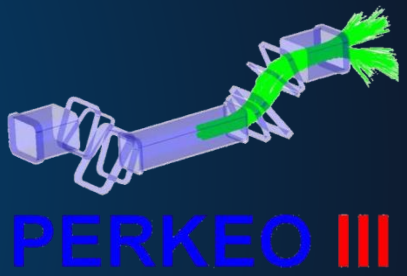
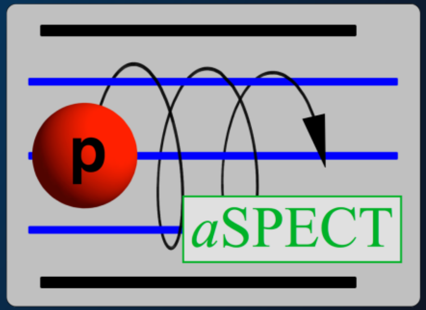
Neutron decay:

PERKEO III versus aSPECT

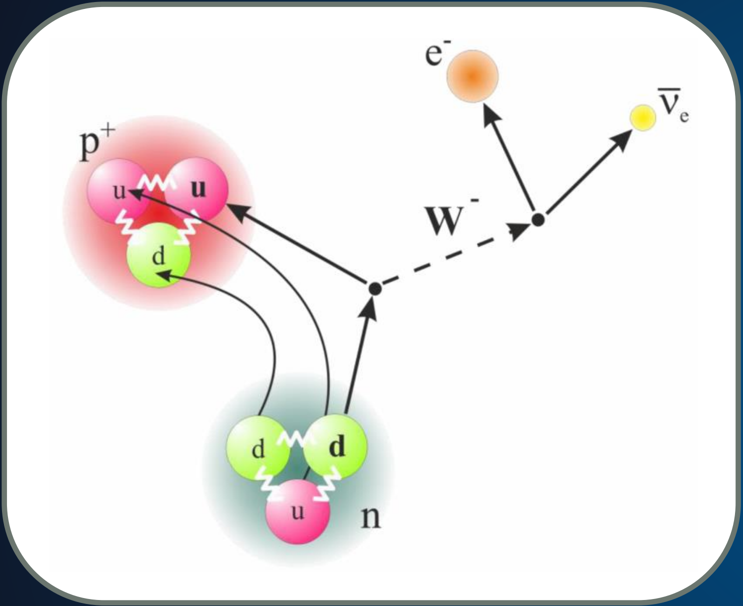
OUTLINE

- Introduction and Motivation
- Measurement principle: PERKEO III versus aSPECT
- Experimental results: PERKEO III versus aSPECT
- Outlook





Neutron β-Decay



Low energy regime

$$E_{kin_{max,P}} = 752\text{eV}\ ,\ E_{kin_{max,e}} = 782\text{keV}$$

Long lifetime (result from UCNτ 2021)

$$\tau_n = 887.75 \pm 0.28_{stat} + 0.22/{-0.16}_{syst}$$

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

With G_F from muon decay and Δ_R=0.0247 [arXiv:1812.03352v3]

Coupling constants:
axial-vector g_A
vector g_V

$$\lambda = \frac{G_A}{G_V}$$

$$|V_{ud}|^2 = \frac{5099.34\text{S}}{\tau_n(1+3\lambda^2)(1+\Delta_R)}$$

Weak interaction parameters

$$M \propto G_F V_{ud} \left(\bar{\psi}_p \gamma_\mu (1 + \lambda \gamma_5)\, \psi_n \right) \cdot \left(\bar{\psi}_e \gamma_\mu (1 - \gamma_5)\, \psi_{\bar{\nu}_e} \right)$$

- G_F: *Fermi constant*
- V_{ud}: Cabibbo-Kobayashi-Maskawa (CKM) Matrixelement
- λ: *Ratio of axial-vector (A) to vector (V) coupling constant*

$$\lambda = \left| \frac{g_A}{g_V} \right| e^{i\phi}$$

Neutron decay observables

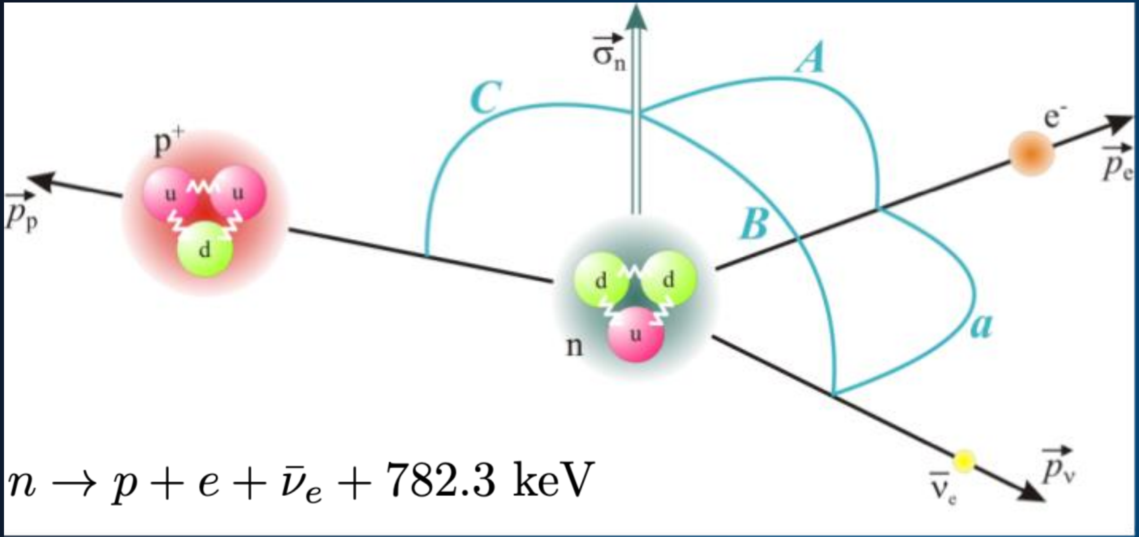
- Neutron lifetime $\rightarrow \tau_n(V_{ud}, \lambda)$
- Correlation coefficients $\rightarrow \lambda$

$$dW \propto 1 + a \frac{\vec{p}_e \vec{p}_{\bar{\nu}_e}}{E_e E_{\bar{\nu}_e}} + b \frac{m_e}{E_e} + \frac{\vec{\sigma}_n}{\sigma_n} \left(A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_{\bar{\nu}_e}}{E_{\bar{\nu}_e}} + \cdots \right)$$

$$\frac{dA}{d\lambda} \approx 0.37$$

$$\frac{da}{d\lambda} \approx 0.30$$

Correlation coefficients



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

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

beyond SM: b Fierz term

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

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{2(2\pi)^5} G_F^2 |V_{ud}|^2 (1+3|\lambda|^2) p_e E_e (E_0 - E_e)^2$$
$$\times \left(1 + a\frac{\vec{p}_e \vec{p}_{\overline{\nu}_e}}{E_e E_{\overline{\nu}_e}} + b\frac{m_e}{E_e} + \frac{\vec{\sigma}_n}{\sigma_n}\left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_{\overline{\nu}_e}}{E_{\overline{\nu}_e}} + \cdots\right)\right)$$

Test of the standard model

SM: $\lambda = {}^{L_A}/_{L_V}$, $L_V = 1, L_A = \lambda$, $L_S = L_T = R_V = R_A = R_S = R_T = 0$

$$a = \frac{1}{\xi}(|L_V|^2 - |L_A|^2 - |L_S|^2 + |L_T|^2 + |R_V|^2 - |R_A|^2 - |R_S|^2 + |R_T|^2)$$

$$A = \frac{2}{\xi}\Re(-|L_V|^2 - L_V L_A^* + |L_T|^2 + L_S L_T^* + |R_A|^2 + R_V R_A^* - |R_T|^2 - R_S R_T^*)$$

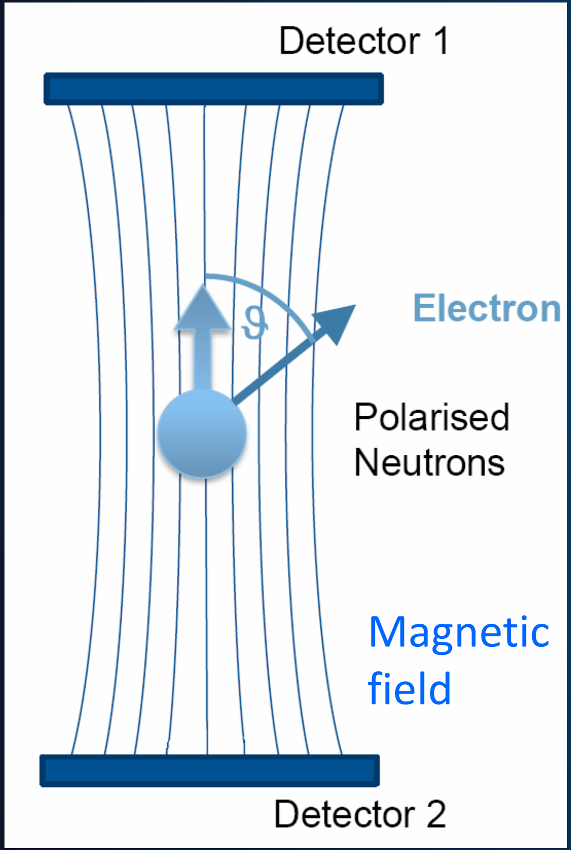
aSPECT: measurement a and b

PERKEO III: measurement A and b

SM: $a = \frac{1-|\lambda|^2}{1+3|\lambda|^2}$, $A = -2\frac{|\lambda|^2 - Re(\lambda)}{1+3|\lambda|^2}$

beyond SM (left handed): $b \approx \frac{L_S L_V + 3 L_A L_T}{L_V^2 + L_S^2 + 3(L_A^2 + L_T^2)} \approx 2\frac{L_S + 3\lambda L_T}{1+3\lambda^2}$

PERKEO III



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

Magnetic field as quantisation axis

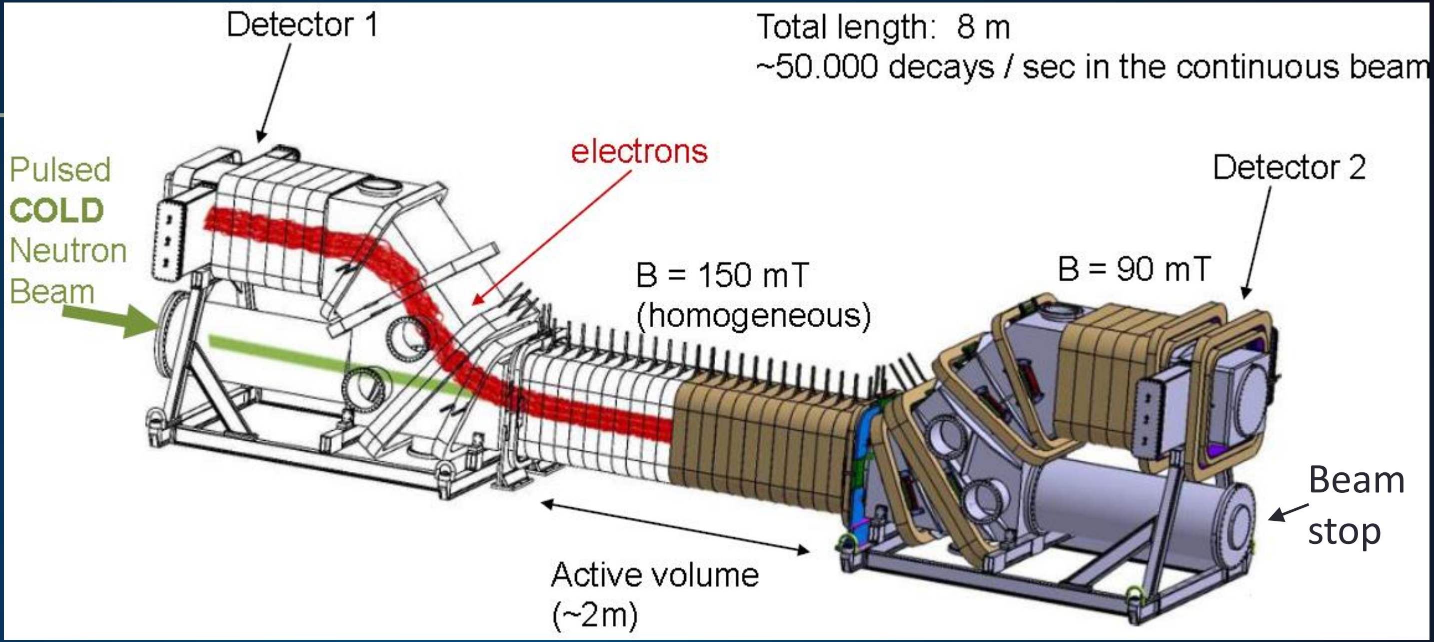
Integration over both hemispheres one for each detector: $\int cos\vartheta \rightarrow \frac{1}{2}$

Experimental asymmetry A_{exp}, with neutron (beam) polarisation P_n

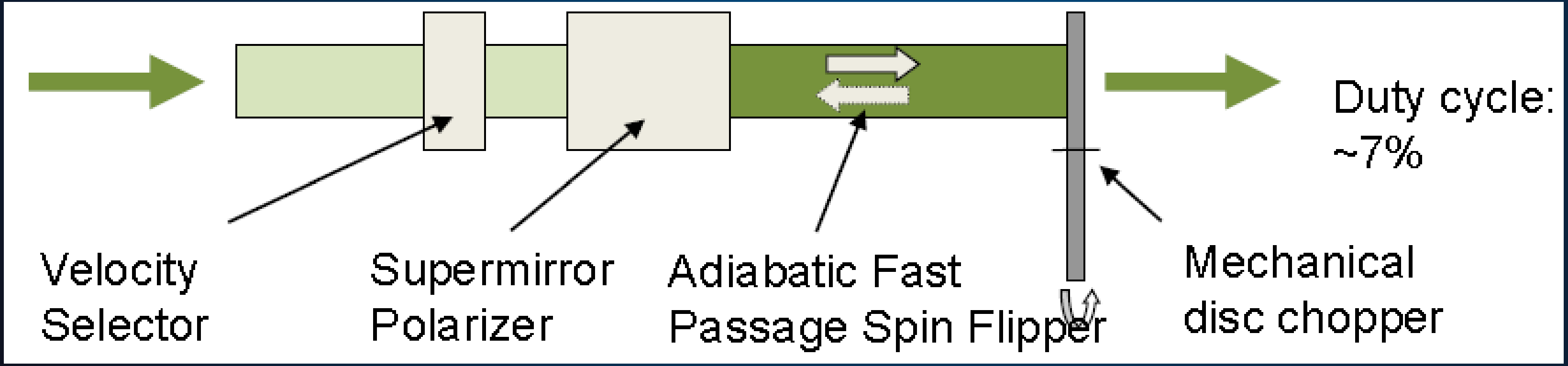
$$A_{exp} = \frac{N^{\Uparrow} - N^{\Downarrow}}{N^{\Uparrow} + N^{\Downarrow}} = \frac{1}{2}\frac{v}{c} P_n A$$

PERKEO III

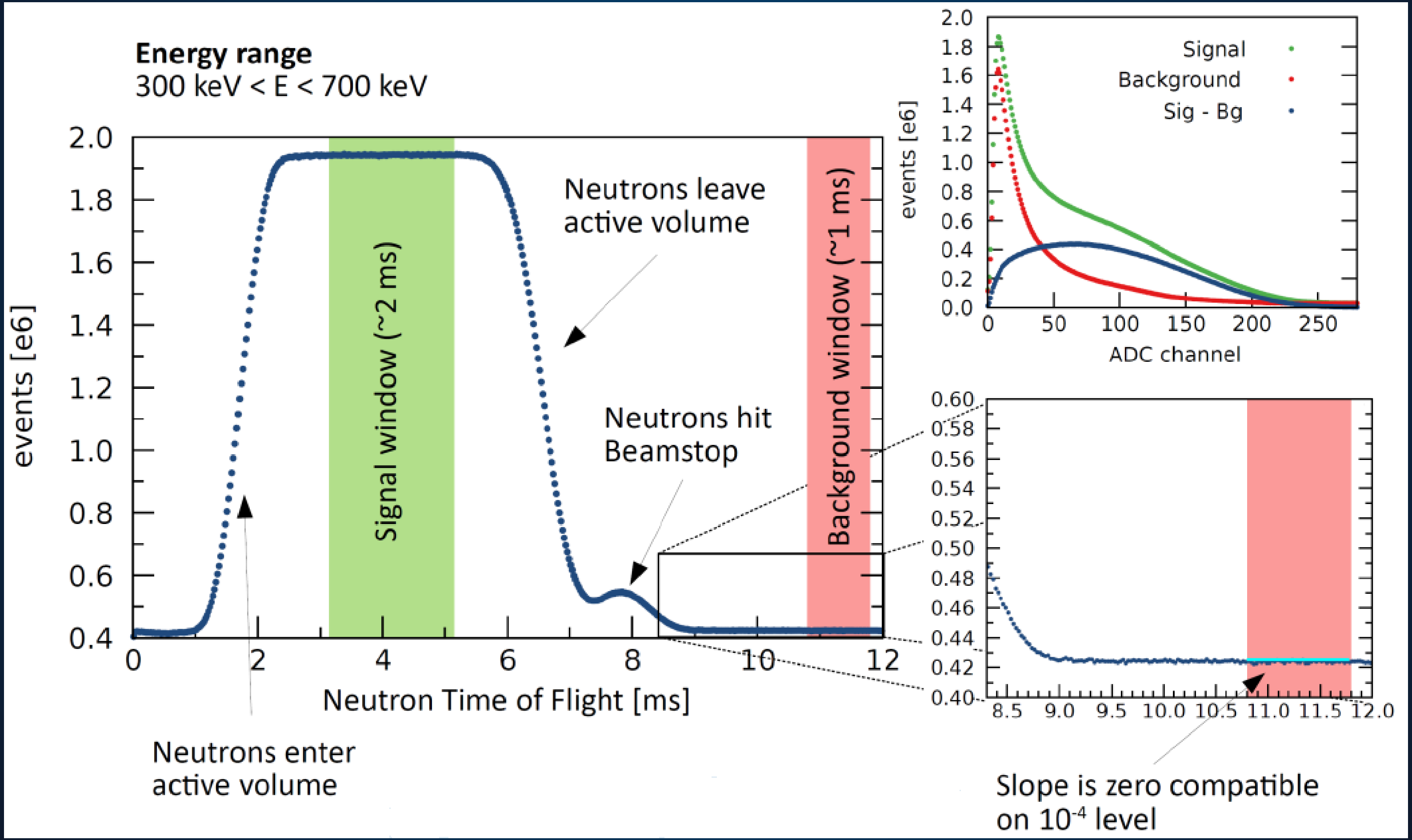
U. Schmidt CKM2023 7



Beam preparation

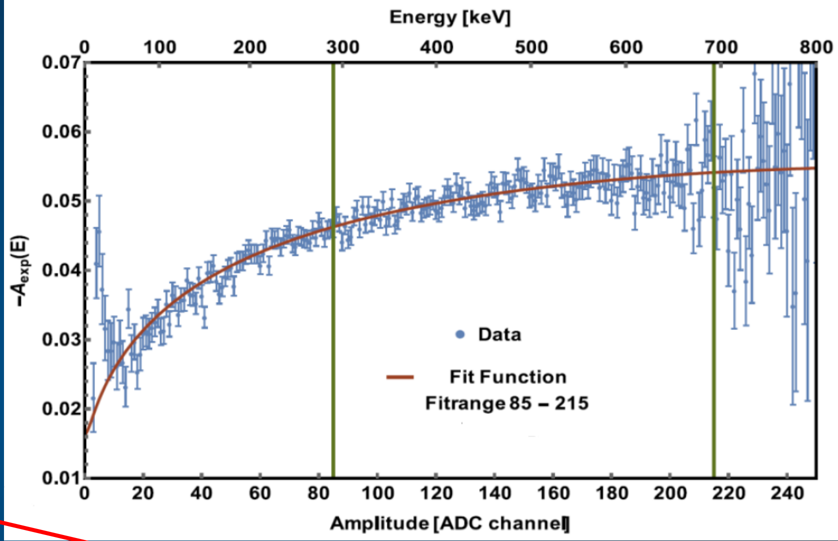


PERKEO III Pulsed neutron beam



PERKEO III Energy dependent analysis

First order: $A_{exp}(E_e) = \frac{1}{2}\beta(E_e)P_n A$



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

$$A_{exp}(E_e) = \frac{N^{\Uparrow}(E_e) - N^{\Downarrow}(E_e)}{N^{\Uparrow}(E_e) + N^{\Downarrow}(E_e)} = f(\lambda, b, E_e)$$

Theoretical corrections:
Recoil order corrections
Radiative (outer) corrections dependent on λ and E_e
[Ivanov et al, Phys. Rev. D,2013]
[F. Glück, arXiv:2205.05042v2]

Detector model and background effects:
Energy resolution and non-linear energy dependent corrections on λ and E_e

Other systematics:
Neutron beam polarization P_n, magnetic mirror effect non energy dependent

PERKEO III Results

[Phys.Rev.Let. **122**, 242501 (2019)]

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

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

$$V_{ud} = \sqrt{\frac{5099.34s}{\tau_n(1+3\lambda^2)(1+\Delta_R)}}$$
$$= 0.97301(10)_{RC}(44)_{\tau_n}(45)_{\lambda}$$
$$= 0.97301(58) \quad (\tau_n = 879.7(8)s)$$

[Phys.Rev.Let. **125**, 112501 (2020)]

SM:

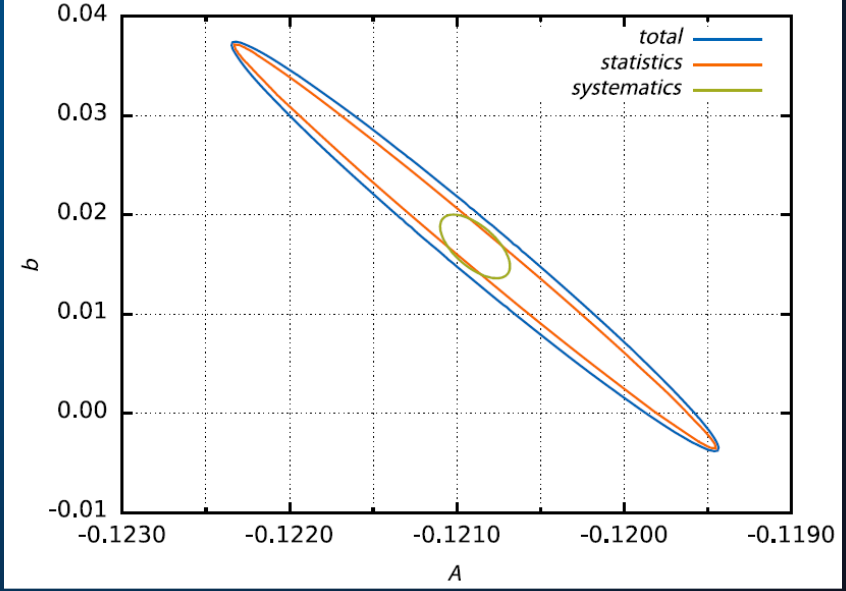
$\lambda = -1.27607(68), A = -0.11972(25)$

Beyond SM:

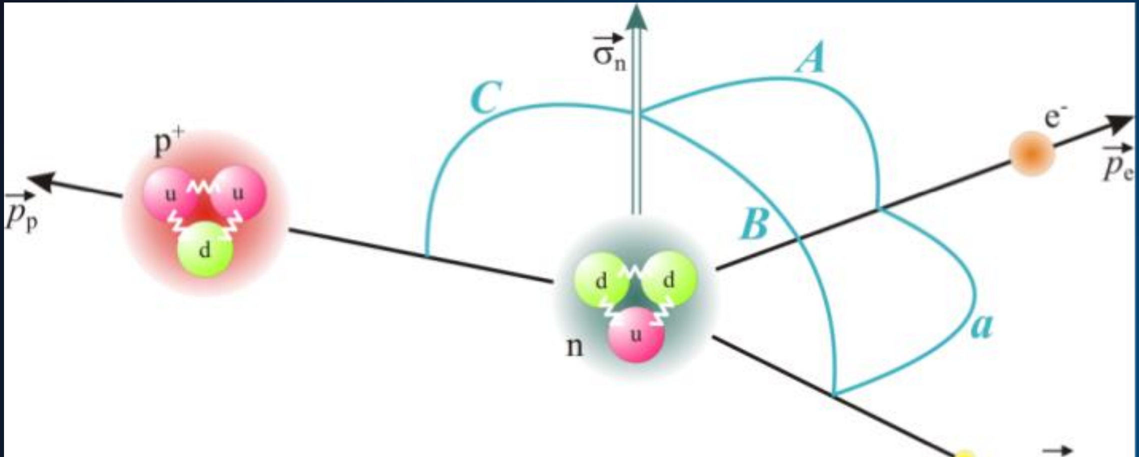
$A = -0.1209(14)_{stat}(2)_{sys} = -0.1209(15)$

$b = 0.017(20)_{stat}(3)_{sys} = 0.017(21)$

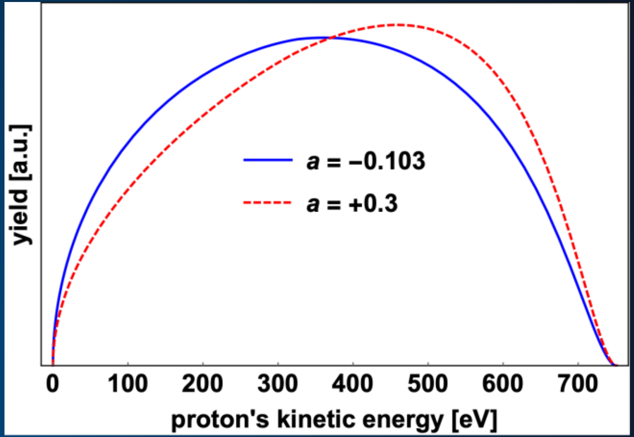
$\rho_{A,b} = -0.985$



Differential proton spectrum

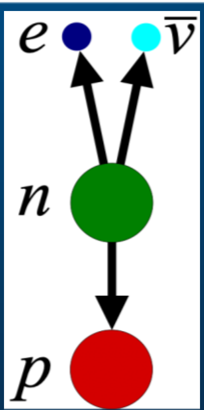


$$n \rightarrow p + e + \bar{\nu}_e + 782.3 \text{ keV}$$

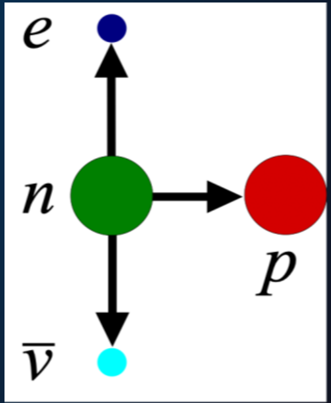


$$dW \propto 1 + a \frac{\vec{p}_e \vec{p}_{\bar{\nu}_e}}{E_e E_{\bar{\nu}_e}}$$

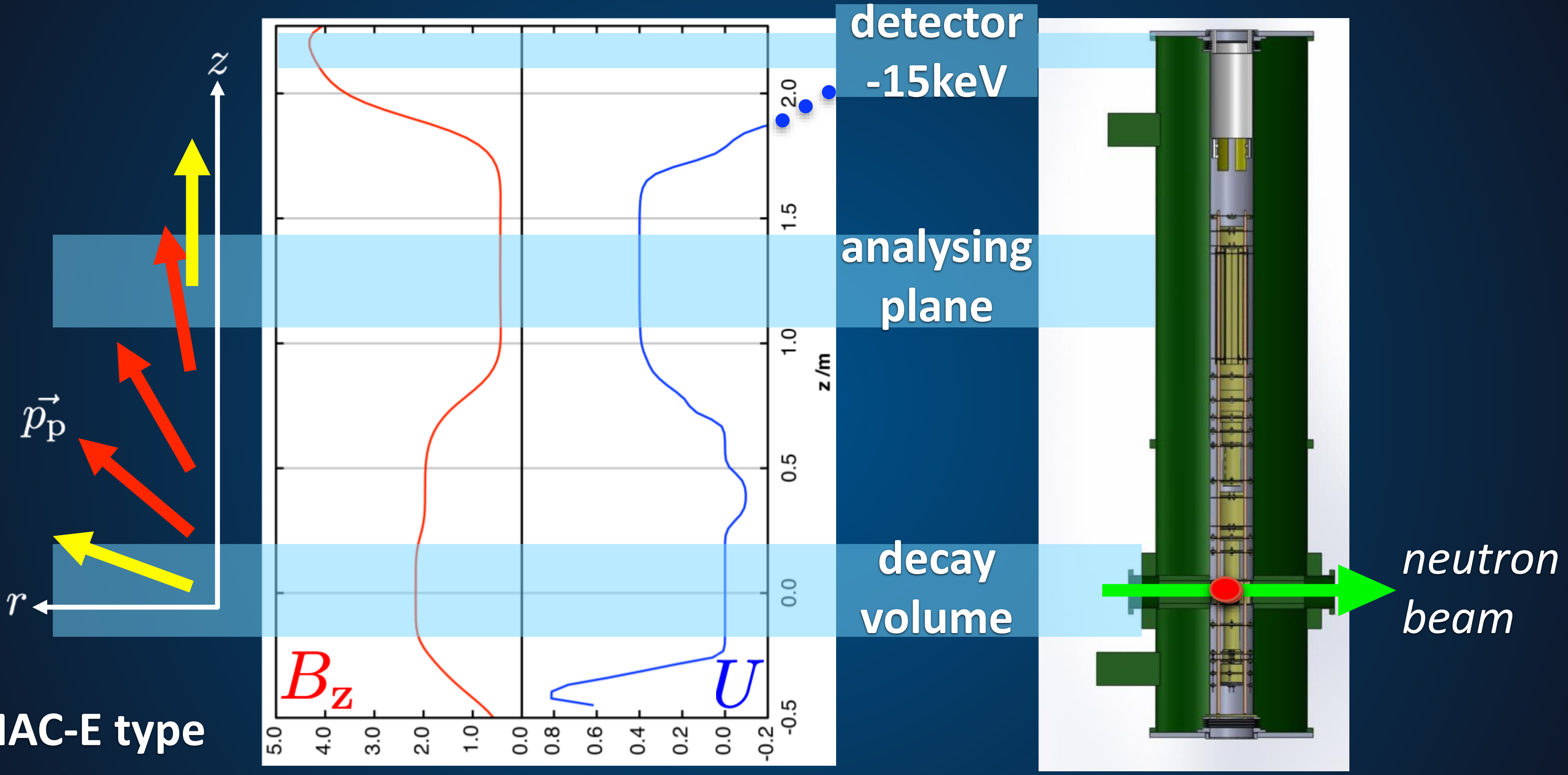
$a > 0$



$a < 0$



*a*SPECT - measurement principle



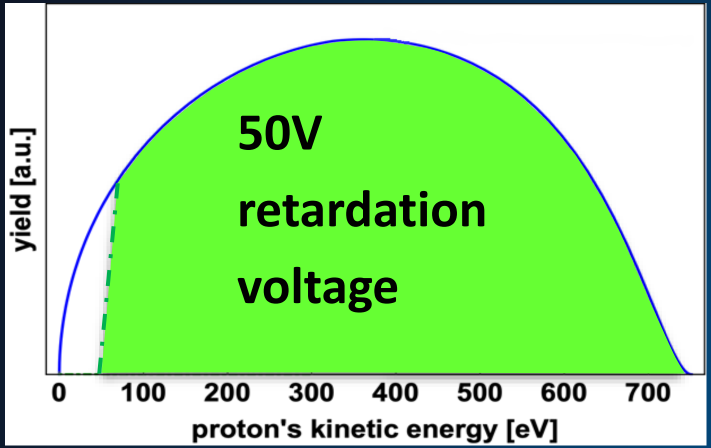
MAC-E type spectrometer

mag. flux density [T]

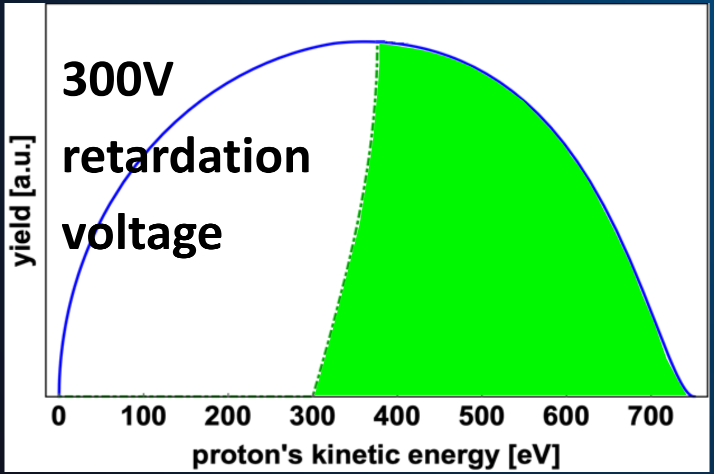
retardation voltage [kV]

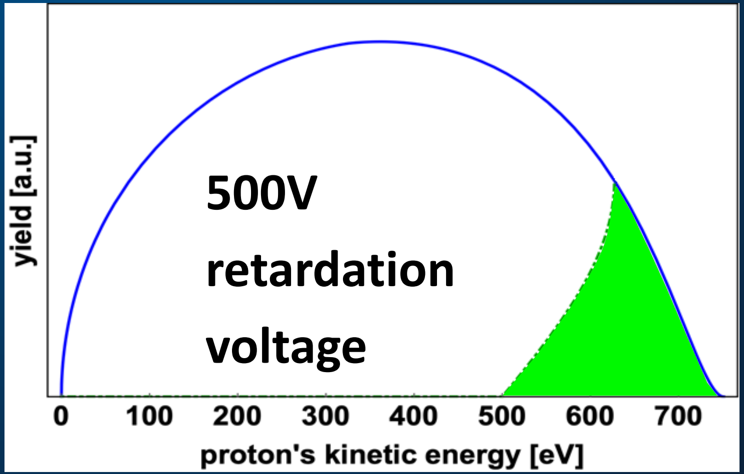
cut through aSPECT cryostat

*a*SPECT – Transmission measurement

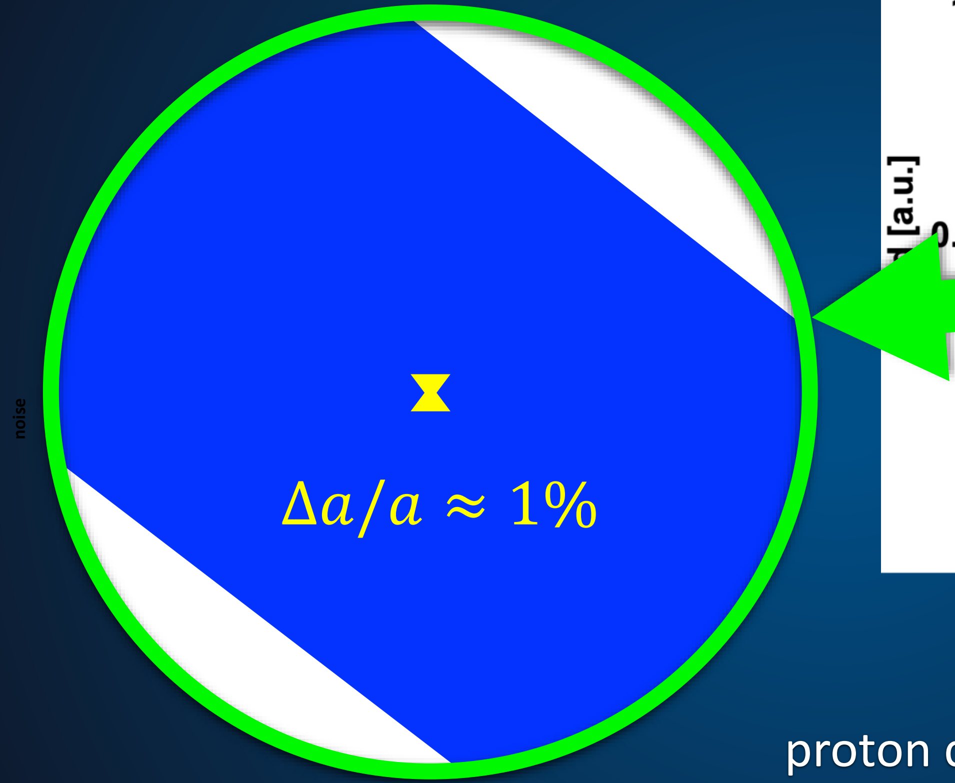


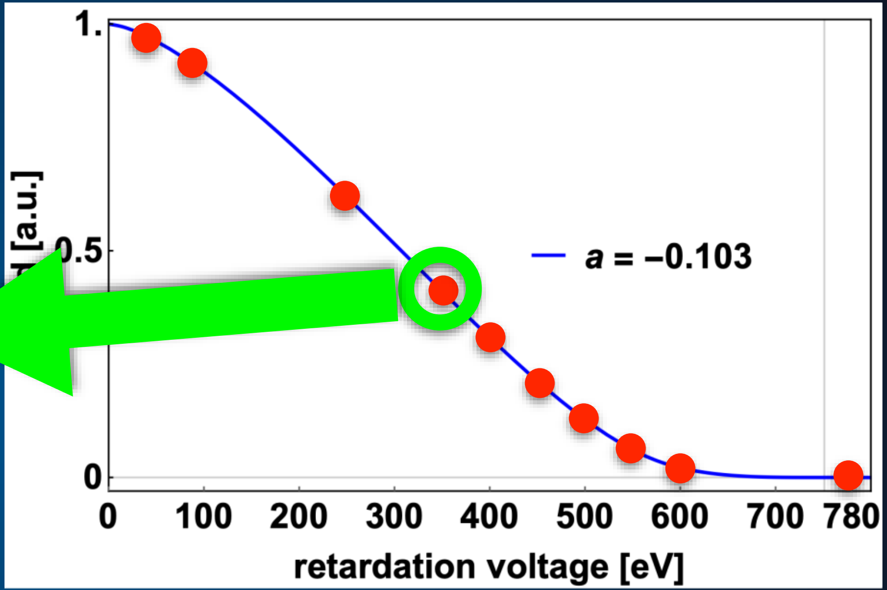
$$f_{trans}(T, U_{AP}, r = B_{AP}/B_{DV})$$



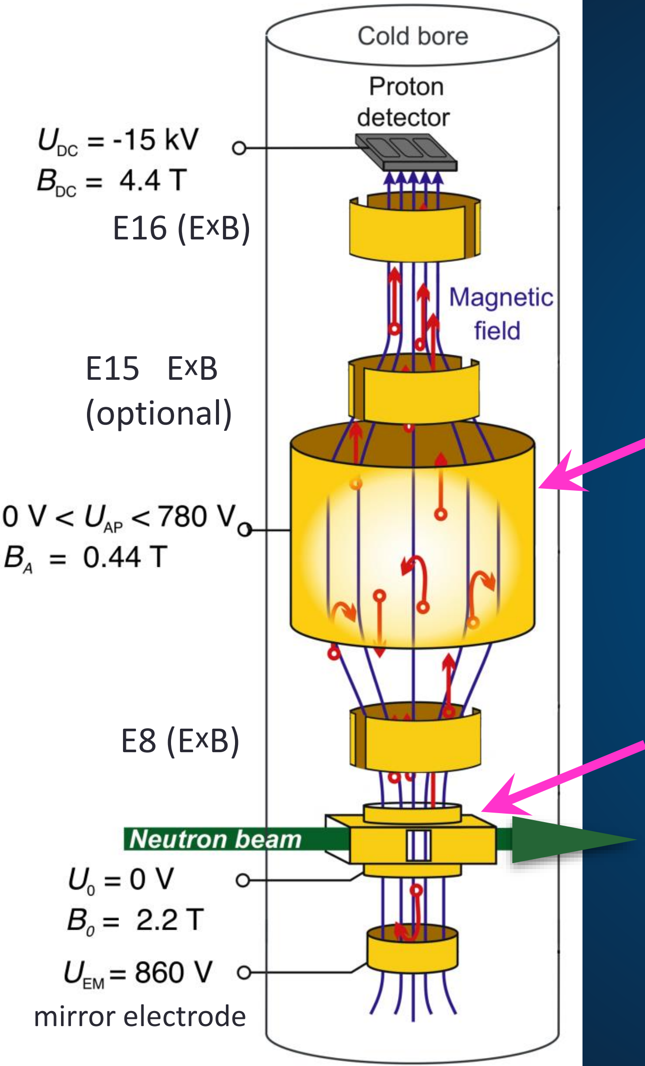


Integral proton spectrum

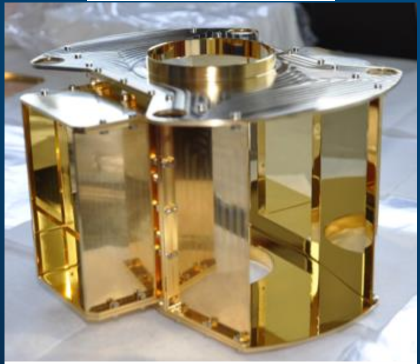




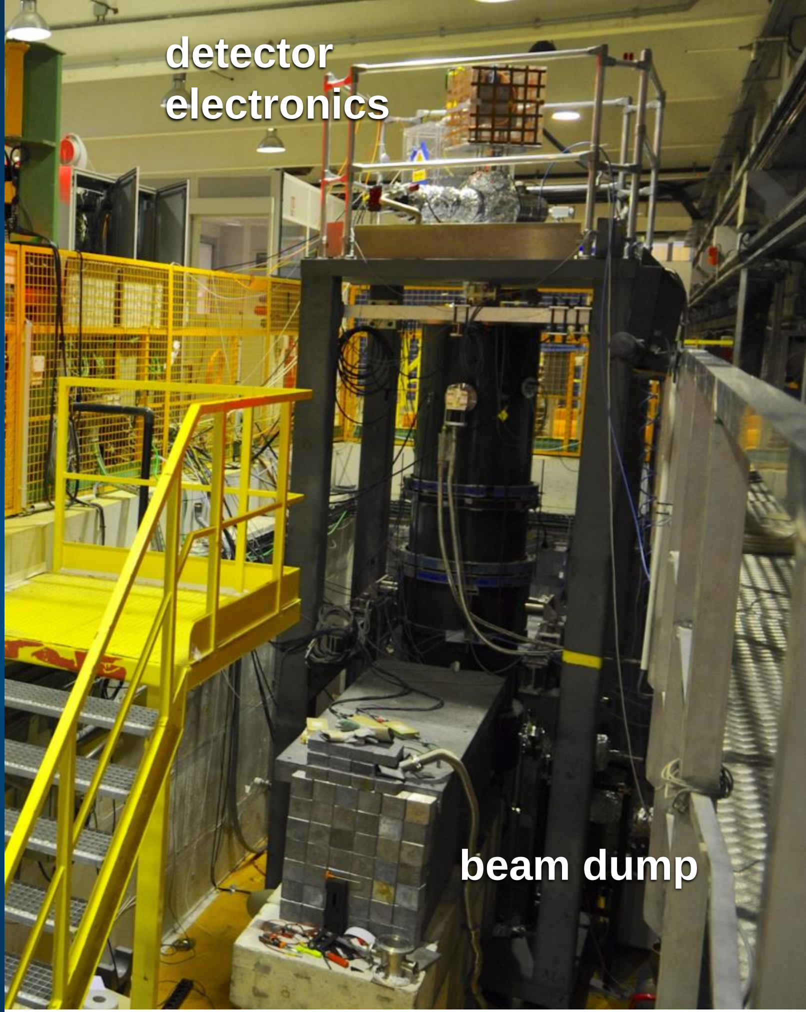
proton count rate per pad ~440Hz @ 50V
constant background ~ 6Hz(decay electrons)



AP electrode



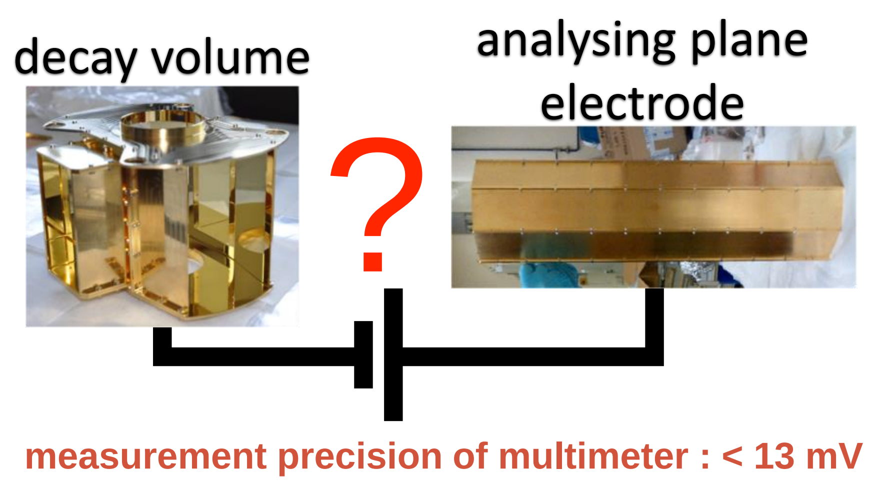
DV electrode

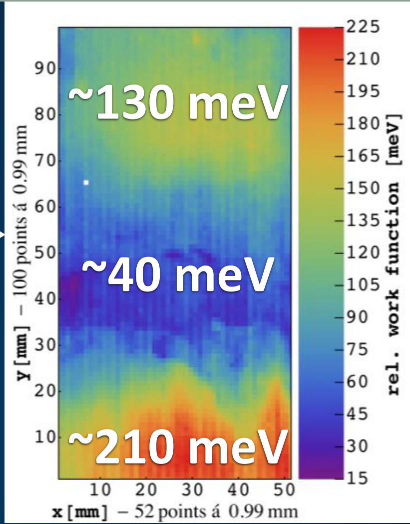


full setup at PF1B, ILL

Retardation voltage - WF measurements

$$\Delta U_{\mathrm{AP}} = 10\ \mathrm{mV}$$
$$\cong$$
$$\Delta\, a/a \approx\ 0.1\ \%$$





Production run
***a*SPECT**
2013
~120 K
≤ 10^{-9} mbar

↔

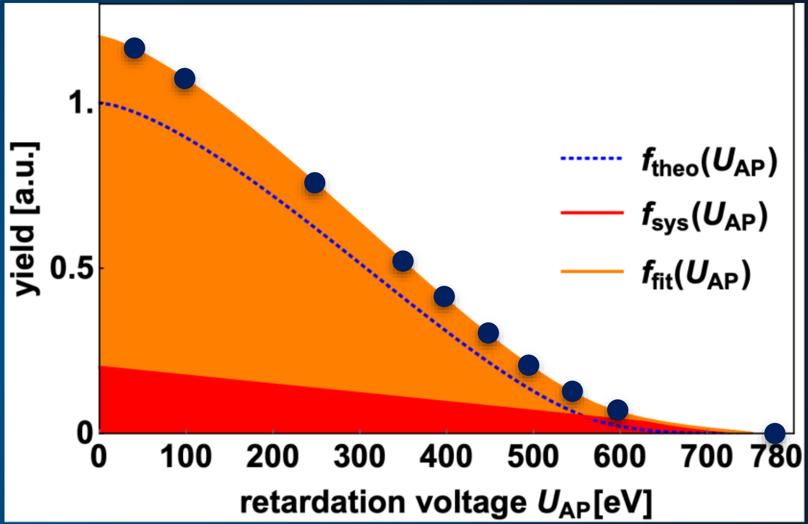
WF measurements with Kelvin probe under ambient and HV conditions
until 2017

- ✓ **Aging effects < 20 meV**
- ✓ **Temperature effects < 10 meV**
- ✓ **Air-vacuum difference < 11 meV**

Data analysis

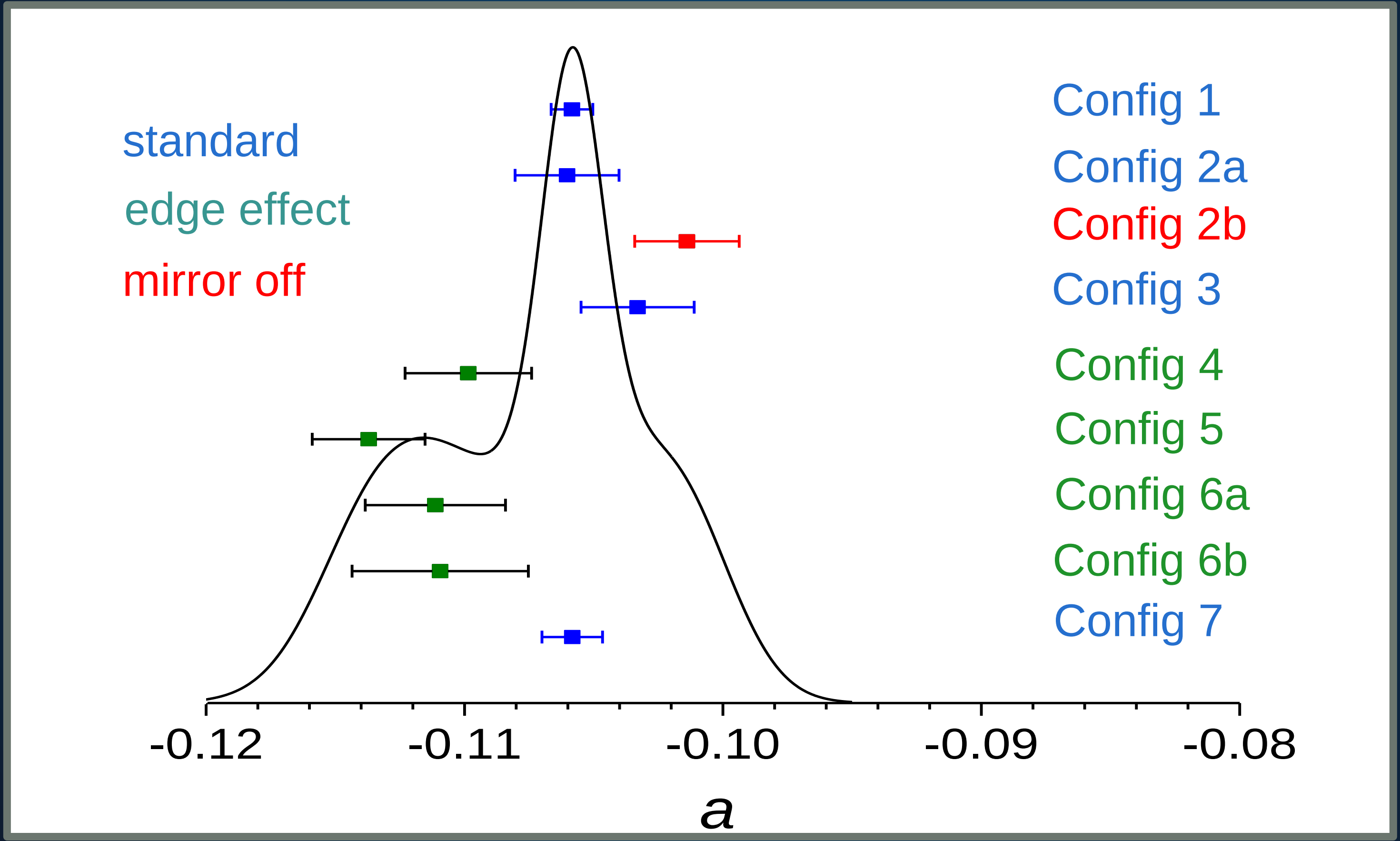
Systematic effects

A. Temporal stability and normalization
B. Magnetic field ratio <rB>
C. Retardation voltage <UAP>
D. Background
E. Edge effect
F. Backscattering and below-threshold losses
G. Dead time and pile-up
H. Proton traps in the DV region

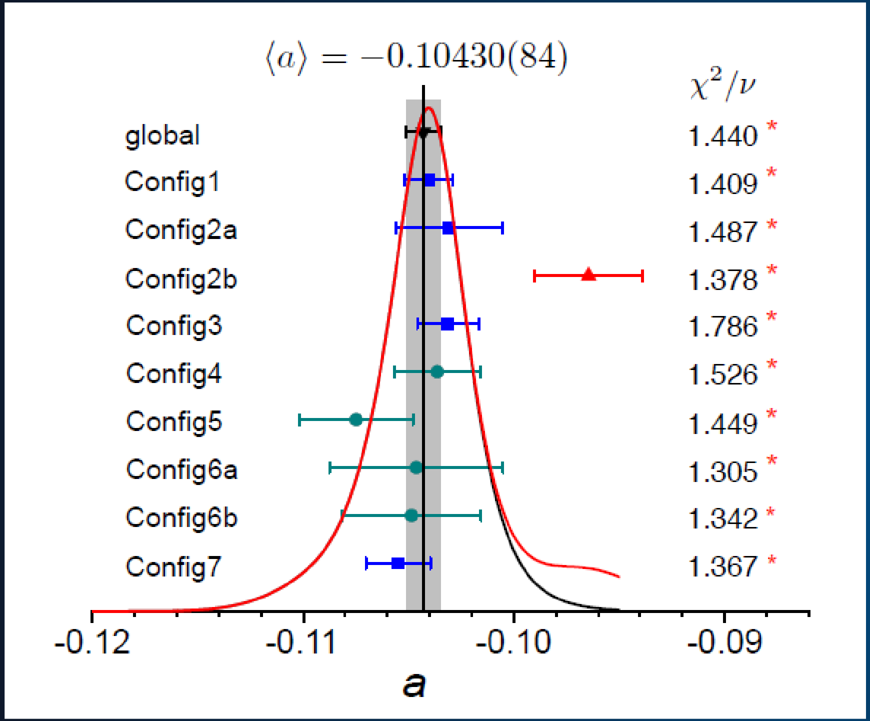


$$f_{fit}(U_{AP}) = f_{theo}(U_{AP}, a) + \sum_i f_{sys_i}(U_{AP})$$

Raw data


standard
edge effect
mirror off
Config 1
Config 2a
Config 2b
Config 3
Config 4
Config 5
Config 6a
Config 6b
Config 7
-0.12
-0.11
-0.10
-0.09
-0.08
a

Global fit results



Error scaling data of integral proton spectra	Error scaling systematic corrections	χ^2_G/ν	p value	a
1.00	1.00	1.44	3.1×10^{-6}	−0.104 30(84)*
1.20	1.00	1.17	0.029	−0.104 30(84)*
1.00	1.20	1.27	0.0018	−0.104 33(82)*
1.20	1.20	1.00	0.49	−0.104 32(80)

144 datapoints int. proton spectrum

192 auxiliar measurements & Monte Carlo results

68 fit parameter $\nu = 268$ (degree of freedom)

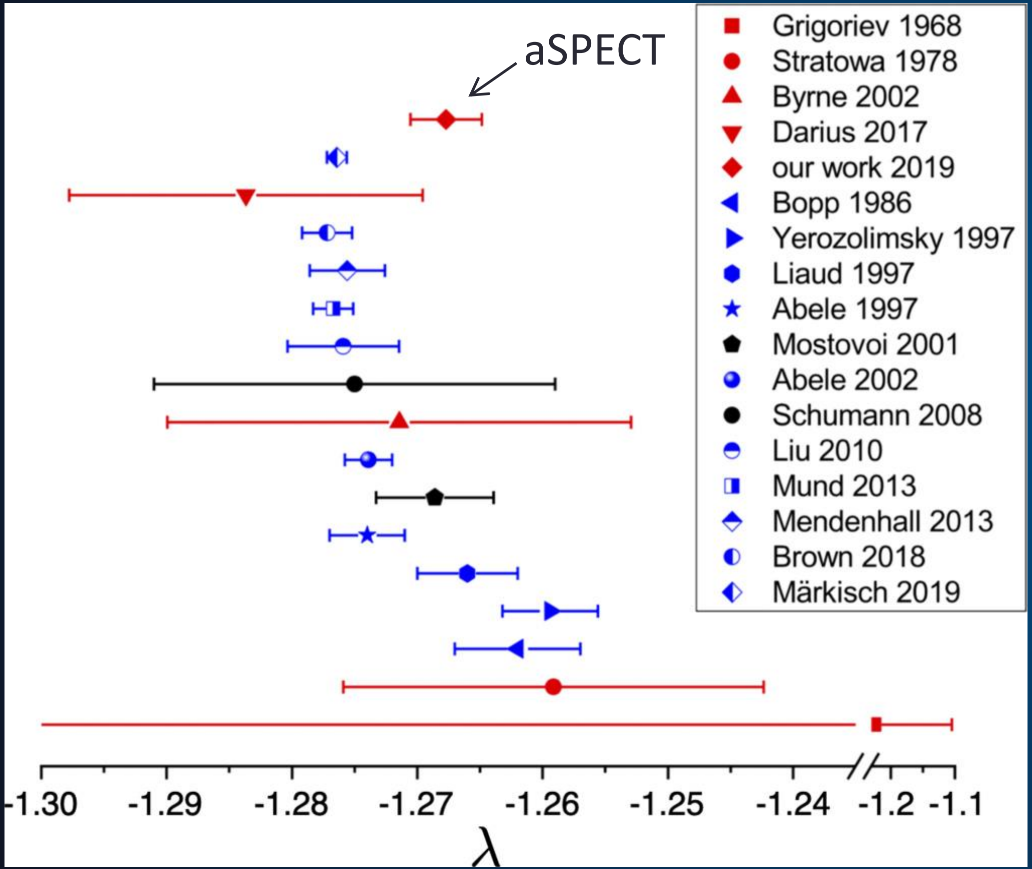
$\frac{\chi^2}{\nu} = 1.440, \quad p\ value: 3.0 \cdot 10^{-6}$

$\sigma^2_{nd} = 6.8 \cdot 10^{-6}$

$(< 10^{-4} \rightarrow near\ normal\ distributed)$

$a = -0.10430(84), \Delta a/a = 0.8\%$

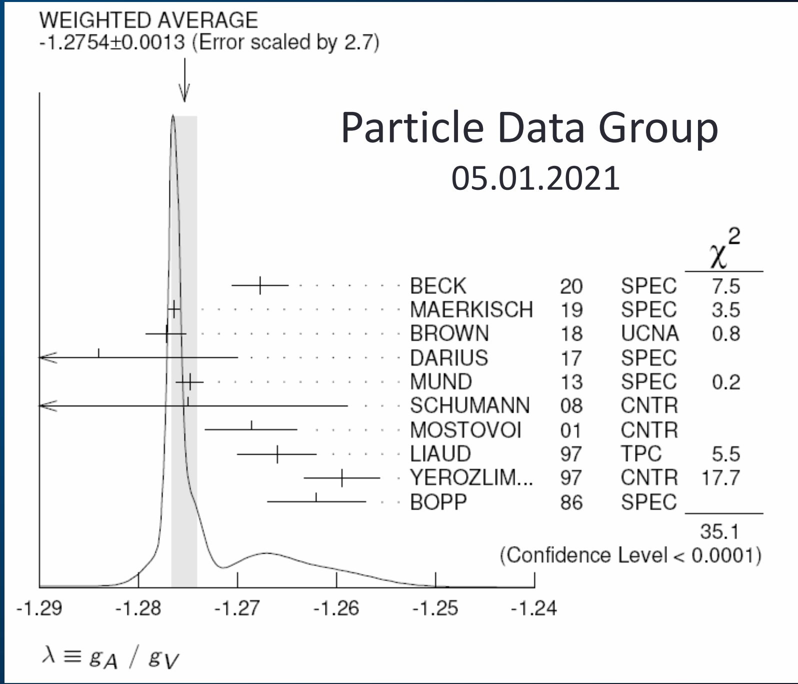
Global fit result λ



aSPECT result:

$$\lambda = -1.2677 \pm 0.0028$$

Phys.Rev. C 101, 055506 (2020)



Reanalysis

Went something wrong?

→ normalization of the errors of the independent variables (x-errors)

after proper normalisation:

$\chi\hat{}2/\nu \;= 1.440 \;\rightarrow\; \chi\hat{}2/\nu \;= 1.2$

Revised Systematic effects

F. Backscattering and below-threshold losses: effects from channeling?

Recoil and radiative Correction:

arXiv:2205.05042v2 [hep-ph] 16 Nov 2022, Ferenc Glück

4 body kinematic (real photon →Bremstrahlung)

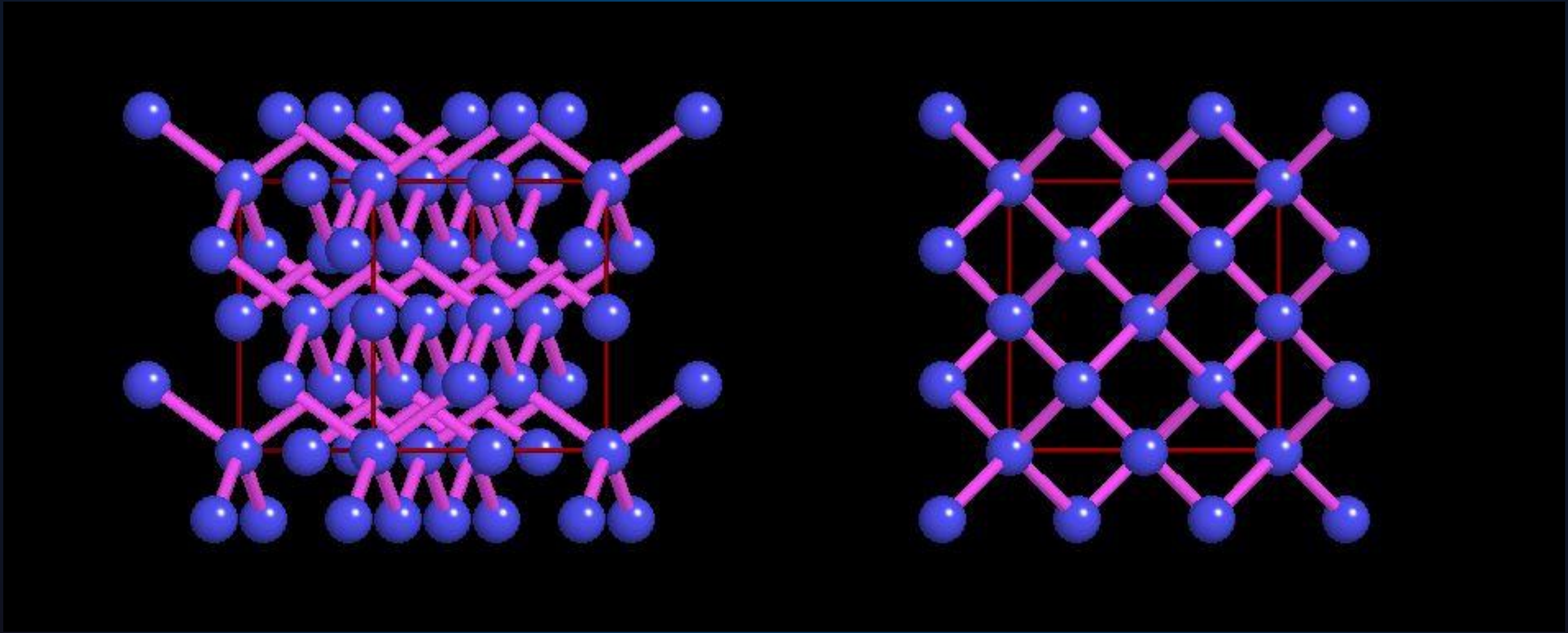
Codes:

SANDI: (Semi-Analytical Neutron Decay Integrator)

GENDER: GEneration of polarized Neutron (and nuclear beta) Decay Events with Radiative and recoil corrections

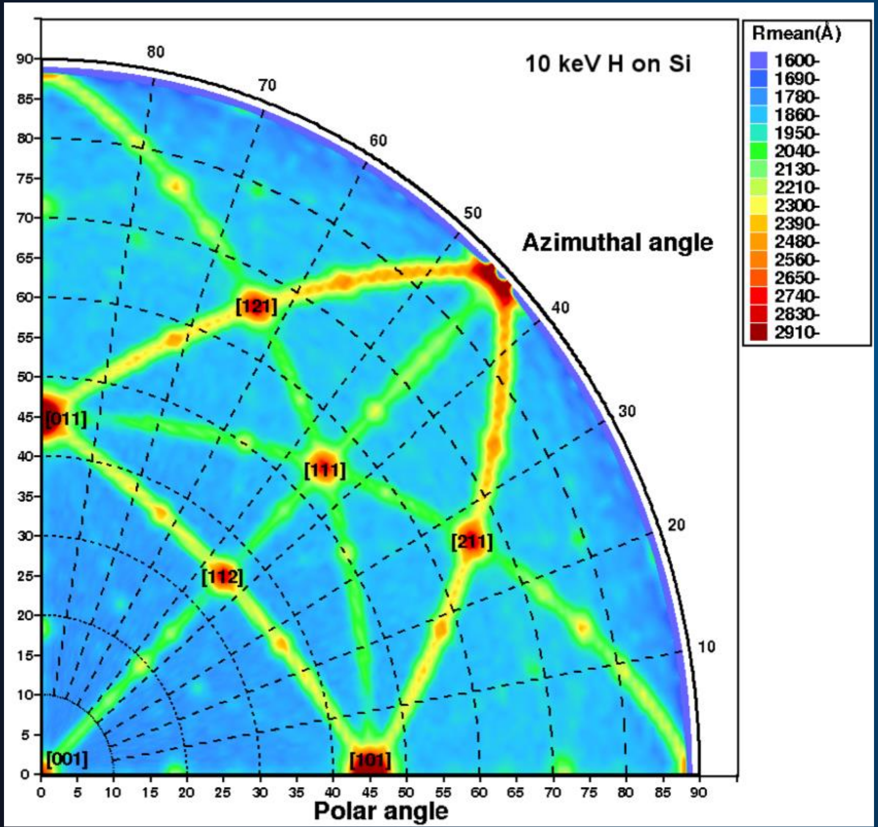
What is Channeling?

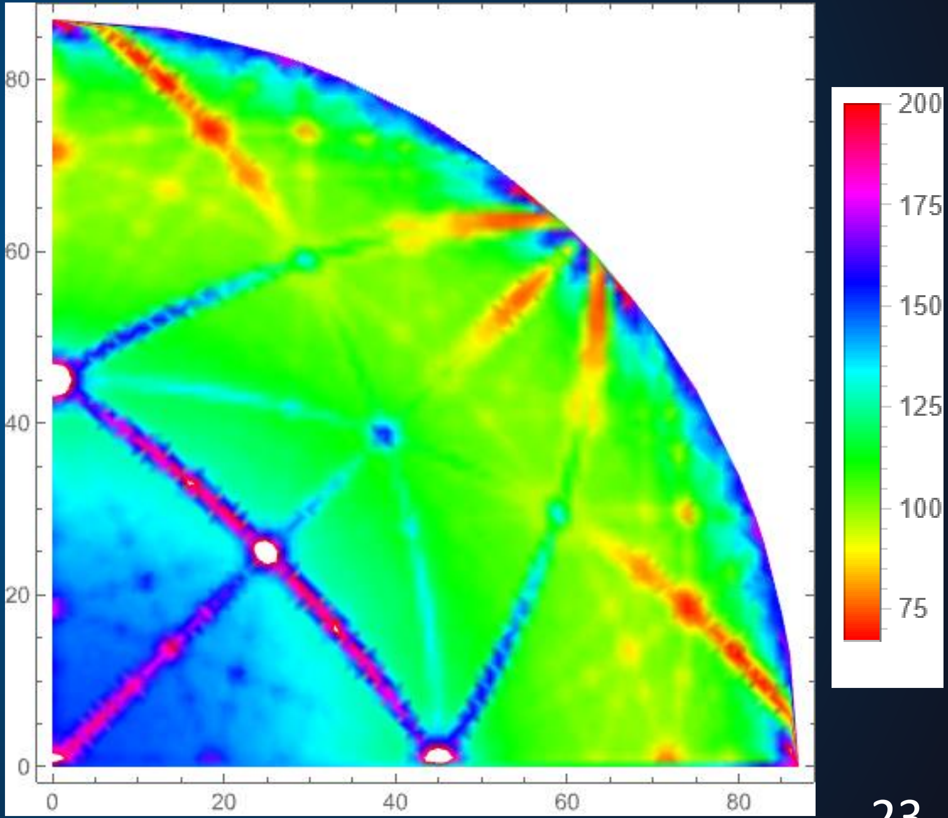
Lock on the same crystal structure from to different direction i.e. different angles



Average penetration depth [Å] calculated with MDRANGE

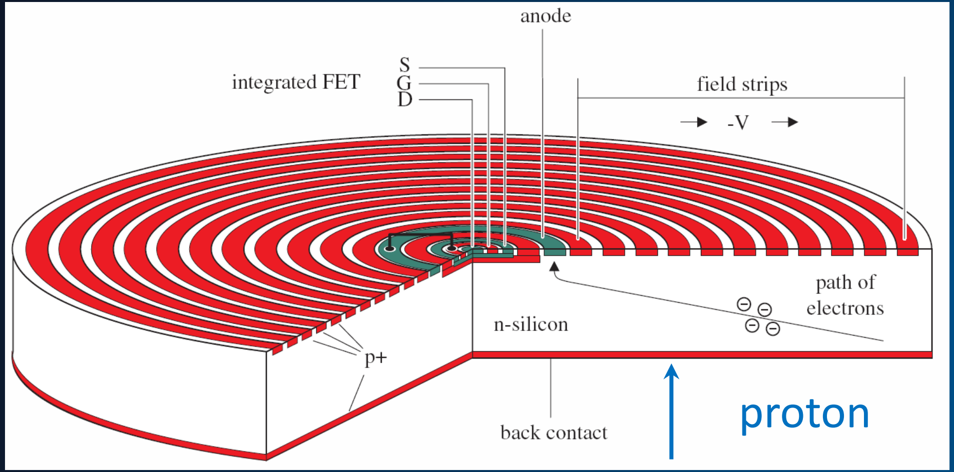
Average penetration depth [nm] calculated with Crystal-Trim, only small angles are comparable due to different scatting geometry

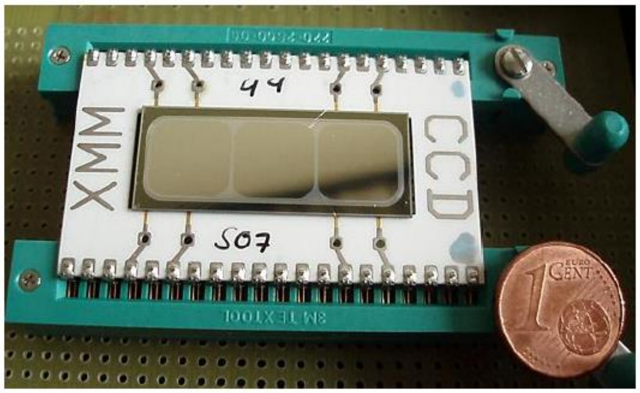




Silicon drift detector

Silicon Drift Detector





max. penetration depth 200nm for 15 keV protons

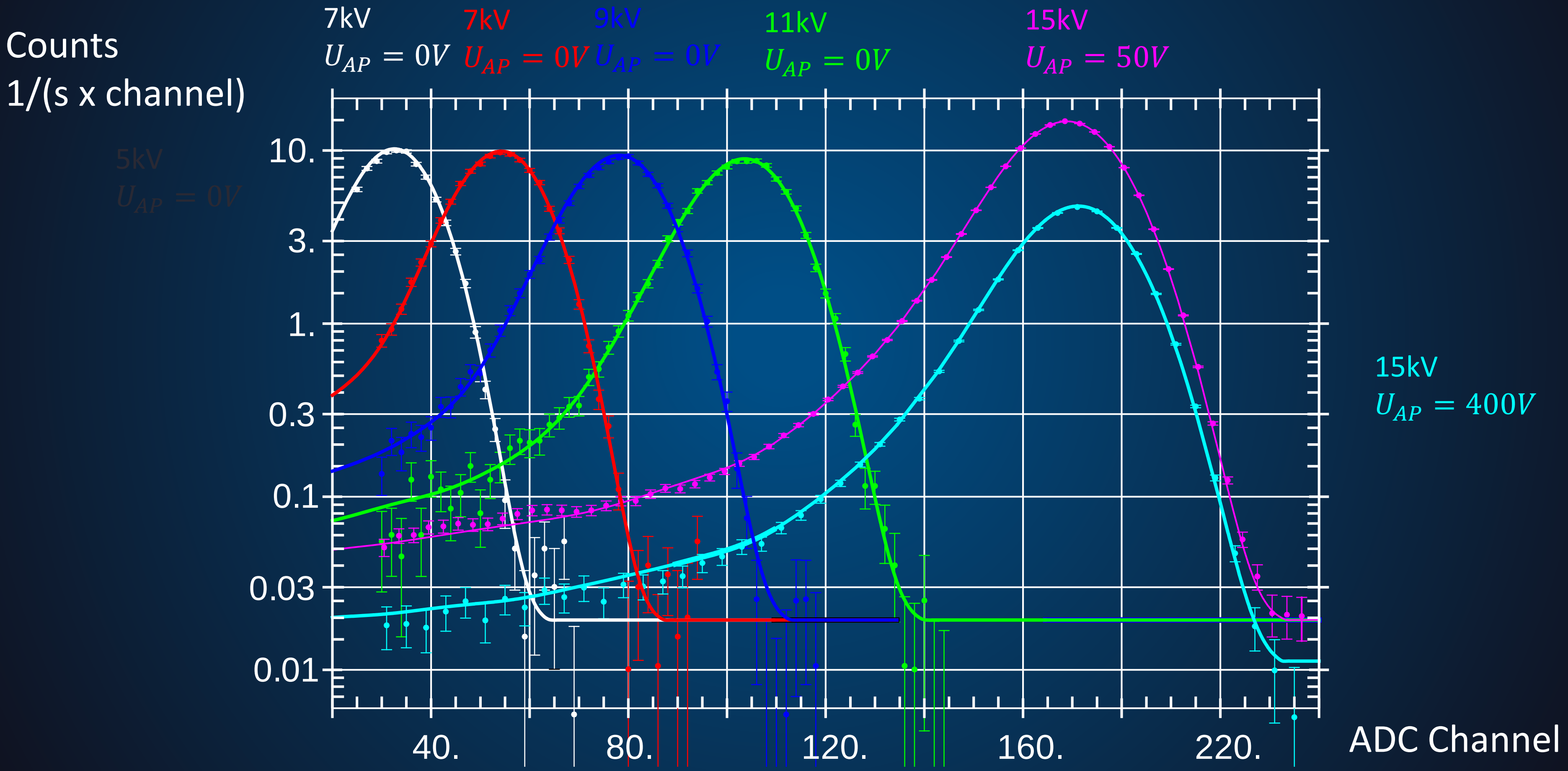
dead layer (back contact) $\Delta z \approx 30$ nm of aluminum

charge collection efficiency for electrons inside the n-silicon

$$f_{CCE}(z) = \begin{cases} 0 & \text{for } z' = z - \Delta z \\ S + B\left(z'/_L\right)^c & \text{for } 0 \le z' \le L \\ 1 - Ae^{-\frac{z'-L}{\tau}} & \text{for } L \le z' \le D \end{cases}$$

$$A = (1-S)\frac{\tau c}{L+\tau c}, \qquad B = (1-S)\left(1 - \frac{\tau c}{L+\tau c}\right)$$

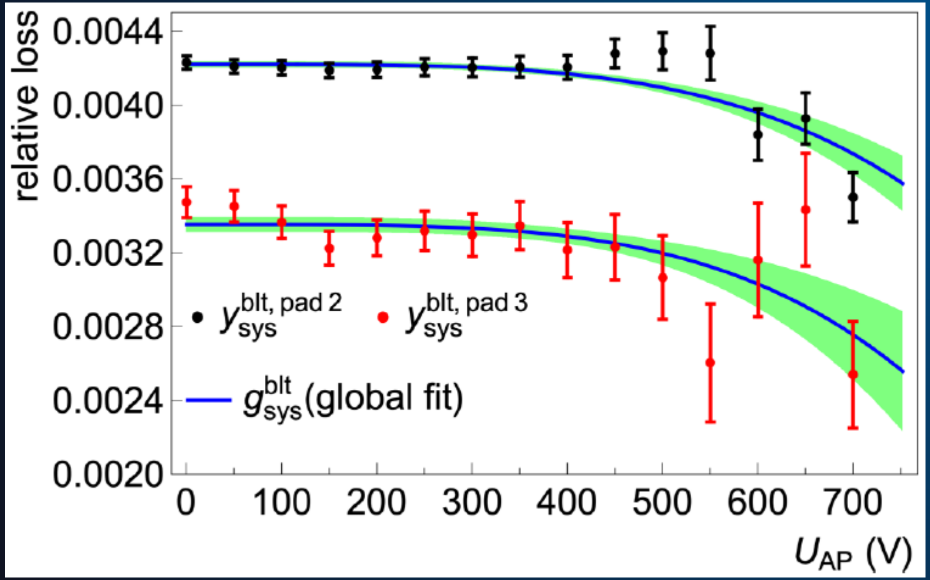
Pulse height spectra

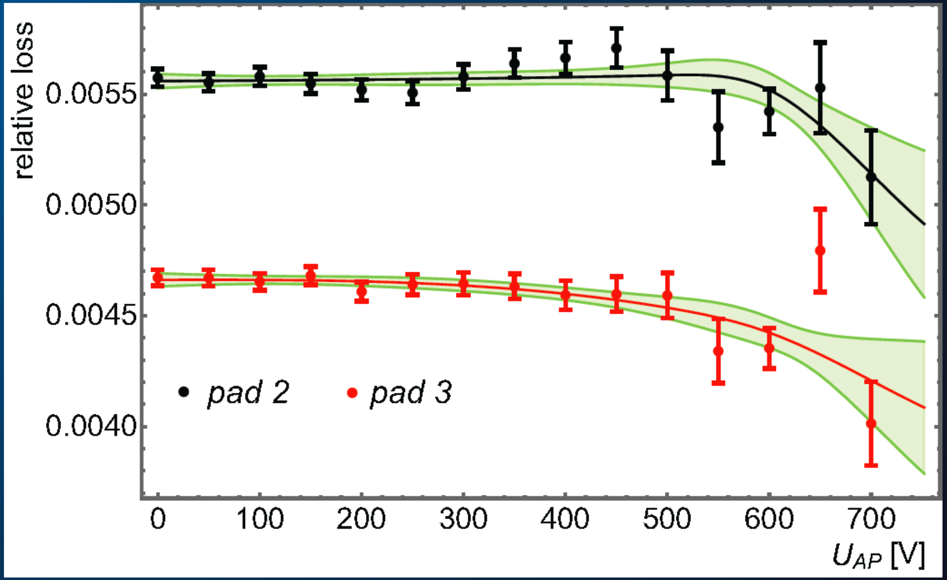


Below threshold losses

Without channeling

With channeling





PERKEO III versus aSPECT

Reanalysis aSPECT [arXiv:2308.16170v1 [nucl-ex] 30 Aug 2023]

$\lambda = -1.2668(27)$

$a = -0.10402(82)$

Old value: $\lambda = -1.2677(28)$

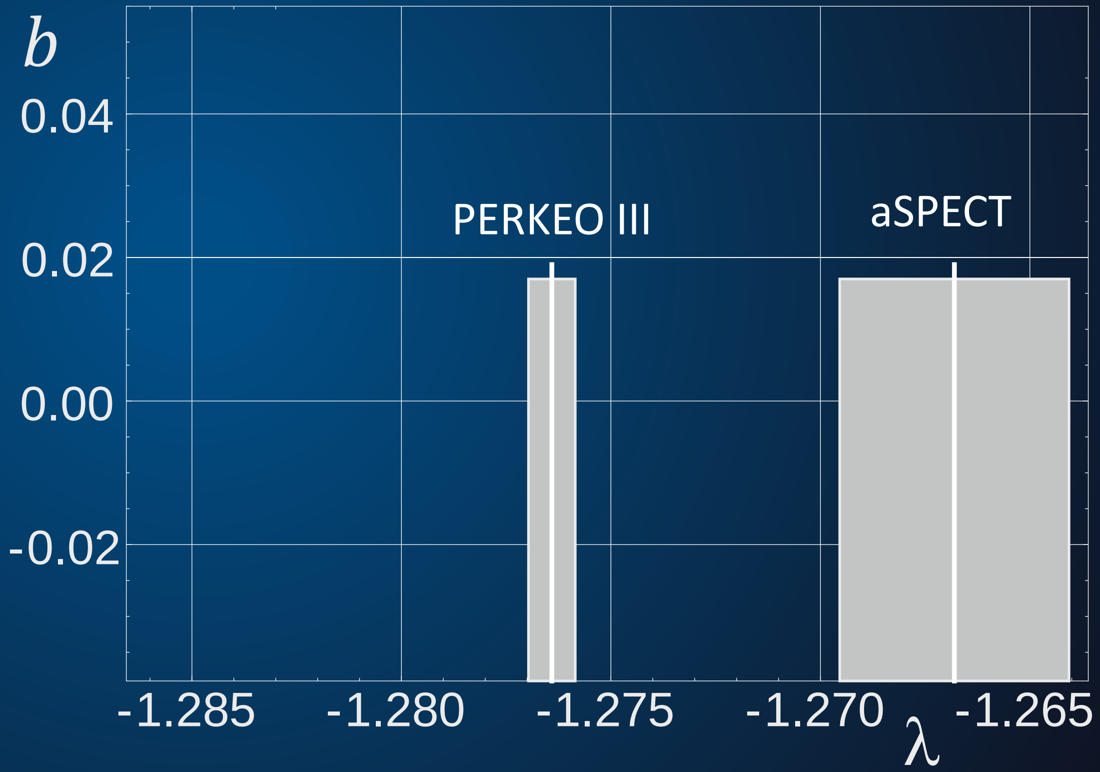
SM: $b = 0$

PERKEO III

[Phys.Rev.Let. **125**, 112501 (2020)]

$\lambda = -1.27607(68)$

$A = -0.11972(25)$



PERKEO III versus aSPECT summary

Reanalysis aSPECT [arXiv:2308.16170v1 [nucl-ex] 30 Aug 2023]

a= $-0.1046(14)$ $b = -0.010(19)$

$\rho_{a,b} = 0.808$

Beyond SM

PERKEO III

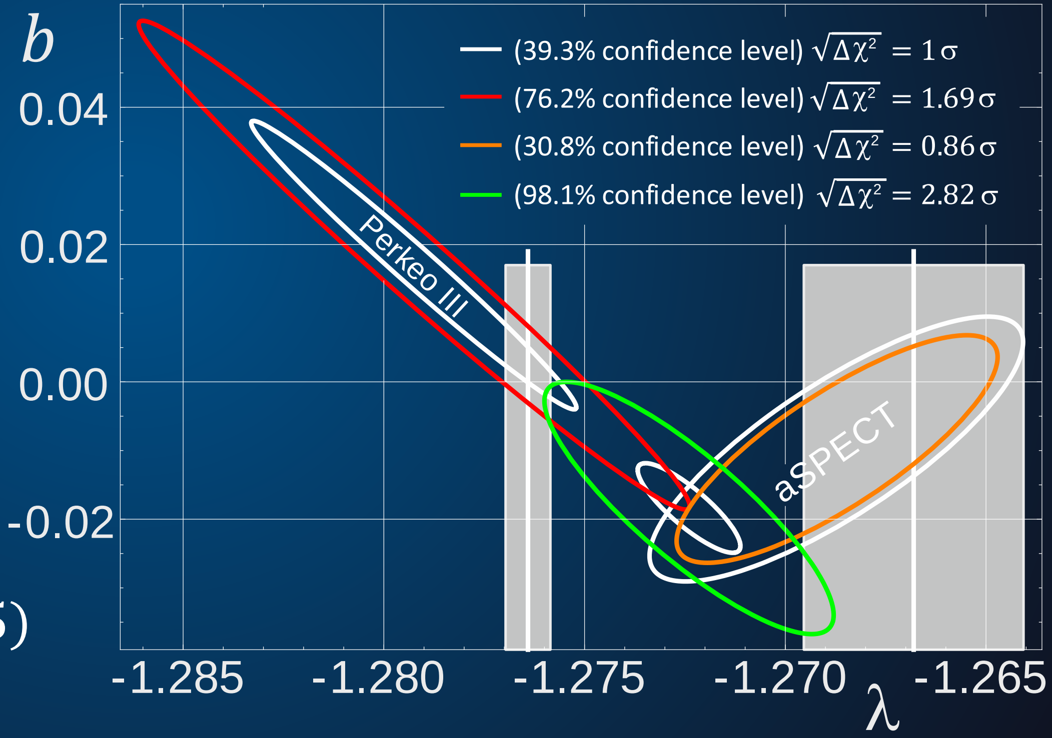
[Phys.Rev.Let. **125**, 112501 (2020)]

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

$b = 0.017(20)_{stat}(3)_{sys} = 0.017(21)$

Combined result

$\lambda = -1.2724(13), b = -0.0184(65)$



Outlook

- Ongoing data analysis of unpolarized data set (2020) measured with PERKEO III. Likely results in an independent b value with reduced errors.
- Upcoming experiments Nab and PERC likely can solve the puzzle PERKEO III versus aSPECT.
- Nab (at the fundamental beam line at the SNS, Oak Ridge National Laboratory) will measure a and b with a somewhat different approach to measure the proton energy spectrum and therefore different systematics compared to aSPECT.
- PERC will measure A and b. Details see next talk by Bastian Märkisch.

Thank You