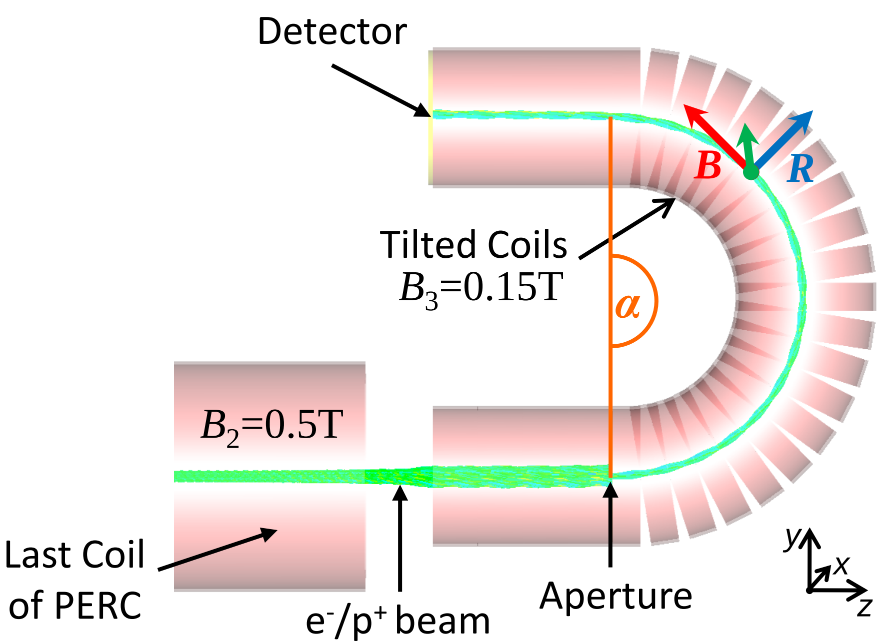


$$\mathbf{v_d} \propto \frac{\boldsymbol{R} \times \boldsymbol{B}}{qR^2B^2}$$

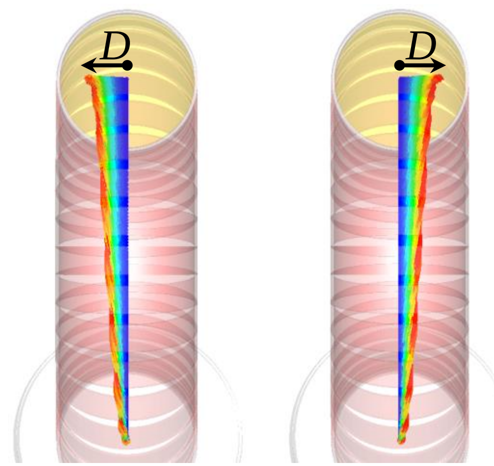


Novel **R×B** drift momentum spectrometer



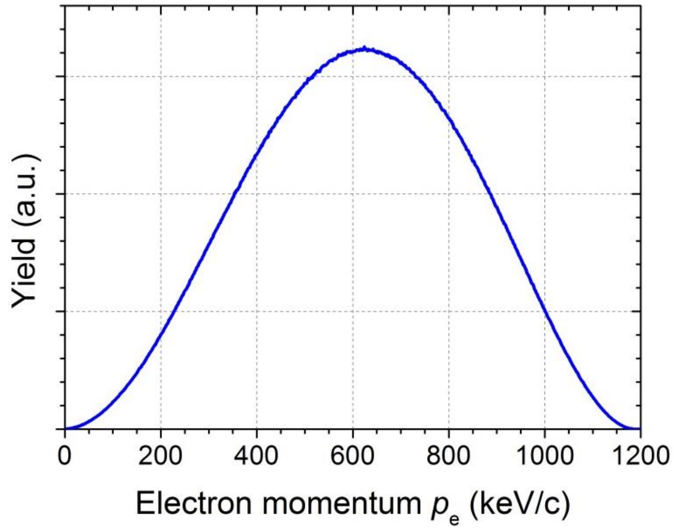


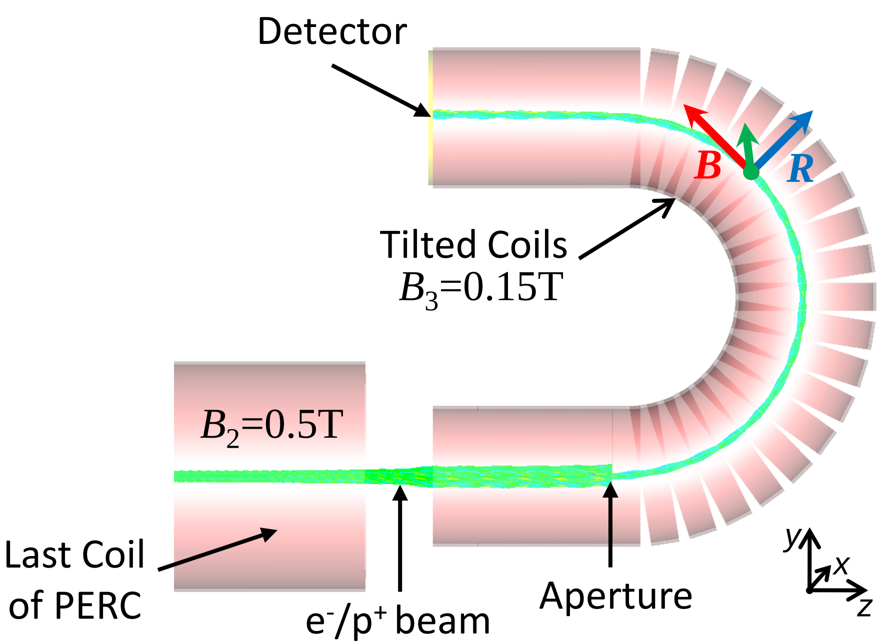
$$\mathbf{v_d} \propto \frac{\mathbf{R} \times \mathbf{B}}{qR^2B^2}$$

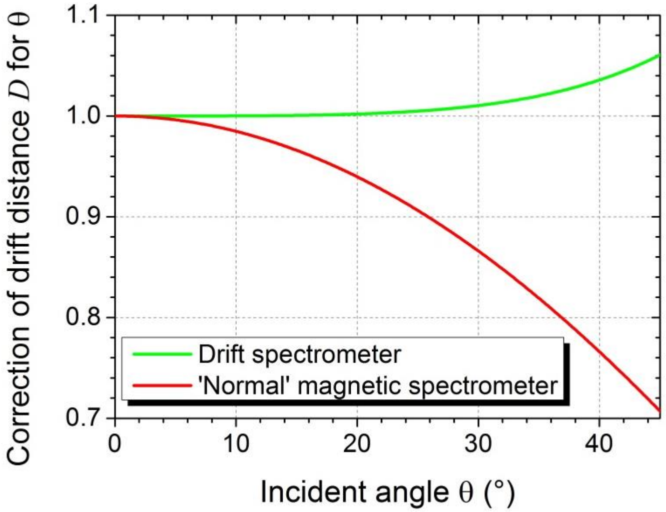


$$D(p,\theta) = \int_T v_d \, dt = \frac{p}{qB_3} \cdot \alpha \cdot \frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

Novel **R×B** drift momentum spectrometer

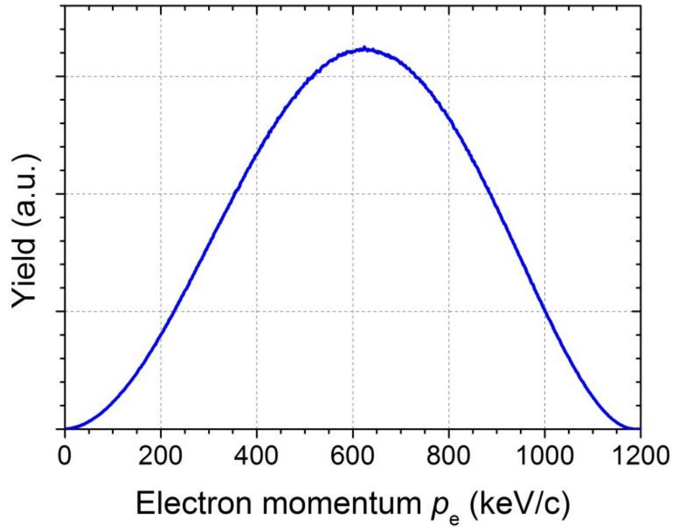


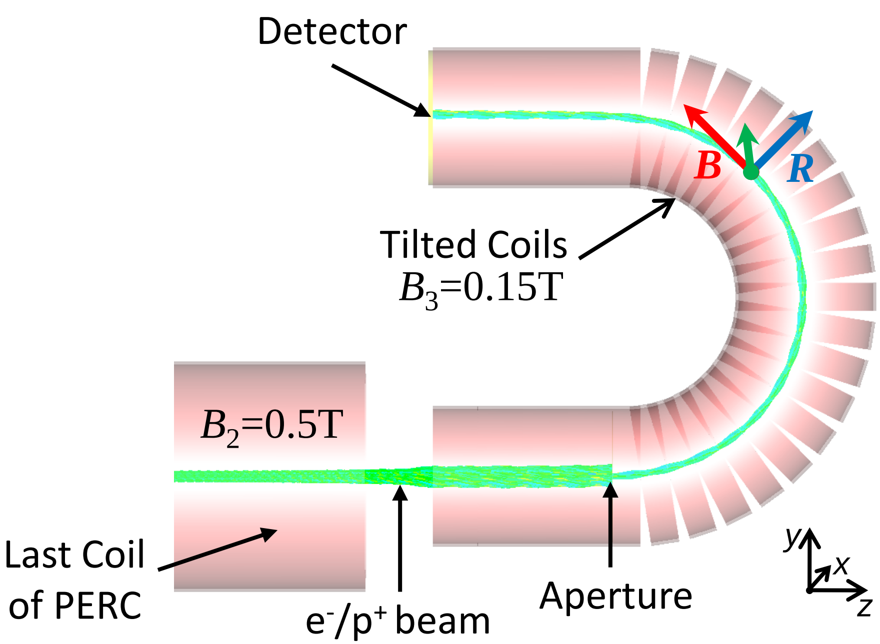


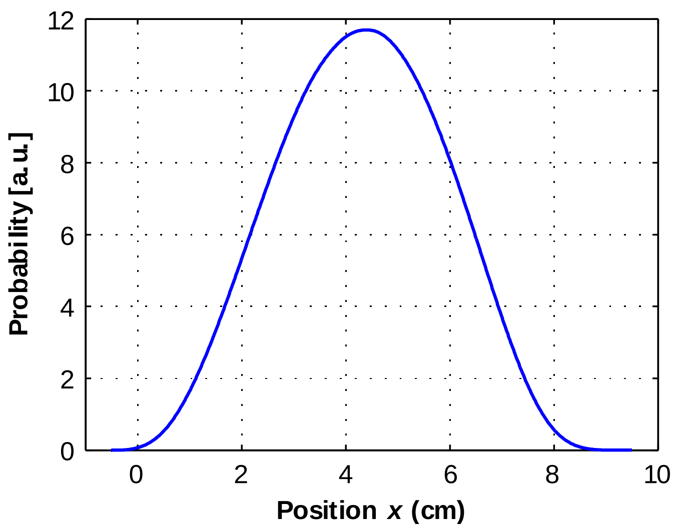


$$D(p,\theta) = \int_T v_d \mathrm{d}t = \frac{p}{qB_3} \cdot \alpha \cdot \frac{1}{2}(\cos\theta + \frac{1}{\cos\theta})$$

Novel R×B drift momentum spectrometer

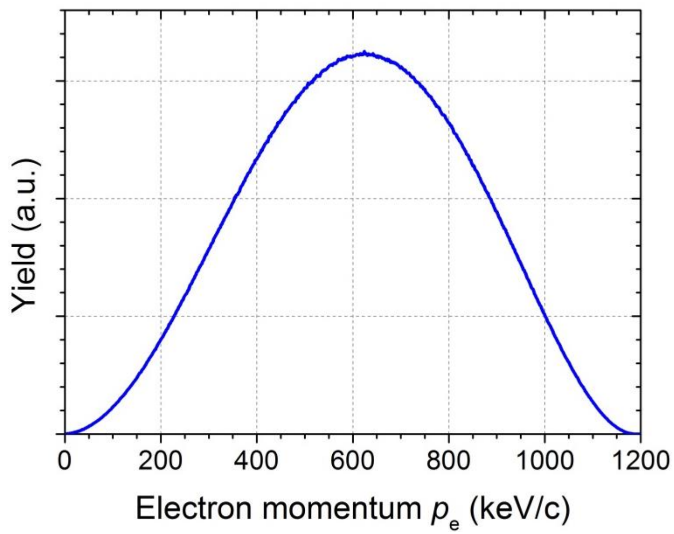


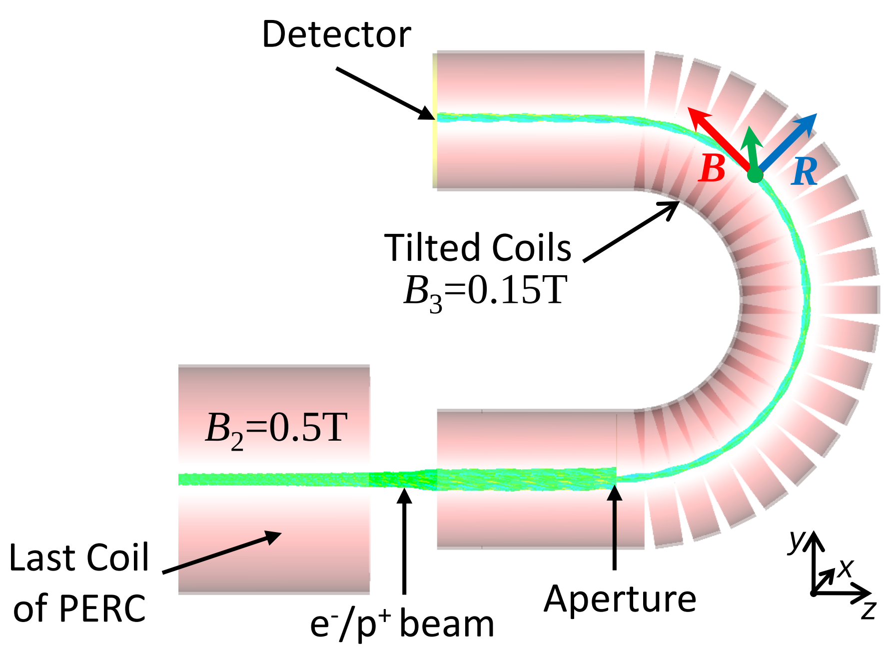




Momentum resolution of 14.4 keV/c per mm can be achieved

Novel **R×B** drift momentum spectrometer





- \+ adiabatic transport of particles
- \+ low momentum measurements
- \+ large acceptance of θ
- \+ small corrections for θ

- – small drift distances □(cm)

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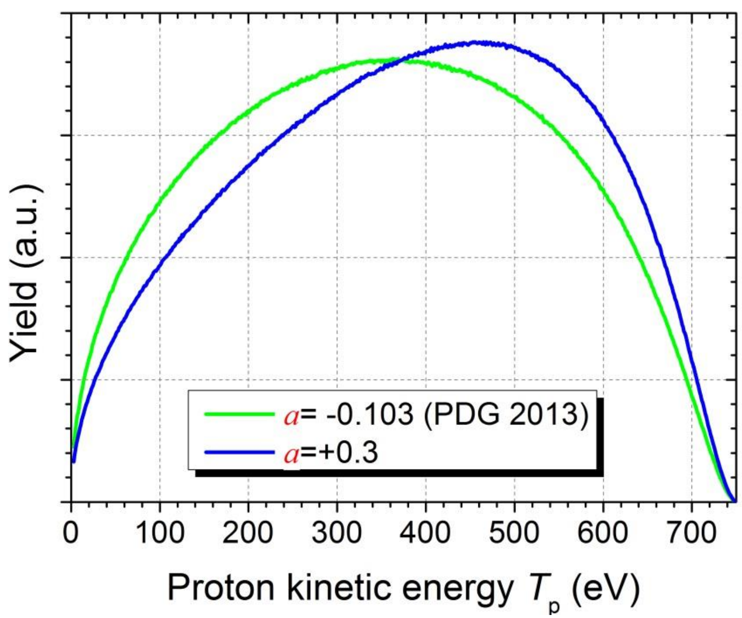
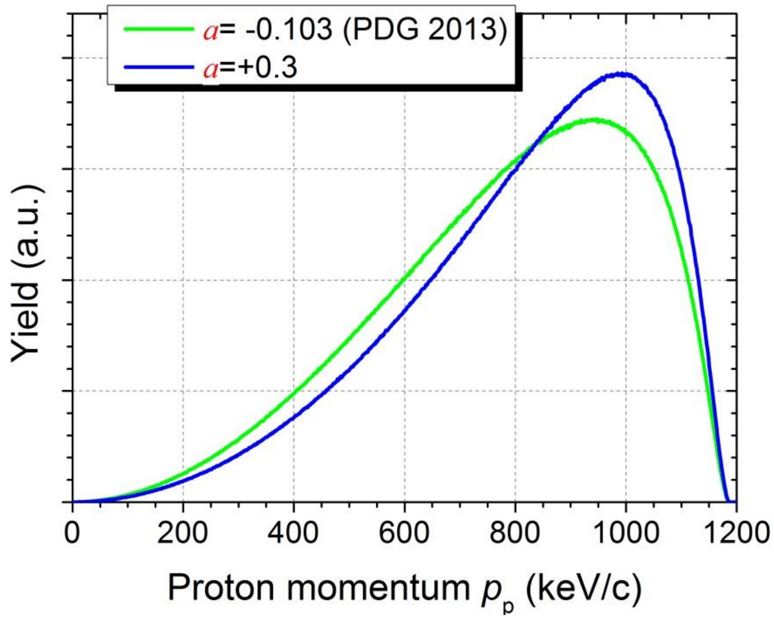
Future prospects for *a*: **R×B** @ PERC

Proton energy spectrum



Proton momentum spectrum



goal: < 0.1 %

\+ extremely versatile

Summary and Outlook

- Current best value for a=-0.1017(51) dates from 1978
- Data analyses of 2013 beam times of *a*SPECT and aCORN are in progress
- Expect a new value for a with < 3 % precision
- Nab and PERC intend to measure a with <0.1% precision
- UCNb (UCNB), Nab, and PERC aim to perform *first* measurement of Fierz term b in neutron β-decay
- Novel $\mathbf{R}\times\mathbf{B}$ spectrometer for momentum measurements
- Several detector concepts for PERC under investigation
- a and b improve limits on scalar and tensor currents
- 10^{-3} level b measurements complementary to improved LHC results