Decay Correlations in Pulsed Neutron Beams at ILL, MLZ, and ESS

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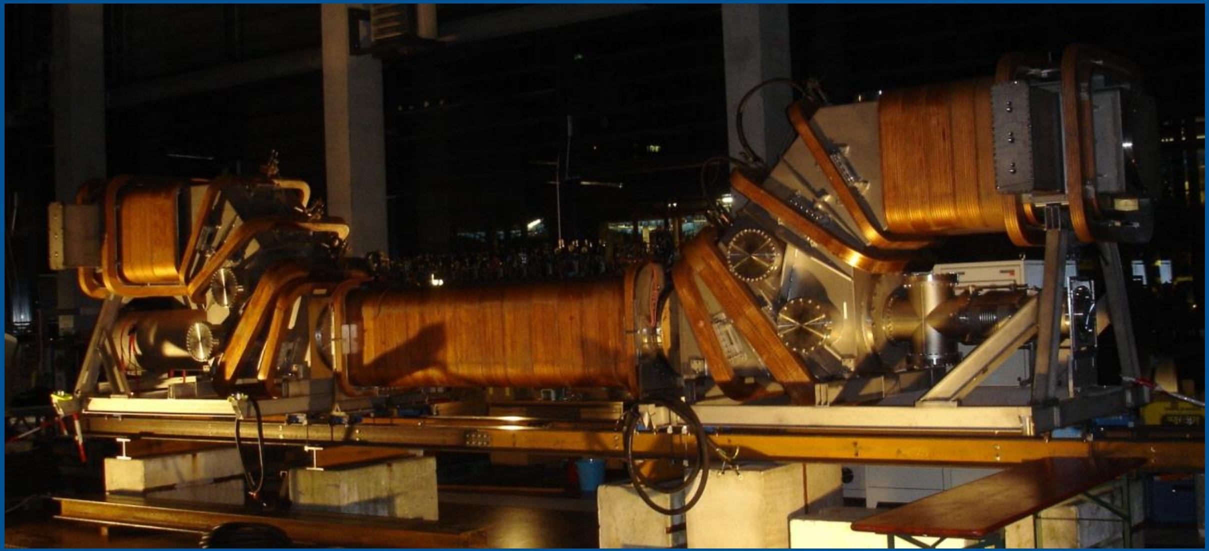


PERKEO III

FPSTS19, Oak Ridge

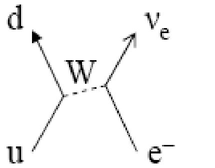
Neutron Decay Data is Useful

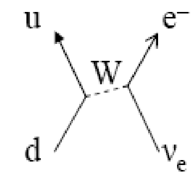
Within Standard Model

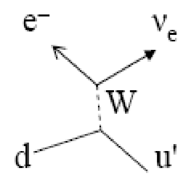
Many processes share the same Feynman diagram.

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

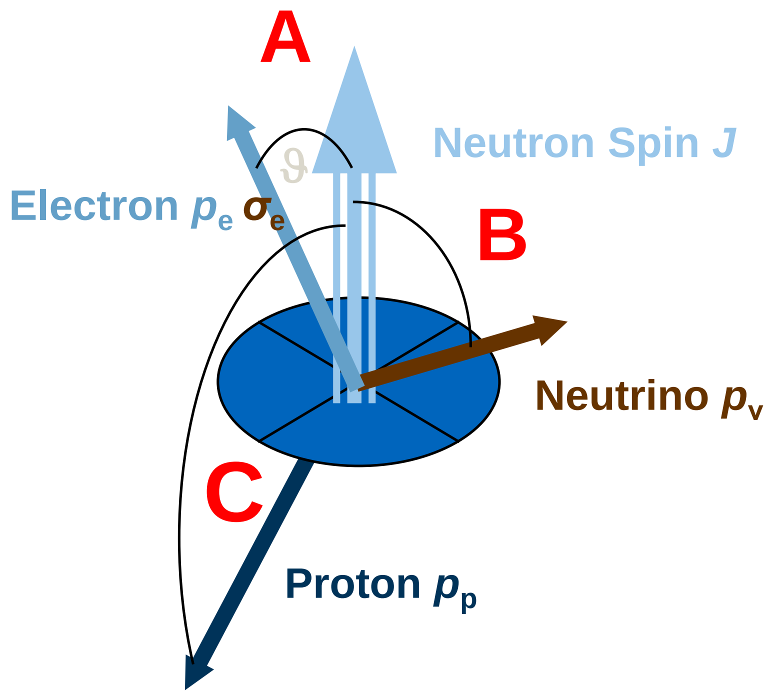
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \Delta$$

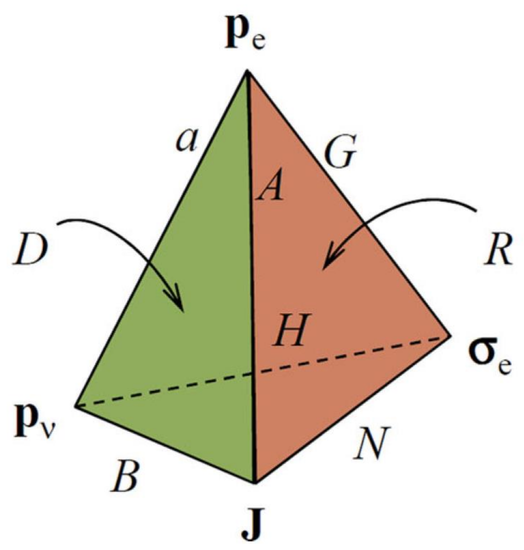
Search for new (effective) couplings: scalar, tensor, right-handed

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*

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

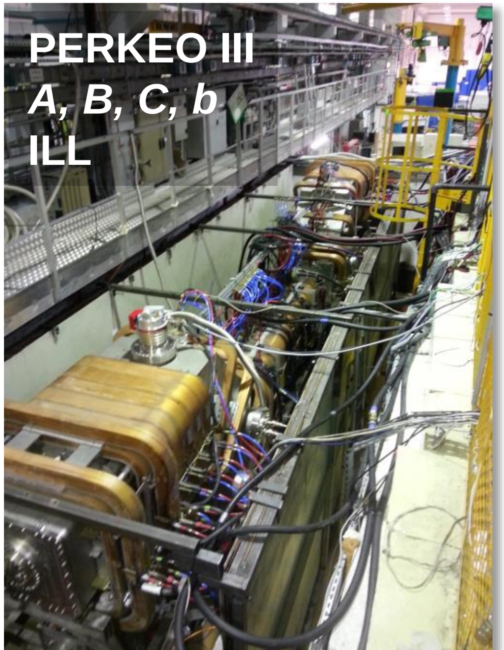


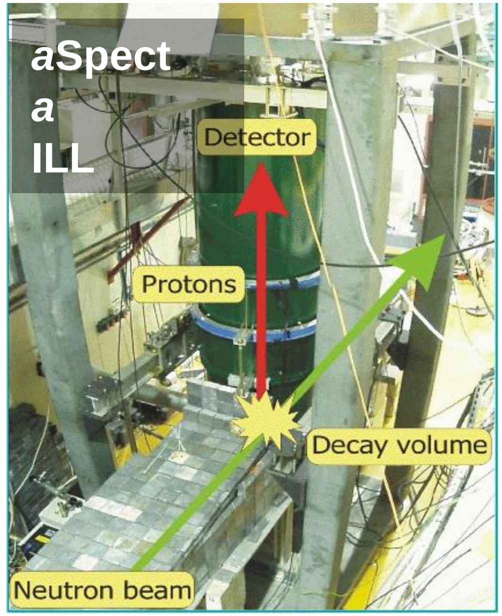


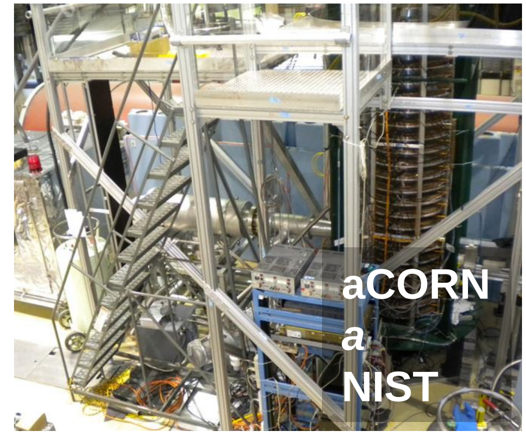
O. Naviliat-Cuncic and M. Gonzalez-Alonso, Ann. Phys. 525, 8–9, 600–619 (2013)
Dubbers and Schmidt, Rev. Mod. Phys (2012)

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

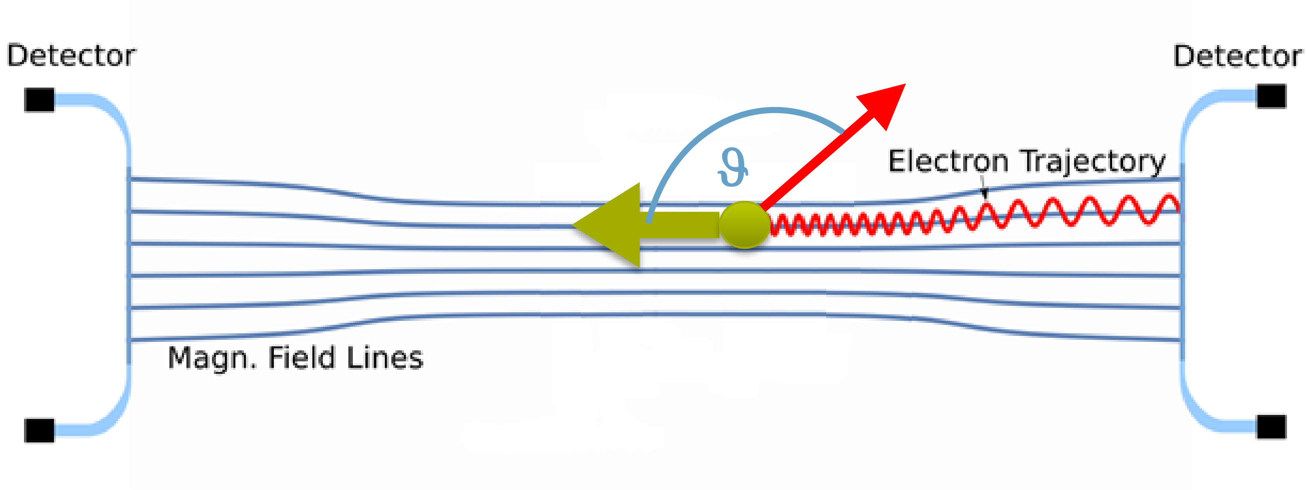
Current Neutron Correlation Experiments







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

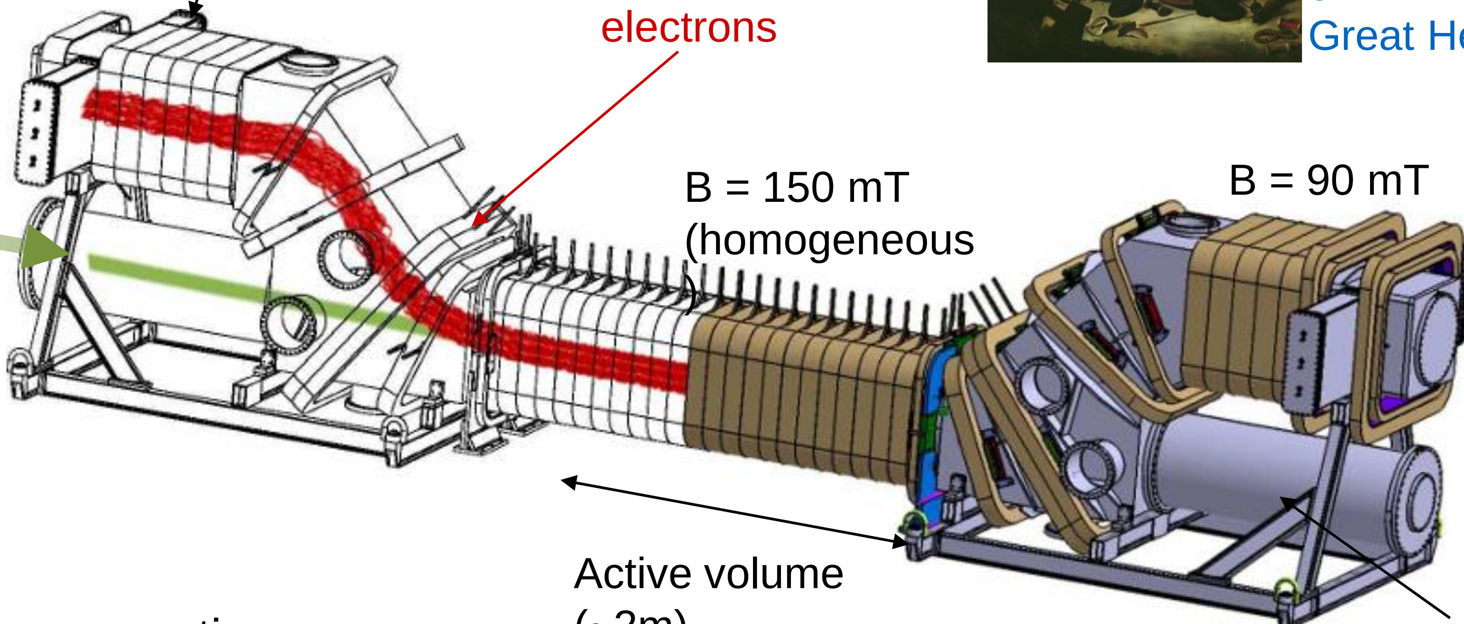
$$\cos\vartheta \rightarrow 1/2$$

Experimental asymmetry, polarisation *P*

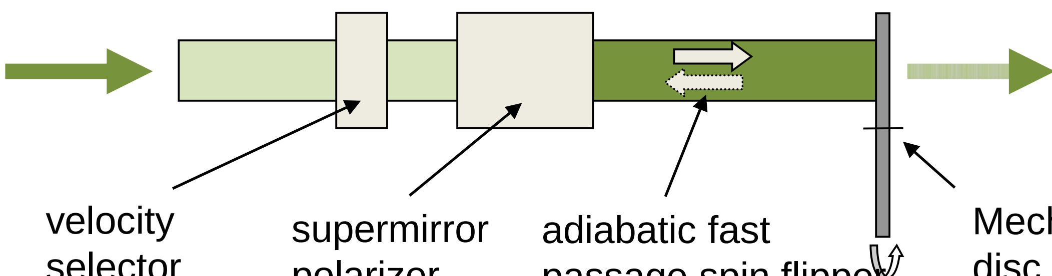
$$A_{\mathrm{exp}} = \frac{N^{\Uparrow} - N^{\Downarrow}}{N^{\Uparrow} + N^{\Downarrow}} = \frac{1}{2}\frac{v}{c} P A$$

Spectrometer PERKEO III

Perkeo,
guardian of the
Great Heidelberg Tun

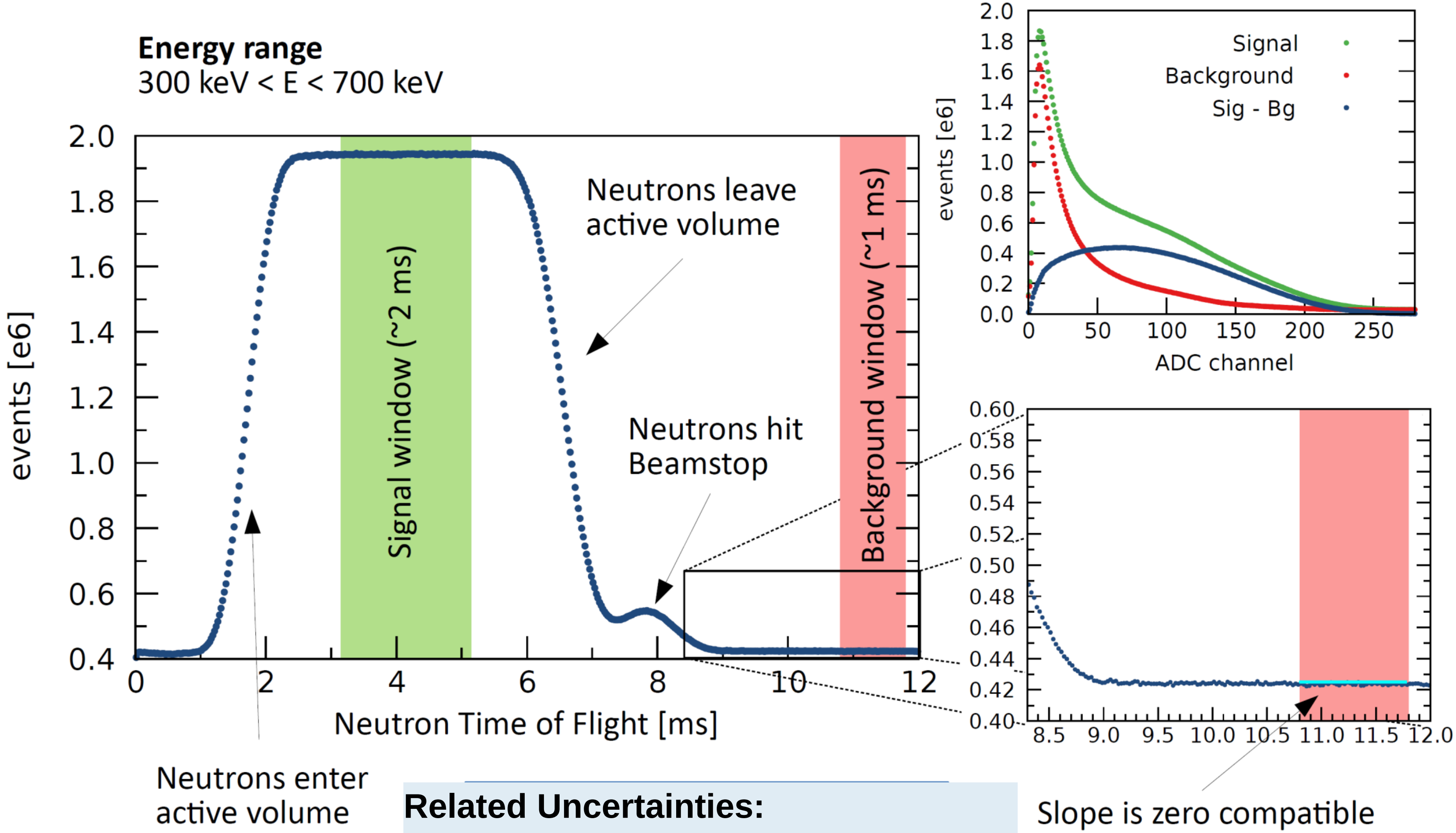


Beam preparation:



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

PERKEO III: Pulsed Neutron Beam



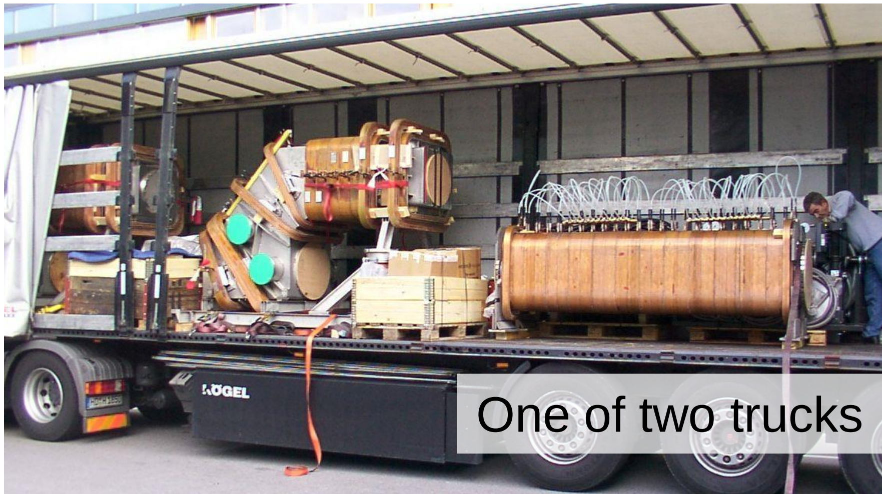
Slope is zero compatible on 10^{-4} level

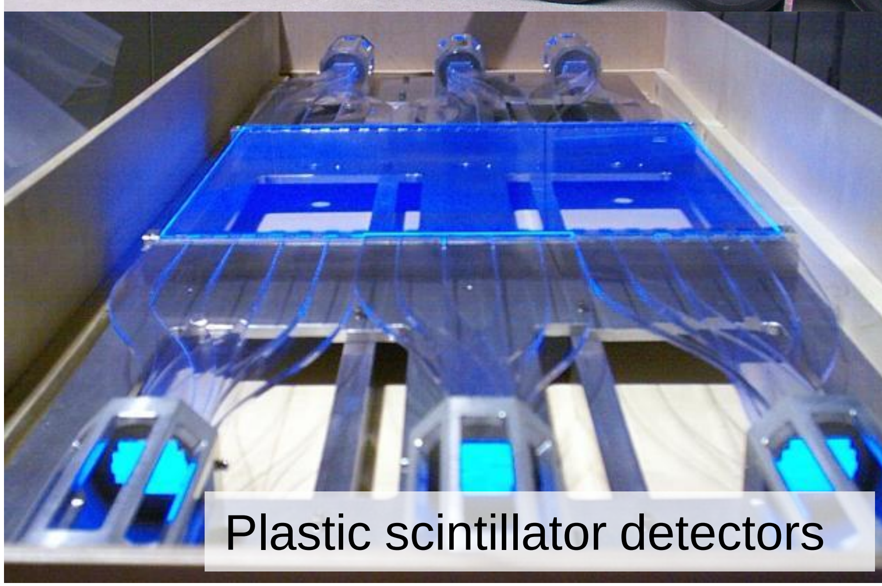
Related Uncertainties:

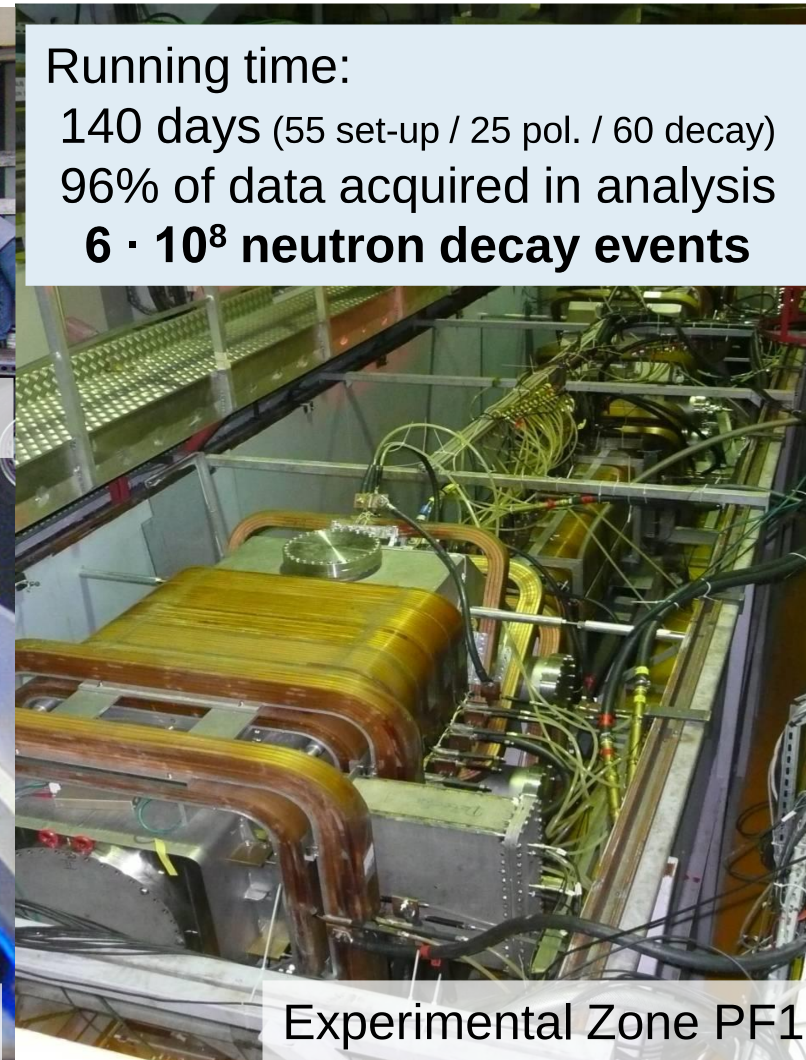
Time dependence $\Delta A/A = 0.8\times10^{-4}$

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

Temporary Installation at PF1b, ILL


One of two trucks


Plastic scintillator detectors



Running time:

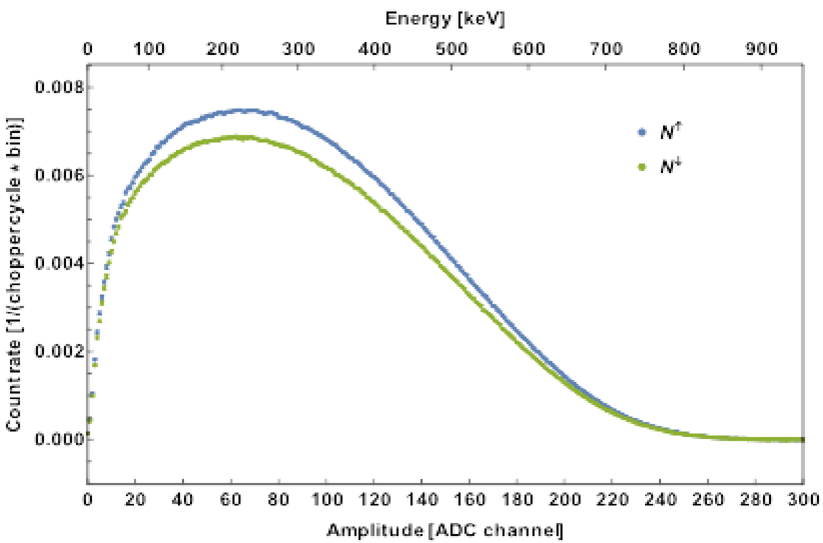
140 days (55 set-up / 25 pol. / 60 decay)

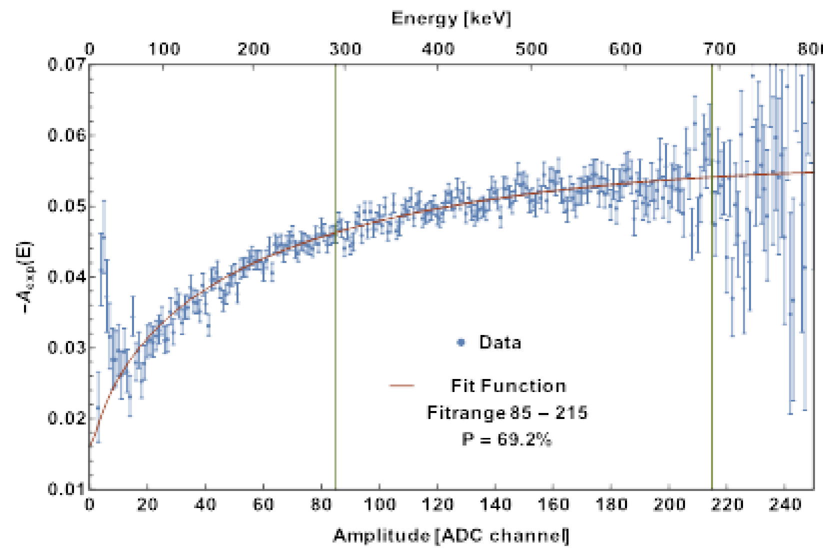
96% of data acquired in analysis

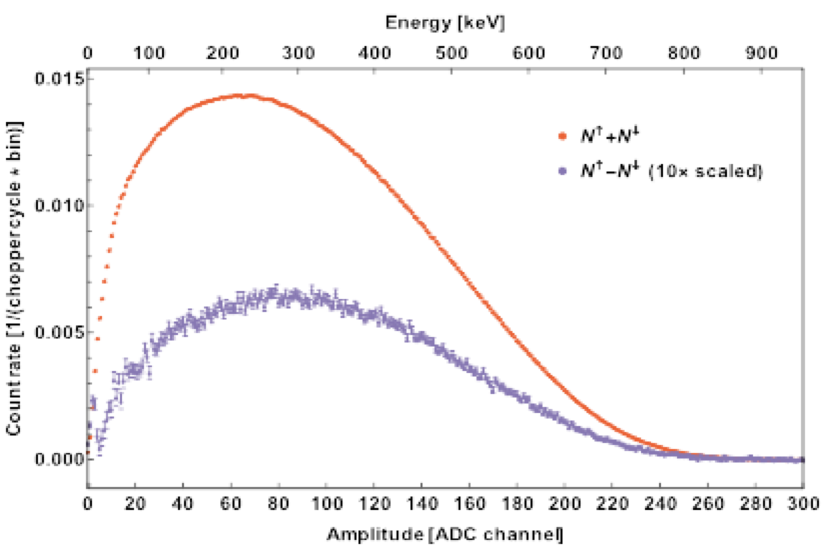
$6 \cdot 10^8$ neutron decay events

Experimental Zone PF1b

Asymmetry Extraction







Fit a single free parameter λ to experimental asym.

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

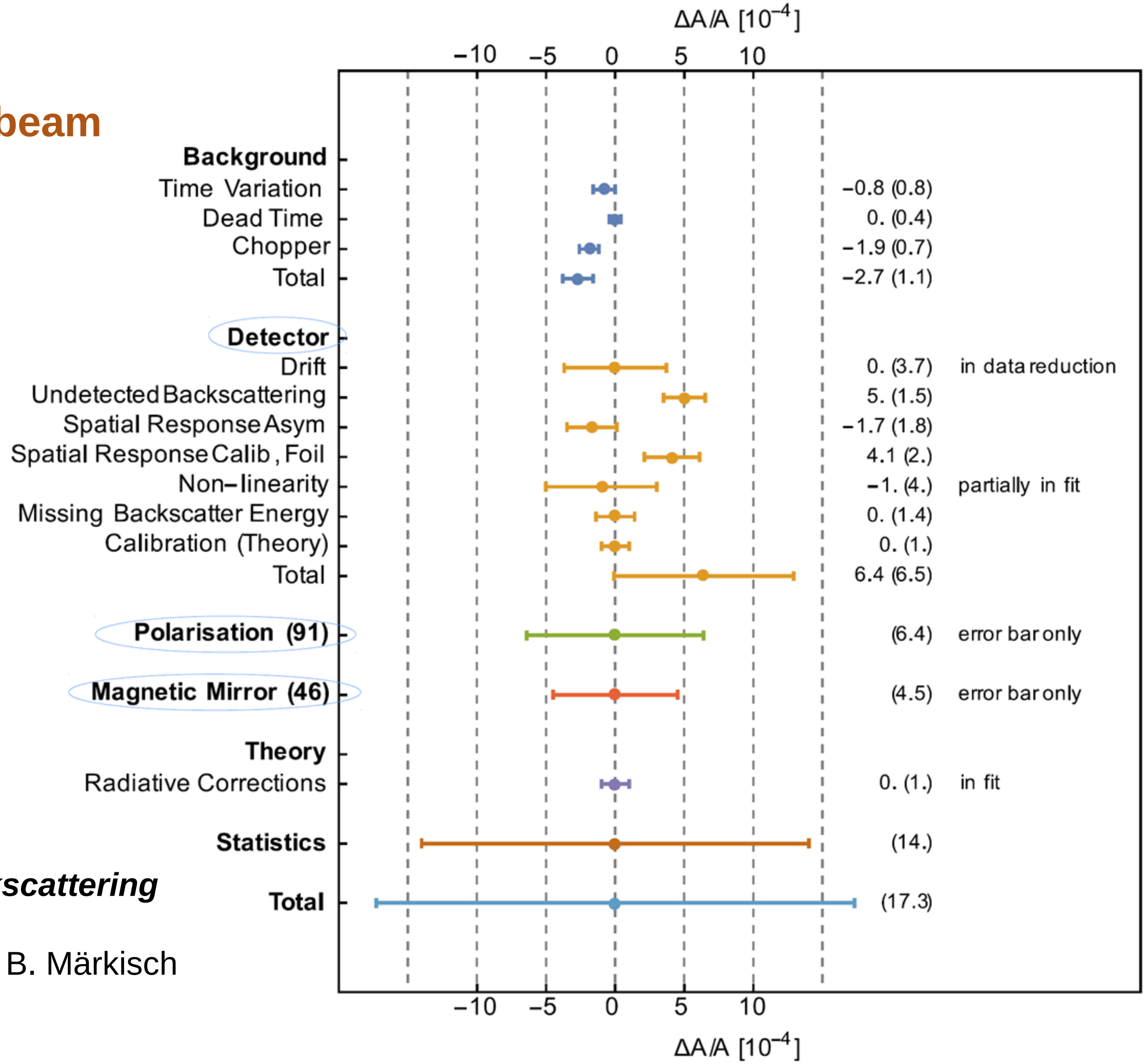
Largest neutron decay data set

6×10^8 events in analysis (1 of 4 subsets shown)

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

Summary of Corrections and Uncertainties

First measurement of λ using a pulsed beam



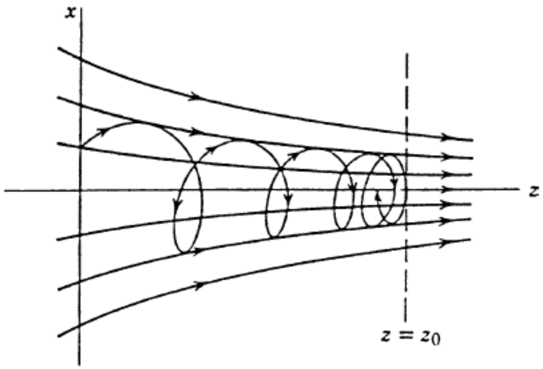
see also

Undetected Electron Backscattering in PERKEO III

C. Roick, H. Saul, H. Abele, B. Märkisch

arXiv:1905.10189

Magnetic Mirror Effect



Magnetic flux through cross section of gyration is *adiabatic invariant*

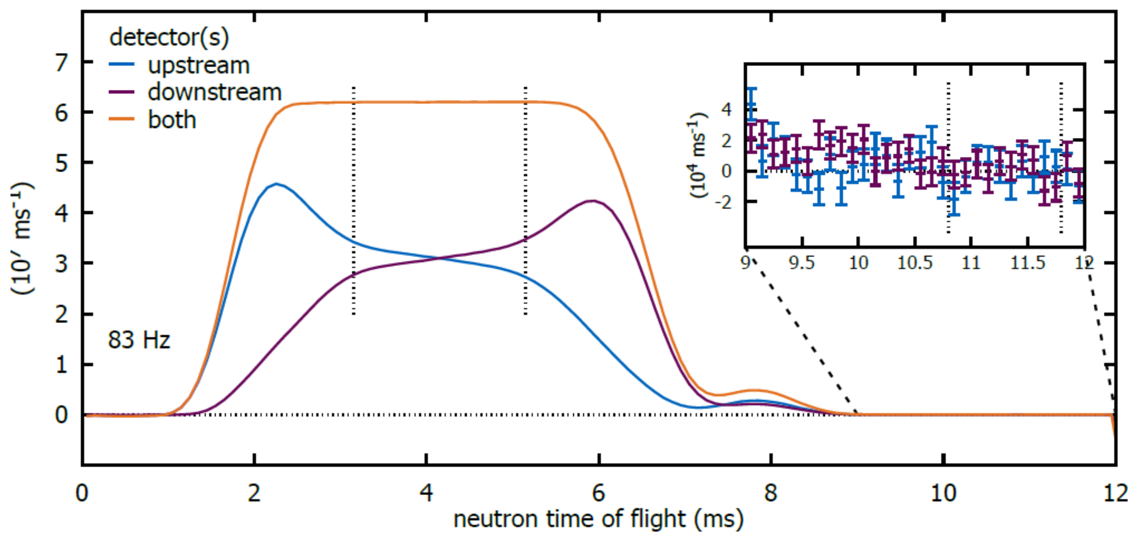
$$B_0 \times r_0{}^2 = B_1 \times r_1{}^2$$

Critical angle for reflection

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

Magnetic field drops by 1% towards the ends of the decay volume:

Significant change in on solid angle and rate on **single** detector.



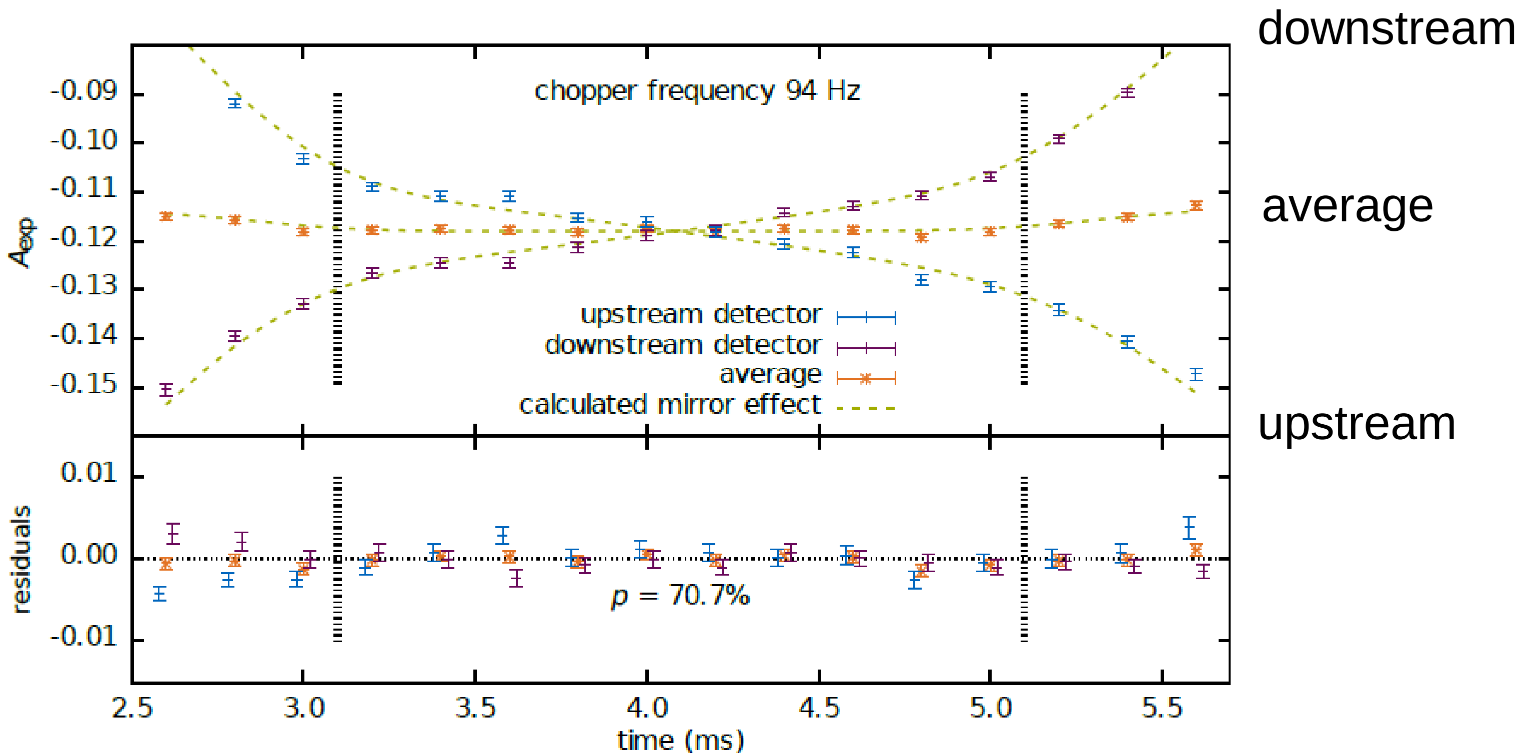
PRL 122, 222503 (2019)

Magnetic Mirror Effect

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

Remaining **correction** calculated from measurements of the magnetic field and neutron pulse. Correction: $\Delta A/A = 46.1(4.5) \times 10^{-4}$

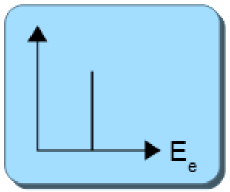
Selection of time-window during analysis.



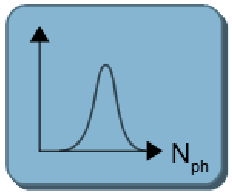
Detector Model

Major improvements to precise description of the detector response enable consistent energy-dependent analysis (H. Saul, C. Roick).

Free parameters: Non-linearity, gain, photo-electrons, norms

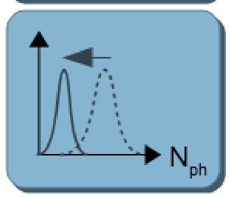


Electrons:
discrete energy
or spectrum



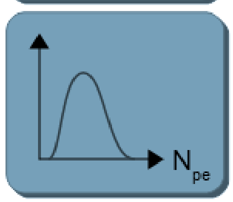
Scintillation:
$N_{ph} = f(E_e)$
poisson statistics

Non-linearity of scintillation light production

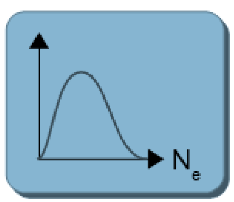


Photon transport:
$N'_{ph} = f(E_e, x, y)$
binomial statistics

Non-uniformity of detector response

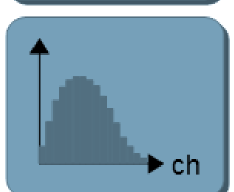


Photon to photoelectron conversion:
$N_{pe} = f(N_{ph})$
binomial statistics



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

Higher moments of the distribution

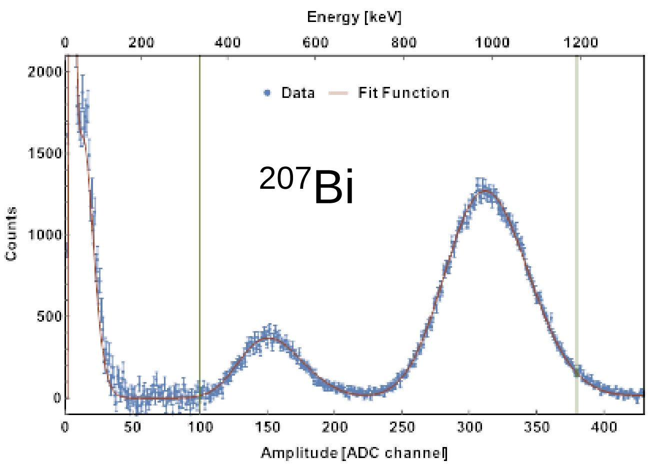


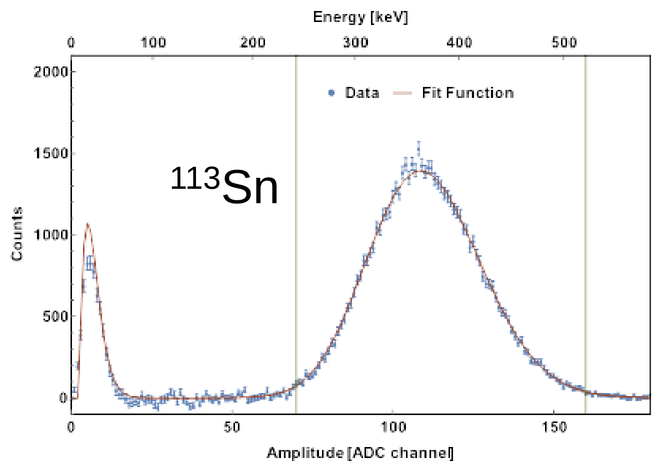
Signal processing + charge integration:
$A_{QDC} = f(N_e)$
gaussian noise

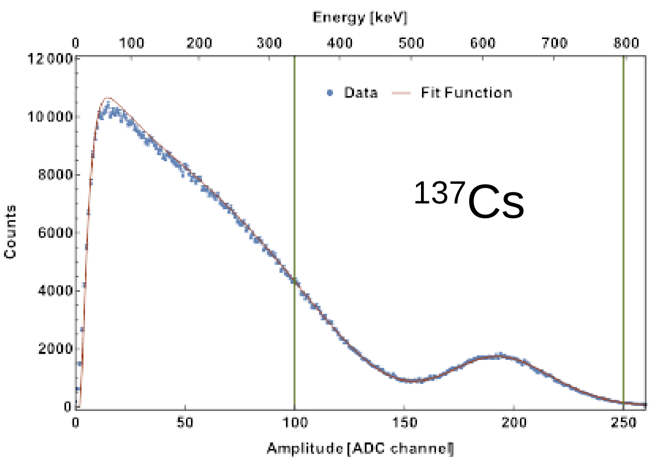
Non-linearity of electronics

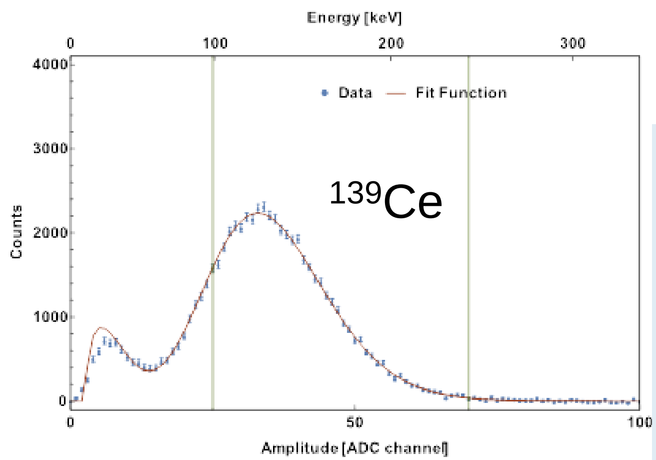
PERKEO III Detector Calibration Fit

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









114 full calibration sets measured in ~60 days

Simultaneous fit:
X^2/NDF = 1.0 – 1.3

Free parameters:
Non-linearity, gain, photo-electrons, norms

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

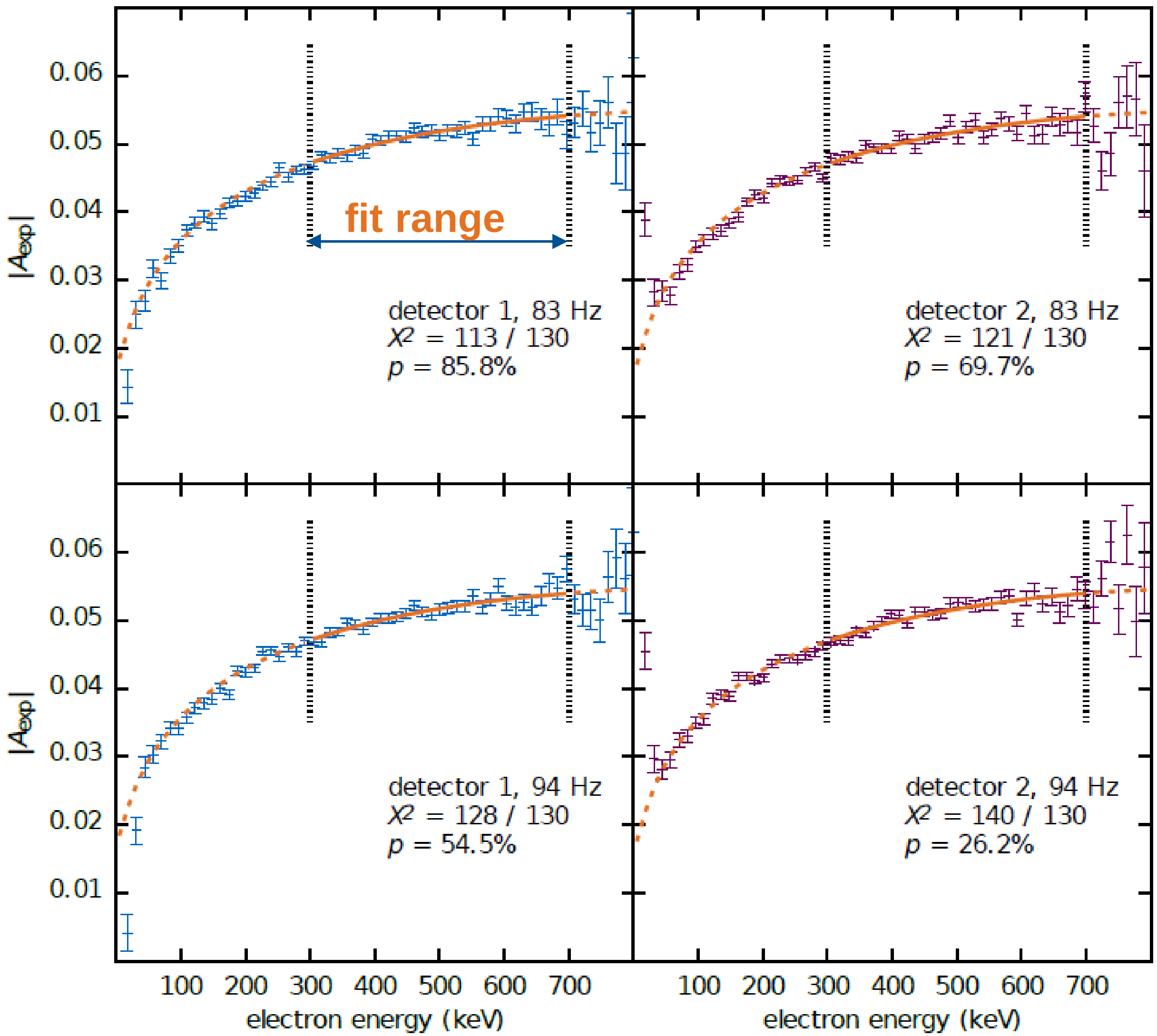
Asymmetry: Four datasets

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: λ



PERKEO III Result

Analysis blinded by separate analysis by independent teams:

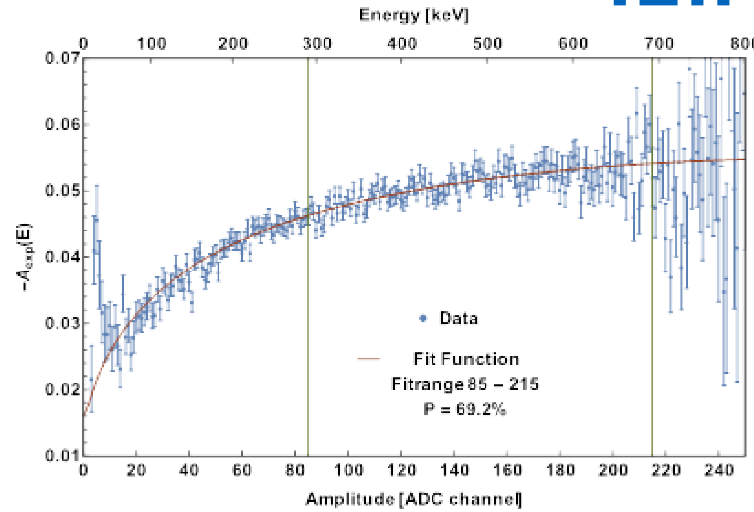
- electron measurement,
- neutron polarisation: opaque ^3He spin filters,
- magnetic mirror effect

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

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

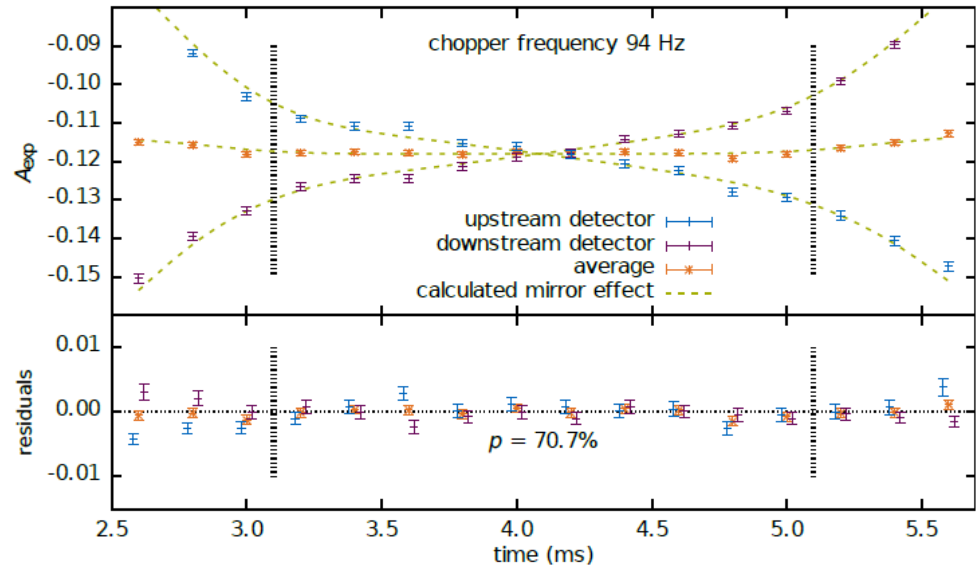
$$\frac{\Delta\lambda}{\lambda} = 4.4 \times 10^{-4}$$

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)



Time-dependent mirror effect

Time-avg. correction: $\Delta A/A = 46.1(4.5) \times 10^{-4}$



Nucleon Axial Coupling: Status

All new 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:

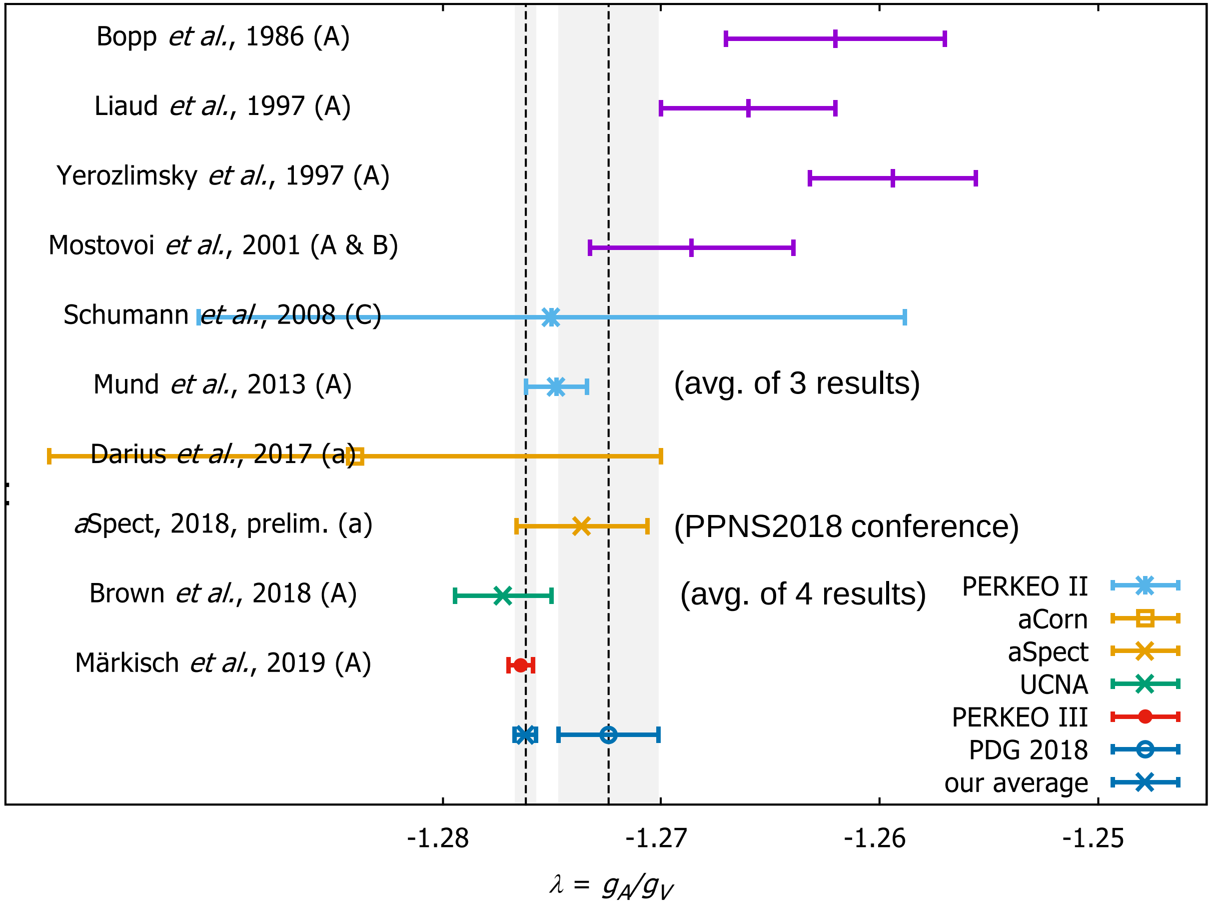
$\lambda = -1.2724(23)$; $S = 2.4$

New average (all measurements):

$\lambda = -1.2756(10)$; $S = 2.15$

Only UCNA, PERKEO II & III:

$\lambda = -1.2762(5)$

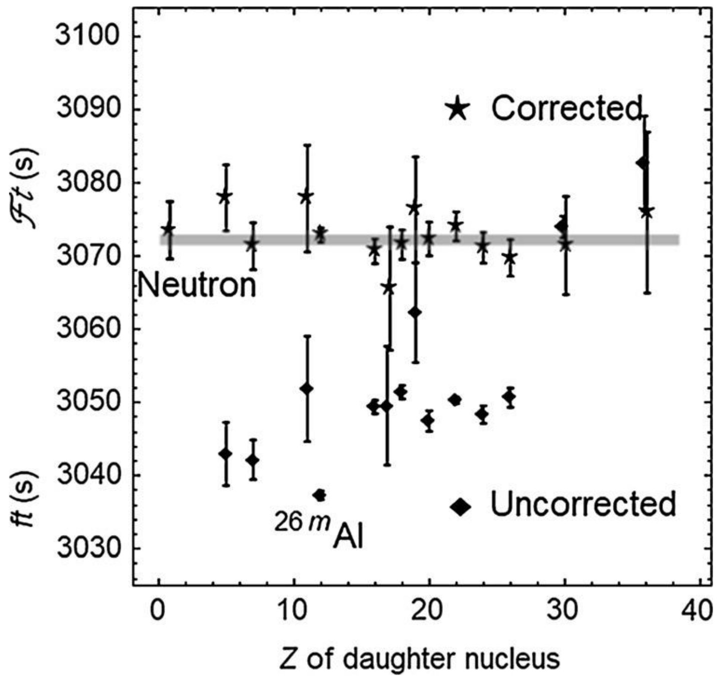


Comparison to Superallowed Nuclear Decays

Neutron data confirms nuclear data with competitive precision – without nuclear structure effects !

Vector part of neutron Ft

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



Using updated (conservative) *world averages:*

$$\lambda = -1.2756(10);\ S = 2.15$$

$$\tau = 879.7(8);\ S = 1.9$$

Nuclear data from Hardy & Towner, PRC 91 (2015) 025501.

D. Dubbers, at al., Phys. Lett. B 791, 6-10 (2019)

PERKEO III result only:

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

Superallowed decays:

$$V_{ud} = 0.97395(23)$$

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

No Dark Side to Neutron Decay!

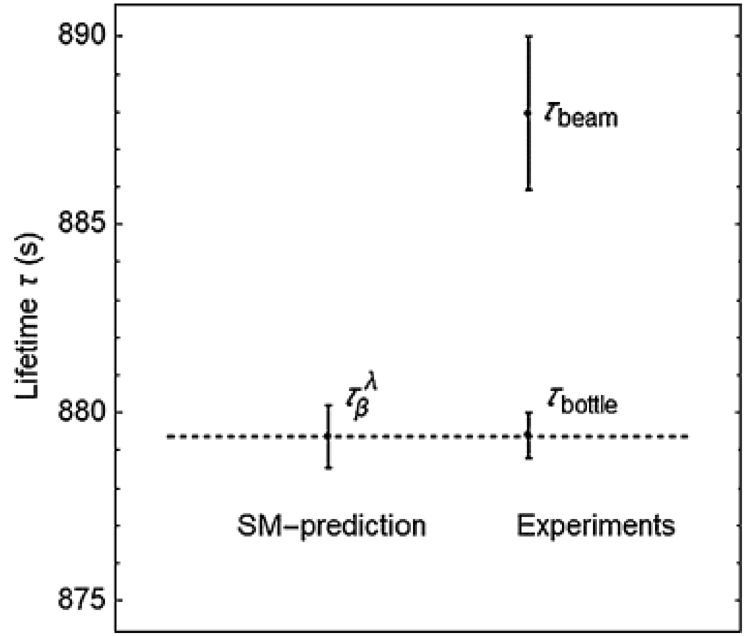
Assuming V-A, neutron lifetime can be inferred using our (conservative) world-average of neutron decay data, *including **all** measurements.*

$$\tau_\beta^\lambda = \frac{2}{\ln 2} \frac{\overline{\mathcal{F}t}_{0^+\to 0^+}}{f(1+\delta_R')(1+3\lambda^2)} = \frac{5172.3(1.1)\ \mathrm{s}}{1+3\lambda^2}$$

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.

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



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

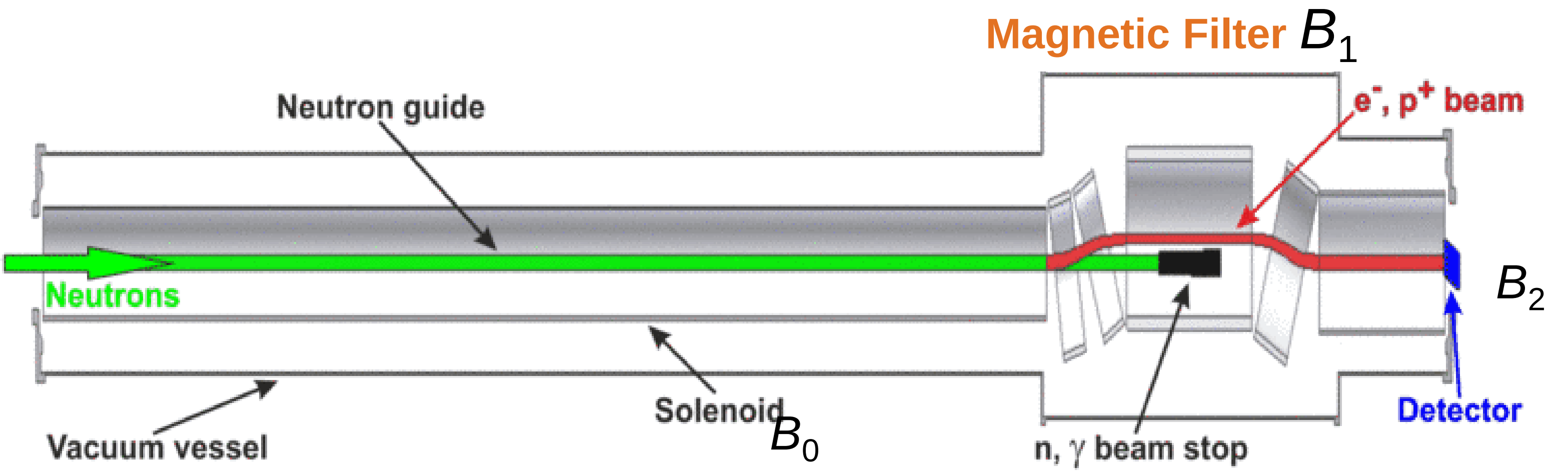
The next generation:
PERC (Proton Electron Radiation Channel) at MLZ

Goal: Order of magnitude improvement. New observables.

Priority Programme SPP1491 of the German Research Foundation

SLOW NEUTRONS
DFG SPP 1491

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) $B_1/B_0 = 2\ldots12$

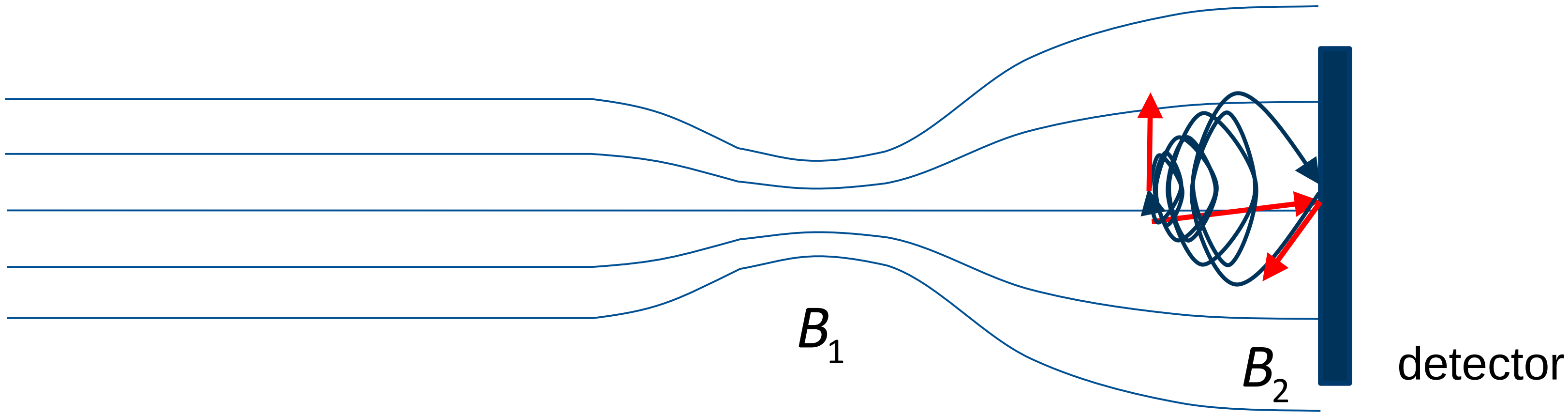
Source for specialised spectrometers

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

Backscatter Suppression in PERC

Backscattering typically major source of systematic error in electron spectroscopy, but:

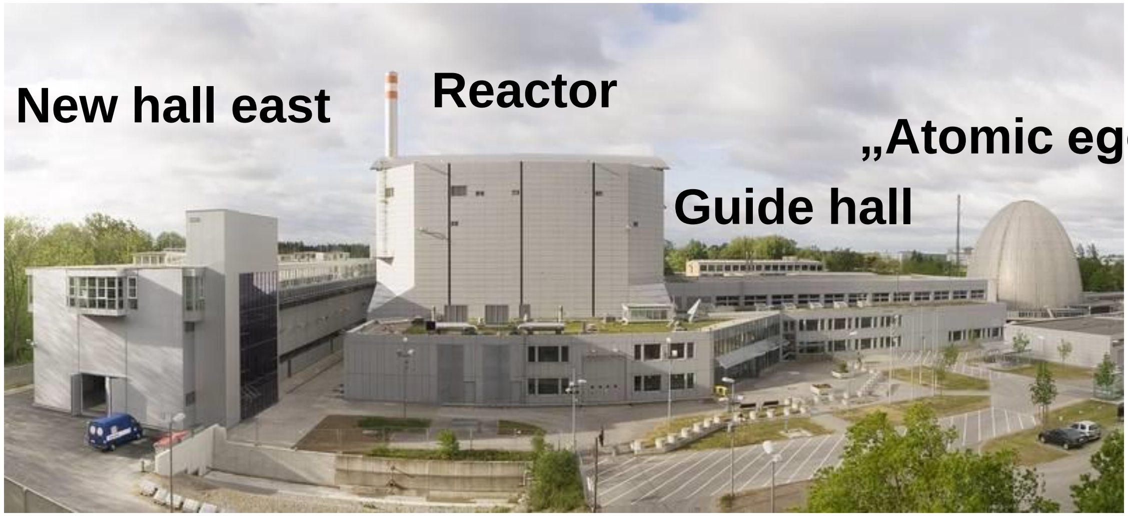


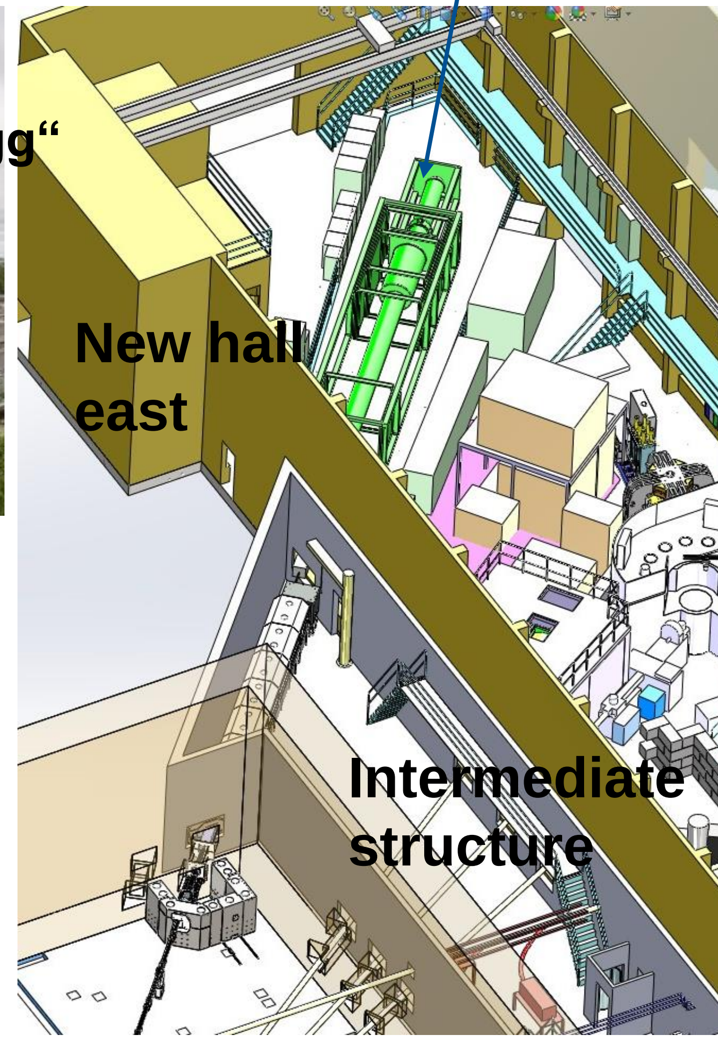
Incident angle on detector $\theta_2 < 15°$ → backscattering **small**
Efficient solid angle **suppression** by magnetic mirror

$$\frac{\Omega}{2\pi} = \frac{B_2}{2B_1} \approx 1/32$$

→ One detector only is sufficient. But PERC will still have an upstream backscatter detector detector with ~95% beam coverage: active electron "dump"

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

Experimental area: 5m x 25m

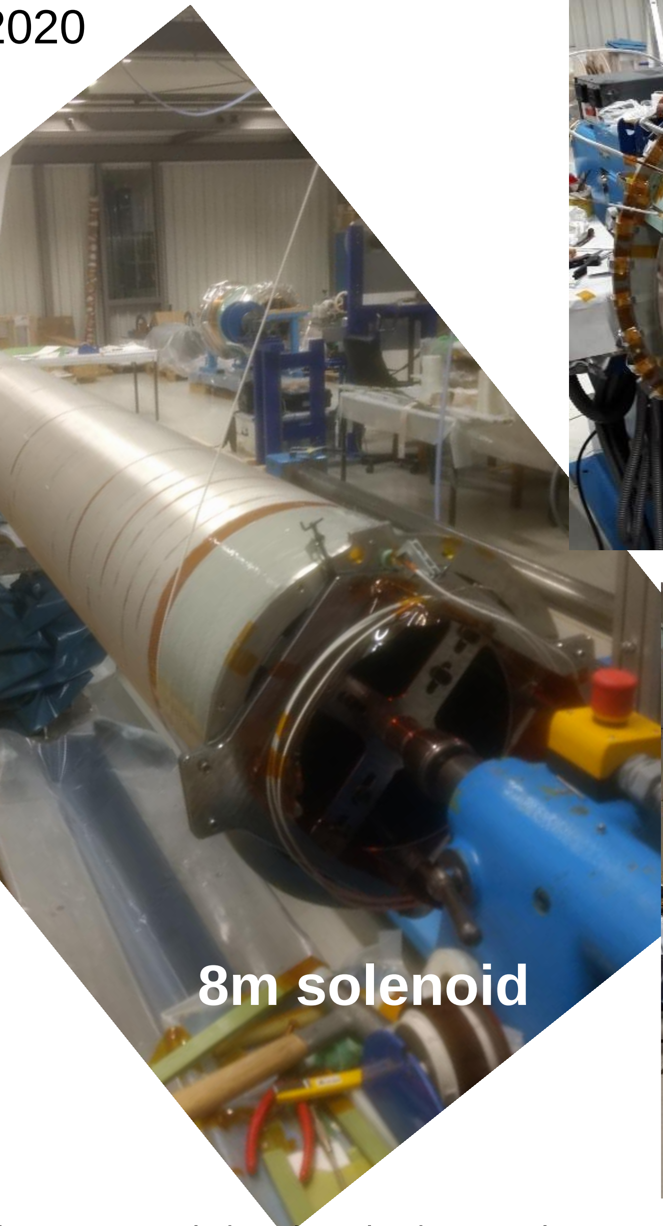
Beamline Shielding for MEPHISTO

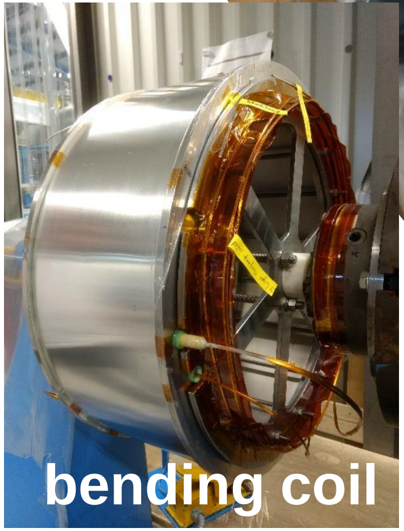
Guides, selector, …
***READY* to be installed.**

PERC Magnet Status

Delivery Spring 2020

(Needs to be redone - ongoing)





Cold Beamline for Particle Physics at ESS

ESS design goal is same time average neutron flux as ILL.

Peak brightness in pulse: 30 × ILL

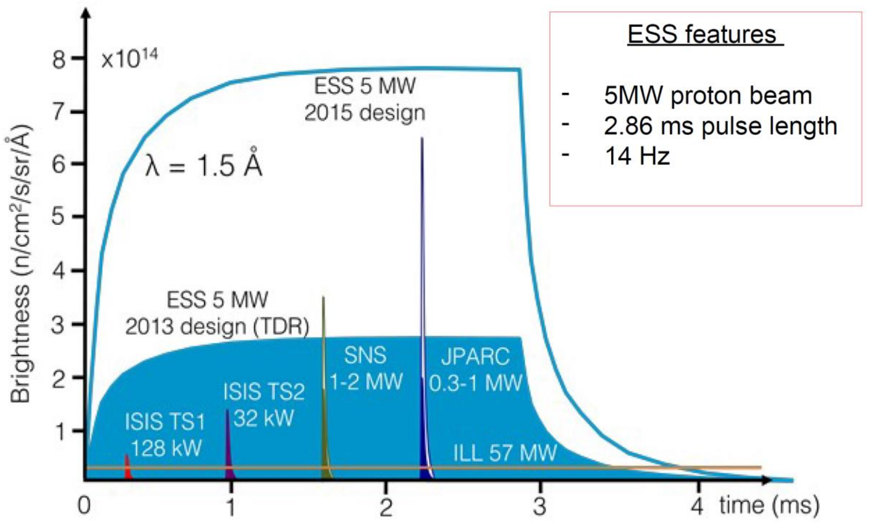
Using pulsed beam for particle physics already at reactor sources!

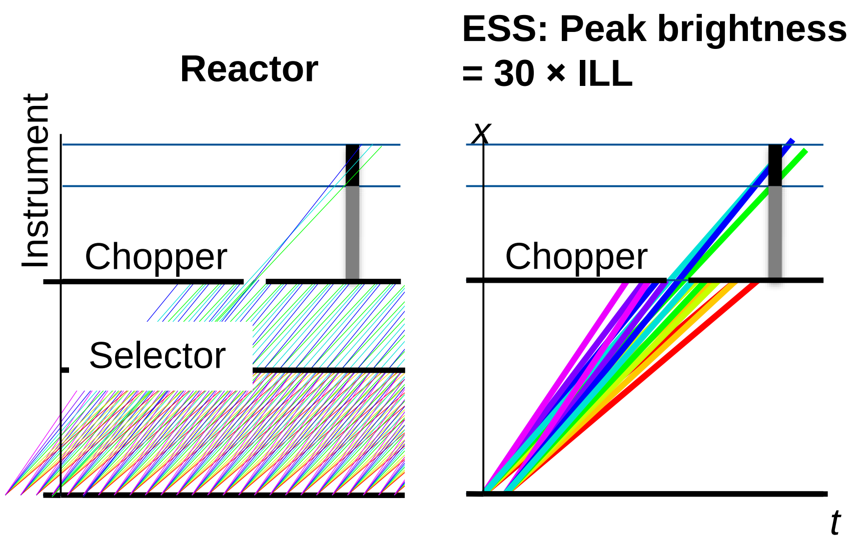
Statistics gain factor for a PERC-like system: x 15 !

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





Proposed Magnet Concept for ANNI / ESS
(Nordita Workshop, Stockholm, Dec 2018)

Long decay volume

Either with guide and longer - like PERC,

or with larger cross section and shorter for divergence acceptance - like PERKEO III

Beam separation

enables continuous polarimetry - but need shielding!

Upstream detector

Fully capable upstream detector, well shielded against beam background:

Backscatter detection. Veto via time-of-flight, see Roick et al., PRC 2018

Ensure full energy reconstruction for primary detector.

Magnetic barrier field for downstream detector

Improved systematics

Enable slight gradient field in decay volume for improved extraction

ESS: Beamline for Particle Physics Guide and Chopper System

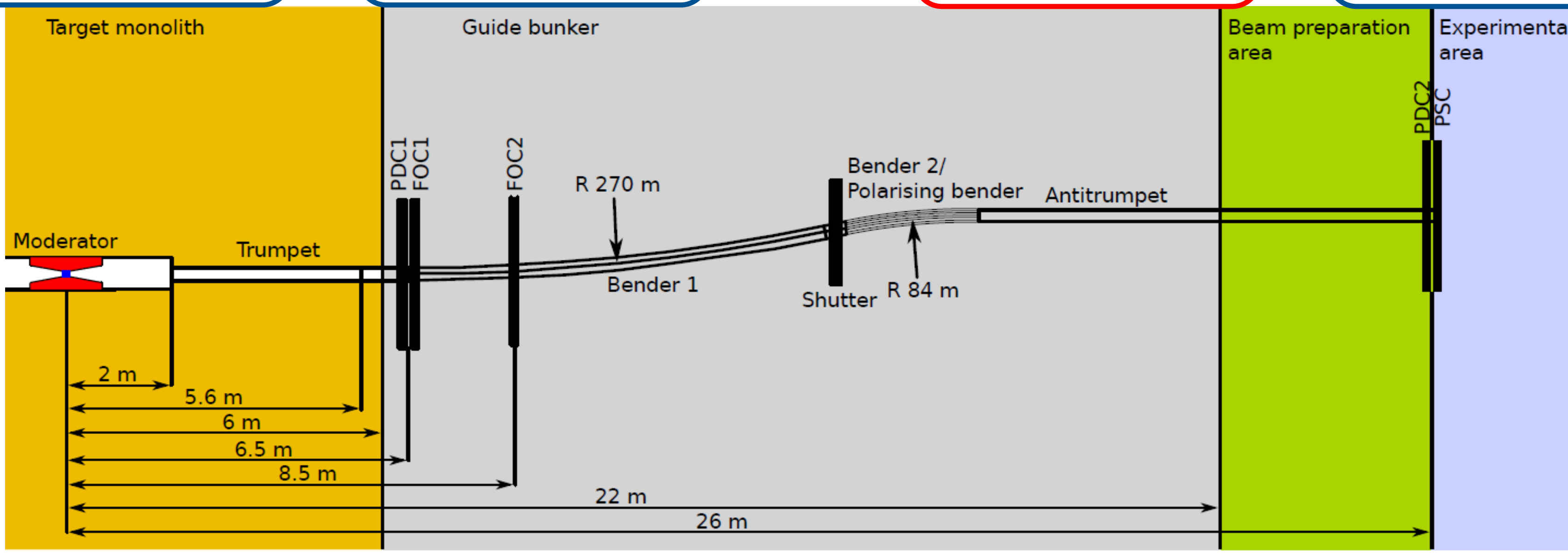
Goal:
Short guide

Requirement;
2 × out of sight

⇒

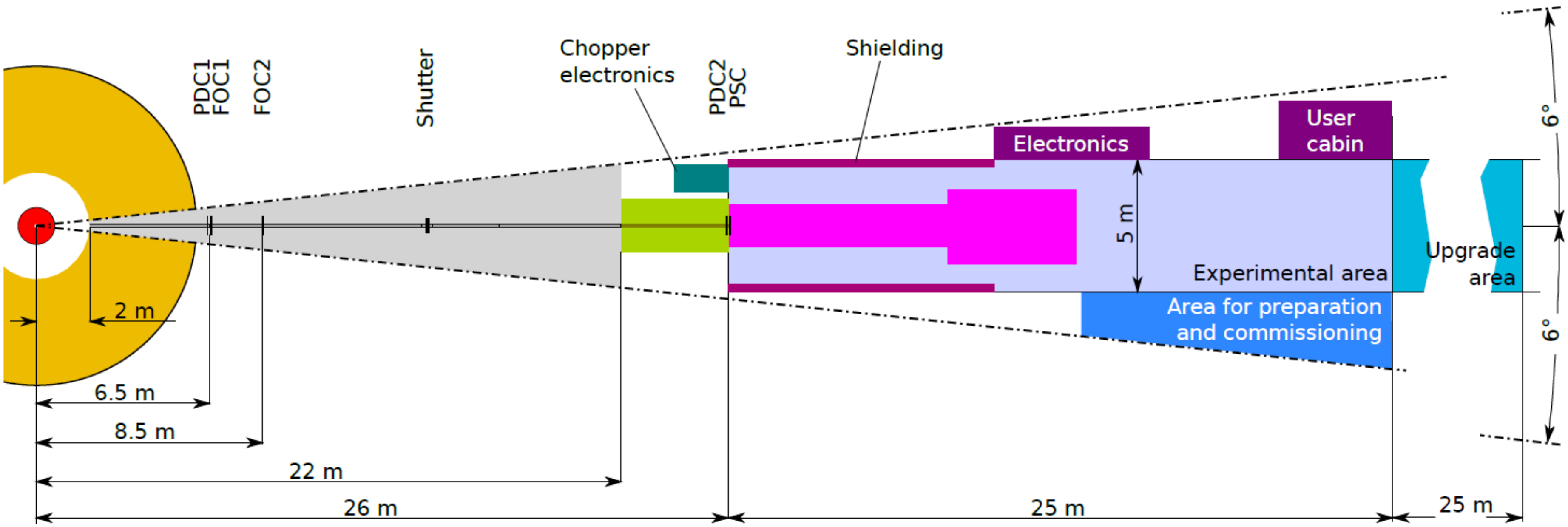
Strong curvature

Multi-channel benders



Element	Dist [m]	Rad [m]	Len [m]	X-section [cm^2]	NOC	m value	γ^* [mrad]	λ^* [Å]
Trumpet	2.0	∞	3.6	$9 \times 6 \rightarrow 13 \times 6$	1	LR: 3.5, TB: 3.0		
Straight 1	5.6	∞	0.9	13×6	1	3.0		
Bender 1	6.5	270	8.0	13×6	2	LRT: 3.0, B: 3.5	14.7	2.44
Straight 2	14.5	∞	0.4	13×6	2	3.0		
Bender 2 or Polarizing bender	6.5	-84	2.5	13×6	6	LRB: 3.0, T: 3.5	14.7	2.44
Antitrumpet	17.4	∞	4.6	$13 \times 6 \rightarrow 11 \times 7$	1	LR: 3.5, TB: 3.0		

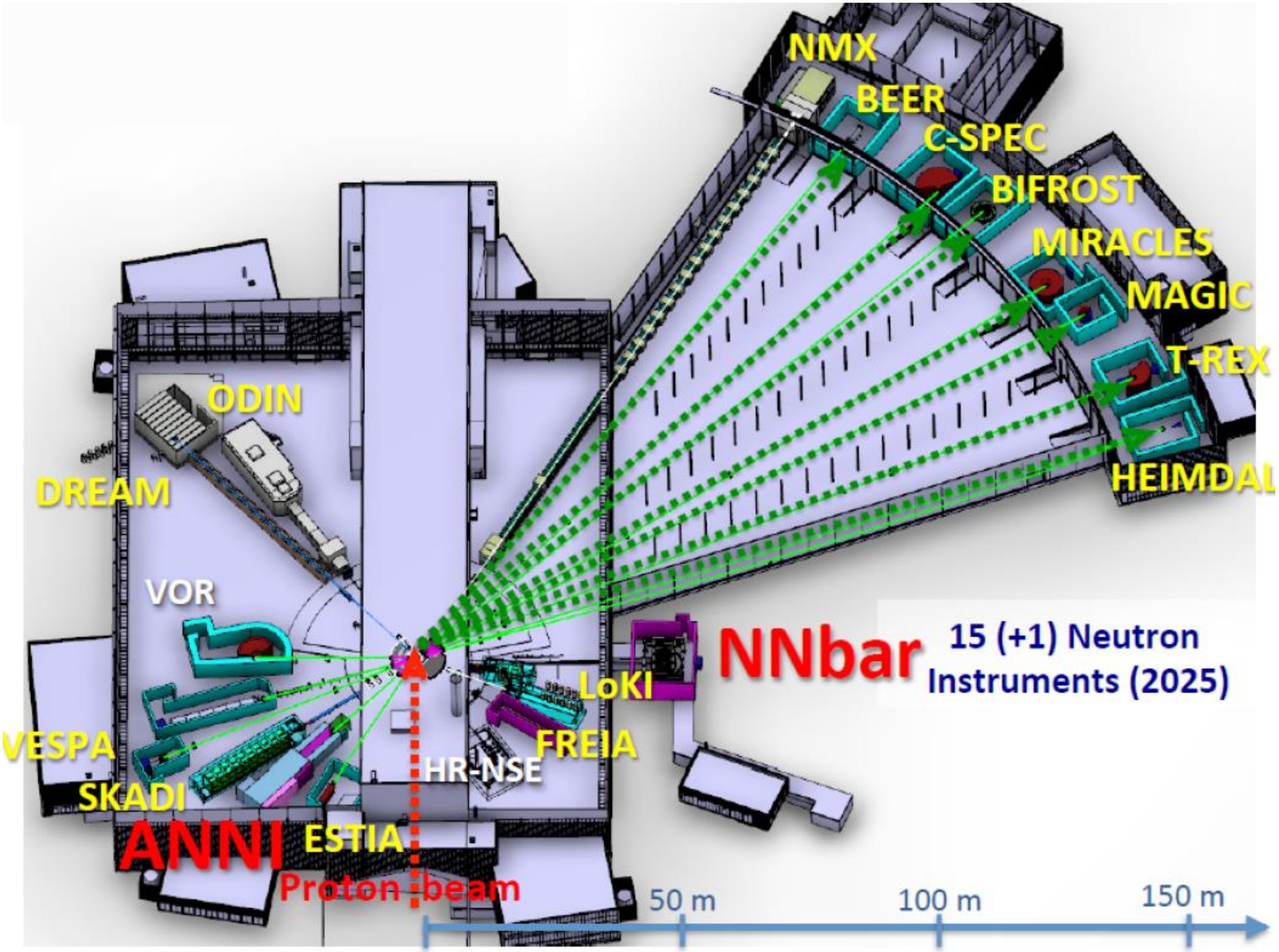
ESS: Beamline for Particle Physics Ground Floor Plan



2 frame overlap choppers (FOC1, FOC2), 2 pulse-defining choppers (PDC1, PDC2), 1 pulse-suppressing chopper PSC.

Experimental area 5 x 25 m, upgradable to 50 m length

ESS: Tentative Beam Line Location



A. Schreyer, „Workshop on Particle Physics at ESS“, Jul. 2016, Lund, Sweden

Summary and Outlook

Pulsed cold beams enable

unprecedented statistics (or better signal / background) (at pulsed sources), and greatly improved control of systematics,

(background, edge effect, mirror effect, neutron polarisation, …)

Newer **results on the beta asymmetry** / axial coupling constant:

consistent, small corrections, blinded*. Improvement by factor 5.

Prospects to improve neutron correlations by another **order of magnitude**

Particle Physics with Cold and Ultra-Cold Neutrons

SLOW NEUTRONS
DFG SPP 1491

DFG Deutsche Forschungsgemeinschaft

Excellence Cluster Universe

ORIGINS Excellence Cluster

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung