# Measurement of the nucleon axial coupling in neutron beta decay

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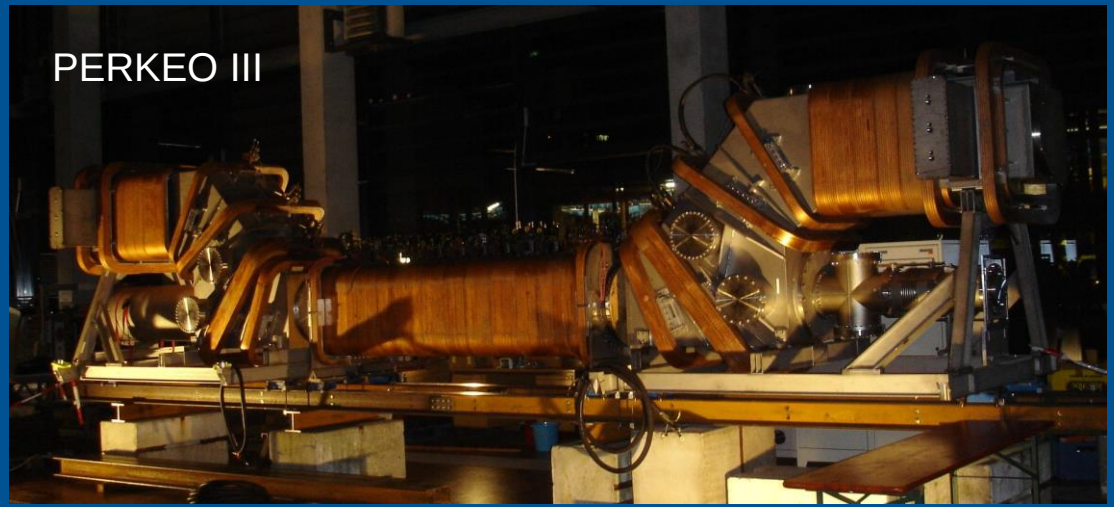


PSI2019, 22.10.2019

# Measurement of the nucleon axial coupling in neutron beta decay

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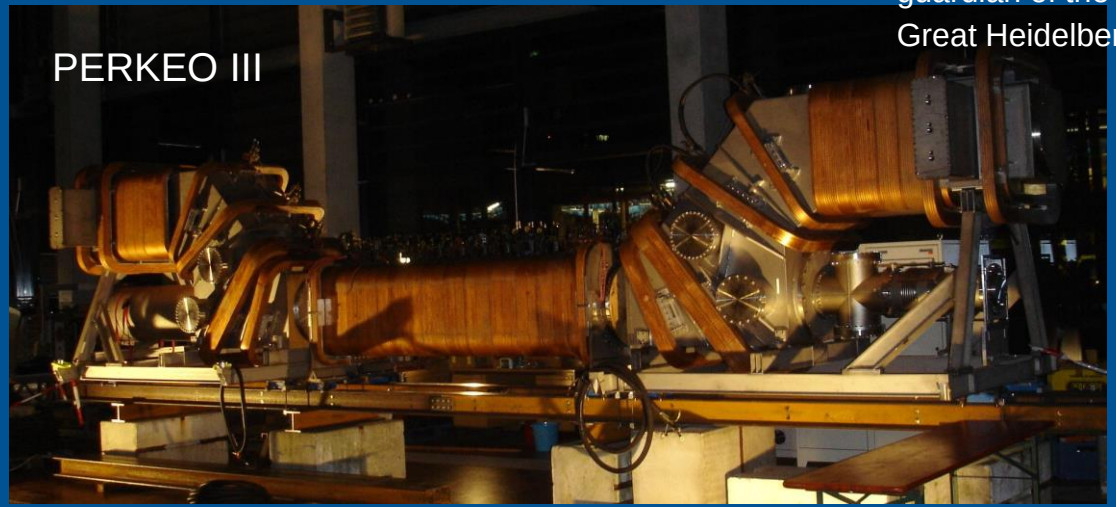
guardian of the
Great Heidelberg Tun

Spectrometer originally built by Heidelberg University,

Now run by TUM, TU Wien, Heidelberg, ILL




PSI2019, 22.10.2019

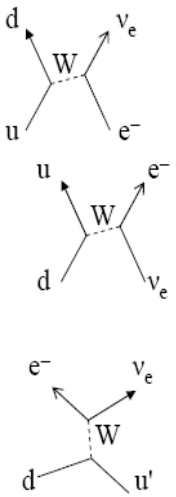
# Neutron Decay Data is Useful

## Within Standard Model

Many processes share the same Feynman diagram.

Couplings have to be determined in neutron decay!

| | |
|---|---|
| Primordial element formation | $n + e^+ \rightarrow p + \nu'_e$ |
| ($^2$H, $^3$He, $^4$He, $^7$Li, … ) | $p + e^- \rightarrow n + \nu_e$ |
| | $n \rightarrow p + e^- + \nu'_e$ |
| Solar cycle | $p + p \rightarrow {}^2H + e^+ + \nu_e$ |
| | $p + p + e^- \rightarrow {}^2H + \nu_e$ |
| Neutron star formation | $p + e^- \rightarrow n + \nu_e$ |
| Pion decay | $\pi^- \rightarrow \pi^0 + e^-$ |
| 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. |




Input parameter to searches for physics **Beyond the Standard Model** (BSM)

Unitarity test of the first row of the quark mixing CKM matrix on the $10^{-4}$ level sensitive to new physics at the 10 TeV scale:

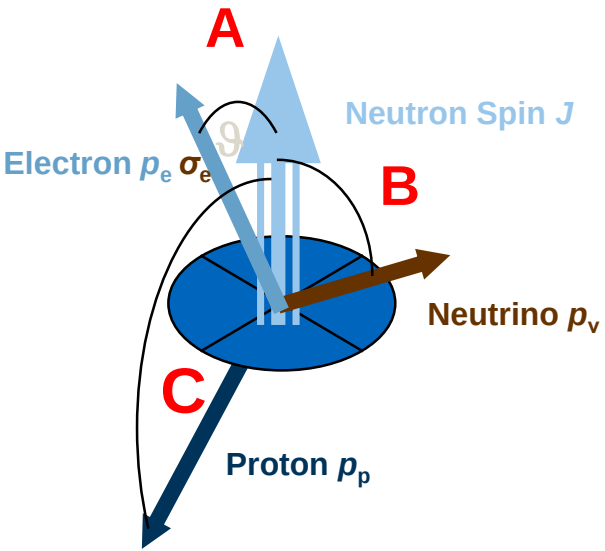
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \Delta$$

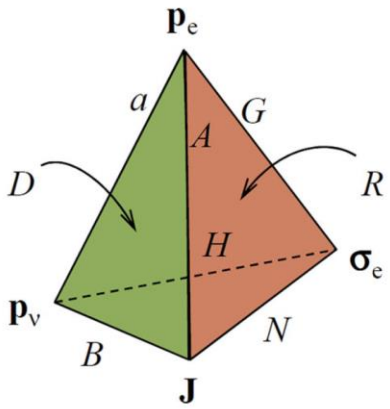
Search for new (effective) couplings: scalar, tensor, right-handed

# Correlations in Neutron Decay

Determination of $\lambda = g_A/g_V$ from neutron decay via angular correlations:
(typically) **beta asymmetry *A***, or electron-neutrino correlation *a*

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




*O. Naviliat-Cuncic and M. Gonzalez-Alonso,* Ann. Phys. 525, 8–9, 600–619 (2013)
Dubbers and Schmidt, Rev. Mod. Phys (2012)

Typically, **specialised** instruments / setups required for different observables.

# Quark-level EFT Lagrangian

$$\mathcal{L}_{\rm CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \times \Big[ (1+\epsilon_L)\ \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d$$

$$+\ \epsilon_R\ \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d$$

$$+\ \epsilon_S\ \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}d$$

$$-\ \epsilon_P\ \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d$$

$$+\ \epsilon_T\ \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \Big] + \text{h.c.}$$

$$\lambda = (1-2\varepsilon_R)\, g_A / g_V$$

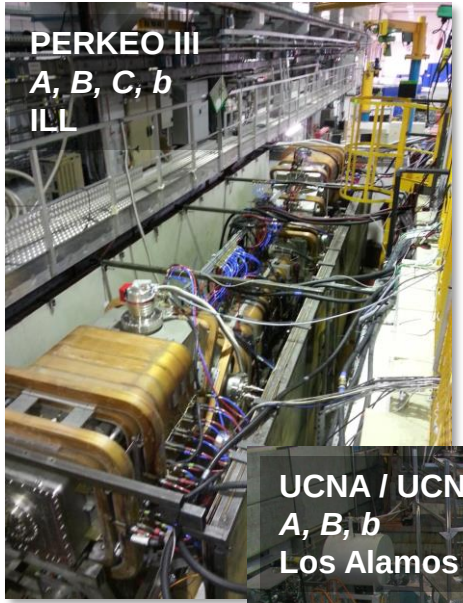
$$+\quad \epsilon_i \longrightarrow \tilde{\epsilon}_i \qquad (1-\gamma_5)\nu_\ell \longrightarrow (1+\gamma_5)\nu_\ell$$

V. Cirigliano

Limit on pseudoscalar from pion decay; limit on scalar from superallowed nuclear decays; limit on tensor driven by neutron decay.

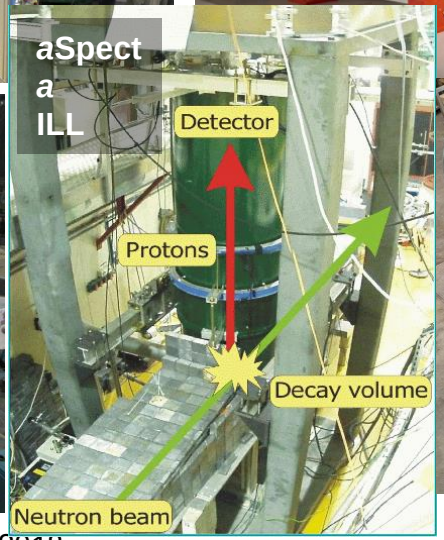
Recent review:
M. González-Alonso, O. Naviliat-Cuncic, N. Severijns, *„New physics searches in nuclear and neutron β decay"*, Prog. Part. Nucl. Phys. 104, 165-223 (2019).

# Current Neutron Decay Experiments





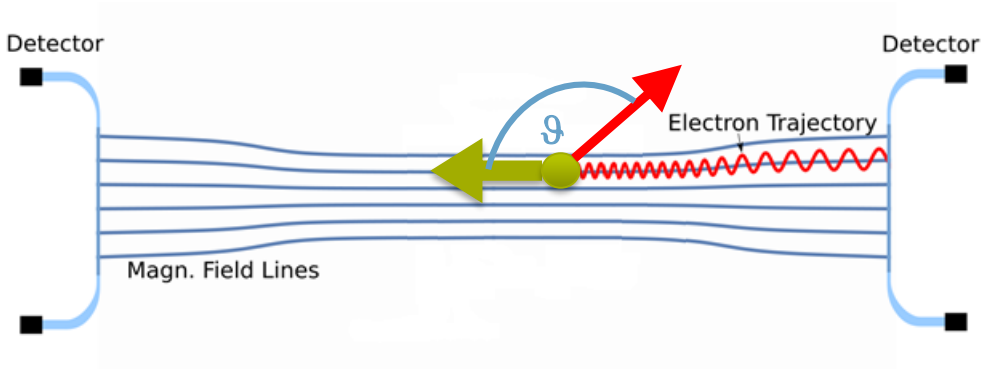






**BRAND**
ILL / ESS

# PERKEO: Measuring Beta Asymmetry




electron angular distribution:

$$W(\vartheta, E) = 1 + \frac{v}{c} A \cos\vartheta$$

within Standard Model:

$$A = -2\,\frac{\lambda^2 + \lambda}{1 + 3\lambda^2} \qquad \lambda = \frac{g_A}{g_V}$$

magnetic field for spin alignment

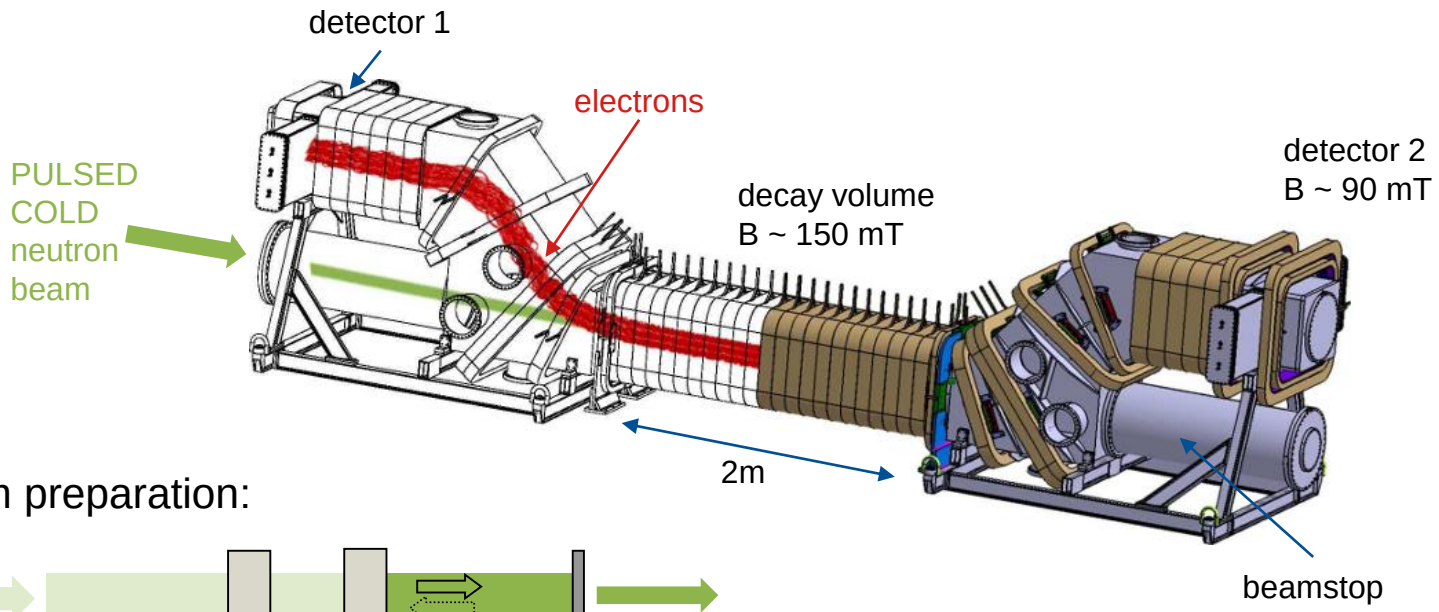
integration over hemispheres:
2 × 2 π detection

$\cos\vartheta \rightarrow 1/2$

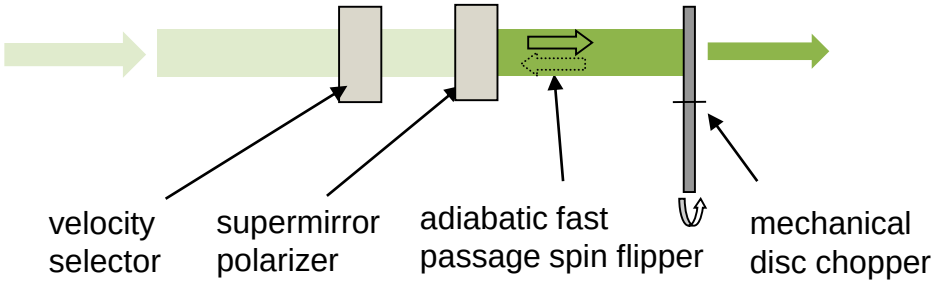
experimental asymmetry, polarisation *P*

$$A_{\text{exp}} = \frac{N^{\Uparrow} - N^{\Downarrow}}{N^{\Uparrow} + N^{\Downarrow}} = \frac{1}{2}\frac{v}{c} P A$$

# Spectrometer PERKEO III

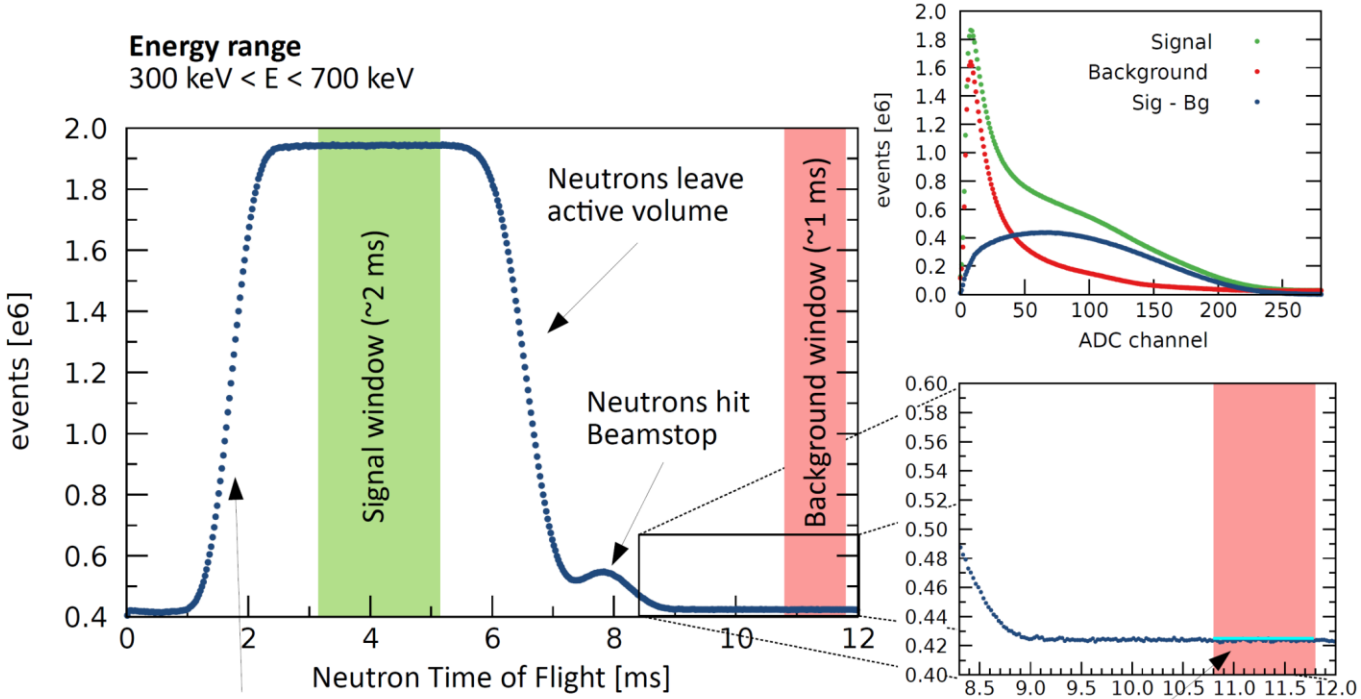



Beam preparation:




~50.000 decays/s in *continuous* beam
time avg. ~200 $s^{-1}$ in pulsed mode

# PERKEO III: Pulsed Neutron Beam




Neutrons enter active volume

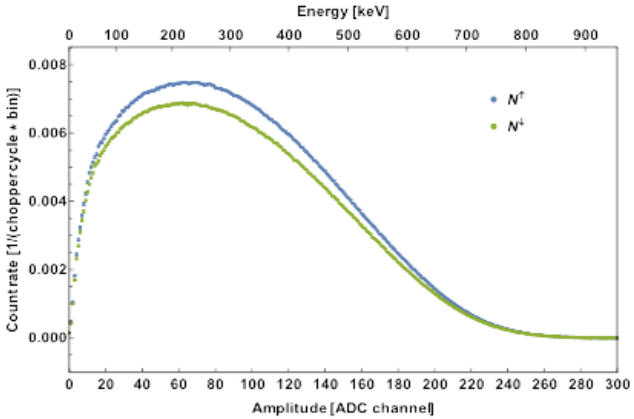
**Related Uncertainties:**

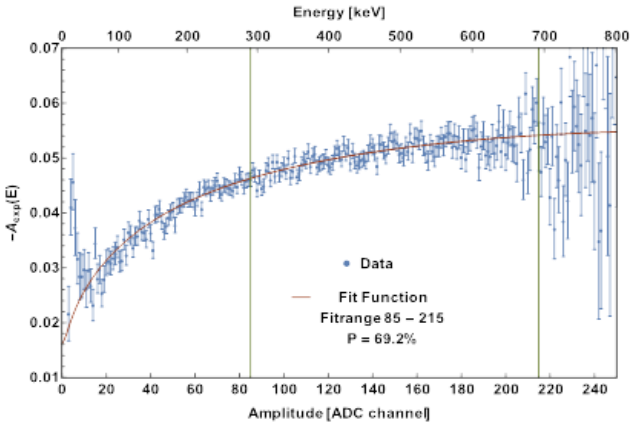
Time dependence $\Delta A/A = 0.8\times10^{-4}$

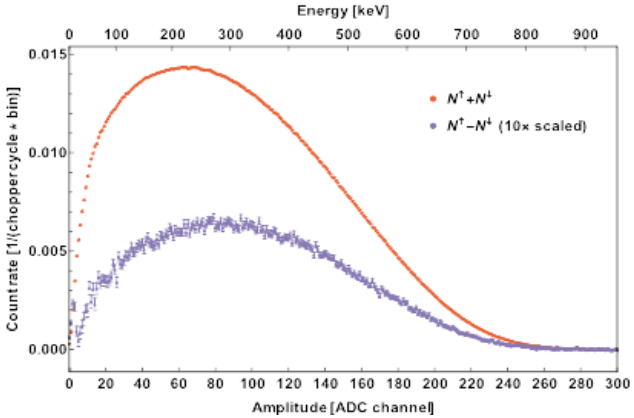
Chopper disc uniformity $\Delta A/A = 0.7\times10^{-4}$

e is zero compatible
$0^{-4}$ level

# Asymmetry Extraction




$$A_{exp}(E_e) = \frac{N^{\uparrow}(E_e) - N^{\downarrow}(E_e)}{N^{\uparrow}(E_e) + N^{\downarrow}(E_e)} = \frac{1}{2} P_n \frac{v}{c} A$$

Largest neutron decay data set

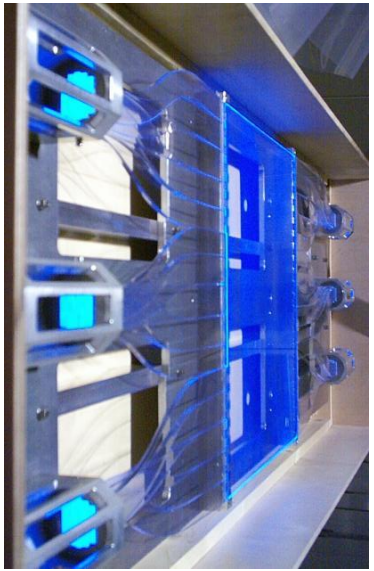
1 of 4 subsets shown

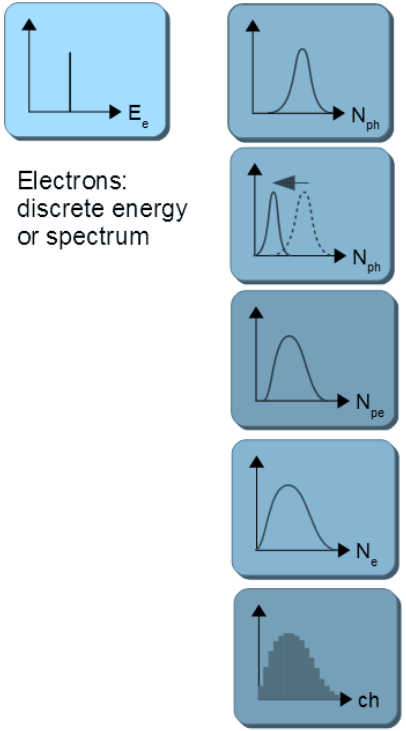
$6 \times 10^8$ events in analysis

**Statistical Uncertainty:** $\Delta A/A = 14 \times 10^{-4}$

# Detector Model

Major improvements to the description of the detector response enable consistent energy-dependent analysis.






Electrons:
discrete energy
or spectrum

Scintillation:
$N_{ph} = f(E_e)$
*poisson statistics*

**Non-linearity** of scintillation light production

Photon transport:
$N'_{ph} = f(E_e, x, y)$
*binomial statistics*

**Non-uniformity** of detector response

Photon to photoelectron conversion:
$N_{pe} = f(N_{ph})$
*binomial statistics*

Electron multiplication (PMT):
$N_e = f(N_{pe})$
*poisson statitisics at N=19 stages*

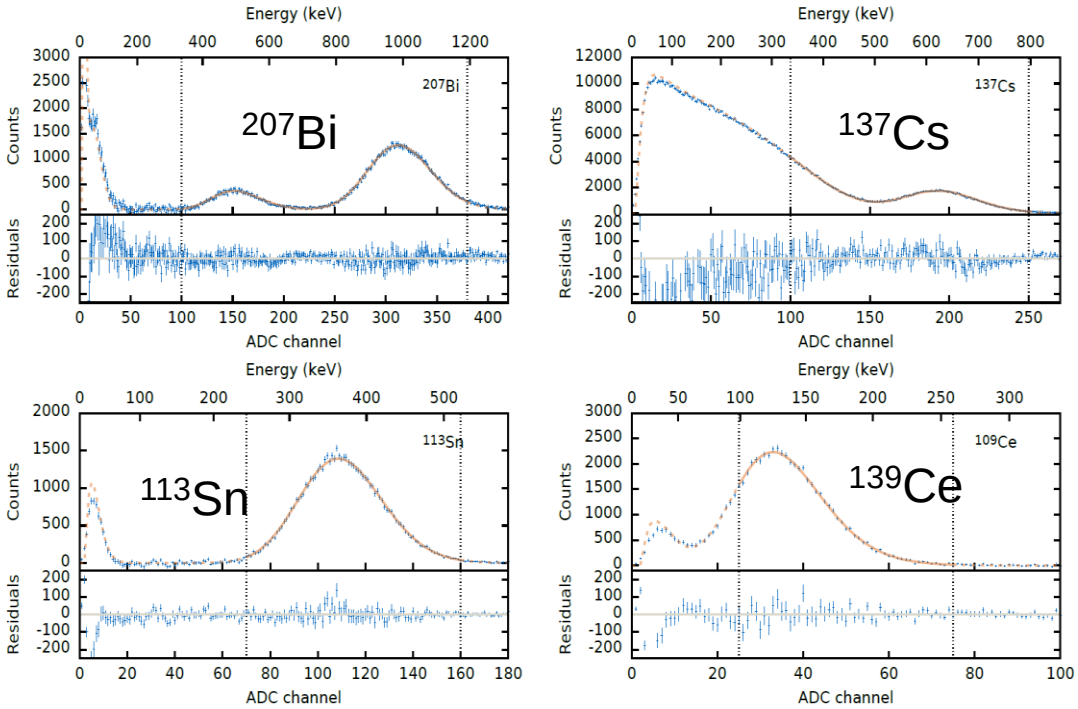
Higher moments of the distribution

Signal processing + charge integration:
$A_{QDC} = f(N_e)$
*gaussian noise*

**Non-linearity** of electronics

# Detector Calibration Fit

Calibration, drift monitoring and uniformity scans using electron-conversion sources




(+ hourly drift measurements + weekly uniformity scans)

114 full calibration sets measured in ~60 days

Simultaneous fit, **free parameters:**

***non-linearity, gain, photo-electrons, norms***

$X^2$/NDF = 1.0 – 1.3

**Related Uncertainties**

Sources: $\Delta A/A = 1\times10^{-4}$

Statistics: $\Delta A/A = 0.1\times10^{-4}$

Non-linearity: $\Delta A/A = 4\times10^{-4}$

Stability: $\Delta A/A = 3.7\times10^{-4}$

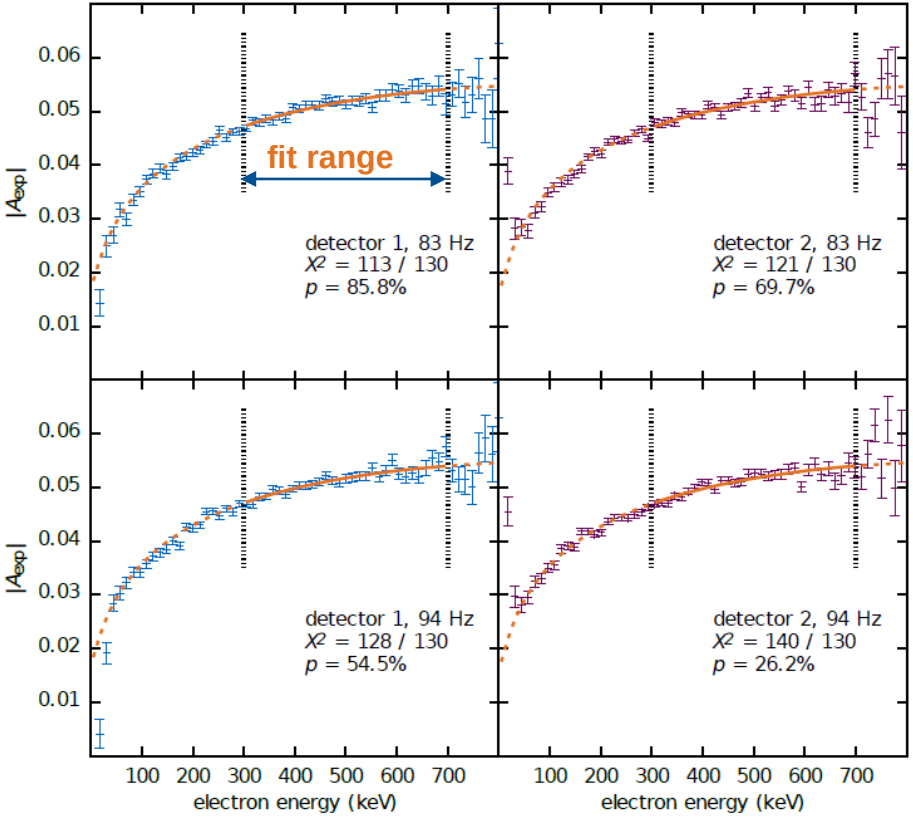
# Asymmetry: Four datasets

Two chopper frequencies (background systematics), two detectors

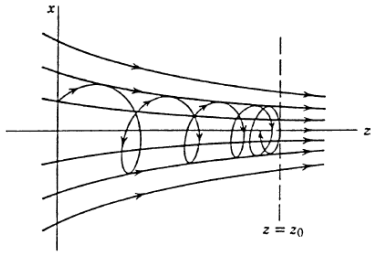
Fit to energy-dependence of experimental asymmetry $A_{exp}(E_e)$,

Model includes detector response (no unfolding)

**Only a single free parameter: $\lambda$**



# Magnetic Mirror Effect



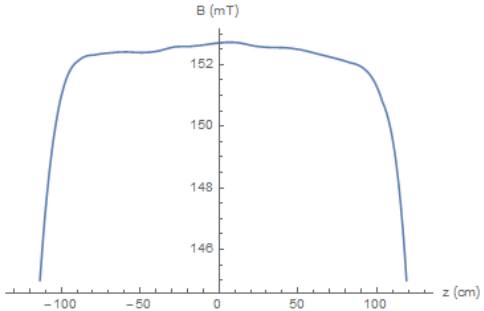

Flux through cross section of gyration is *adiabatic invariant*

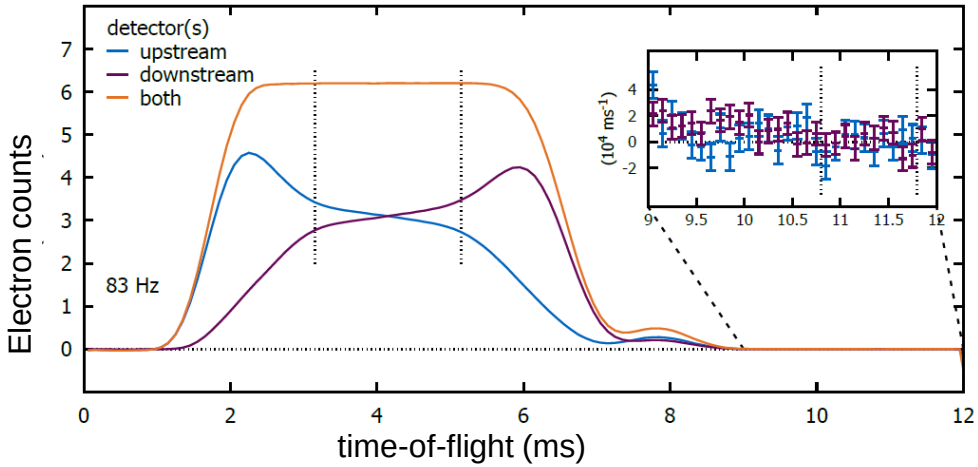
$$B_0 \times r_0^2 = B_1 \times r_1^2$$

Critical angle for reflection

$$\Theta_c = \arcsin\sqrt{\frac{B_1}{B_0}}$$

Magnetic field curvature leads to significant rate change on **single** detector:



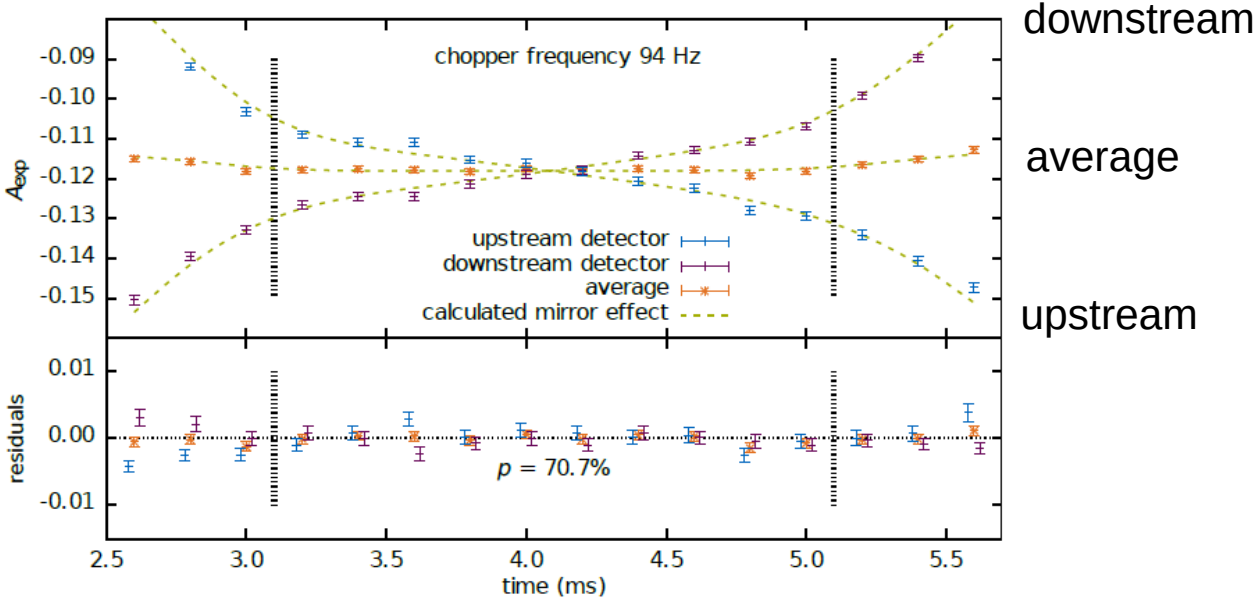



# Magnetic Mirror Effect

Most of the effect cancels by **averaging** detectors.

Calculate **correction** from measurements of the magnetic field and neutron pulse.

Correction: $\Delta A/A = 46.1(4.5) \times 10^{-4}$



# PERKEO III Result

**Analysis blinded** by separate analysis by independent teams:

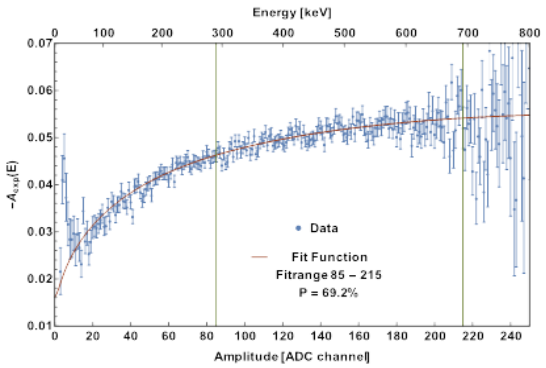
- electron measurement,
- neutron polarisation: opaque $^3$He spin filters,
- magnetic mirror effect

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

$$\lambda = -1.27641(45)_{\mathrm{stat}}(33)_{\mathrm{sys}}$$
$$= -1.27641(56)$$
$$A = -0.11985(17)_{\mathrm{stat}}(12)_{\mathrm{sys}}$$
$$= -0.11985(21).$$

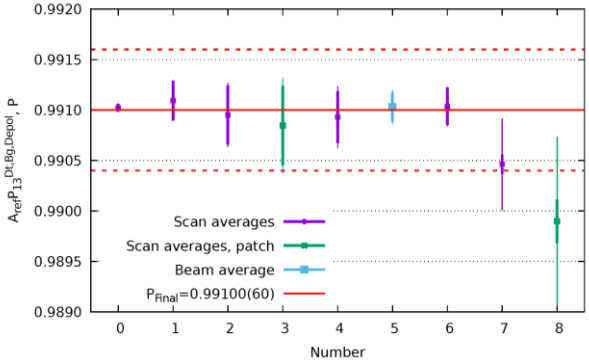
$$\frac{\Delta\lambda}{\lambda} = 4.4 \times 10^{-4}$$

B. Märkisch, **H. Mest**, **H. Saul**, **X. Wang**, H. Abele, D. Dubbers, **M. Klopf**, A. Petoukhov, **C. Roick**, T. Soldner, **D. Werder**, Phys. Rev. Lett. 122, 222503 (2019)



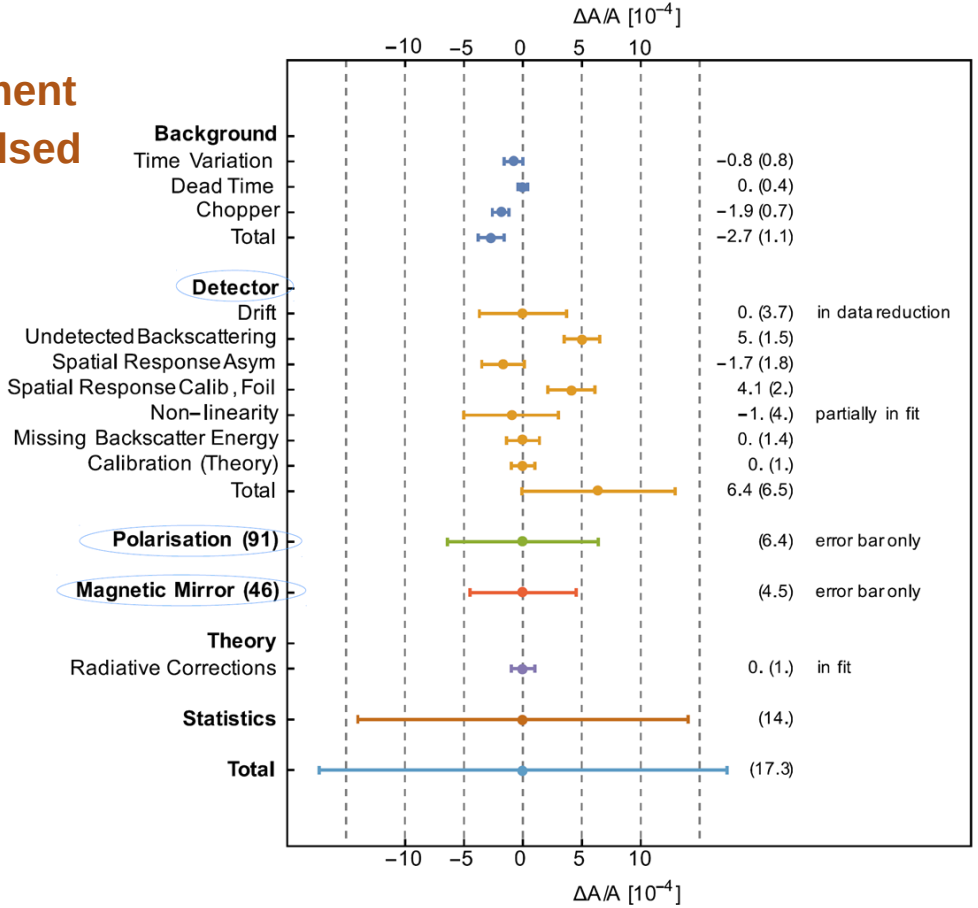

Measurement of beam polarisation with $^3$He cells

- in front of and behind instrument
- at three different times during measurement
- scan over beam cross section and wavelength



# Summary of Corrections and Uncertainties

**First measurement of λ using a pulsed beam**




*see also*
***Undetected Electron Backscattering in PERKEO III***
C. Roick, H. Saul, H. Abele, B. Märkisch
arXiv:1905.10189

# Nucleon Axial Coupling: Status

New beta asymmetry results **consistent** – but disagree with older measurements.
Newer measurements of *A* have order of magnitude **smaller corrections**.
UCNA and PERKEO III: **blinded analysis**.

PERKEO III:

$$\lambda = -1.27641(56),$$

$$\frac{\Delta\lambda}{\lambda} = 4.4 \times 10^{-4}$$

PDG 2018:

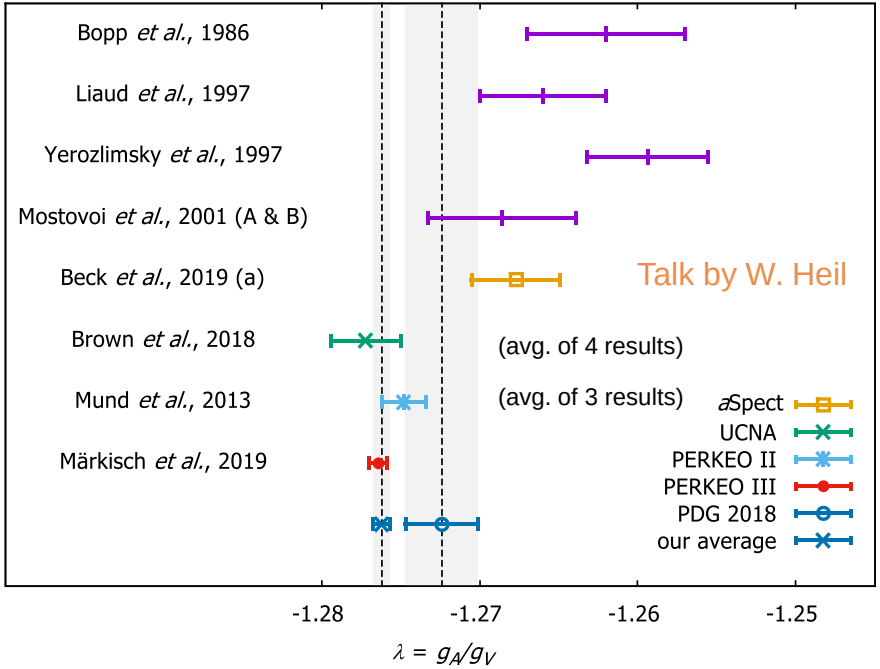
$$\lambda = -1.2724(23);\ S = 2.4$$

New average (all measurements):

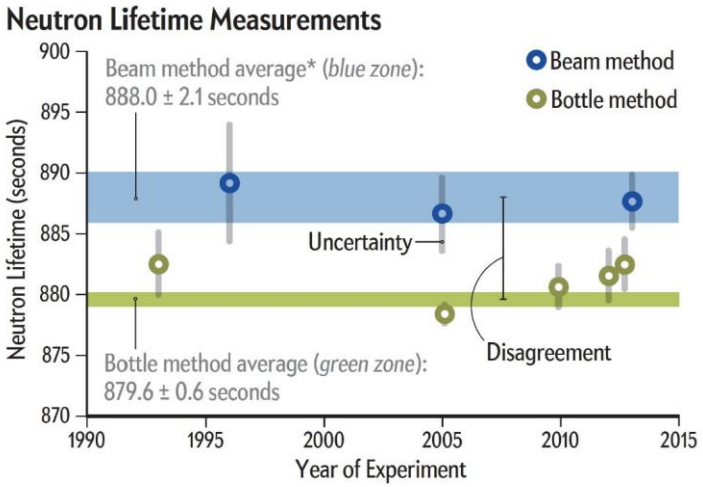
$$\lambda = -1.2754(11);\ S = 2.23$$

Only beta asymmetry according to PDG procedure:

$$\lambda = -1.2757(5)$$



# „The Neutron Enigma“




*Picture: Scientific American G.L. Greene, P. Geltenbort: The Neutron Enigma, Sci. Am. 314, 36 (2016).*

**Bottle** experiments measure total lifetime, inclusive:

$$\tau_n^{\text{beam}} = \frac{\tau_n}{\text{Br}(n \to p + \text{anything})}$$

**Beam** experiments measure protons only:

$$\frac{1}{N(n)} \frac{dN(p)}{dt} = -(\lambda \text{Br}(n \to p))t$$

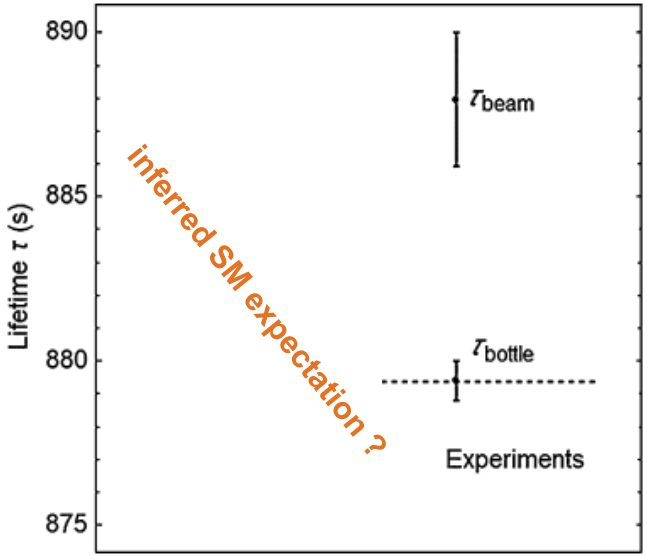
# Dark Side to Neutron Decay?

Assuming the V-A structure of the standard model, neutron lifetime can be inferred:

$$\tau_\beta^\lambda = \frac{2}{\ln 2}\frac{\overline{Ft}_{0^+\to 0^+}}{f(1+\delta_R')(1+3\lambda^2)} = \frac{5172.3(1.1)\ \mathrm{s}}{1+3\lambda^2}$$

**Inputs**

- global results on nuclear *Ft*
  (Hardy, Towner, Phys. Rev. C (2015)
- updated world-average of $\lambda = gA/gV$ to include **PERKEO III precision result**
- (unaffected by common rad. corrections)




D. Dubbers, H. Saul, B. Märkisch, T. Soldner and H. Abele Phys. Lett. B 791, 6-10 (2019)

# No Dark Side to Neutron Decay!

Assuming V-A, neutron lifetime can be inferred using our (conservative) world-average of neutron decay data, *including* ***all*** *measurements.*

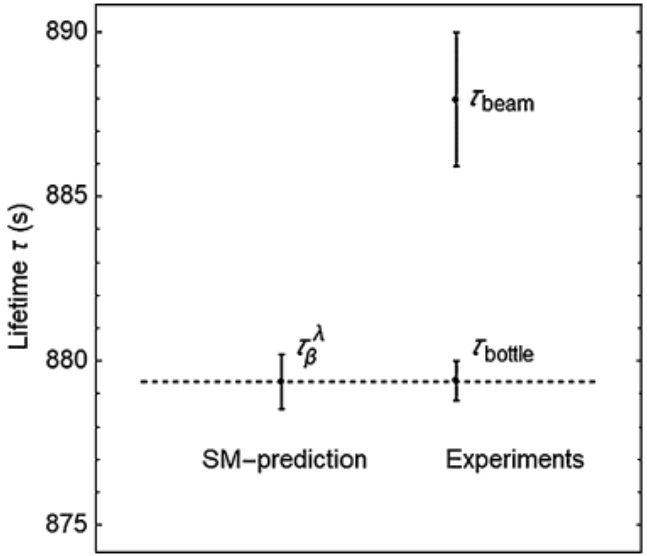
$$\tau_\beta^\lambda = \frac{2}{\ln 2}\frac{\overline{Ft}_{0^+\to 0^+}}{f(1+\delta_R')(1+3\lambda^2)} = \frac{5172.3(1.1)\ \mathrm{s}}{1+3\lambda^2}$$

Globally, there's very little room for new physics: $BR_{DM} < 0.30\%$ 95% C.L.

***Exotic decay channels are not the cause of the neutron lifetime anomaly.***

*Some channels excluded by experiments (UCNτ, UCNA, PERKEO II); contradiction to the existence of heavy neutron stars, …*

See also: A. Czarnecki, W.J. Marciano, A. Sirlin, Phys. Rev. Lett. 120 (2018) and arXiv:1907.06737




D. Dubbers, H. Saul, B. Märkisch, T. Soldner and H. Abele Phys. Lett. B 791, 6-10 (2019)

# Direct Limit: Constraints on the Dark Matter Interpretation $n \rightarrow \chi + e^+e^-$

**Strategy**

search for coincident $e^+e^-$ events in existing PERKEO II data

**Challenges**

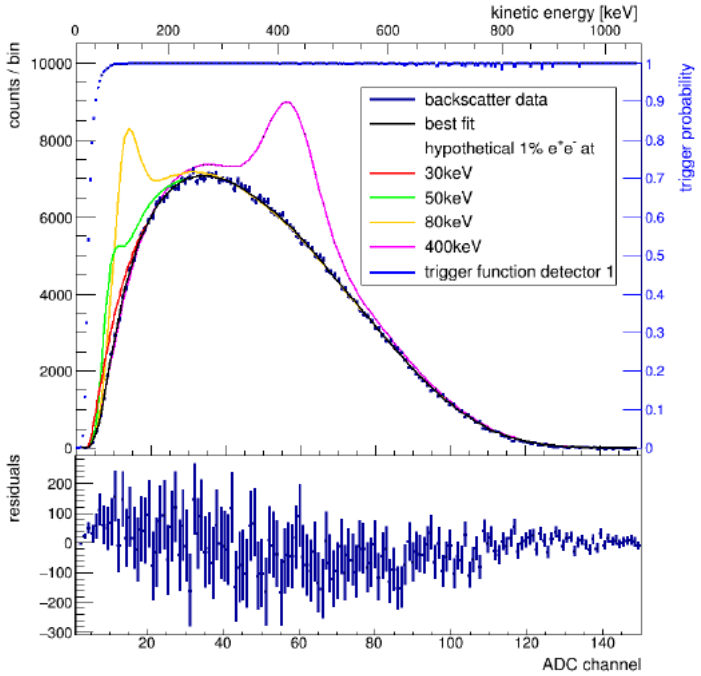
„normal“ backscattering is main background (well understood)

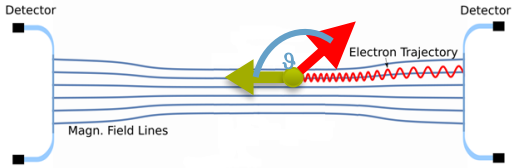
low-energy detector calibration

detector trigger function (measured!)

**Exclude this decay channel in 95% of the relevant energy range.**

M. Klopf, E. Jericha, B. Märkisch, H. Saul, T. Soldner, H. Abele, Phys. Rev. Lett., 122, 222503 (2019), *and* EPJ Web Conf. PPNS2019, in press



# $V_{ud}$ from Neutron Decay

$V_{ud}$ from neutron decay requires only two experimental inputs:

neutron lifetime $\tau$

nucleon axial coupling: $\lambda = g_A/g_V$

Talks by A. Saunders, V. Ezhov, and C. Morris on Thursday

Using „master formula“ with new radiative corrections $\Delta_R$, world-average of the neutron lifetime, our result on $\lambda$

$$V_{ud} = \left(\frac{5099.34\,\mathrm{s}}{\tau_n(1+3\lambda^2)(1+\Delta_R)}\right)^{1/2}$$
$$= 0.97301(10)_{\mathrm{RC}}(44)_{\tau_n}(35)_{\lambda}$$
$$= 0.97301(58),$$

C.-Y. Seng, M. Gorchtein, M.J. Ramsey-Musolf
Phys. Rev. Lett.121 (2018) 241804

C.-Y. Seng, M. Gorchtein, M.J. Ramsey-Musolf
Phys. Rev. D 100 (2019) 013001

Agreement with superallowed decays:

$V_{ud} = 0.97395(23)$ Seng et al. arXiv:1812.03352v2

Neutron result only 2.5 times less precise. Tension with CKM unitarity?

See talk by Z. Berezhiani

# Fierz Interference Term b

Sensitive to scalar and tensor interaction

$$b \simeq \frac{g_S g_V + 3 g_A g_T}{g_V^2 + g_S^2 + 3\left(g_A^2 + g_T^2\right)} \simeq 2\frac{g_S + 3\lambda g_T}{1 + 3\lambda^2}$$

Modifies decay rate / spectrum **and** asymmetries

$$d\Gamma \propto \left(1 + b\frac{m_e}{E_e}\right)$$

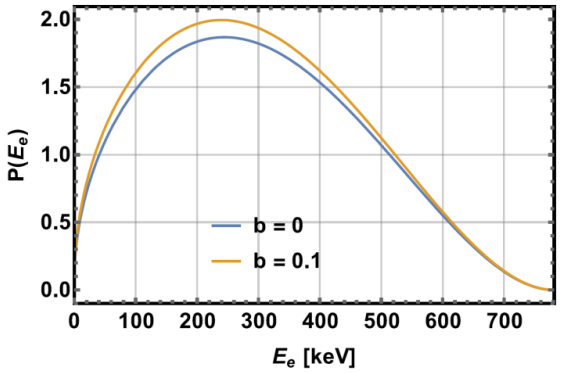
$$A_{\mathrm{exp}}(E) \rightarrow \frac{A_{\mathrm{exp}}(E)}{1 + b\frac{m_e}{E}}$$

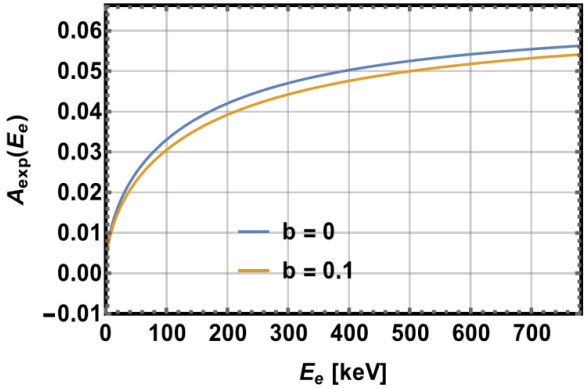
First result by UCNA from spectral shape:

$$b = 0.067(0.005)_{\mathrm{stat}}\left(^{+0.090}_{-0.061}\right)_{\mathrm{sys}}$$

Hickerson et al., Phys. Rev. C 96, 2017

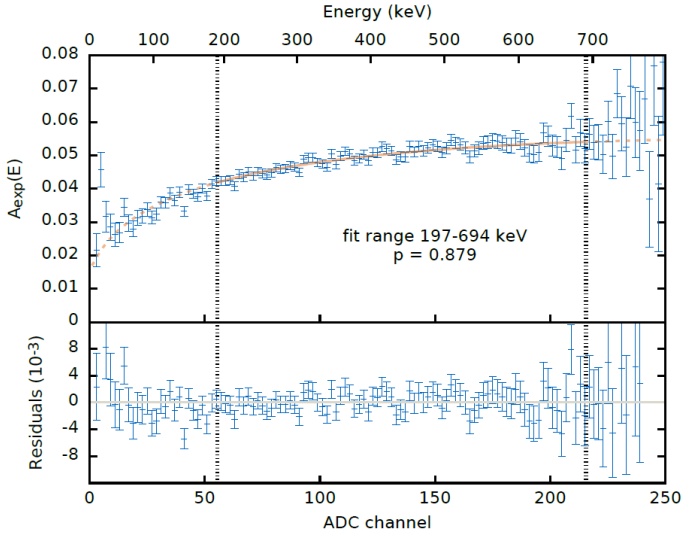
Experimental asymmetry is far less sensitive to detector systematics, but statistically less sensitive by order of magnitude



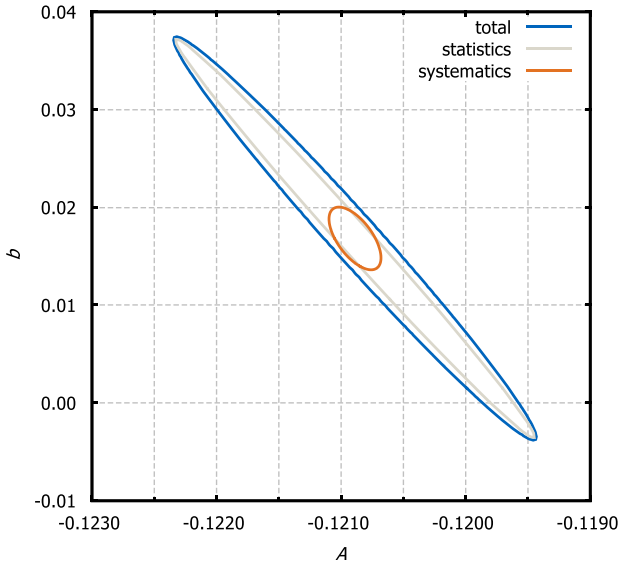



# Limit on the Fierz Interference Term

Correlated analysis with beta asymmetry parameter $A(\lambda)$ and Fierz interference term $b$,
Subset of data used for SM analysis. Extended energy range used for fit 197-694 keV.




$$A = -0.12089(14),$$
$$b = 0.017(20)_{\text{stat}}(3)_{\text{sys}} = 0.017(21)$$
$$\rho_{A,b} = -0.985,$$




$-0.035 \leq b \leq 0.068.$ 90% C.L.

H. Saul et al., in preparation

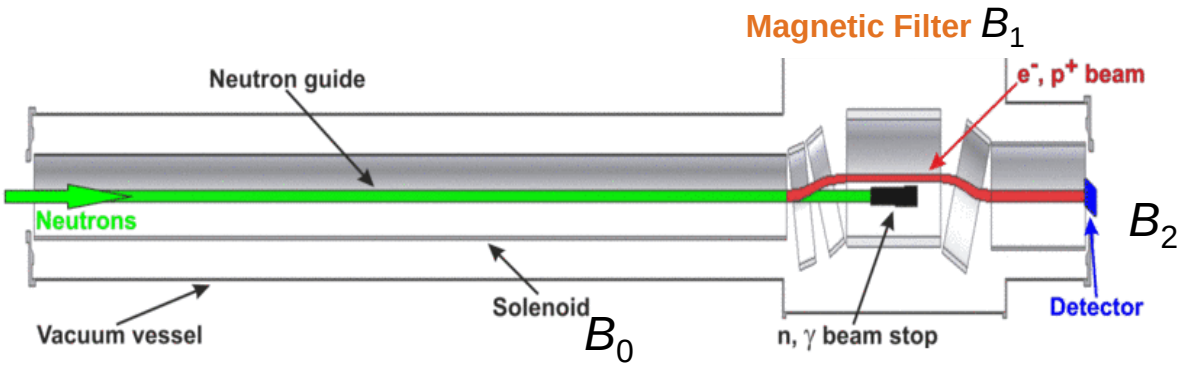
The next generation:

PERC (Proton Electron Radiation Channel) at MLZ / FRM

Goal:  Order of magnitude improvement. New observables.

Priority Programme SPP1491 of
the German Research Foundation

# Proton Electron Radiation Channel (PERC)




**Active volume** in a 8 m long *neutron-guide*, $B_0$ = 1.5 T: phase space density and statistics

**Magnetic Filter**, $B_1$ = 6 T: phase space, systematics
(solid angle, backscatter suppression)

$$B_1 / B_0 = 2 \ldots 12$$

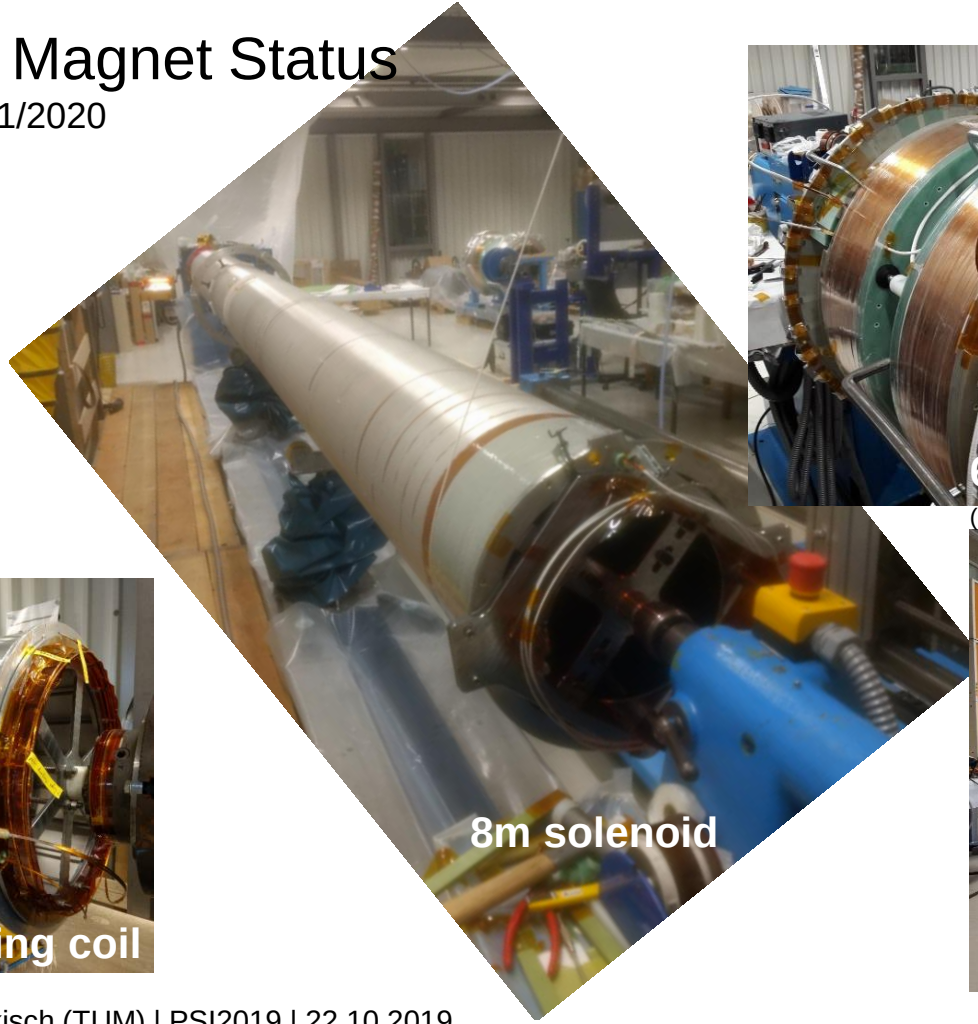
**Source** for specialised spectrometers

D. Dubbers et al., *Nucl. Instr. Meth. A* **596** (2008) 238 and arXiv:0709.4440

Design of the Magnetic System of the Neutron Decay Facility PERC
X. Wang, C. Drescher *et al*. (PERC Collaboration), EPJ Web Conf., in press, arxiv:1905.10249

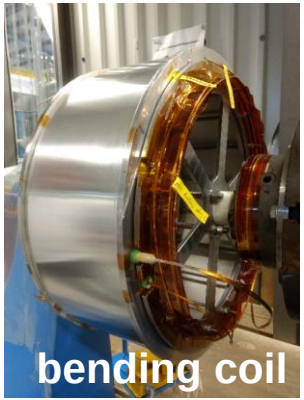
# PERC Magnet Status

Delivery Q1/2020

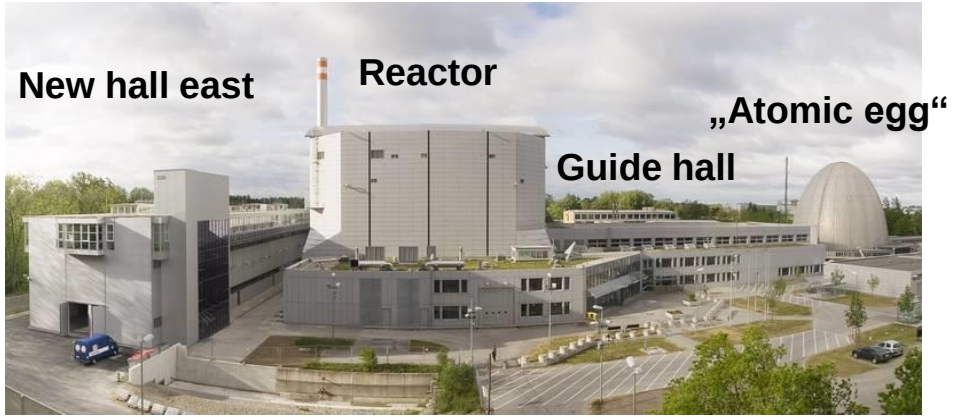


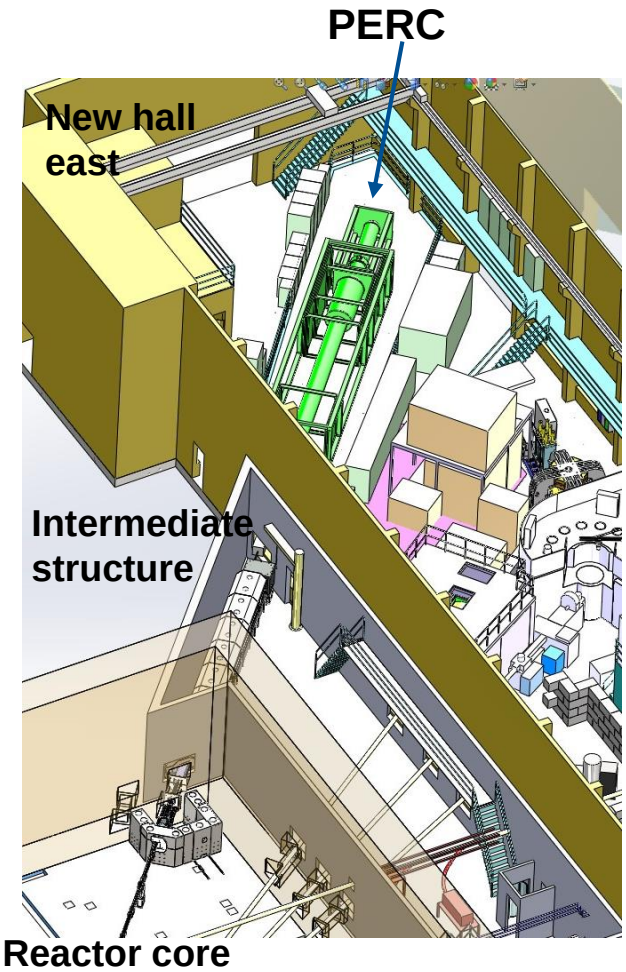


(Needs to be redone - ongoing)




# Beam Site Mephisto, FRM II, Garching




Neutron guide:

length 40 m, R = 3000 m, *m* = 2.5

Expected intensity equal to PF1b at ILL, $2\times10^{10}$ $s^{-1}cm^{-2}$

Only very few neighbours:

low ambient background

**All guide components ready to be installed.**

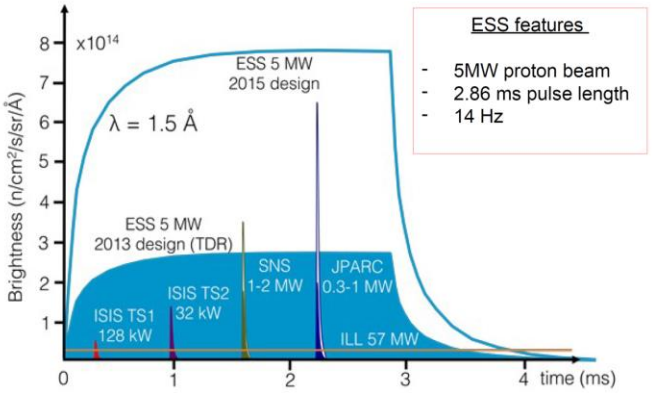
# Cold Beamline for Particle Physics at ESS

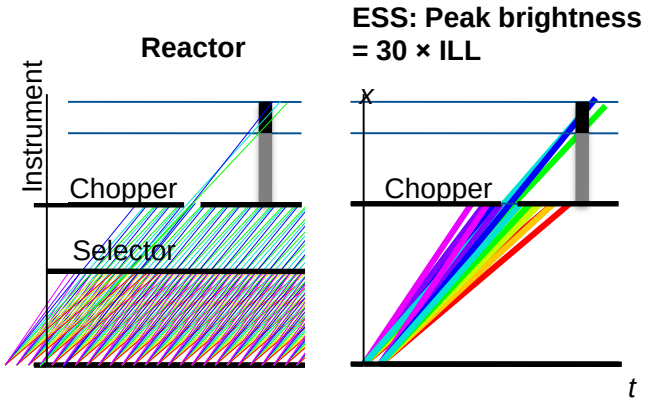
ESS design goal is same time average neutron flux as ILL. Peak brightness in pulse: 30 × ILL

Using pulsed beam for particle physics already at reactor sources!

**Statistics gain factor for a PERC-like system: x 15 !**

Status: particle physics ranked first on “ESS instrument suite – Capability Gap Analysis”




***ANNI – A pulsed cold neutron beam facility for particle physics at the ESS***
T. Soldner, H. Abele, G. Konrad, B. Märkisch,
F. Piegsa, U. Schmidt, C. Theroine, P. Torres Sánchez,
EPJ Web Conf. (2019), in press, arXiv:1811.11692

Talk by V. Santoro on Thursday

# Summary

Newer measurements of the **beta asymmetry**: consistent, small corrections, blinded*.

$$A_{avg} = 0.11958(18);\ \ S = 1 \quad \lambda_{A,avg} = -1.2757(5)$$

$V_{ud}$ **from neutron decay** is becoming competitive with nuclear decays:

$$V_{ud}(PERKEO\ III) = 0.97301(58)$$

SM analysis of *A* combined with lifetime and $Ft$ values from superallowed decays yields best limit on **tensor couplings:**

$$-0.0048 < \frac{C_T}{C_A} < 0.0007\ \ (95\%\ C.L.)$$

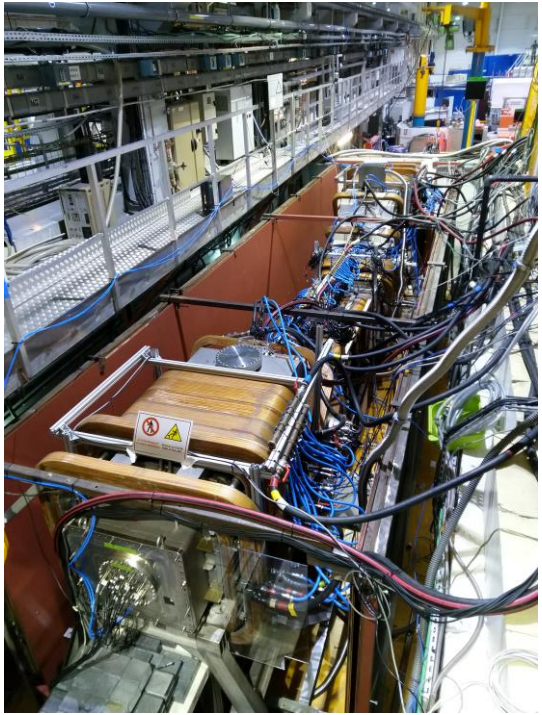
New limit on the **Fierz interference** from neutron decay with combined $A$–$b$ analysis

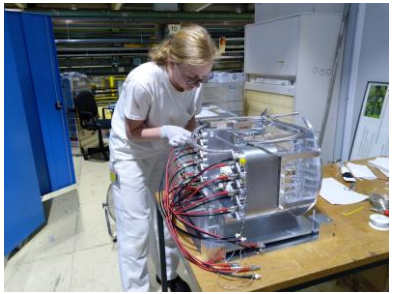
$$-0.035 < b < 0.068\ (90\%\ C.L.)$$

**Exotic decays** are not the origin of the “neutron lifetime enigma”.

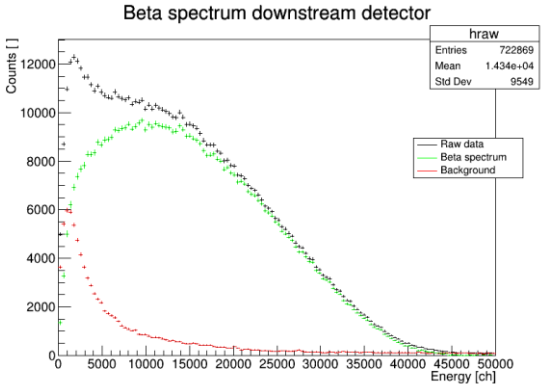
Particle Physics with Cold and Ultra-Cold Neutrons

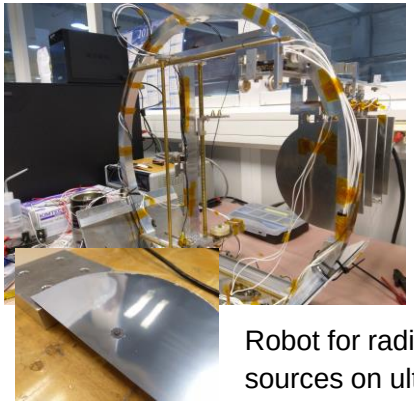
# Ongoing Measurement of the Beta Spectrum at ILL, Grenoble





New detectors optimized for uniformity

Robot for radioactive calibration sources on ultra-thin carbon foil support 4µg/cm²