Neutron Hidden-Neutron Oscillations

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On behalf of the collaboration

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Hidden sectors

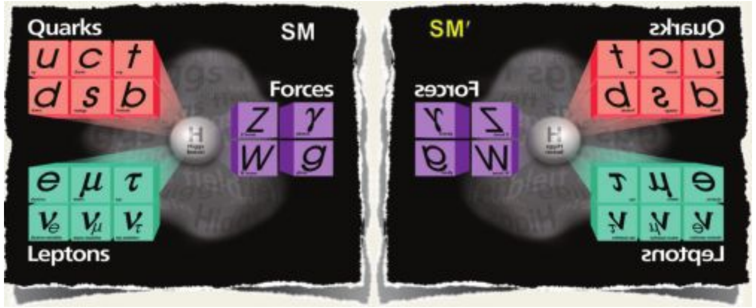
50's First proposal: restore P symmetry by adding new particles
[T. D. Lee and C. N. Yang, Phys. Rev. 104 (1956) 254]

90's Exact copy of SM particles: SM'
[R. Foot. Jou. Mod, Phys. A, 29 (2014) 11n12:1430013]

1. SM and SM' only interact through gravity
   (candidate for DM)

2. n–n': A baryon number violating process
   (hints for baryogenesis)

3. Solution to **anomalies** in precision measurements
   (e.g. neutron-lifetime puzzle)
   [Jack T. Wilson, et al, Phys. Rev. Res 2, 023316 (2020)]



$$\mathcal{L}_{total} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{Mixing}$$

n–n' mixing

- **Simple phenomenological model (2 parameters)**
- **Verifiable in low energy experiments**
- **Maximal mixing at $\delta m = \Delta E$**

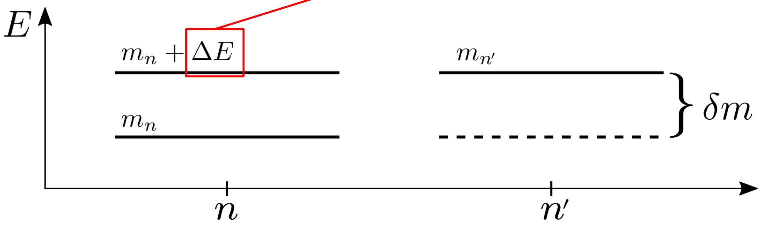
neutron - matter interaction

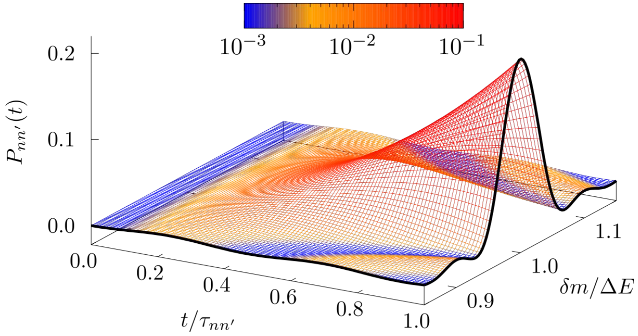
mixing term $(= 1/\tau_{nn'})$

$$\hat{H} = \begin{pmatrix} m_n + \Delta E & \epsilon_{nn'} \\ \epsilon_{nn'} & m_n + \delta m \end{pmatrix}$$

mass splitting

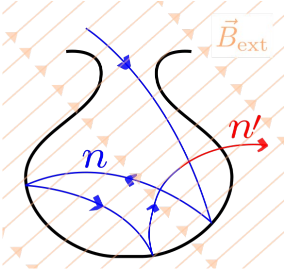
Experimentally tuned to scan δm



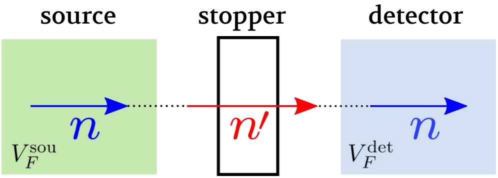


$$P_{nn'} = \frac{4\sin^2([\Delta E - \delta m]t/2])}{\tau_{nn'}^2(\Delta E - \delta m)^2}$$

State of the art

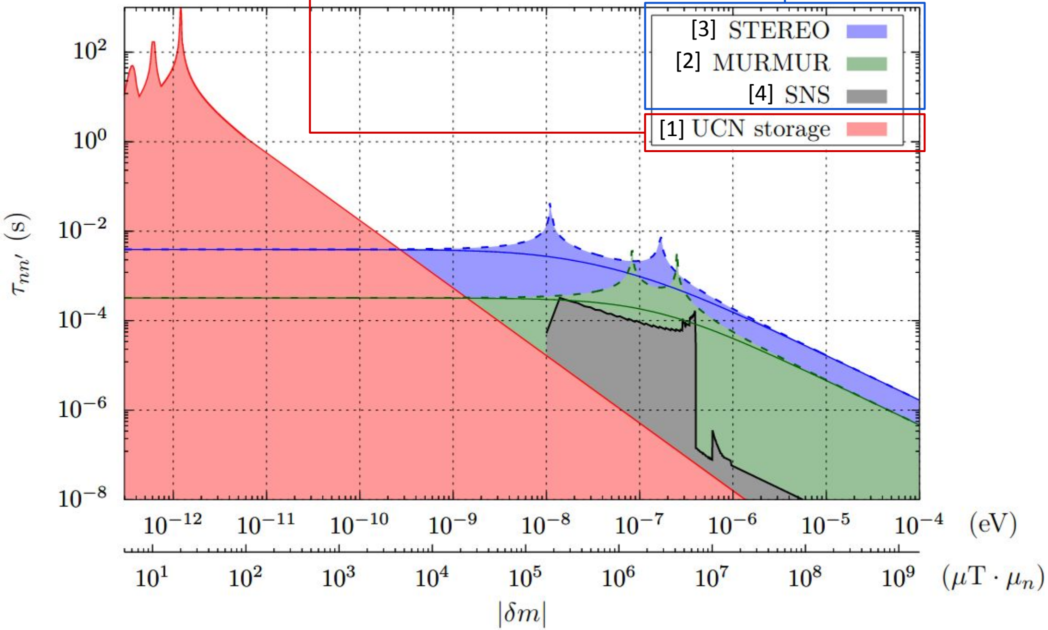


UCN storage



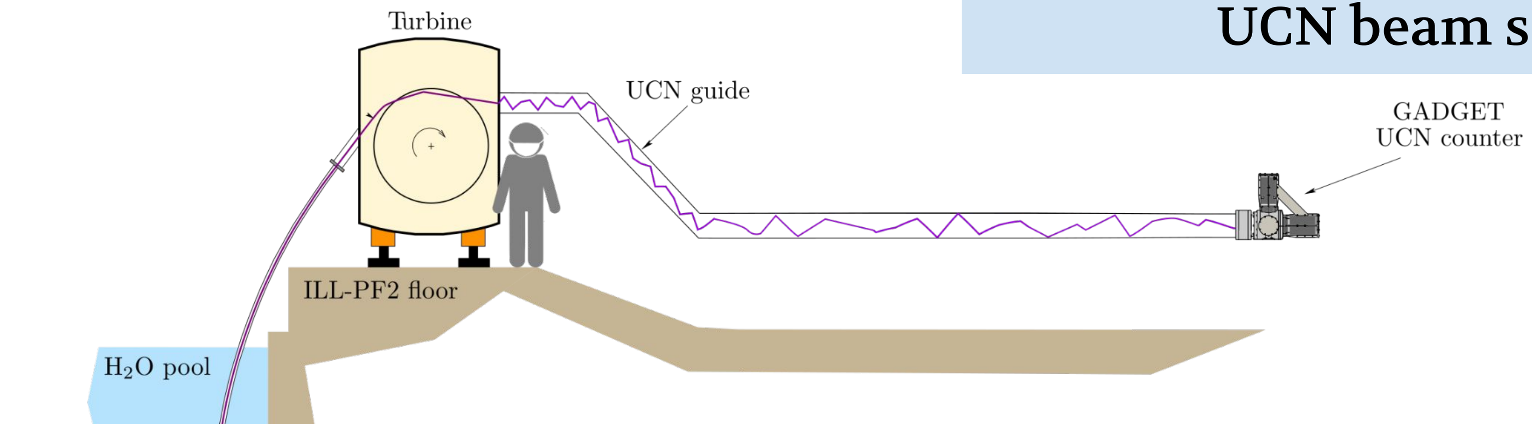
Regeneration

- Around 10 experiments have constrained the parameter space (95% C.L.)
- A 5σ anomaly [5] in UCN storage motivated the search at low δm
- Regeneration setups are efficient at high ***δm***. Storage UCN at low ***δm***
- SNS tests [4] reject n–n' in beam experiments measuring τ_n

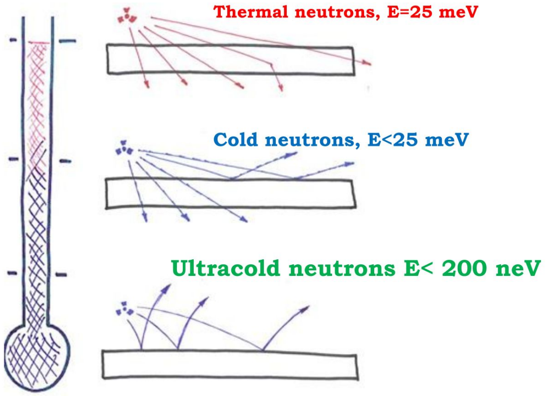


[1] C. Abel *et al.* (2020). arXiv:2009.11046 [hep-ph].
[2] C. Stasser, *et al.* (2021). arXiv:2007.11335 [nucl-ex].
[3] H. Almazán, *et al.* (2021). arXiv:2111.01519 [hep-ex].
[4] L.J. Broussard *et al.*, (2021). arXiv:2111.05543 [nucl-ex].
[5] Z. Berezhiani, F. Nesti, (2012). arXiv:1203.1035 [hep-ph].

UCN beam setup

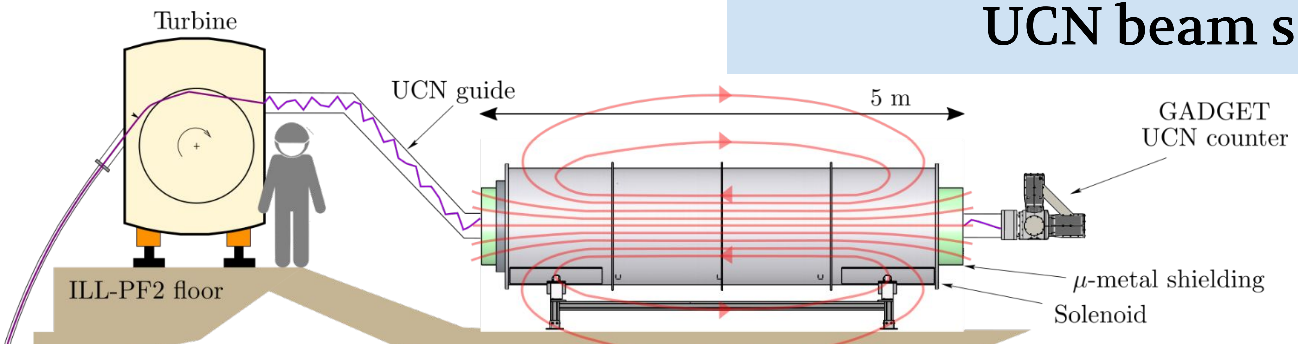


- UCN from ^{235}U fission at ILL's reactor

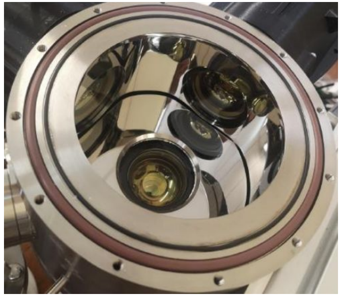


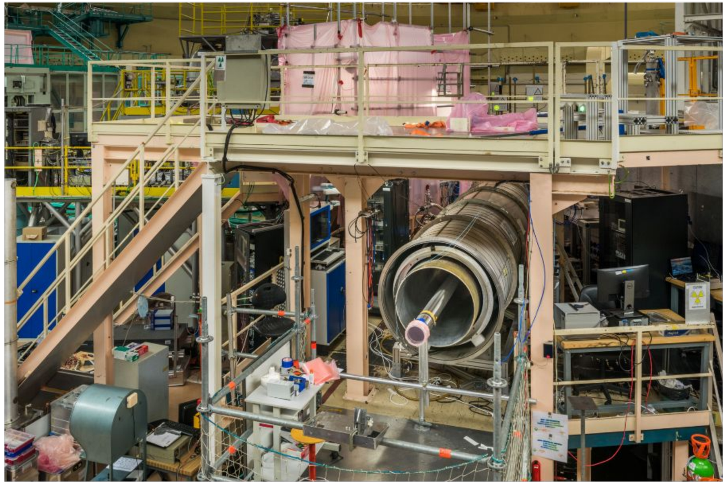
ILL reactor - Data taking: autumn 2020

UCN beam setup



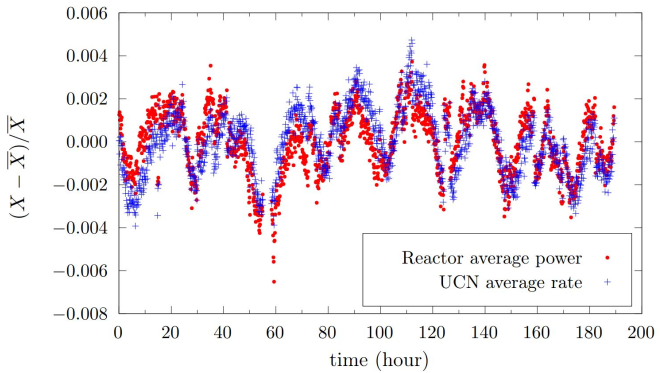
- B-field to probe n–n' with $\delta m \in [2 : 69]$ feV, i.e. $B \in [30 : 1100]$ μT
- Mu-metal magnetic shielding & compensation coils
- n–n' signal: UCN flux drop



Data collection strategy

- UCN counting affected by long-term variations (e.g. reactor power fluctuations)

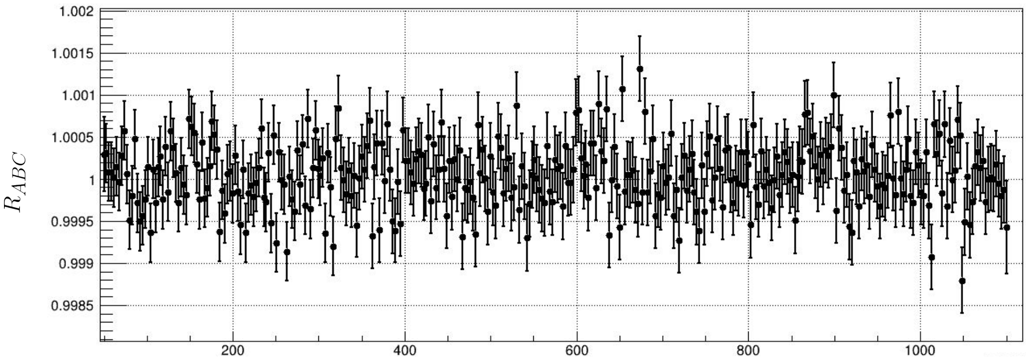


- B-field scanning sequence:

$$\{A, B, B, C\} \rightarrow \{B - 20\,\mu T, B, B, B + 20\,\mu T\}$$

- Self-normalized UCN flux:

$$R_{ABC} = \frac{N_B + N_B}{N_A + N_C} \begin{cases} = 1, & \text{if no oscillations} \\ < 1, & \text{if } B \approx \delta m/\mu_n \\ > 1, & \text{if } A \text{ or } C \approx \delta m/\mu_n, \end{cases}$$



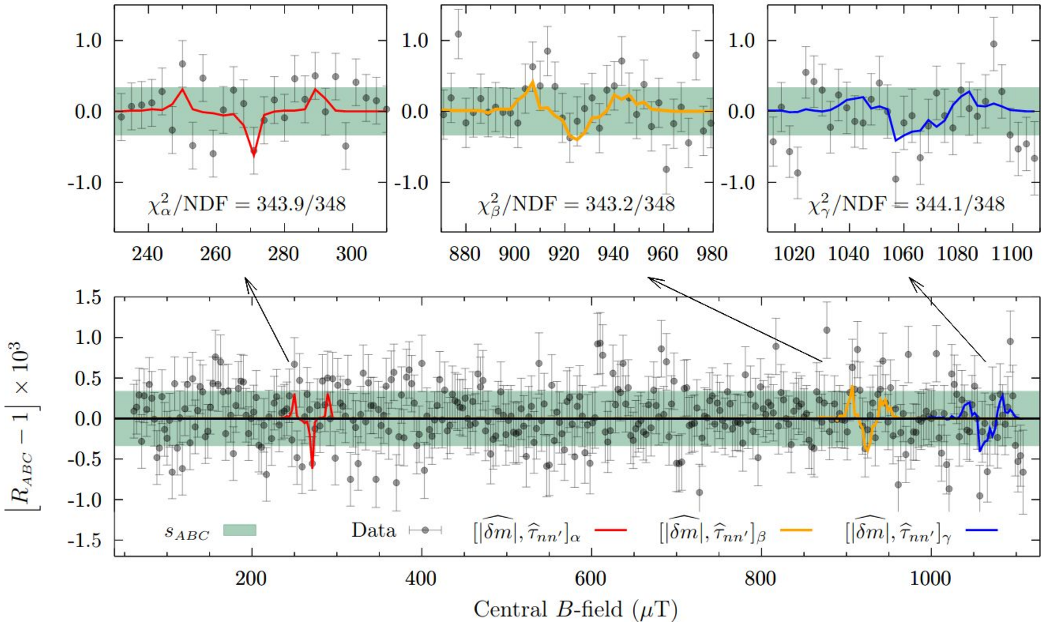
B [μT]

Analysis

- **Oscillation probability computed from**

$$\frac{\partial}{\partial t}\hat{\rho} = -i[\hat{H} \cdot \hat{\rho}] = -i\hat{H}\hat{\rho} + i\hat{\rho}\hat{H}^{\dagger}$$

- **Fitted parameters: $\boldsymbol{\delta m}$ *and* $\boldsymbol{\tau_{nn'}}$**



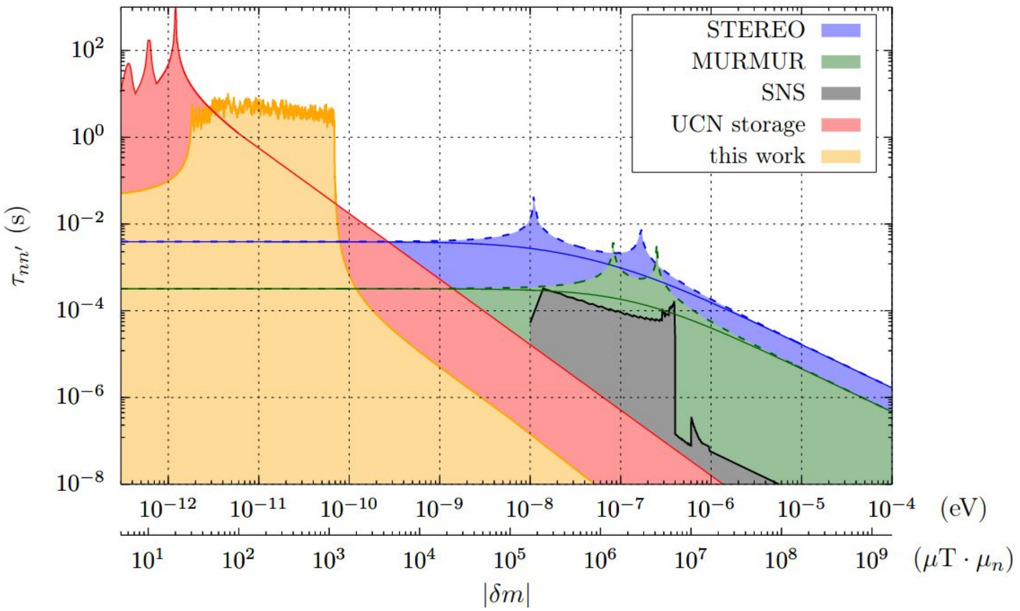
- **No significant signal ($\boldsymbol{\chi^2_{null}}$ / NDF = 348.5/349) but…**

New exclusion region

- New exclusion in $\delta m \in$ [6 - 72] feV : $\tau_{nn'} < 1$ s (95 % C.L.)

- Future beam experiments would fill the parameter space gap between UCN and regeneration experiments

- New physics could still be found at large δm



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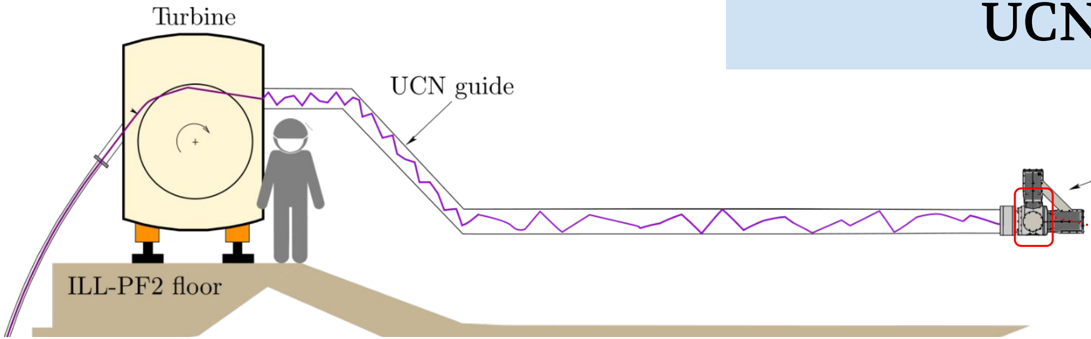
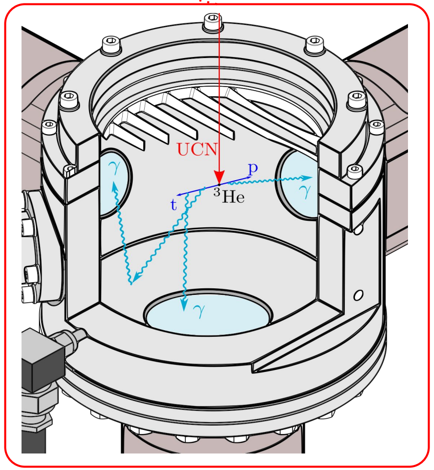
Thank you

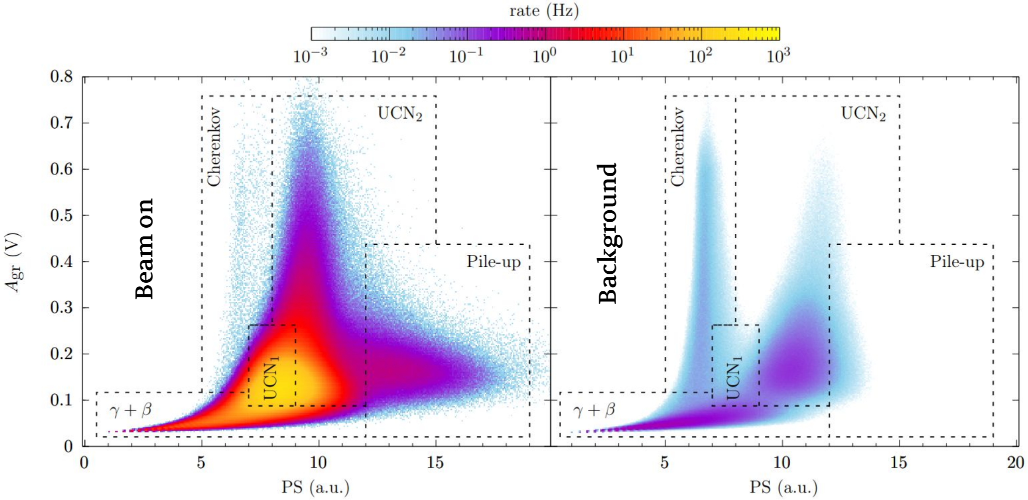
Spare

UCN beam setup





- High UCN rate: ~ 500 kHz (First test of the n2EDM counter **GADGET**)
- PSA: background contribution < 0.01%



Fitting function

- *R* computed theoretically as

$$R_{\text{theo}}(\Delta E;\delta m,\tau_{nn'}) = \frac{N_B}{N_A+N_C} = \frac{2N_0\exp\left[-n_{\text{col}}\overline{P}(\mu B;\delta m,\tau_{nn'})\right]}{N_0\exp\left[-n_{\text{col}}\overline{P}(\mu A;\delta m,\tau_{nn'})\right]+N_0\exp\left[-n_{\text{col}}\overline{P}(\mu C;\delta m,\tau_{nn'})\right]}$$

with $\overline{P}$ obtained from the **numerical solution** of

$$\frac{d}{dt}\begin{pmatrix}\psi_n\\ \psi_{n'}\end{pmatrix} = \begin{pmatrix}m_n+\Delta E & 1/\tau_{nn'}\\ 1/\tau_{nn'} & m_n+\delta m\end{pmatrix}\begin{pmatrix}\psi_n\\ \psi_{n'}\end{pmatrix}$$

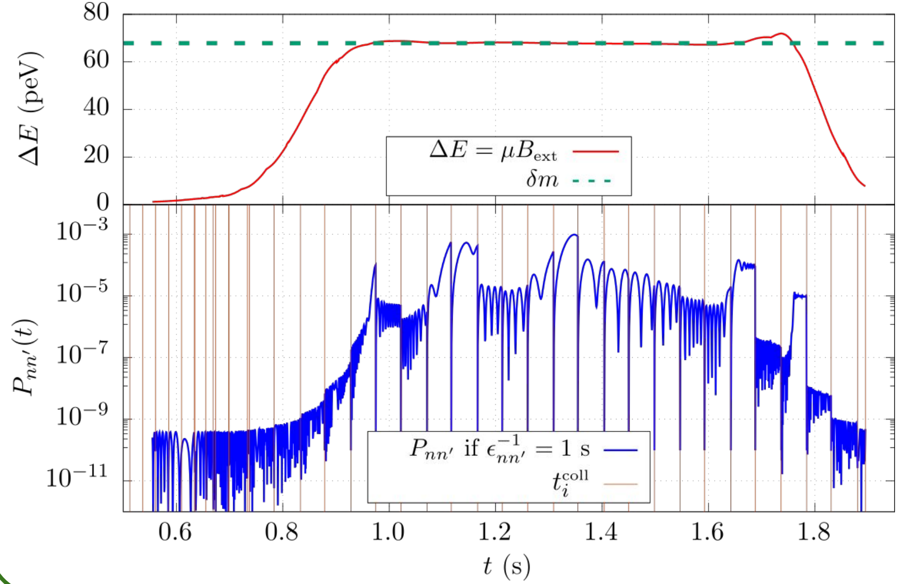
as

$$\overline{P}(\Delta E;\delta m,\tau_{nn'}) = \frac{1}{N_n}\sum_i^{N_n}\sum_j^{N_{\text{col}}}\left|\psi_{n'}(t_{i,j}^{\text{col}})\right|^2$$

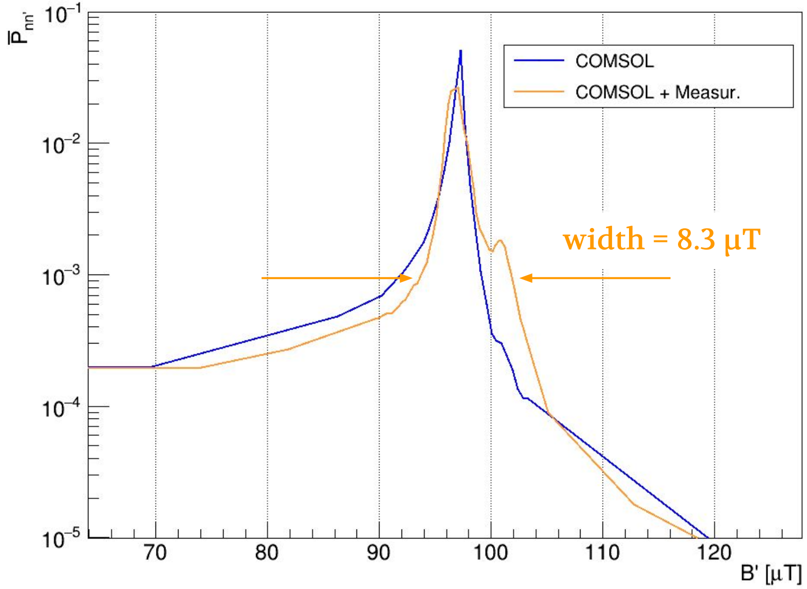
- UCN trajectories from **MC** simulations

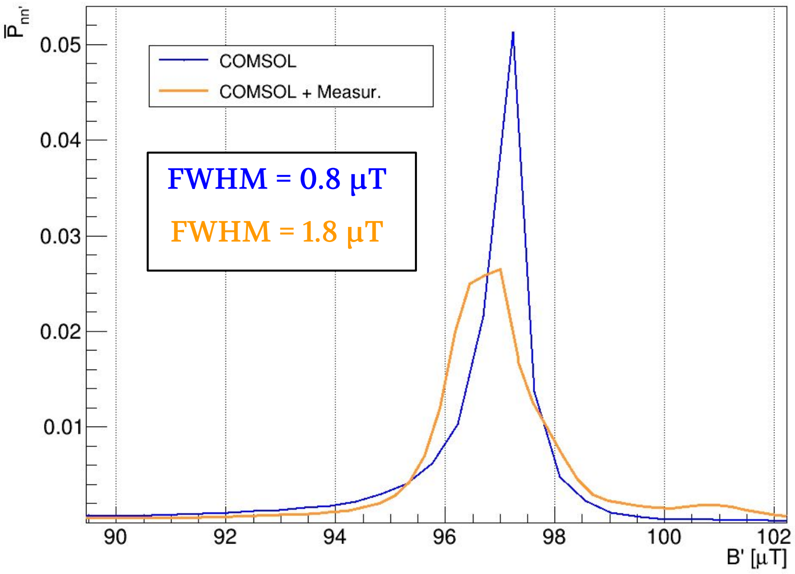
- Measured **field inhomogeneities** included in the algorithm

sample track for $\tau_{nn'}$ = 1 s, δm = 68 peV



Resonance width

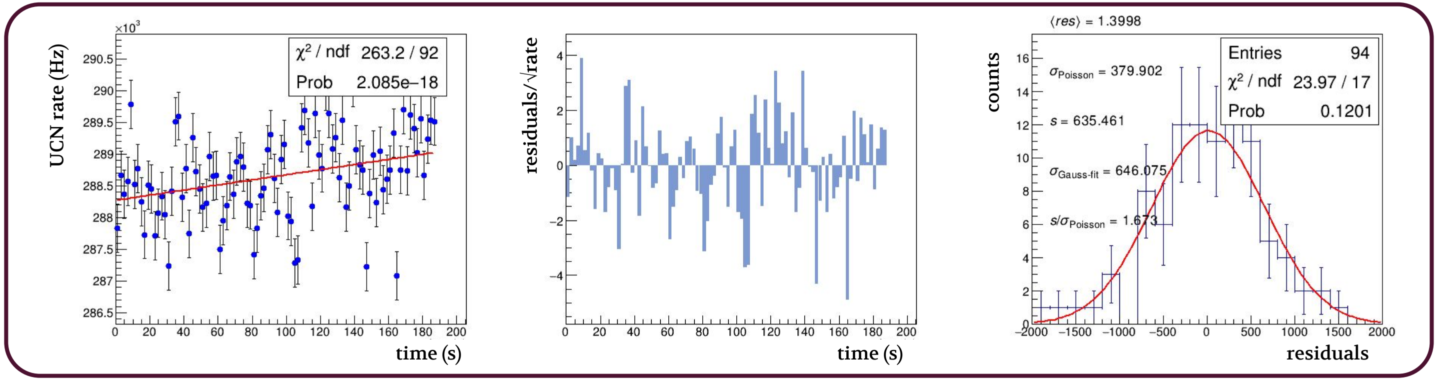




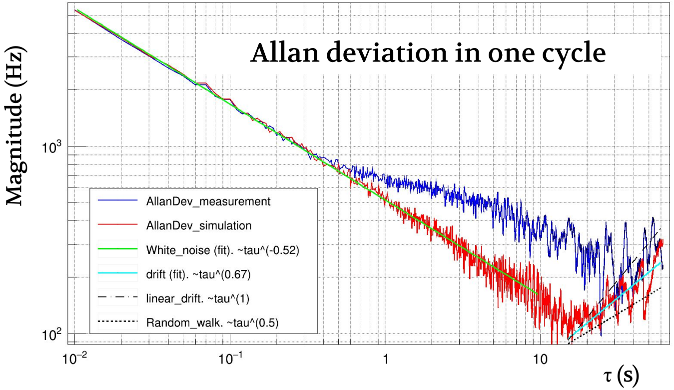
On the search for non-statistical fluctuations

- Non-stat. fluctuations already at the second time scale

Rate analysis in one cycle

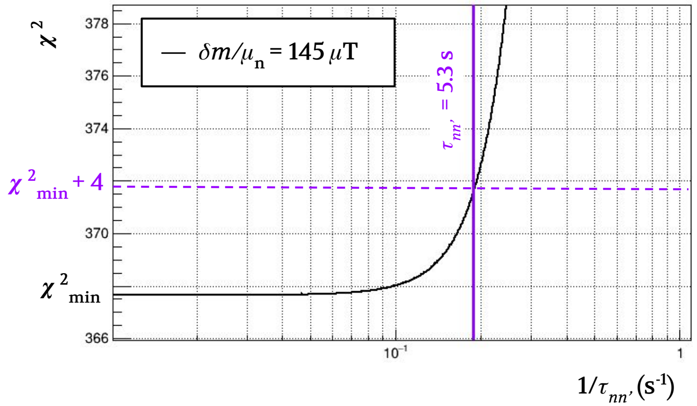


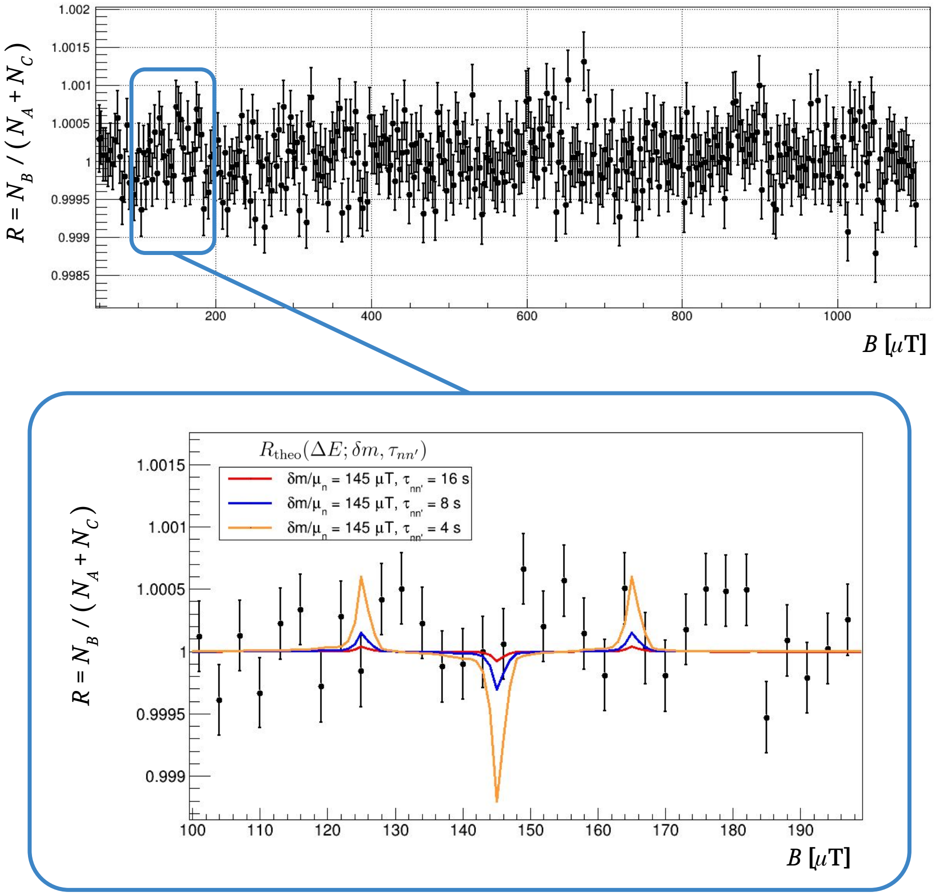
- **Allan deviation of the counting rate**: White noise (statistical fluctuations) lost at τ > 0.6 s



From R points to parameter exclusion

- No signal, but parameter exclusion
- To set a limit on $\tau_{nn'}$ at a given δm, we look at the agreement between R_{theo} and R_{exp}
  - The longer the $\tau_{nn'}$ the smaller the signal
  - $\chi^2 = \Sigma_i (R_{\text{exp}} - R_{\text{theo}})^2/\delta R_{\text{exp}}^2$; $i = 1, \ldots, 350$
  - Limit at $\chi^2 = \chi^2_{\text{min}} + 4$ (95% C.L.)



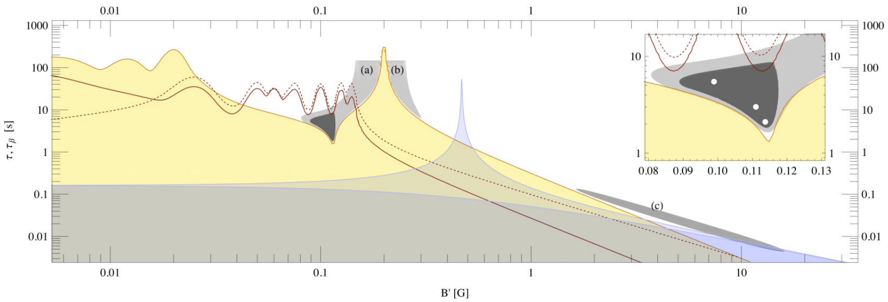


Bonus track

- Berezhiani's approach: No mass splitting but mirror field

$$\hat{H} = \begin{pmatrix} \mu\vec{\sigma}\cdot\vec{B} & 1/\tau_{nn'} \\ 1/\tau_{nn'} & \mu\vec{\sigma}\cdot\vec{B}' \end{pmatrix}$$

Mirror magnetic field



- Beam UCN experiment comparison against ratio channel
  [Berezhiani, Z., & Nesti, F. (2012). Eur. Phys. Jour. C, 72(4).]