τSPECT: measurement of the free neutron lifetime to test hadronic contributions to electroweak precision observables

Town Meeting: Hadron Physics in Horizon Europe

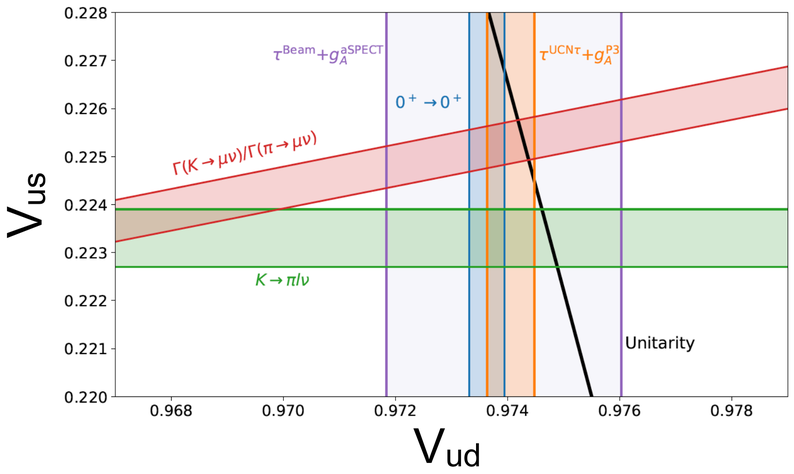
Prof. Dr. Martin Fertl (presenter: Prof. Dr. Randolf Pohl)
July 2nd, 2025

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

The STRONG 2025 physics case for neutron lifetime experiments

CKM matrix unitarity



Best fit deviates by 2.8σ
from unitarity circle

Figure from:
L. Hayen, Ann. Rev. Nucl. Part. Sci. 74 (2024) 497

Further sources:
V.Cirigliano, A. Crivellin, M. Hoferichter,
M. Moulson; Physics Letters B 838 (2023) 137748

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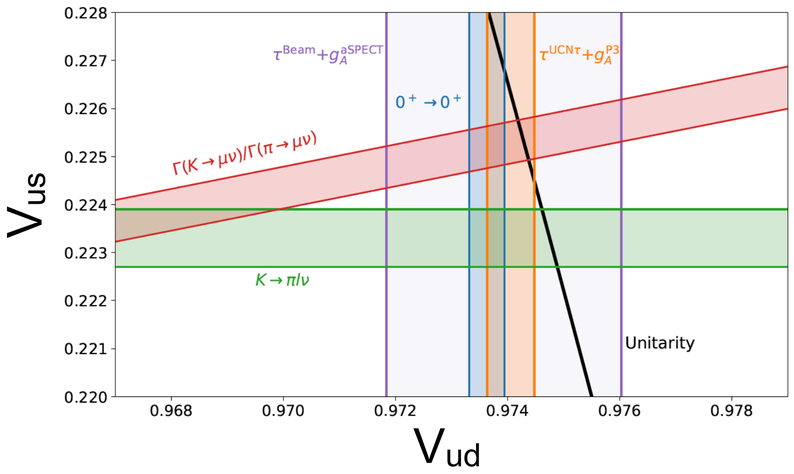

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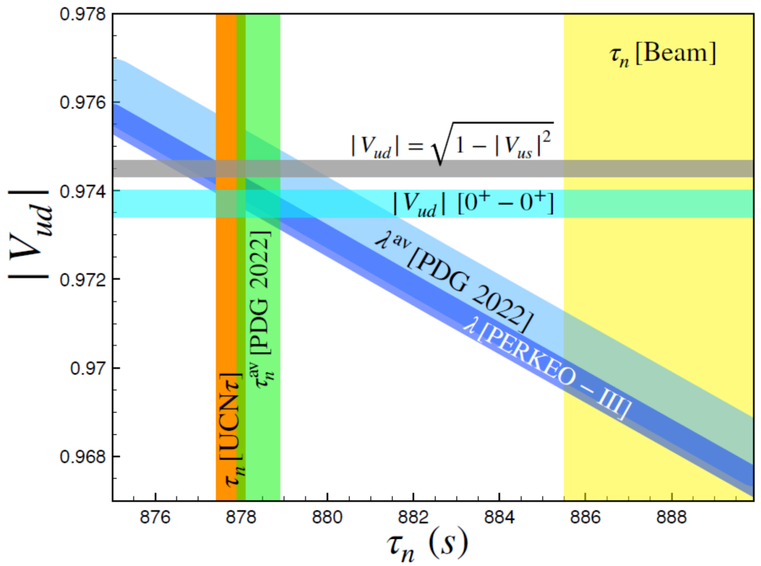

Tensions among various methods to extract V_{ud}, in particular PDG averages and most precise measurements

M. Gorchtein and C.-Y. Seng;
Universe 2023, 9(9), 422

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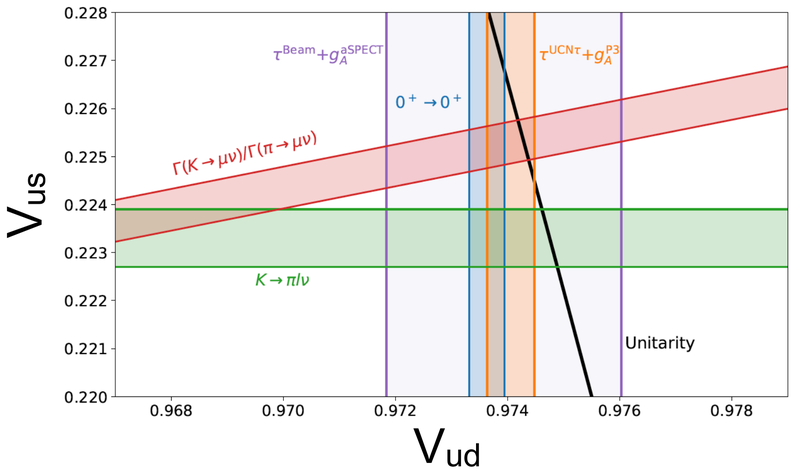

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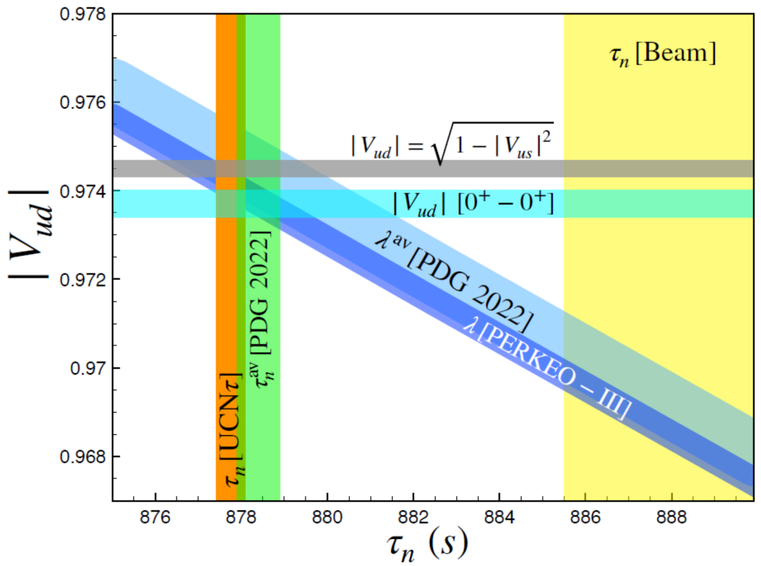

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SM relation of V_{ud}, λ, and τ_n

$$|V_{ud}|^2 = \frac{(5263.284 \pm 0.017)\ \mathrm{s}}{\tau_n (1+3g_A^2)(1+45.37(27)\times 10^{-3})(1+27.04(7)\times 10^{-3})}$$

Current uncertainties:

SM theory:	2.7 x 10^{-4}
g_A (Perkeo III):	4.4 x 10^{-4}
τ_n (UCNτ, 2024):	2.7 x 10^{-4}
V_{ud} (UCNτ and PERKEOIII):	4.2 x 10^{-4}
V_{ud} (0^+)	3.0 x 10^{-4}

Longterm science goal:

V_{ud} at 10^{-4} w/o nucl. structure corrections

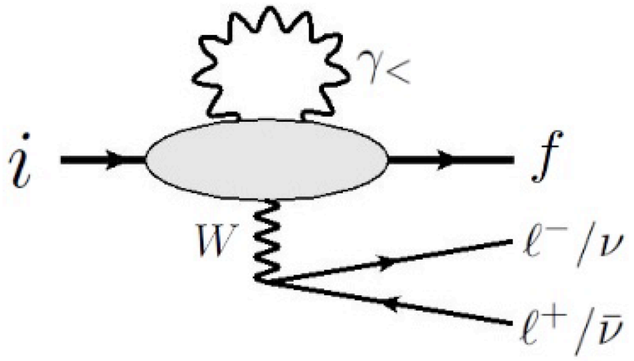
P. Vander Griend et al., arXiv:2501.17916
B. Märkisch, et al., Phys. Rev. Lett. 122, 242501, 2019R.
R. Musedinovic, et al., arXiv:2409.05560
L. Hayen, Ann. Rev. Nucl. Part. Sci. 74 (2024) 497

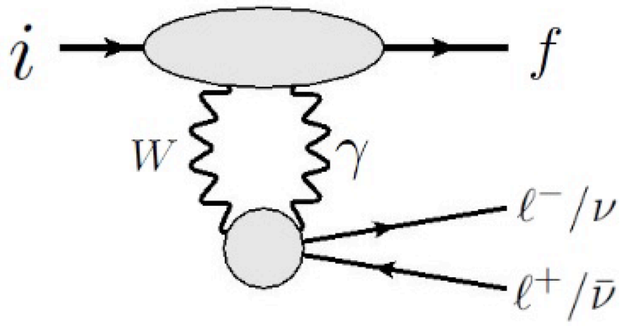
The STRONG 2025 physics case for neutron lifetime experiments: hadronic physics

A 10^{-4} - test of **CKM unitarity**, free of nuclear structure corrections needs a commensurate **neutron-based value of V_{ud}** from the **measurements of τ_n and λ**, to fully leverage the sensitivity to BSM physics.

Precision hadronic physics calculations required and in turn **tested by neutron experiments.**

One-loop Feynman diagrams of electroweak RC that probe non-perturbative strong interactions.





M. Gorchtein and C.-Y. Seng; Universe 2023, 9(9), 422

$\Box^A_{\gamma W}$ (axial-vector) and $\Box^V_{\gamma W}$ (vector):

Determination through:

⇒ dispersive and non-dispersive approaches

C.-Y. Seng, et al., Phys. Rev. Lett. 121, 241804, 2018

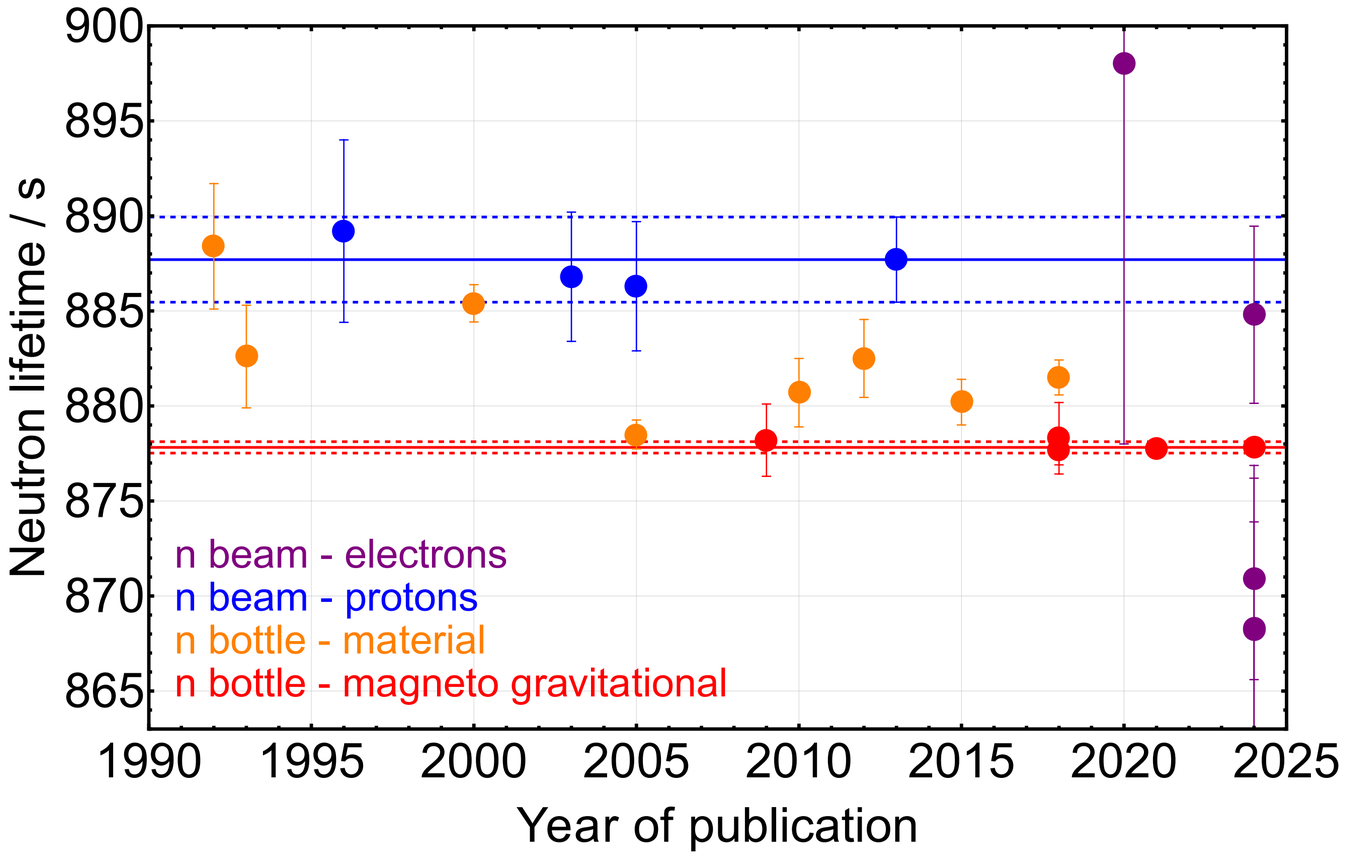
⇒ lattice QCD

Ma, et al., Phys. Rev. Lett. **132**, 191901, 2024

Ideal synergy with Mikhail Gorshteyn.

The STRONG 2025 physics case for neutron lifetime experiments

Neutron lifetime puzzle



New in 2024

Update from cold neutron beam coupled to ^{3}He-doped TPC at JPARC

Y. Fuwa, et al., arXiv:2412.19519

Improved result from magneto gravitational trap experiment UCNτ

$$\tau_{\mathrm{n,UCN}\tau,2024} = \left(877.82 \pm 0.22\ {}_{\mathrm{stat.}}\ {}^{+0.22}_{-0.17}\ {}_{\mathrm{syst.}}\right)\ \mathrm{s}$$

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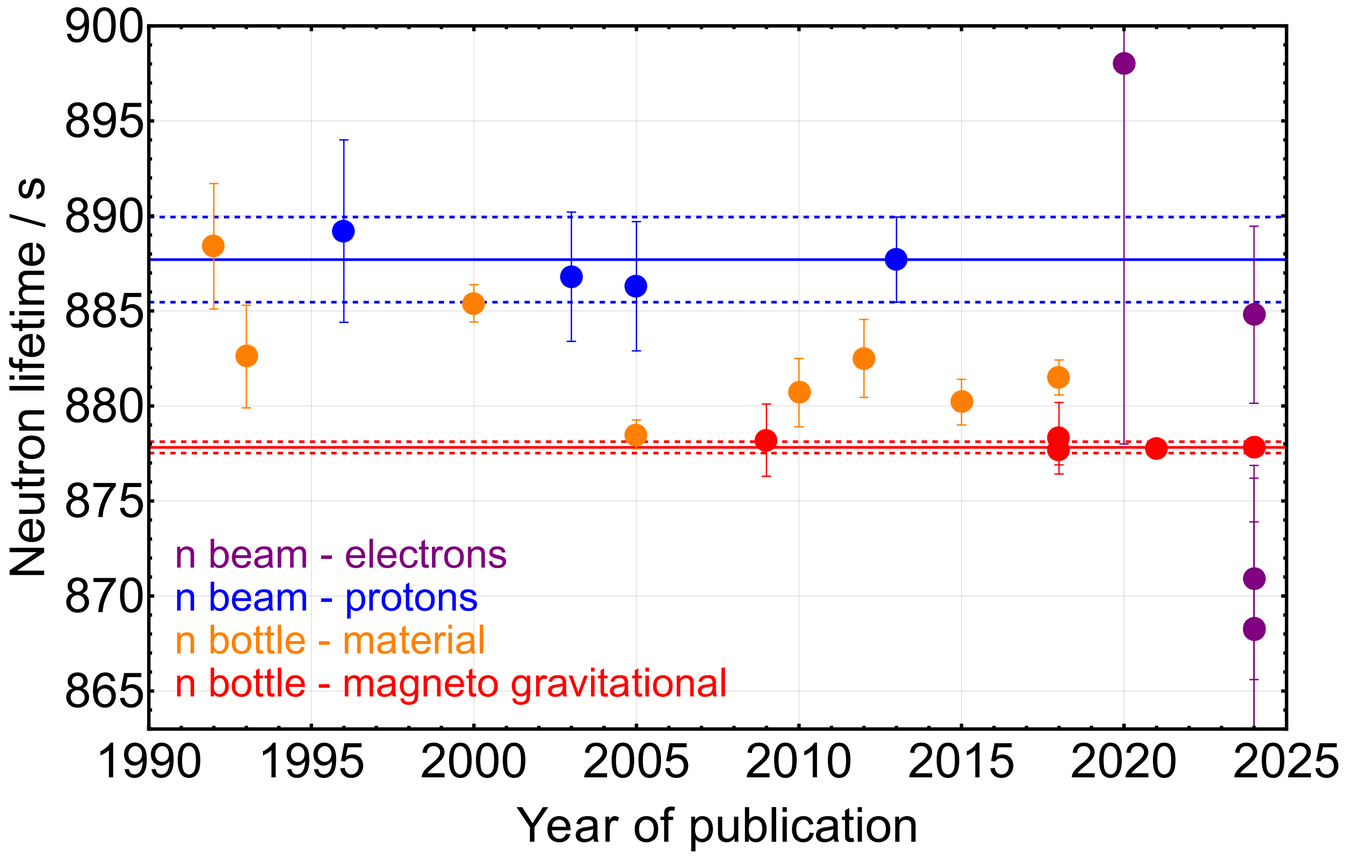

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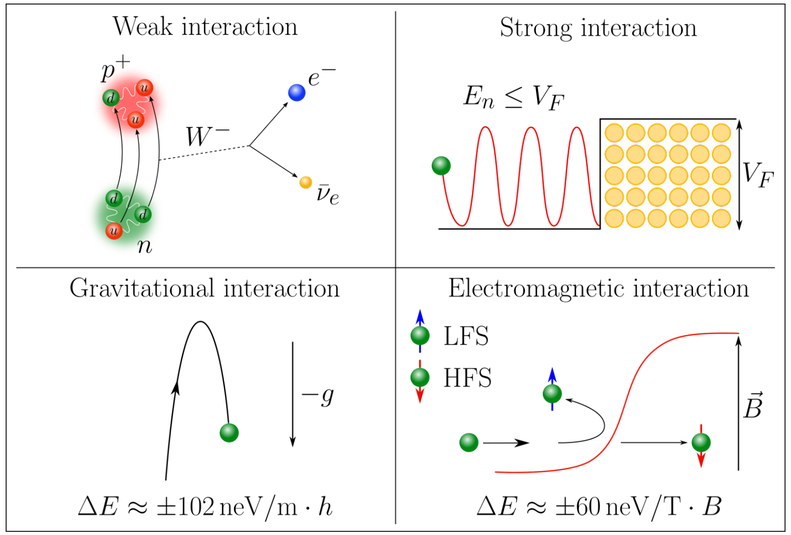
Persistent discrepancy between results from “cold beam decay” and “UCN storage” experiments at more than 4σ-level

Urgent need for complementary ans independent experiment!

Fully-magnetic UCN storage in the τSPECT experiment

UCN (ultra cold neutrons) are special as their kinetic energy (< 300 neV(!)) is on the same scale as their magnetic, gravitational and strong interaction with matter and fields

⇒ confinement in e.g. fully magnetic “bottles”



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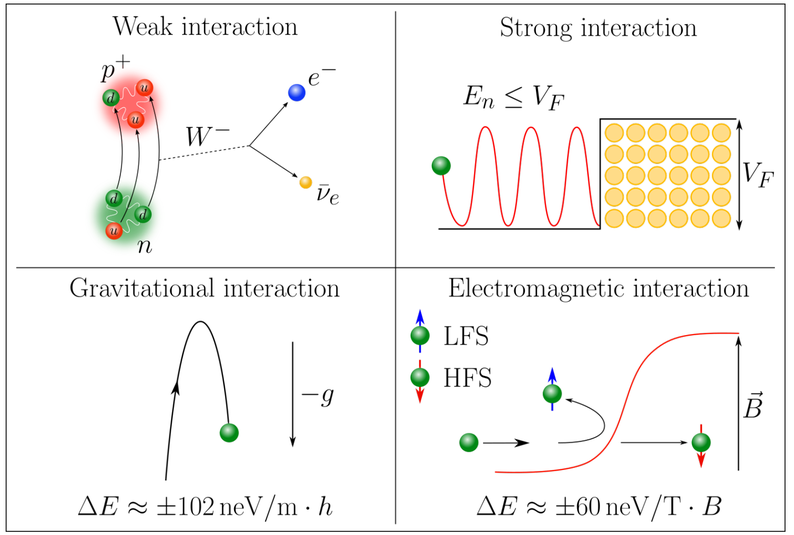
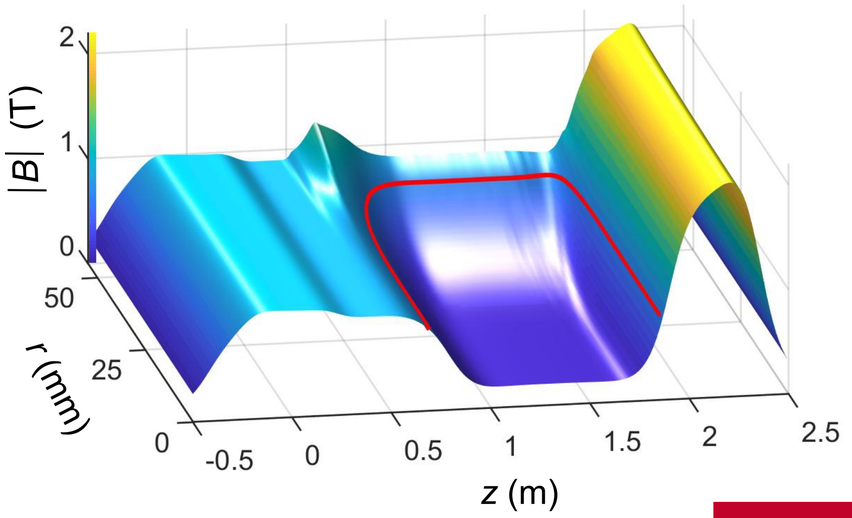
τSPECT uniquely deploys:

- a fully magnetic bottle built from SC and permanent magnets
- in-situ spin polarization of UCN (at magnetic wall)
- in-situ spin-flip to make externally produced UCN trappable without moving or ramping magnetic walls
- in combination with in-situ neutron detection





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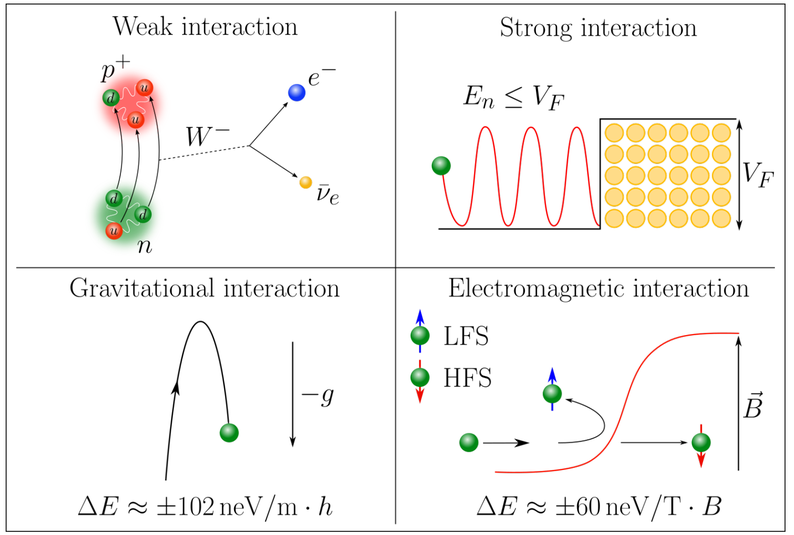

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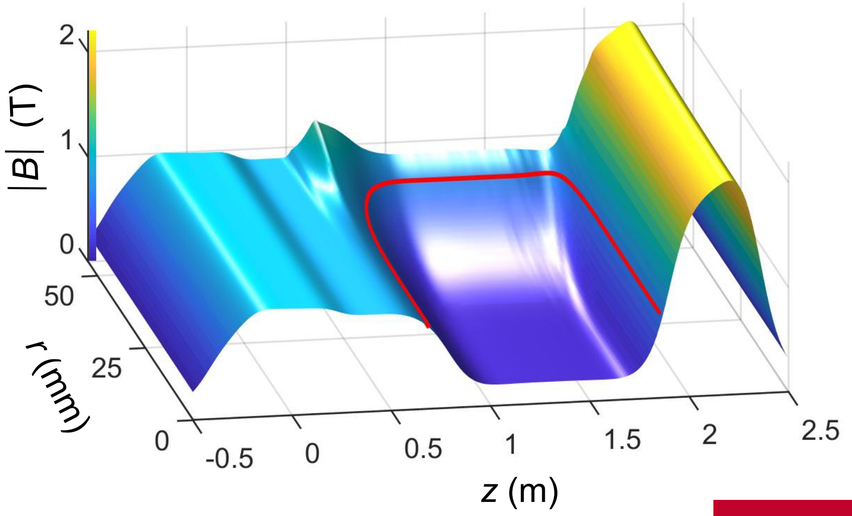
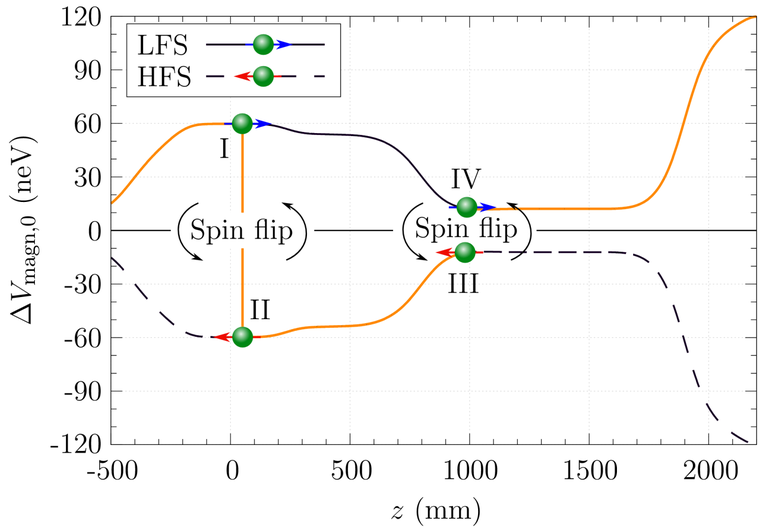


τSPECT is highly complementray to UCNτ experiment and will scrutinize their stated uncertainties with the ultimate goal to surpass their sensitivity in the future.

Initial results of the τSPECT experiment

Successful demonstration of the unique UCN-spin-flip loading scheme in Mainz



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τSPECT: a spin-flip loaded magnetic ultracold neutron trap for a determination of the neutron lifetime

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Journal of Physics G: Nuclear and Particle Physics, Volume 51, Number 11

Citation J Auler *et al* 2024 *J. Phys. G: Nucl. Part. Phys.* **51** 115103

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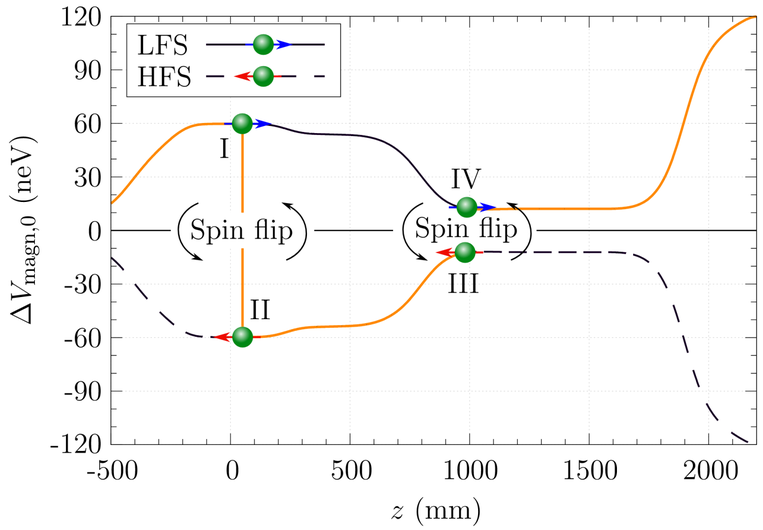
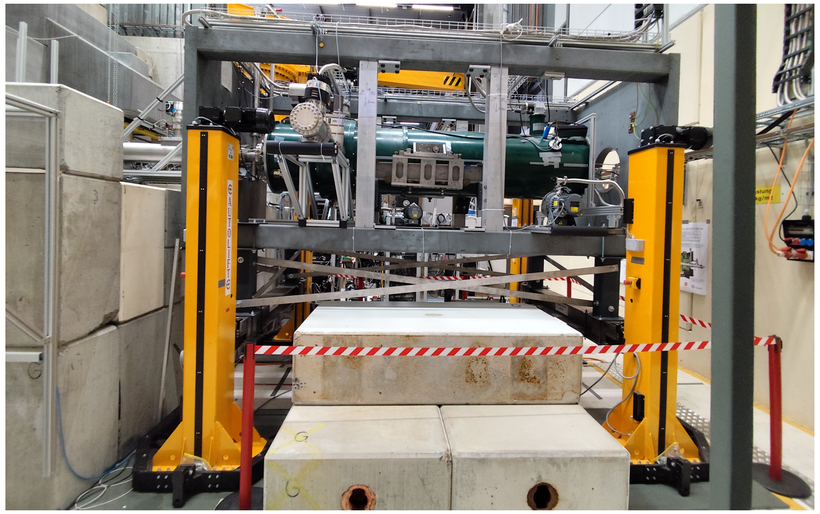


Successfully transported, and reassembled τSPECT at the UCN source of PSI in 2023! Since then high performance operation!



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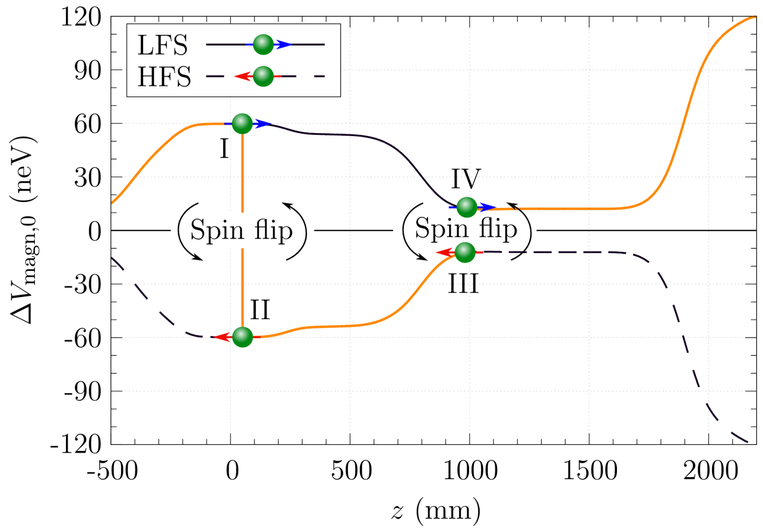

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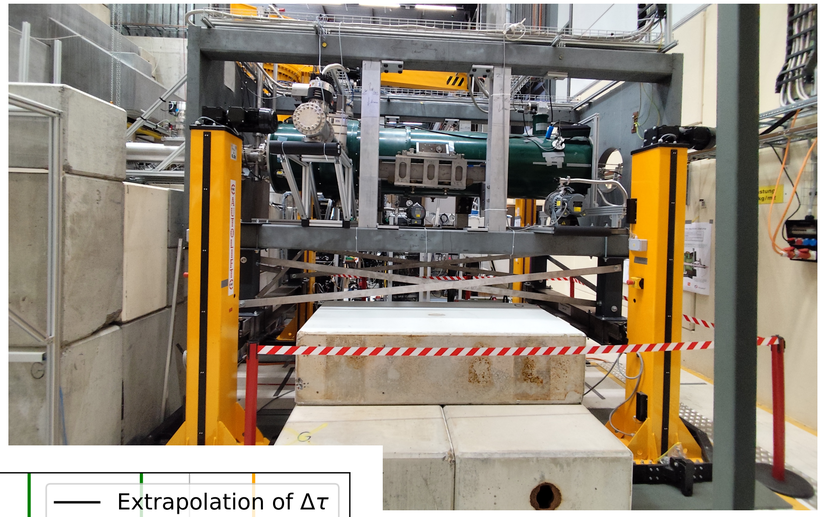
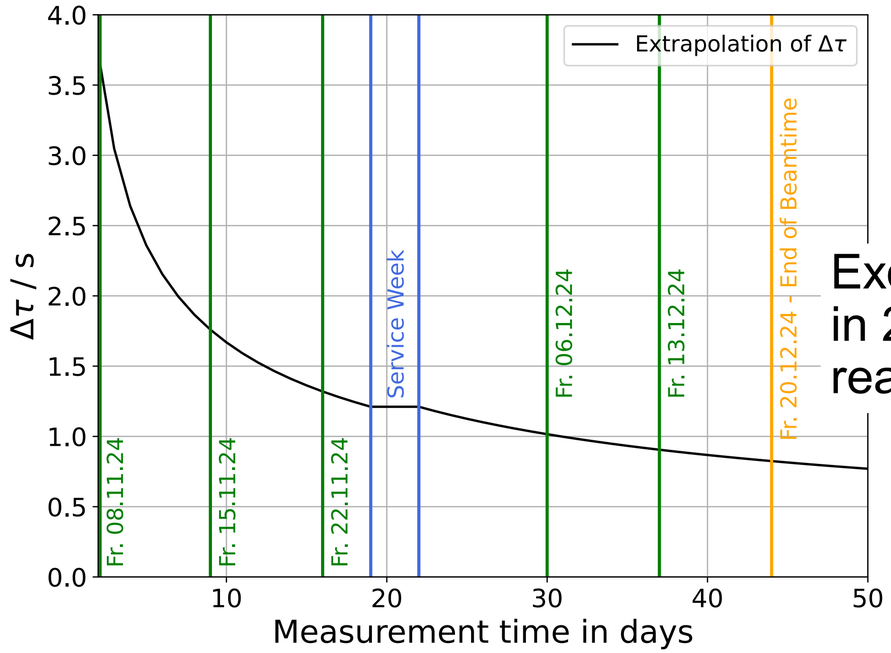
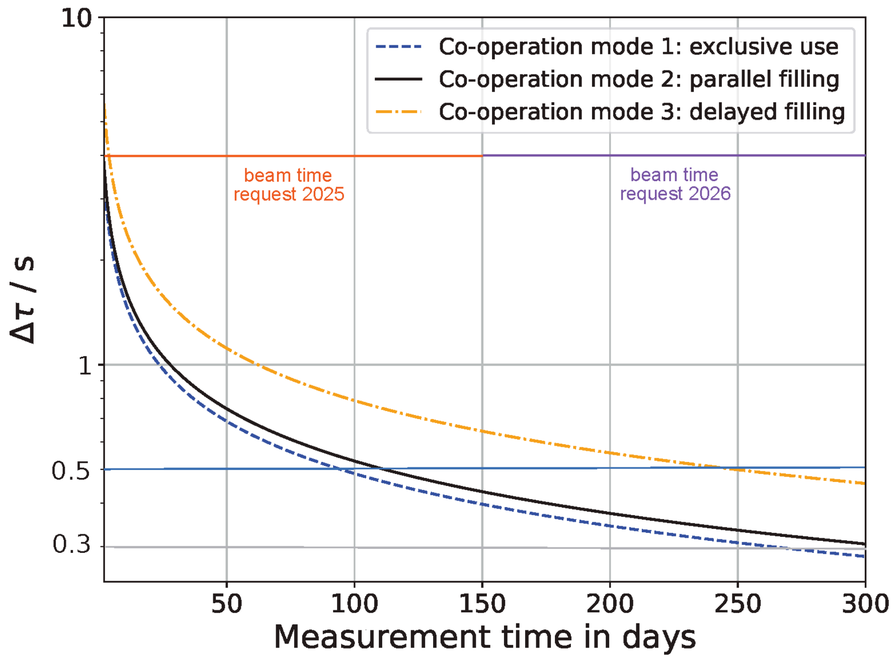




Excellent performance in 2024 with statistical reach of 1s uncertainty!

τSPECT goals and timeline within STRONG 2025

Extrapolation of statistical sensitivity
from 2024 performance



τSPECT is the

***only* operating neutron lifetime experiment in Europe**

to scrutinize the neutron lifetime puzzle and to provide the indispensable input fora neutron-based extraction of V_{ud}

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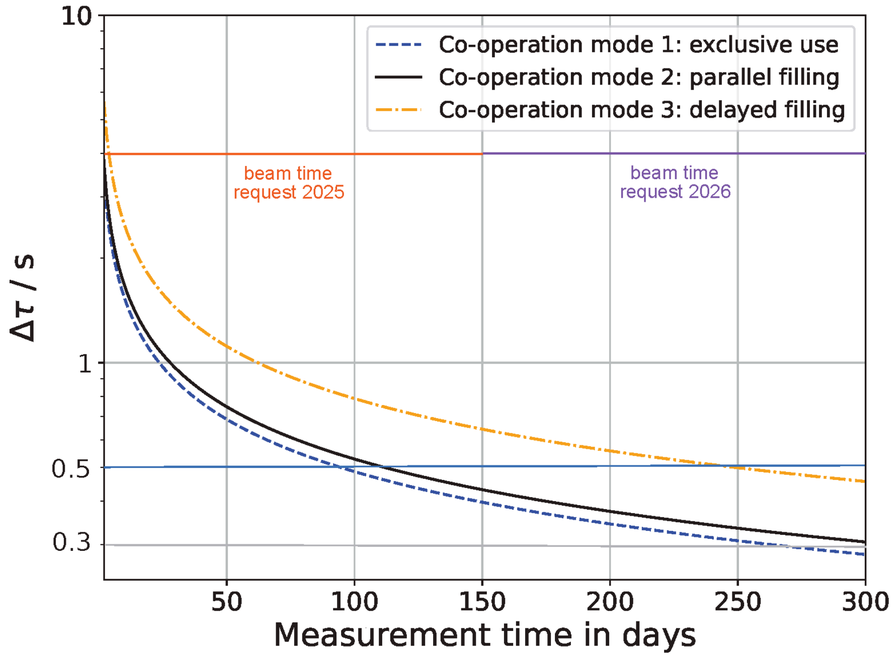

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to scrutinize the neutron lifetime puzzle and to provide the indispensable input fora neutron-based extraction of V_{ud}

1) **Support the travel for experimental shifts** at PSI to collect data in 2026 with τSPECT and the preparation of τSPECT operation at upgraded UCN source.

   (M1-M48, *Milestone at M16: finished data taking*)

2) Support **one PhD student for three years** to complement the analysis team that extracts (M1-M36).

3) Support travel to **collaboration meetings** in Mainz, at PSI, and further collaborators (M4, M16, M28, M40).

4) Financial support for the organization of two **topic-focused** workshops possibly at ECT* or MITP to bring the European and international community together.

   (*Milestones at M16 and M32*)

Proposal for STRONG 2025: budget and collaborators

Support of PhD student (3 years, 75% EG13, direct + indirect = total):	210 kEUR	+	52.5 kEUR	=	262.5 kEUR
Support for travels for data taking, collaboration meeting:	4 x (30 kEUR	+	10 kEUR)	=	120.0 kEUR
Support for two topical workshops:	2 x (15 kEUR	+	3.75 kEUR)	=	37.5 kEUR
Total budget request for 4 years:	***360 kEUR***	***+***	***90 kEUR***	***=***	***450 kEUR***

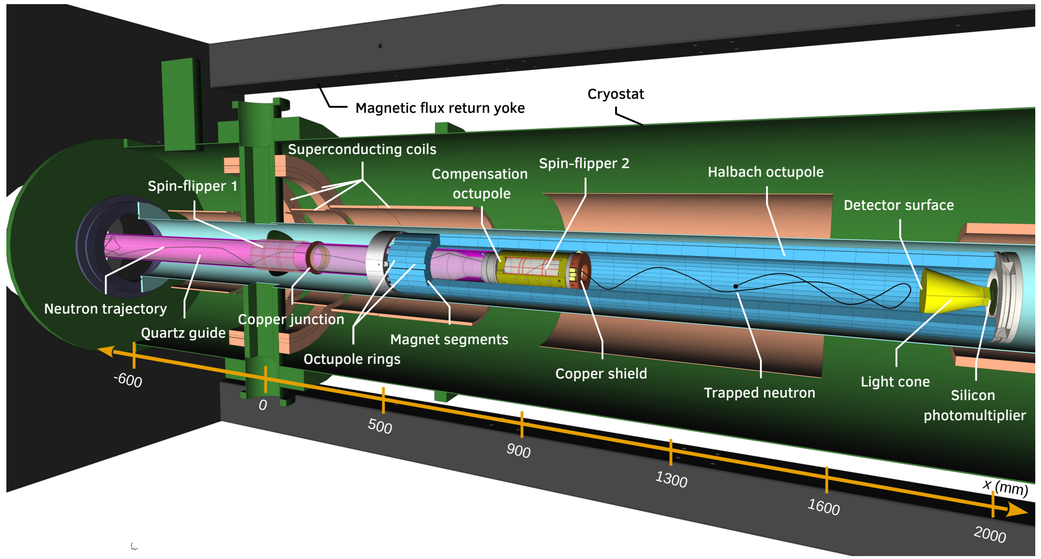
Participating partners:

Prof. Dr. Martin Fertl, S. Vanneste, N. Pfeifer, J. Auler, V. Ermuth, S. Kaufmann (all JGU Mainz)

Dr. Dieter Ries and Dr. Bernhard Lauss (Paul Scherrer Institute, Switzerland)

Backups

A fully-magnetic UCN bottle for the τSPECT experiment



Complete magnetic storage eliminates any loss channel related to material wall interactions

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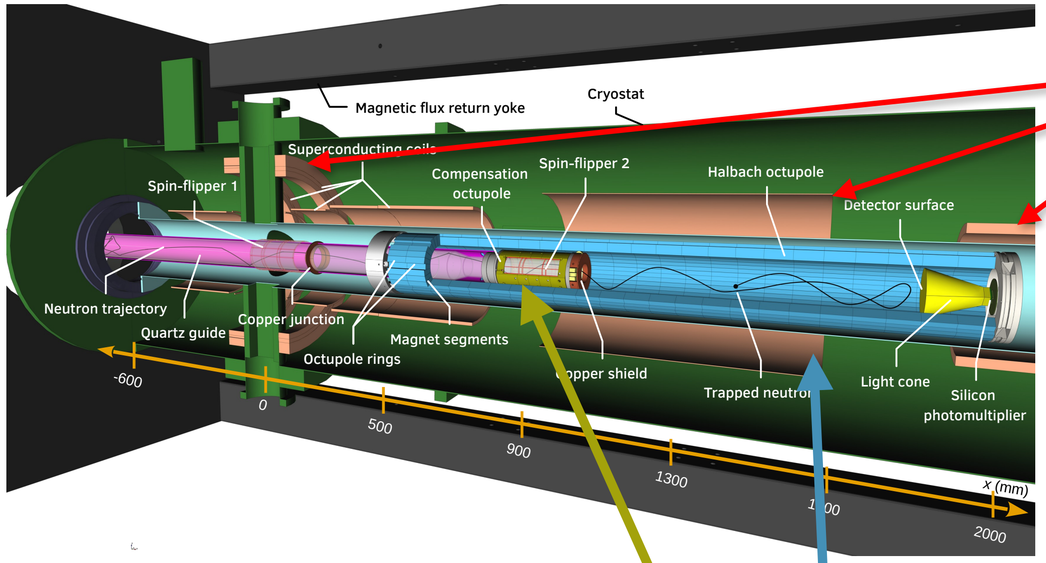
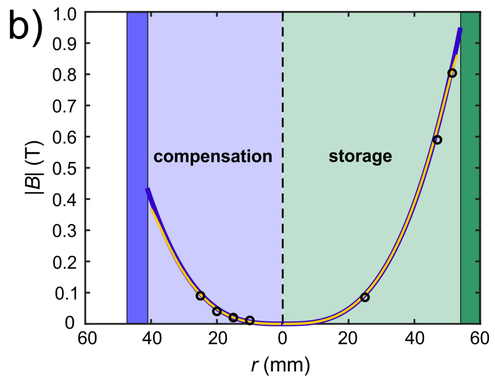
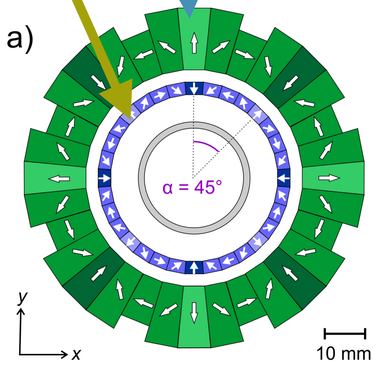


Superconducting solenoids for axial magnetic field

Transverse B field





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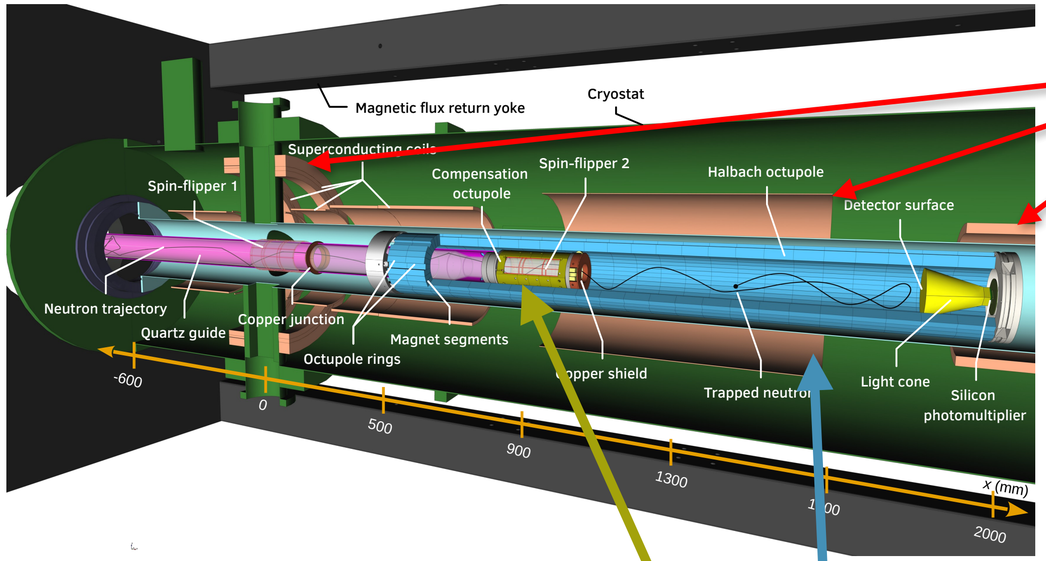
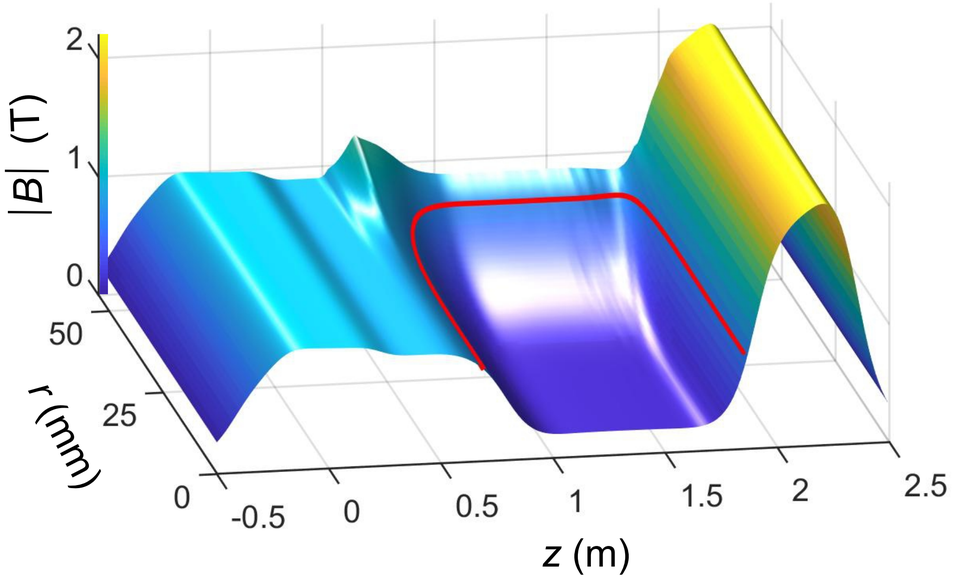


Superconducting solenoids for axial magnetic field

Superposition of axial and radial field



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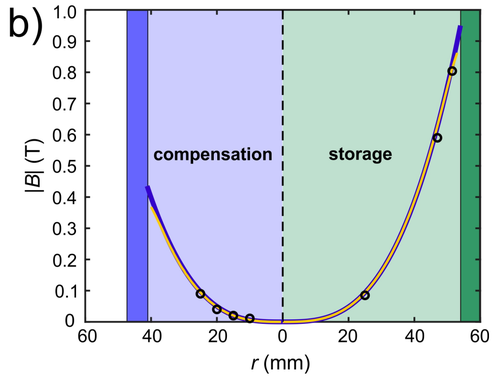
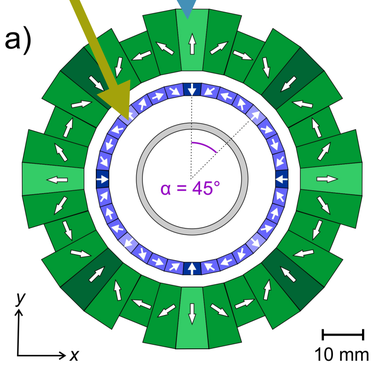
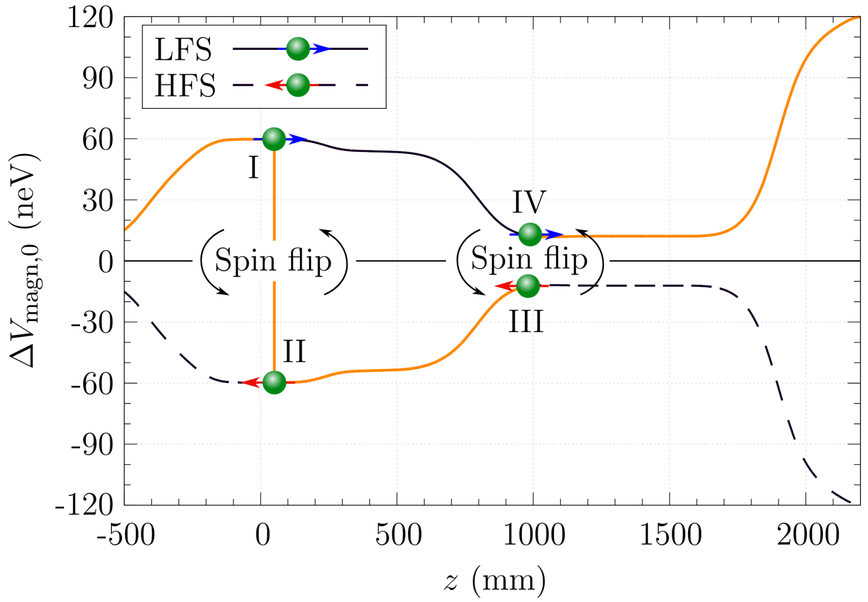




The spin-flip loading scheme of τSPECT



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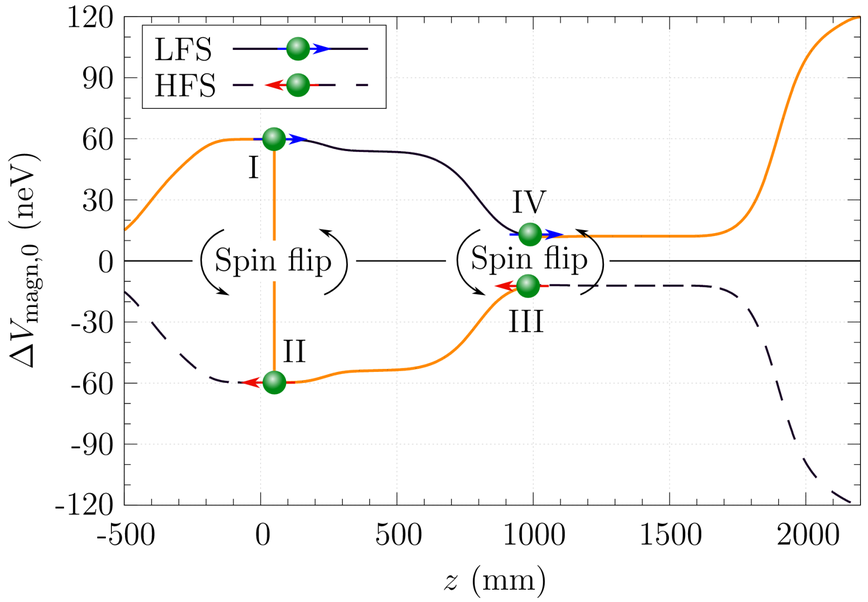

Loading of the trap with LFS UCN either by:

- Single spin flip (HFS ⇒ LFS)
- Double spin flip (LFS ⇒ HFS ⇒ LFS)

Additional deceleration of UCN in double spin flip scheme

Implemented as adiabatic fast passage spin flipper (AFP)

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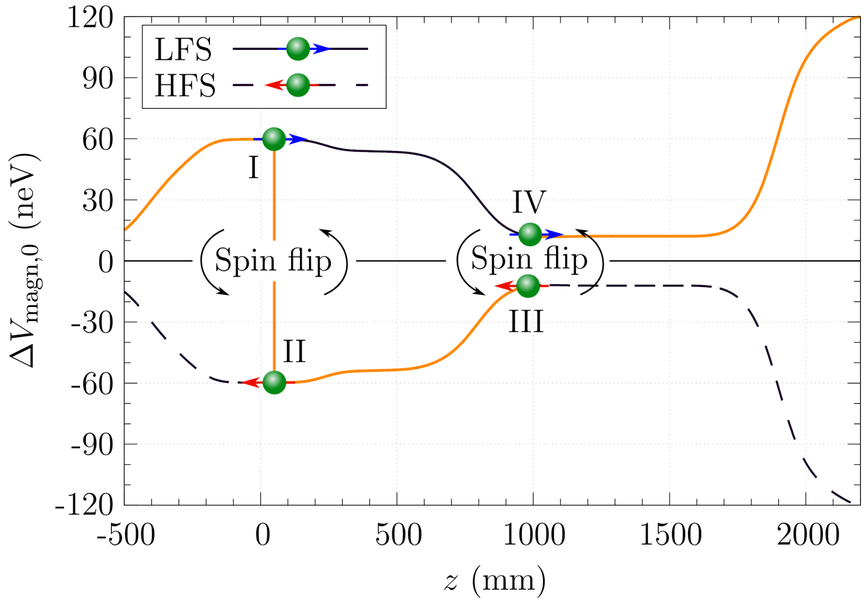

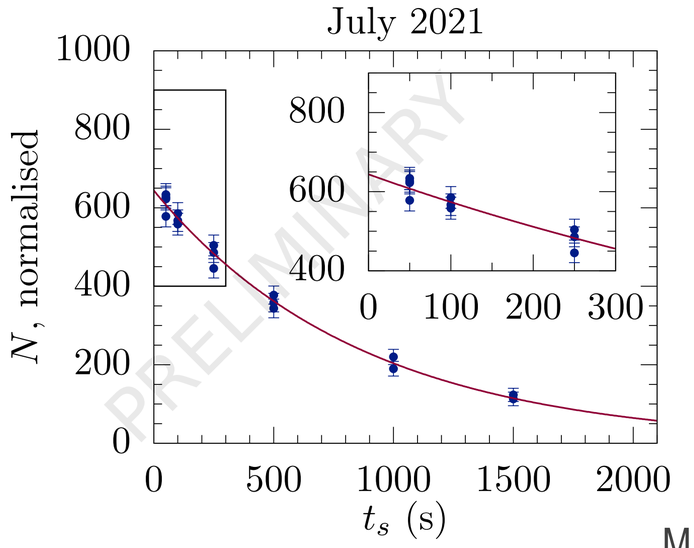

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Demonstrated a working experiment in Mainz up to spring 2023
Extracted storage time: (869 ± 29) s

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