ETH zürich

New Proposal:
Search for Neutron to Mirror-Neutron Oscillations

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PSI BV52 Open Users Meeting

IPA PAUL SCHERRER INSTITUT PSI KU LEUVEN JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ JAGIELLONIAN UNIVERSITY IN KRAKÓW INFN Laboratori Nazionali del Gran Sasso

Overview

- Motivation
- Principle of Experiment
- Development in 2020 and results of test beam
- Proposal for 2021
- Beamtime Request

Motivation: The Mirror World

- Proposed by Lee & Yang (1957) to restore Parity in the weak sector
- For every left-handed SM particle, add a right-handed mirror particle
- Interesting cosmologically
  - Viable DM Candidate [1]
  - Consequences for high energy cosmic rays [2,3]
- Feebly coupled to SM
- Mass degenerate with ordinary matter
  - Implies maximal mixing in the vacuum
  - Search channel: look for anomalous disappearance of neutrons
  - Degeneracy can be lifted by magnetic fields and *mirror magnetic fields*

[1] Z. Berezhiani Int. J. Mod. Phys. A 33, 31 (2018) 1844034
[2] Z. Berezhiani, L. Bento PLB 635 (5-6) (2006) 253-259
[3] Z. Berezhiani, A. Gazizov EPJC 72 (8) 2111 (2012)

Experiments up to 2009

- Experiments by nEDM Collaboration at PSI [1,2,3] & Serebrov et. al. [4,5]
- Initial focus on case B' = 0 [1,2,4]
- Compare storage time with B=0 to large B
  - Best limit τ > 448s [5]
- Limited consideration of nonzero B' ≠ 0 [3,5]
  - Look for sidereal signal if mirror matter is not bound to Earth
  - Look for resonant enhancement at B≈B'
- Each experimental collaboration reported a null result

[1] G. Ban et al. PRL 99 (2007) 161603
[2] K. Bodek et al. NIM A 661 (2009) 141-143
[3] I. Altarev et al. PRD 80 (2009) 032003
[4] A.P. Serebrov et al. PLB 663 (2008) 181-185
[5] A.P. Serebrov et al. NIM A 611 (2009) 137-140

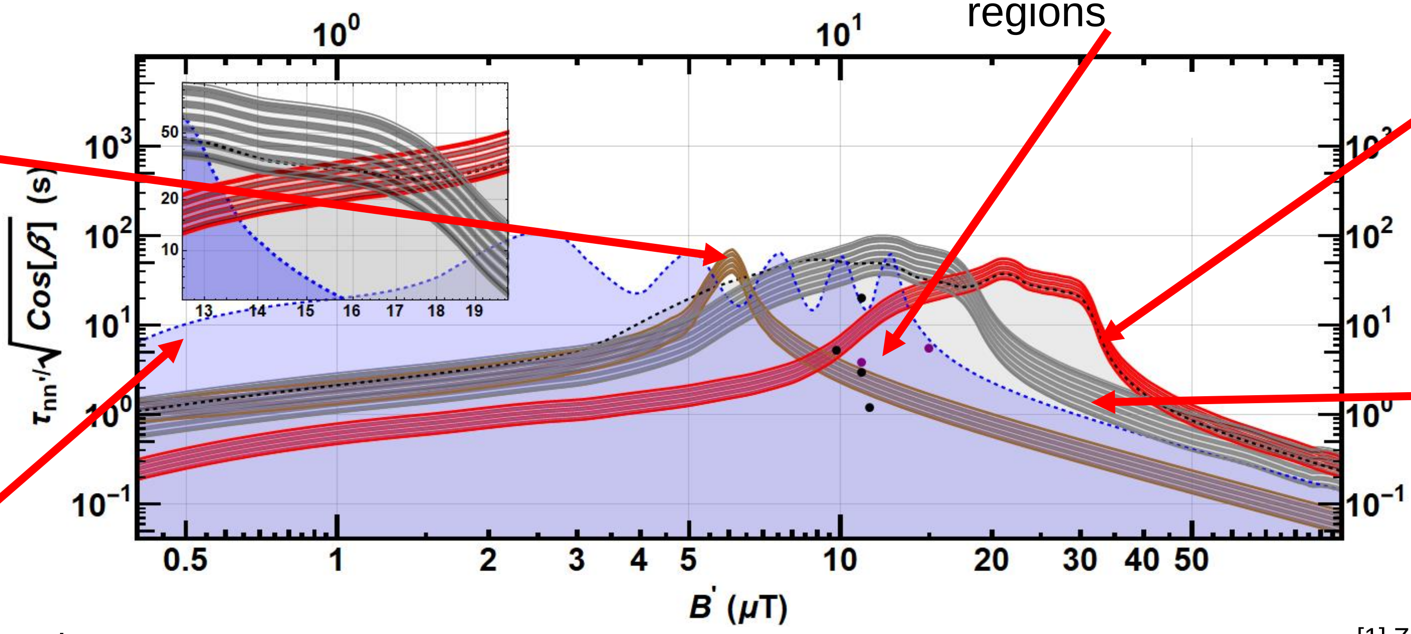
The Berezhiani-Nesti Signal

- External reanalysis [1] of data taken using apparatus of [2] revealed 5.2 σ dependence of neutron loss on B direction
  - Further consideration of the B field conditions in [2] resulted in revised signal regions [3]
  - A further experiment [3] found a 2.5 σ discrepancy

Points indicate 2009 & 2012 preferred regions

Red: 2σ region indicated by original 5.2σ anomaly [2], as revised in [3]

Brown: 2σ region (from [3]) indicated by 3σ anomaly in [4]



Grey: 2σ region indicated by 2.5σ anomaly in [3]

Blue: exclusion by [5] (PSI nEDM)

Figure Courtesy P. MohanMurthy

[1] Z. Berezhiani, F. Nesti Eur. Phys. J. C (2012) 74:1974
[2] A.P. Serebrov et al. NIM A (2009) 611,141
[3] Z. Berezhiani et al. Eur. Phys. J. C (2018) 78:717

The 2017 PSI Measurement

- Aim: Test the signal regions proposed in 2012 [1]
- 45 days of datataking using PSI nEDM Apparatus
  - Chamber ~21L volume, t_s=180s, 380s, typical 11-14k UCN after 380s
  - B = 10 μT tuned to match signal regions, B = 20 μT to capture high B' with long tail
  - Normalisation of initial UCN
- Partly excluded several regions of interest [2]
- Interesting parameter space remains, including revised and new regions of interest [3]

[1] Z. Berezhiani, F. Nesti Eur. Phys. J. C (2012) 74:1974
[2] PhD Thesis P. MohanMurthy; C. Abel et al. PLB 812, 135993 (2021)
[3] Z. Berezhiani et al. Eur. Phys. J. C (2018) 78:717

What are the remaining interesting regions?

Orange: exclusion from PSI nEDM 2017 Measurement [1]

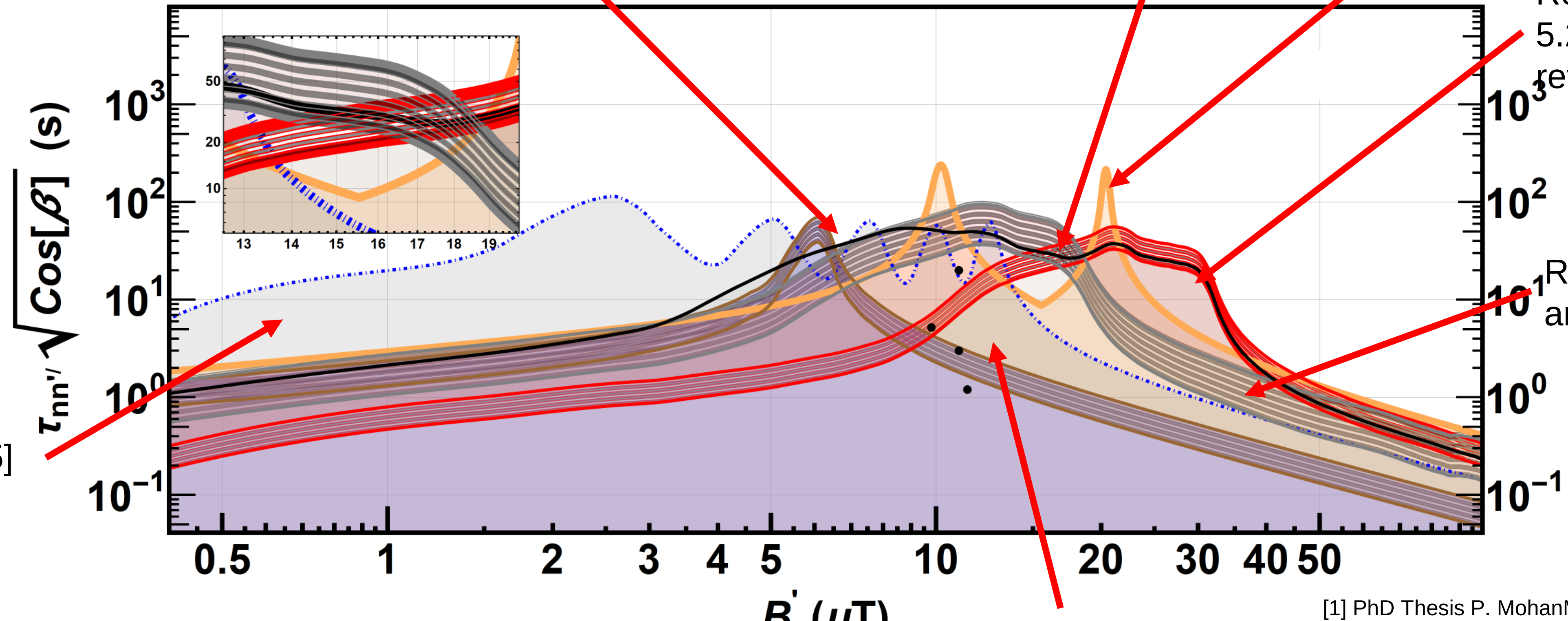
Region (from [3]) from 3σ anomaly in [4]

Overlap region still allowed

Region from original 5.2σ anomaly [2], revised in [3]

Region from 2.5σ anomaly in [3]

Excluded [5]



Original "signals" excluded [2]

Figure from PhD Thesis P. MohanMurthy

[1] PhD Thesis P. MohanMurthy; C. Abel et al. EPJ Web of Conferences 219, 07001 (2019)
[2] Z. Berezhiani, F. Nesti Eur. Phys. J. C (2012) 74:1974
[3] Z. Berezhiani et al. Eur. Phys. J. C (2018) 78:717
[4] G. Ban et al. PRL 99, 161603 (2007)
[5] I. Alterev et al. PRD 80 (3) (2009) 032003

Principle of Experiment

- Goal: either confirm or comprehensively exclude regions compatible with previously observed excesses
- Store UCN in a material trap in known magnetic field
- Compare loss rate with B up versus B down

Storage time

Angle between B' and B

$$\tau_{nn'}(B,B') = \sqrt{\frac{t_s}{\langle t_f\rangle A_{\uparrow\downarrow}}}\sqrt{f(B,B')\cos\beta}$$

Oscillation time

Lineshape, peak at B'=B

Mean free time

Asymmetry B up vs down

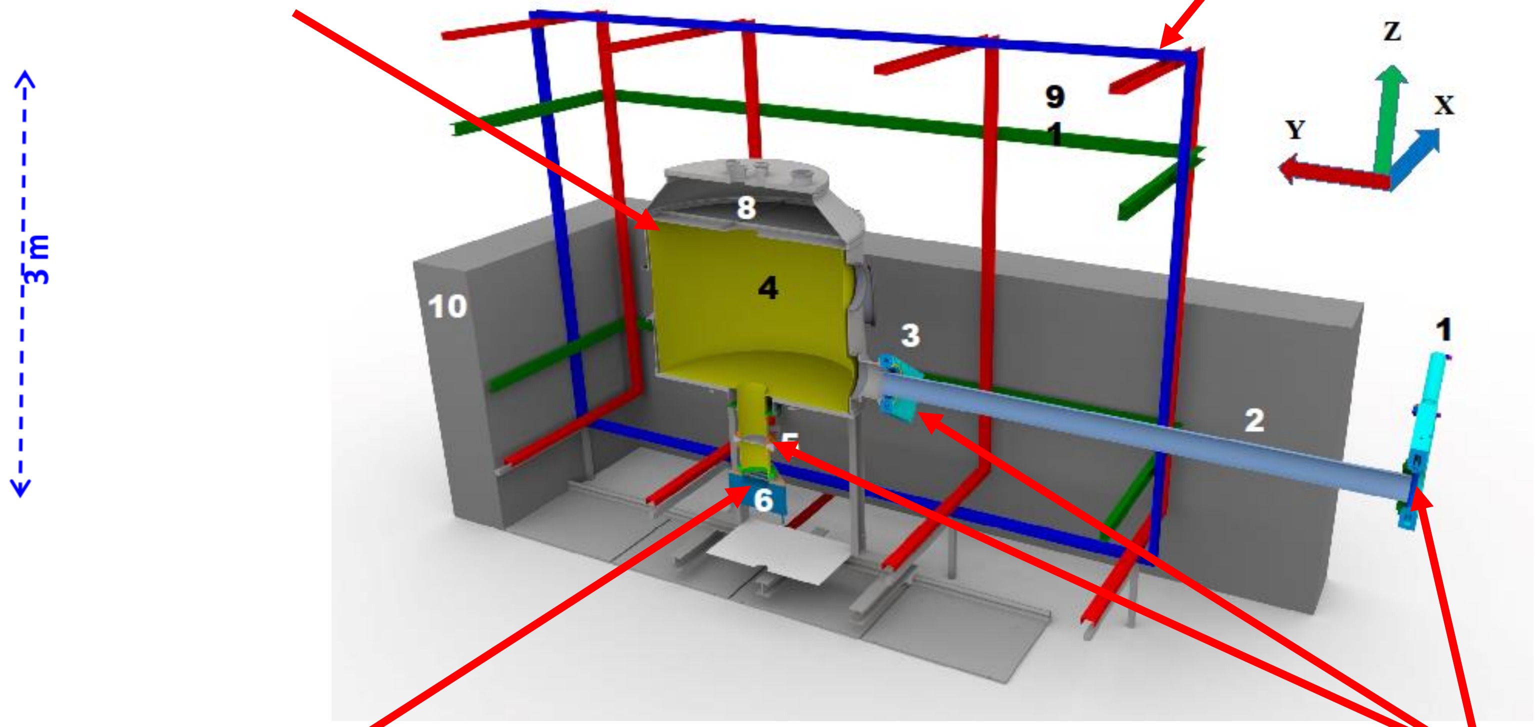
Principle of Experiment

- Design Philosophy:
  - Storage measurement
  - Use a big trap to maximise UCN counts
  - Normalise initial UCN by counting some UCN during filling
  - Scan applied magnetic field to tune
- B’=0 oscillation time already well constrained:
  - Do not need to test B=0 case, eliminating costly magnetic shielding
  - Target magnetic field homogeneity on level of µT

Principle of Experiment

Vacuum Tank Containing Storage Vessel

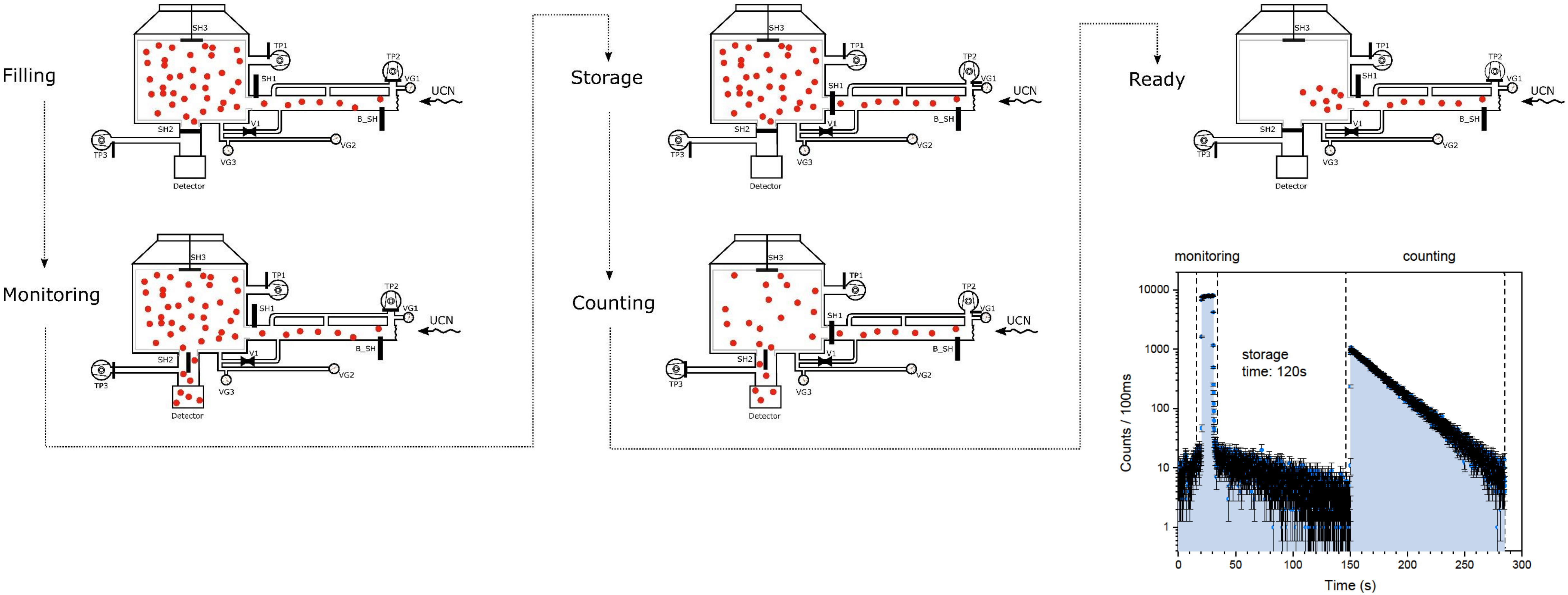
Coil System



Detector

Shutters

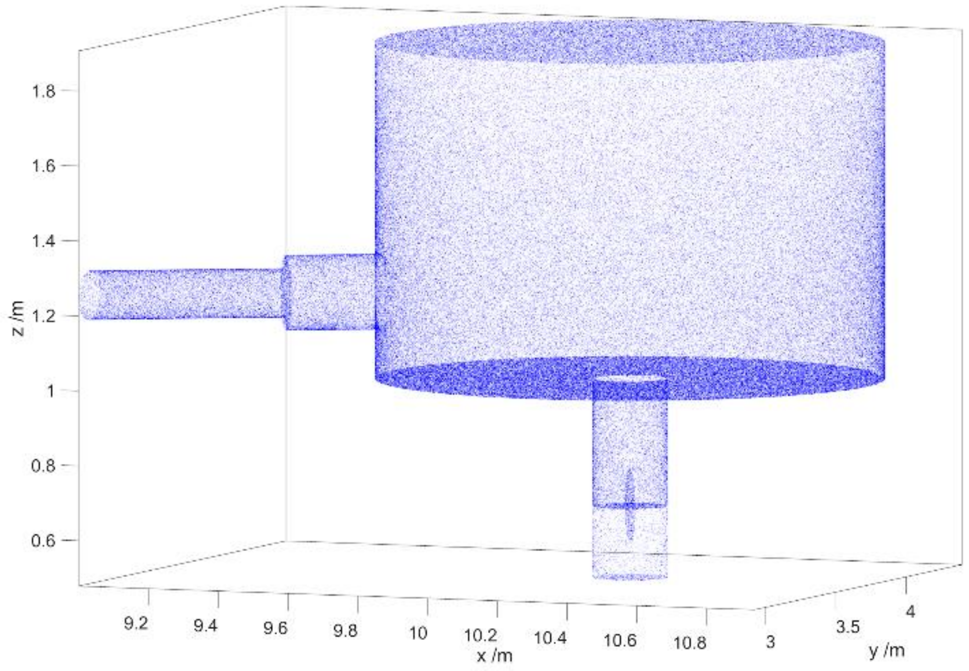
Storage Cycle



Monte Carlo Simulations

- Detailed simulation of source & experiment with MCUCN [1]
  - Benchmarked & calibrated against many measurements
  - Tuned to match measured data

- Critical component of analysis:
  - $<t_f>$ free flight time
  - Lineshape *f (B,B')*



$$\tau_{nn'}(B,B') = \sqrt{\frac{t_s}{\langle t_f \rangle A_{\uparrow\downarrow}}}\sqrt{f(B,B')}\cos\beta$$

[1] G. Bison et al., Eur. Phys. J. A (2020) 56:33

The Collaboration

N. J. Ayres, V. Bondar, S. Emmenegger[1], K. Kirch[2], J. Krempel
ETH Zürich, Switzerland

G. Bison, P.-J. Chiu[1,3], M. Daum, C.B. Doorenbos[1,3], B. Lauss, D. Pais[1,3], I. Rienäcker[1,3], P. Schmidt-Wellenburg, G. Zsigmond
Paul Scherrer Institut, Villigen, Switzerland

D. Ries, B. Shen[1]
Department of Chemistry – TRIGA site, Johannes Gutenberg University Mainz, Mainz, Germany

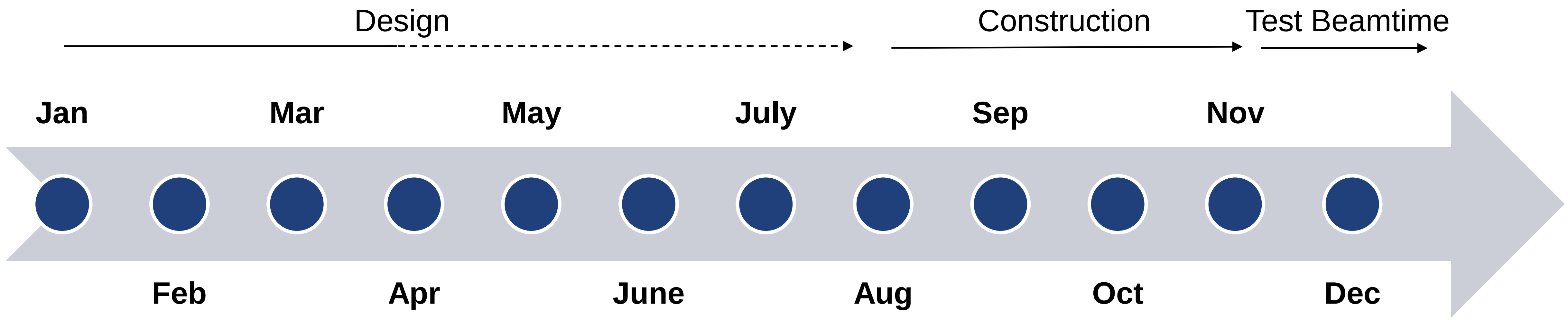
K. Bodek, D. Rozpedzik, J. Zejma
Jagellonian University, Cracow, Poland

R. T. Dinani, N. Severijns
Katholieke Universiteit, Leuven, Belgium

Z. Berezhiani[4], R. Biondi, N. Rossi
INFN, Laboratori Nazionali del Gran Sasso, Assergi AQ, Italy

- Substantial overlap with nEDM collaboration
  - Experience with similar experiments
  - Much hardware already exists

Activities in 2020

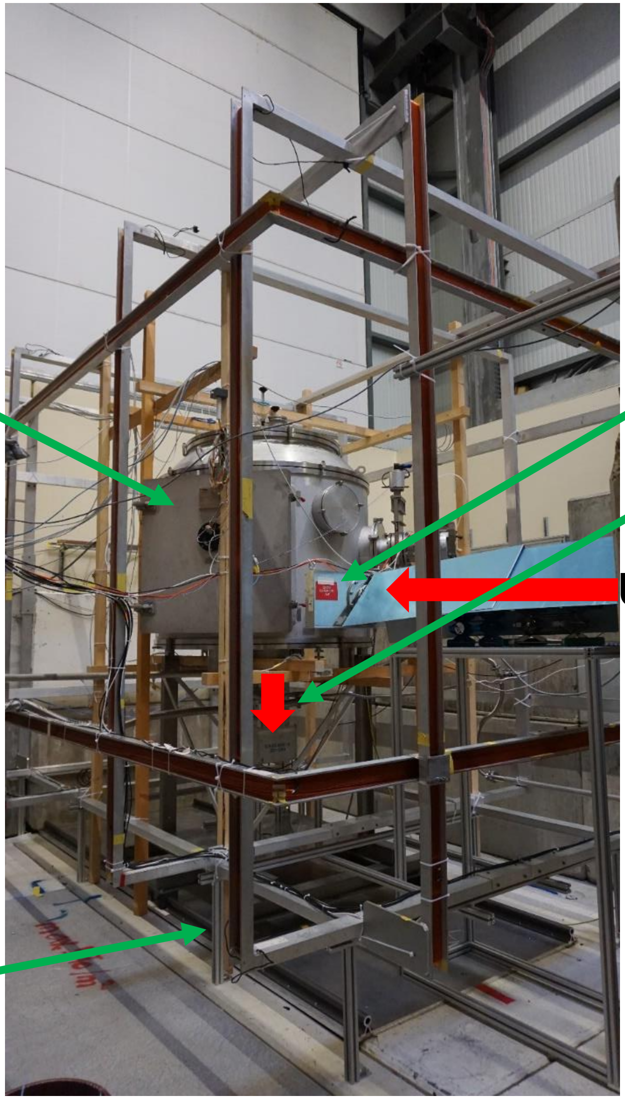


Limited operations caused substantial delay in construction and prevented travel for collaborators outside of Switzerland, however beamtime of 2020 could be well utilised

Setup in Area West

Vacuum Tank

Rail System

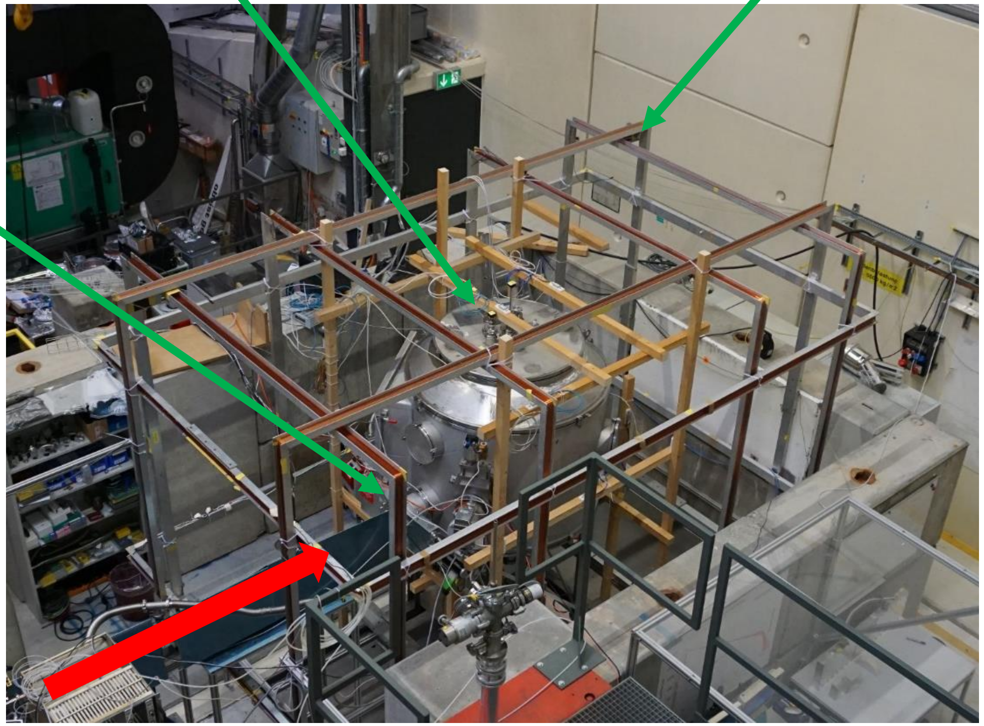


Shutters

UCN

Fluxgate Array

Coil System

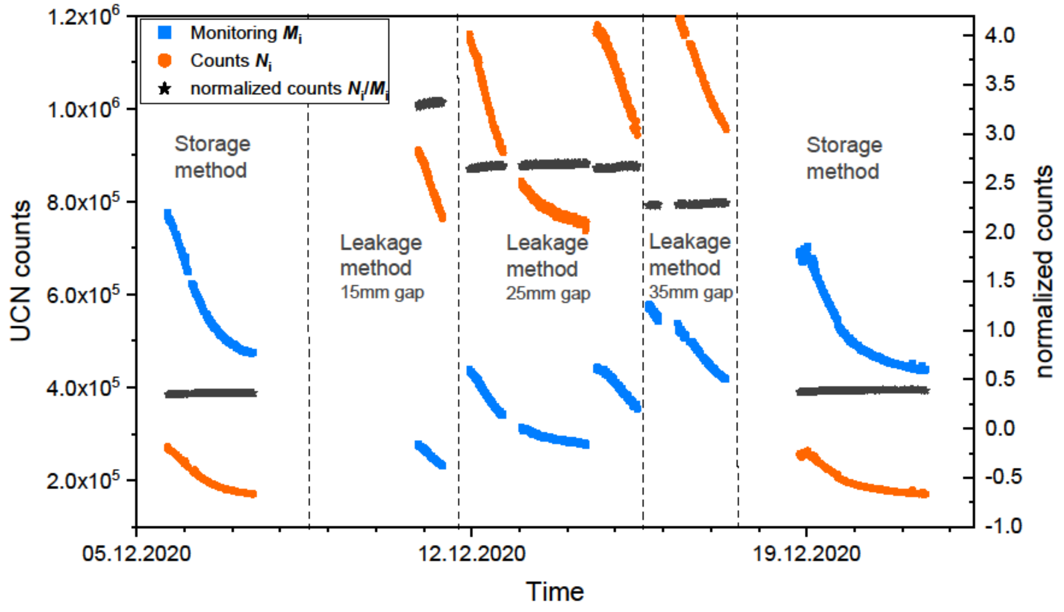


UCN

Test Beamtime 2020

- Commissioning of UCN components
- Validate and optimise Monitoring scheme
- ~12 days physics datataking
  - Storage technique
  - Leakage technique

- Analysis of both physics datasets ongoing



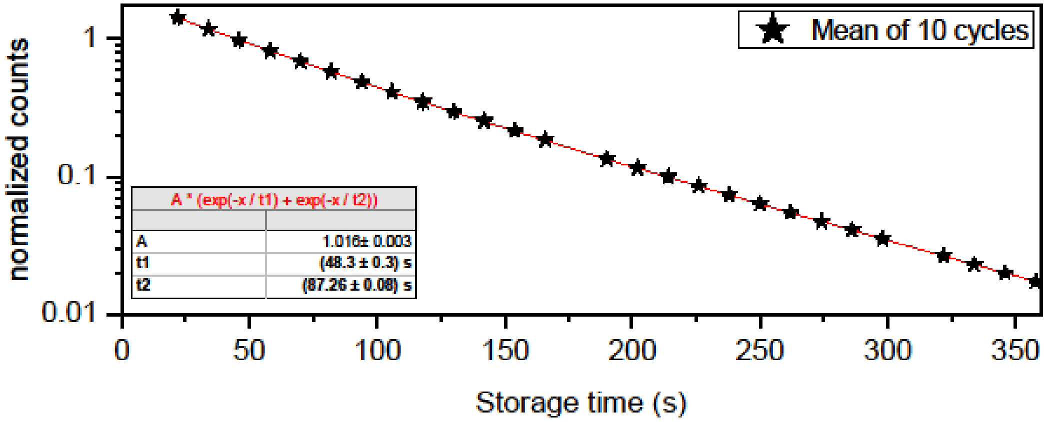
Measured UCN Performance

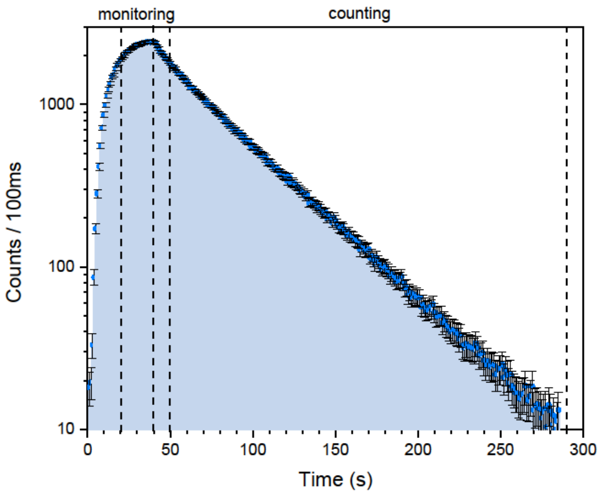
- 350,000 UCN after 100s
- 270,000 UCN after 120s
- 90,000 UCN after 200s

- Monitor Counts 800,000

- Leakage method also showed good performance

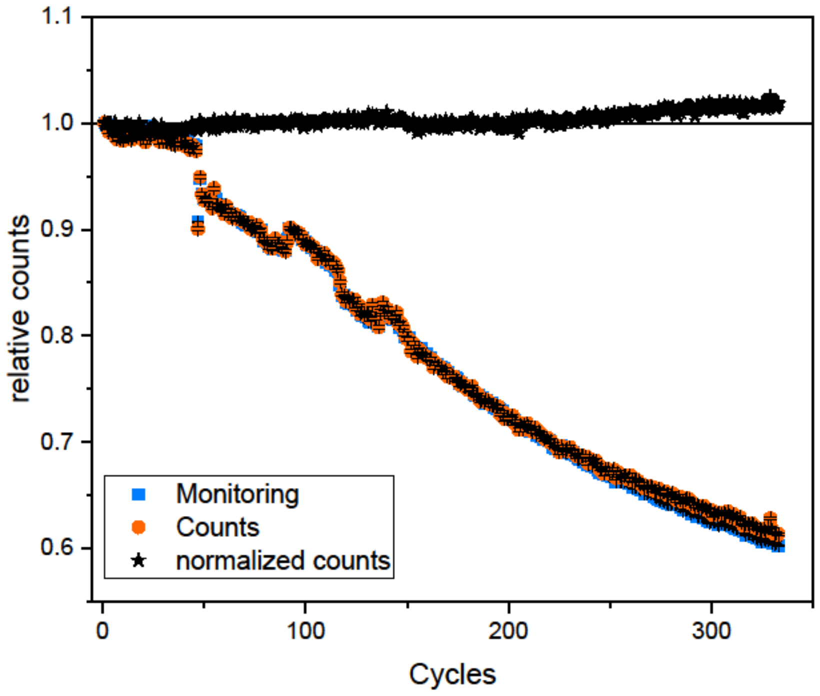
- Performance good, but room for improvement





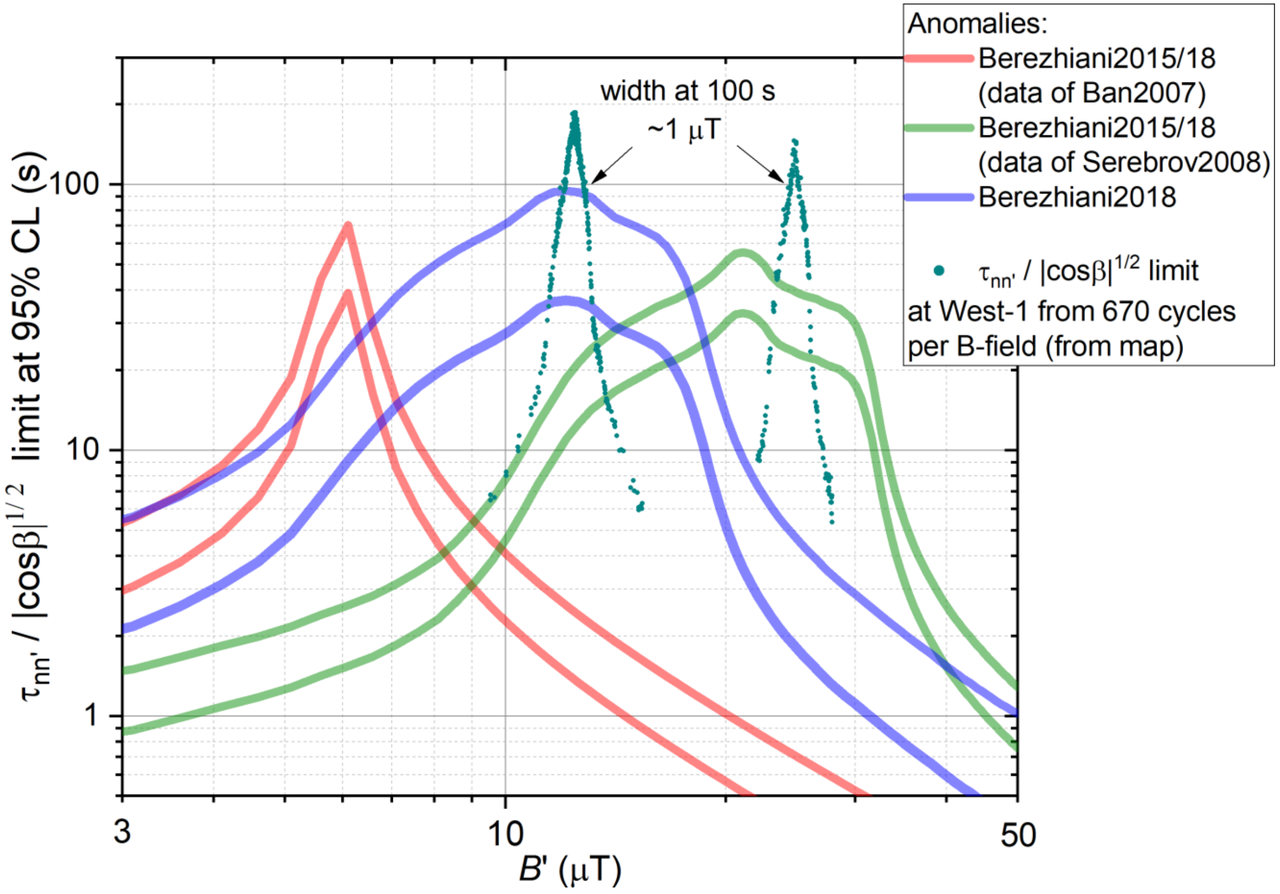
Demonstration of Normalization Strategy

- Key goal of test beam was to demonstrate ability to compensate for drifts in UCN source output
- Normalizing count rate after storage to the count rate during the last part of filling
- Uncompensated slow drift removed by using drift resistant “ABBA” measurement scheme



Typical drift in output over 1.5 days measurement

Projected Sensitivity



Simulated exclusion plot for approx. 3 days running

Preliminary, based on:

- UCN Performance as Dec 2020
- Assumed “realistically bad” B field configuration

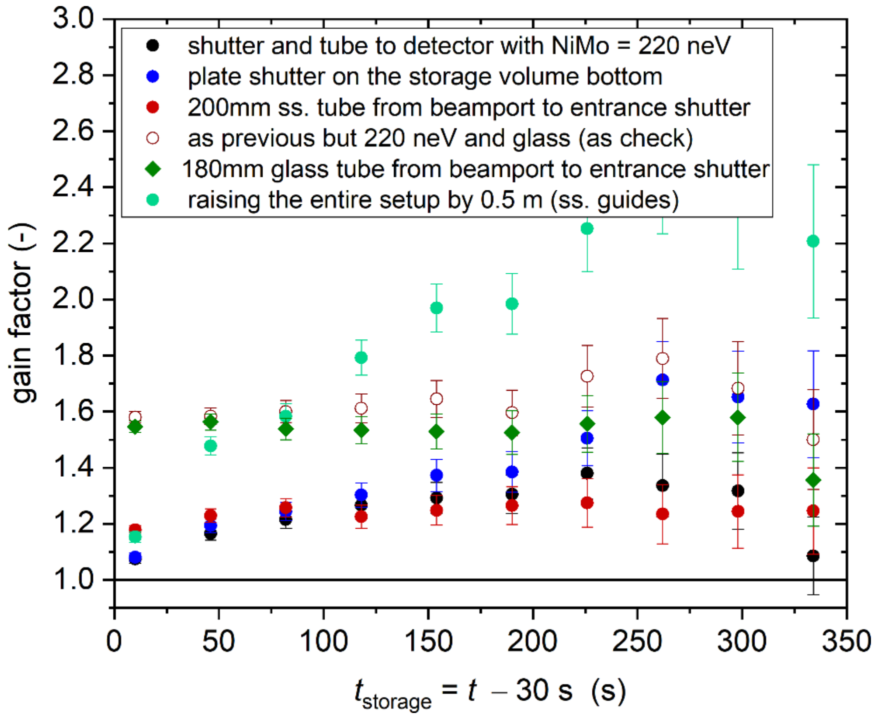
$$\tau_{nn'}(B,B') = \sqrt{\frac{t_s}{\langle t_f \rangle A_{\uparrow\downarrow}}}\sqrt{f(B,B')\cos\beta}$$

Planned UCN Upgrades for 2021

- Electropolish inside of storage chamber
- Coat lower shutters and guides with NiMo
- Enlarged filling UCN guides from source to experiment

- Under consideration:
  - Replace emptying shutter to a design flush with bottom of storage chamber
  - Raise height of entire apparatus

- Simulations show factor of 1.5 to 2.3 achievable



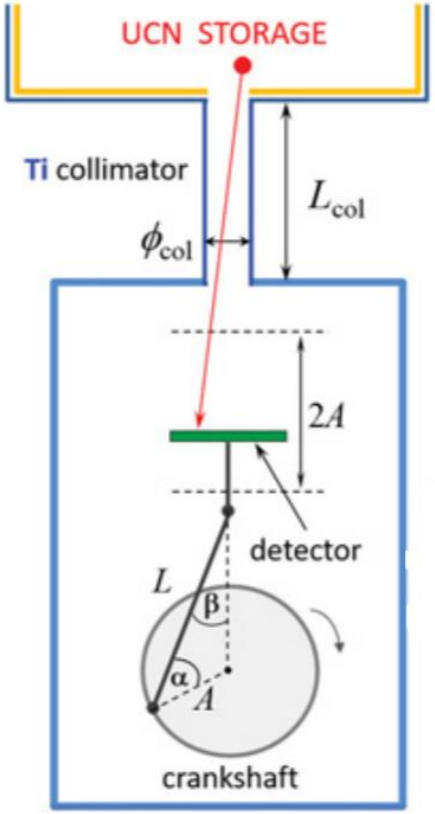
Magnetic Field Mapping

- To interpret UCN measurements in terms of mirror neutrons, we need to know the magnetic field
  - Exact field shape is an important input to Monte Carlo simulations
  - For ease of analysis, also important to achieve symmetrical fields
- Cannot interpolate from external fluxgates due to local fields
- Internal mapper device built at ETH, to be used Q1 2021

Supplementary measurements with oscillating UCN detector

- Use oscillating UCN detector OTUS [1] to measure stored UCN velocity distribution
- Use endoscopic UCN detector [2] to measure UCN height distribution

- Useful additional input to and crosscheck of critical Monte Carlo simulations



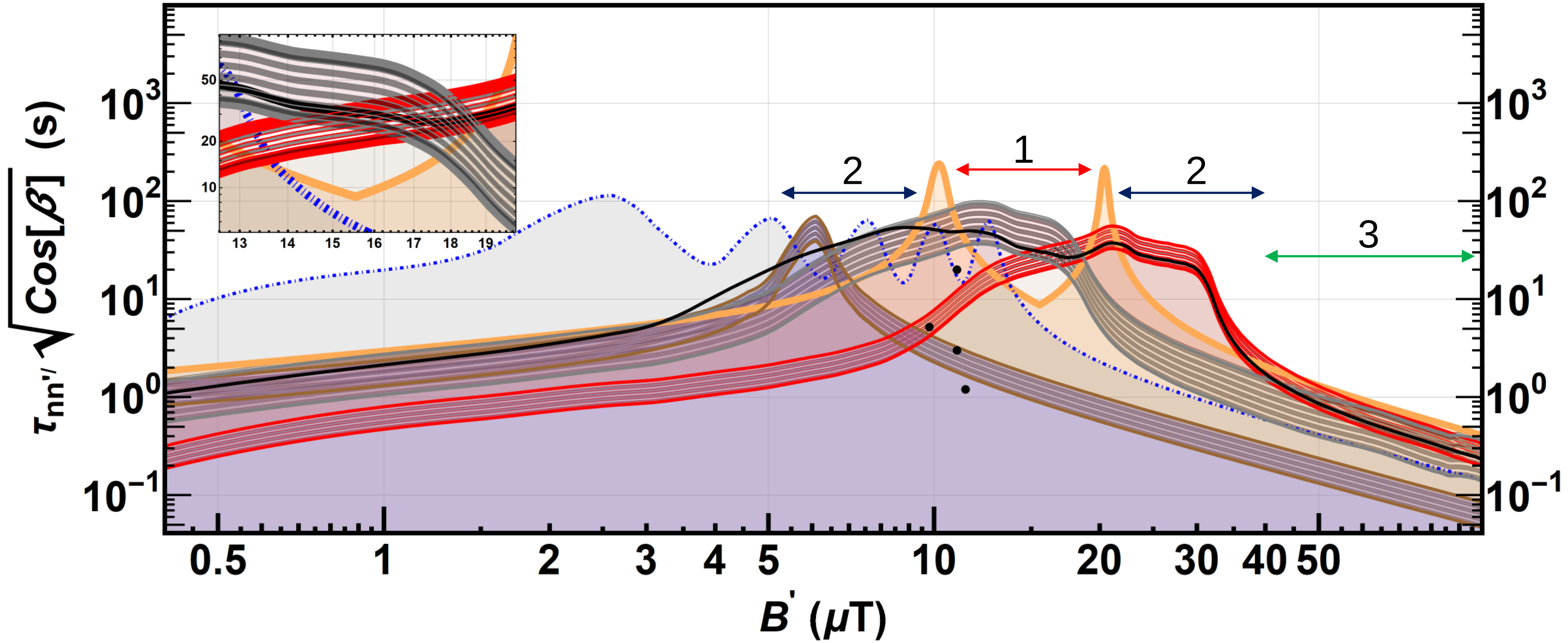
OTUS [1]

[1] D. Rozpedzik et. al. EPJ Web Conf 219, 10007 (2019)
[2] L. Göltl et. al. EPJ A **49**, 9 (2013)

Beamtime Request 2021

- 14 Weeks at PSI West-1 UCN Beamline
  - 10 days recommissioning and characterising UCN upgrade performance
  - 66 days physics datataking campaign, to cover
    1. B’ = 12µT - 19µT
    2. B’ = 22µT - 40µT and 2.5 µT – 7 µT
    3. B’ = 40µT - 100µT
  - 10 days supplementary measurements with oscillating UCN detector and endoscopic UCN detector
- Measurements mostly automated and could still take place under PSI Limited Operations I – III scenarios

B’ to cover



$\tau_{nn'}/\sqrt{Cos[\beta]}$ (s)
10^3
10^2
10^1
10^0
10^{-1}
0.5
1
2
3
4
5
10
20
30
40
50
B' (μT)
1
2
2
3
50
20
10
13
14
15
16
17
18
19

Summary

- Mirror particles can explain several physical phenomena [1-3]
- Statistically significant anomalies found in previous experiments [4,5]
- Demonstrated feasibility of experiment

- We are requesting 14 weeks of beamtime at PSI UCN West-1 for our main physics run

[1] Z. Berezhiani Int. J. Mod. Phys. A 33, 31 (2018) 1844034
[2] Z. Berezhiani, L. Bento PLB 635 (5-6) (2006) 253-259
[3] Z. Berezhiani, A. Gazizov EPJC 72 (8) 2111 (2012)
[4] Z. Berezhiani, F. Nesti Eur. Phys. J. C (2012) 74:1974
[5] Z. Berezhiani et al. Eur. Phys. J. C (2018) 78:717

Backup

Mirror Neutrons & Neutron Lifetime puzzle

- Long standing discrepancy between neutron lifetime measured by beam vs bottle experiments

- Beam: Start with known neutron flux, count decay products
- Bottle: Count neutrons surviving after different storage times
- In some scenarios oscillation of neutrons into mirror neutrons could explain the discrepancy
  - Tension with recent measurements of g_A [e.g. Czarneki et al. PRD 100, 073008 (2019)]

Competing & Complementary Experiments

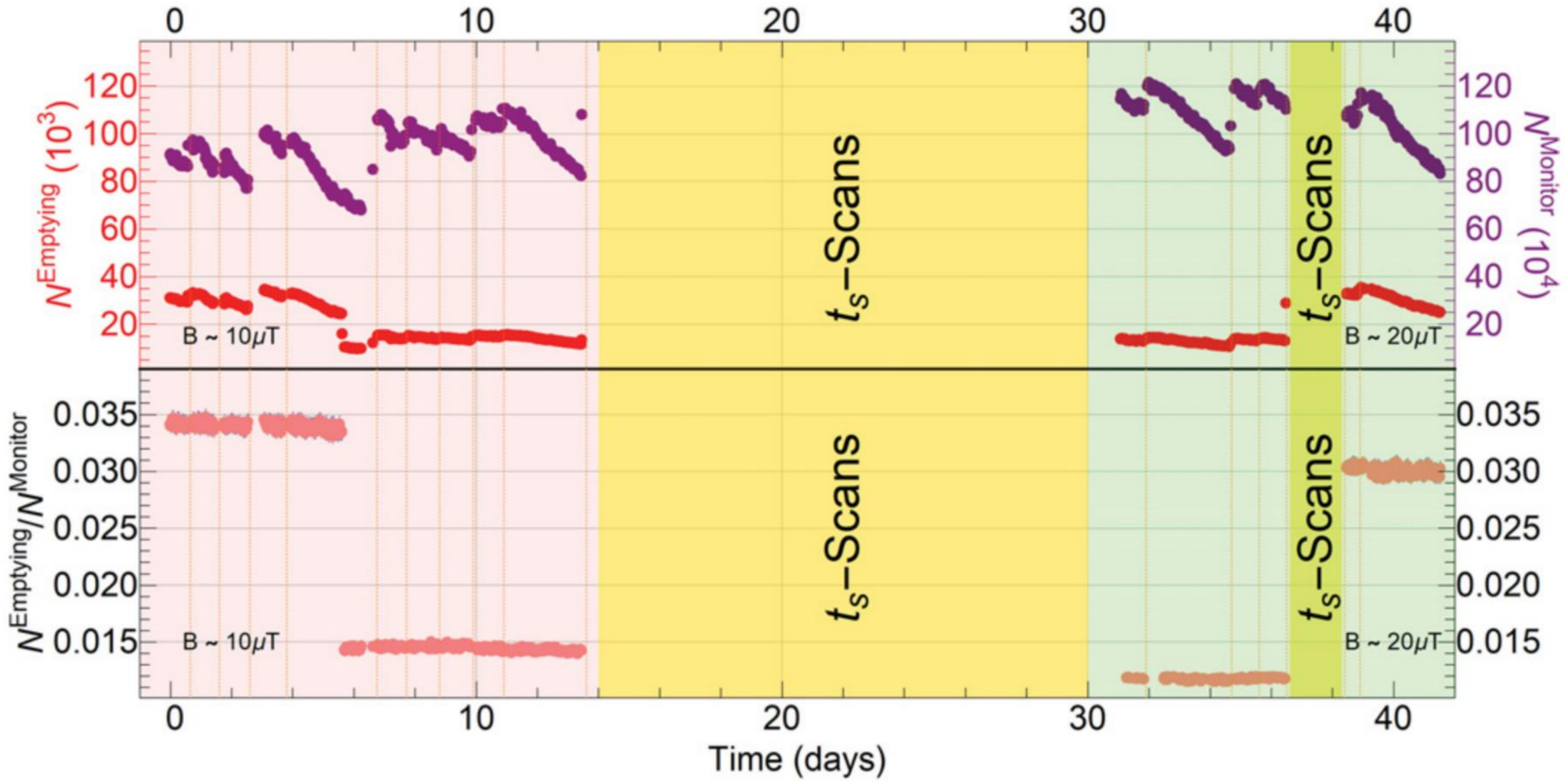
- Neutron Regeneration Experiment discussed: search for n->n'->n [1]

- Many experiments to measure the neutron lifetime
  - New experiments using conventional and magnetic traps, and beam-type experiments

- Ongoing study of neutron decay parameters

[1] L.J. Broussard et al. EPJ Web of Conferences 219, 07002 (2019)

The 2017 PSI Measurement



Example height distributions in upgrade scenarios