Results from the *a*SPECT experiment

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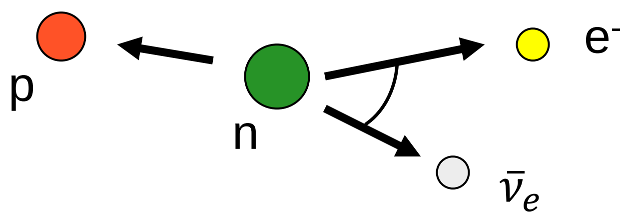
N.B.: I thank W. Heil, C. Schmidt, and G. Konrad for slides.

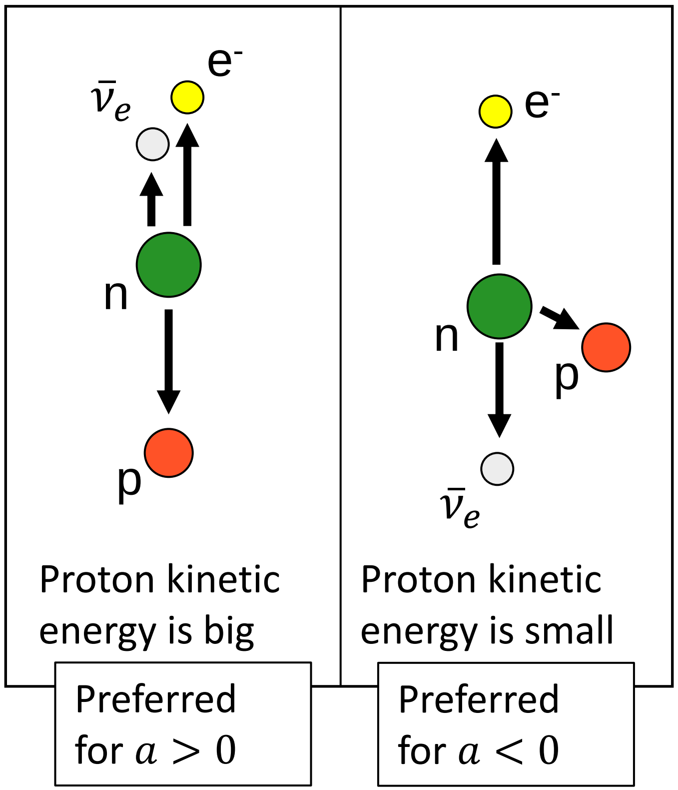
The Neutrino Electron Correlation and the Proton Spectrum in Neutron Decay

The correlation coefficient *a*

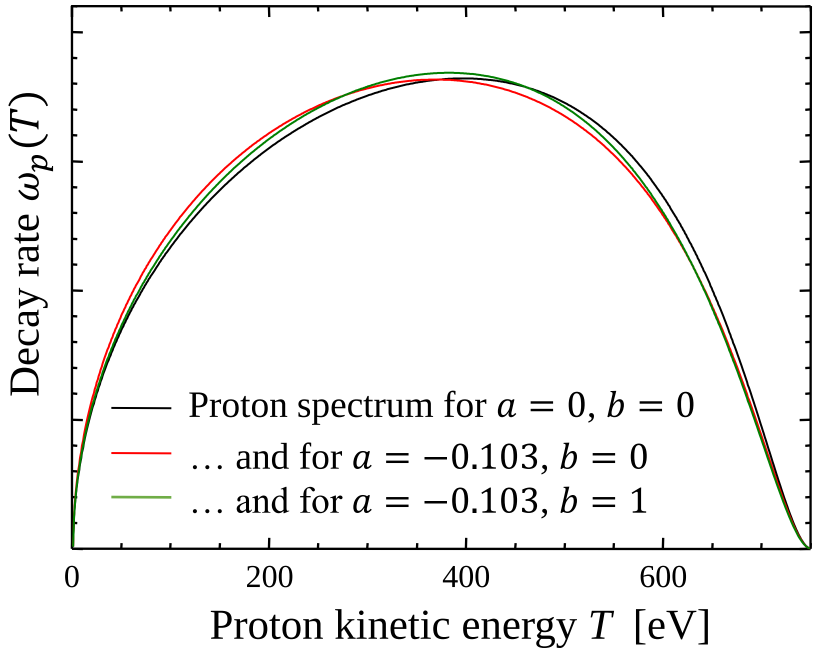


$$d\Gamma \propto \rho(E_e)\left(1 + a\,\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\,\frac{m_e}{E_e}\right)$$

C.F. v. Weizsäcker, Z. f. Phys. 102,572 (1936), M. Fierz, Z. f. Phys. 104, 553 (1937), J.D. Jackson et al., PR 106, 517 (1957)

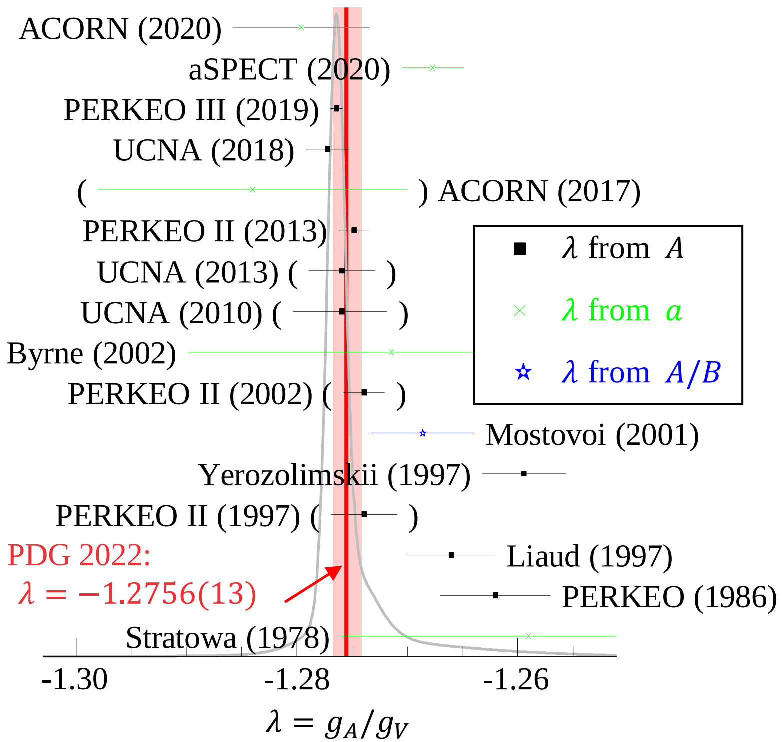


Sensitivity of the proton spectrum to *a* and *b*:



Motivation

1. Goal: Determination of ratio $\lambda = g_A/g_V$ from $A = -2\left(\mathrm{Re}\,\lambda + |\lambda|^2\right)/\left(1+3|\lambda|^2\right)$ or $a = \left(1-|\lambda|^2\right)/\left(1+3|\lambda|^2\right)$:



2. Goal: Test of unitarity of Cabibbo-Kobayashi-Maskawa (CKM) matrix from $|V_{ud}|^2 \propto \tau_n^{-1}\left(1+3\lambda^2\right)^{-1}$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

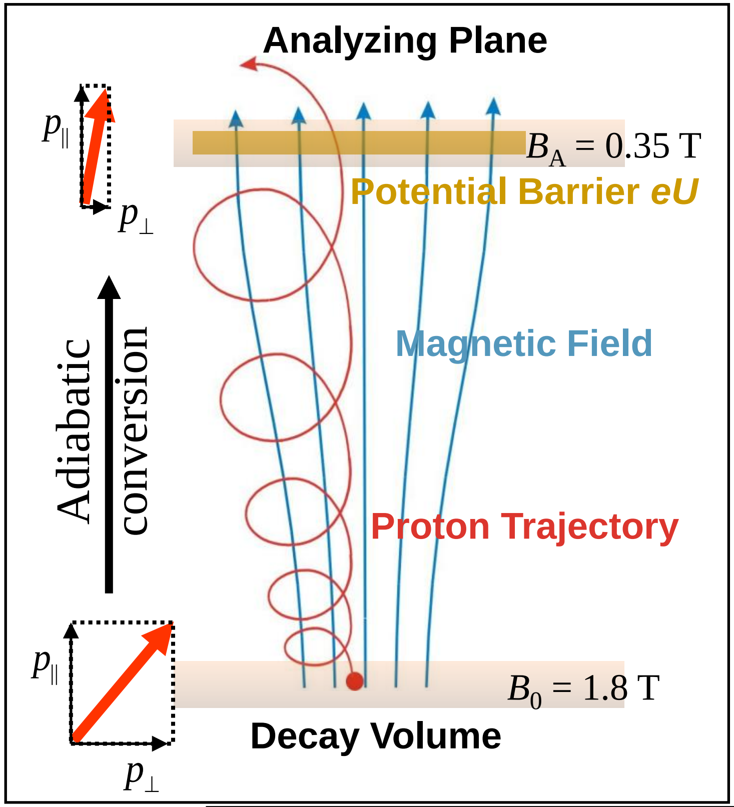
Various unitarity tests possible; the most precise one in the first row:

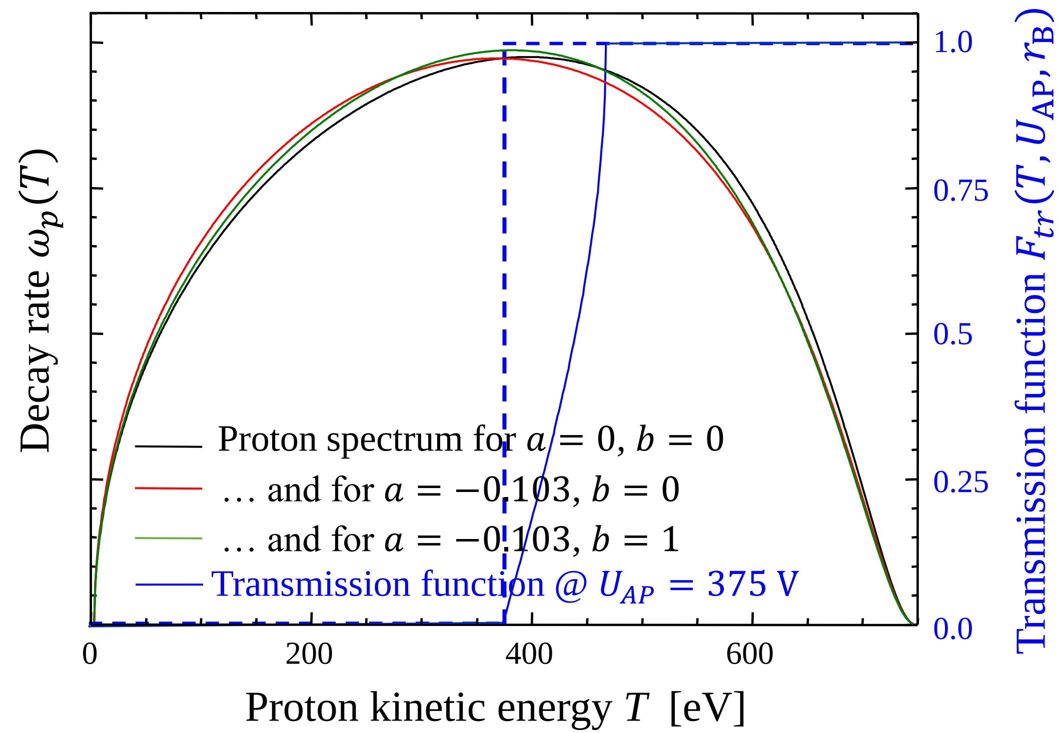
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \overset{!}{=} 1$$

This seems to be violated by $2-3\sigma$ (PDG2022)

3. Goal: Other searches for Beyond Standard Model Physics: S,T interactions (fermions with "wrong" helicity), e.g. through additional W or Z bosons; weak magnetism; second class currents, …

Principle of a Retardation Spectrometer

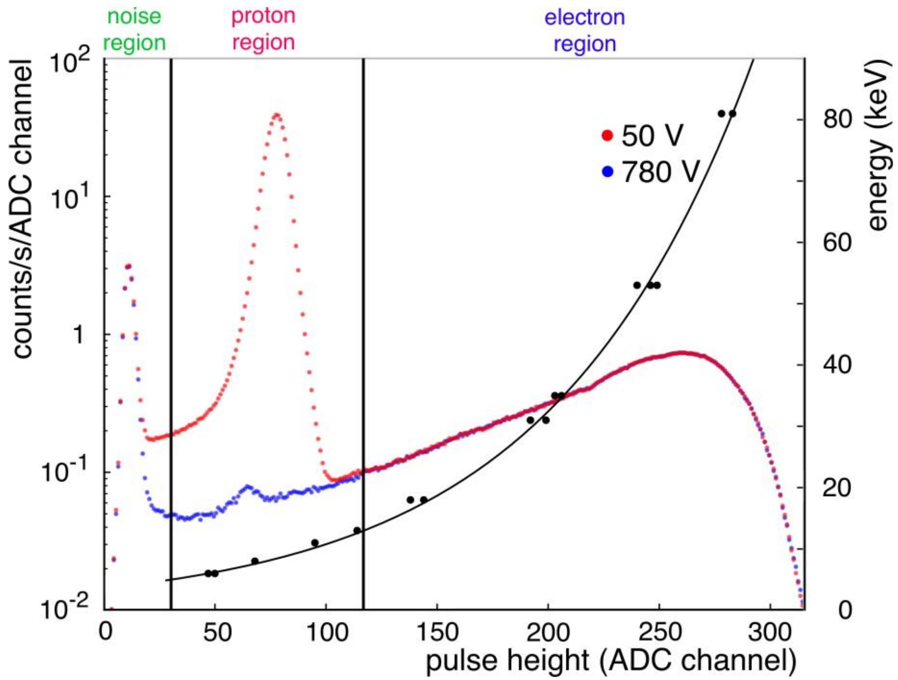


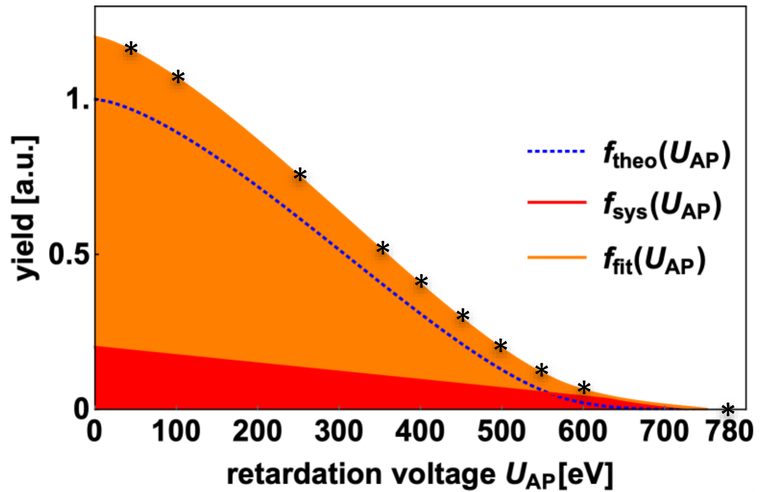


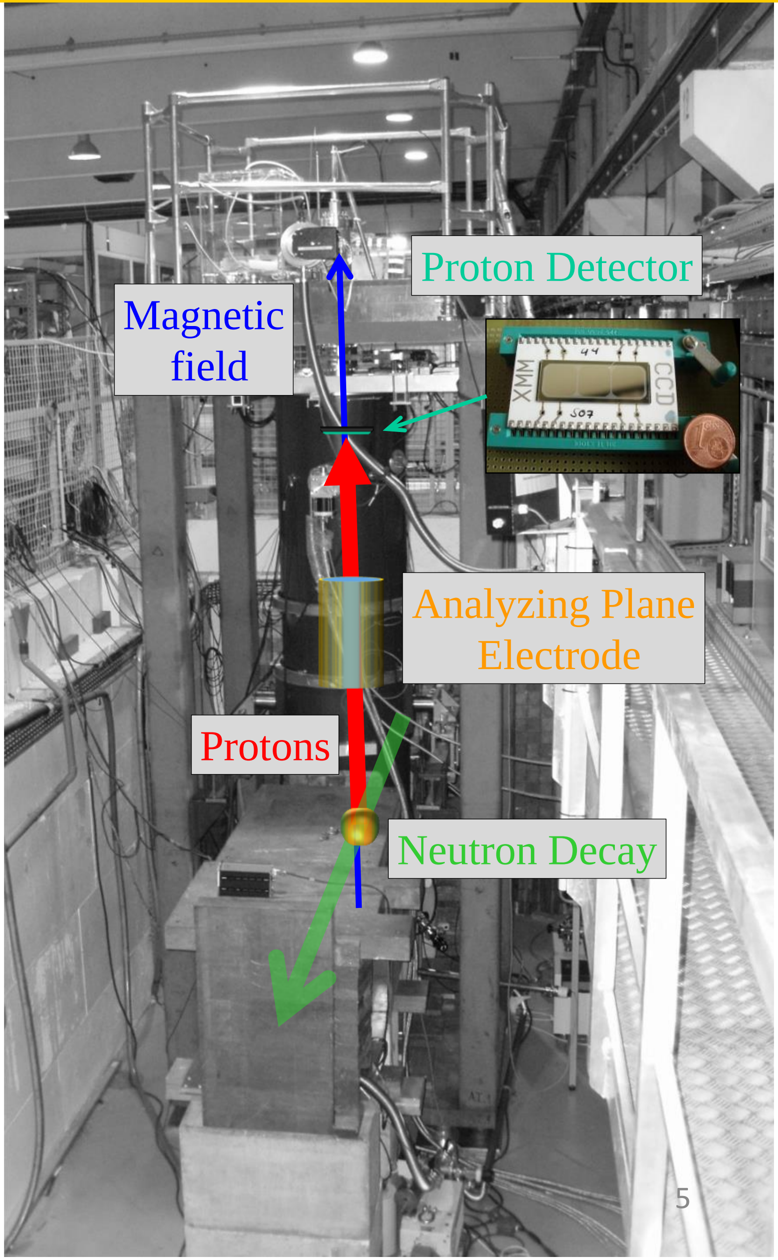
Transmission function $F_{tr}(T, U_{AP}, r_B = B_A/B_0)$ in the adiabatic limit:

$$F_{tr}(T, U_{AP}, r_B) = \begin{cases} 0 & T < eU_{AP} \\ 1 - \sqrt{1 - r_B^{-1}\left(1 - \frac{eU_{AP}}{T}\right)} & \text{otherwise} \\ 1 & T > eU_{AP}/(1 - r_B) \end{cases}$$

Principle of *a*SPECT spectrometer







Global fit

$$f_{fit}(U_{AP}) = f_{theo}(U_{AP}) + \sum f_{sys}^{j}(U_{AP})$$

$$\int w_p(T,a)F_{tr}(T,U_{AP},r_B)dT$$

$$\sum f_{sys}^{j}(U_{AP},r_B,a,N_0,\{fpar_j\})$$

Minimization of global χ^2:

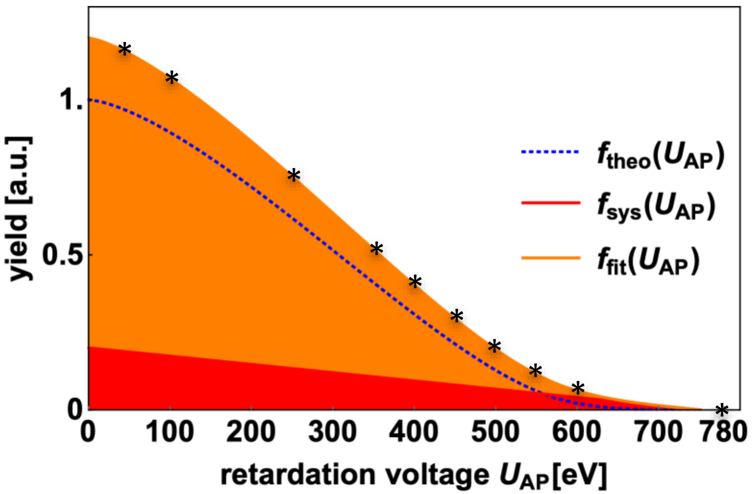
This is the usual fit to the model function after inclusion of systematic corrections

$$\chi^2_{global} = \sum_{configs,pads}\left(\sum_i^n \frac{\left(y_{exp,i} - f_{fit}(U_{AP},r_B,a,N_0,\{fpar_j\})\right)^2}{\left(\Delta y_{exp,i}\right)^2} + \sum_j \sum_k^{n_j} \frac{\left(y_{sys,k}^{j} - g_{sys}^{j}(U_{AP},T,r_B,\{gpar_j\})\right)^2}{\left(\Delta y_{sys,k}^{j}\right)^2}\right)$$

These are fits to the results of auxiliary measurements and simulations, e.g. to the measurements of $r_B = B_A/B_0$

Systematic uncertainties

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

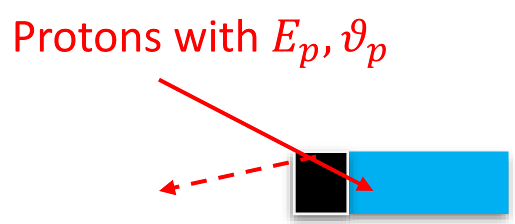


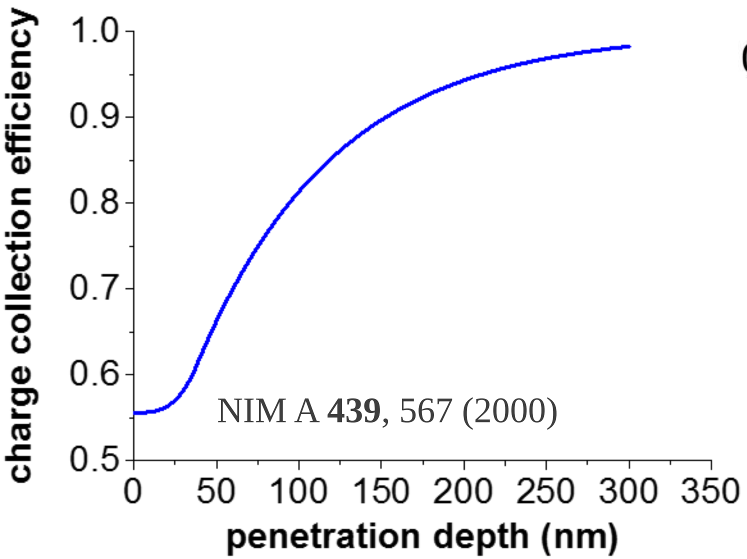
$$f_{fit}(U_{AP}) = f_{theo}(U_{AP}) + f_{sys}(U_{AP})$$

$$\boxed{f_{fit}(U_{AP}) = f_{theo}(U_{AP}) + \sum f_{sys}^{j}(U_{AP})}$$

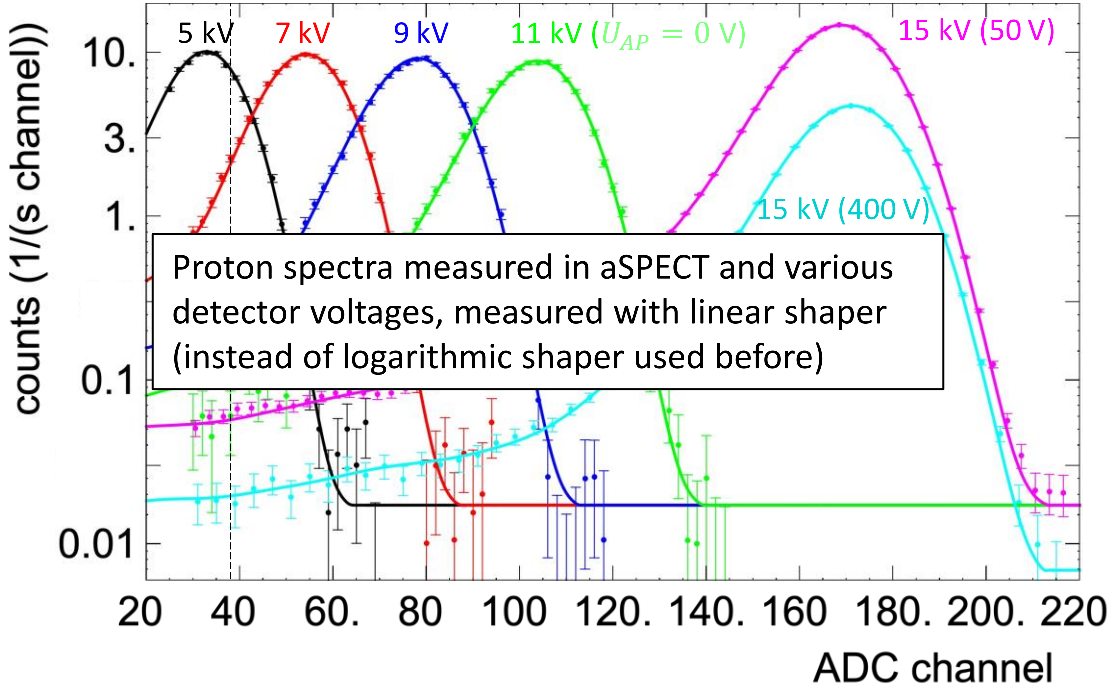
Proton detection efficiency

Silicon drift detector (SDD)

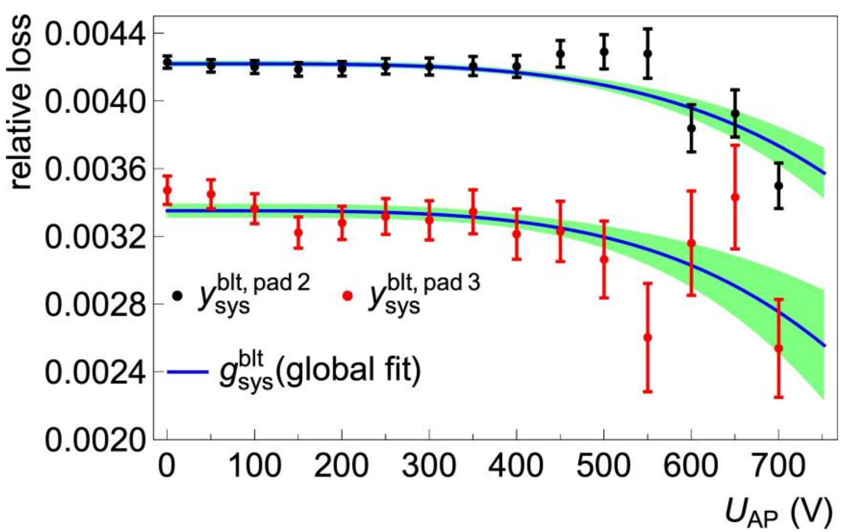




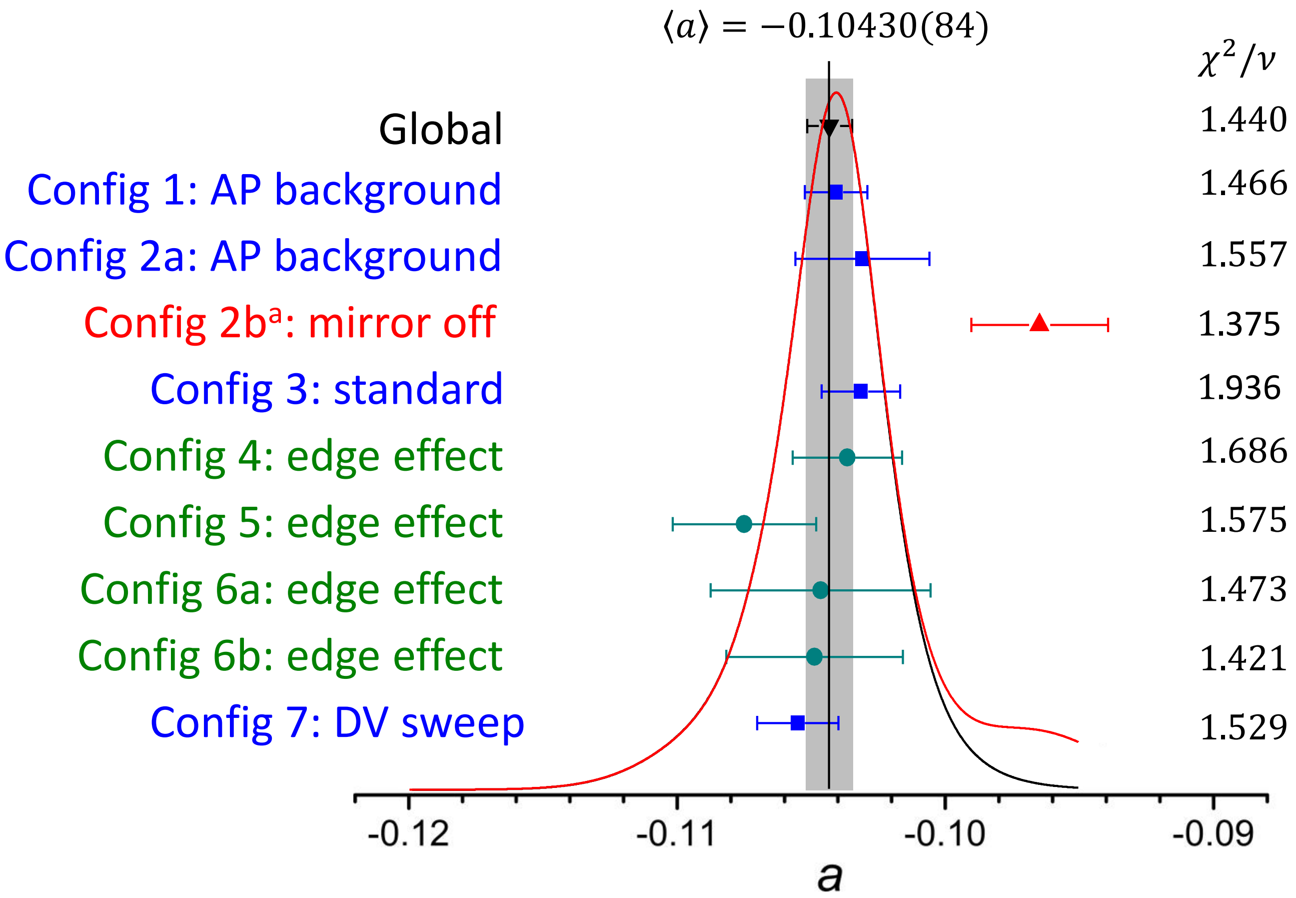
Charge collection efficiency in active layer of similar detector (Simulation with SRIM)



Proton spectra measured in aSPECT and various detector voltages, measured with linear shaper (instead of logarithmic shaper used before)



Global fit results



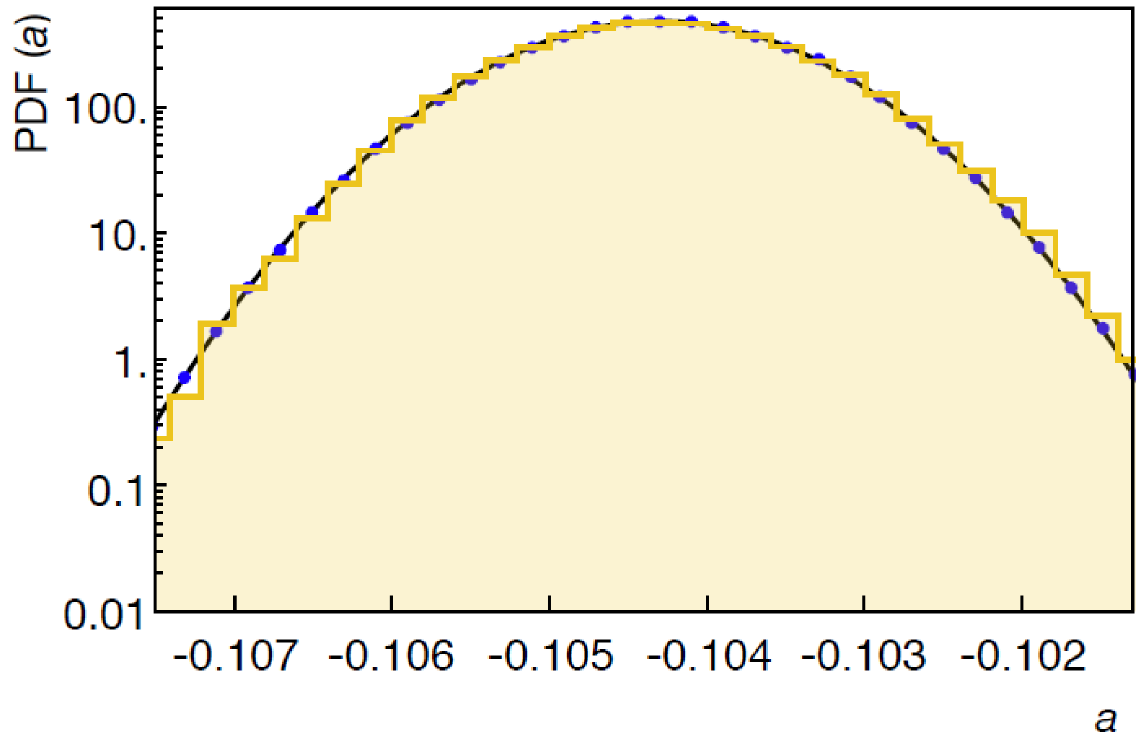
[a] Config 2b is not used in fit, as corrections from proton backscattering from bottom flange or eventual unwanted neutron beam polarization are undetermined.

Discussion of uncertainty

Three methods to determine mean value and uncertainty for a:

- Normal distribution from χ^2- fit shown on last slide, after scaling (black line).
- Maximum likelihood profile (blue points)
- $PDF(a)$ from Markov chain Monte-Carlo calculation (yellow line).

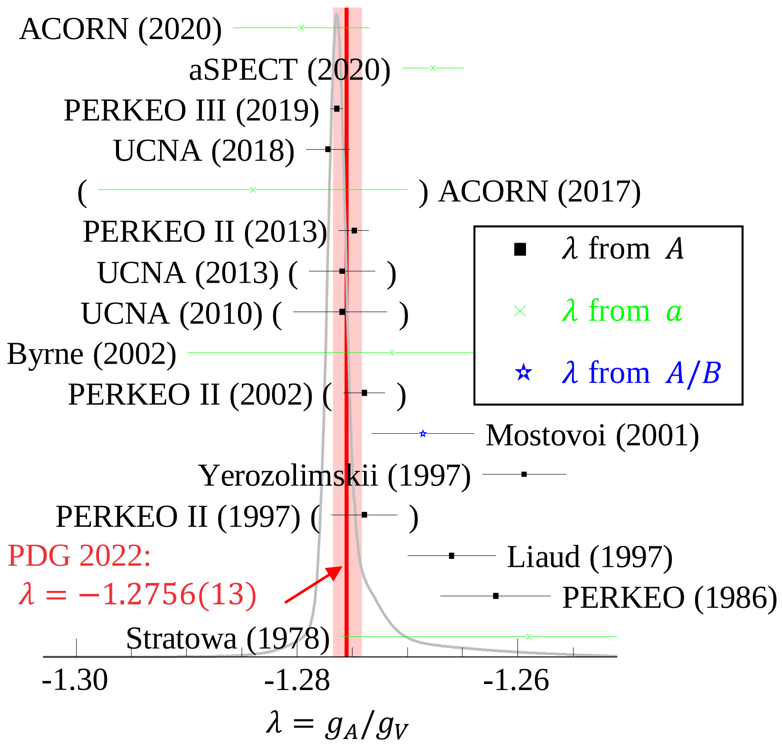
All methods find the same mean value and uncertainty.



Potential reason for bad p-value: Non-Gaussian fluctuations of neutron beam fluence, or HV-induced background.

Error scaling in $y_{exp,i}$	Error scaling in $y^j_{sys,k}$	χ^2_{global}/ν	p-value	a
$1\times$	$1\times$	1.44	$3.1 \cdot 10^{-6}$	$-0.10430(84)$
$1.2\times$	$1\times$	1.17	2.9%	$-0.10430(84)$
$1\times$	$1.2\times$	1.27	0.18%	$-0.10433(82)$
$1.2\times$	$1.2\times$	1.00	0.49	$-0.10432(80)$

Short discussion



- ACORN and aSPECT values for λ are not significantly different, although they tell a different story.
- aSPECT result is consistent with prior (2018) and new (2022) PDG average, but is in tension with result from PERKEO III (3 sigma).
- New average (that includes PERKEO III, aSPECT, and ACORN) is $\lambda = -1.2756(13)$ with scale factor $S = 2.6$ (PDG 2022)

Further analysis

The following slides are a preview on further analysis efforts. They are **preliminary**, that means, they are not meant for further use. Numbers may change slightly until submission for publication (planned for end of this month). The most important findings are:

Uncertainty in retardation voltages: Due to a programming mistake, the random component of the uncertainty in the retardation voltage settings was not propagated into the global fit. We are correcting this, and we are obtaining a small shift of the central in our result for a.

Proton detection efficiency: We added two additional effects to our model for the proton detection efficiency:

- A small number of protons are backscattered from the detector. Most backscattered protons pick up an electron and are neutralized. This was not visible in our previous SRIM simulation, and we had overestimated the probability that the protons return to the detector and deposit additional energy in their second attempt.
- Our detector simulation didn't include channeling, that is, the movement of protons into the crystal along major crystal axis which leads to increased range. We verified the effect with a special version of SRIM (CRYSTAL-TRIM)*.

While both effects alter the proton detection efficiency substantially (in average by $3 \cdot 10^{-4}$), the effect on our a value after proton detection efficiency calibration is negligible.

* We thank W. Khalid (TU Vienna) for bringing up the issue and for independent investigations. More information will be in his upcoming Ph.D. thesis

Further analysis (2)

Radiative corrections: No physics change, but we improved numerical accuracy to obtain smoother correction from F. Glück, ArXiV: 2205.14397. Effect on a is negligible.

Non-Standard model analysis: We included the possibility of a non-zero Fierz term b into our global fit. The Fierz-term b and the neutrino electron correlation coefficient a are strongly correlated.

New result (preliminary, see caveats on last slide):

	a	Δa	b	Δb	χ^2_{global}/ν	p-value
aSPECT 2020 (SM)	-0.10430	0.00084			$1.44\ (\nu = 268)$	$3.1 \cdot 10^{-6}$
Reanalysis, SM	-0.10407	0.00082			$1.25\ (\nu = 268)$	$3.5 \cdot 10^{-3}$
Reanalysis, BSM	-0.10451	0.00140	-0.0082	0.0194	$1.25\ (\nu = 267)$	$3.2 \cdot 10^{-3}$

Other recent determination of the Fierz term b in neutron beta decay:

$b = 0.066(41)(24)$ (UCNA)

$b = 0.017(20)(3)$ (PERKEO III)

Combined analysis of aSPECT AND PERKEO III: In aSPECT, the Fierz term b is correlated with λ. In PERKEO III (or UCNA), they are anti-correlated. Combining the results of both, one can reconcile the difference between the λ values of aSPECT and PERKEO III:

$$\lambda_c = -1.2725(13),\ b_c = -0.0181(65).$$

However, high energy physics data and pion decay disfavor this interpretation.

Summary

The aSPECT collaboration determined the neutrino electron correlation coefficient a:

$$a = -0.10430(84) \quad \text{(SM fit)}, \quad \lambda = -1.2677(28)$$ PRC 101, 055506 (2020)

A slight revision, and a BSM analysis which allows for a non-zero Fierz term, will be submitted for publication soon.

New experiments are needed, and are under preparation (PERC, UCNA+, Nab, pNab) that determine λ from the beta asymmetry A and neutrino electron correlation coefficient a with higher accuracy.

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** not on picture   +Ph.D. Student with aSPECT as main project*