Neutron Beta Decay with PERKEO and PERC Status and Perspectives

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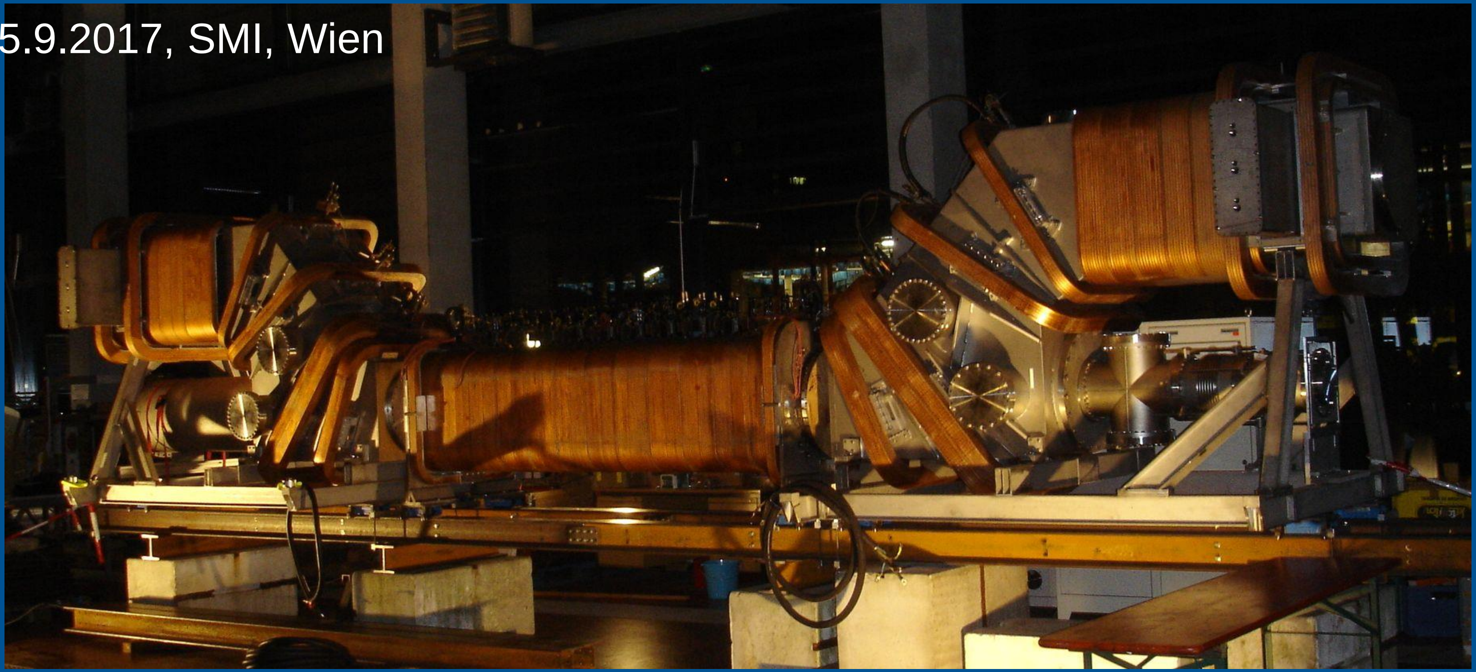


Spectrometer originally built by Heidelberg University,
Now run by TUM, TU Wien, Heidelberg, ILL

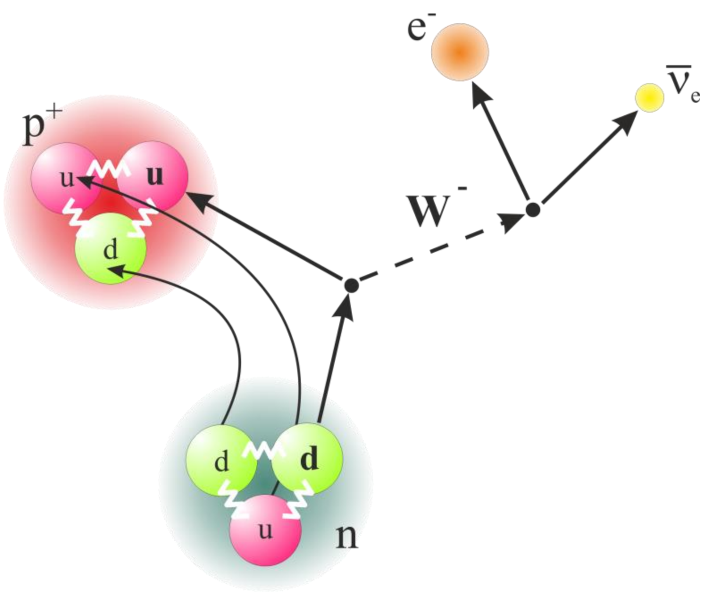
Outline

Motivation — Searches for new physics in neutron decay:
Precise data and precise predictions

PERKEO Measurements
- Beta Asymmetry A (axial vector coupling constant)
- Fierz Interference b (scalar / tensor interactions)
- Proton Asymmetry C (right handed currents)

Next generation instrument: PERC

Neutron Beta-Decay



Low energy

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

Long lifetime

τ = 880.3(1.1) s

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

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

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

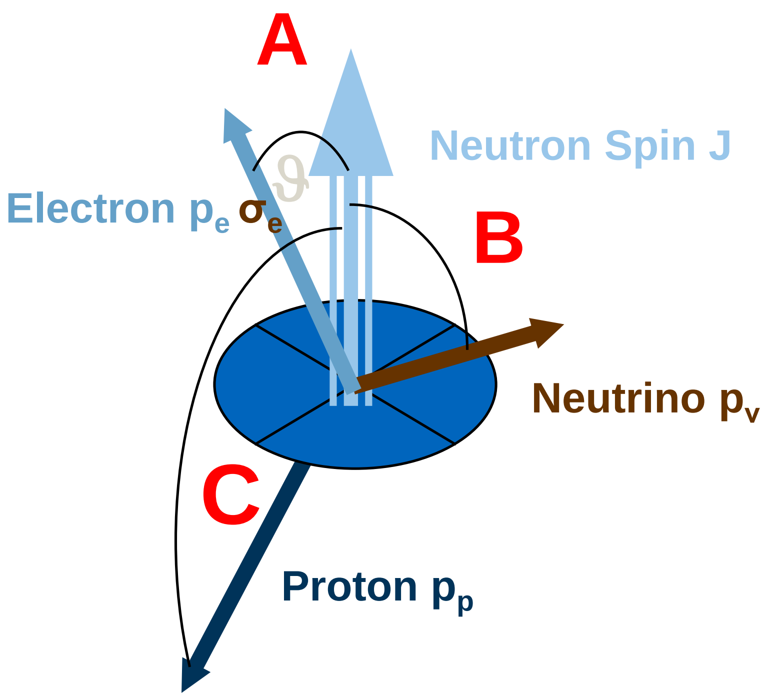
Quark mixing

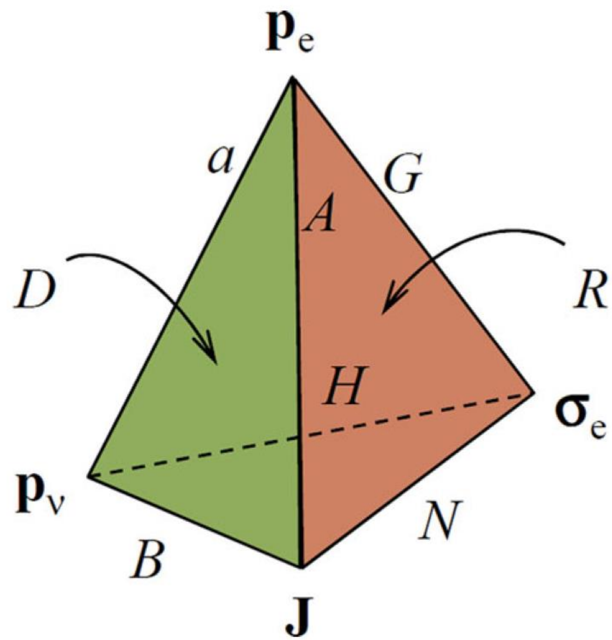
Cabibbo-Kobayashi-Maskawa matrix element

$$V_{ud}$$

Correlations in Neutron Decay

Two free parameters in Standard Model – many observables:
correlations, energy spectra and lifetime
Search for traces of New Physics in deviations from Standard Model prediction.





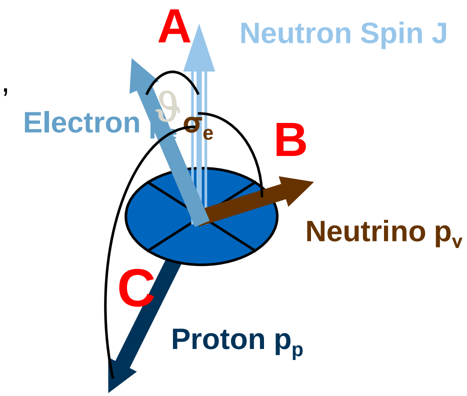
Naviliat-Cuncic and Gonzalez-Alonso, Ann. Phys. 525, 8–9, 600–619 (2013)
Dubbers and Schmidt, Rev. Mod. Phys (2012)

Correlation Coefficients

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

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

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



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

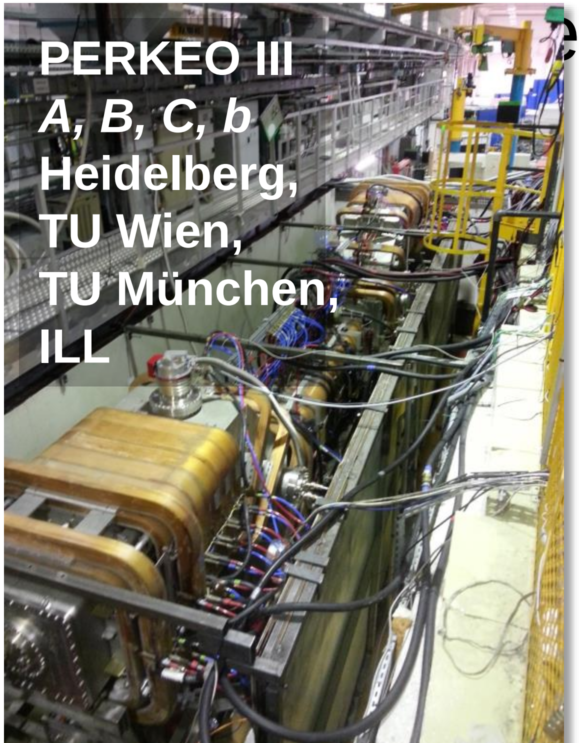
Goal of next generation PERC: $O(10^{-3} - 10^{-4})$ for some observables

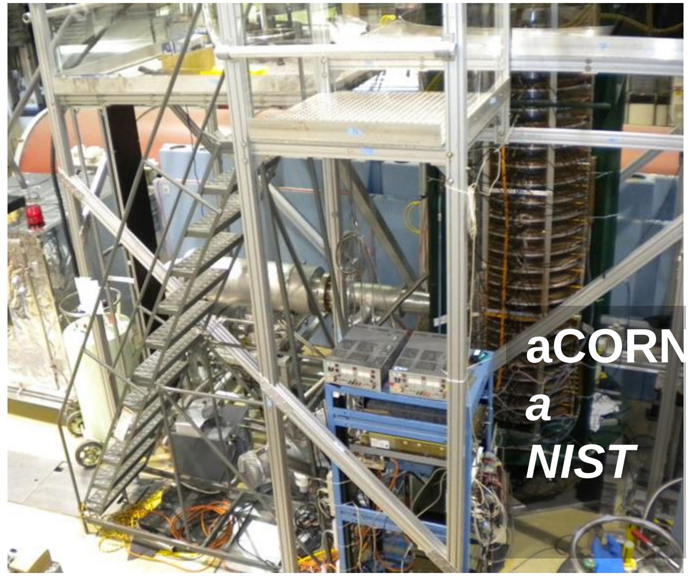
PERKEO III

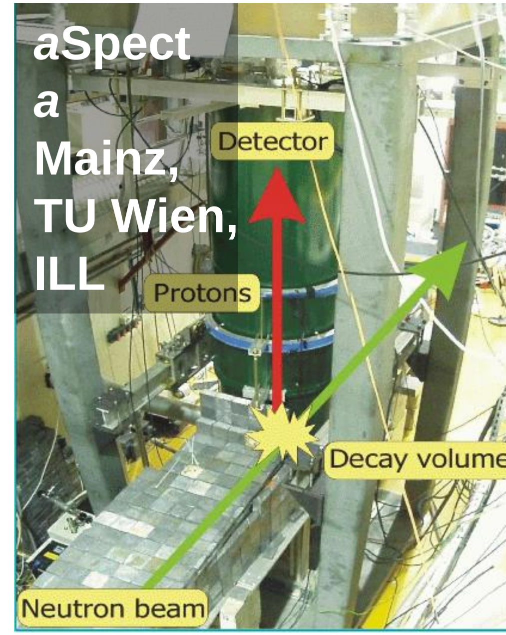
Parameter		λ-dependence	Violates	Value	Rel. Prec.
A	Beta Asymmetry	$-2\cdot\frac{\lvert\lambda\rvert^2+\mathrm{Re}(\lambda)}{1+3\lvert\lambda\rvert^2}$	P	-0.1184(10)	$8\cdot10^{-3}$
B	Neutrino Asymmetry	$2\cdot\frac{\lvert\lambda\rvert^2-\mathrm{Re}(\lambda)}{1+3\lvert\lambda\rvert^2}$	P	0.9807(30)	$3\cdot10^{-3}$
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*	

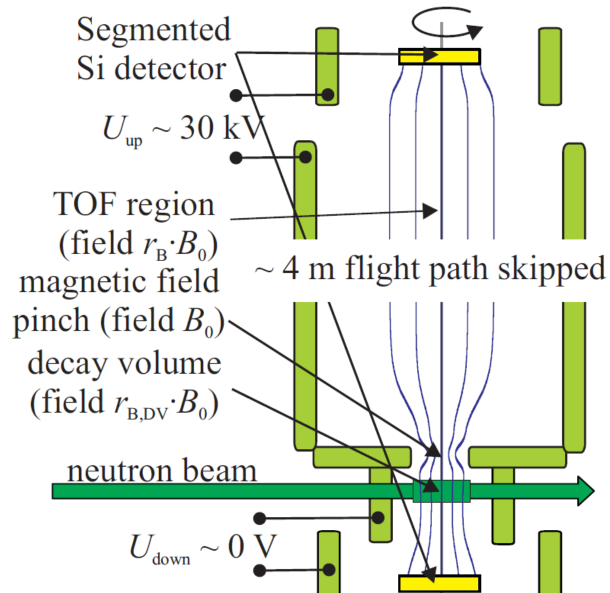
[PDG2014]

ent Neutron Decay Experiments





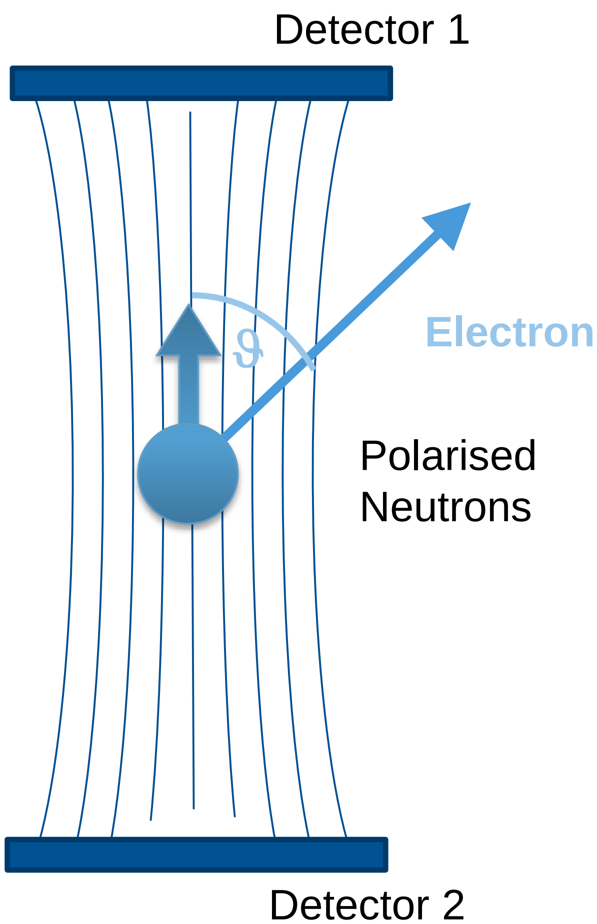




Nab
a, b
SNS

… 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

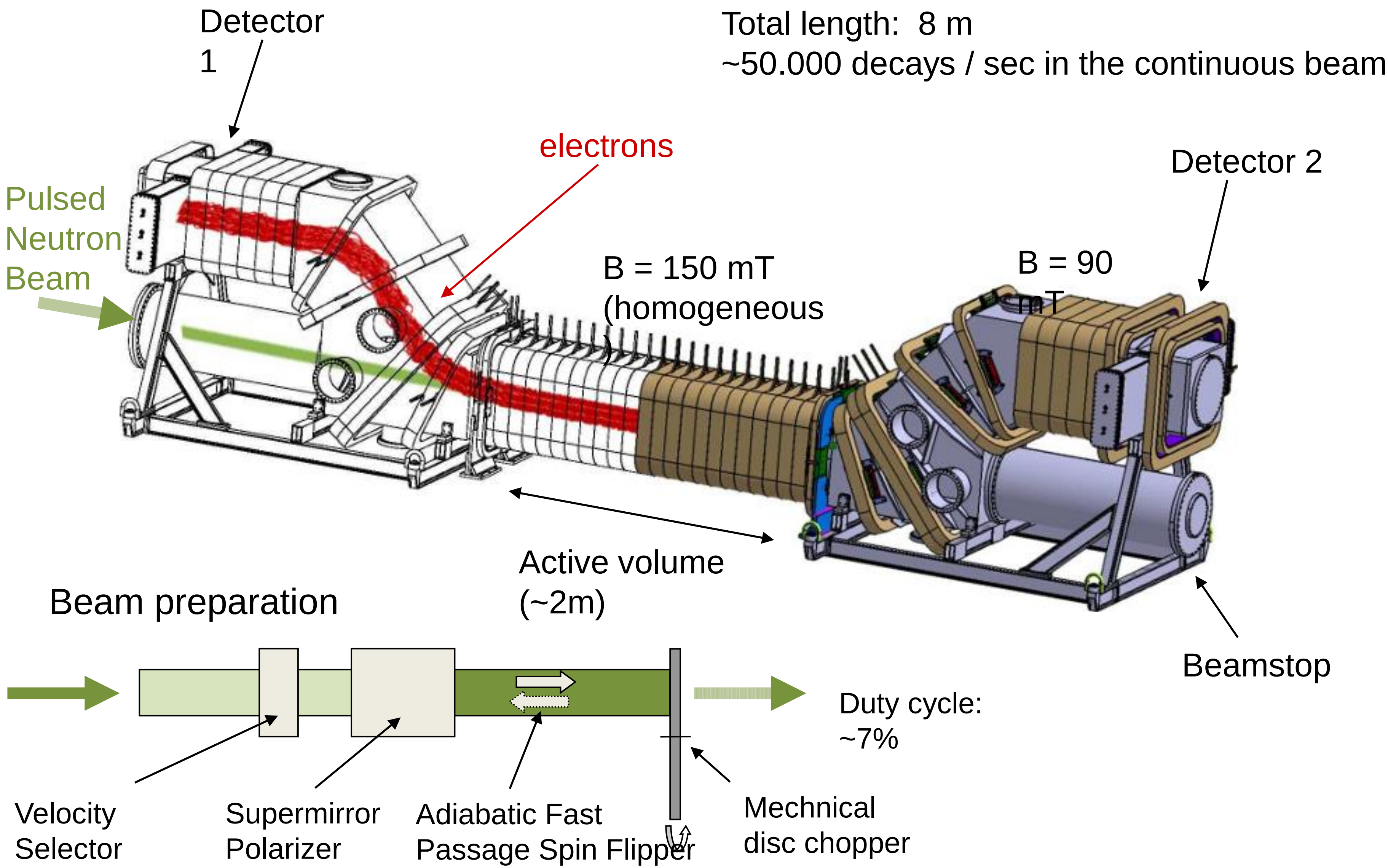
Integration over hemispheres: $\cos\vartheta \rightarrow 1/2$

2 × 2π detection

Experimental asymmetry, polarisation *P*

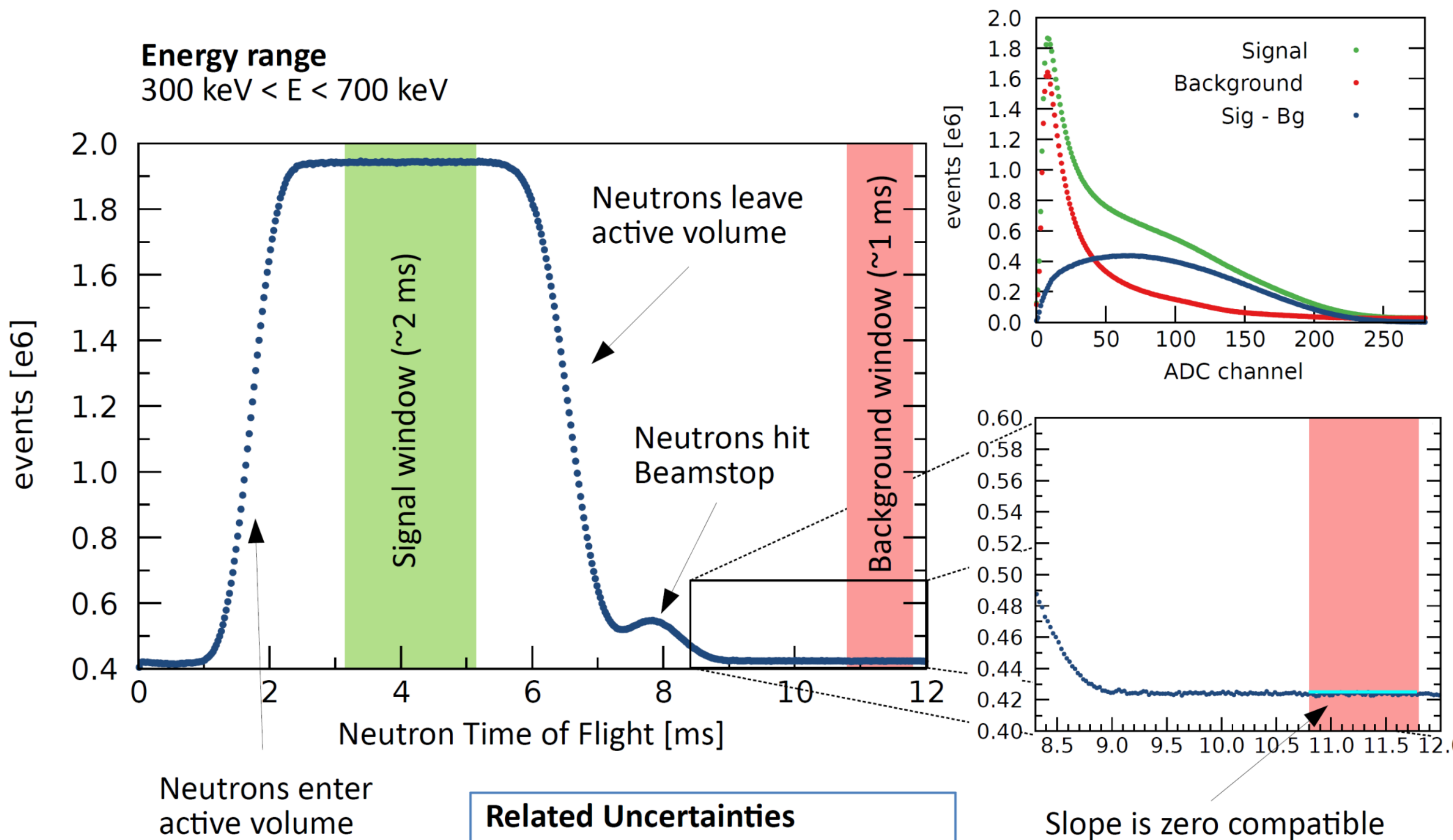
$$A_{exp} = \frac{N^{\Uparrow} - N^{\Downarrow}}{N^{\Uparrow} + N^{\Downarrow}} = \tfrac{1}{2}\tfrac{v}{c} P A$$

Spectrometer PERKEO III



PERKEO III: Pulsed Neutron Beam

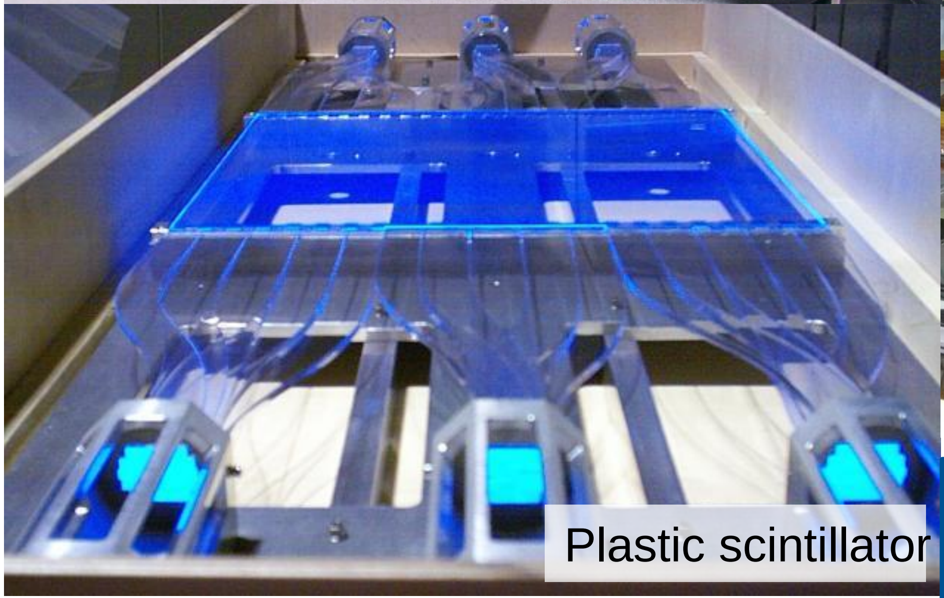
Sacrifise ~2 orders of magnitude in statistics to address important systematic: background; continuous beam 50.000 s^{-1} ; pulsed 250 s^{-1}



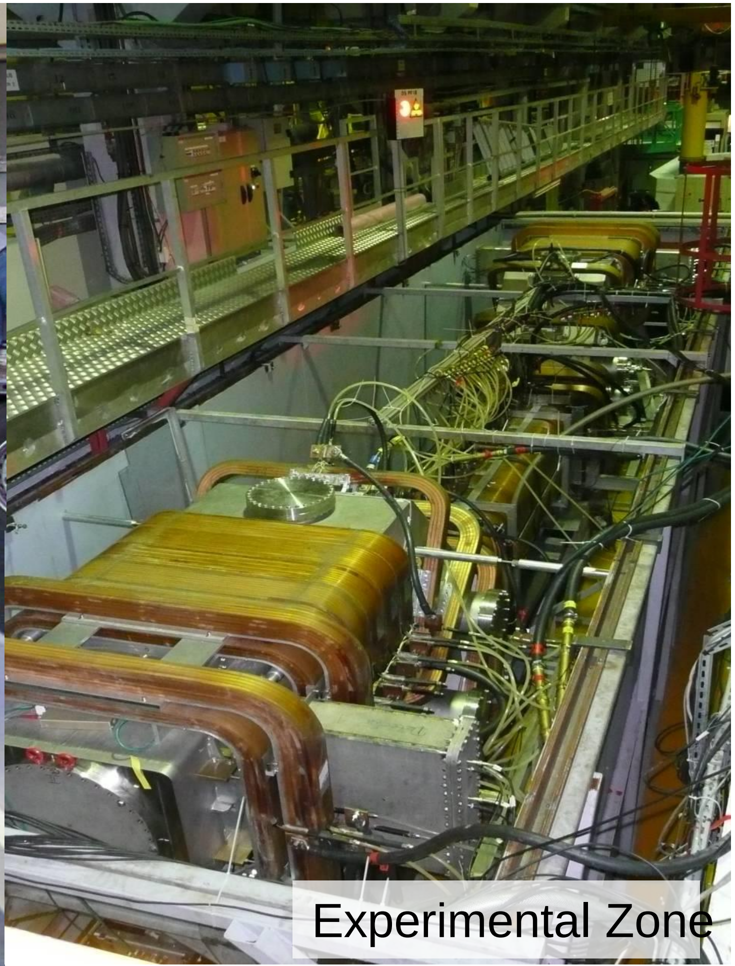
Related Uncertainties
Time Dependence: $\Delta A/A=1*10^{-4}$
Undetected: $\Delta A/A=1*10^{-4}$

Installation at PF1B, ILL

One of two trucks



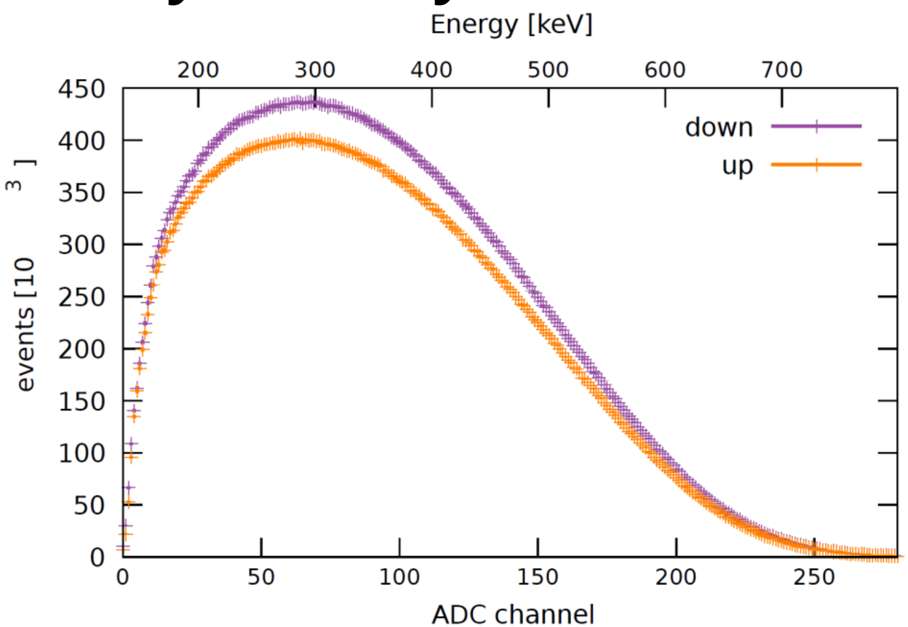
Plastic scintillator

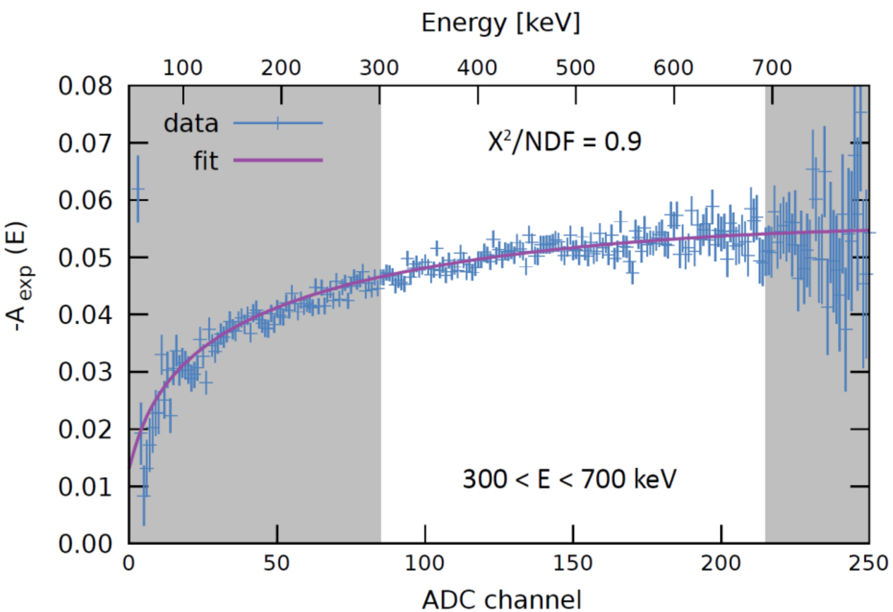


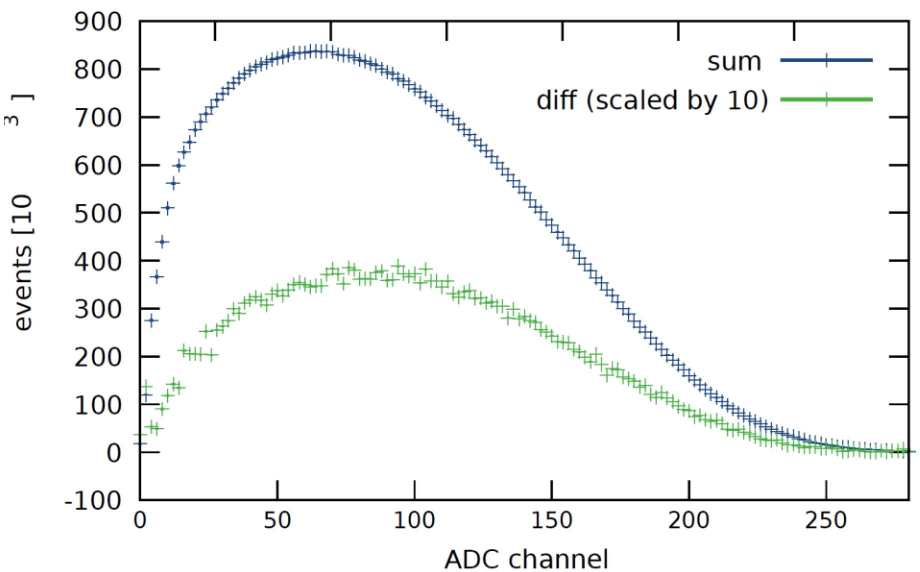
Experimental Zone

140 days (55 set-up / 25 pol. / 60 decay)
96% of data acquired in analysis
$6 \cdot 10^8$ neutron decay events

Asymmetry Extraction







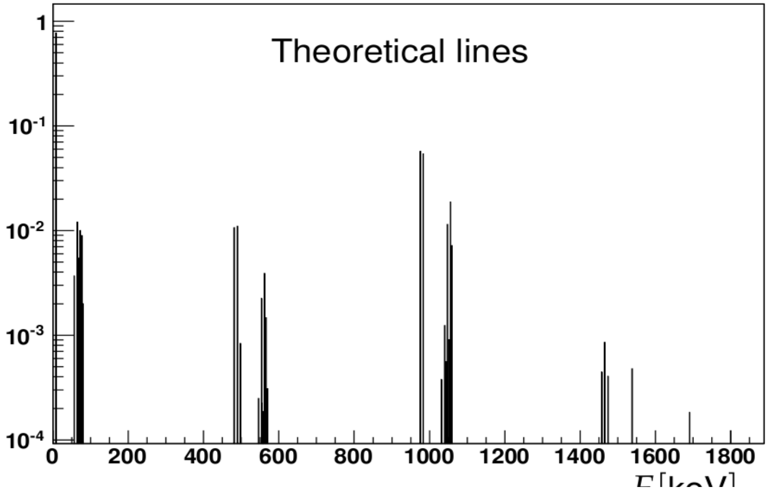
$$A_{exp}\left(E_e\right) = \frac{N^{\uparrow}\left(E_e\right) - N^{\downarrow}\left(E_e\right)}{N^{\uparrow}\left(E_e\right) + N^{\downarrow}\left(E_e\right)} = \frac{1}{2} P_n \frac{v}{c} A$$

1 of 4 datasets shown

$6 \cdot 10^8$ events in analysis

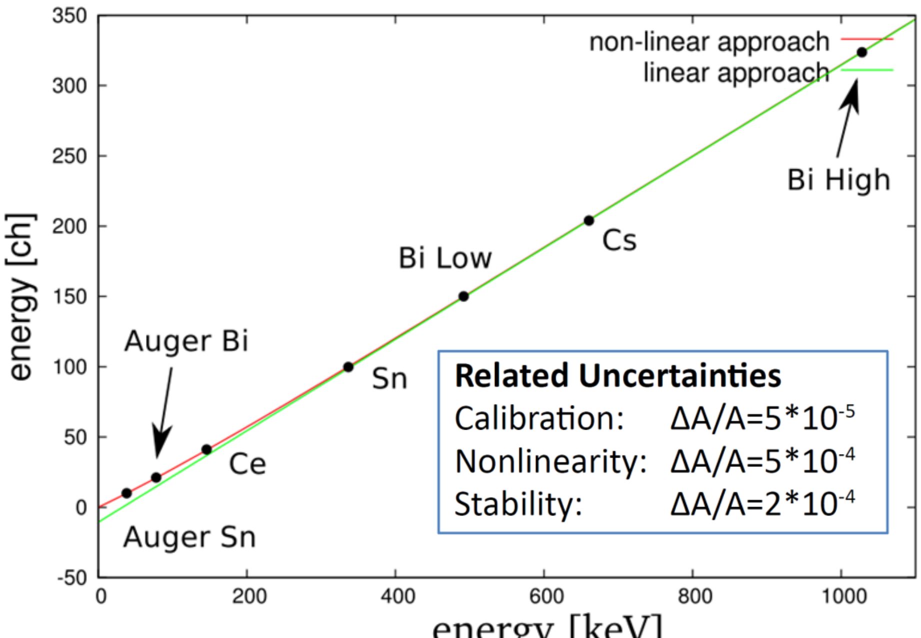
Statistical Uncertainty
$\Delta A/A = 14 * 10^{-4}$

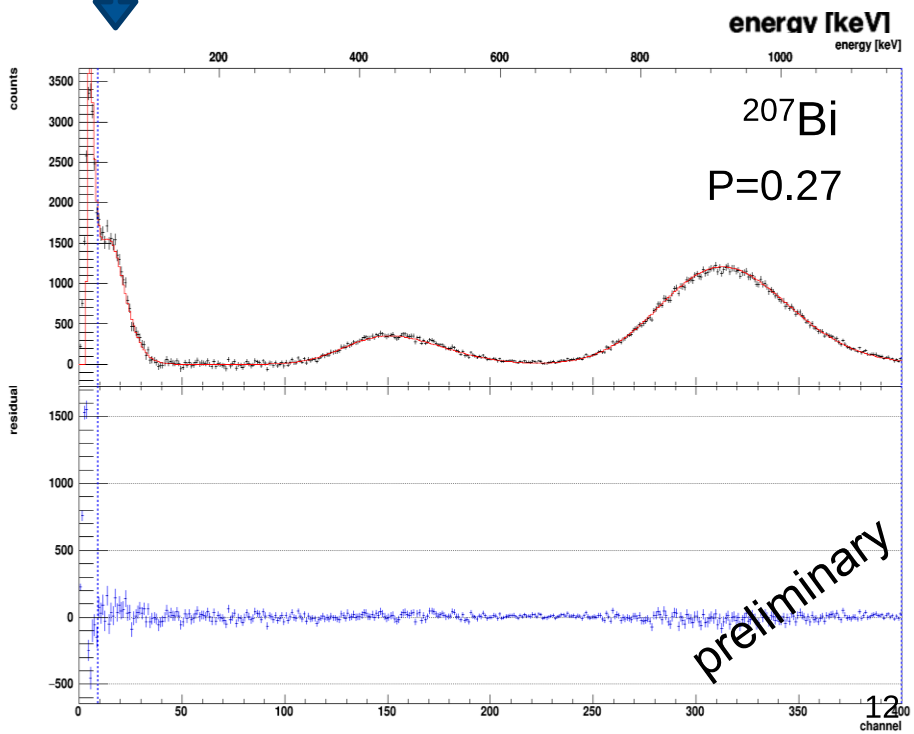
Detector Response



theoretical spectrum (~200 lines)
+ source properties

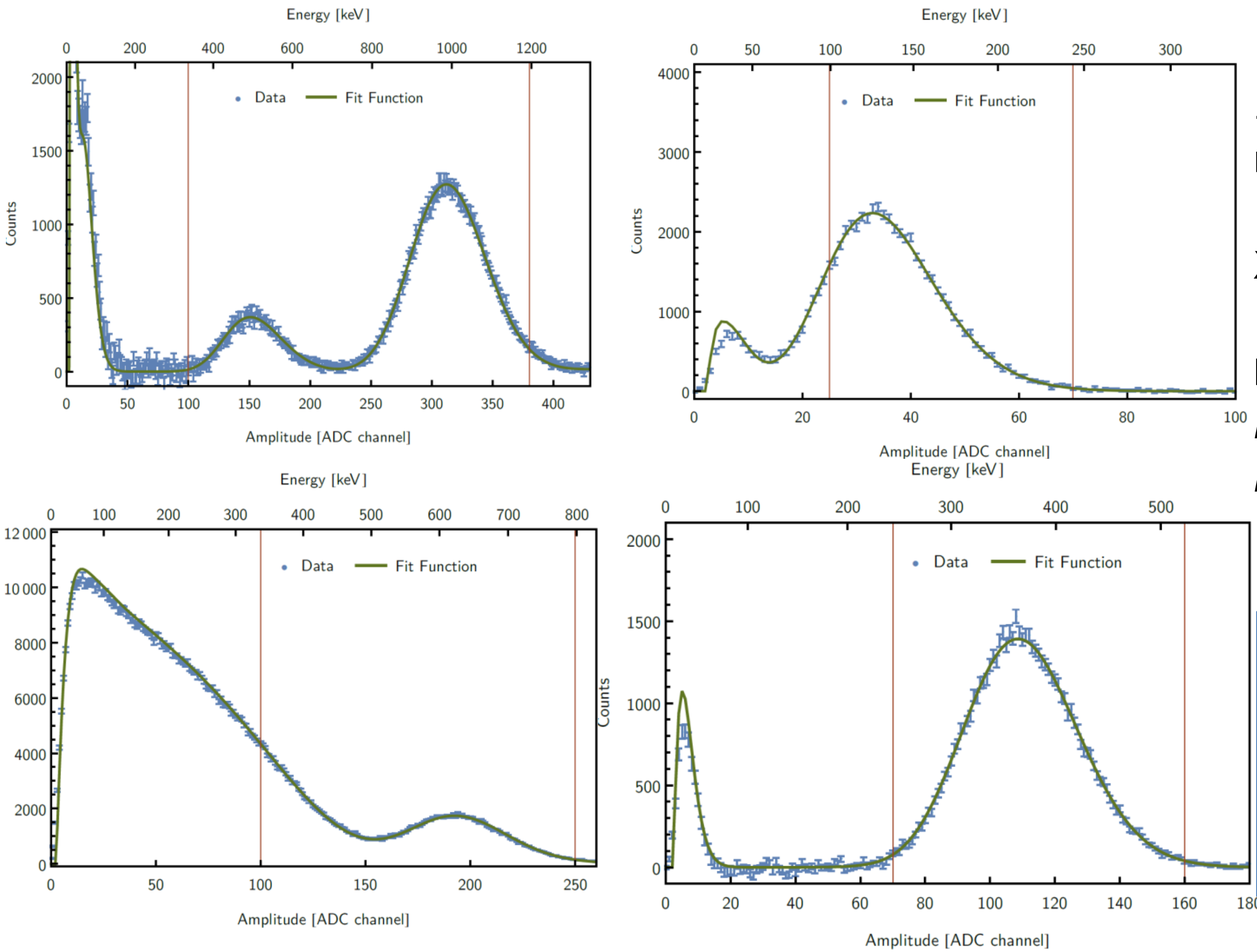
model of detector properties
(non-linearity of photon production,
PMT statistics (incl. higher moments),
Noise)





PERKEO III Detector Calibration Fit

Calibratoin: drift control: hourly; full set: twice daily; 2D response: weekly



114 Full Calibration sets measured (4 sources)

$X^2/NDF = 1.0 – 1.2$

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

Related Uncertainties
Sources: $\Delta A/A=1.5*10^{-4}$
Statistics: $\Delta A/A=0.1*10^{-4}$
Non-linearity:
$\Delta A/A=5.0*10^{-4}$

Error Budget

Effect on Asymmetry A	Relative Correction (10^{-4})	Relative Uncertainty (10^{-4})
Neutron beam		
Polarization	blinded)	10
Spinflip efficiency		
Background		
Time variation	-0.4	0.4
Undetected		1
Electrons		
Magn. mirror effect	(blinded)	4
Undetected backscattering	5	2
Lost backscatter energy		1.4
Electron detector		
Deadtime	$(5)^*$	0.3
Stability		4.2
Non-uniformity	3.1	1.5
Non-linearity	*	5
Rate-dependence		3
Calibration		1.5
Theory		
Ext. radiative corr.	$(-10)^*$	1
Total systematics		12.2
Statistics		14.0
Total		**19**

Blinding by separate analysis

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

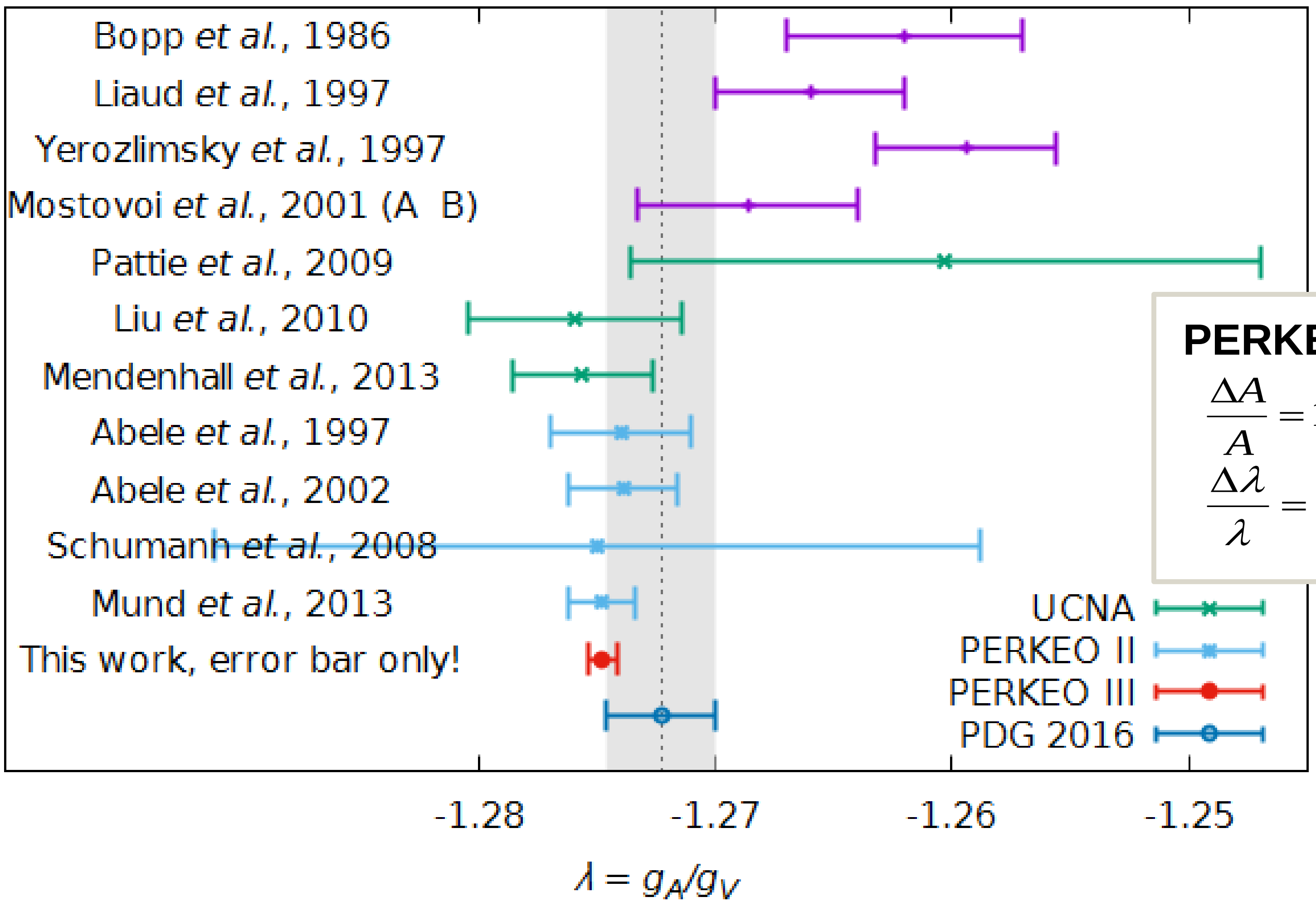
Result (still blinded):

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

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

Finalising blinded values

AXIAL VECTOR- TO VECTOR COUPLING CONSTANT



PERKEO III:

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

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

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:

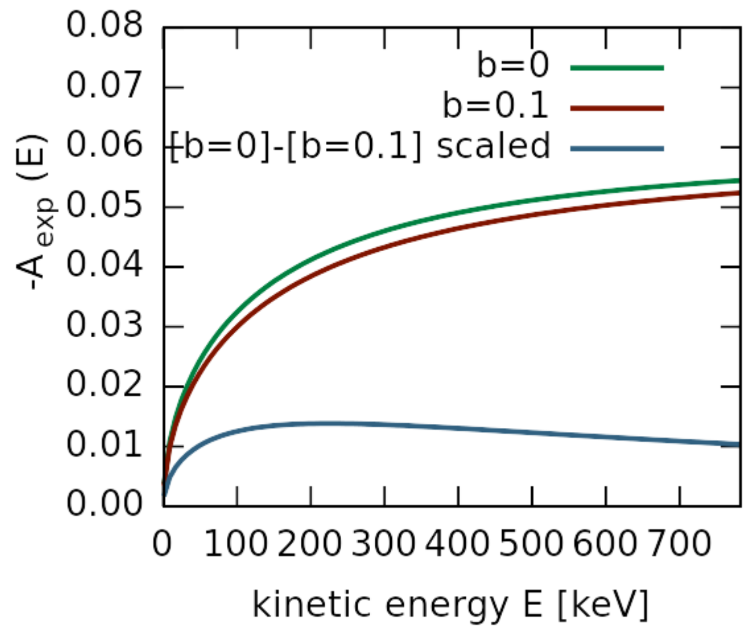
$$d\Gamma \propto \left(1 + b\frac{m_e}{E_e}\right) \qquad A_{exp}(E) \rightarrow \frac{A_{exp}(E)}{1 + b\frac{m_e}{E}}$$

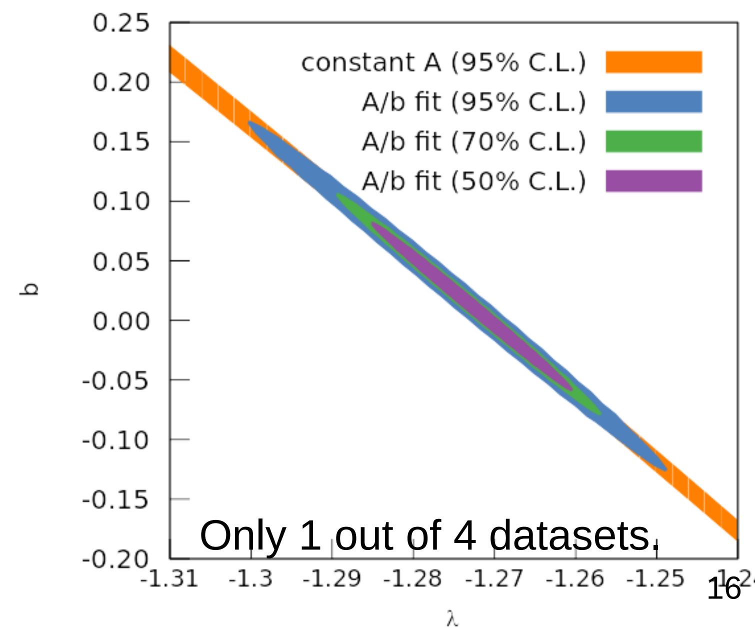
Requirement:
Calibration etc. independent of neutron data

Reach of existing PERKEO III data

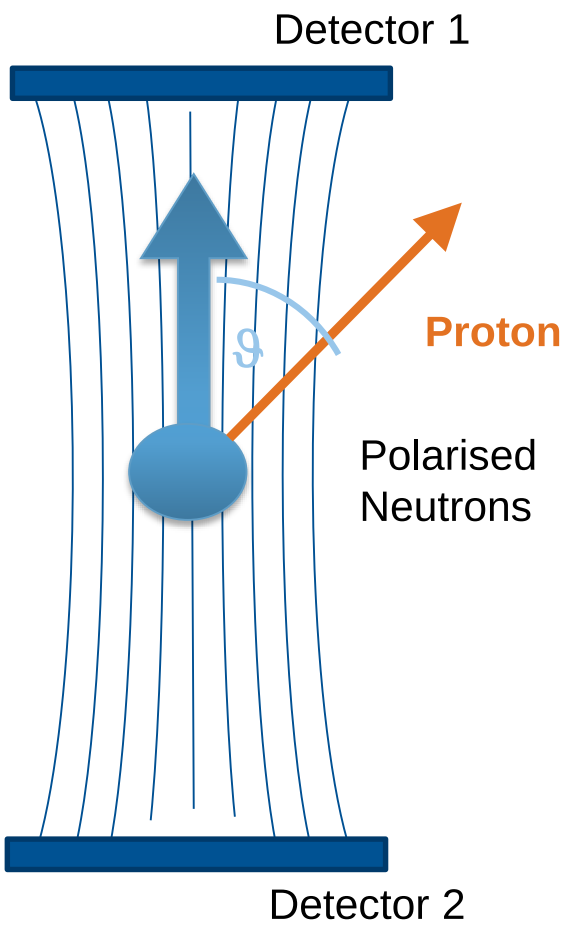
$\Delta b \approx 3\times10^{-2}$ from asymmetry.

Pending approval by the collaboration.





Proton Asymmetry *C*



Proton Asymmetry

$$C = x_C \cdot \frac{4\mathrm{Re}\left(\lambda\right)}{1 + 3\left|\lambda\right|^2}$$

Experimental Asymmetry

$$C_{exp} = \frac{N^{\downarrow} - N^{\uparrow}}{N^{\downarrow} + N^{\uparrow}}$$

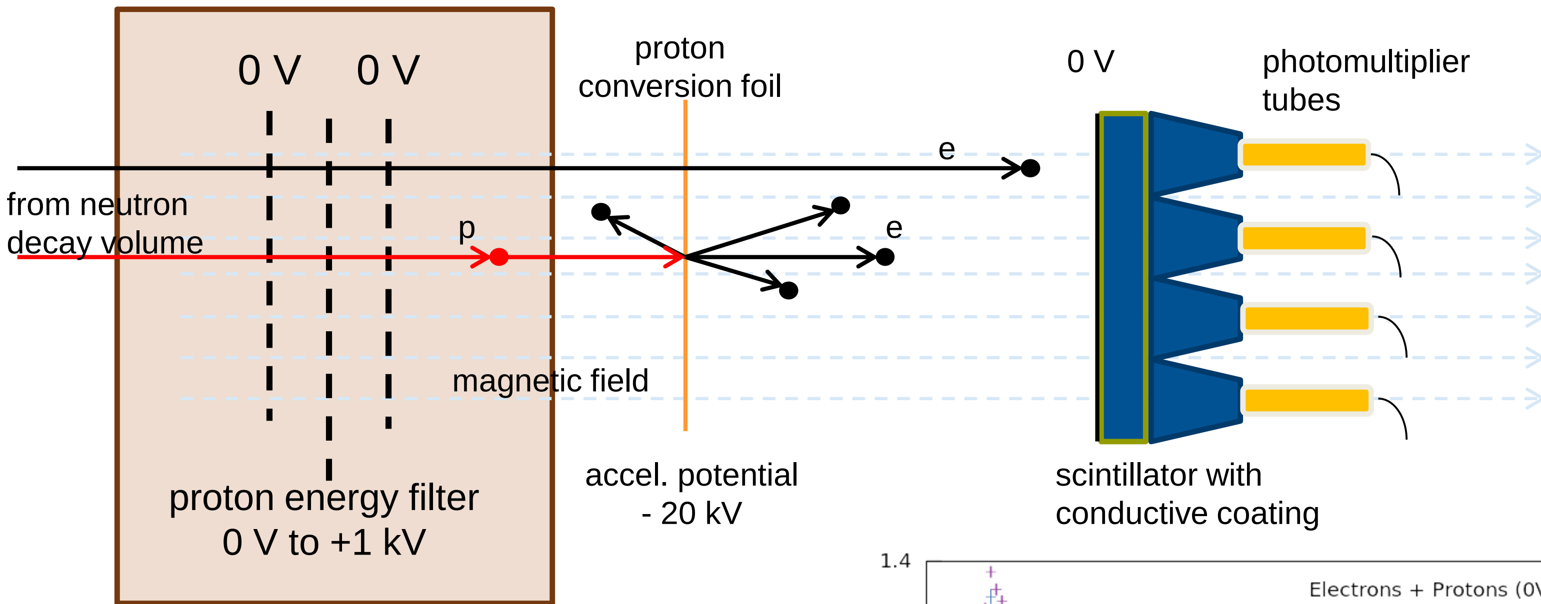
Present value

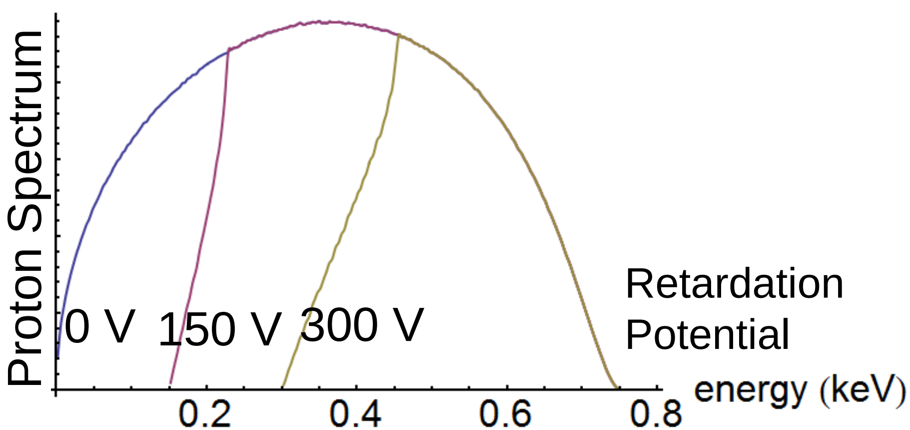
C = -0.2377(26)
[Schumann et. Al, 2008 / PERKEO II]

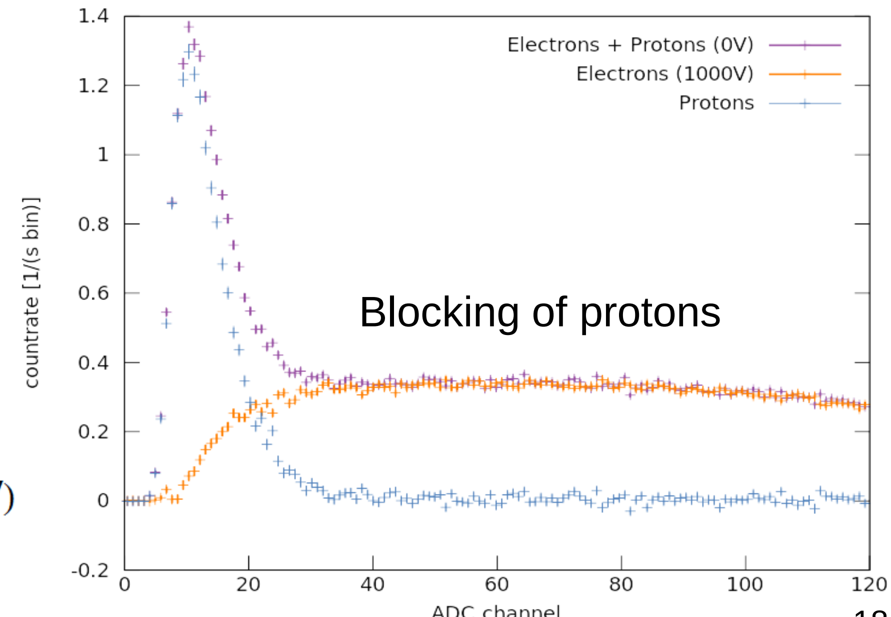
Kinetic energies

Electrons: E_e < 782 keV
Protons: E_p < 0.75 keV

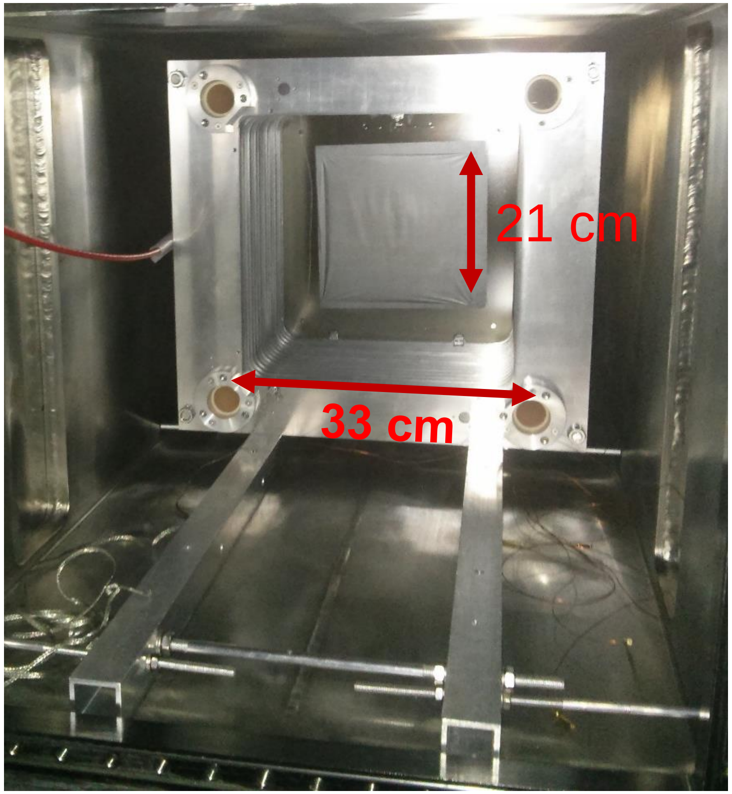
Proton (and Electron) Detection







Electron / Proton Detector: HV and Conversion Foil



Field gradient: 1 kV/cm
Max. field: -32 kV
30 coated and polished electrodes
Voltage divider inside vacuum
Ultra thin carbon foil
(~30 µg/cm²), D. Seiler (TUM)

- 2 detectors with each 8 lightguides each
- manufactured at UHD for PERKEO III
- Transparent conductive coating
- water-cooled, bakeable (120°C)

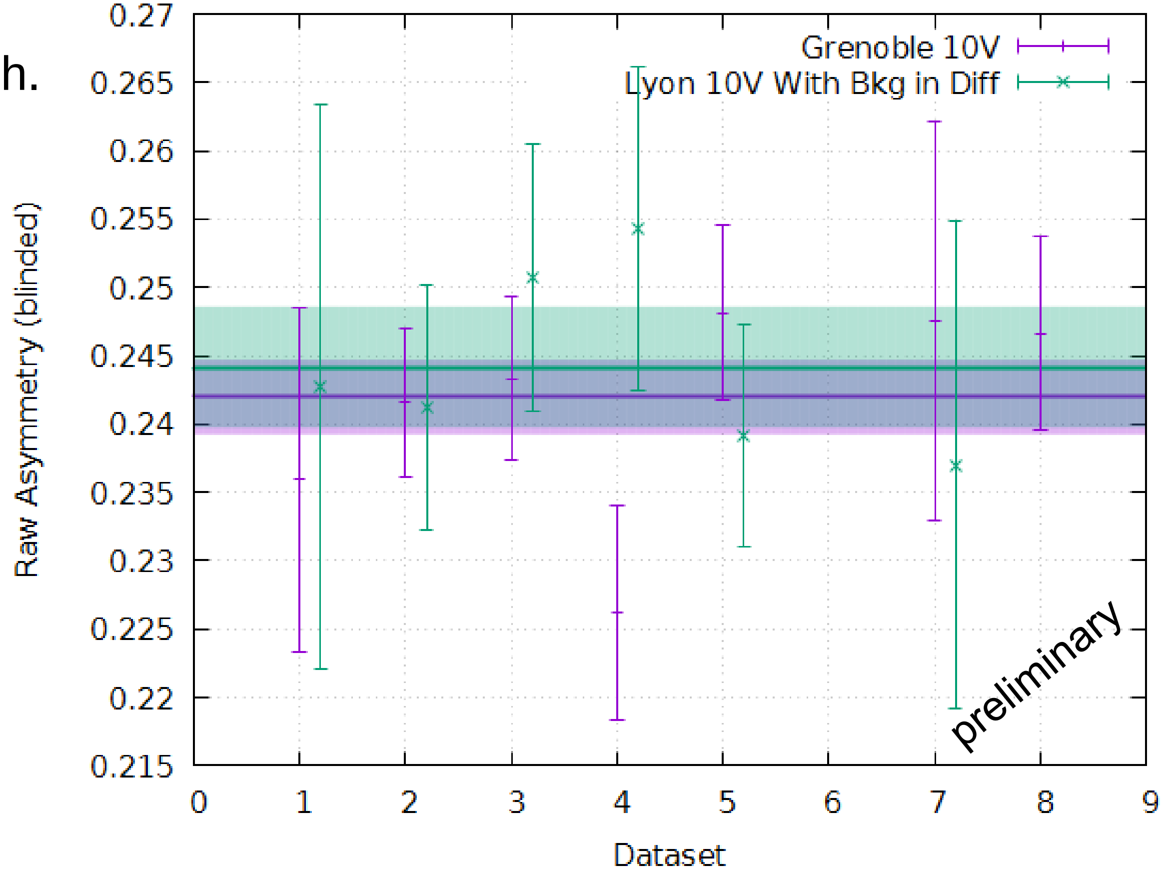
Proton Asymmetries – Uncorrected Data (Blinded)

Status: systematics mostly addressed (TUW / TUM / Heidelberg)
Data consistent.

Systematically new approach.
Proton energy depencence.
Prototype for PERC.

Likely minor improvement over PERKEO II.

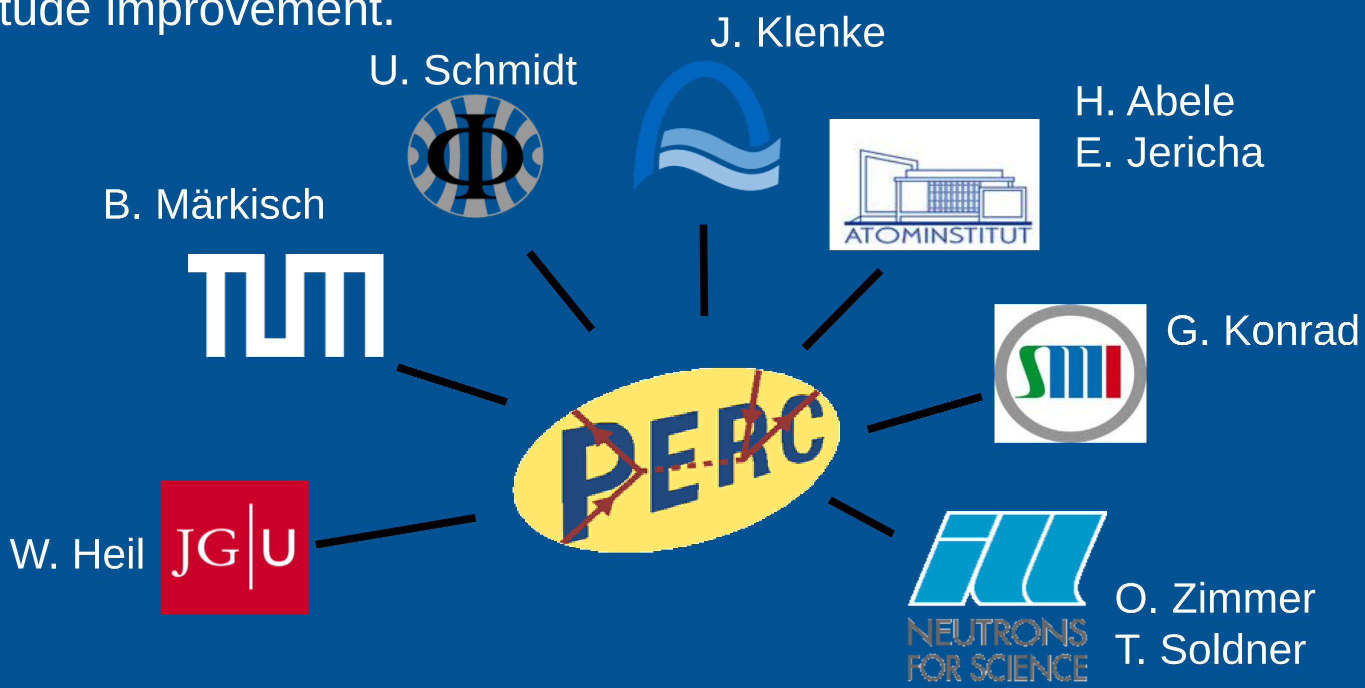
Analysis ongoing.



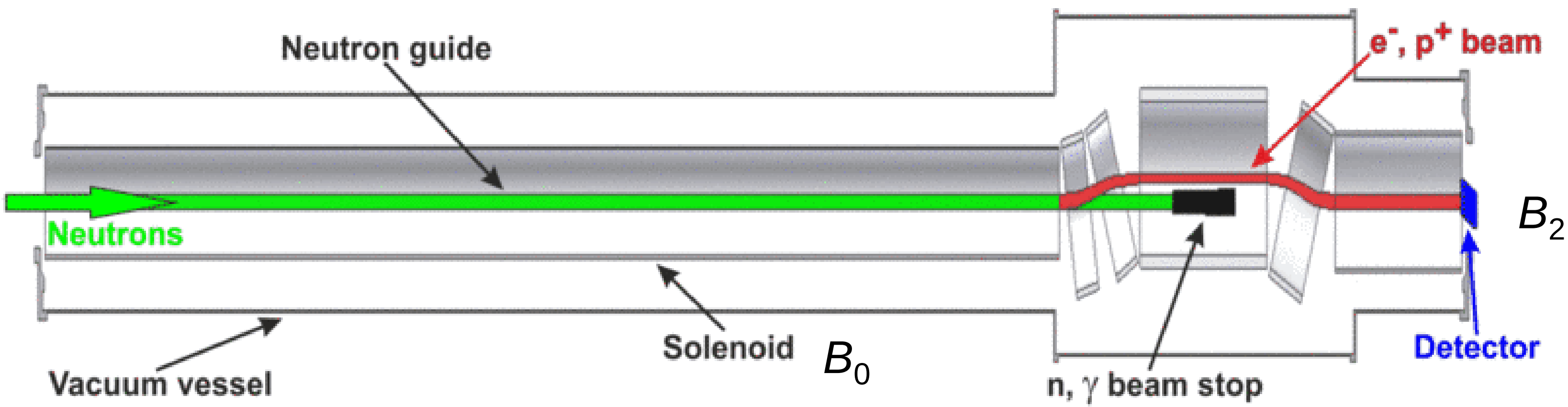
The next generation:

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

Goal: Order of magnitude improvement.



Proton Electron Radiation Channel (PERC)



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

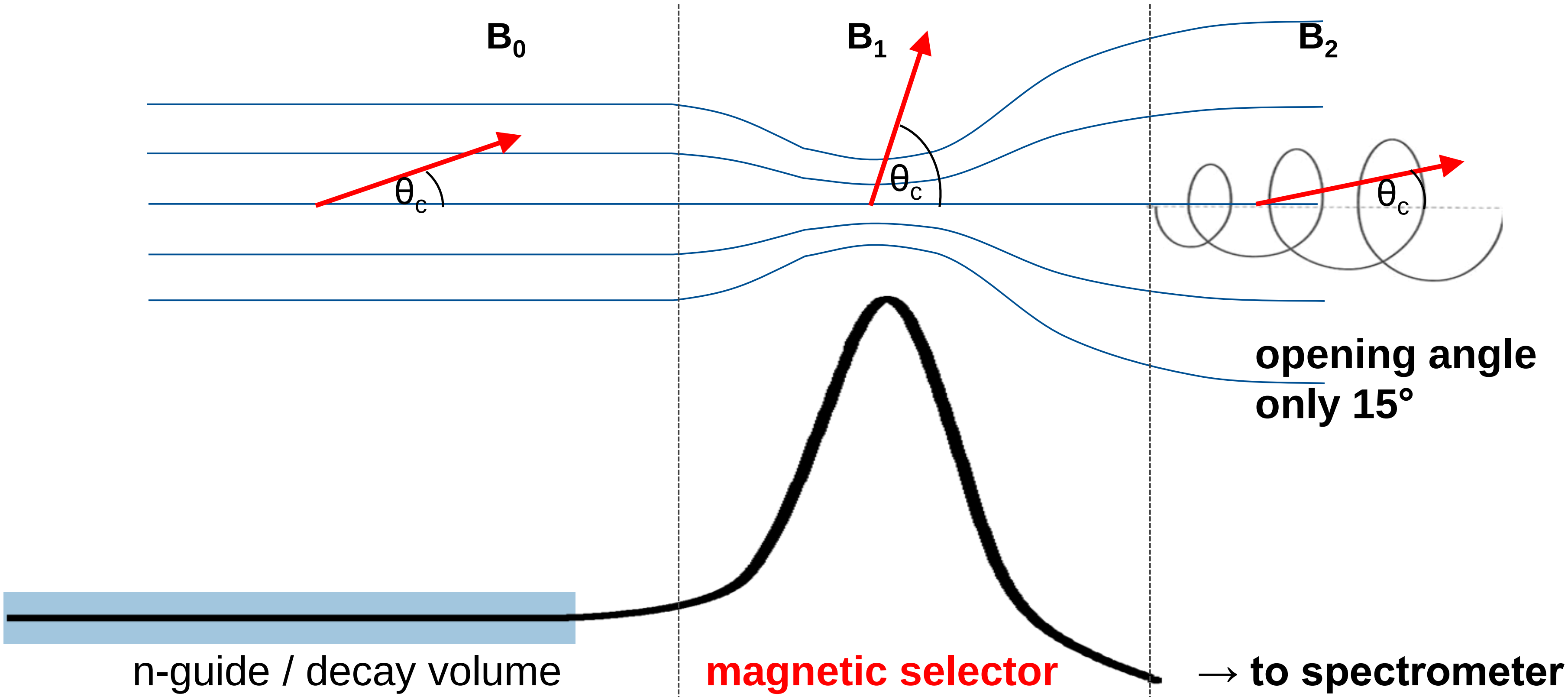
Magnetic Filter, B_1 = 6T: phase space, systematics $B_1/B_0 = 2\ldots12$
(solid angle, backscatter suppression)

Source for specialised spectrometers

Aims to improve results by an **order of magnitude**. New Observables.

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

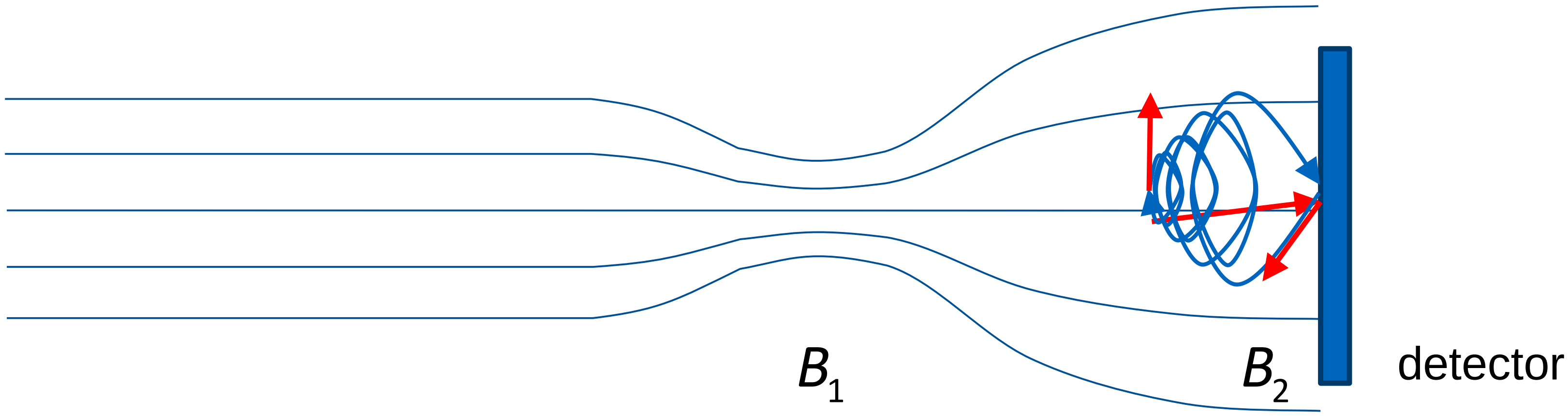
PERC: Magnetic Barrier



Magnetic field	B_0 = 1.5 T	B_1 = 6 T	B_2 = 0.375 T
Radius of gyration	< 1 mm	< .5 mm	< 2 mm
Opening angle θ_c	30°	90°	15°
Beam size	5 cm	2.5 cm	10 cm

Backscatter Suppression in PERC

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



Incident angle on detector $\theta_2 < 15°$ → backscattering **small**

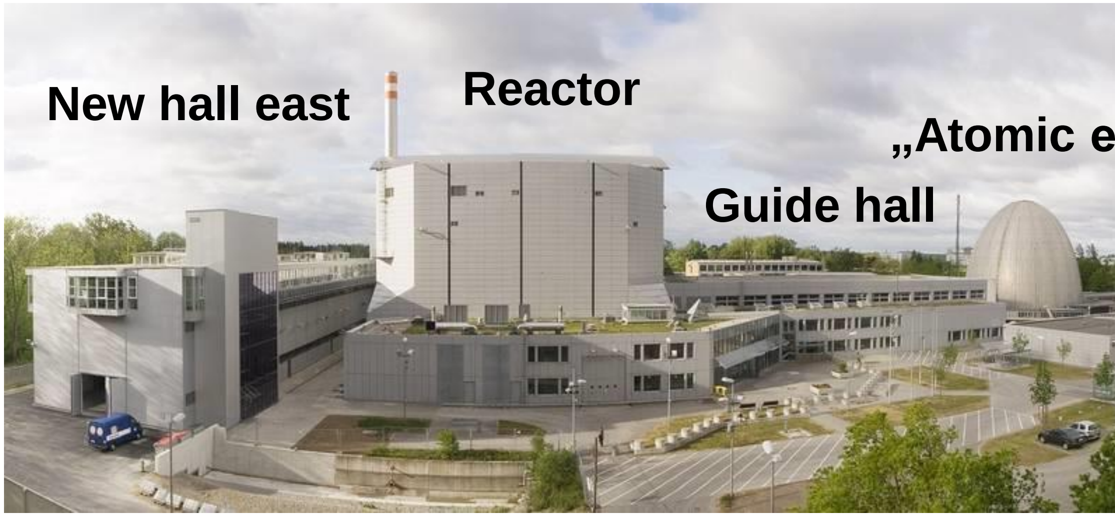
Efficient solid angle **suppression** by magnetic mirror

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

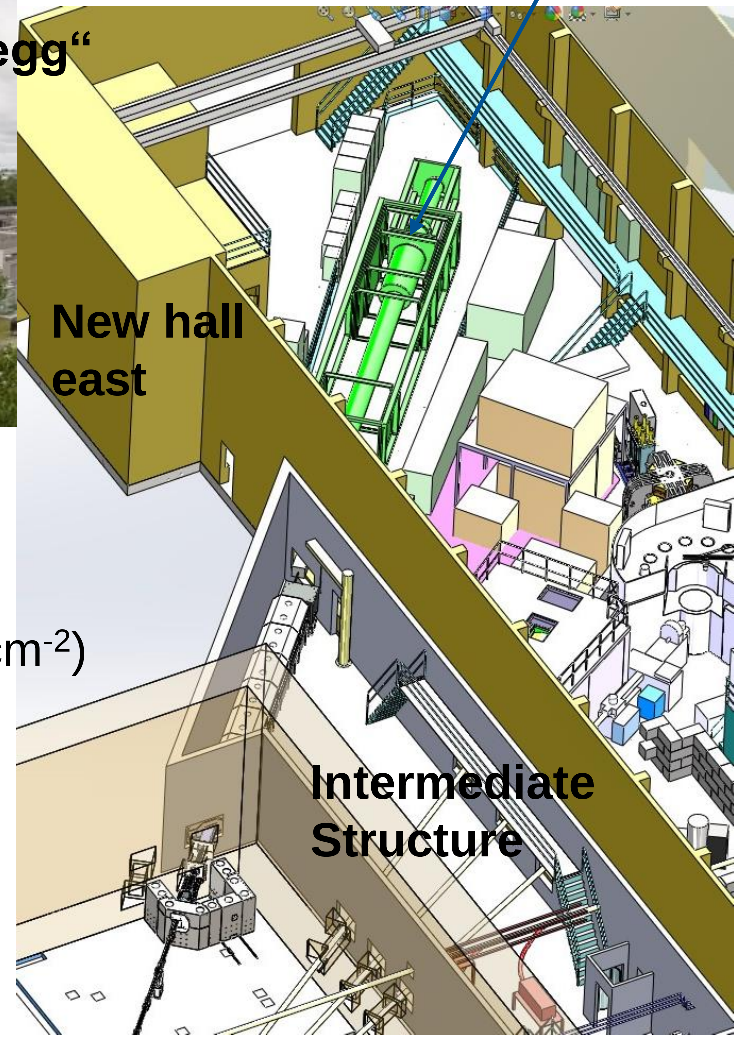
→ One detector only is sufficient!

(But we will still have an upstream detector)

Beam Site Mephisto, FRM II



PERC



Reactor Core

“Empty” new hall

Neutron guide: length 40 m, R = 3000 m, m = 2.5

Expected intensity equal to PF1B at ILL ($2{\times}10^{10}\ s^{-1}cm^{-2}$)

Only very few neighbours: low ambient background

Easy ground level access, Fixed installation

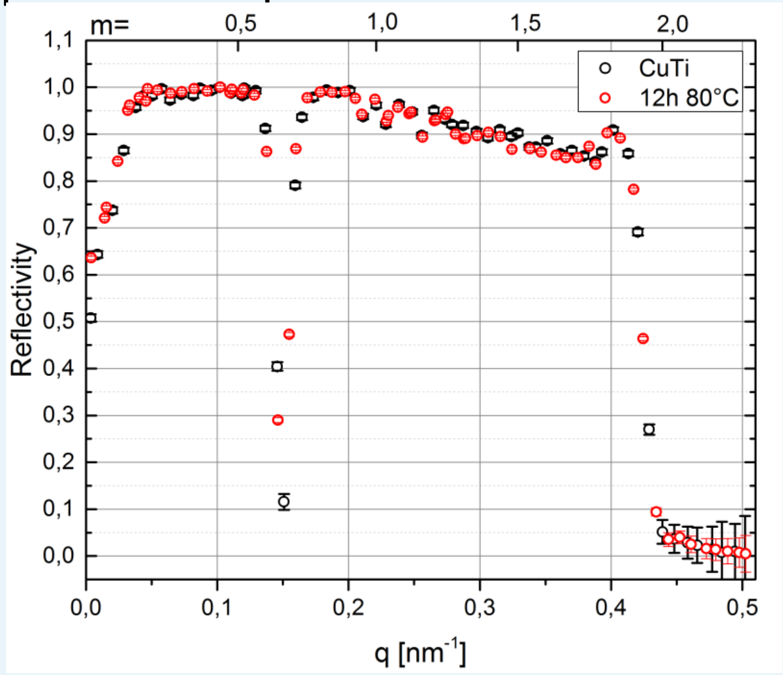
Status: All major components of beam line
ready or in production

Neutron Spin Control

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

- polarisation 99.7%: FeSi polarisers
- spin flipper: AFP 100.00%
- guide in strong magnetic field: only 10^{-4} depolarization per bounce allowed
- measurement with ^{3}He spin filters (T. Soldner, C. Klauser)

Non-magnetic CuTi mirror m=2
preserves spin direction



Production quality
(except for the too thin top layer)

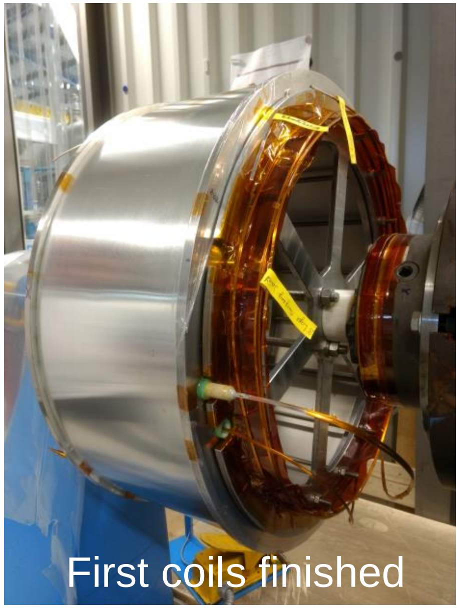
Much increased maximum angle of reflection (m=2)

Much better reflectivity

Reduces neutron losses in PERC by factor > 2; Background!

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

PERC Magnet in Production

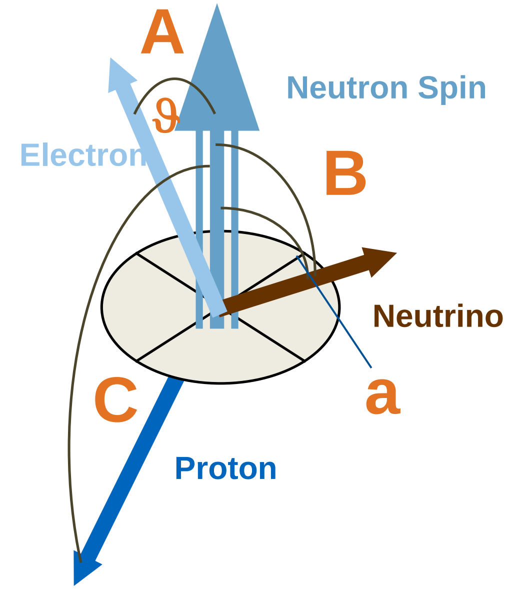


Observables and Statistics

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

Polarised neutrons

- β-asymmetry ***A*** — $\Delta A \sim 5 \cdot 10^{-4}$
- Proton asymmetry ***C*** — $\Delta C \sim 3 \cdot 10^{-4}$
  Neutrino asymmetry ***B*** — $\Delta B \sim 1 \cdot 10^{-3}$
- Weak magnetism f_{WM} — $> 3\ \sigma$
  from β-asymmetry or polarised spectra



Unpolarised neutrons

Correlation ***a*** — $\Delta a \sim 5 \cdot 10^{-3}$
from proton spectrum

Fierz coefficient ***b*** — $\Delta b \sim 1 \cdot 10^{-3}$
from electron spectrum or β-asymmetry

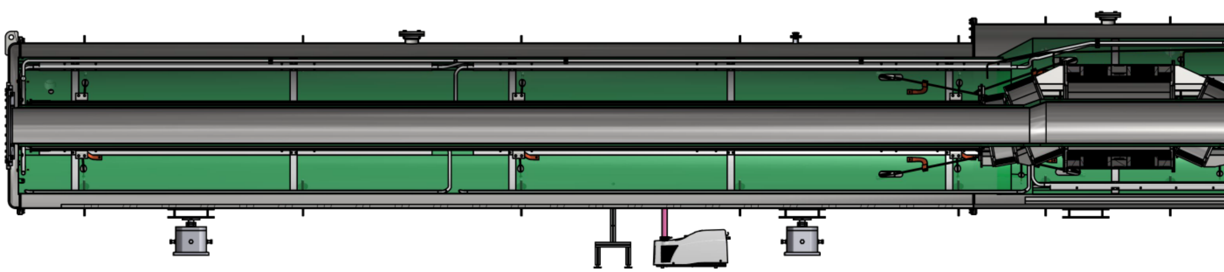
Electron helicity ***h***

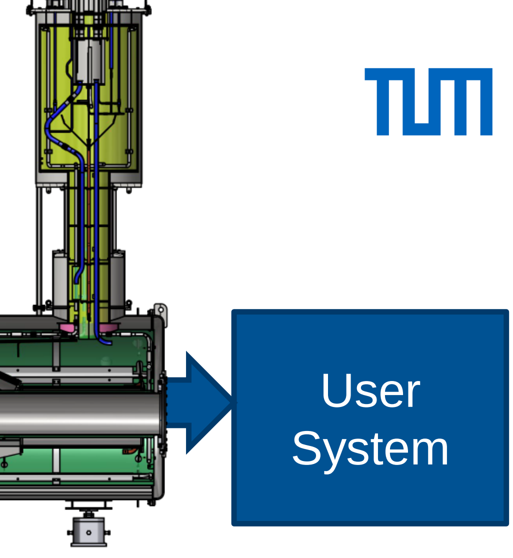
Time for 10^9 events

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

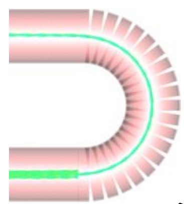
PERC is a Facility

Clean source of electrons and protons from neutron decay



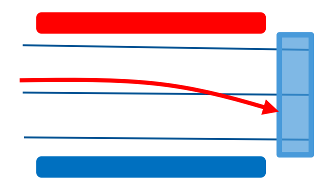


R×B spectrometer

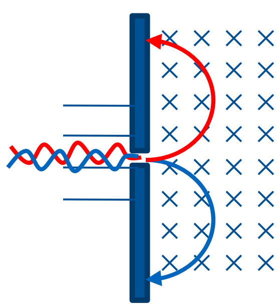


New Frontier
Group: G. Konrad, SMI

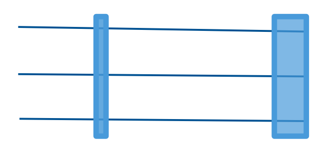
Wien filter for protons



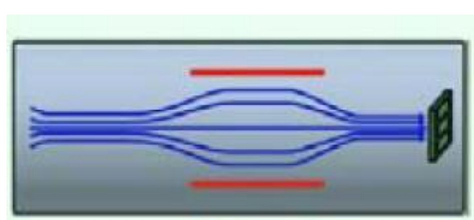
Magnetic spectrometer



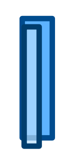
Electrostatic chopper & p detector



MAC-E filter
(“aSPECT”)



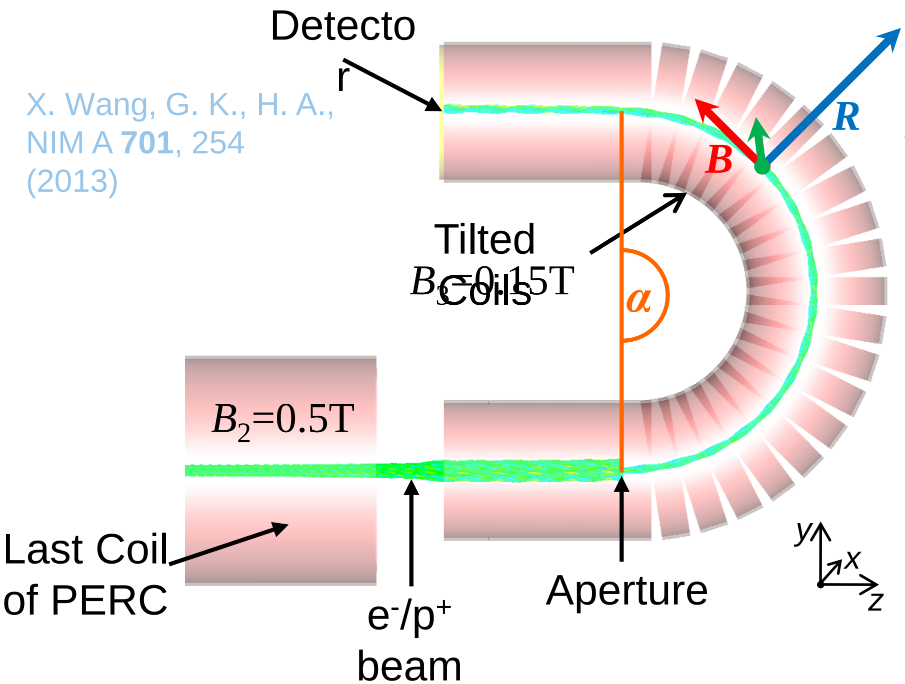
Electron or proton detector



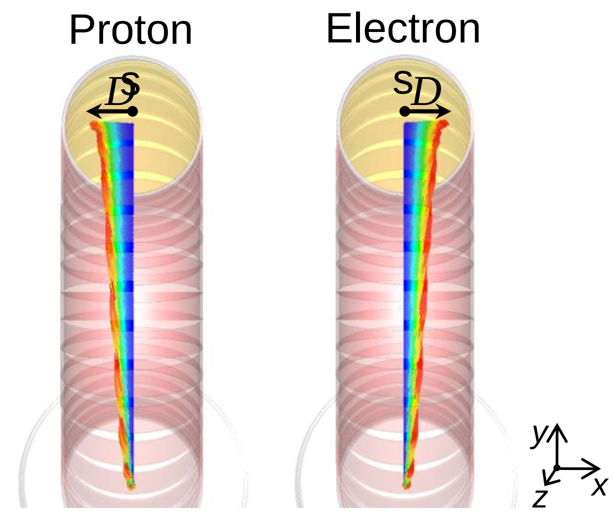
Scintillator, Silicon, …

R×B Drift Momentum Spectrometer

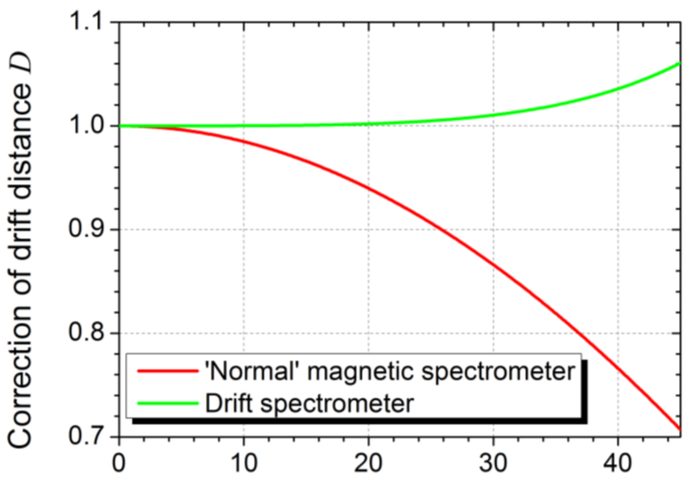
X. Wang, G. K., H. A., NIM A **701**, 254 (2013)



$$v_d \propto \frac{\mathbf{R}\times\mathbf{B}}{qR^2B^2}$$



$$D(p,\theta) = \int_T v_d \mathrm{d}t = \frac{p}{qB_3}\cdot\alpha\cdot\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$



- \+ extremely versatile
- \+ adiabatic transport of particles
- \+ low momentum measurements
- \+ small corrections for θ
- \+ large acceptance of θ

Gertud Konrad, SMI

Summary & Outlook

Low energy precision searches are complementary and competitive to searches for New Physics at the high energy frontier. Searches for new couplings in charged weak currents.

Upcoming **PERKEO III** Results:

Beta Asymmetry A
Fierz Interference b
Proton Asymmetry C

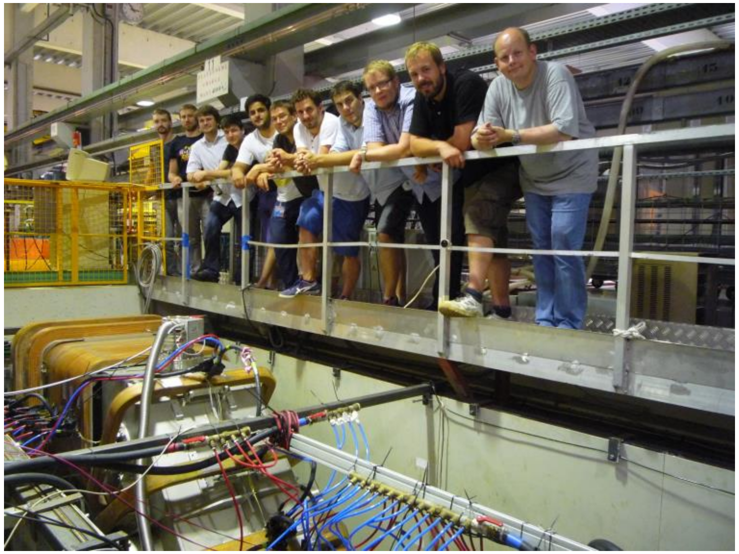
PERC Ready within ~ 18 months

Long-term future (next decade):
cold beam line **ANNI** at ESS
(talk by T. Soldner)

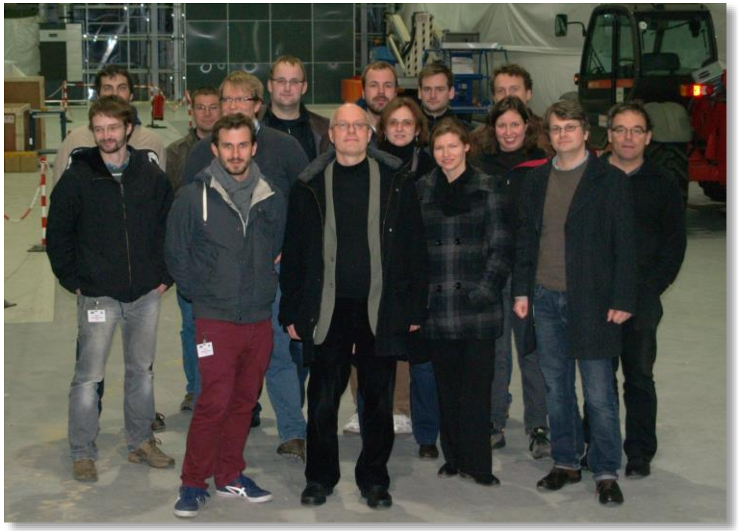
Thanks go to …

PERKEO III A

PERKEO III C



PERC



Many partners missing from the pictures…

Extra

PERC Systematic Error Budget

Source of error	Correction	Error	Comment
Non-uniform n-flux F	2.5×10^{-4}	5×10^{-5}	For $\Delta F/F$=10% over 1cm width
Other edge effects on e/p-window	4×10^{-4}	1×10^{-4}	For max. gyration radius = worst case
Magn. mirror effect for cont's n-beam Magn. mirror effect for pulsed n-beam	2×10^{-2} 5×10^{-5}	4×10^{-4} $< 10^{-5}$	For $\Delta B/B$=10% over 7m length
Non-adiabatic e/p-transport	5×10^{-5}	5×10^{-5}	
Background from n-guide	2×10^{-3}	1×10^{-4}	is separately measurable
Background from n-beam stop	2×10^{-4}	1×10^{-5}	is separately measurable
Backscattering off e/p-beam dump	5×10^{-5}	1×10^{-5}	
Backscattering off e/p-window	2×10^{-5}	1×10^{-5}	
Backscattering off organic scintillator ... with active e/p-beam dump	2×10^{-3} -	4×10^{-4} 1×10^{-4}	worst case worst case
Neutron polarisation	3×10^{-3}	$\mathbf{1 \times 10^{-4}}$	C. Klauser et al.

Note: not every error source contributes to all measurements
Nucl. Instr. Meth. A **596** (2008) 238 and arXiv:0709.4440

All errors $O(10^{-4})$ or smaller:
More than one order of magnitude improvement