CKM Unitarity and Neutron Beta Decay

Measuring V_{ud} in Neutron Beta Decay

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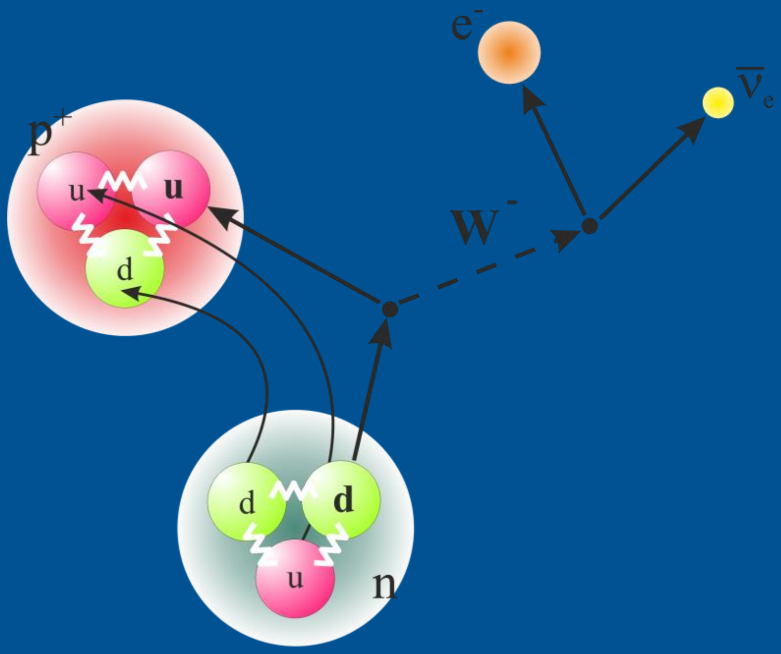
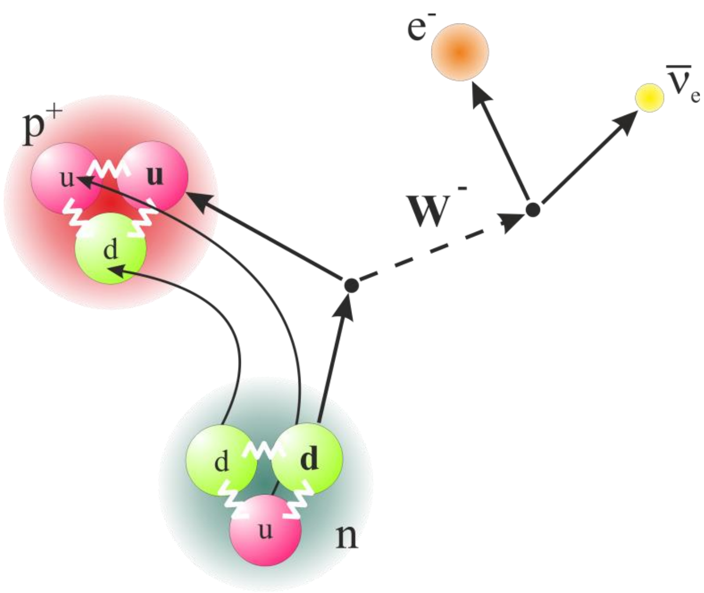
CKM Matrix Element V_{ud}
Effective CC Couplings

Neutron Lifetime
Neutron Decay Corellations



Neutron Beta-Decay



Low energy

$E_{p,max}$ = 752 eV $E_{e,max}$ = 782 keV

Long lifetime

τ = 880.3(1.1) s

$$\tau^{-1} = G_F^2 |V_{ud}|^2 (1+3\lambda^2) \frac{f^R m_e^5 c^4}{2\pi^3 \hbar^7}$$

Only small, precisely known radiative corrections

Two free parameters within SM (G_F from muon decay)

Ratio of coupling constants

Axial-vector g_A und vector g_V

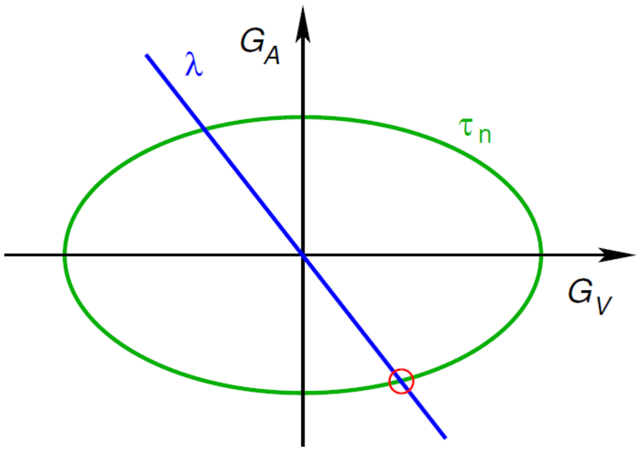
$$\lambda = \frac{g_A}{g_V}$$

Quark mixing

Cabibbo-Kobayashi-Maskawa matrix element

$$V_{ud}$$

V_{ud} from Neutron Decay



from D. Pocanic arXiv:1704.00192v1

Ellipse: $G_V^2 + 3G_A^2 = \frac{\text{const.}}{\tau_n}$

Line: $G_A = \lambda G_V \quad (\lambda < 0)$

$$|V_{ud}|^2 = \frac{(4908.7 \pm 1.9)s}{\tau(1+3\lambda^2)}$$

Marciano , Sirlin PRL 96 (2006)

Status today:
(using PDG 2016 averages)

$|V_{ud}| = 0.97585\ (18)_{RC}(55)_{\tau}(146)_{\lambda}$

Future prospects:
New experiments: Nab, PERC
Penelope / HOPE / τSpect / UCNτ / BL3

$|V_{ud}| = 0.97xxx\ (18)_{RC}(11)_{\tau}(8)_{\lambda}$

Near future (this year‘s results):
aCorn, aSpect?, UCNA, PERKEO III

$|V_{ud}| = 0.97xxx\ (18)_{RC}(2\times22)_{\tau}(2\times40)_{\lambda}$
(new avg lifetime & upcoming PERKEO III result)

For comparision:
average of 14 nuclei ($0^+ \rightarrow 0^+$):

$|V_{ud}| = 0.97417\ (18)_{RC}(9)_{NS}(6)_{exp}$
J.C. Hardy & I. S. Towner, PRC91, 025501 (2015)

Neutron Classification

Cold neutrons

moderated in thermal bath (e.g. liquid D_2)

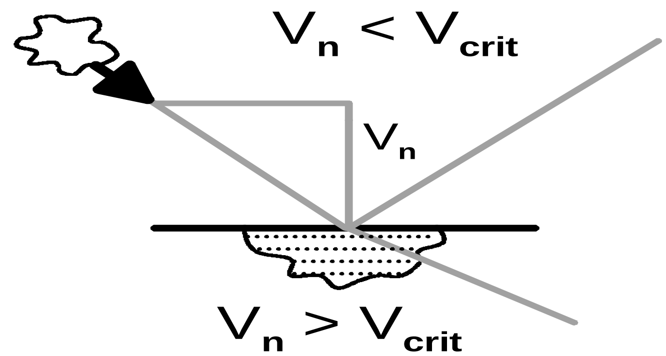
E ~ 3 meV, T ~ 40 K, v ~ 800 m/s, λ~ 0.5nm

high flux densities: $2{\cdot}10^{10}\ s^{-1}\ cm^{-2}$

density ~$10^5\ cm^{-3}$

decay rate of up to $10^{6}\ s^{-1}$ per metre

(typ. correlation measurements)



Fermi potential	~ **100 neV**
Gravity $\Delta E = m_n\, g\, \Delta h$	~ **100 neV** / m
Magnetic field $\Delta E = \mu_n\, B$	~ **60 neV** / Tesla

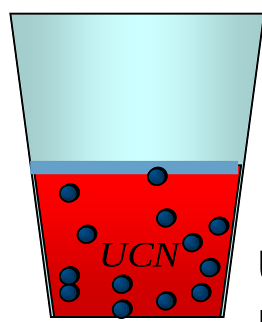
Ultracold neutrons (UCN)

E < 300 neV, T ~ 1 mK, v < 7 m/s, λ > 60nm

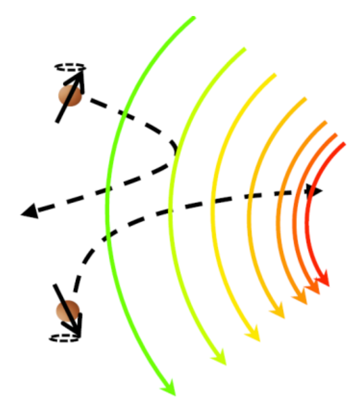
reflect from surfaces under any incident angle : storable

moderate densities: ~$30\ cm^{-3}$

(typ. neutron lifetime, EDM)



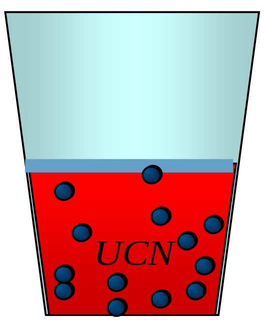
UCN „bottle“
Material storage and gravity!



Measurement of the neutron lifetime τ_n

Storage experiments with UCN

"counting the survivors"



$N(t_1), N(t_2)$

$$\frac{1}{\tau_m} = \frac{1}{t_2 - t_1} \cdot \ln \frac{N(t_1)}{N(t_2)}$$

$$\frac{1}{\tau_m} = \frac{1}{\tau_\beta} + \underbrace{\frac{1}{\tau_{wall}}} + \underbrace{\frac{1}{\tau_{leak}} + \frac{1}{\tau_{vacuum}} + \ldots}$$

→ 0 (experiment)

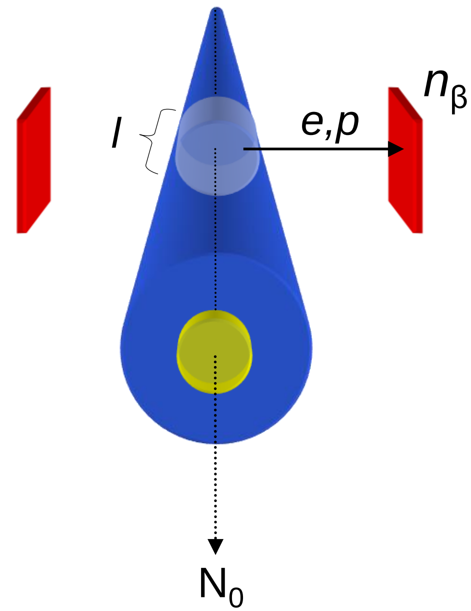
$$\frac{1}{\tau_{wall}} = \mu \cdot v_{eff}$$ → 0 (extrapolation)

$$\Rightarrow \quad \frac{1}{\tau_m} = \frac{1}{\tau_\beta}$$

relative measurements

In-beam experiments with cold neutrons

"counting the dead"

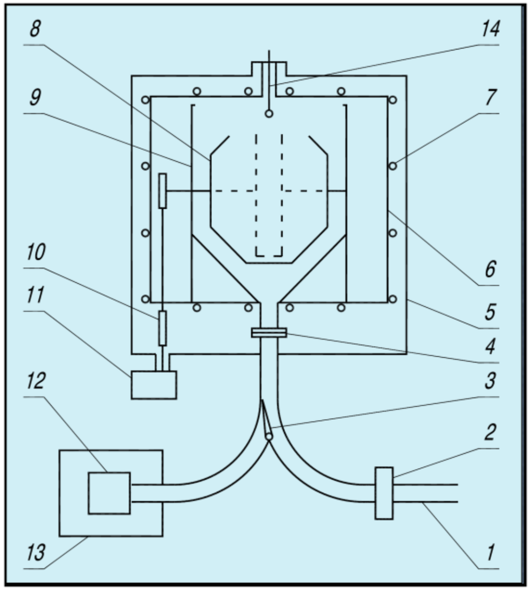


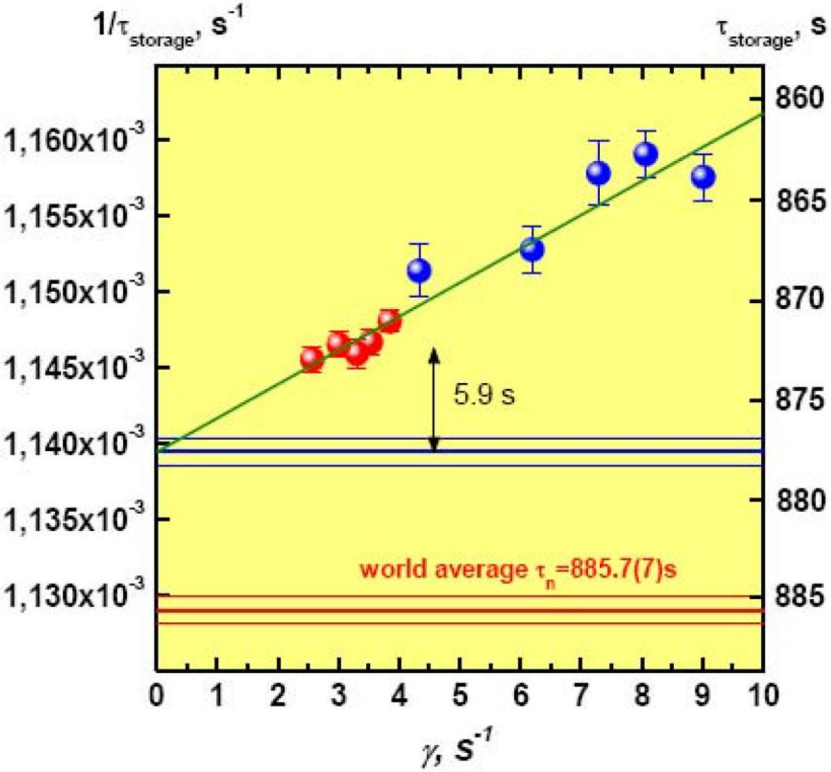
$$n_\beta = \frac{dN}{dt} = -\frac{N_0}{\tau_n} e^{-\frac{l}{v \cdot \tau_n}}$$

absolute measurements

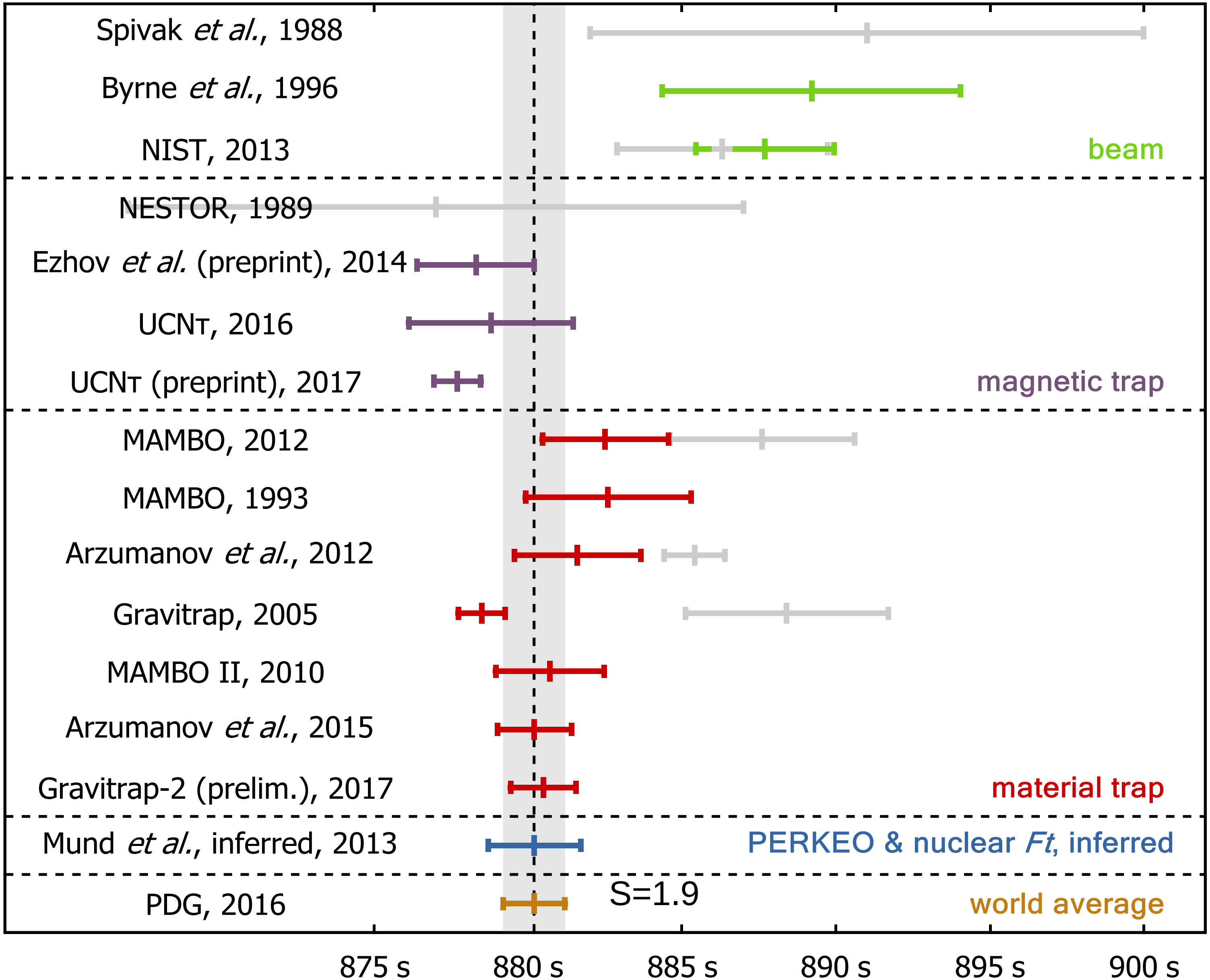
Gravitrap at ILL

Previous most precise measurement





Neutron Lifetime Measurements



$887.7(12)_{stat}(19)_{sys}$

$877.7(7)_{stat}(3)_{sys}$

$878.5(7)_{stat}(3)_{sys}$

$880.5(7)_{stat}(8)_{sys}$

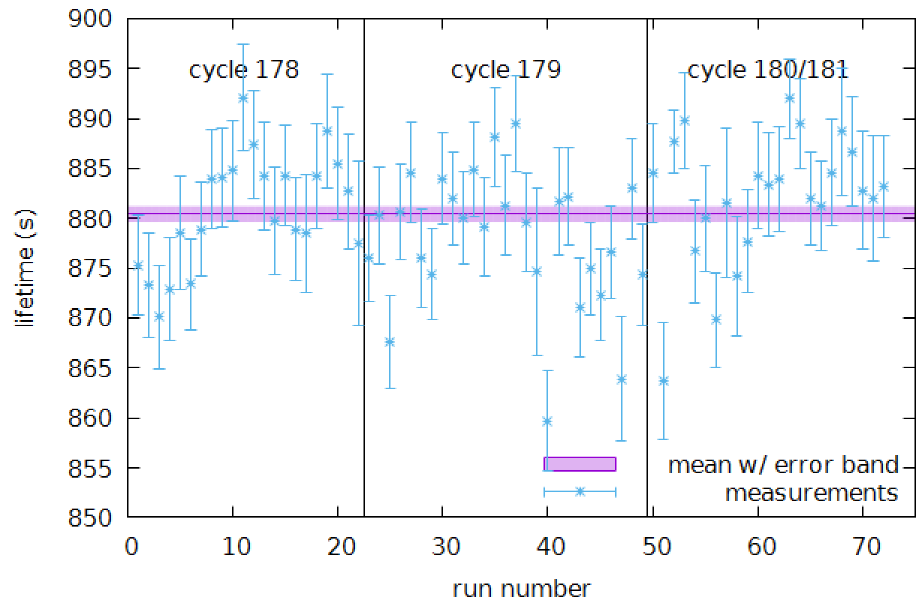
New avg?

879.4(8) S=1.9

New Gravitrap II

Lifetime measurement by fill-and-empty.
Massively larger than previous experiment.
Running at ILL, Grenoble.

Many systematic studies (coating, losses, temperature)
Next: Change from LN temperature to LHe cooling (10K) to reduce wall losses.

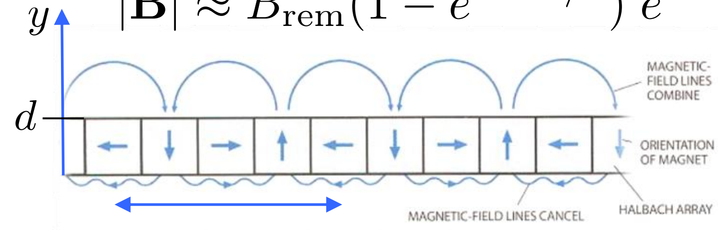


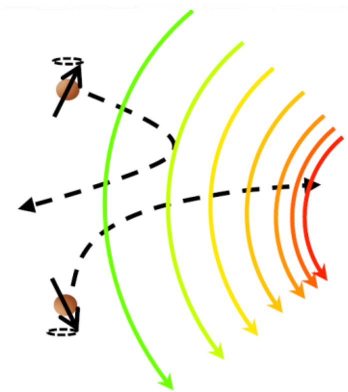
UCNτ Magneto-gravitational trap

Operated at LANL

~5500 permanent magnets

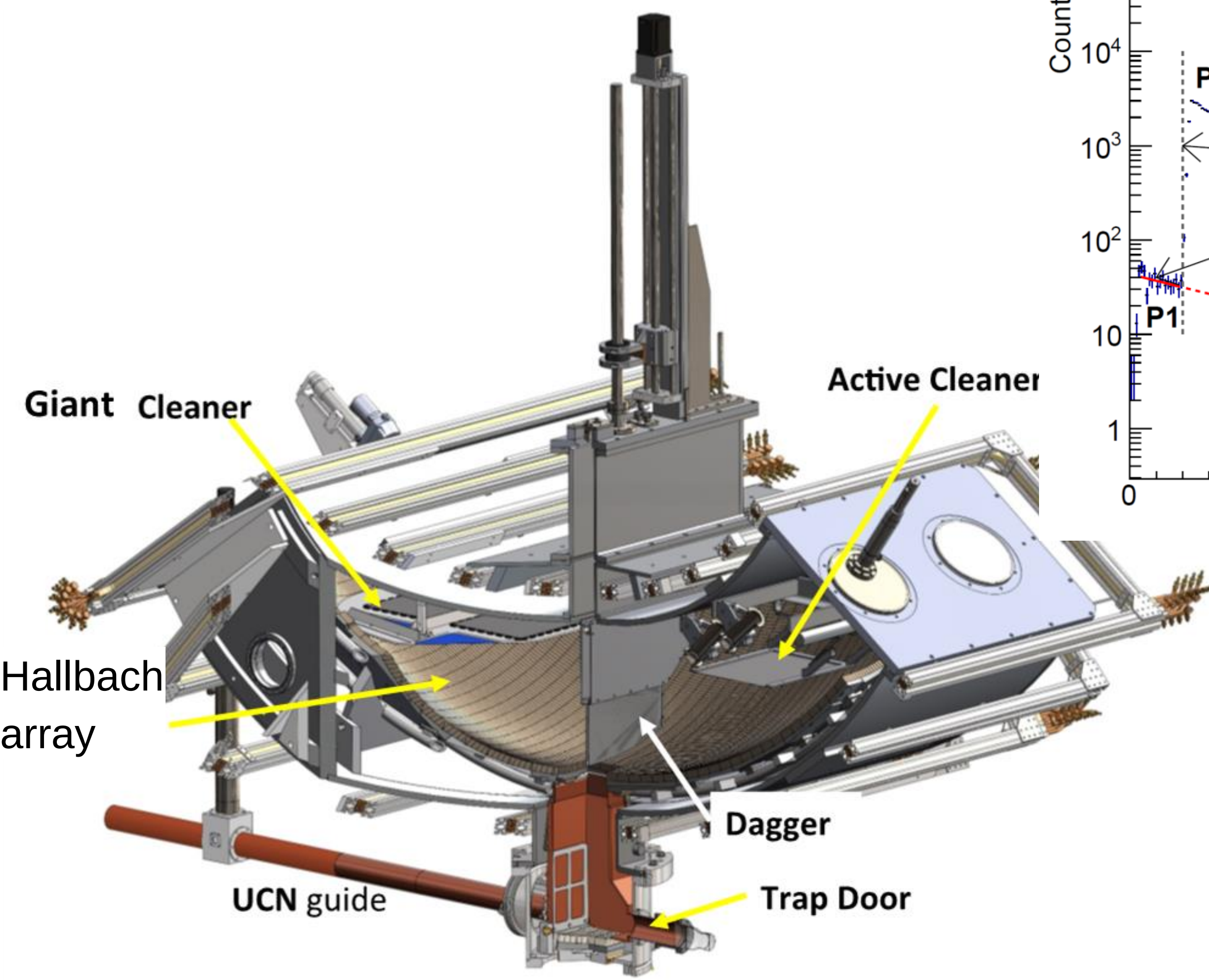
$$|\mathbf{B}| \approx B_{\mathrm{rem}}(1 - e^{-2\pi d/\lambda})\, e^{-2\pi y/\lambda}$$

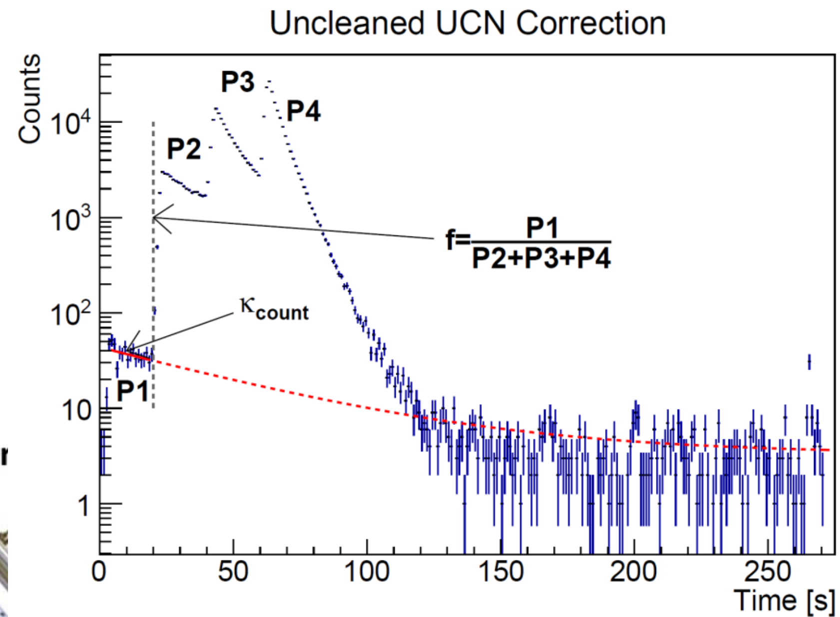




Material: C.-Y. Liu
EXA2017

UCNτ Magneto-gravitational trap





R. W. Pattie, et al.,
arXiv 1707.01817:

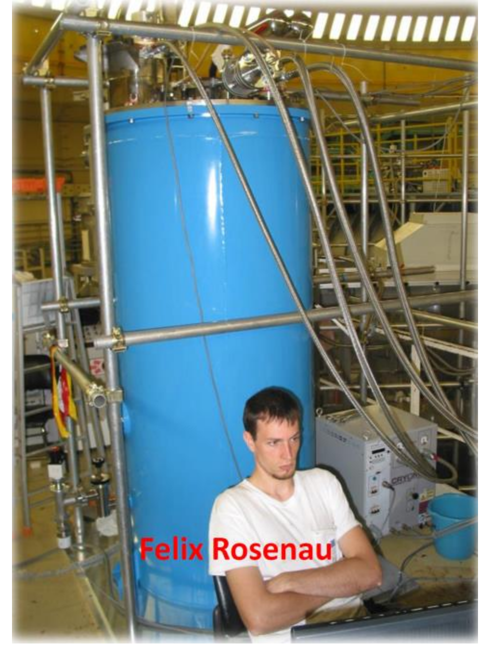
$877.7(7)_{stat}(3)_{sys}$

Material: C.-Y. Liu
EXA2017

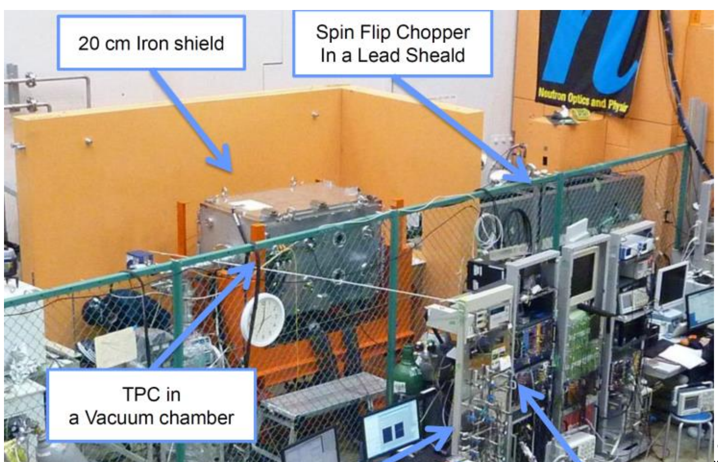
More Neutron Lifetime Exp.

permanent magnet multipole + SC magnet,
8l volume, new UCN source
short term goal 2s, long term < 0.3s
*running at **Mainz***

HOPE

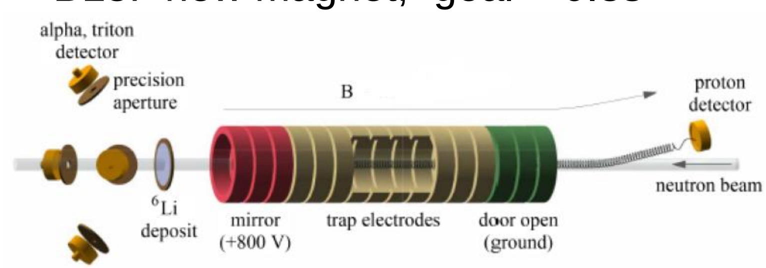


permanent magnet octupole + SC magnet,
2l volume, new UCN source
Goal: 1s -- running at **ILL**, Grenoble



J-PARC TPC
Pulsed beam
Status: 1%
Goal 0.1%

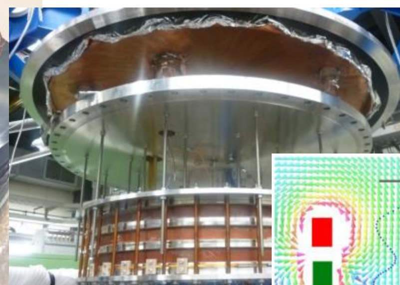
NIST BL2: goal 1s
BL3: new magnet; goal < 0.3s

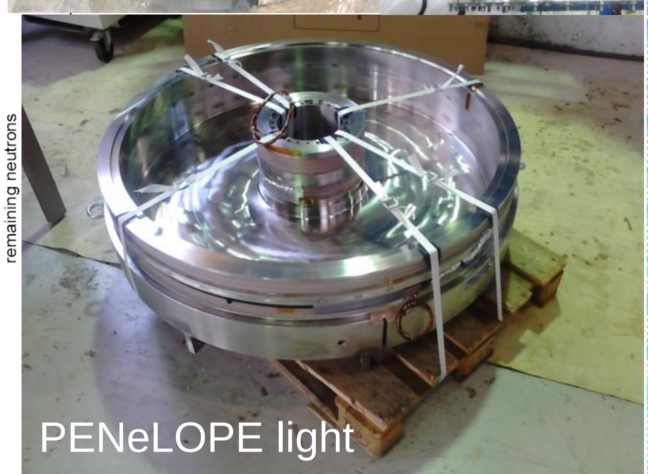


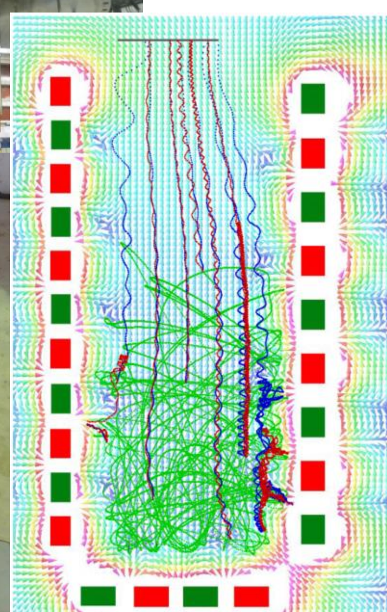
PENeLOPE (TUM)

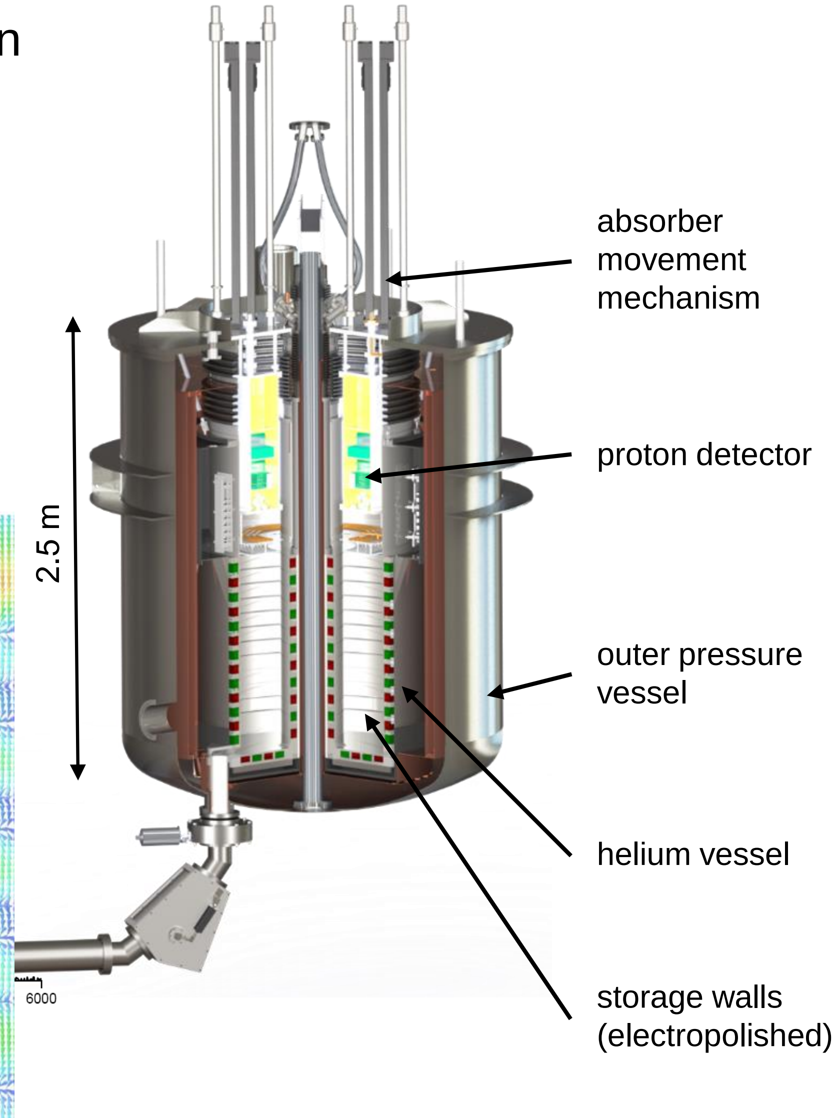
Magnetic & Gravitational trapping avoids material losses altogether!
(HOPE/ILL, Ezhov/ILL, τSpect/Mainz, UCNτ/LANL, PENeLOPE/TUM): store only one spin-direction

PENeLOPE aims at a precision of ± 0.1 s
Measure protons and neutrons directly from decay. Also fill-and-empty.

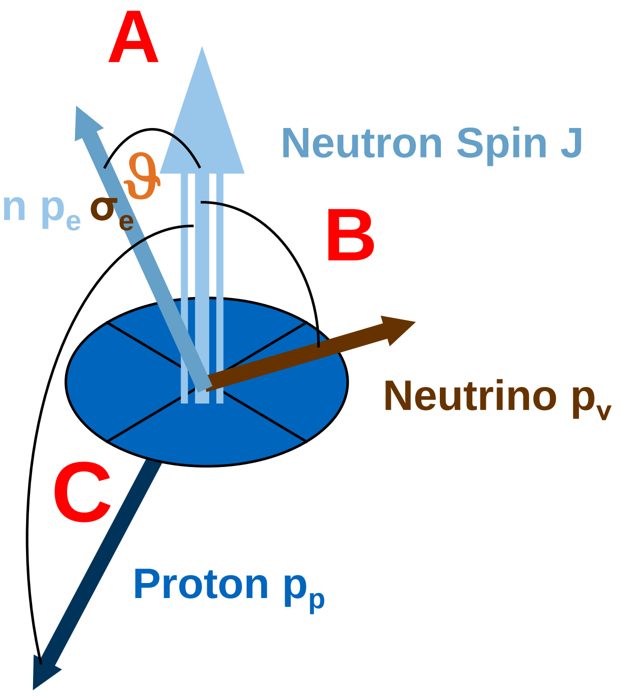


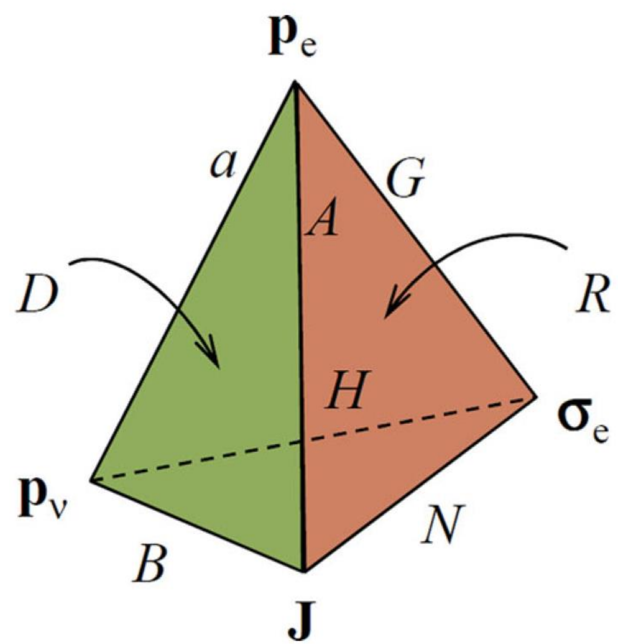






Neutron Decay Correlations





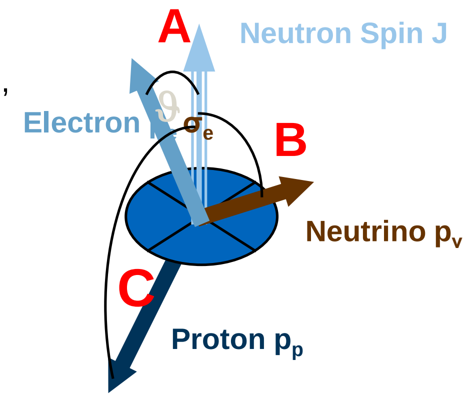
Naviliat-Cuncic and Gonzalez-Alonso, Ann. Phys. 525, 8–9, 600–619 (2013)
Dubbers and Schmidt, Rev. Mod. Phys (2012)

Correlation Coefficients

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{2(2\pi)^5} G_F^2 |V_{ud}|^2 \left(1+3|\lambda|^2\right) p_e E_e \left(E_0 - E_e\right)^2$$

Jackson, Treiman, Wyld, Nucl. Phys. 4, 1957

$$\times\left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \frac{\langle\vec{\sigma}_n\rangle}{\vec{\sigma}_n}\cdot\left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right)\right]$$



Typical current relative precision $O(10^{-2} - 10^{-3})$

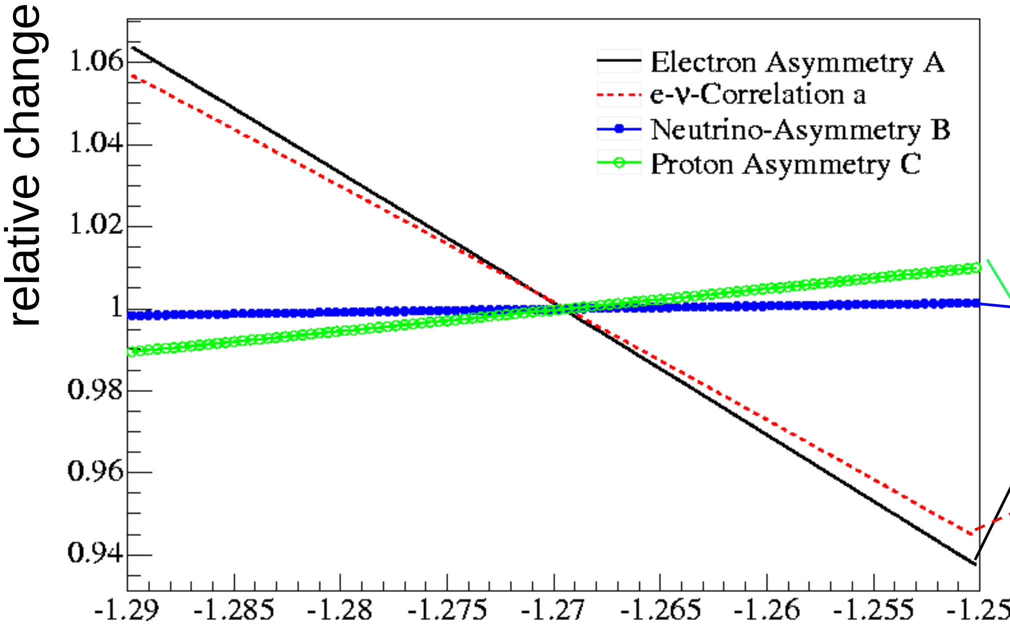
Goal of next generation PERC: $O(10^{-3} - 10^{-4})$ for some observables

PERKEO III / PERC

Parameter		λ-dependence	Violates	Value	Rel. Prec.
A	Beta Asymmetry	$-2 \cdot \frac{\lvert\lambda\rvert^2 + \mathrm{Re}(\lambda)}{1+3\lvert\lambda\rvert^2}$	P	-0.1184(10)	$8\cdot10^{-3}$
B	Neutrino Asymmetry	$2 \cdot \frac{\lvert\lambda\rvert^2 - \mathrm{Re}(\lambda)}{1+3\lvert\lambda\rvert^2}$	P	0.9807(30)	$3\cdot10^{-3}$
C	Proton Asymmetry	$x_C \cdot \frac{4\mathrm{Re}(\lambda)}{1+3\lvert\lambda\rvert^2}$	P	-0.2377(26)	$1\cdot10^{-2}$
D	Triple Correlation	$2 \cdot \frac{\mathrm{Im}(\lambda)}{1+3\lvert\lambda\rvert^2}$	T	1.2(2.0) 10^{-4}	
a	Electron Neutrino Angular Correlation	$\frac{1-\lvert\lambda\rvert^2}{1+3\lvert\lambda\rvert^2}$		-0.103(4)	$4\cdot10^{-2}$
b	Fierz Interference Term	0 (in SM)		*none*	

[PDG2014]

Determination of $\lambda = g_A/g_V$



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

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

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

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

$\lambda = g_A/g_V$

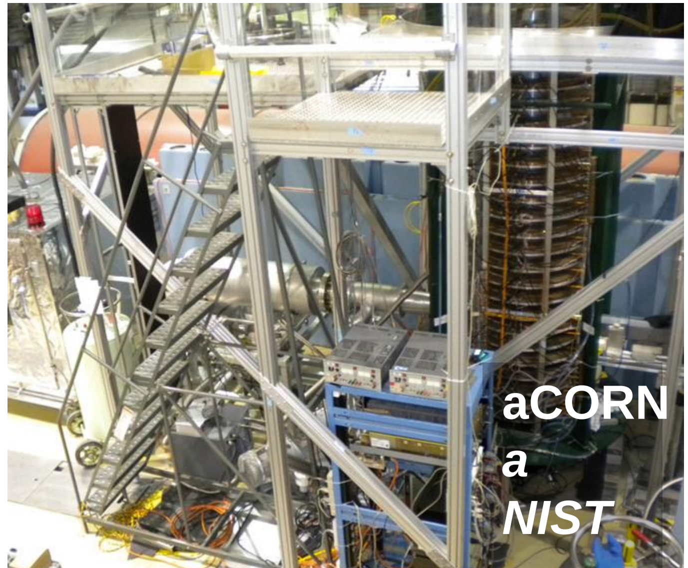
$A_{PDG} = -0.1184 \pm 0.0010$ 1.1%

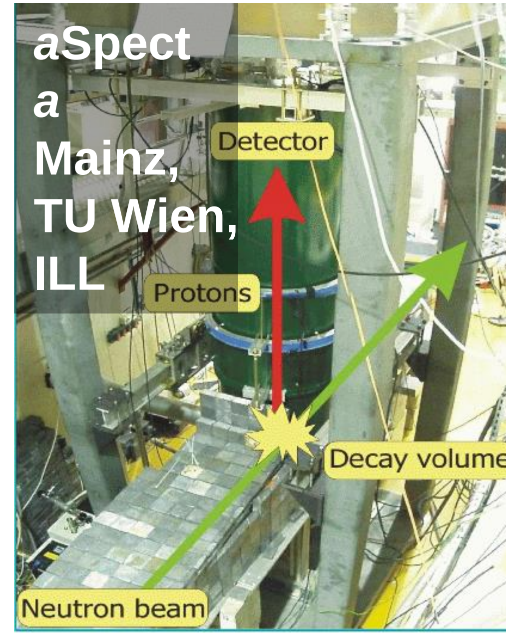
$B_{PDG} = 0.9807 \pm 0.0030$ 0.3%

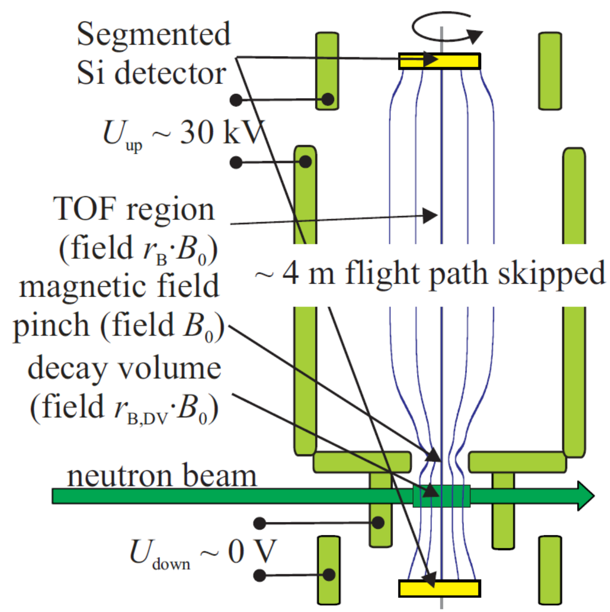
$C = -0.2377 \pm 0.0026$ 1.1%

$a_{PDG} = -0.103 \pm 0.004$ 3.9%

Current Neutron Decay Experiments



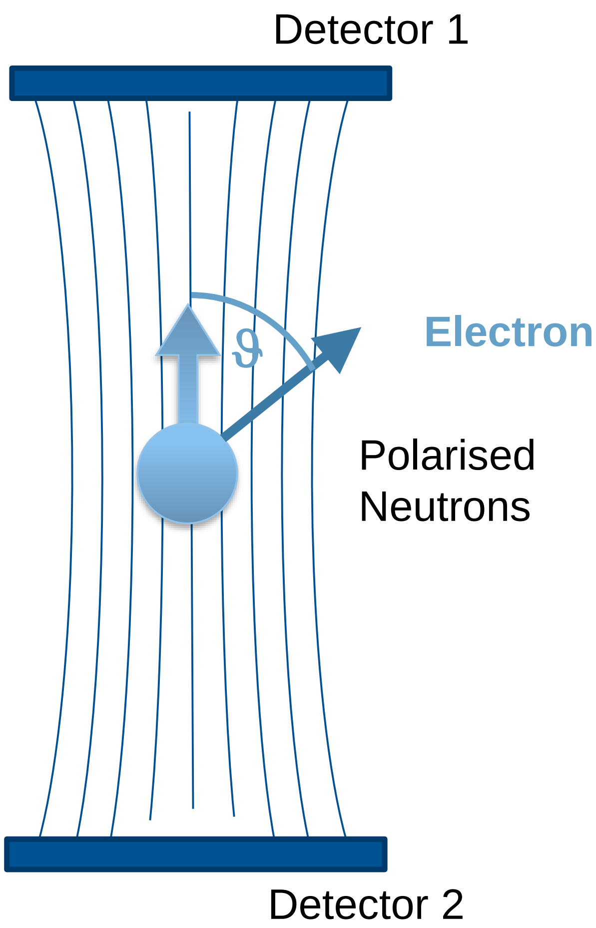




Nab
a, b
SNS

… and PERC

PERKEO: Measuring Beta Asymmetry *A*



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 to as quantisation axis

Integration over hemispheres:
2 × 2π detection

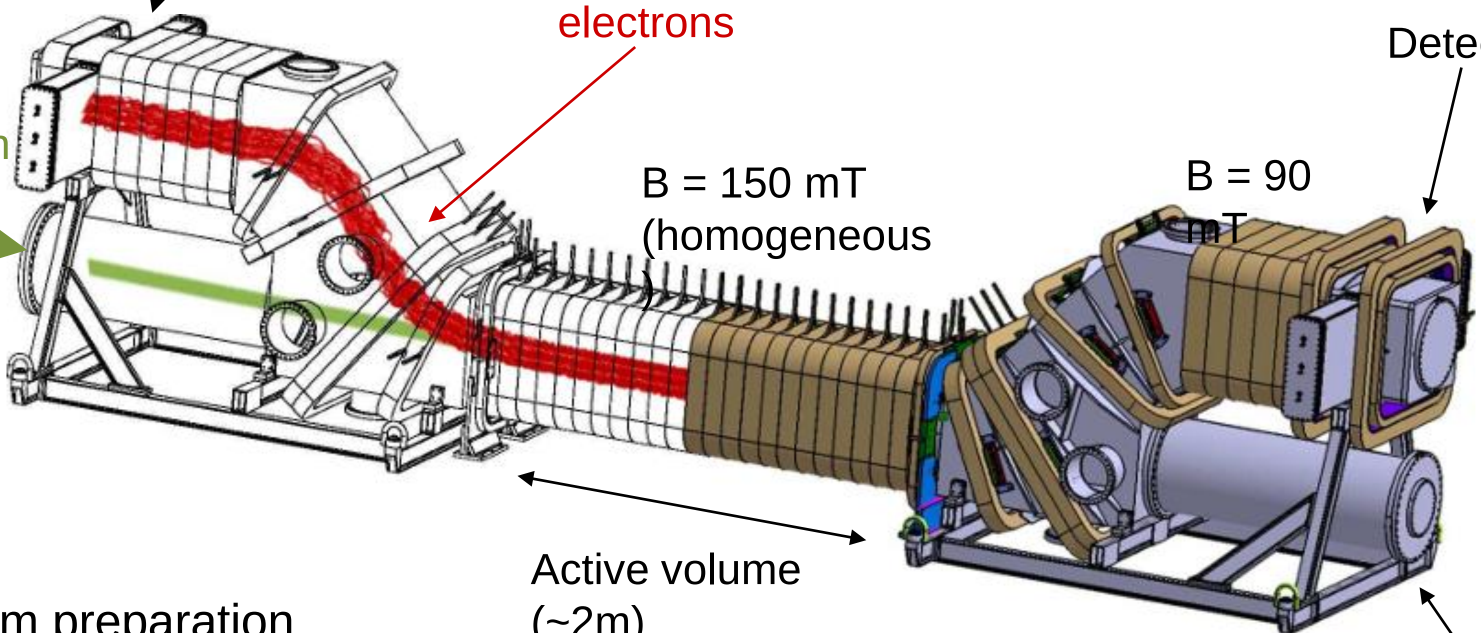
$$\cos\vartheta \rightarrow 1/2$$

Experimental asymmetry, polarisation *P*

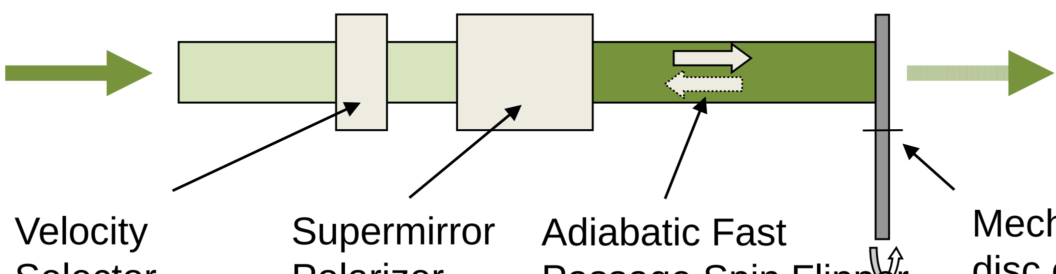
$$A_{\exp} = \frac{N^{\Uparrow} - N^{\Downarrow}}{N^{\Uparrow} + N^{\Downarrow}} = \tfrac{1}{2}\tfrac{v}{c} P A$$

Spectrometer PERKEO III

Total length: 8 m
~50.000 decays / sec in the continuous beam

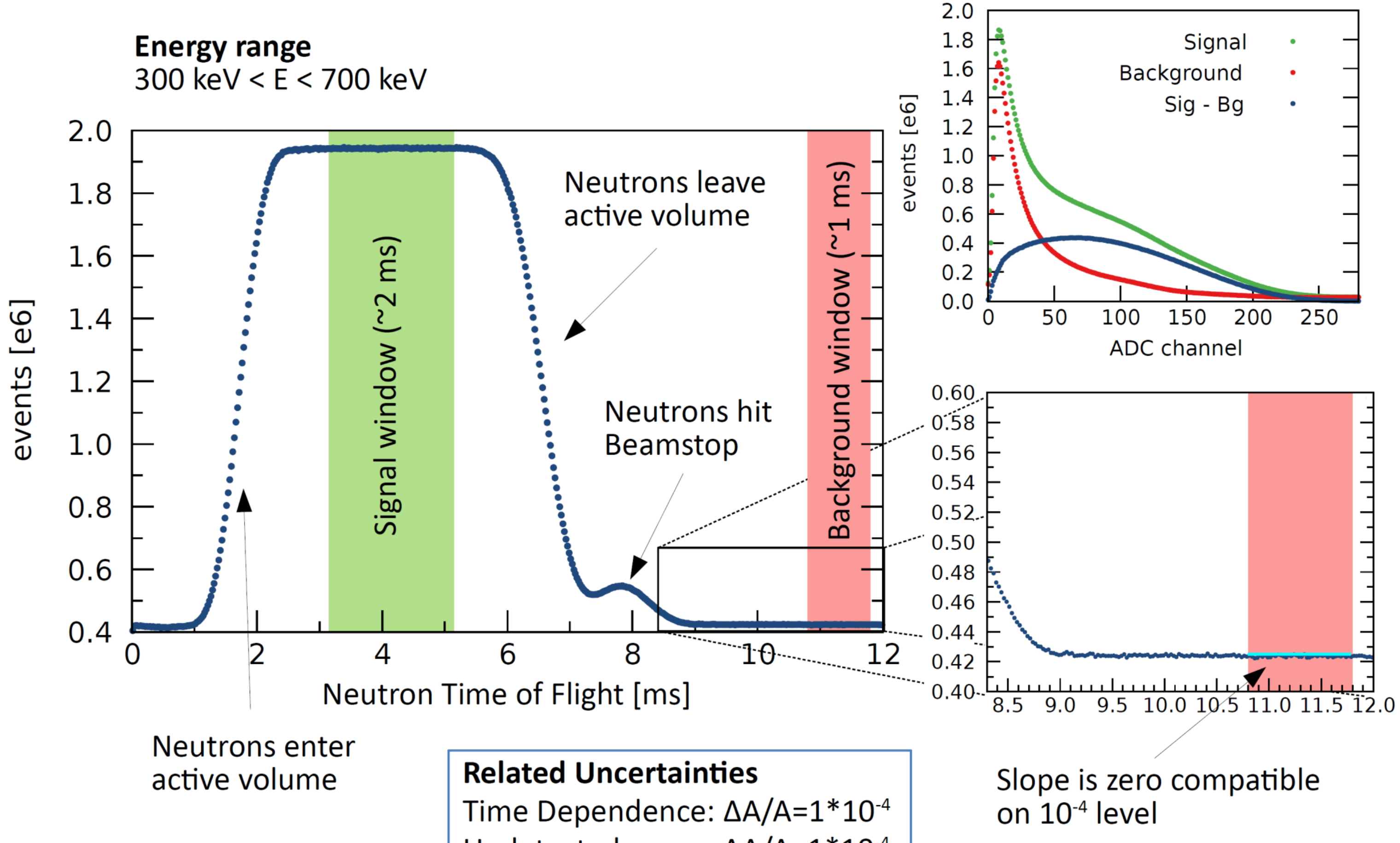


Beam preparation



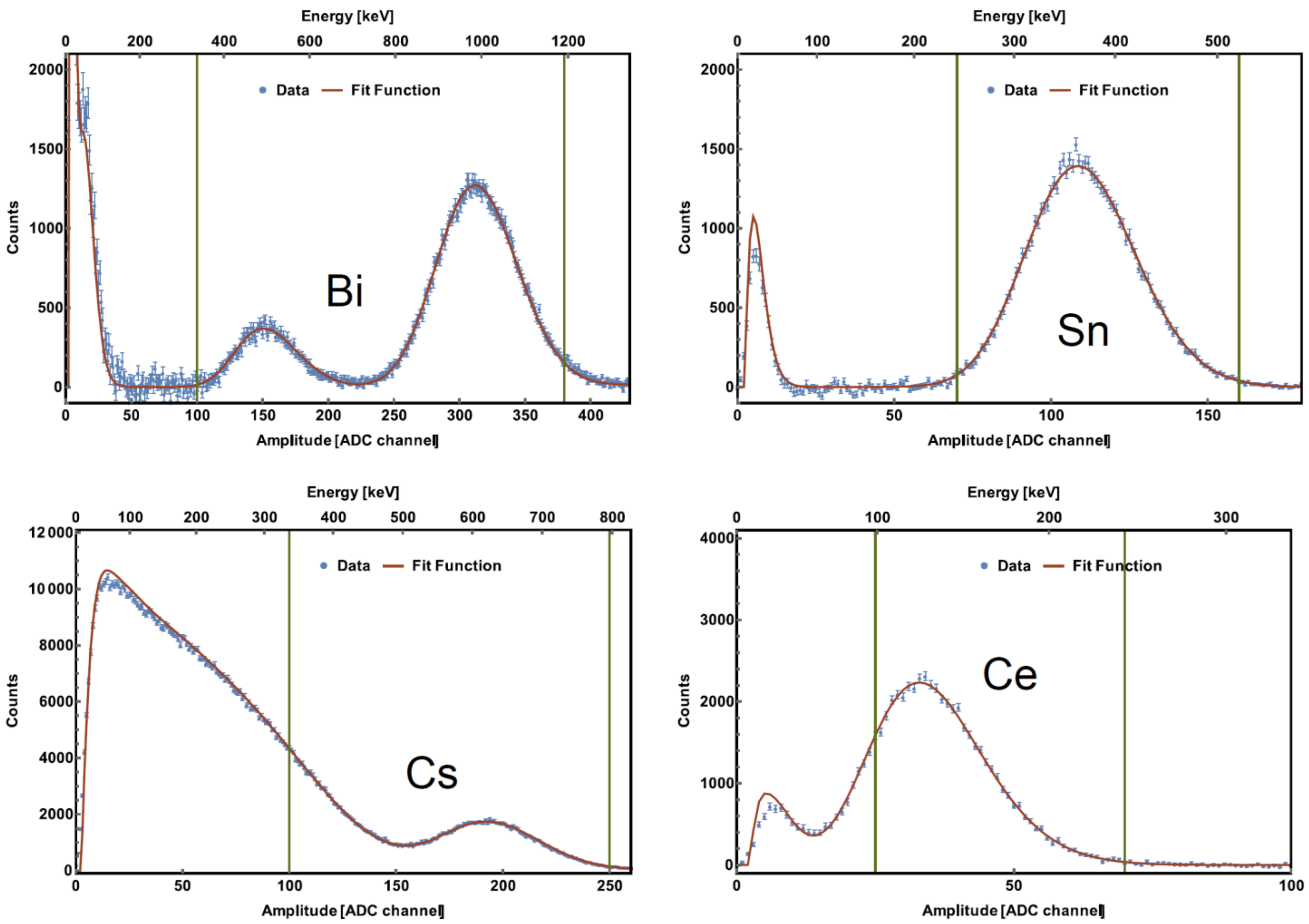
PERKEO III: Pulsed Neutron Beam

Sacrifise ~2 orders of magnitude in statistics to address important systematic: background; continuous beam 50.000 s^{-1} ; pulsed 250 s^{-1}



Related Uncertainties
Time Dependence: $\Delta A/A = 1*10^{-4}$
Undetected: $\Delta A/A = 1*10^{-4}$

PERKEO III: Calibration Fits



Green bars indicate fit region

114 full calibrations in (twice per day)

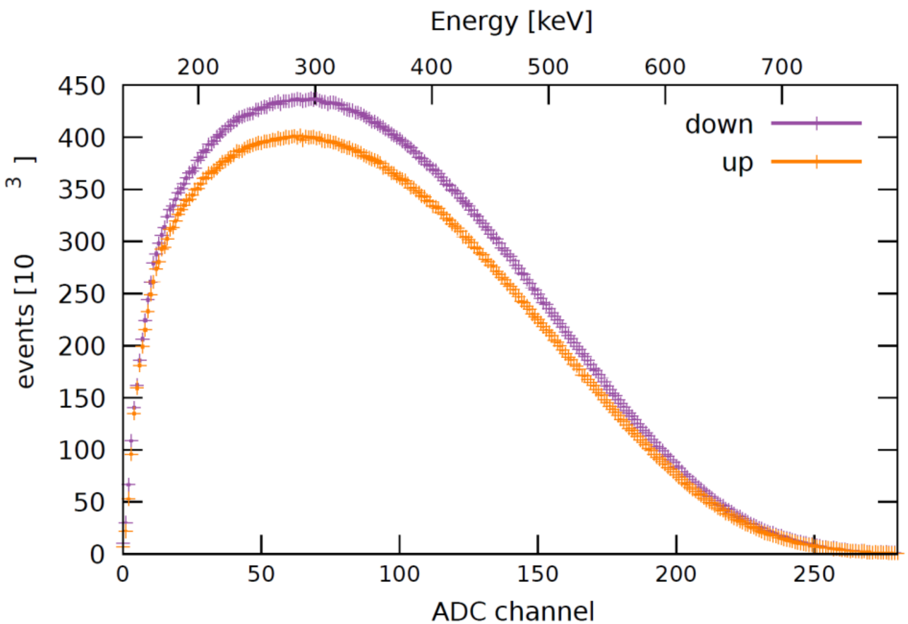
Simultaneous Fit:
X^2/NDF = 1.0 – 1.3

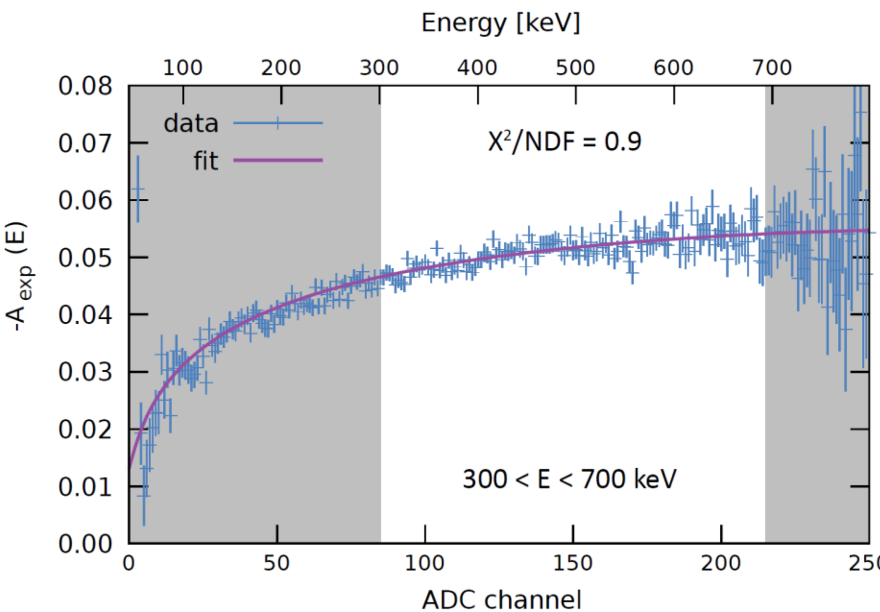
Free parameters:
Non-linearity, gain, PE + norms

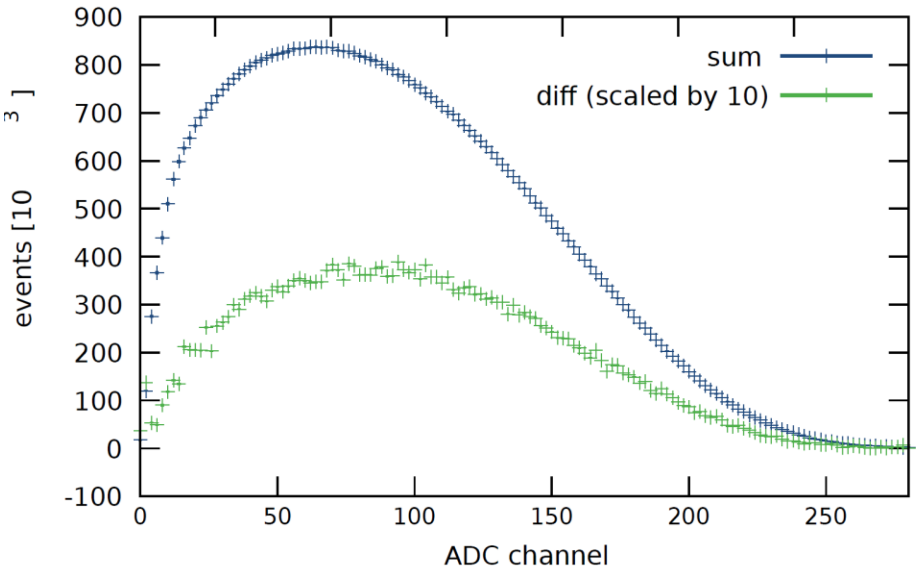
In addition:
Hourly drift measurements

~weekly 2D uniformity scan

Asymmetry Extraction







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

1 of 4 datasets shown

$6 \cdot 10^8$ events in analysis

Result (still blinded):

$$\frac{\Delta A}{A} = 1.9 \cdot 10^{-3}$$

$$\frac{\Delta \lambda}{\lambda} = 4.8 \cdot 10^{-4}$$

PERKEO III Error budget

Source	Correction ΔA/A (10^{-4})	Uncertainty ΔA/A (10^{-4})
Neutron beam		
Polarisation	*blinded*	8
Spin flip efficiency	*blinded*	
Background		
Deadtime		0.4
Time variation	-0.8	0.8
Chopper Background	-0.9	0.4
Electrons		
Magnetic mirror effect	*blinded*	6
Detector		
Non-linearity	-2.0	4.0
Non-uniformity	-4.8	1.5
Stability		3.7
Calibration Sources	1.6	0.8
Rate Dependence of ADCs		1.3
Undetected Backscattering	5.0	1.5
Lost backscatter energy		1.4
Theory		
Radiative Corrections	-10	1
Total Systematics		11.8
Statistics		14.0
Total		18.4

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

Separate Analysis

PDG 2016 world average:

$\Delta A/A = 8.4 \cdot 10^{-3}$

$\Delta\lambda/\lambda = 1.8 \cdot 10^{-3}$

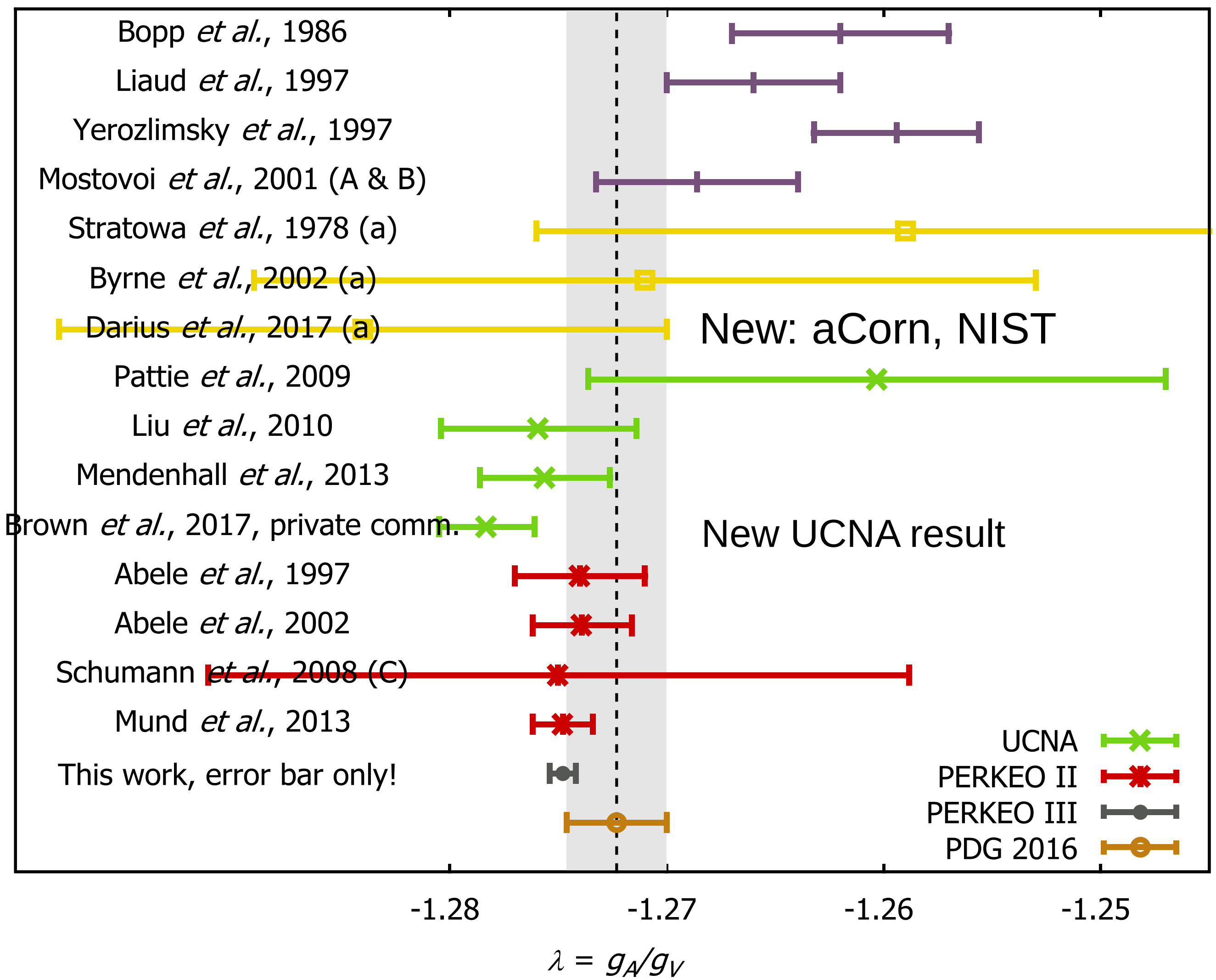
This measurement:

$\Delta A/A = 1.8 \cdot 10^{-3}$

$\Delta\lambda/\lambda = 5 \cdot 10^{-4}$

Finally, close to being unblinded (inconsistencies in indep. analyses resolved)

AXIAL VECTOR- TO VECTOR COUPLING CONSTANT



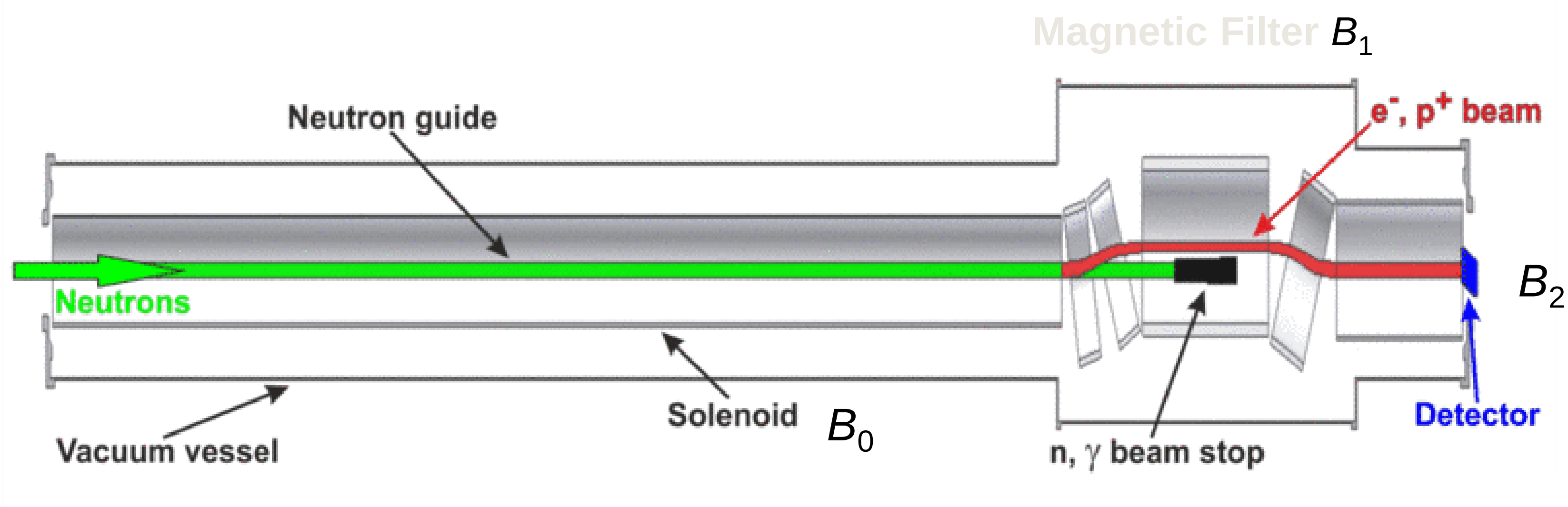
Electron-Neutroino Correlation „a“: Results soon from aSpect, Mainz

Nab goal: competitive with „A“

Goal of Nab, PERC $\Delta\lambda/\lambda \sim O(10^{-4})$

PDG 2016
-1.2723(23)

Proton Electron Radiation Channel (PERC)



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

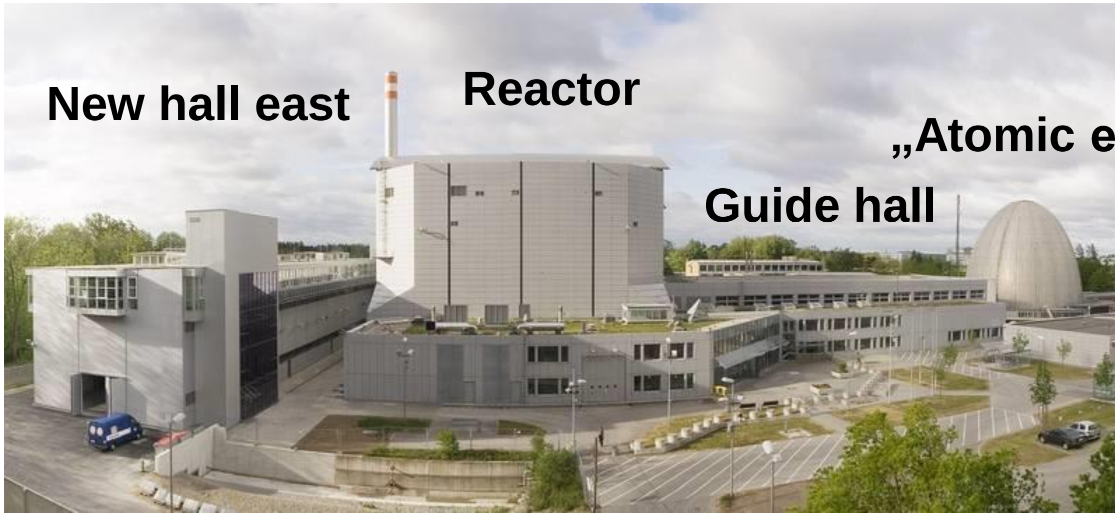
Magnetic Filter, B_1 = 6T: phase space, systematics $B_1/B_0 = 2\ldots12$
(solid angle, backscatter suppression)

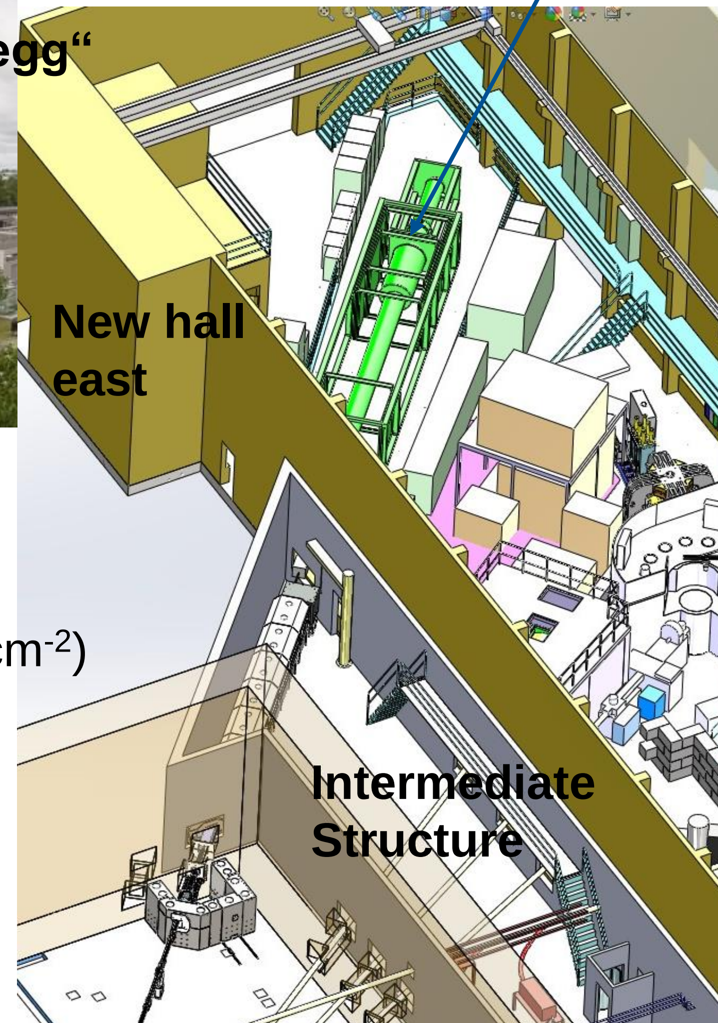
Source for specialised spectrometers

Aims to improve results by an **order of magnitude: 10^{-4}**. New Observables.

Nucl. Instr. Meth. A **596** (2008) 238 and arXiv:0709.4440

Beam Site Mephisto, FRM II





"Empty" new hall

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

Easy ground level access, Fixed installation

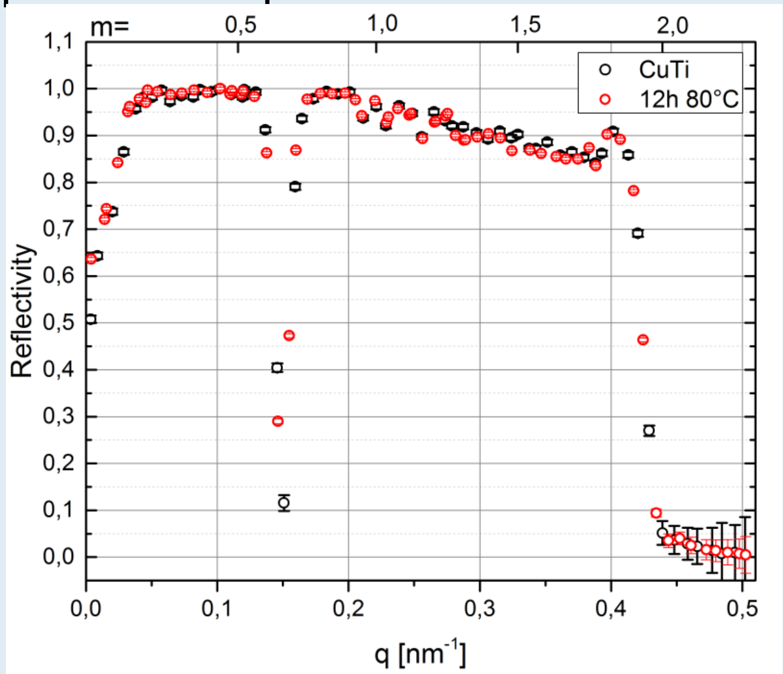
Status: **All major components of the beam line ready or in production**

PERC: Neutron Spin Control

$O(10^{-4})$ precision requires neutron spin control on the same level:

- polarisation 99.7%: FeSi polarisers – Soldner / Petoukhov et al. (ILL)
- spin flipper: AFP 100.00%
- guide in strong magnetic field: only 10^{-4} depolarization per bounce allowed
- measurement with ^{3}He spin filters – Soldner et al. (ILL)

Non-magnetic CuTi mirror m=2
preserves spin direction



Production quality
(except for the too thin top layer)

Large maximum angle of reflection, high reflectivity

Reduces neutron losses in PERC by factor > 2: background!

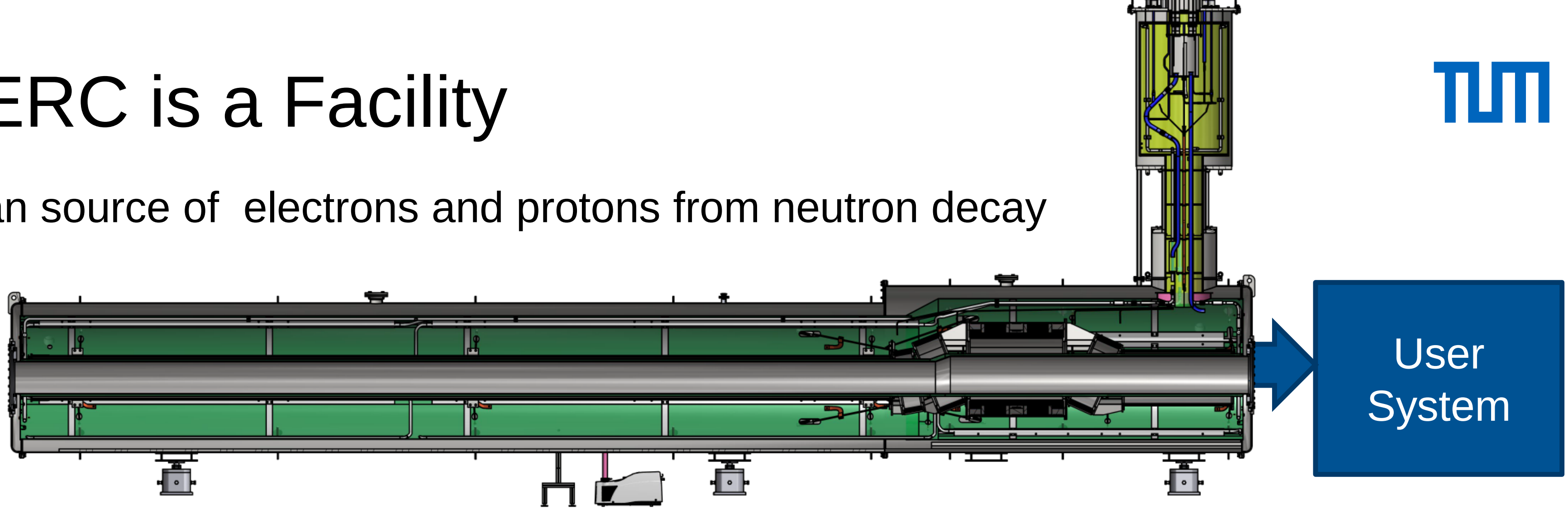
(Mildly) backable (>80°C). Beneficial for vacuum conditions.

Hollering (TUM), Rebrova / Schmidt (HD)

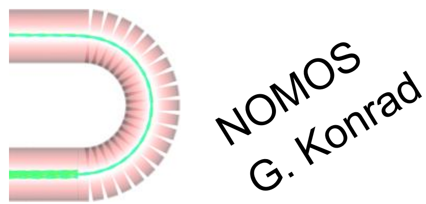
Status of the PERC Magnet

PERC is a Facility

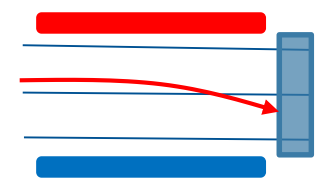
Clean source of electrons and protons from neutron decay



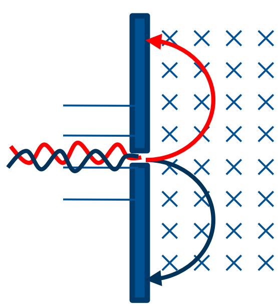
R×B spectrometer



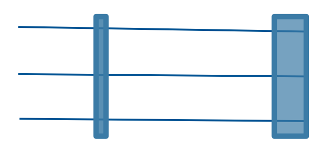
Wien filter for protons



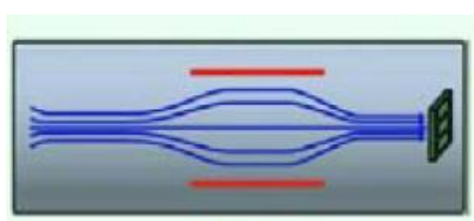
Magnetic spectrometer



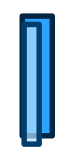
Electrostatic chopper & p detector



MAC-E filter (“aSPECT”)



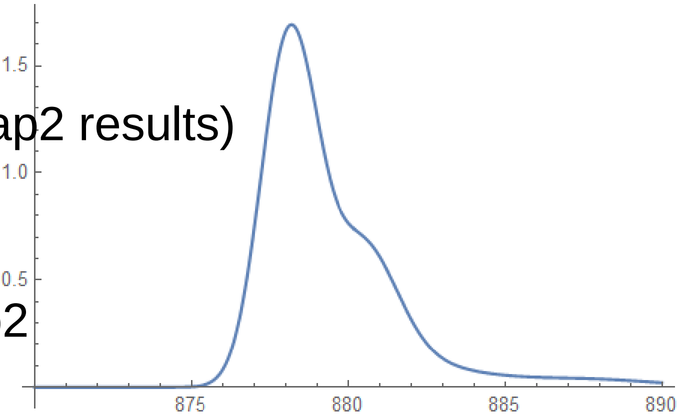
Electron or proton detector



Scintillator, Silicon, …

Prospects

Tremendous ongoing efforts to improve V_{ud} from neutron decay



Lifetime τ

Potential new average (including UCNtau + Gravitrap2 results)

$\tau = 879.4(8)$ s; S = 1.9

Many new experimental results to be expected:

UCNtau, HOPE, tauSpect, PENeLOPE, Gravitrap2

Current Goal: O(0.1s)

Ratio of coupling constants λ

New (upcoming) results by

aCorn, UCNA, PERKEO III, aSpect

Next generation

Nab a 0.1% PERC A 0.05%

Long-term future (next decade): cold beam line **ANNI** at **ESS** (more than order of magnitude More statistics in pulsed beam)

PERC (Proton Electron Radiation Channel) at FRM II / MLZ

U. Schmidt

J. Klenke

H. Abele
E. Jericha

ATOMINSTITUT

B. Märkisch

G. Konrad

PERC

W. Heil

NEUTRONS FOR SCIENCE

O. Zimmer
T. Soldner

Wilhelm und Else Heraeus-Seminar
„Particle Physics with Cold and Ultra-Cold Neutrons“

Wednesday 24th – Friday 26th October 2018

Physikzentrum Bad Honnef

Scientific Organizers:

Hartmut Abele, Atominstitut, TU Wien

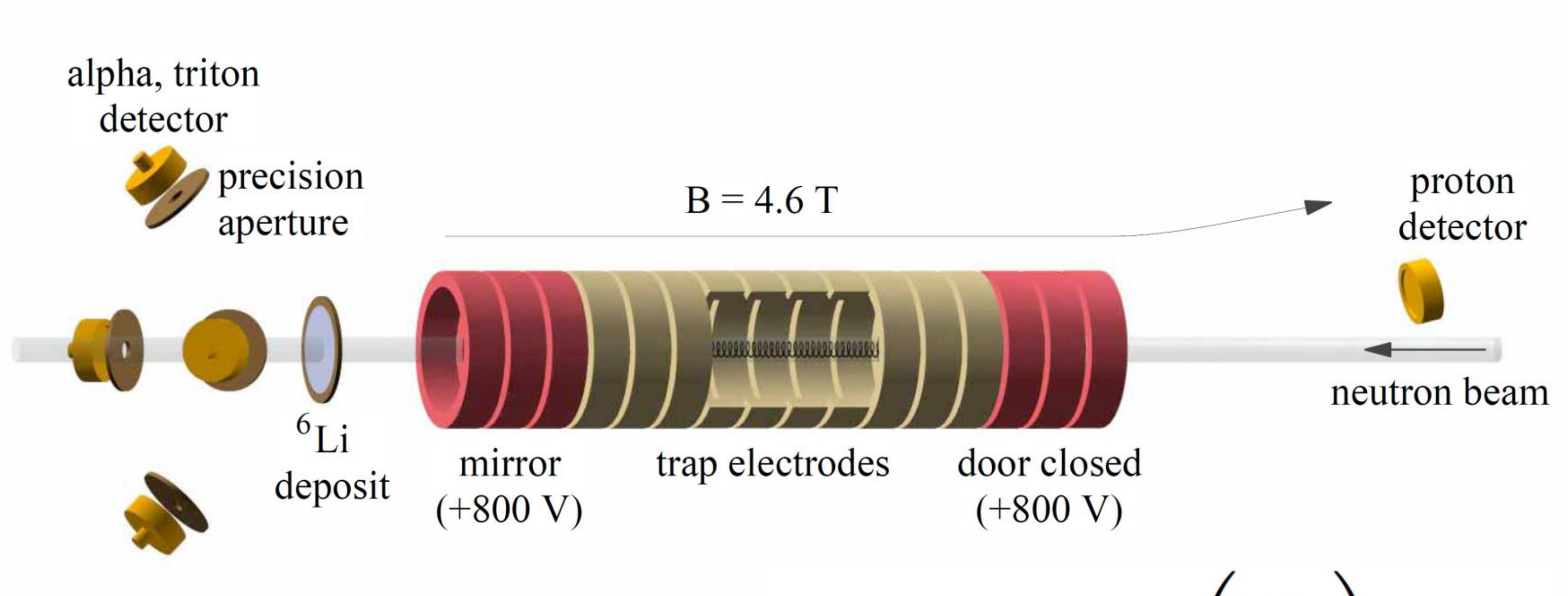
Bastian Märkisch, TU München

experiment	observable	goal uncert.	technique	facility/group
BL2	τ	1 s	cold n beam	NIST
BL3	τ	< 0.3 s	cold n beam	NIST
JPARC τ	τ	< 0.3 s	cold n beam	J-PARC
Gravitrap	τ	0.2 s	UCN/material bottle	PNPI and ILL
Ježov	τ	0.3 s	UCN/magnetic bottle	PNPI and ILL
HOPE	τ	0.5 s	UCN/magnetic bottle	ILL (supertherm. source)
PENELOPE	τ	0.1 s	UCN/magnetic bottle	TU Munich
Mainz	τ	0.2 s	UCN/magnetic bottle	Mainz TRIGA source
UCNτ	τ	$\ll 1$ s	UCN/magnetic bottle	LANSCE UCN source
UCNA	A	0.2%	UCN	LANSCE UCN source
PERKEO III	A	0.19%	cold n beam	MLZ (Munich) and ILL
PERC	A	0.05%	cold n beam	Munich
aCORN	a	$\sim$1%	cold n beam	NIST
aSPECT	a	$\sim$1%	cold n beam	Mainz and ILL
Nab	a	0.1%	cold n beam	SNS

Table 1: Ongoing and planned/funded neutron beta decay measurements, indicating the observable measured, the goal uncertainty level, as well as the general measurement method applied.

from D. Pocanic arXiv:1704.00192v1

Beam Method: NIST Experiment



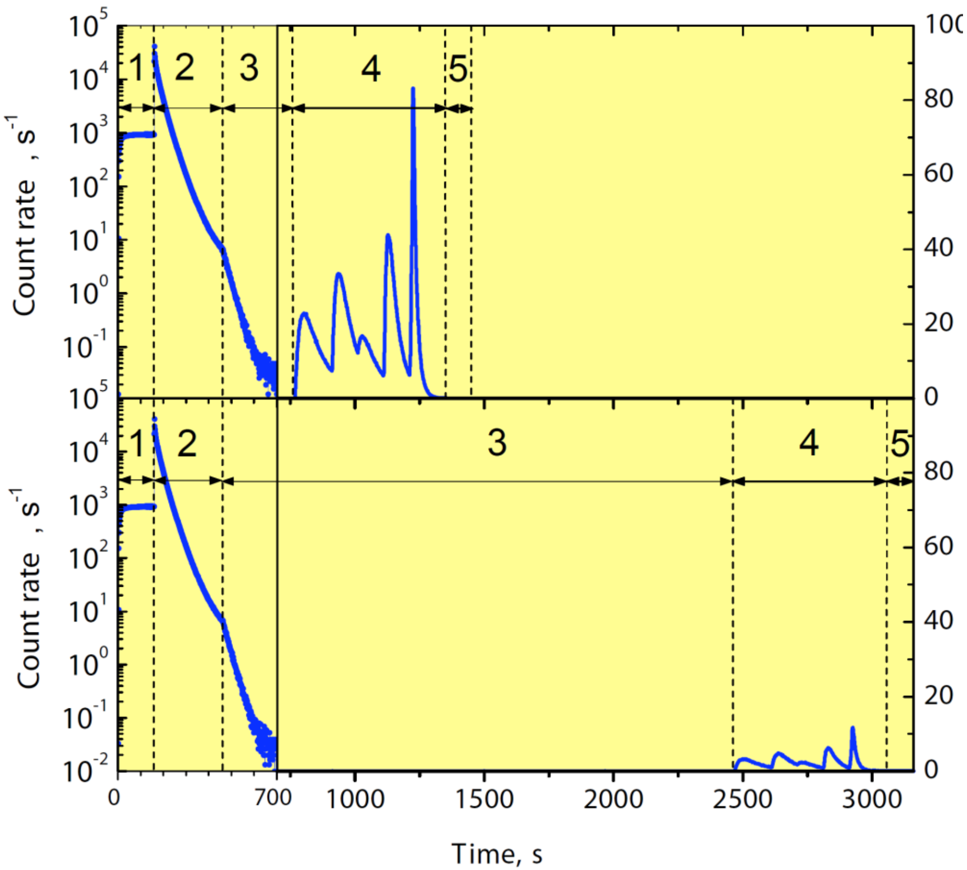
$$\tau_n = \dot{N}_{\alpha+t} \left(\frac{L}{\dot{N}_p} \right) \frac{\epsilon_p}{\epsilon_0 v_0}$$

$\frac{L}{\dot{N}_p}$	Proton rate measured as function of trap length
ϵ_p	Proton detection efficiency
$\dot{N}_{\alpha+t}$	n + ^{6}Li reaction product counting
ϵ_0	Neutron flux monitor efficiency fo v_0

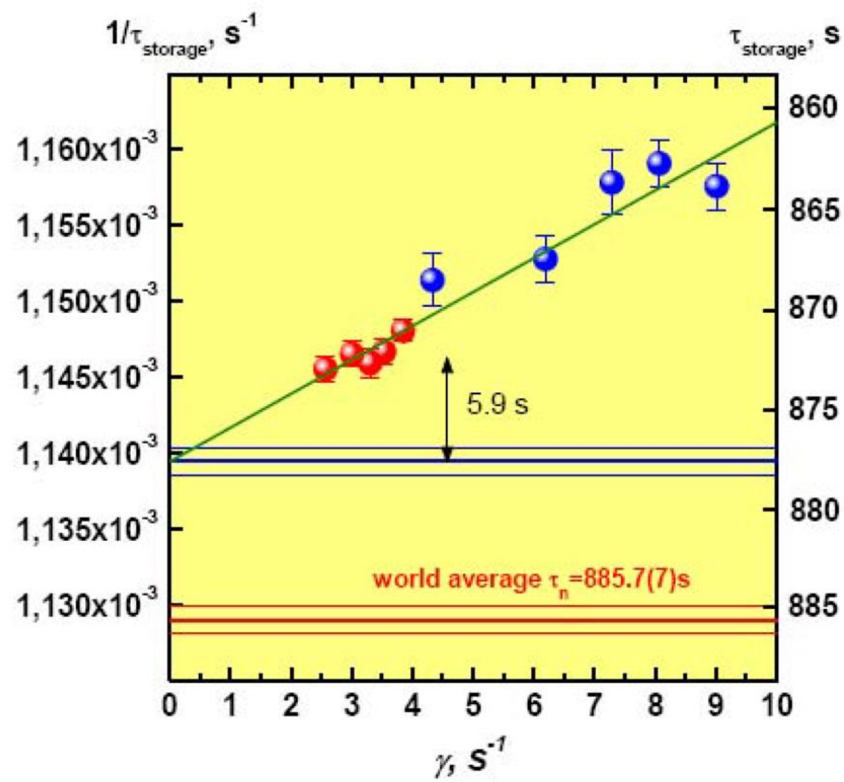
S. Dewey

Result: 878.5(7)$_{stat}$(3)$_{sys}$

Measurement cycle measures
UCN spectral dependence



Small final extrapolation

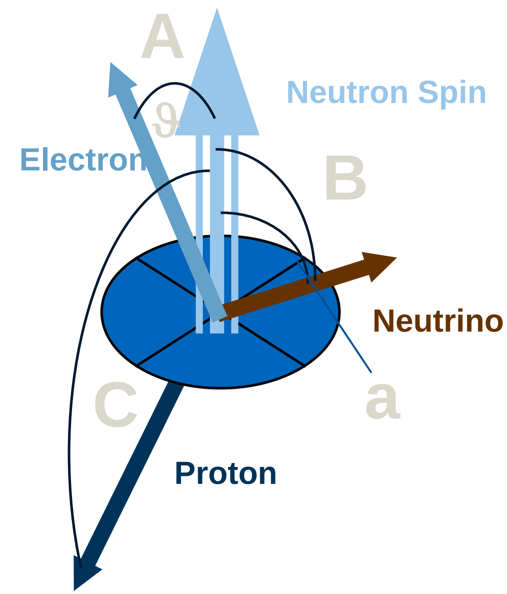


Observables and Statistics

Focus on *non-coincident* measurements due to high count rates:

Polarised neutrons

- β-asymmetry ***A*** — ***ΔA ~ 5 · 10⁻⁴***
- Proton asymmetry ***C*** — ***ΔC ~ 3 · 10⁻⁴***
  Neutrino asymmetry ***B*** — ***ΔB ~ 1 · 10⁻³***
- Weak magnetism f_{WM} — ***> 3 σ***
  from β-asymmetry or polarised spectra



Unpolarised neutrons

Correlation ***a*** — ***Δa ~ 5 · 10⁻³***
from proton spectrum
Fierz coefficient ***b*** — ***Δb ~ 1 · 10⁻³***
from electron spectrum or β-asymmetry
Electron helicity ***h***

Time for 10^9 events

- 5 hours (unpolarised)
- 1 day polarised 98%
- 2 days polarised 99.7%
- ×25 for pulsed mode

Fierz Interference Term *b*

Sensitive to scalar and tensor couplings

$$b = 2\frac{S - 3\lambda^2 T}{1 + 3\lambda^2}, \quad S = \frac{g_S}{g_V}, \quad T = \frac{g_T}{g_A}$$

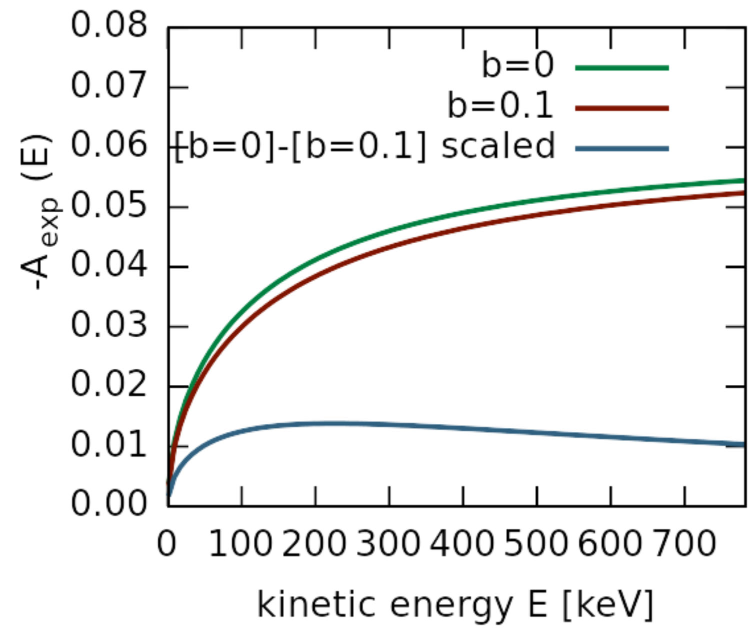
within SM: *b = 0*

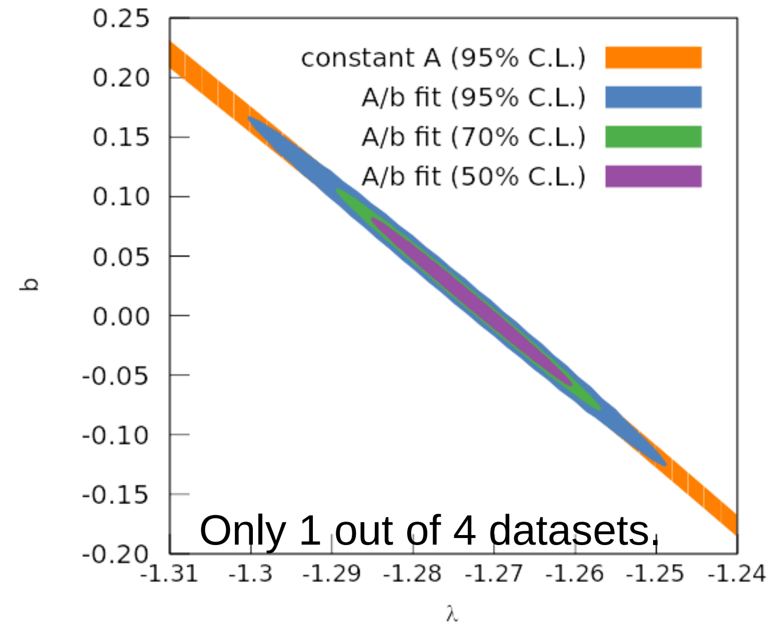
Enters decay rate / spectra and asymmetries:

$$d\Gamma \propto \left(1 + b\frac{m_e}{E_e}\right) \qquad A_{exp}(E) \to \frac{A_{exp}(E)}{1 + b\frac{m_e}{E}}$$

Requirement:
Calibration etc. independent of neutron data

Reach of existing PERKEO III data
$\Delta b \approx 3 \times 10^{-2}$ from asymmetry.
Pending approval by the collaboration.





Extra