Ingo Rienäcker :: UCN group :: Paul Scherrer Institute

An experiment to search for magnetic field correlated neutron to mirror neutron oscillations

LTP Seminar November 2021

History of mirror matter

τ–θ puzzle (1954)

Parity violation in weak Kaon decay

$\theta^+ = K^+ \rightarrow \pi^+\pi^0$ (P = +1)

$\tau^+ = K^+ \rightarrow \pi^+\pi^+\pi^-$ (P = -1)

Lee and Yang:

Question of Parity Conservation in Weak Interactions

Physical Review Volume 104, Number 1 (1956)

*"One way out of the difficulty is to assume that **parity is not strictly conserved**, so that $\theta^+$and $\tau^+$are two different decay modes of the same particle…"*

$$\mathscr{L}_{total} = \mathscr{L}_{SM} + \mathscr{L}'_{SM'} + \mathscr{L}^{mixing}_{SM-SM'}$$

Kobzarev, I. Yu., Okun, L. B., and Pomeranchuk, I. Ya., Sov. J. Nucl. Phys. **3**, 837 (1966)

R. Foot, H. Lew, R.R. Volkas Physics Letters B 272 67-70 (1991)

*"If such asymmetry is indeed found, the question could still be raised whether there could not exist **corresponding elementary particles exhibiting opposite asymmetry** such that in the **broader sense there will still be over-all right-left symmetry**."*

Motivation for the search for mirror matter

- Possible dark matter candidate
- Baryon number violation $|\Delta B = 1|$

  Neutral SM particles can oscillate into their mirror partner sterile state
  neutron - mirror neutron oscillation: $n \leftrightarrow n'$

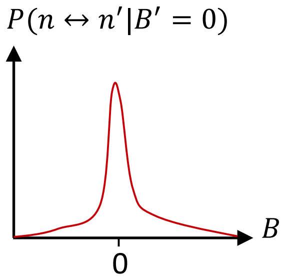
Z. Berezhiani and L. Bento 2, PRL 96, 081801 (2006):

- Limits obtained from $n \leftrightarrow \bar{n}$ searches still allow for a $n \leftrightarrow n'$ oscillation time of the free neutron of around 1s

- $n \leftrightarrow n'$ suppressed in the presence of magnetic fields (if $B' = 0$)

Neutron – Mirror neutron
two state system

$$i\frac{d\Psi}{dt} = H\Psi, \qquad H = \begin{pmatrix} \mu B\sigma & \varepsilon \\ \varepsilon & \mu B'\sigma \end{pmatrix} \qquad \tau_{osc} = \varepsilon^{-1}$$



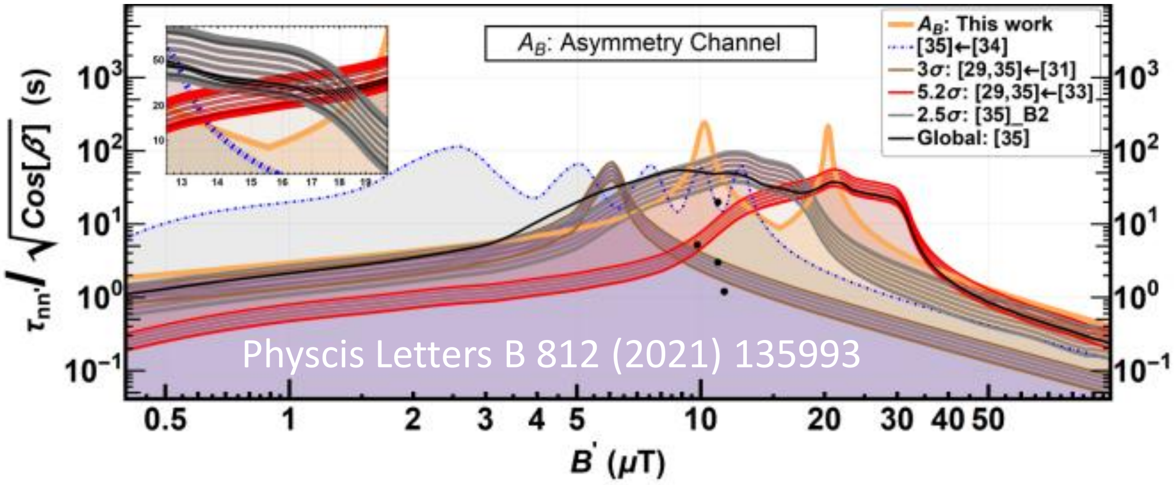
Previous experimental efforts

- $\boldsymbol{B' = 0}$:

  Best experimental limit $\tau_{osc} > 448s$ (90% CL)

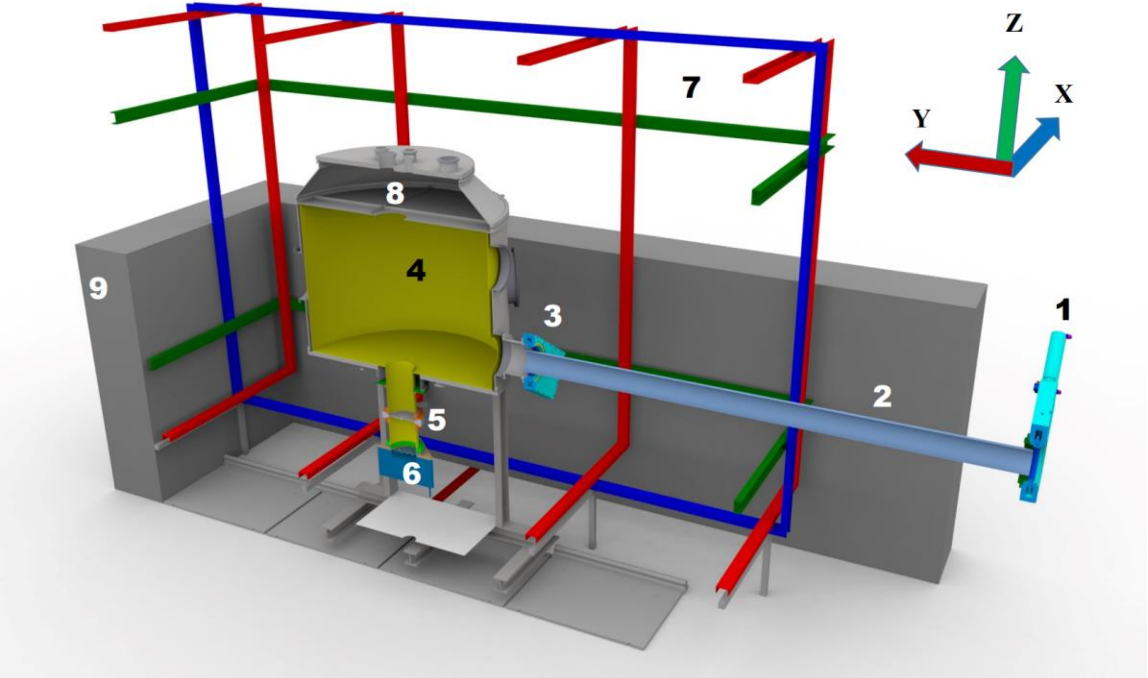
  (Serebrov et. al. Nunclear Instruments and Methods in Physics Research A 611 (2009) 137–140A)

- $\boldsymbol{B' \neq 0}$: (e.g. mirror matter trapped inside the earth Eur.Phys.J.C64:421-431,2009)



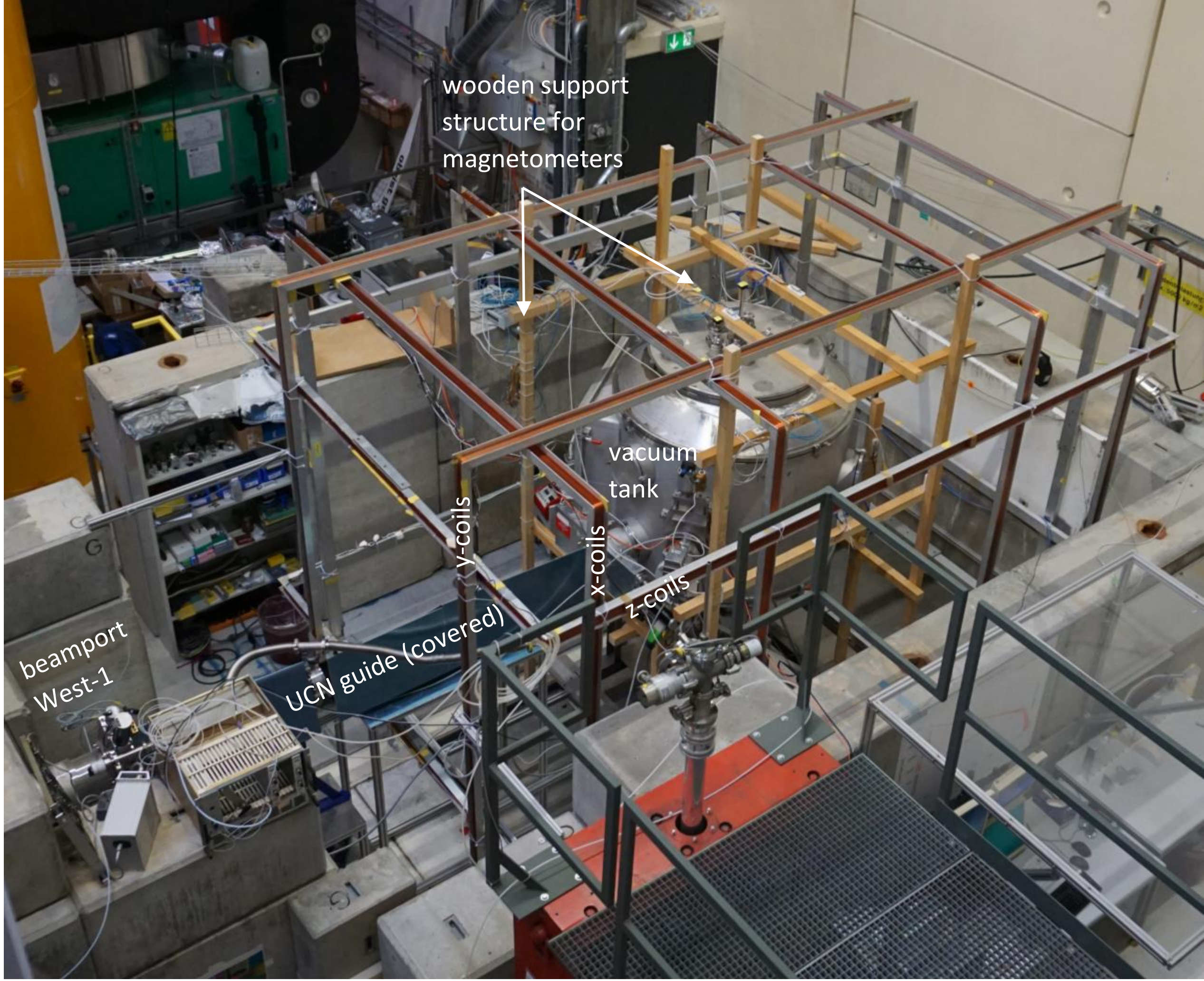
Experimental setup

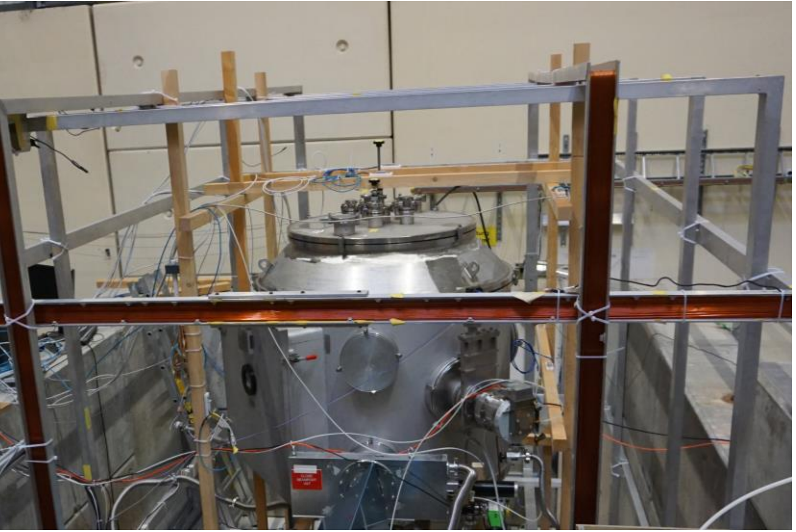
We search for anomalous neutron losses ($n \leftrightarrow n'$) in resonance with an external magnetic field during the storage of ultracold neutrons



1. Beamline shutter (SH_{beam})
2. UCN filling guide
3. Filling shutter (SH_1)
4. UCN storage volume **($\approx$ 1.5 m³)**
5. Emptying guide and shutter (SH_2)
6. UCN detector
7. Coil system **(up to $\approx$ 400 µT)**
8. Vacuum tank
9. Concrete shielding


y-coils
z-coils
x-coils
vacuum
tank
UCN guide (covered)
<- detector
wooden support
structure for
magnetometers

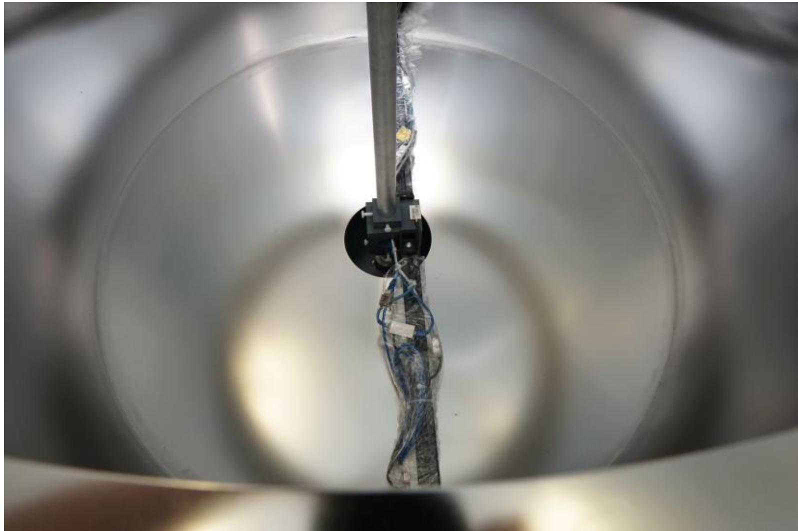

wooden support
structure for
magnetometers
vacuum
tank
y-coils
x-coils
z-coils
UCN guide (covered)
beamport
West-1



Vacuum tank outside

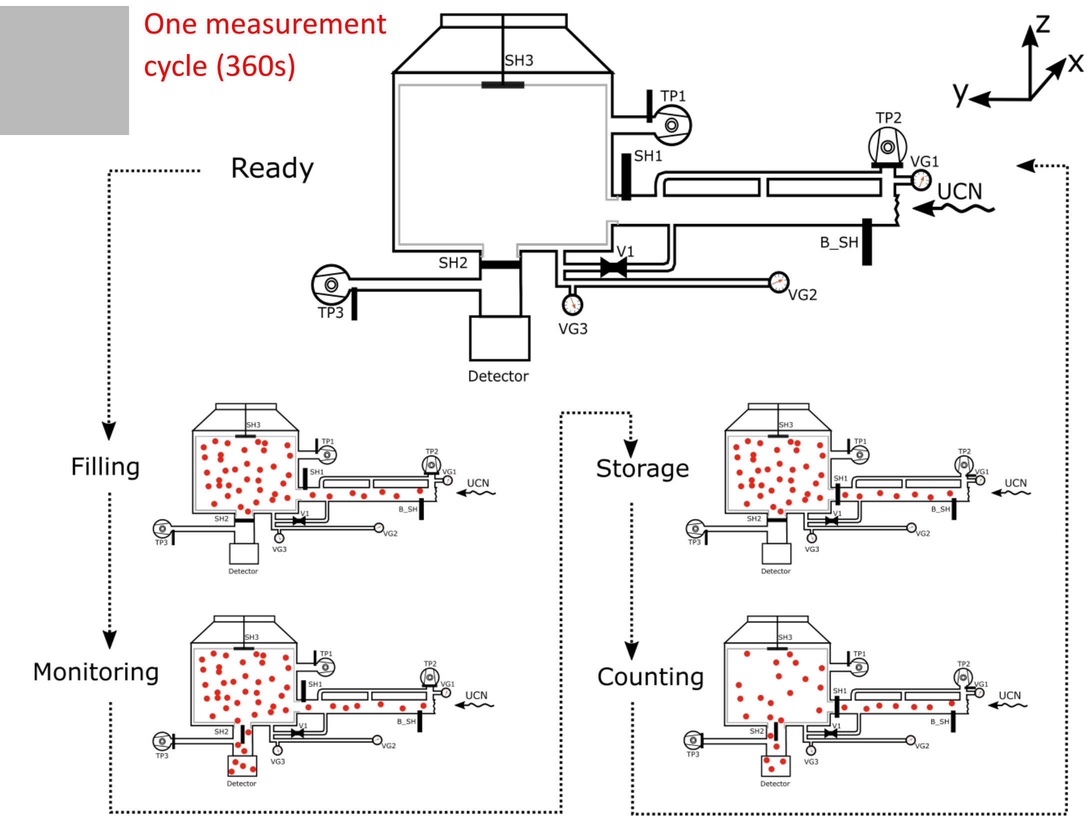
Vacuum tank inside

Stainless steal storage volume before electropolishing



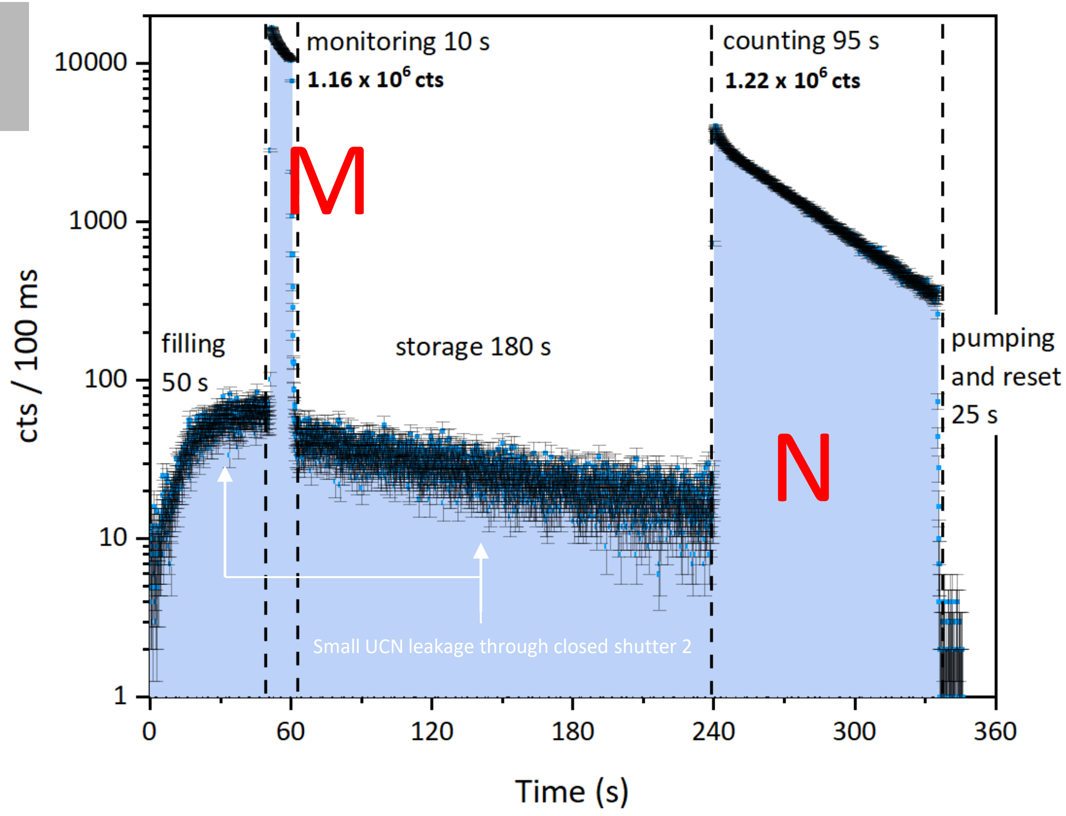
After electropolishing with magnetic fiel mapper inserted

Measurement method



- Ultracold neutrons can be stored due to total reflection on materials with high Fermi potential (stainless steel)
- After a $n \leftrightarrow n'$ oscillation in resonance with the external magnetic field the sterile mirror neutron escapes the storage volume and the neutron is lost
- A monitoring phase determines the initial ultracold neutron density after filling

Ultracold neutron counts time spectrum

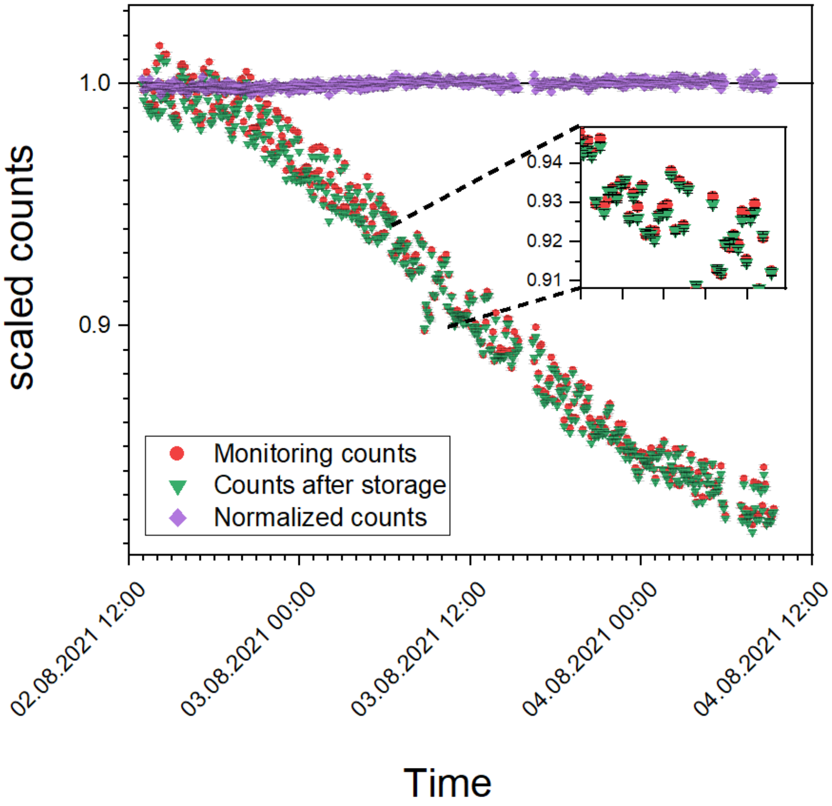


- Filling/monitoring/storage/counting times are optimized for the highest daily sensitivity on the $n \leftrightarrow n'$ oscillation time

- Normalized counts:

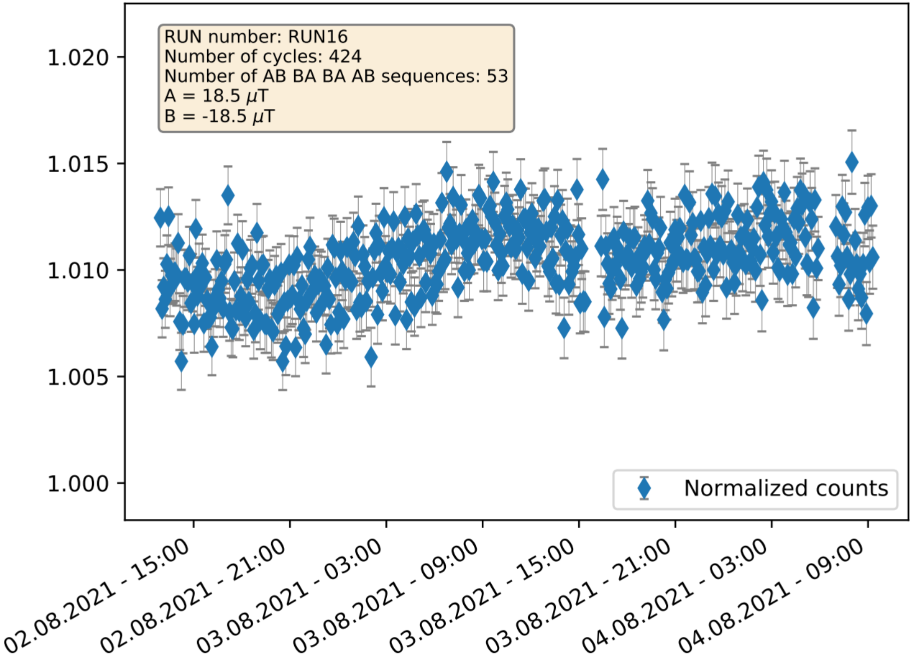
$$n = \frac{N}{M}$$

Normalized counts



- Reasons for temporal drifts and scatter of the initial UCN density
  - HIPA beam current / position on target
  - Status of the UCN source solid deuterium moderator
  - UCN shutter timings
  - …

Residual drifts of normalized counts

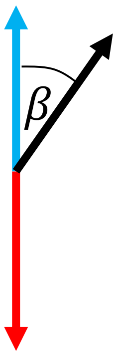


- A change of the UCN storage properties of the apparatus will lead to a B-field uncorrelated drift, e.g.:
  - Vaccum (UCN losses during storage due to collision with gas molecules)
  - Temperature of the storage volume (UCN losses on wall collisions)
  - Changes in the initial UCN energy spectrum
  - …

Asymmetry and sequences

- Mirror neutron signature:

A cycle: $+\boldsymbol{B}$



$\boldsymbol{B}'$ potential mirror magnetic field

B cycle: $-\boldsymbol{B}$

$$n_B > n_A \quad \rightarrow \quad \alpha = \frac{n_A - n_B}{n_A + n_B} \neq 0$$

- We calculate the asymmetry α between the normalized counts of cycles with $+\boldsymbol{B}$ ("A cycles") and $-\boldsymbol{B}$ ("B cycles") vertical magnetic field

- To compensate for remaining drifts we measure sequences of 8 cycles:

$$A\,B \quad B\,A \quad B\,A \quad A\,B$$

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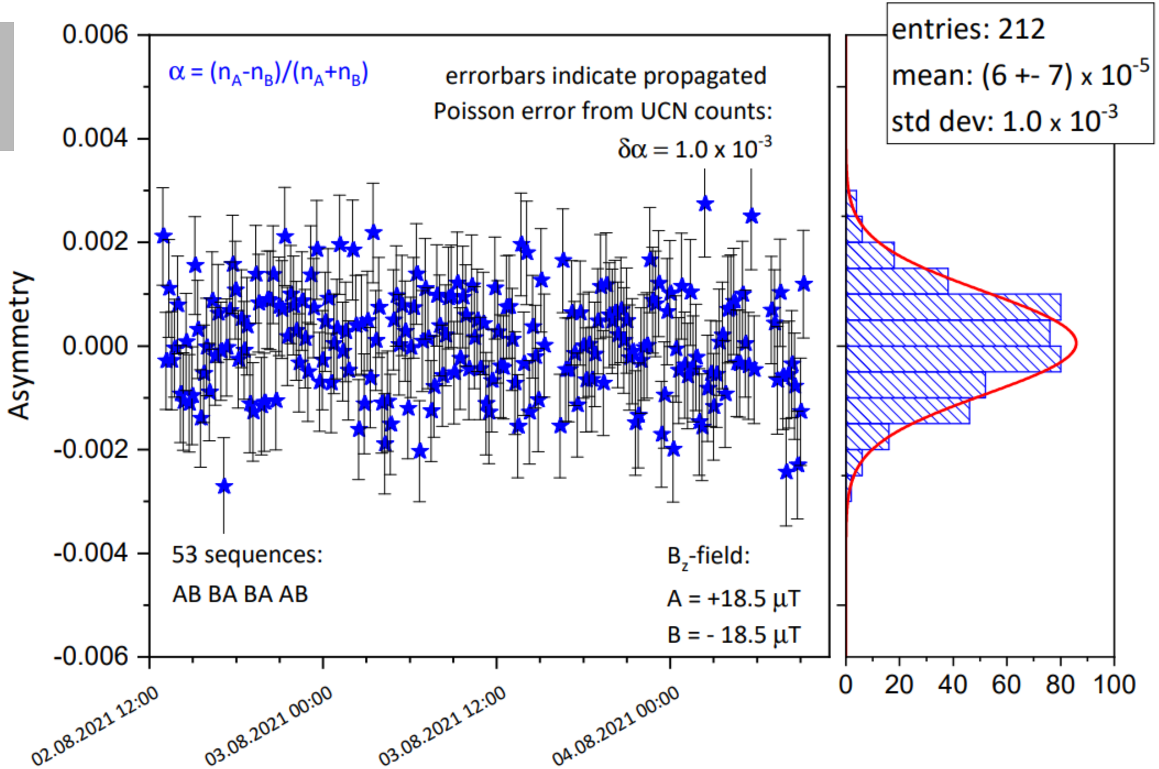
Asymmetry data



- The distribution of the asymmetries per sequence are consistent with the propagated Poisson UCN counting error
- We measured this asymmetry during 57 runs at different B-field settings

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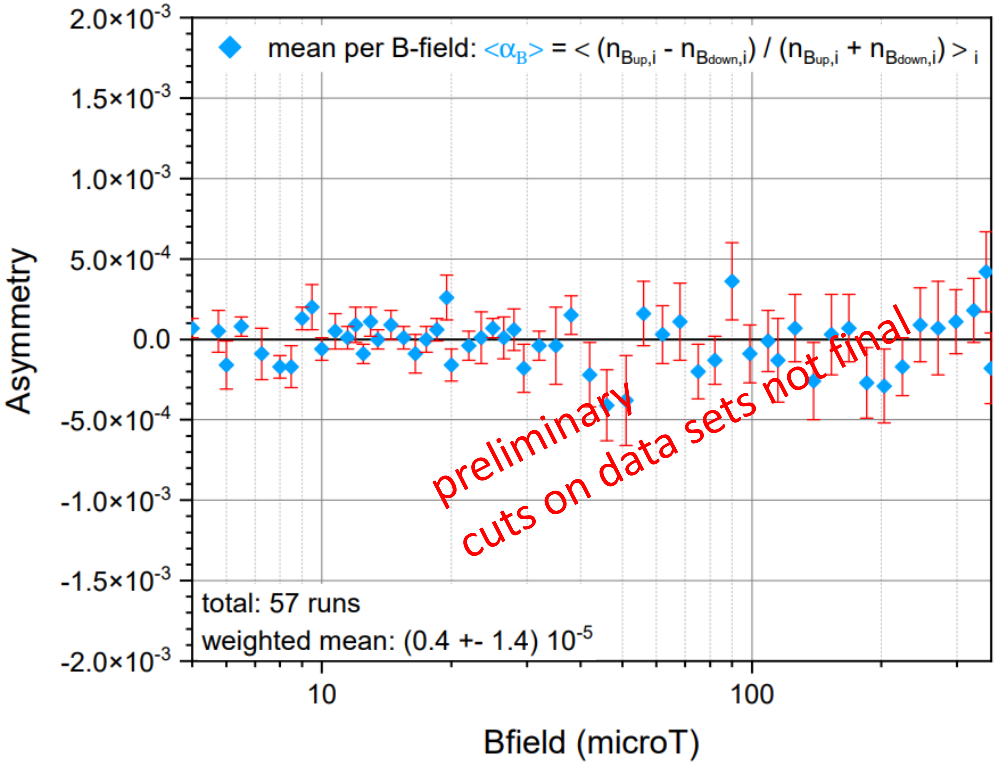
Preliminary results



- We scanned succesfully the parameters space of B-fields between $5 - 360\ \mu T$
- A comprehensive analysis of the offline B-field mapping campaign is still ongoing
- Final limits on mirror neutron oscillation time will depend on the homogeneity and symmetry of the $\pm \boldsymbol{B}$ - Fields

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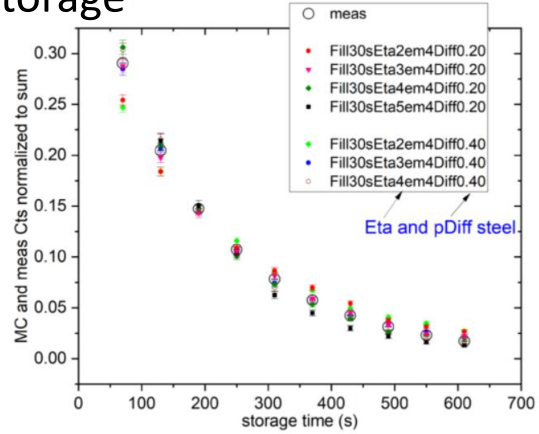
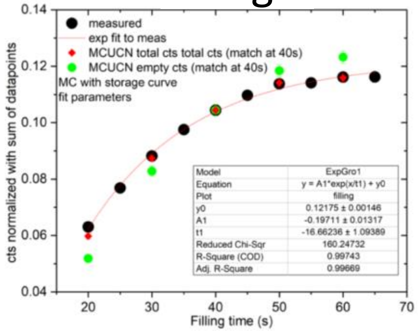
MC Simulation

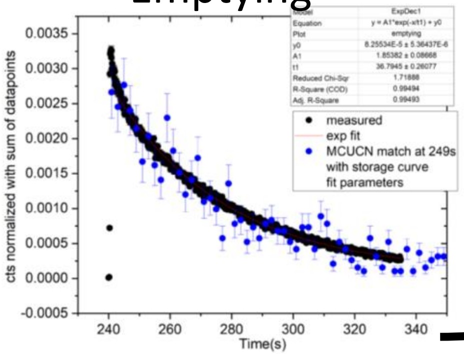
Storage



Filling



Emptying

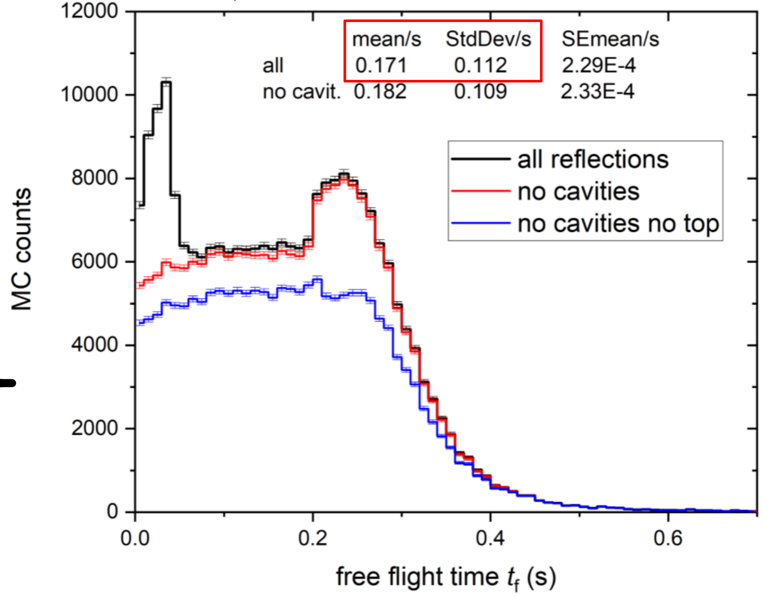


Calibrate simulation

Eur.Phys.J. C (2018) 78:717

$$\frac{\tau_{osc}^2}{\cos\beta} = \frac{t_s}{\langle t_f \rangle \, \alpha} f(B, B')$$

ongoing



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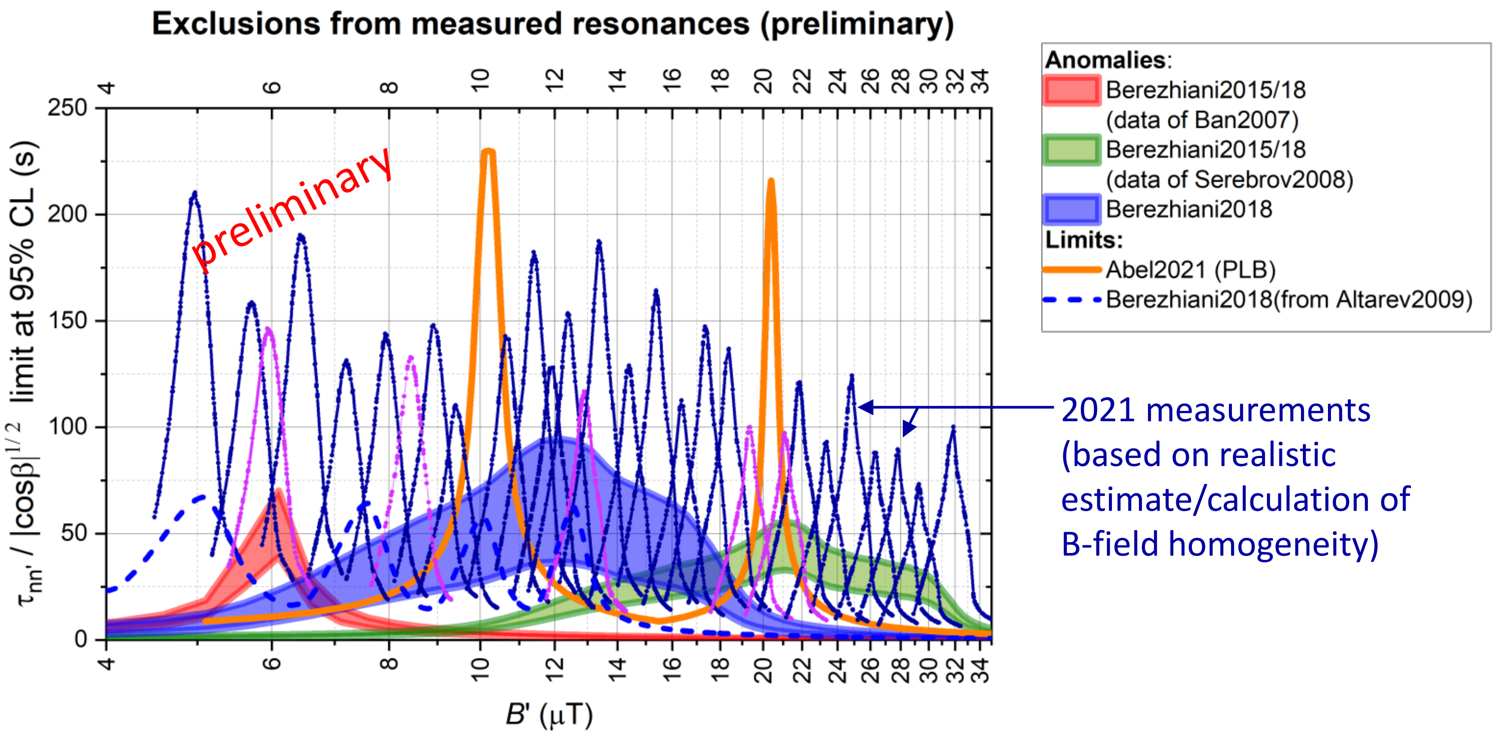

2021 measurements (based on realistic estimate/calculation of B-field homogeneity)

Conclusion and Outlook

- A search for mirror neutron oscillations is motivated by
  - the possibility for new dark matter candidates
  - Baryon number violation
  - ...

  and the reports of signal-like events from previous data sets at $\boldsymbol{B}' \neq \mathbf{0}$

- Analysis of the UCN counts during the 2021 measurement campaign close to completion

- Analysis of B-fields ongoing