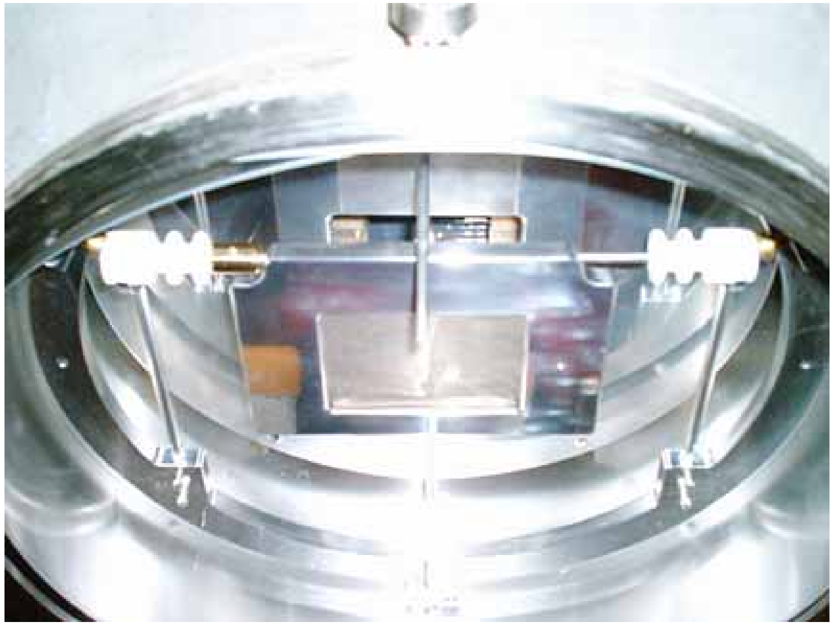


Precision Measurements in Neutron Decay

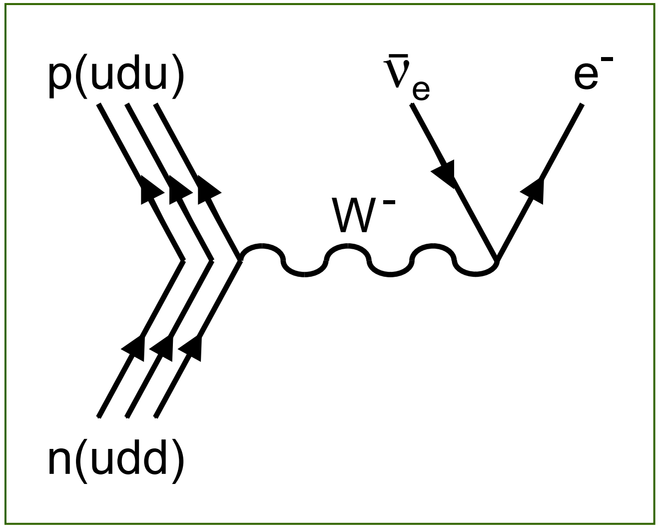
Marc Schumann
Physikalisches Institut,
University of Heidelberg

PERKEO II Collaboration

Neutron Decay

- Lifetime $\tau \approx$ 15 min
- electron E_{max} = 782 keV
- only first particle generation
- Standard Model, *V–A* Theory:

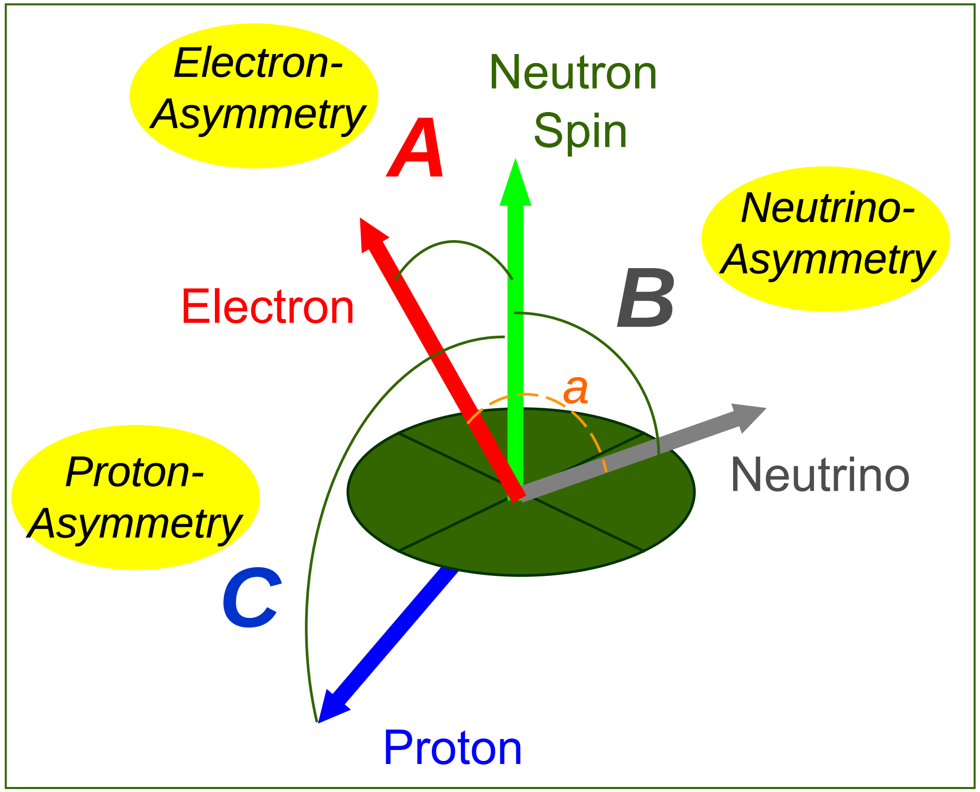
$$\tau \propto \frac{1}{|V_{ud}|^2 \, (g_V^2 + 3 g_A^2)} \qquad \lambda = \frac{g_A}{g_V}$$



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

Neutron Physics
= Particle Physics at low Energy

(Our) Observables in Neutron Decay



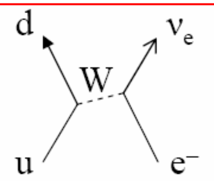
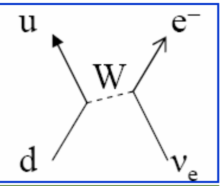
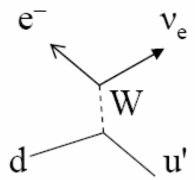
Transition Probability:

$$\mathrm{d}\omega \propto G_F^2 \, |V_{ud}|^2 \, F(E) \left(1 + a\,\frac{\mathbf{p}_e \mathbf{p}_\nu}{E E_\nu} + b\,\frac{m_e}{E} + \langle \mathbf{s}_n \rangle \left[A\,\frac{\mathbf{p}_e}{E} + B\,\frac{\mathbf{p}_\nu}{E_\nu} + D\,\frac{\mathbf{p}_e \times \mathbf{p}_\nu}{E E_\nu} \right] \right)$$

1. Determination of $\lambda = g_A/g_V$

- Electron Asymmetry: $$A = -2\,\frac{\lambda^2+\lambda}{1+3\lambda^2}$$

- All semileptonic processes are governed by this number:

Cosmology	Primordial element formation	$n + e+ \rightarrow p + \nu'_e$	$\sigma_\nu \sim 1/\tau$	
	(^{2}H, ^{3}He, ^{4}He, ^{7}Li, …)	$p + e^- \rightarrow n + \nu_e$	$\sigma_\nu \sim 1/\tau$	
		$n \rightarrow p + e^- + \nu'_e$	τ	
Astronomy	Solar cycle	$p + p \rightarrow {}^2H + e^+ + \nu_e$		
		$p + p + e^- \rightarrow {}^2H + \nu_e$ etc.	$\sim (g_A/g_V)^5$	
	Neutron star formation	$p + e^- \rightarrow n + \nu_e$		
Particle Physics	Pion decay	$\pi^- \rightarrow \pi^0 + e^- + \nu'_e$		
	Neutrino detectors	$\nu'_e + p \rightarrow e^+ + n$		
	Neutrino forward scattering	$\nu_e + n \rightarrow e^- + p$ etc.		
	W and Z production	$u' + d \rightarrow W^- \rightarrow e^- + \nu'_e$ etc.		

courtesy of D. Dubbers

2. Right–handed Currents in weak i.a.

- Weak interaction is maximally parity violating in the SM
- SM describes parity violation; no motivation given $\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)$
- Cosmology: early universe should be LR–symmetric

Left–Right–Symmetric Models *eg: PRL **38**, 22 (1977)*

- $\mathrm{SU}(4)_{EC} \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \longrightarrow \mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)$
- 2 bosons (W_1, W_2) in the „symmetric base“; W_2 very heavy

$$\begin{pmatrix} W_L \\ W_R \end{pmatrix} = \begin{pmatrix} \cos\zeta & -\sin\zeta \\ e^{i\phi}\sin\zeta & e^{i\phi}\cos\zeta \end{pmatrix} \begin{pmatrix} W_1 \\ W_2 \end{pmatrix} \qquad \lambda' = \frac{g'_A}{g'_V} \qquad \delta = \frac{m_1^2}{m_2^2}$$

ν–asymmetry *B* is sensitive right–handed currents

Right–handed Currents?

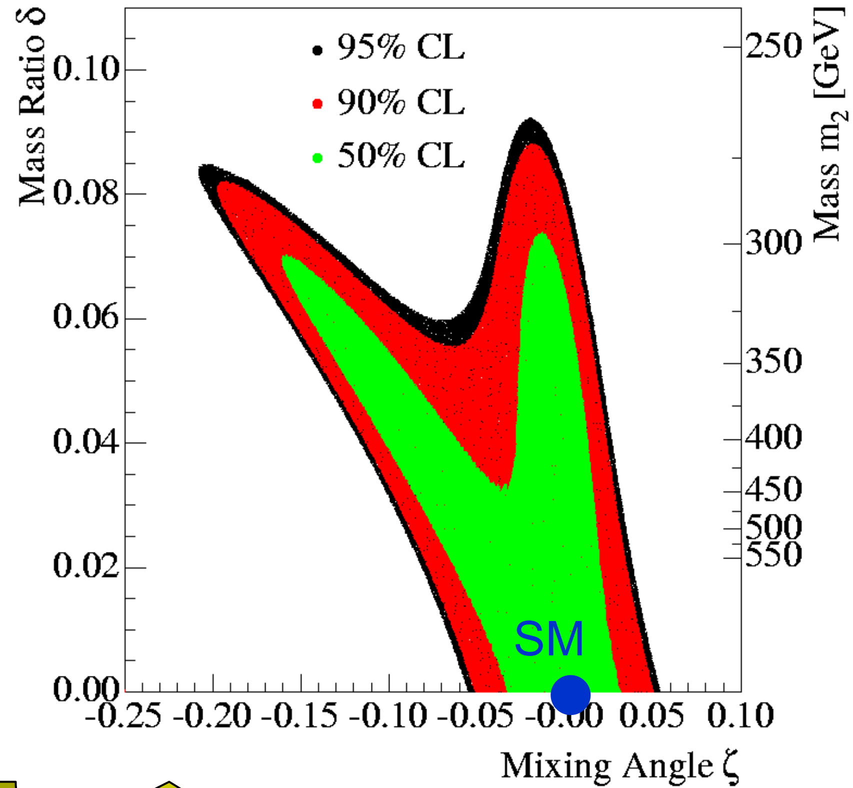
Standard Model

$$
\begin{aligned}
A &= -2\,\frac{\lambda^2+\lambda}{1+3\lambda^2}\\
B &= 2\,\frac{\lambda^2-\lambda}{1+3\lambda^2}\\
a &= \frac{1-\lambda^2}{1+3\lambda^2}\\
R_{ft} &= \frac{2}{1+3\lambda^2} \qquad R_{ft} = \frac{f^R\tau_n\ln(2)}{ft_{0^+\to 0^+}}
\end{aligned}
$$

Manifest LR-Symmetric Model

$$
\begin{aligned}
A &= 2\,\frac{\lambda'(r_V r_A-1)+\lambda'^2(r_A^2-1)}{(1+r_V^2)+3\lambda'^2(1+r_A^2)}\\
B &= 2\,\frac{\lambda'^2(1-r_A^2)+\lambda'(r_V r_A-1)}{(1+r_V^2)+3\lambda'^2(1+r_A^2)}\\
a &= \frac{(1+r_V^2)-\lambda'^2(1+r_A^2)}{(1+r_V^2)+3\lambda'^2(1+r_A^2)}\\
R_{ft} &= \frac{2(1+r_V^2)}{(1+r_V^2)+3\lambda'^2(1+r_A^2)}
\end{aligned}
$$

$$(A, B, \tau_n) \longrightarrow (\lambda', \zeta, \delta = \frac{m_1^2}{m_2^2})$$



3. Scalar and Tensor Couplings

Most general Lagrangian:

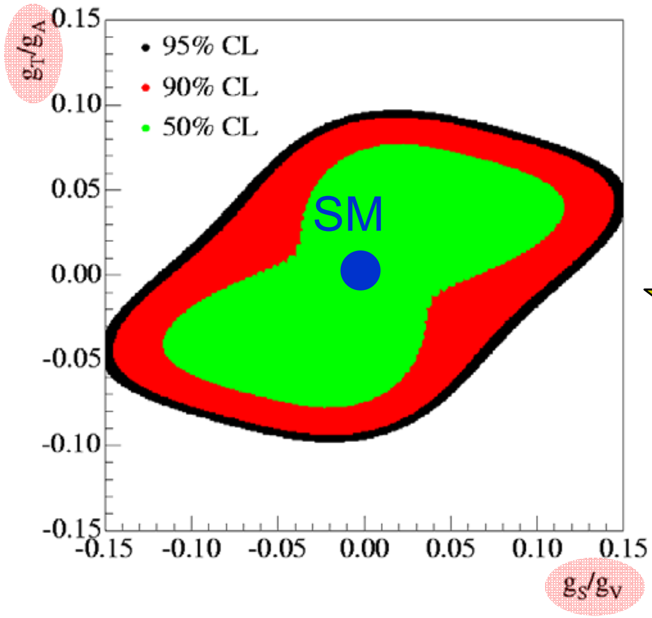
$$\mathcal{L} = \sum_k (\overline{p}\Omega_k n)\,(\overline{e}\Omega_k(g_k + g'_k\gamma^5)\nu_e) + \text{h.c.}$$

$$\begin{aligned}
\Omega_S &= 1 && \text{Scalar}\\
\Omega_V &= \gamma^\mu && \text{Vector}\\
\Omega_T &= \frac{1}{\sqrt{2}}\sigma^{\mu\nu} && \text{Tensor}\\
\Omega_A &= \gamma^\mu\gamma^5 && \text{Axial-vector}\\
&\cancel{\Omega_P = \gamma^5 \quad \text{Pseudo-scalar}}
\end{aligned}$$

Right-handed Scalar and Tensor Model:

*e.g.: Sov.J.Nucl. Phys. **53**, 260 (1991); Rev.Mod.Phys. **78**, 991 (2006)*

$$\frac{g'_V}{g_V} = 1 \qquad \frac{g'_A}{g_A} = 1 \qquad \frac{g'_S}{g_V} = -\frac{g_S}{g_V} \qquad \frac{g'_T}{g_A} = -\frac{g_T}{g_A}$$



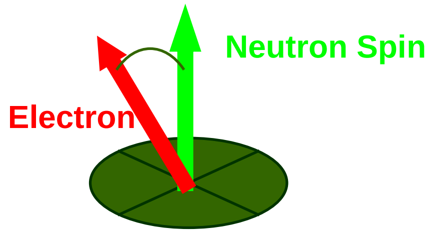
$$\begin{aligned}
A &= -2\,\frac{g_A^2 + g_A g_V + g_S g_T + g_T^2}{g_V + 2g_A^2 + g_S + 3g_T^2}\\
B &= 2\,\frac{g_A^2 - g_A g_V + g_S g_T - g_T^2}{g_V + 2g_A^2 + g_S + 3g_T^2}\\
a &= \frac{g_V^2 - g_A^2 - g_S^2 + g_T^2}{g_V + 2g_A^2 + g_S + 3g_T^2}\\
C &= 4x_C\,\frac{g_A g_V + g_T^2}{g_V + 2g_A^2 + g_S + 3g_T^2}\\
R_{ft} &= 2\,\frac{g_V^2 + g_S^2}{g_V + 2g_A^2 + g_S + 3g_T^2}
\end{aligned}$$

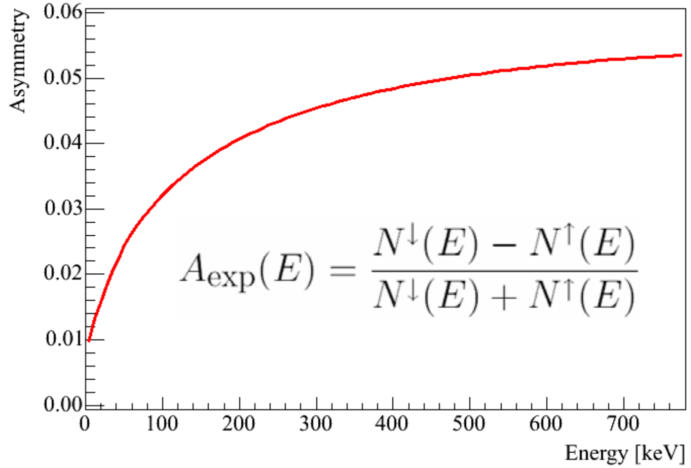
$$x_C = 0.27484$$

The experimental Signature

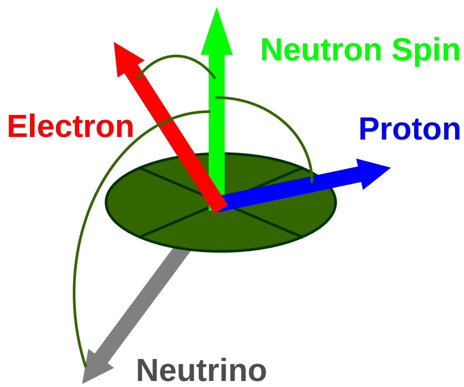
Systematically clean method: Integration over two hemispheres

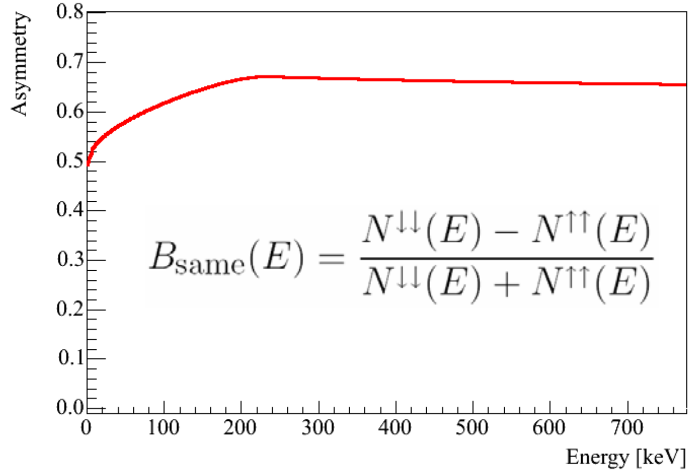
- Electron Asymmetry *A*
  - → measure only electrons



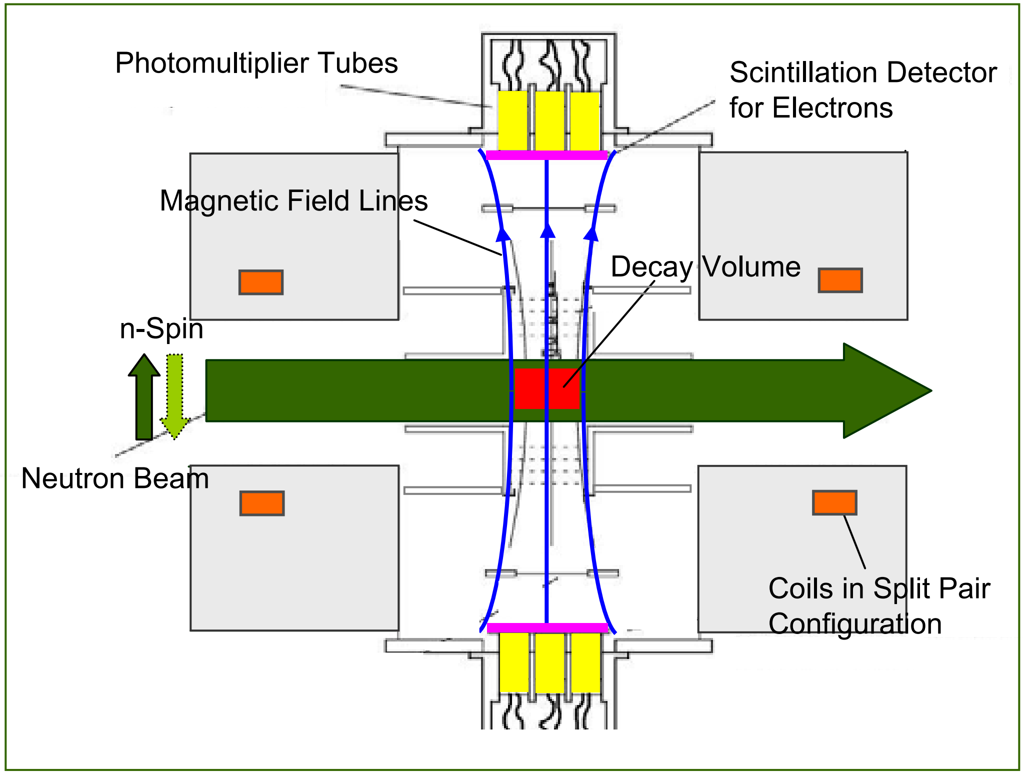


- Neutrino Asymmetry *B* – same hemisphere
  - → coincidence measurement
  - → low dependence on energy calibration and energy resolution
  - → obtain proton asymmetry *C* from *B*–measurement





The Spectrometer: PERKEO II



Magnetic field (1 T):

- perpendicular to neutron beam
- parallel alignment of neutron spin
- separation into hemispheres
  - ⇒ integration over hemispheres
  - ⇒ 2 x 2 π detector
- guide e^-, p onto detectors
  - ⇒ detect all particles
- low background

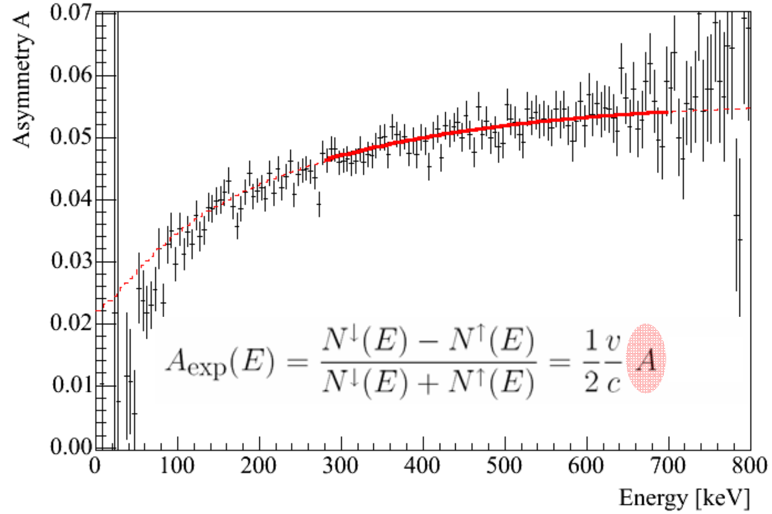
Electron Asymmetry A

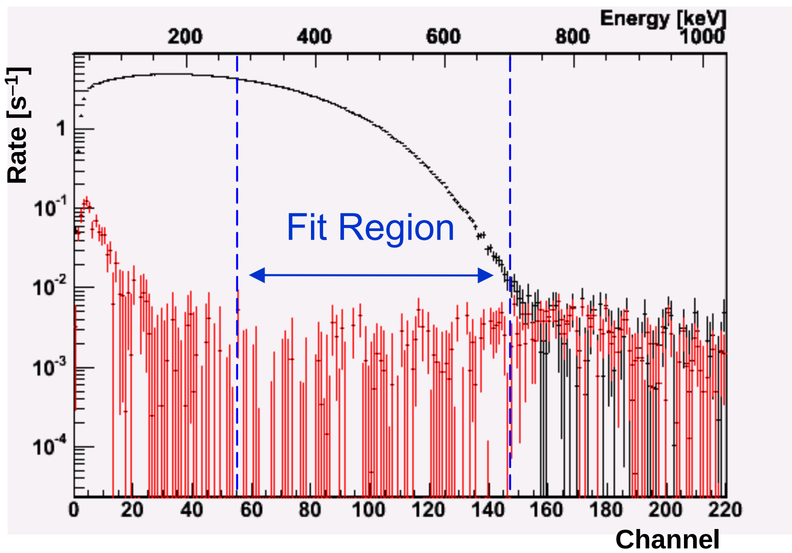
Results of PhD thesis D. Mund

- Polarization heavily improved
  (Supermirror Polarizers and ^{3}He cells)
- 160 Million Events
- Still limited by Statistics
- Small Background effects (0.1%).
  Background cannot be further reduced with this setup
- almost no (0.4%) corrections to asymmetry *A* are left

Our Result *(preliminary)*:

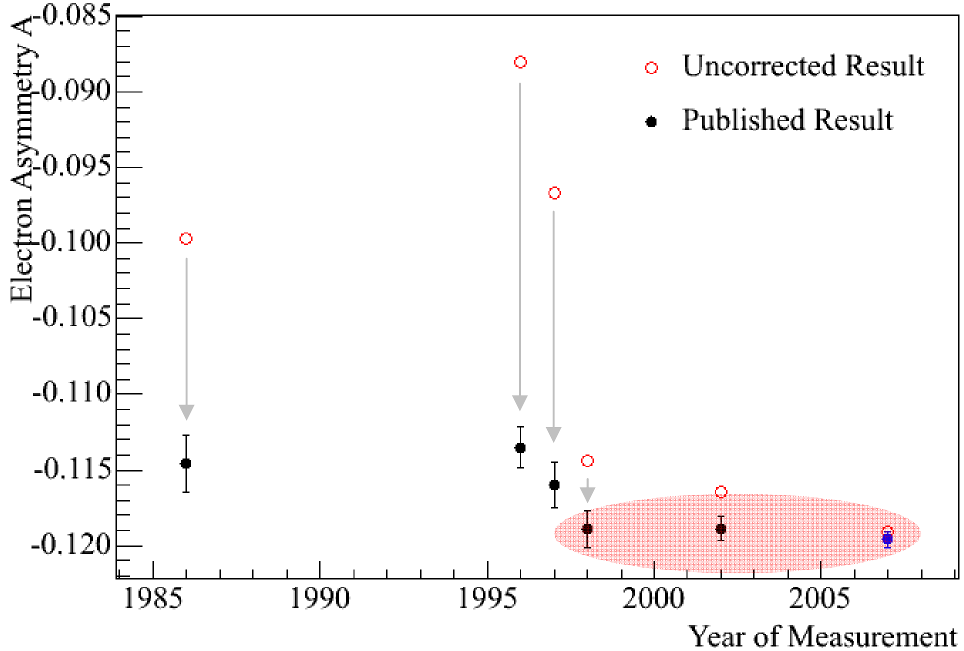
$A = -0.1196(5)$





Electron Asymmetry Results

- Result confirms former PERKEO II measurements
- Only PERKEO values have small corrections
- averaging all results is not reasonable



- (our) new mean value:

$A_{PII} = 0.1193(4)$

$\lambda_{PII} = -1.2749(11)$ *error: 0.09%*

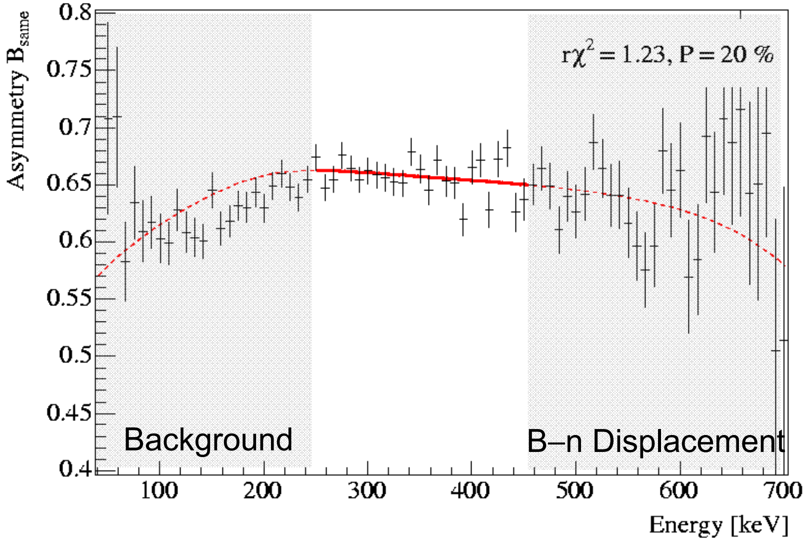
preliminary

Result: Asymmetry *B*

- only experiment that measures *B* in the same hemisphere

$\Rightarrow$ result is almost independent from detector calibration

- result limited by statistics and error in beam position relative to magn. field ($\rightarrow$ magnetic mirror effect)

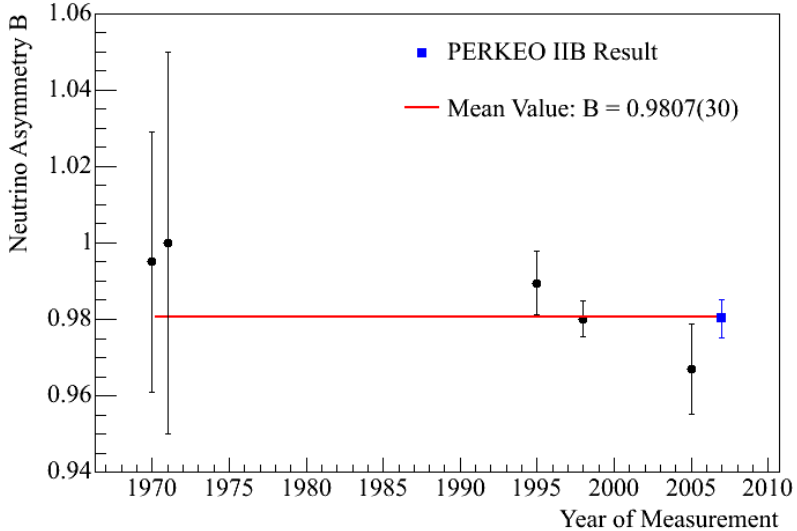


Our Result:

$B = 0.9802(50)$

New mean Value:

$B_{mean} = 0.9807(30)$



Proton–Asymmetry *C*

- measure proton emission w.r.t. neutron spin: $N^\uparrow$, $N^\downarrow$ (coincidence measurement with electrons)
- use electron spectra and integrate over electron energy *E*

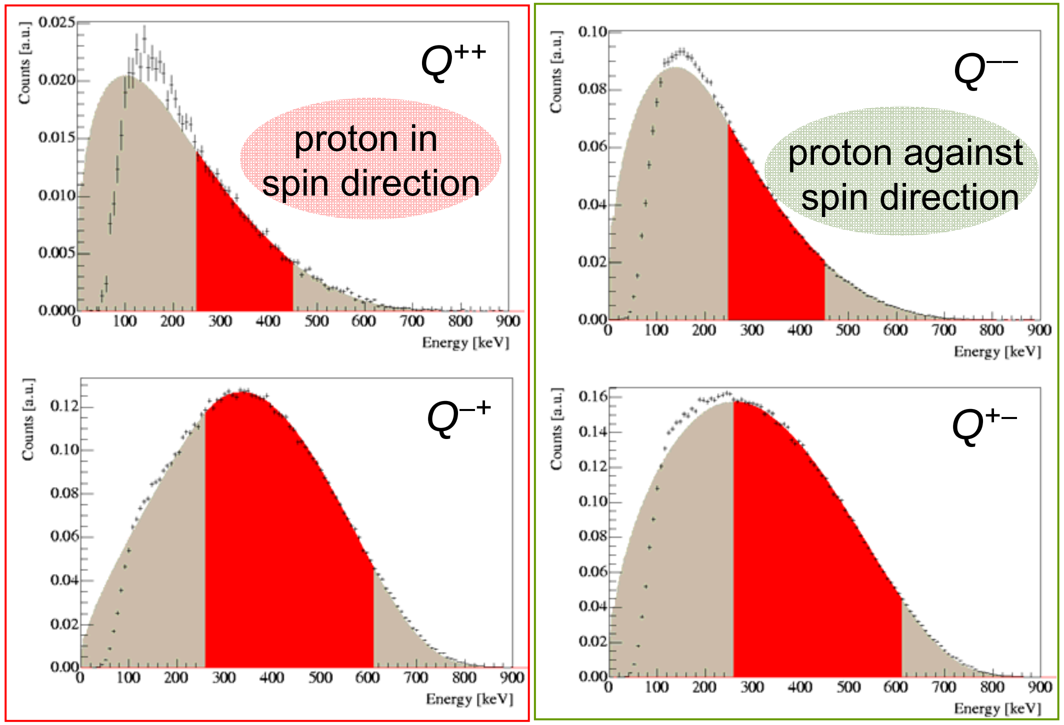
$$N^\uparrow = Q^{++}(E) + Q^{-+}(E) \qquad N^\downarrow = Q^{--}(E) + Q^{+-}(E)$$

- define Proton–Asymmetry

$$C = \frac{\int(Q^{++}(E) + Q^{-+}(E))\mathrm{d}E - \int(Q^{--}(E) + Q^{+-}(E))\mathrm{d}E}{\int(Q^{++}(E) + Q^{-+}(E))\mathrm{d}E + \int(Q^{--}(E) + Q^{+-}(E))\mathrm{d}E}$$

- Problem: Energy threshold for electron detection
- PERKEO II (2001): $C = -0.238(11)$ *PhD M. Kreuz, J. Res. NIST.* ***110*** *(2005)*

Proton–Asymmetry *C*: Results



1) One-parameter fit
2) Extrapolation
3) Integration

Our Result:

C = –0.2377(36)

- first precision measurement of *C*
- error dominated by extrapolation and detector calibration
- *C* is better known than e–ν correlation *a*
- new SM Tests possible:

$$C = x_C(A + B)$$

Input Parameters for χ^2–Scans

- Electron Asymmetry

  A_{PDG} = –0.1173(13) — PDG 2006, error scaled with 2.3

  A_{PII} = –0.1193(4) — only PERKEO II, including new result

  only small corrections

- Neutrino Asymmetry

  B = 0.9807(30) — new mean value

- Proton Asymmetry

  C = –0.2377(36) — first precise value

- e–ν correlation

  a = –0.103(4) — PDG 2006

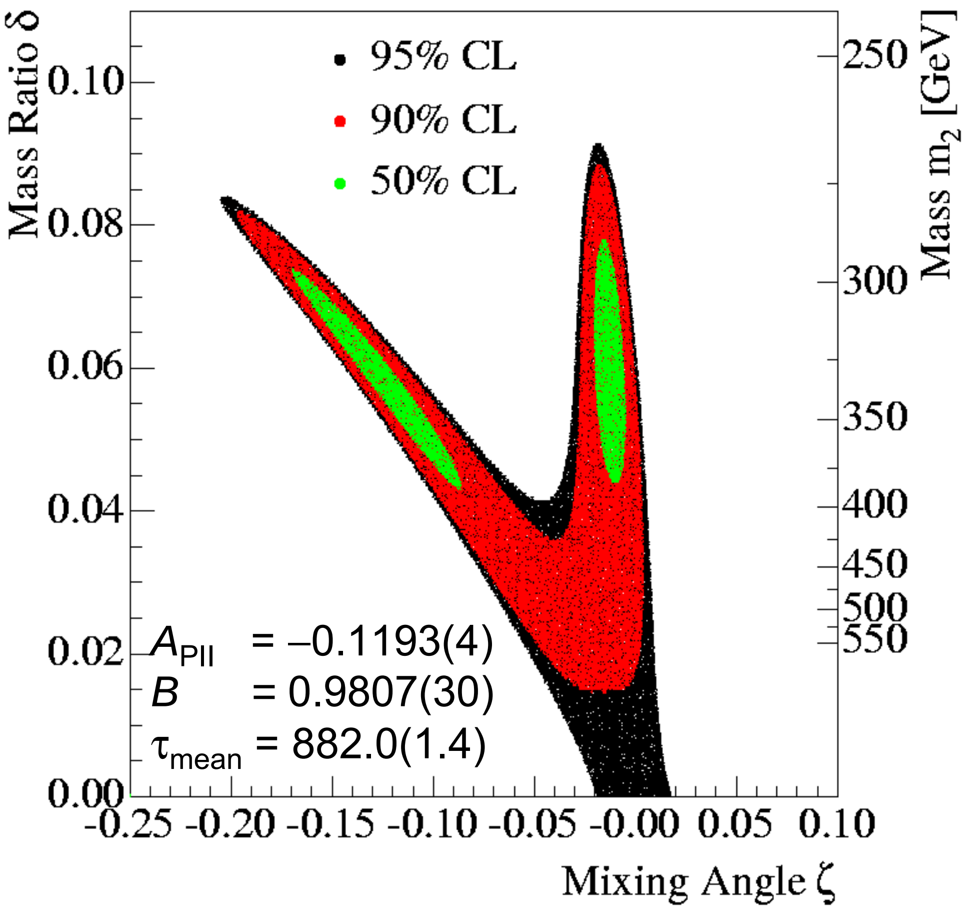
- Neutron Lifetime

  τ_{PDG} = 885.7(8) s — PDG 2006

  τ_{Ser} = 878.5(8) s — Serebrov 2005 *PLB 605, 72 (2005)*

  τ_{mean} = 882.0(14) s — scaling factor 2.47

Right–handed Currents



Neutron Decay Limits (90 % CL):

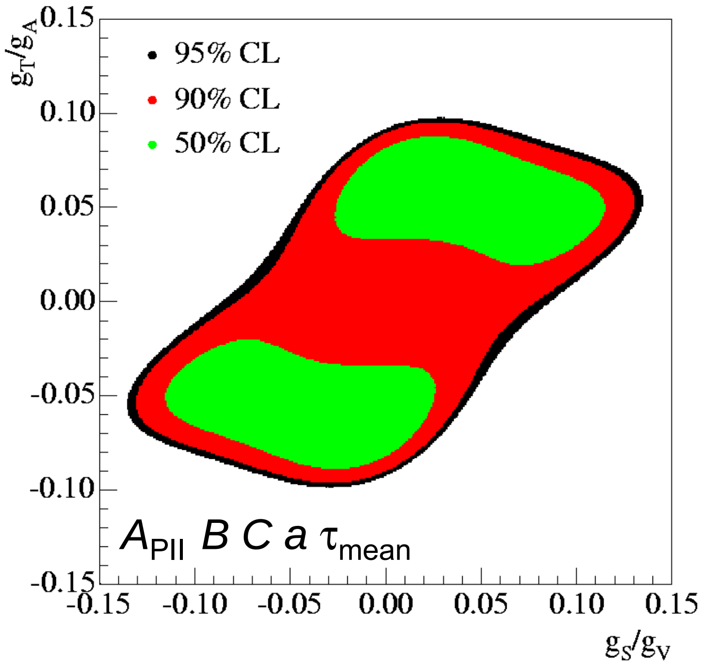
$$-0.1968 \leq \zeta \leq 0.0040$$

$$\delta \leq 0.0885$$

$$\Rightarrow m_2 \geq 270 \text{ GeV}$$

Standard Model included in 95 % CL contour.

Scalar and Tensor Couplings



Neutron decay limits (90% CL):

$|g_S/g_V| \leq 0.130$

$|g_T/g_A| \leq 0.0948$

Standard Model agrees with data.

$g_S \rightarrow$ superallowed β–decays: $|g_S/g_V| \leq 0.0013$ *PRL **94**, 092502 (2005)*

$g_T \rightarrow$ very good limits from n–decay

Summary

PERKEO II allows to measure angular correlations in neutron decay very precisely with low corrections

A = –0.1195(5) *prelim.*

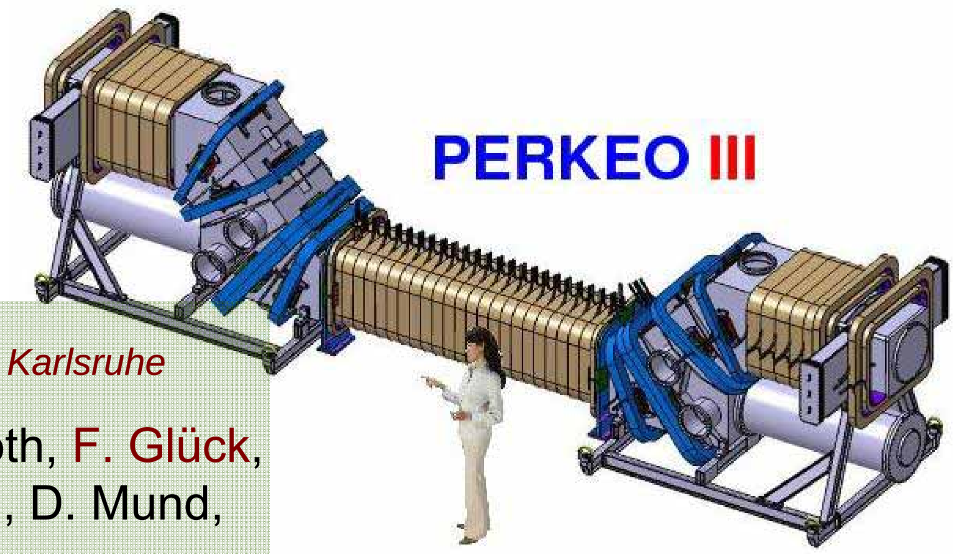
B = 0.9802(50)

C = –0.2377(36)

λ = –1.2749(11) *prelim.*

Standard Model tests

The Future: PERKEO III currently takes data @ ILL



The Team *Uni Heidelberg, ILL, FZ Karlsruhe*

H. Abele, M. Brehm, M. Deissenroth, F. Glück, J. Krempel, M. Kreuz, B. Märkisch, D. Mund, A. Petoukhov, M. S., T. Soldner

Backup

Transition probability

Transition probability for polarized neutrons:

$$d\omega \propto G_F^2 \, |V_{ud}|^2 \, F(E) \left(1 + a\,\frac{\mathbf{p}_e\mathbf{p}_\nu}{EE_\nu} + b\,\frac{m_e}{E} + \langle \mathbf{s}_n \rangle \left[A\,\frac{\mathbf{p}_e}{E} + B\,\frac{\mathbf{p}_\nu}{E_\nu} + D\,\frac{\mathbf{p}_e \times \mathbf{p}_\nu}{EE_\nu} \right] \right)$$

e-ν-correlation β–asymmetry ν–asymmetry triple correlation

a=–0.103(4) A=–0.1173(13) B=0.901(4) D=–4(6)·10^{-4}

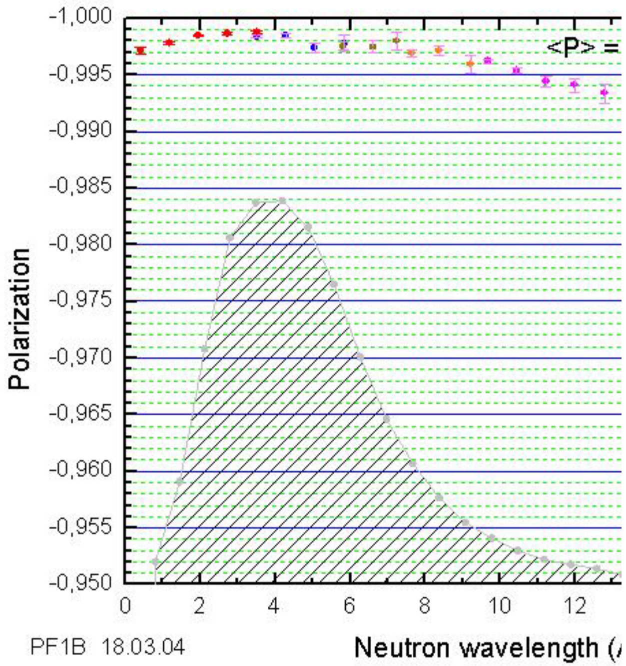
All values from PDG 2006

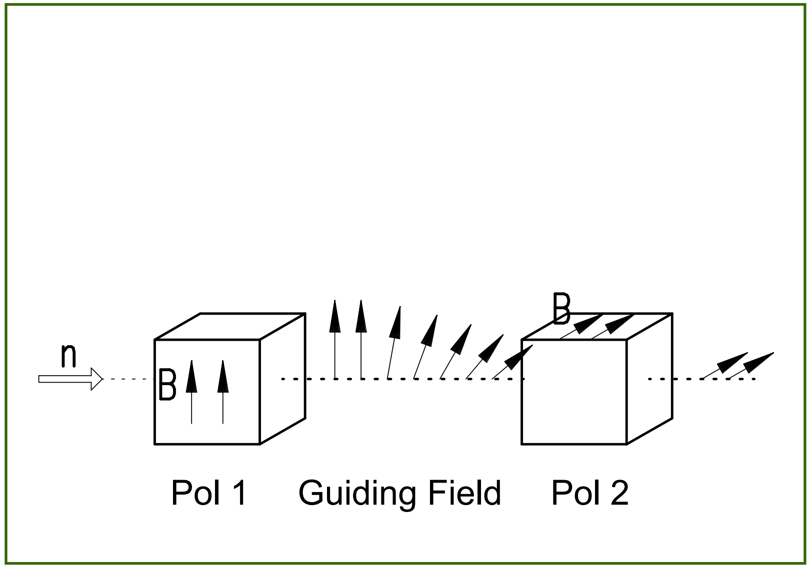
Polarization

- Polarization: 2 supermirror–polarizers in „crossed–geometry“
- Analysis: 2 supermirror–analyzers and ^{3}He–cells

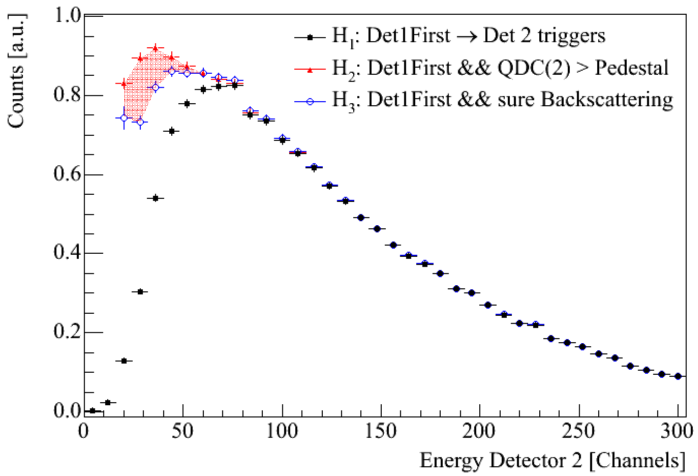
P = (99.72 ± 0.10) % F = (100.0 ± 0.1) %

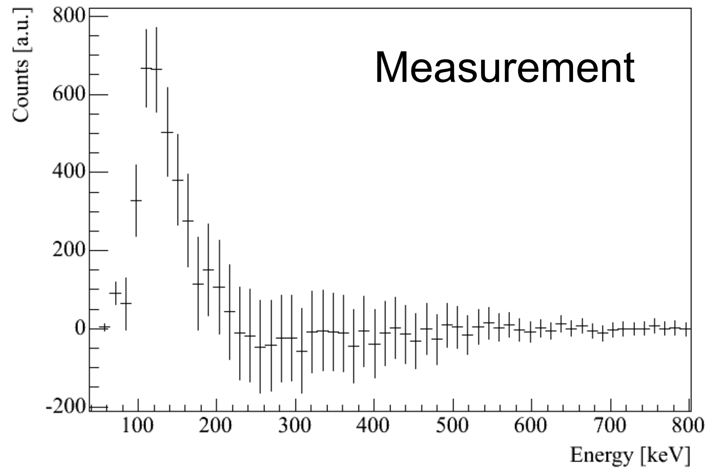
⇒ systematic error is considerably reduced



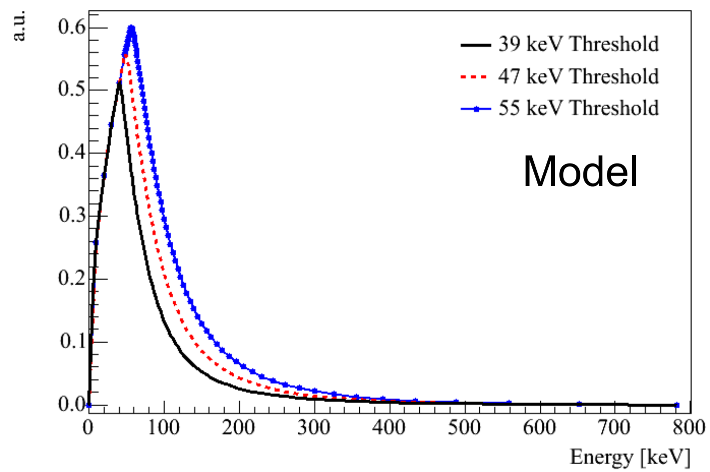


Electron Backscattering





	total BS	wrong assignment
Det 1 First	4.9(2) %	0.15(4) %
Det 2 First	4.5(3) %	0.19(5) %

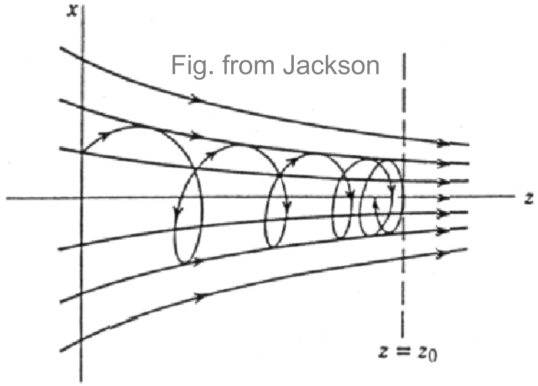


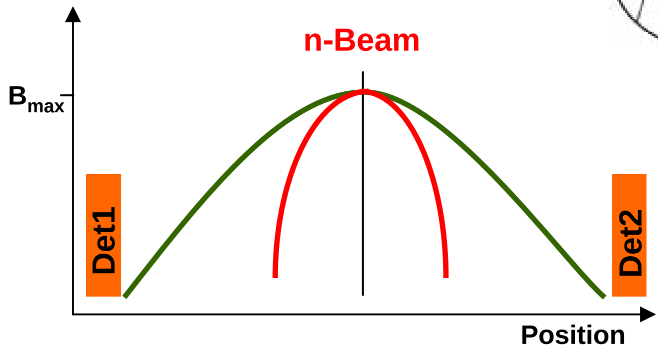
Backscattering effects are neglegible above a threshold of 220 keV.

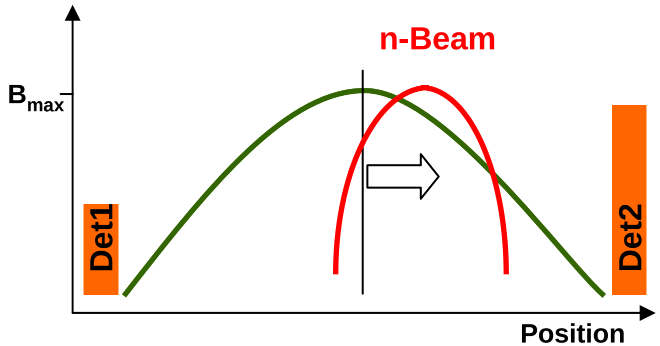
B–n–Displacement

$\Rightarrow$ Changes count rates in detectors

Magnetic Mirror Effect:





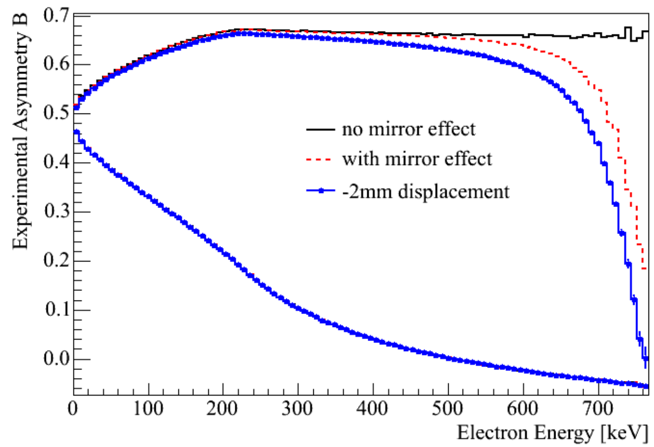


$\Rightarrow$ Changes asymmetries

- Large effect on *B* (same hemisphere)
- Displacement cancels when asymmetry is averaged over two detectors

$\rightarrow$ we have only one good Detector!

- BUT: Determine Δ from data!
- Corrections from MC-simulations

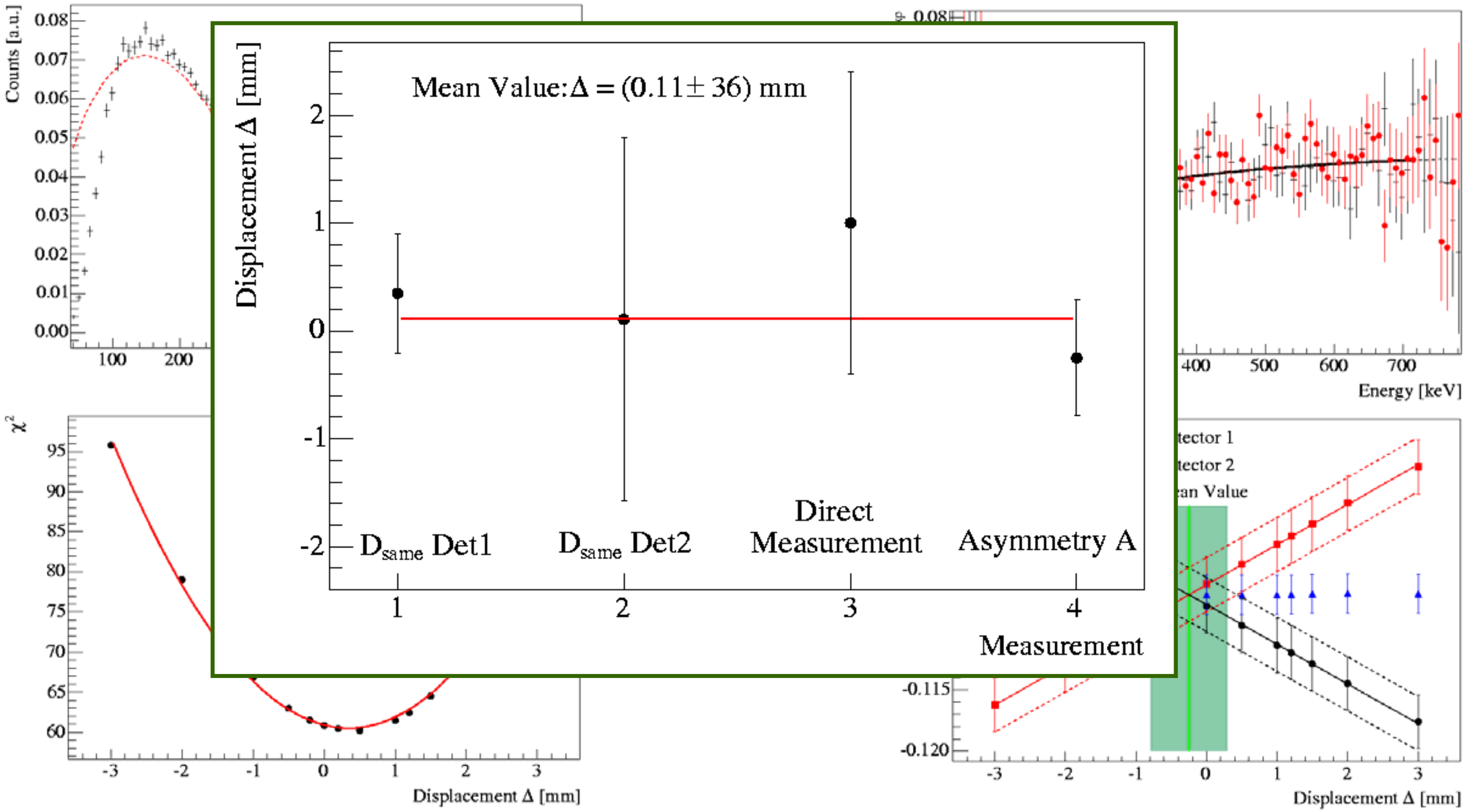


Determination of Displacement

1) Direct Measurement

2) χ^2–Minimization of Sum-Spectrum

3) Analysis of β–Asymmetry A



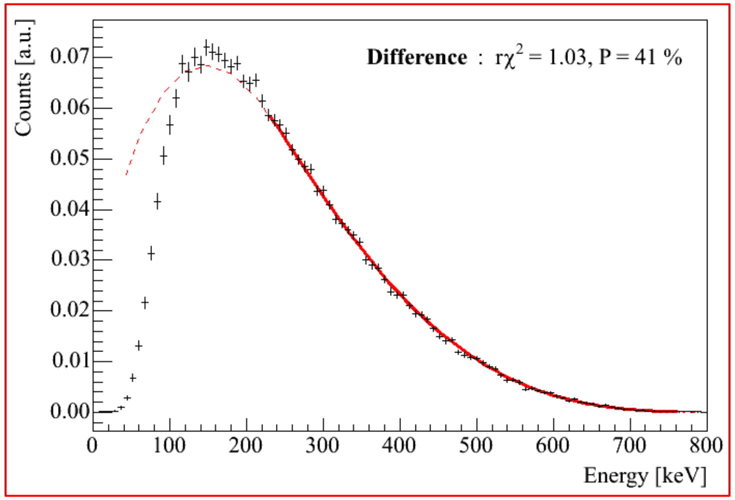
Data Analysis

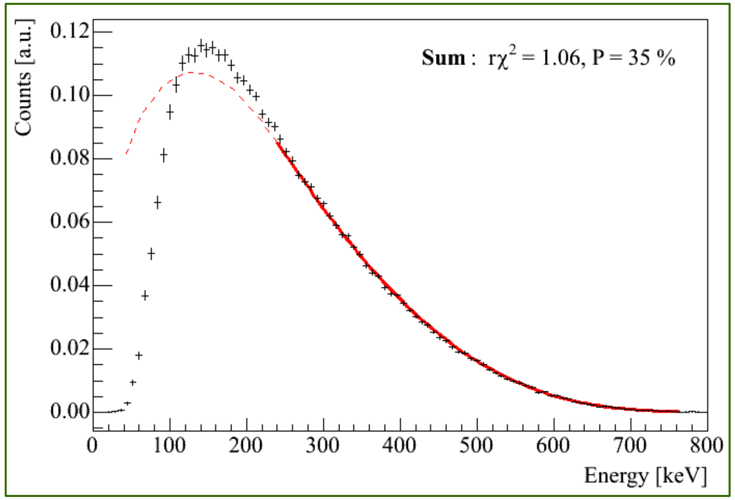
- Information available for analysis:
  - → Electron Energy Spectra
  - → Proton TOF
  - → different detector combinations
  - → Background measured and suppressed by coincidence
  - → accidental coincidences measured
  - → full e⁻ backscattering information

- $$B_{\mathrm{same}}(E) = \frac{N^{\downarrow\downarrow}(E) - N^{\uparrow\uparrow}(E)}{N^{\downarrow\downarrow}(E) + N^{\uparrow\uparrow}(E)}$$

- 1 Parameter Fits!

- all spectra are well described above 240 keV





Corrections and Errors: Asymmetry *B*

		Detector 1		Detector 2	
		Corr. [%]	Error [%]	Corr. [%]	Error [%]
Polarization		+0.3	0.1	+0.3	0.1
Flipper-Efficiency			0.1		0.1
Statistics			1.22		0.36
Coincidence Measurement		-0.29	0.07	-0.18	0.04
Detector			0.02		0.02
Systematics	Mirror Effect	+0.44	0.05	+0.44	0.05
	Displacement	-0.10	0.32	+0.10	0.32
	Other	-0.13	0.07	-0.13	0.07
Other Coefficients			0.07		0.07
Sum		**+0.22**	**1.28**	**+0.53**	**0.52**

Current Limits on right–handed Currents

PDG 2006

PDG gives no limit for ζ!

Limit on W_L-W_R Mixing Angle ζ

Lighter mass eigenstate $W_1 = W_L \cos\zeta - W_R \sin\zeta$. Light ν_R assumed unless noted. Values in brackets are from cosmological and astrophysical considerations.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.12	95	[38] ACKERSTAFF	99D	OPAL	τ decay
< 0.013	90	[39] CZAKON	99	RVUE	Electroweak
< 0.0333		[40] BARENBOIM	97	RVUE	μ decay
< 0.04	90	[41] MISHRA	92	CCFR	νN scattering
−0.0006 to 0.0028	90	[42] AQUINO	91	RVUE	
[none 0.00001–0.02]		[43] BARBIERI	89B	ASTR	SN 1987A
< 0.040	90	[44] JODIDIO	86	ELEC	μ decay
−0.056 to 0.040	90	[44] JODIDIO	86	ELEC	μ decay

All limits depend heavily on assumptions!
⇒ Every new input is useful.

W_R (Right-Handed W Boson) MASS LIMITS

Assuming a light right-handed neutrino, except for BEALL 82, LANGACKER 89B, and COLANGELO 91. $g_R = g_L$ assumed. [Limits in the section MASS LIMITS for W' below are also valid for W_R if $m_{\nu_R} \ll m_{W_R}$.] Some limits assume manifest left-right symmetry, *i.e.*, the equality of left- and right Cabibbo-Kobayashi-Maskawa matrices. For a comprehensive review, see LANGACKER 89B. Limits on the W_L-W_R mixing angle ζ are found in the next section. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
> 715	90	[13] CZAKON	99	RVUE	Electroweak
• • • We do not use the following data for averages, fits, limits, etc. • • •					
[> 3300]	95	[14] CYBURT	05	COSM	Nucleosynthesis; light ν_R
> 310	90	[15] THOMAS	01	CNTR	β^+ decay
> 137	95	[16] ACKERSTAFF	99D	OPAL	τ decay
>1400	68	[17] BARENBOIM	98	RVUE	Electroweak, Z-Z' mixing
> 549	68	[18] BARENBOIM	97	RVUE	μ decay
> 220	95	[19] STAHL	97	RVUE	τ decay
> 220	90	[20] ALLET	96	CNTR	β^+ decay
> 281	90	[21] KUZNETSOV	95	CNTR	Polarized neutron decay
> 282	90	[22] KUZNETSOV	94B	CNTR	Polarized neutron decay
> 439	90	[23] BHATTACH...	93	RVUE	Z-Z' mixing
> 250	90	[24] SEVERIJNS	93	CNTR	β^+ decay

MASS LIMITS for W' (Heavy Charged Vector Boson Other Than W) in Hadron Collider Experiments

Couplings of W' to quarks and leptons are taken to be identical with those of W. The following limits are obtained from $p\overline{p} \to W'X$ with W' decaying to the mode indicated in the comments. New decay channels (*e.g.*, $W' \to WZ$) are assumed to be suppressed. UA1 and UA2 experiments assume that the $t\overline{b}$ channel is not open.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>800	95	ABAZOV	04C	D0	$W' \to q\overline{q}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
225–536	95	[1] ACOSTA	03B	CDF	$W' \to tb$
none 200–480	95	[2] AFFOLDER	02C	CDF	$W' \to WZ$
>786	95	[3] AFFOLDER	01I	CDF	$W' \to e\nu, \mu\nu$
>660	95	[4] ABE	00	CDF	$W' \to \mu\nu$
none 300–420	95	[5] ABE	97G	CDF	$W' \to q\overline{q}$
>720	95	[6] ABACHI	96C	D0	$W' \to e\nu$
>610	95	[7] ABACHI	95E	D0	$W' \to e\nu, \tau\nu$
>652	95	[8] ABE	95M	CDF	$W' \to e\nu$
>251	90	[9] ALITTI	93	UA2	$W' \to q\overline{q}$
none 260–600	95	[10] RIZZO	93	RVUE	$W' \to q\overline{q}$
>220	90	[11] ALBAJAR	89	UA1	$W' \to e\nu$
>209	90	[12] ANSARI	87D	UA2	$W' \to e\nu$

[1] The ACOSTA 03B quoted limit is for $M_{W'} \gg M_{\nu_R}$. For $M_{W'} < M_{\nu_R}$, $M_{W'}$ between 225 and 566 GeV is excluded.

[2] The quoted limit is obtained assuming $W'WZ$ coupling strength is the same as the ordinary WWZ coupling strength in the Standard Model. See their Fig. 2 for the limits on the production cross sections as a function of the W' width.