Neutron decay correlation measurements with PERKEO III and PERC

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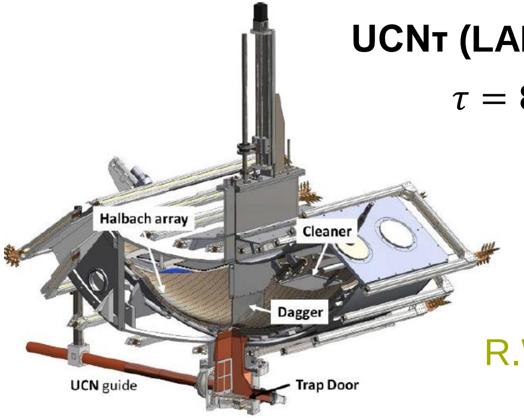
CIPANP 2022, Lake Buena Vista, Florida

V_{ud} from Neutron Decay

With only a factor of two improvement, the most precise determination will come from neutron decay! Requires only two experimental inputs and radiative corrections.

Neutron Lifetime τ_n

UCNτ (LANL), Gravitrap (ILL), PENeLOPE (TUM), τSpect (Mainz), J-PARC, BNL-2 (NIST), …



UCNτ (LANL)

$$\tau = 877.75 \pm 0.33\ \mathrm{s}$$

$$\frac{\Delta\tau}{\tau} = 3.8 \times 10^{-4}$$

Gonzalez *et al.*, Phys. Rev. Lett. 127, 162501 (2021)

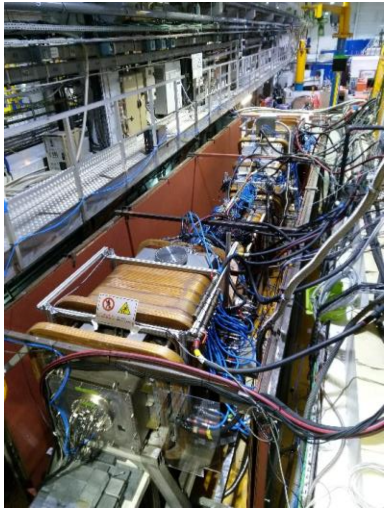
R.W. Pattie plenary Wed

$$V_{ud}^{n,best} = 0.97413(13)_{\text{theory}}(20)_\tau(35)_\lambda = 0.97413(43)$$

Cirigliano et al., arXiv:2208.11707

Nucleon Axial-Coupling: $\lambda = g_A/g_V$

PERKEO III (ILL), UCNA (LANL), aSpect (ILL), aCorn (NIST) Nab (SNS), PERC (MLZ), …



PERKEO III (ILL)

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

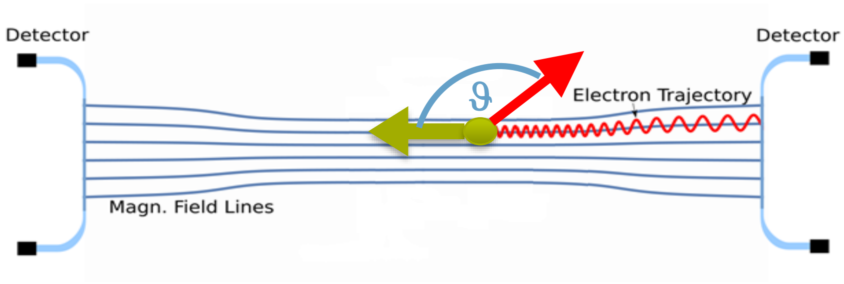
BM *et al.*, Phys. Rev. Lett. 122, 222503 (2019)

Goal of PERC (MLZ)

$$\frac{\Delta\lambda}{\lambda} \leq 1 \times 10^{-4}$$

aSpect, aCorn, Nab, BRAND: this afternoon

PERKEO: Measuring Beta Asymmetry



electron angular distribution:

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

magnetic field for spin alignment

integration over hemispheres: $\cos\vartheta \to 1/2$

2 × 2 π detection

experimental asymmetry, n polarization P

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

within Standard Model:

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

With scalar and tensor interactions:

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

Symmetric layout enables detection of backscattered electrons: full energy detection

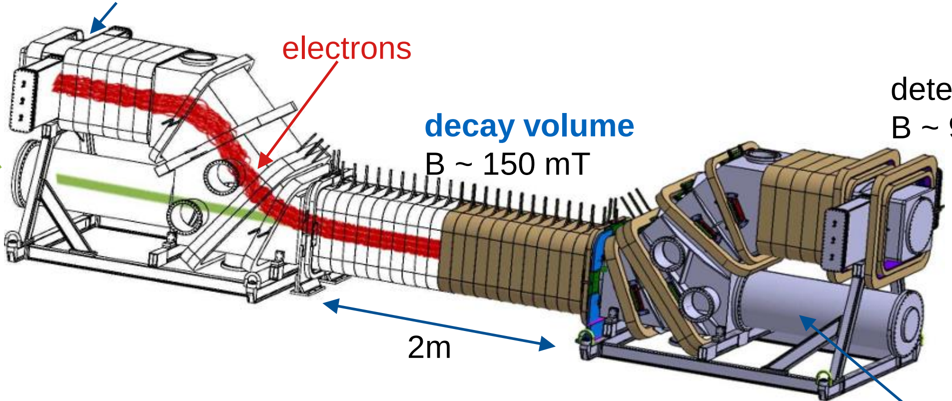
Largest systematic corrections due to neutron polarization and magnetic field uniformity used for blinding

(correction smaller for future experiments: Petoukhov et al., arXiv:2208.14305: P=99.7%)

Neutron Decay Spectrometer PERKEO III at ILL, Grenoble

Designed to use a *pulsed beam* to control or eliminate leading systematic errors.

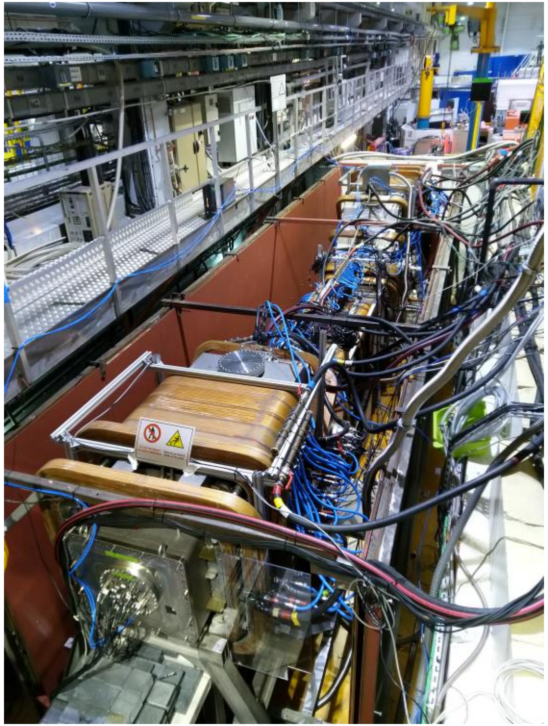
Originally built by University of Heidelberg, now operated by TUM, TU Vienna, HD & ILL.



~50.000 decays/s in *continuous polarized* beam

time avg. ~200 s^{-1} in **pulsed**, polarized mode

~800 s^{-1} in pulsed, unpolarized mode



Temporary setup, installed 4 times at PF1b at ILL: ~3 months of installation, ~3 months characterization, up to 6 months of measurement

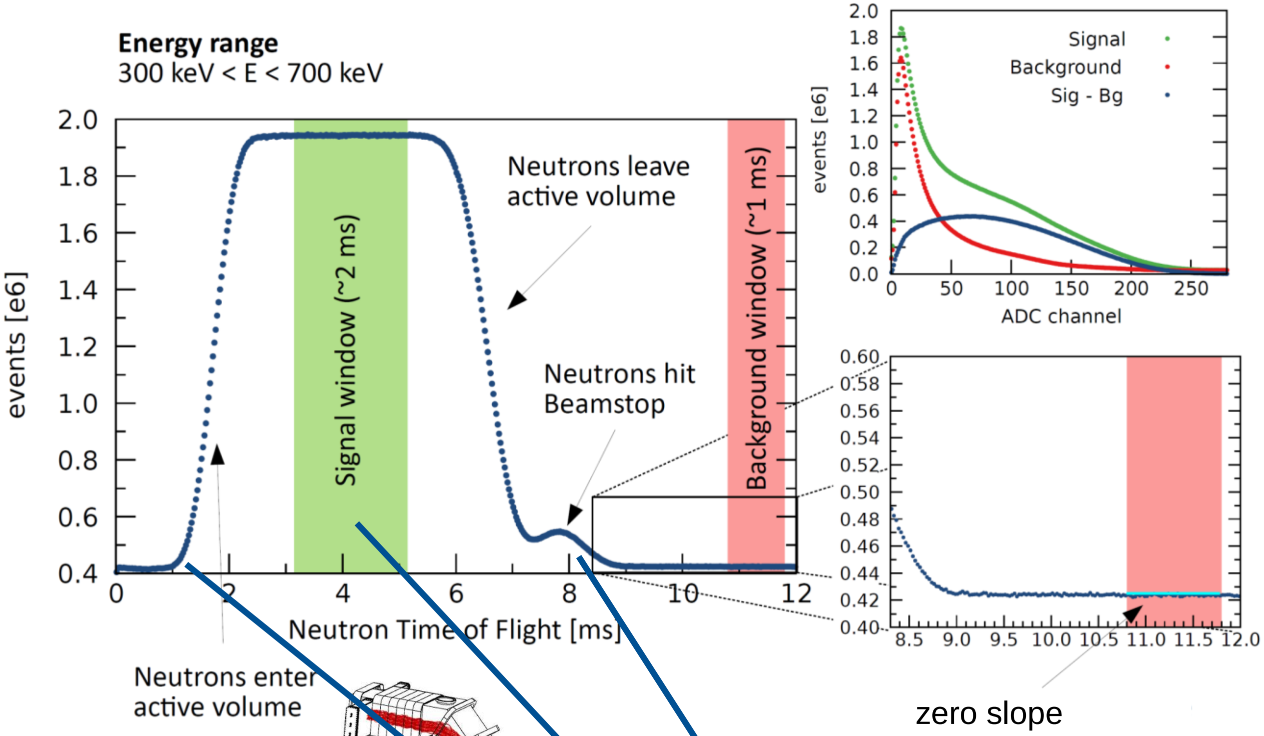
PERKEO III: Pulsed Neutron Beam and Background Control

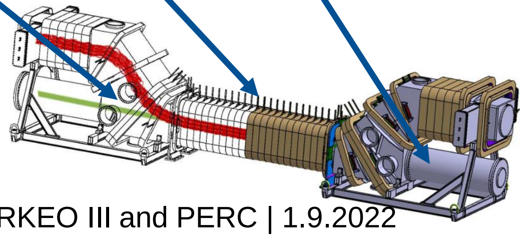
Pulsed beam allows nearly perfect background subtraction

Free neutron pulse does not interact with matter during measurement.
Same background condition in *signal* and *background* time *window.*

Related Uncertainties $\Delta A/A$
Time dependence 0.8×10^{-4}
Chopper disc uniformity 0.7×10^{-4}

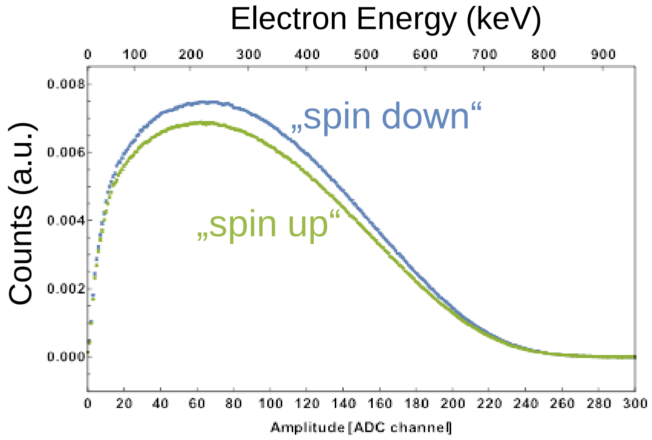
(PERKEO II: 10×10^{-4})

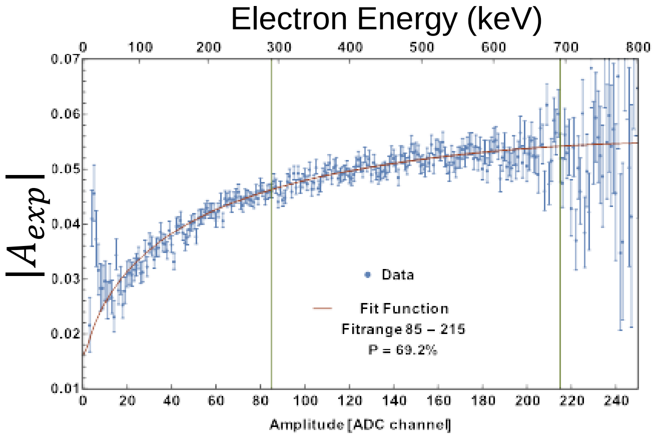




… also eliminates or controls more systematic effects: edge *and* magnetic mirror effects

PERKEO III: Asymmetry Extraction





Asymmetry $A \sim -12\%$ already visible in electron spectra from “spin up” and “spin down” neutrons.

Largest data set from polarized neutron decay by one order of magnitude (PERKEO II): 6×10^8 events in analysis

Single parameter fit to experimental asymmetry:

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

Most corrections to the „raw“ fit result on the $10^{-3} - 10^{-4}$ level only.

Analysis blinded by separate analysis of largest corrections.

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

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

Märkisch, et al., PLR 122, 222503 (2019)

Status of $\lambda = g_A/g_V$ from Decay Correlations

New beta asymmetry A results **consistent** – but disagree with older measurements and new *a*Spect electron-neutrino correlation a result.

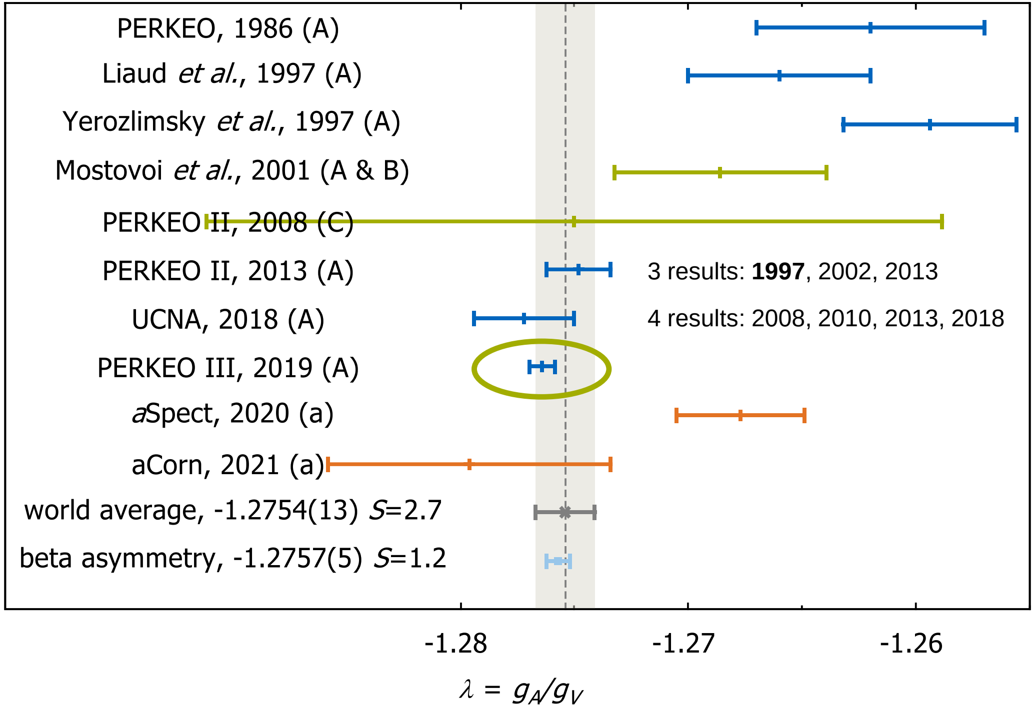
$$A_{avg} = -0.11958(21), \qquad S = 1.2$$

Newer measurements of A have order of magnitude **smaller corrections**.

UCNA, PERKEO III, aCorn, *a*Spect: **blinded analysis** to avoid potential bias.

(Newer results of UCNA & PERKEO II include older results)

Aim of PERC is five-fold improvement.



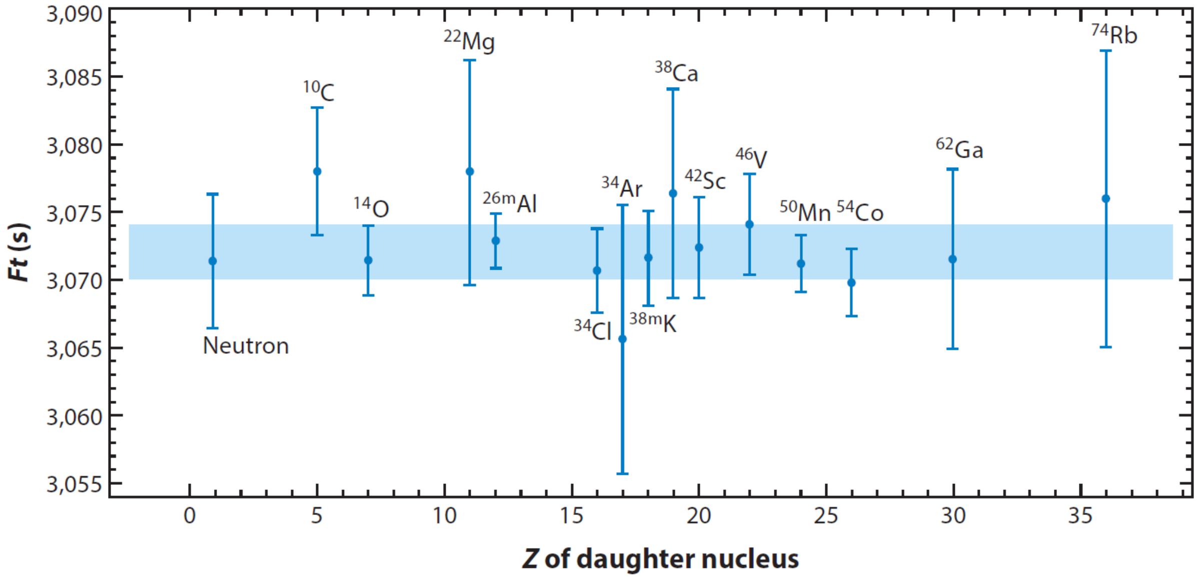
Experimental observables are *not* the correlation parameters: radiative corrections change

See L. Hayen's talk, and Glück arXiv:2205.05042

Comparison to Superallowed Decays

Neutron: vector part of neutron $\mathcal{F}t$

$$\mathcal{F}t_{nV} \equiv f\, t_{nV}(1+\delta_R') = \tfrac{1}{2}\ln 2\, f\tau_n\,(1+3\lambda^2)(1+\delta_R')$$



Neutron data point does not yet include new UCNτ result.

Dubbers & BM, Ann. Rev. Nucl. Part. Sci. 71, 139-163 (2021)
$\mathcal{F}$t values from Hardy & Towner. Phys. Rev. C 102:045501 (2020)

See Severijns et al., arXiv:2109.08895 for a review of nuclear mirror decays

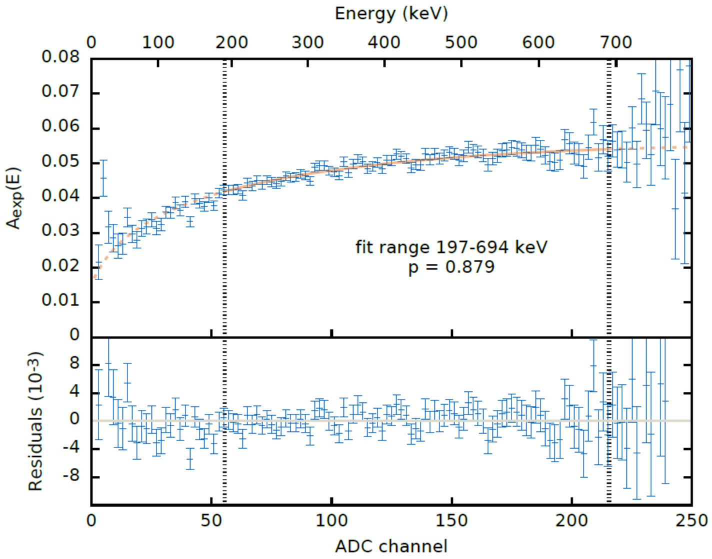
Beyond the SM: Limit on the Fierz Interference Term

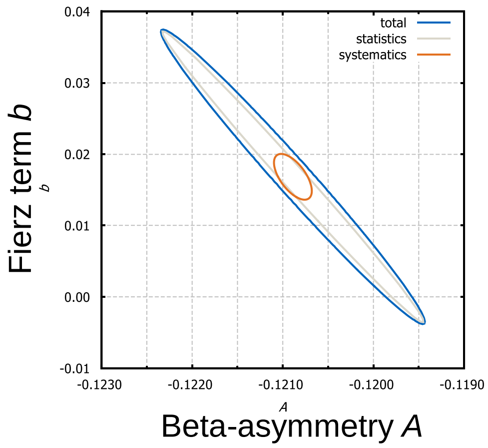
First correlated analysis with beta asymmetry parameter $A(\lambda)$ and Fierz interference term b.

Less sensitive to detector systematics than spectrum, but statistically less sensitive by order of magnitude.

Stronger data selection criteria, but extended fit range, Improvement by factor four.

Limited by statistics. Proof of principle for PERC.





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

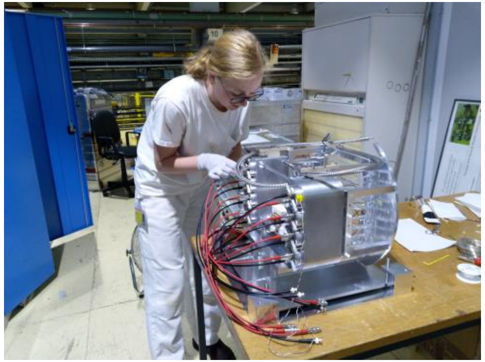
H. Saul, C. Roick, et *al.*,
Phys. Rev. Lett. 125, 112501 (2020)

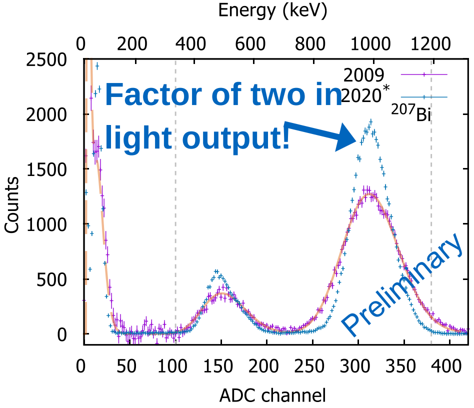
See also new result by UCNA: X. Sun et al., Phys. Rev. C 101, 035503 (2020)

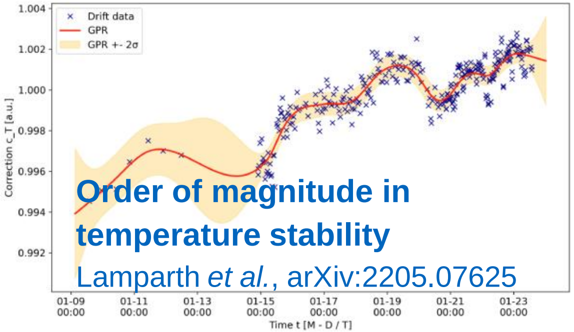
PERKEO III: Beta Spectrum Measurement at ILL `19/`20

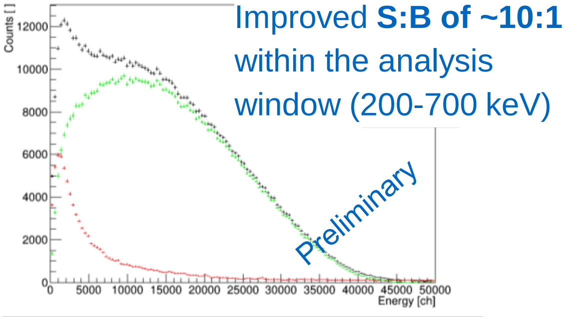
Dedicated run with the *aim* to measure Fierz term $\Delta b \sim 5 \times 10^{-3}$. ~$10^9$ events.

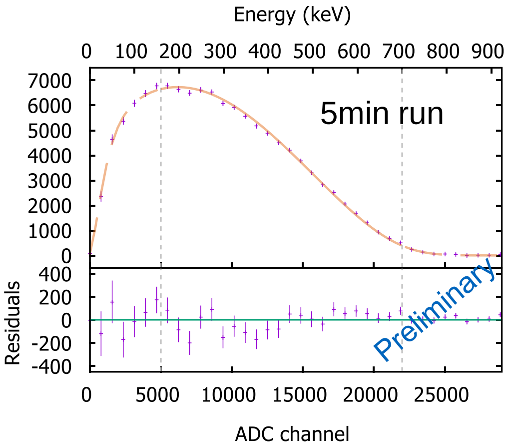
New detectors optimized
for uniformity (~2%) and light output









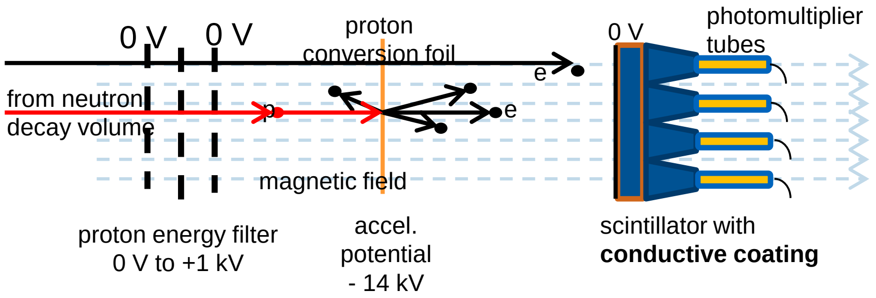


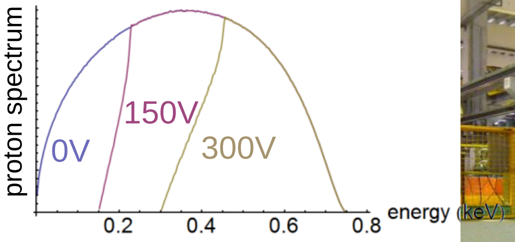
PERKEO III: Proton Asymmetry

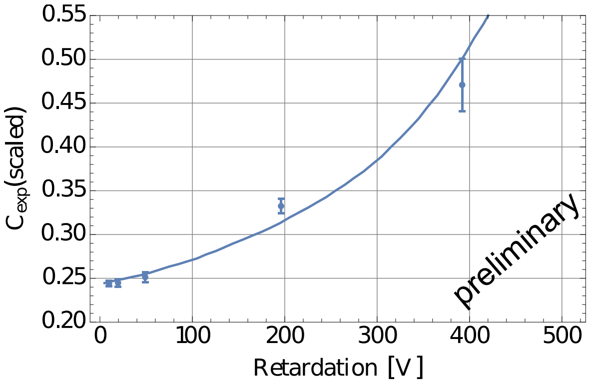
First measurement of the energy-dependence of the proton asymmetry *C*. Proof-of-principle for PERC.

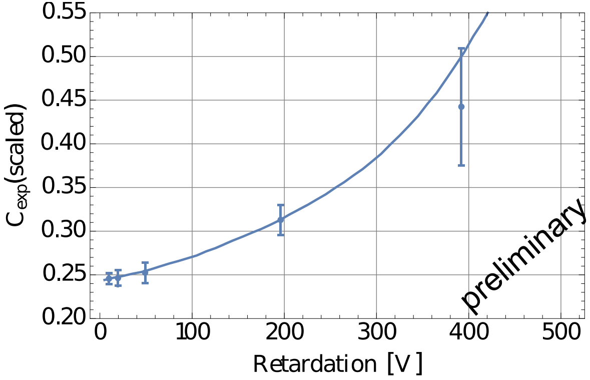
$$C = -4x_C \frac{\lambda}{1+3\lambda^2} = x_C(A+B)$$

Status: Analysis mostly completed. Expect $\Delta C/C \sim 0.01$









Thesis: C. Roick (TUM), L. Raffelt (TUM/HD), M. Klopf (TUW), A. Hollering (TUM)

The next generation:
PERC (Proton Electron Radiation Channel) at MLZ / FRM, Garching

Goal: Order of magnitude improvement.

New observables.

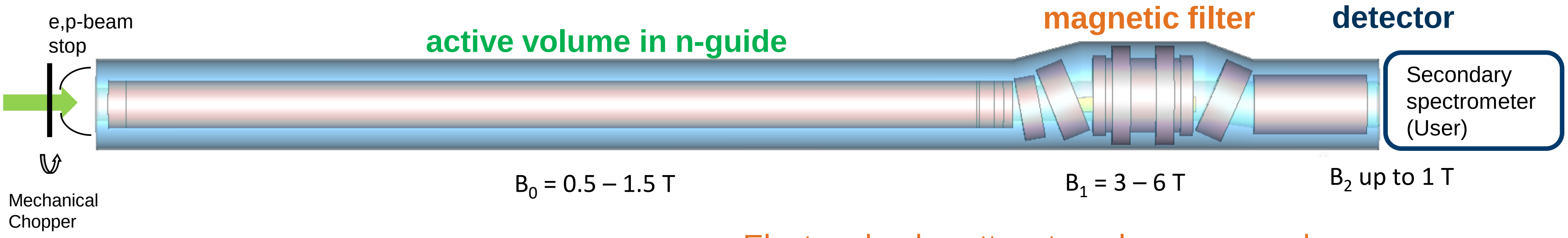
SLOW NEUTRONS
DFG SPP 1491

Priority Programme SPP1491 of the German Research Foundation (DFG)

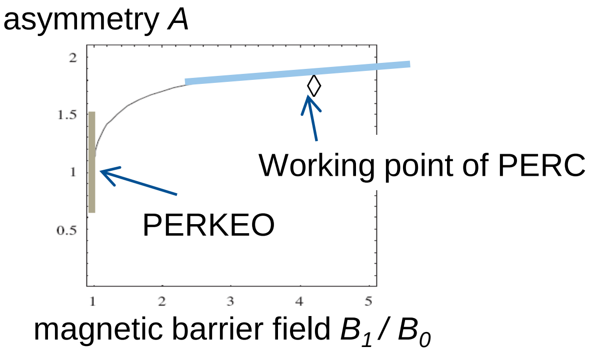
PERC Concept and Systematics

PERC‘s asymmetric layout with magnetic filter improves systematics

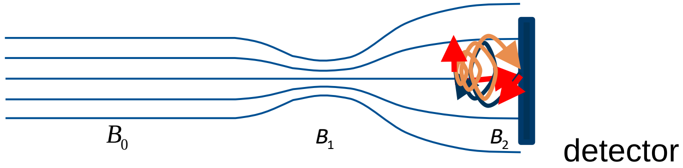
Strong field ensures high phase space density, small detectors, excellent S/B and only a single detector!.



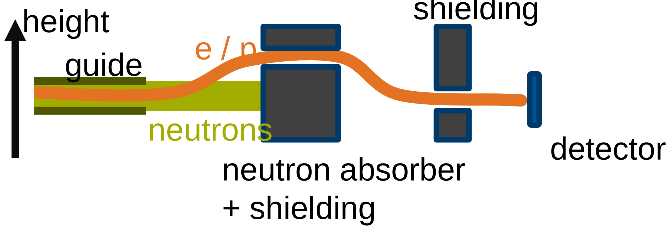
Phase space cut: magnetic field influence



Electron backscatter strongly suppressed



Main detector shielded from background



Non-depolarizing Neutron Guide for PERC

PERC's goal of 10^{-4} measurement accuracy requires neutron spin control on same level

Polarization measurement at 10^{-4} level using ^{3}He cells: C. Klauser, T. Soldner *et al.* (ILL)

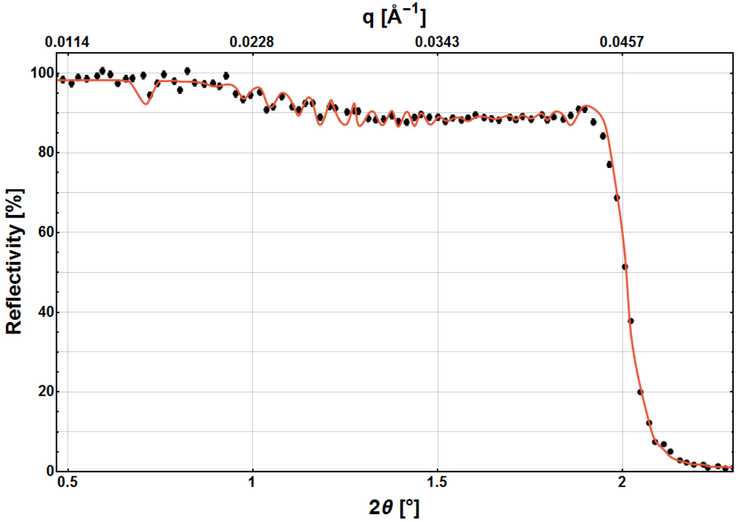
Neutron guide inside PERC magnet at 1.5T (decay volume): only polarization change of 10^{-4} per bounce allowed:

Solution: CuTi m=2 supermirror

Multi-layer system with 190 layers

Challenge is to control interdiffusion of Cu while maintaining neutron optical contrast.

- Very good max. angle of reflection.
- Very good reflectivity > 90% reduces losses inside PERC.
- (Mildly) backable (>80°C). Beneficial for vacuum conditions.

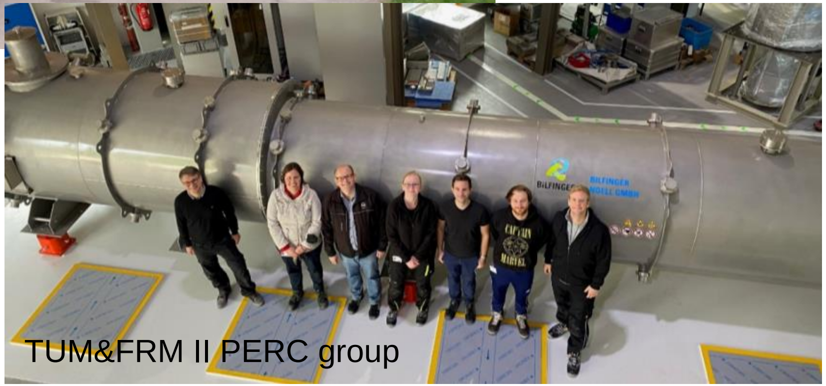


A. Hollering *et al.*, arXiv 2112.00815, Nucl. Instrum. Meth. A, 1032, 166634 (2022)

Cooperation with U. Schmidt (HD), Th. Lauer

J.M. Gomez: further improved mirrors produced with by the FRM neutron optics group (see last MLZ news)

Delivery of the Magnet System PERC



TUM&FRM II PERC group

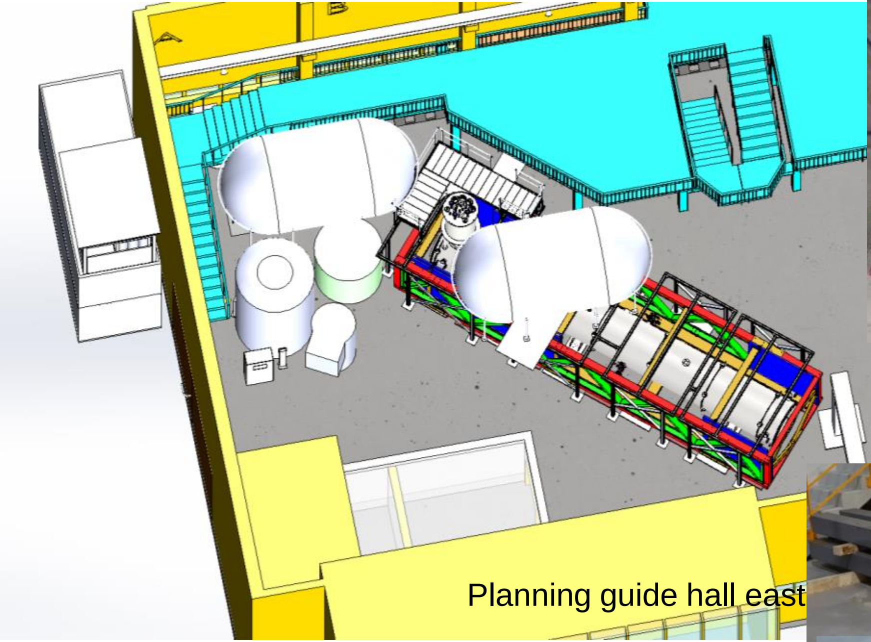
September 2021

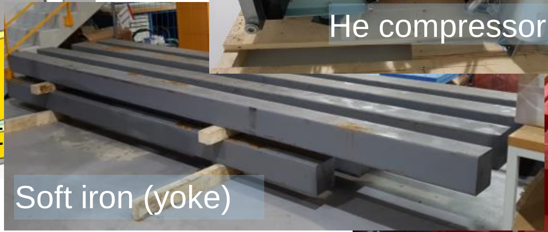
- Delivery on 3 trucks
- Unloading with 3 mobile cranes

https://youtu.be/1LCj3SLxSvI

Construction within next months!

Next steps: installation of He equipment, yoke, MEPHISTO guide, and magnet cold tests!





Start of scientific program 2023

Summary and Outlook

PERKEO III Leading beta asymmetry and Fierz term results. No exotic decay mode. Analysis of proton asymmetry and beta spectrum campaigns ongoing,
Establishes *pulsed cold beam* technique.

PERC Aims at improved measurements of A, (B), C, a, b. Commissioning!

ANNI at ESS Proposed beam line at the ESS.
Statistics gain factor for a PERC-like system: ×15 !
T. Soldner, *et al.*, EPJ Web Conf. 219, 10003 (2019)

DFG Schwerpunktprogramm
SPP1491
SLOW NEUTRONS
DFG SPP 1491
Particle Physics with Cold and Ultra-Cold Neutrons

ORIGINS Excellence Cluster

Extra

Summary of Corrections and Uncertainties

Corrections to the „raw“ fit result on the 10^{-3} – 10^{-4} level only.

Analysis blinded by separate analysis
by independent teams *to avoid potential bias*:

- electron and background measurements,
- neutron polarization: opaque ^{3}He spin filters,
- magnetic mirror effect correction

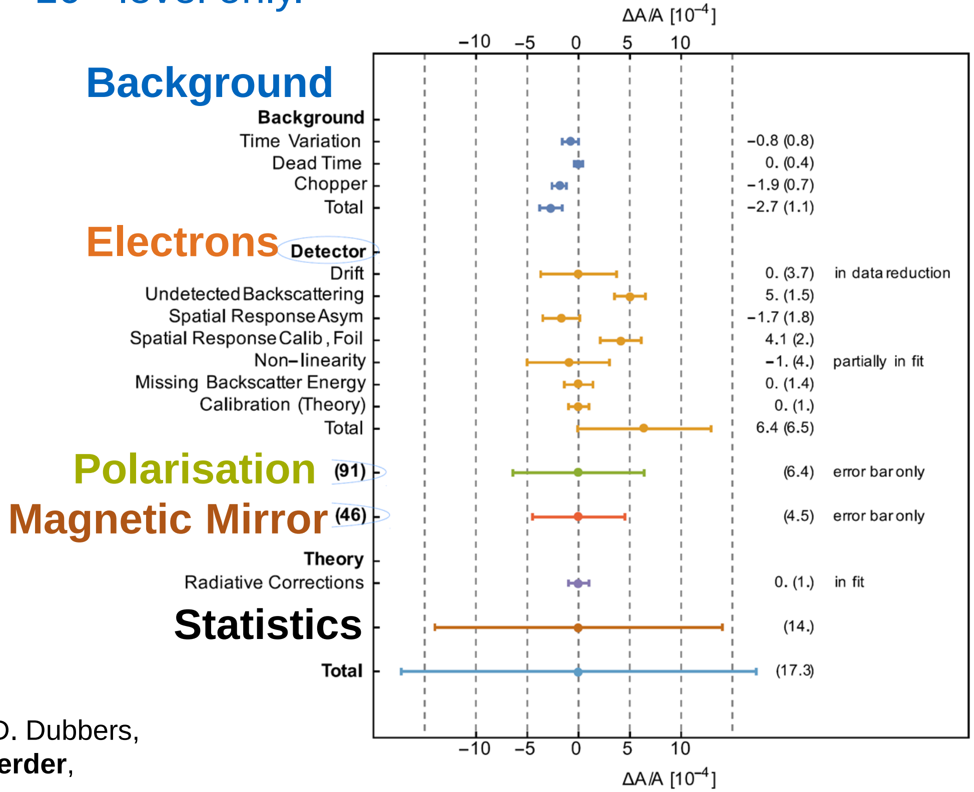
Result:

$$\lambda = -1.27641(45)_{\rm stat}(33)_{\rm sys} = -1.27641(56)$$

$$A = -0.11985(17)_{\rm stat}(12)_{\rm sys} = -0.11985(21).$$

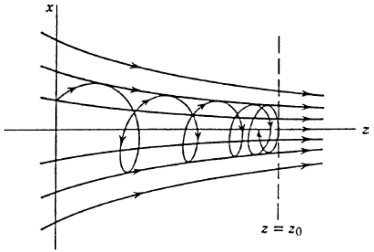
$$A = -2\frac{\lambda^2+\lambda}{1+3\lambda^2}$$

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



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)

Magnetic Mirror Effect



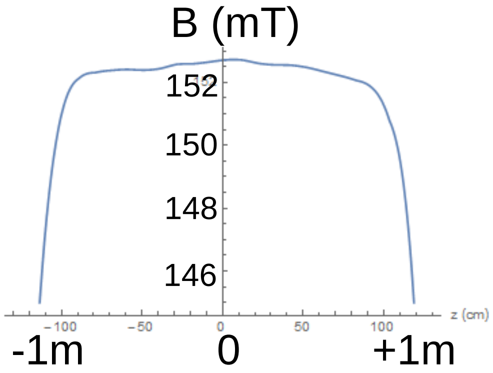
Flux through cross section of gyration is *adiabatic invariant*

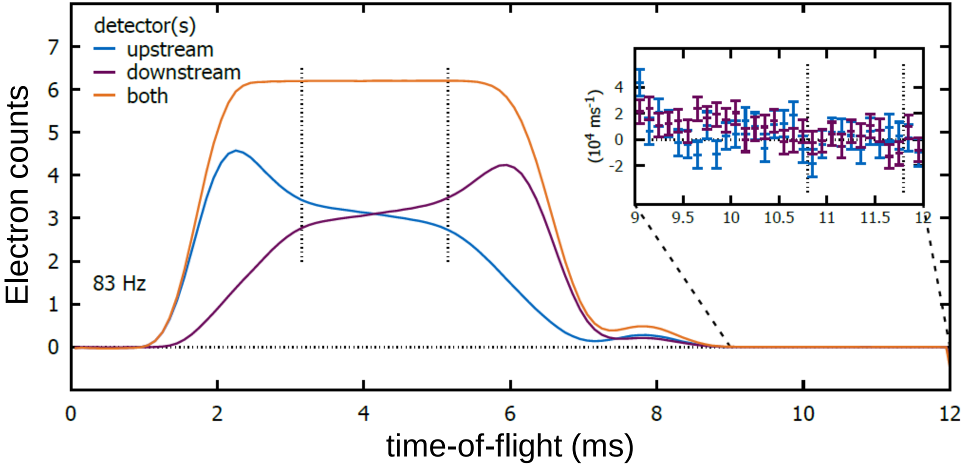
$$B_0 r_0^2 = B_1 r_1^2$$

Critical angle for reflection

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

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



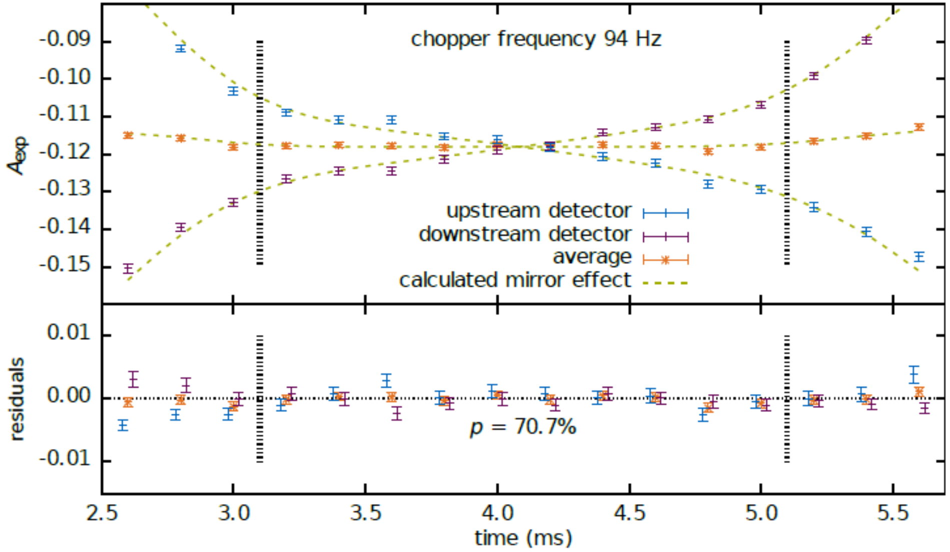


Magnetic Mirror Effect Controlled with Pulsed Beam

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

Calculate **correction** from *measurements* of the magnetic field and neutron pulse:
Interpolation in space and time based on models of the beam optics and magnet.

Result reproduces time-of-flight behavior of asymmetry. **No fit!**



downstream detector

average

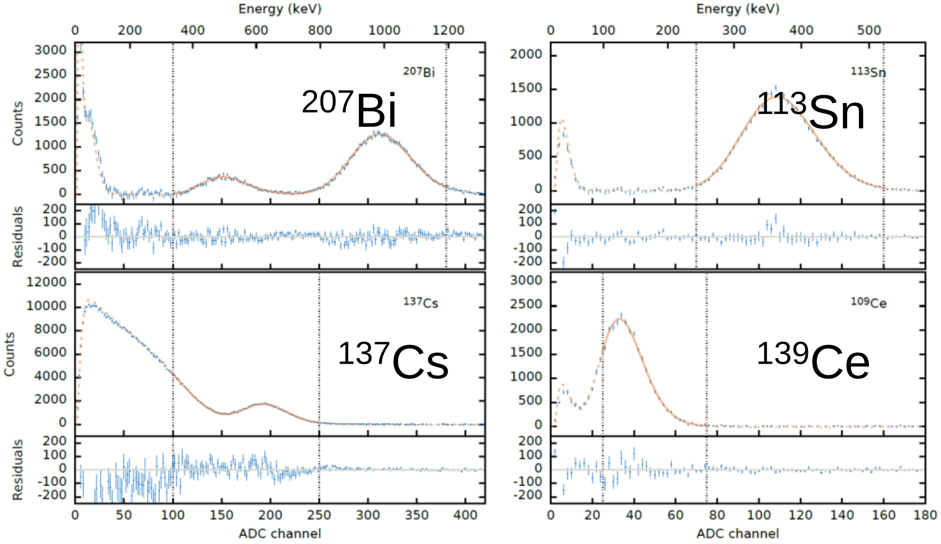
upstream detector

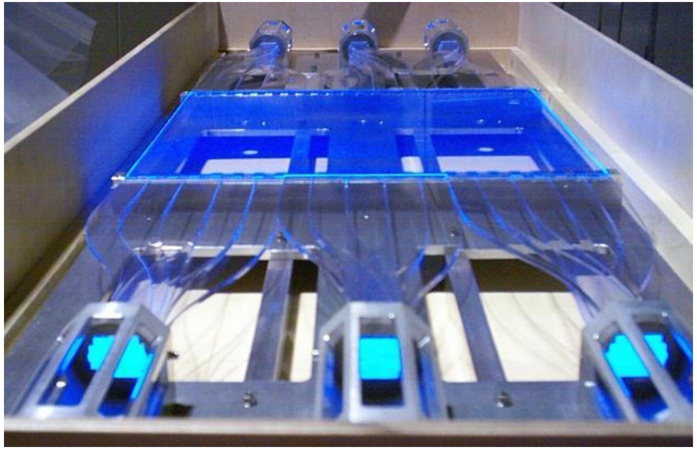
Correction:

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

Detector Calibration

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





114 full calibration sets in ~60 days

Simultaneous fit, **free parameters:**

non-linearity, gain,

photo-electrons, norms

X^2/NDF = 1.0 – 1.3

(+ hourly drift measurements + weekly uniformity scans)

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