Neutron beta decay with pulsed cold neutron beams: PERKEO III and PERC

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PSI 2022

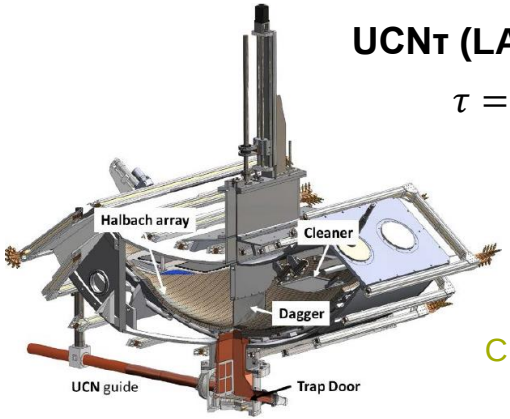
V_{ud} from Neutron Decay

With a factor of two improvement, the most precise determination will come from neutron decay!

Requires only two experimental inputs and radiative corrections. No nuclear corrections.

Neutron Lifetime τ_n

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



UCNτ (LANL)

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

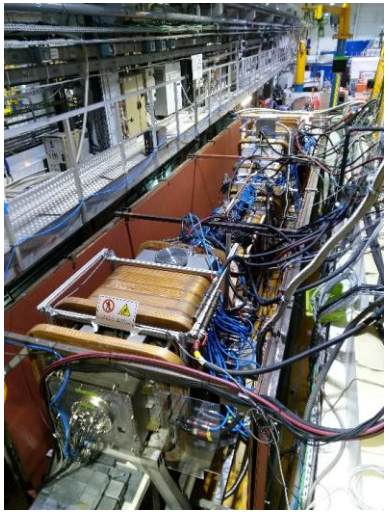
$$\frac{\Delta\tau}{\tau} = 3.8 \times 10^{-4}$$

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

C.-Y. Liu on Tue

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)

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

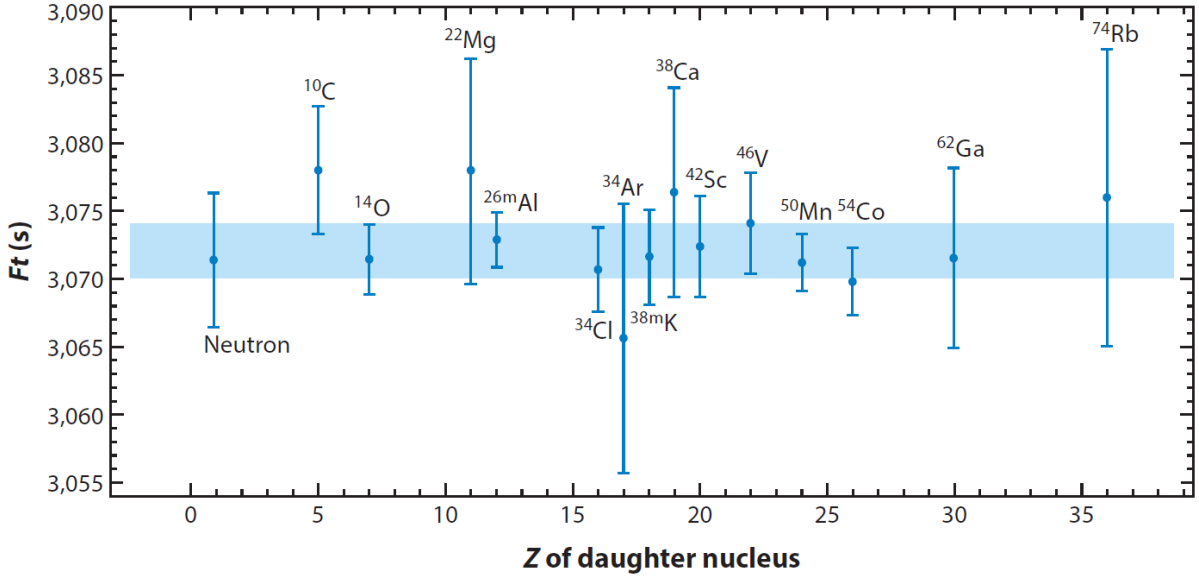
aSpect (U. Schmidt, next talk), aCorn, Nab, BRAND (K. Bodek, Wed)

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

Cirigliano *et al.*, arXiv:2208.11707

Comparison to Superallowed Decays

Neutron: vector part of neutron Ft $\quad Ft_{nV} \equiv f\, t_{nV}(1+\delta'_R) = \frac{1}{2}\ln 2\, f\tau_n\,(1+3\lambda^2)(1+\delta'_R)$



Neutron data point does not yet include new UCNτ result.
λ_{avg} =-1.2754(11), S=2.2 includes all measurements

Dubbers & BM, Ann. Rev. Nucl. Part. Sci. 71, 139-163 (2021)
Ft values from Hardy & Towner. Phys. Rev. C 102:045501 (2020)

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

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.

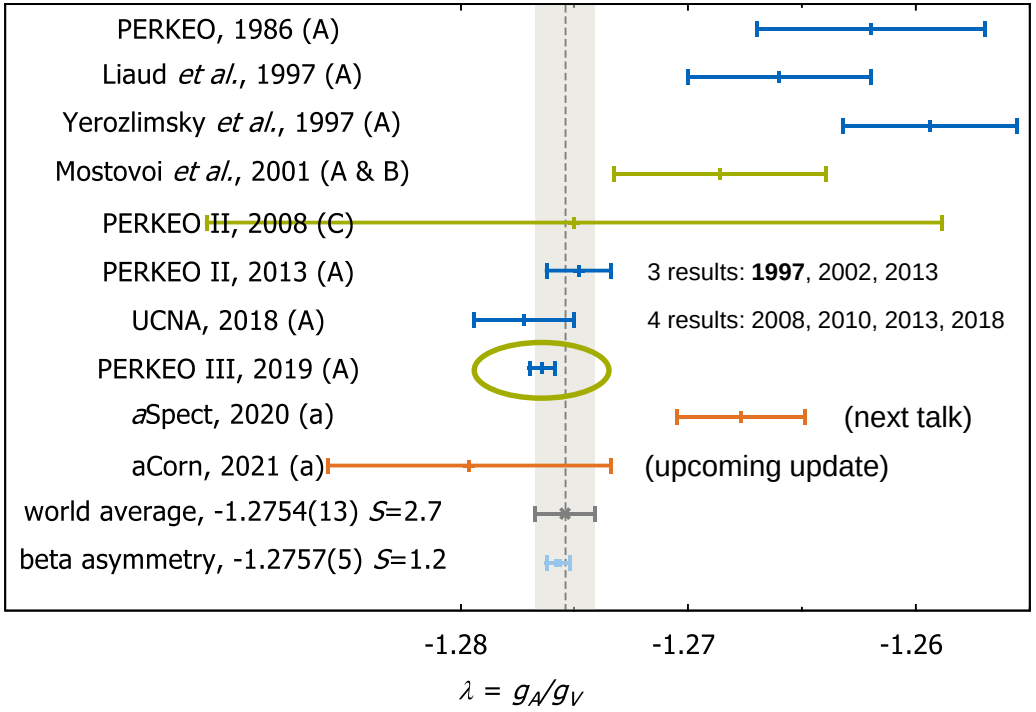
$$A_{avg} = -0.11958(21), \qquad S = 1.2$$

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)

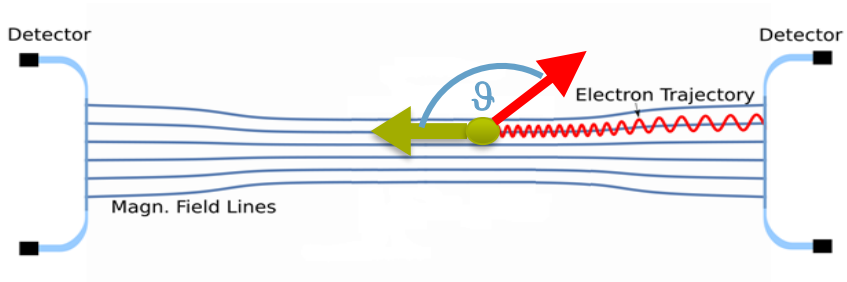
Aim of PERC is five-fold improvement.



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

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

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:
2 × 2 π detection

$$\cos\vartheta \rightarrow 1/2$$

experimental asymmetry, n polarization *P*

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

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:

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

Symmetric layout enables detection of backscattered electrons: full energy detection

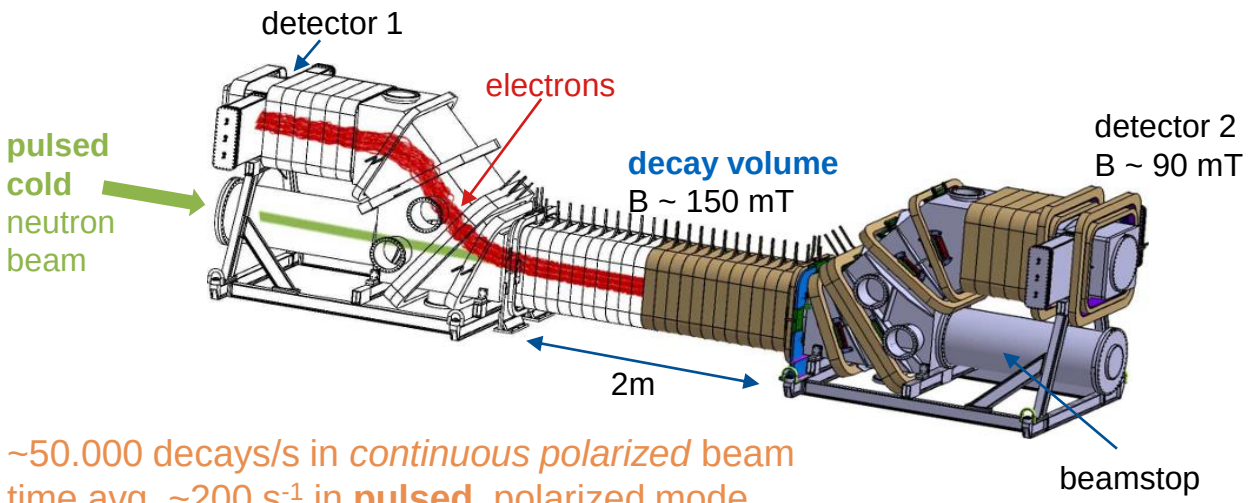
Largest systematic corrections due to **neutron polarization** and **magnetic field** uniformity used for **blinding**

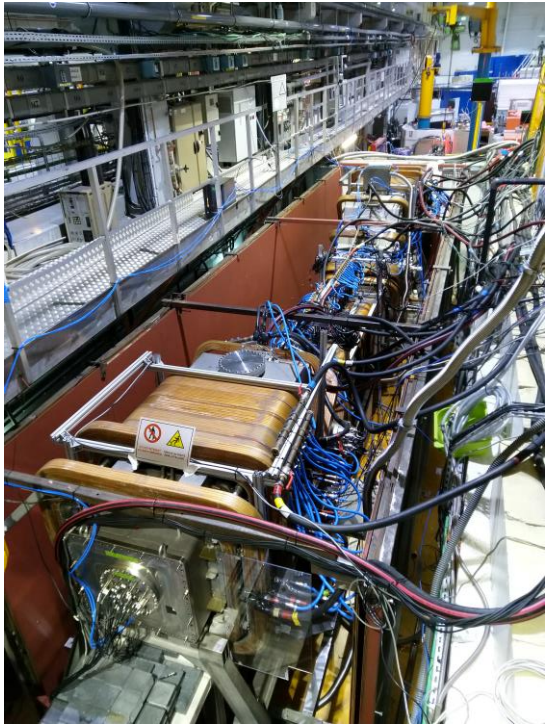
(pol. correction smaller for future experiments: Petoukhov *et al.*, arXiv:2208.14305: $P = 99.7\%$)

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

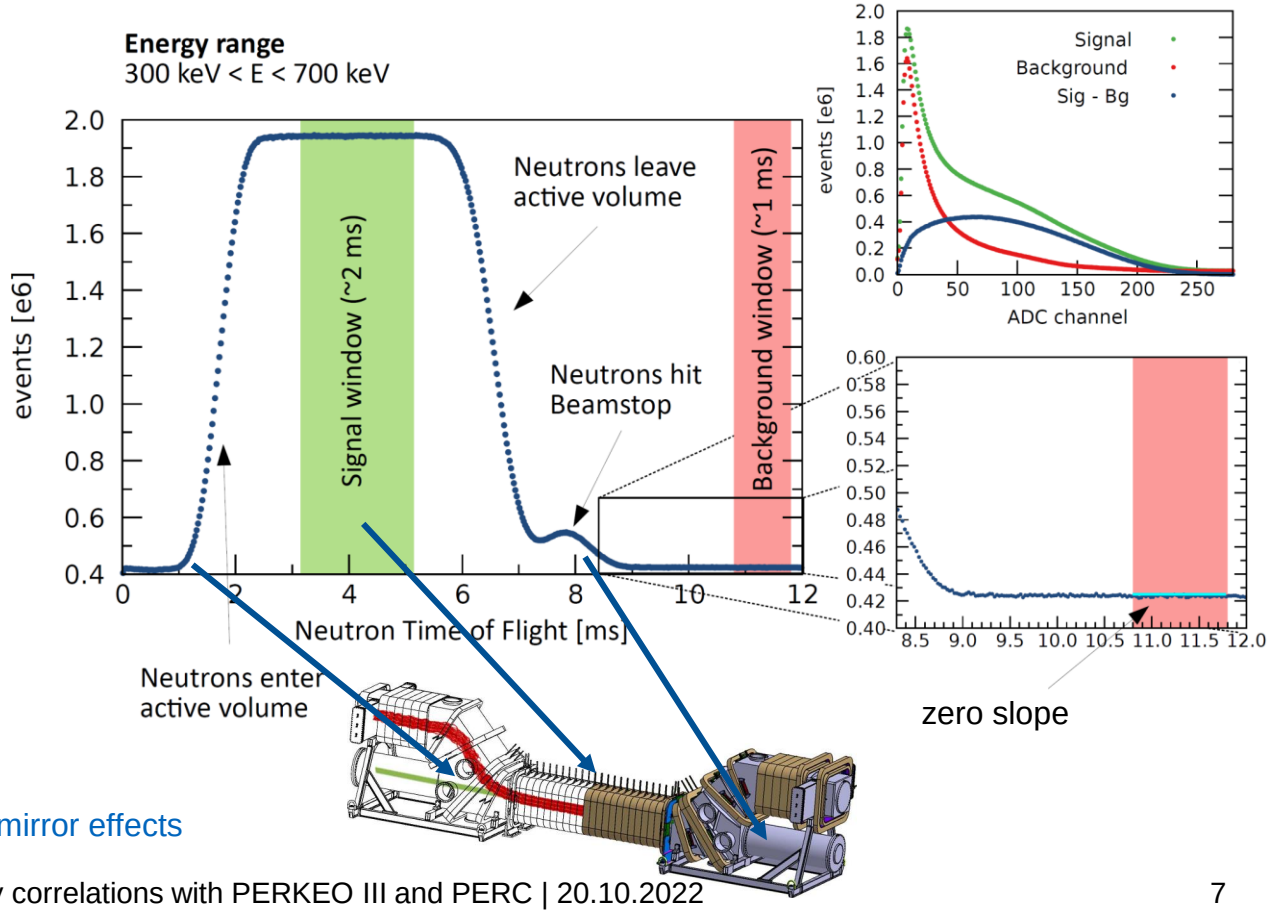
PERKEO III: Pulsed Neutron Beam and Background Control

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})



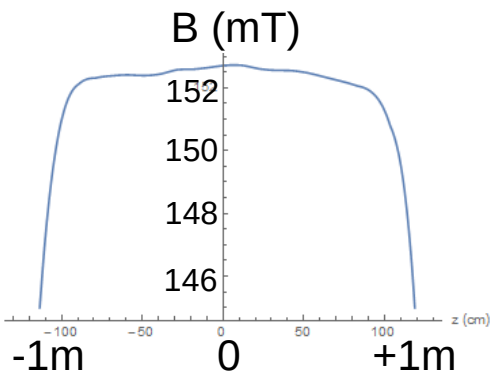
… also eliminates or controls more systematic effects: edge *and* magnetic mirror effects

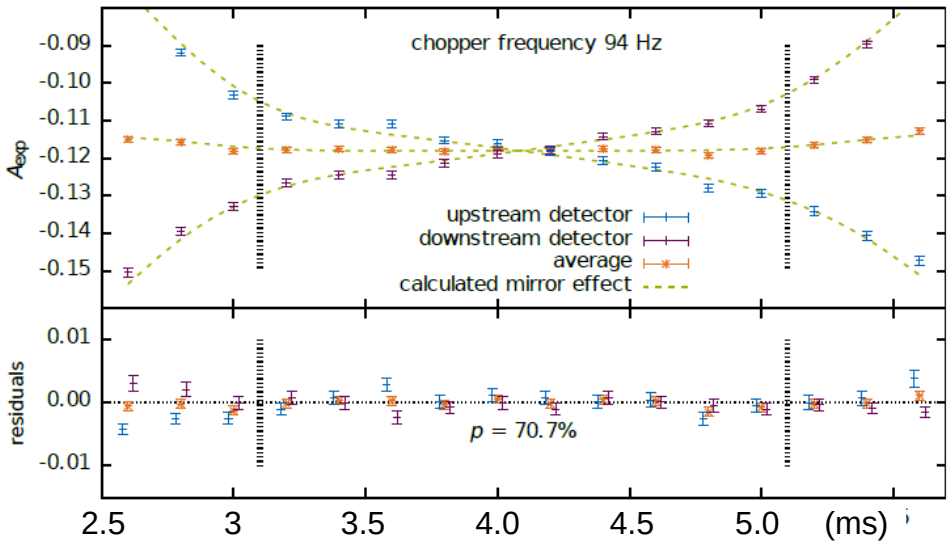
Magnetic Mirror Effect Controlled with Pulsed Beam

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!**

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





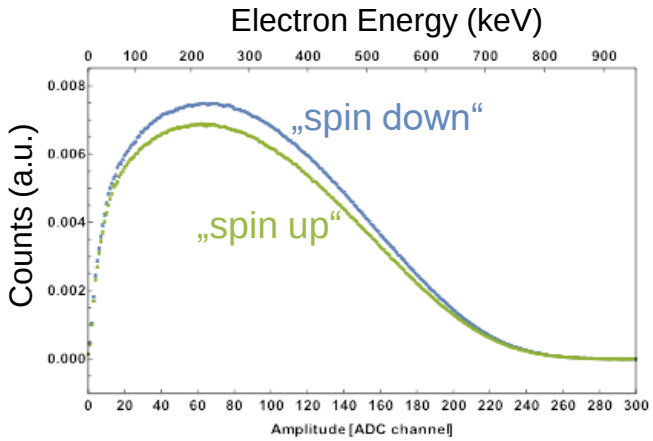
downstream detector

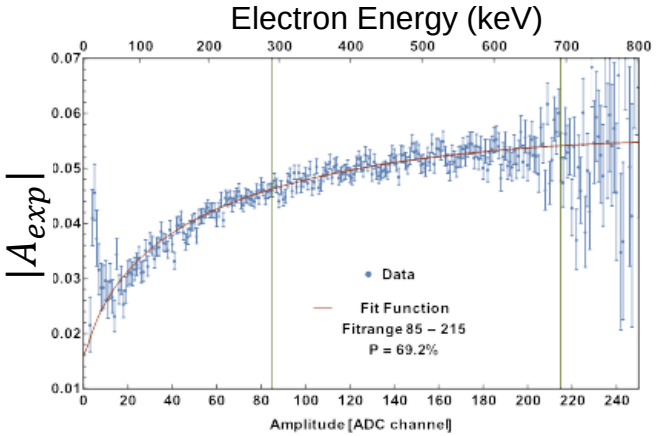
average

upstream detector

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

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: 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.

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

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

Märkisch *et al.*, PRL 122, 222503 (2019)

Fierz Interference Term b

Fierz term b is sensitive to hypothetical scalar and tensor interactions

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

Modifies decay rate / spectrum **and** asymmetries

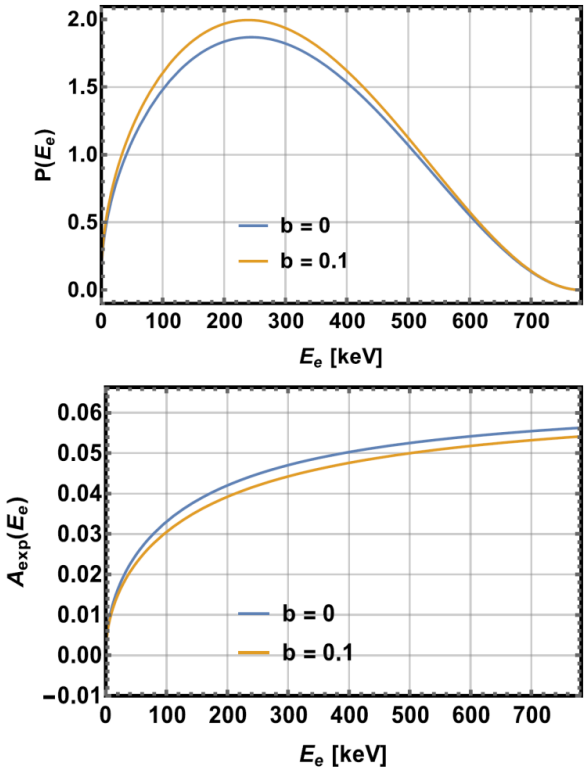
$$d\Gamma \propto \left(1 + b\frac{m_e}{E_e}\right)$$

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

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 an order of magnitude.

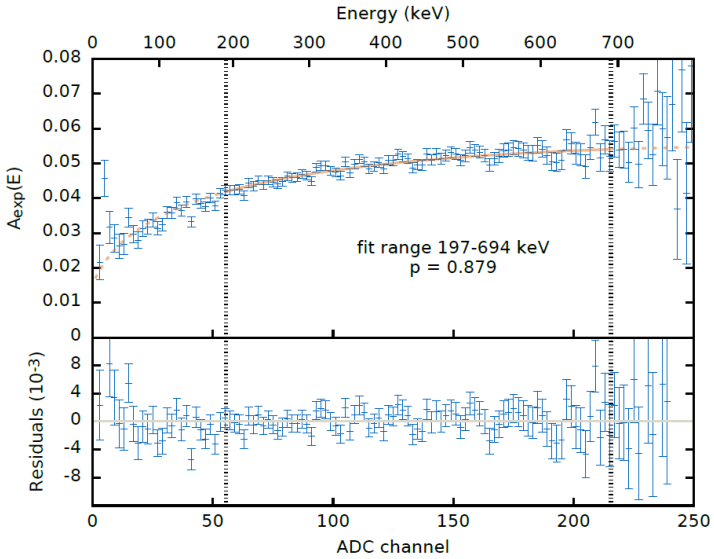
Beyond the SM: Limit on the Fierz Interference Term

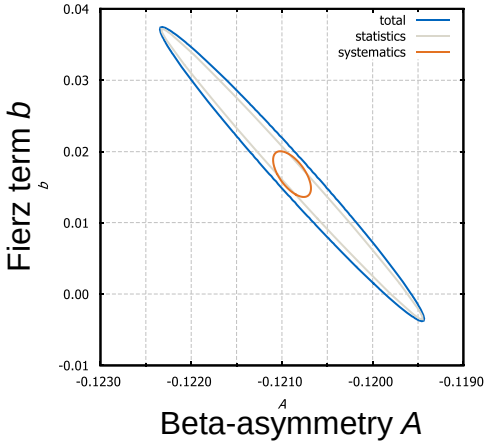
First correlated analysis with beta asymmetry parameter $A(\lambda)$ and Fierz interference term b.

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.





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

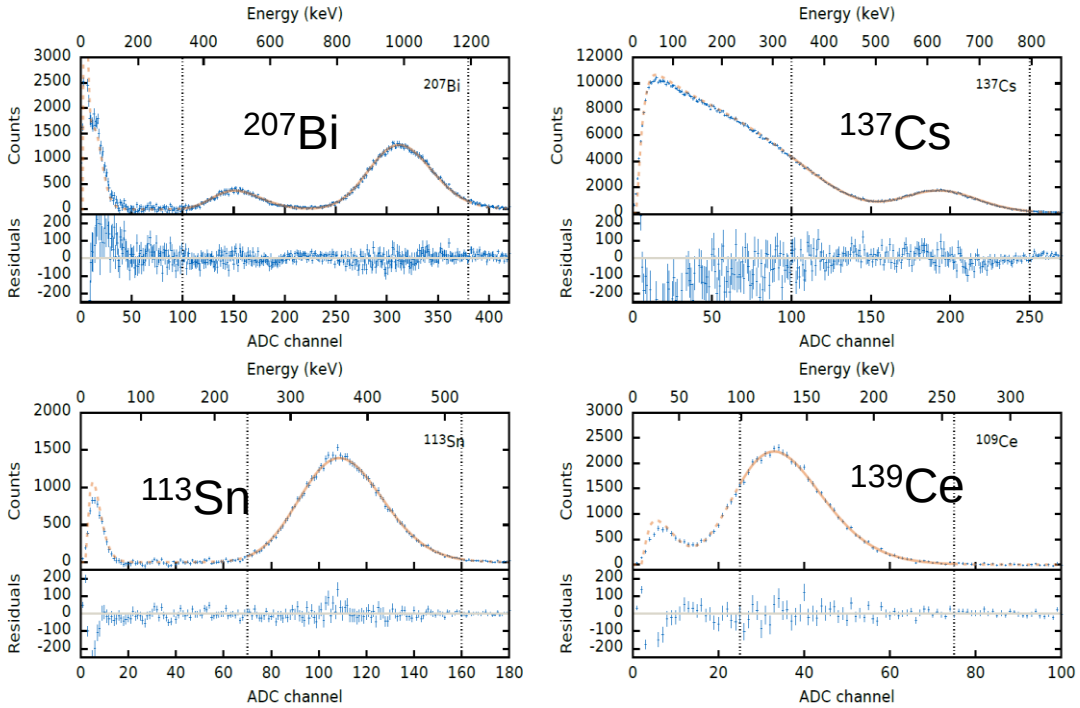
$$A = -0.1209(14)_{\mathrm{stat}}(2)_{\mathrm{sys}} = -0.1209(15),$$
$$b = 0.017(20)_{\mathrm{stat}}(3)_{\mathrm{sys}} = 0.017(21),$$
$$\rho_{A,b} = -0.985,$$

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)

Detector Calibration Fit

Major improvements to the description of the detector response and electron-conversion sources enable consistent *energy-dependent analysis*.



(2x per day calibration + hourly drift measurements + weekly uniformity scans)

Apply detector model to theoretical data. **Free fit parameters:**

non-linearity, gain, photo-electrons, norms

X^2/NDF = 1.0 – 1.3 (for all 96 data sets)

Related Uncertainties ΔA/A

Sources:	1×10^{-4}
Statistics:	0.1×10^{-4}
Non-linearity:	4×10^{-4}
Stability:	3.7×10^{-4}

(PERKEO II: 25×10^{-4})

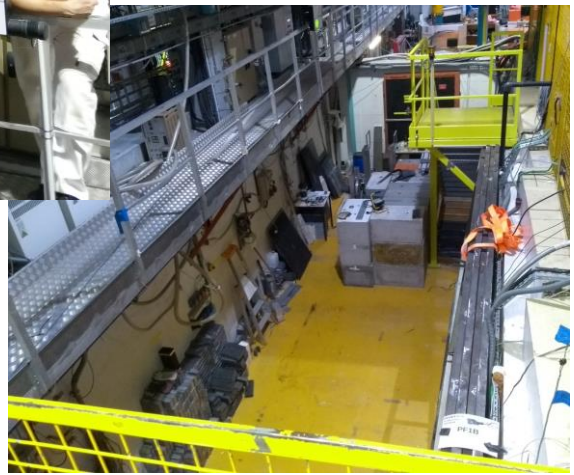
H. Saul, C. Roick, H. Mest

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

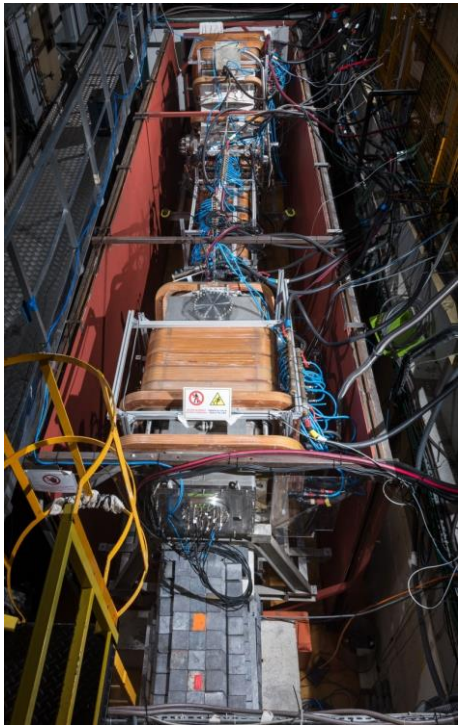
Dedicated run with the *aim* to measure Fierz term $\Delta b \sim 5 \times 10^{-3}$. Obtained 5 ×$10^8$ decay events.

Installation within ~3 months by 12 people

Operation and maintenance mainly by
M. Lamparth, K. Bernert, A. Kropf,
T. Soldner, BM

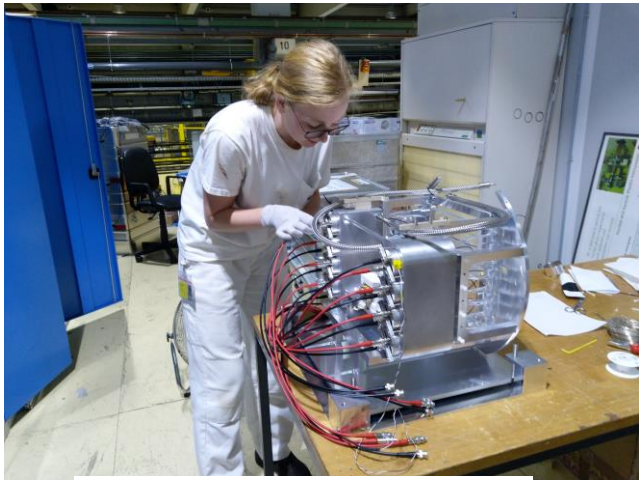


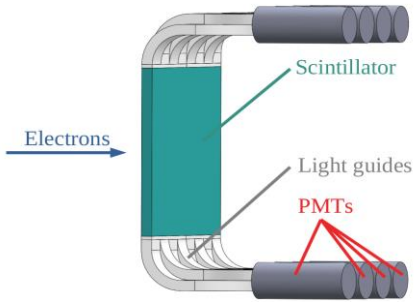
Empty zone, PF1B



PERKEO III installed

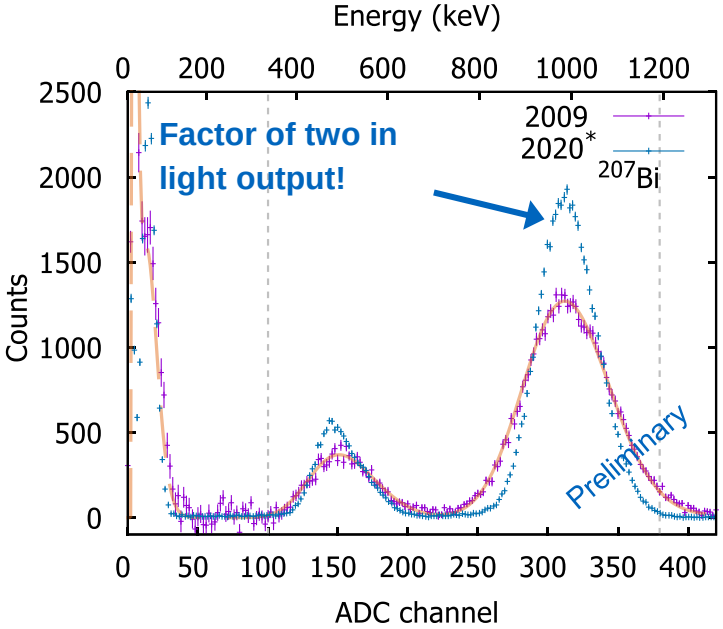
Better Detectors





Shorter, thicker, and bent light guides and thicker scintillators (15mm instead of 5mm):

improved light output by a factor of two!
(> 600 PE / MeV)



„CaliBot“: Robot for Remote Calibration

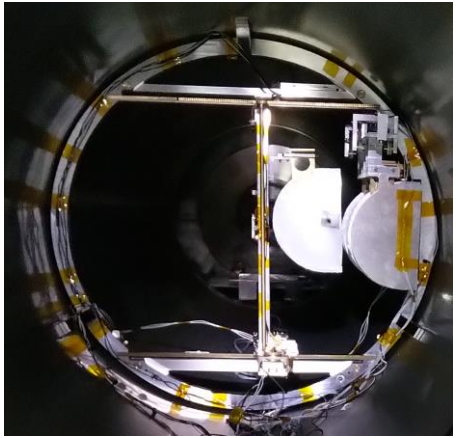
Non-magnetic, UHV-compatible robot which operates in magnetic field:
source changer with 3 piezo motors, located in center of PERKEO.

5 electron conversion sources

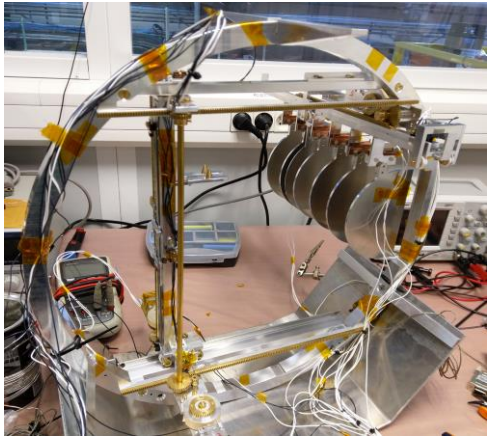
$^{109}\mathrm{Cd}, ^{139}\mathrm{Ce}, ^{207}\mathrm{Bi}, ^{113}\mathrm{Sn}, ^{137}\mathrm{Cs}$

on 4-12µg/cm² carbon foil

drift calibration every 30 min
full calibration with all sources twice per day
daily full 2D scan: uniformity
(beta asymmetry campaign:
every 60min, twice per day, once per week)



50 cm

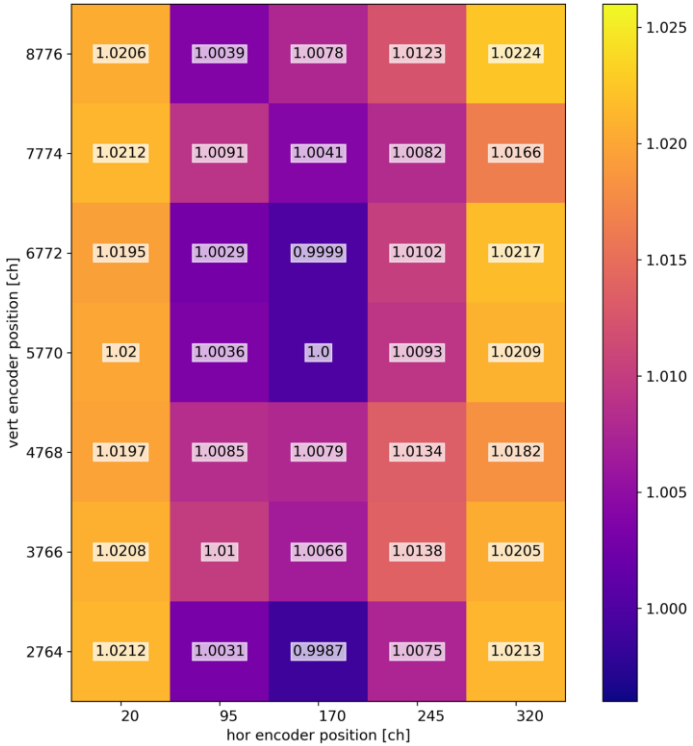


L. Papp (E15),
A. Kropf, H. Saul

Very tricky to get to work reliably. But only failed right after the very last measurement.
Many thanks to K. Bodek and collaborators, and the ILL for the beamtime extension.

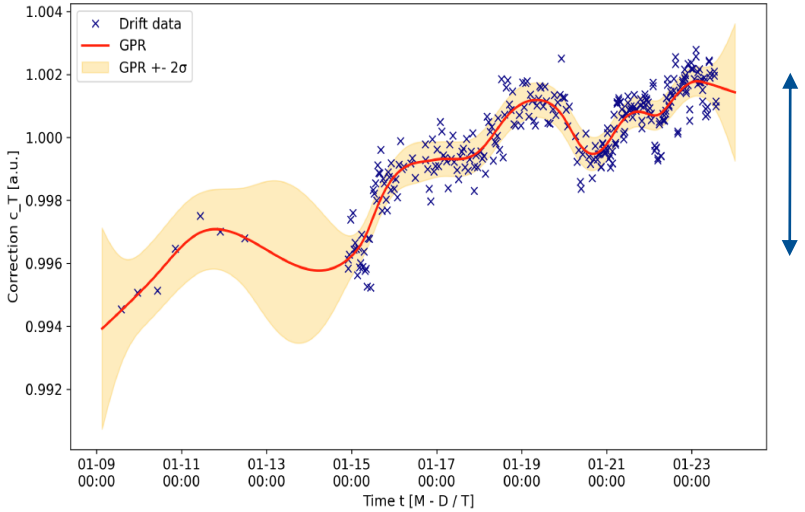
Detector Performance

Uniformity < 2.5% (after offline recalibration)



Order of magnitude improvement in stability

new magnet cooling, temperature stabilization of detector and electronics, operation in winter



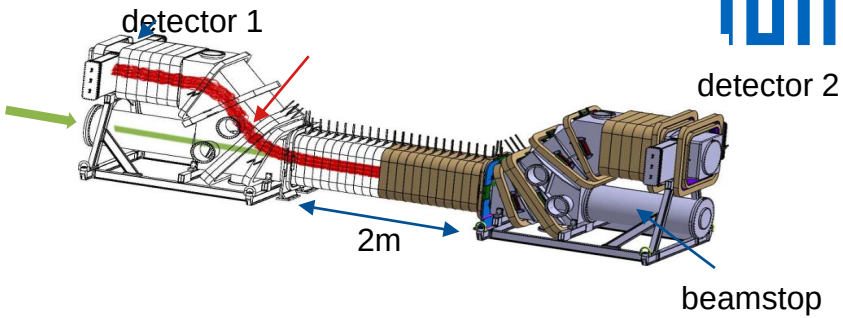
6‰ in 9 days

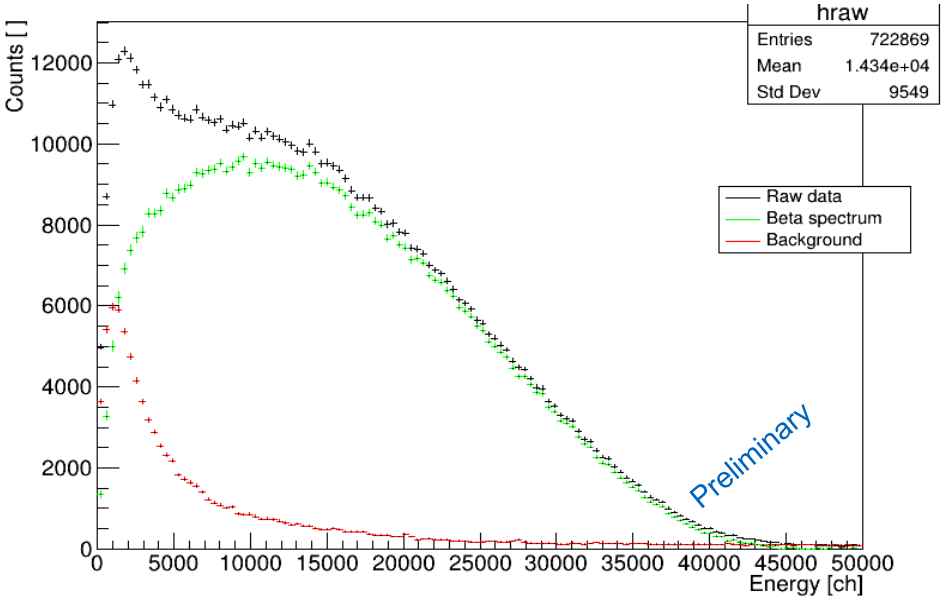
Gaussian Processes used to efficiently recalibrate and to determine mean drift: Lamparth *et al.*, arXiv:2205.07625

M. Lamparth & M. Bestehorn

Background

The detectors of PERKEO III are hard to shield from (ambient) background.
Smaller, but thicker detectors. ~ same volume.





Improved **S:B of ~10:1** within the analysis window (200-700 keV)

Unpolarised measurement: no polarizer.
Instrument changes in surrounding experiments
Improved shielding of own beam?

Still a lot to do….

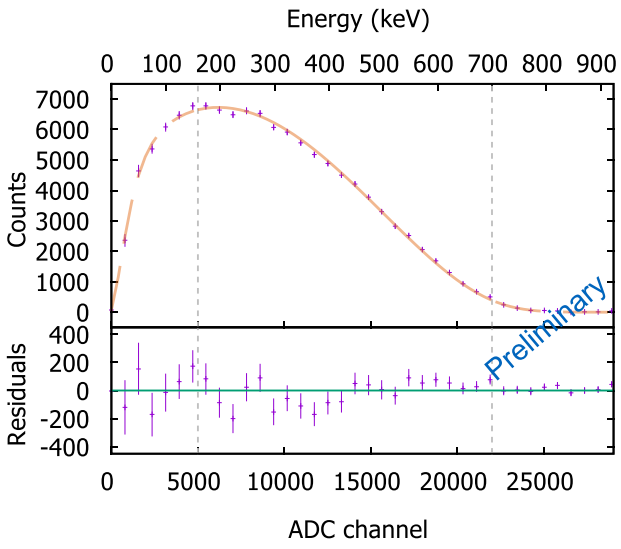
Addressed:

Analysis blinding: artificial offset and scale factor in fit function
Electronics effects: pedestal, rate dependency
Detector: trigger response, spatial response, drift, non-linearity from geometry
Calibration: inaccuracies in source positioning
Background: time variation, chopper

Work in progress:

Calibration: observed non-linearity, quality of fits
Improved treatment of backscatter events: undetected or “shifted” energy
Electronics: observed rate dependence
Edge effects: electrons missing the detectors
Time-dependence of beam cross section

Single parameter fit (number of events) of random 5min dataset with roughly calibrated detector and 2D response correction.

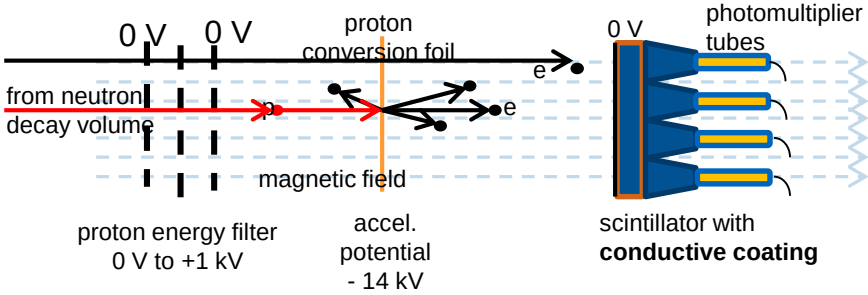


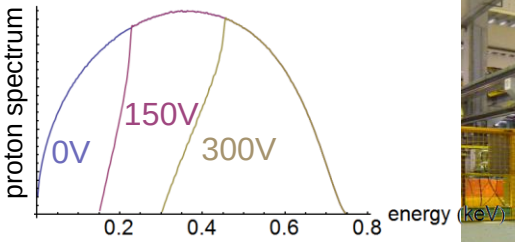
PERKEO III: Proton Asymmetry

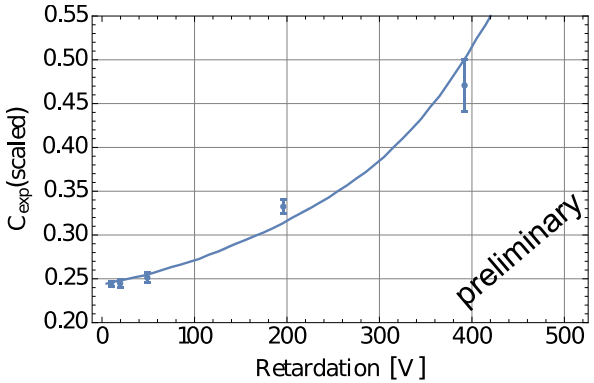
First measurement of the energy-dependence of the proton asymmetry *C*. Proof-of-principle for PERC.

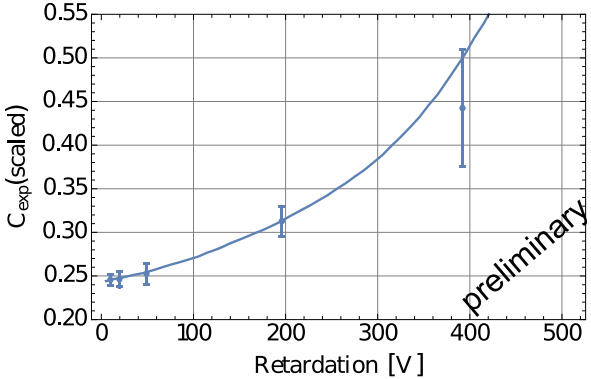
$$C = -4x_C \frac{\lambda}{1+3\lambda^2} = x_C(A+B)$$

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

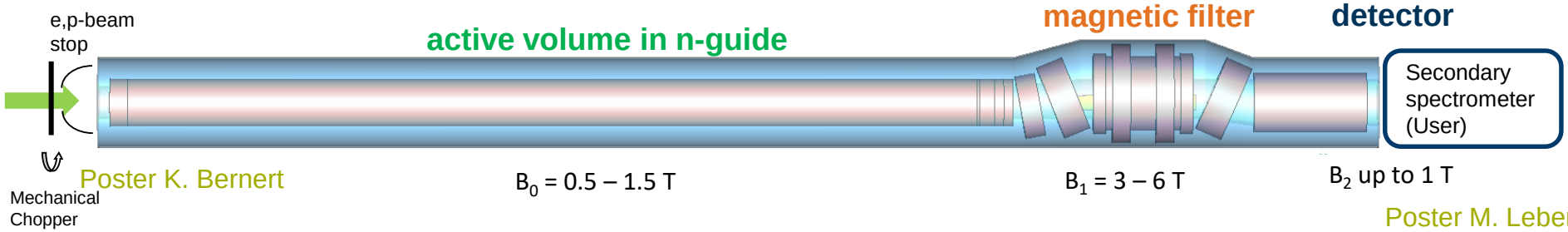
Goal: Order of magnitude improvement.
New observables.

Priority Programme SPP1491 of the German Research Foundation (DFG)

PERC Concept and Systematics

PERC´s asymmetric layout with magnetic filter improves systematics

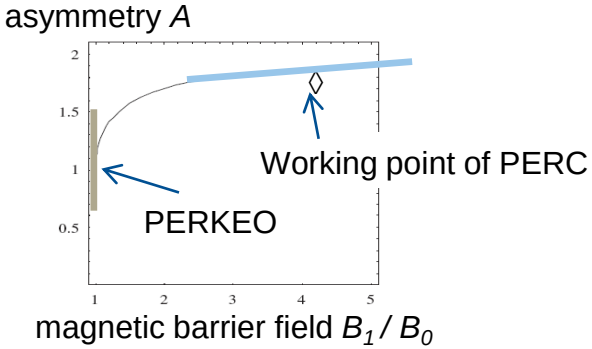
Strong field ensures high phase space density, small detectors, excellent S/B and only a *single* detector!.



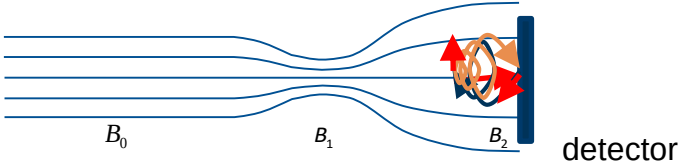
Poster K. Bernert

Poster M. Lebert

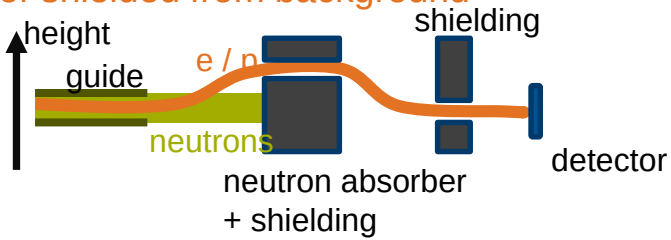
Phase space cut: magnetic field influence



Electron backscatter strongly suppressed



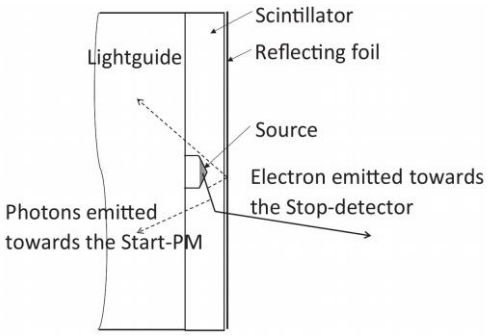
Main detector shielded from background



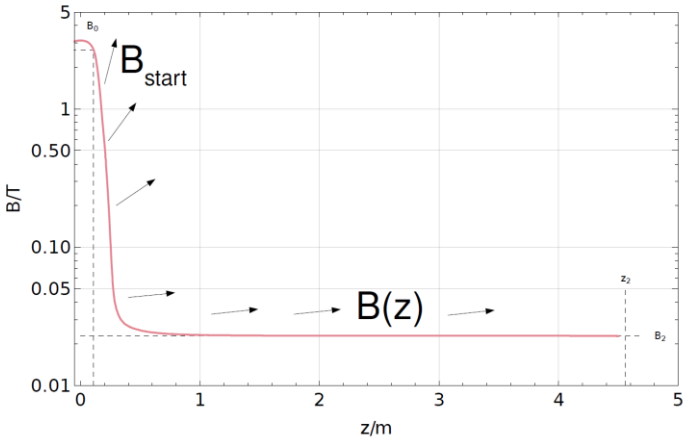
Electron Time-of-Flight for Detector Calibration

New concept to overcome calibration uncertainties at low energies
Identify backscatter events via time difference in upstream/downstream detector.

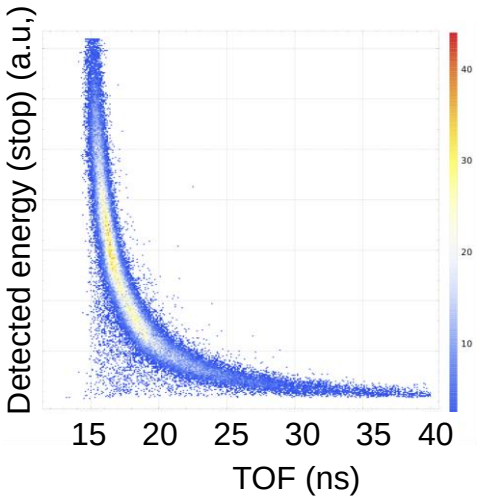
Active source:
Start signal



Adiabatic reduction of magnetic field in flight path reduces opening angle of gyration



Target detector: relate **time-of-flight** to electron energy



C. Roick, D. Dubbers, B. Märkisch, H. Saul, U. Schmidt, Phys. Rev. C 97 (2018)

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)

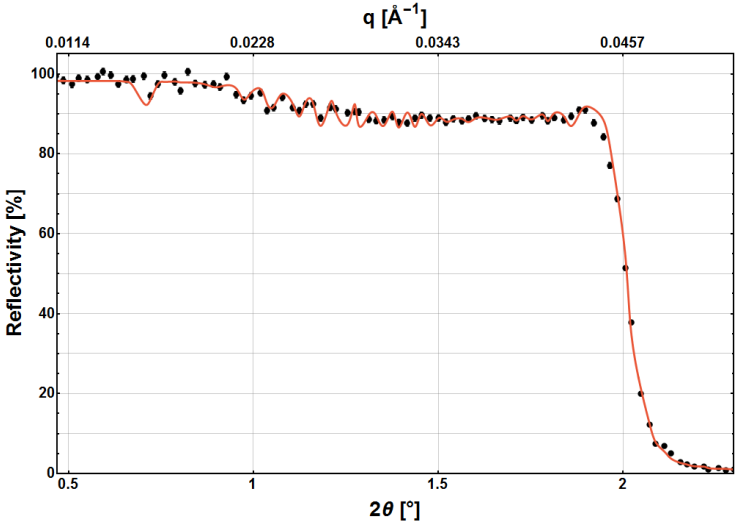
Neutron guide inside PERC magnet at 1.5T (decay volume): only polarization change of 10^{-4} per bounce allowed:

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.

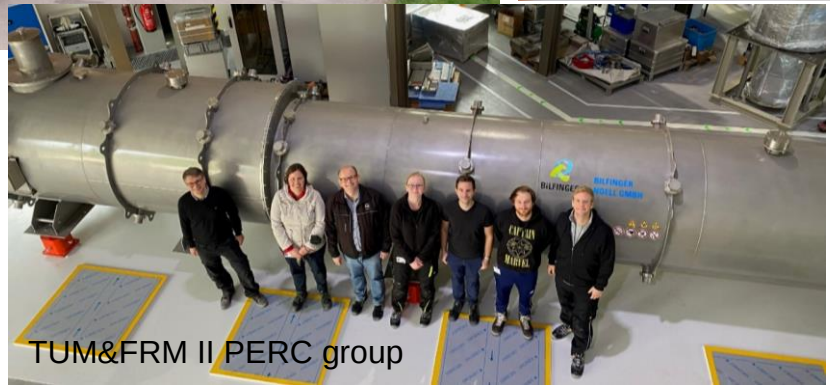


A. Hollering *et al.*, arXiv 2112.00815, Nucl. Instrum. Meth. A, 1032, 166634 (2022)

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

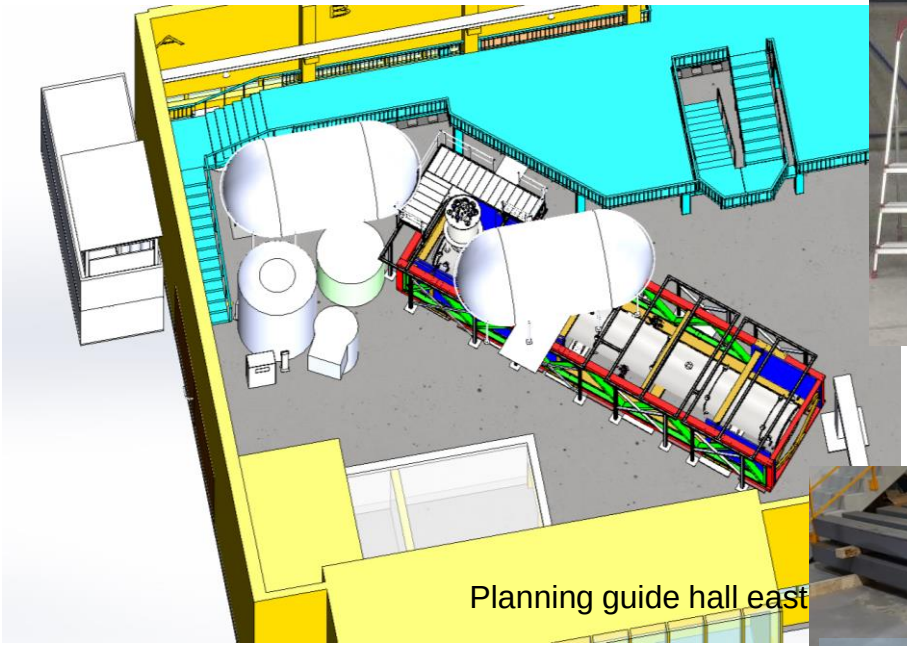
September 2021

- 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

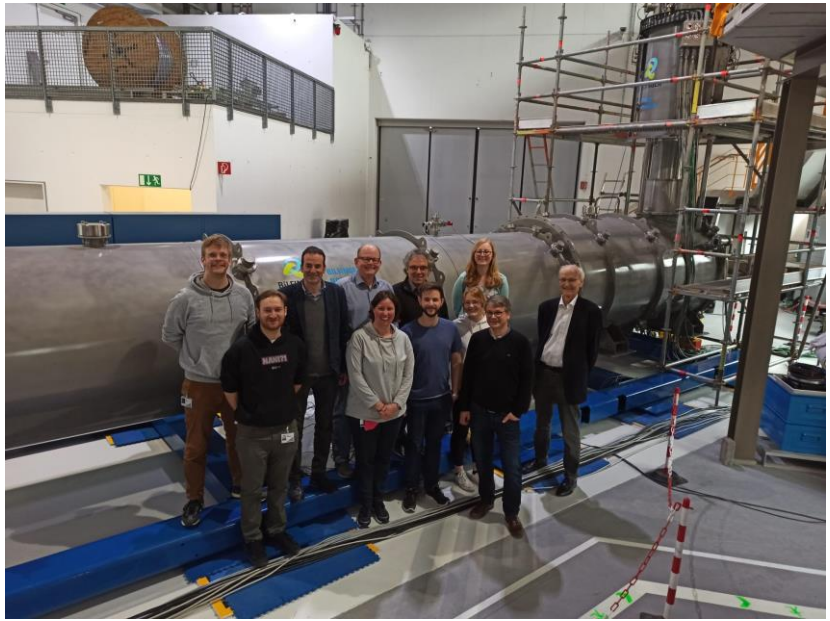
Summary and Outlook

PERKEO III Leading beta asymmetry and Fierz term results. 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