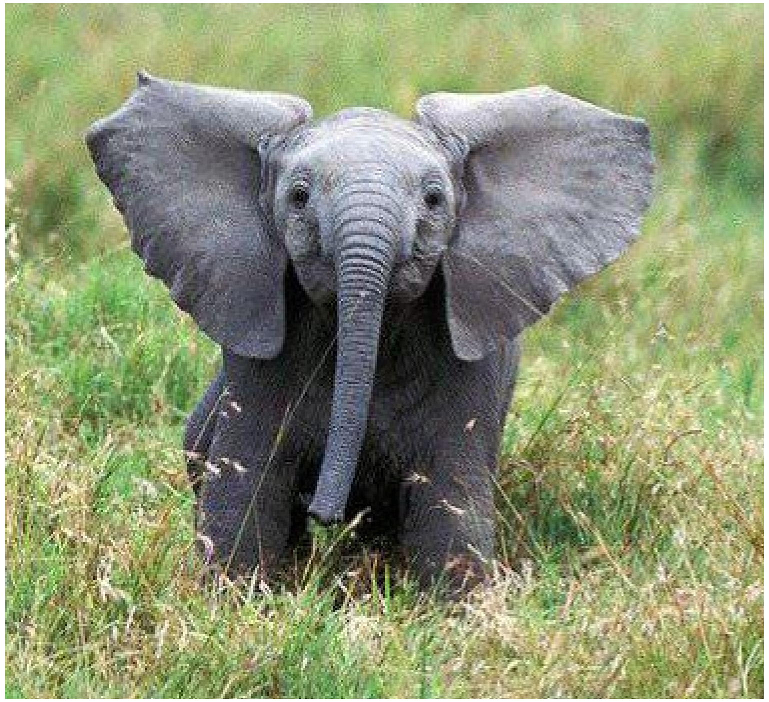
Baby Elephant

a neutron to mirror neutron oscillation experiment at

NEUTRONS FOR SOCIETY



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13/11/2025

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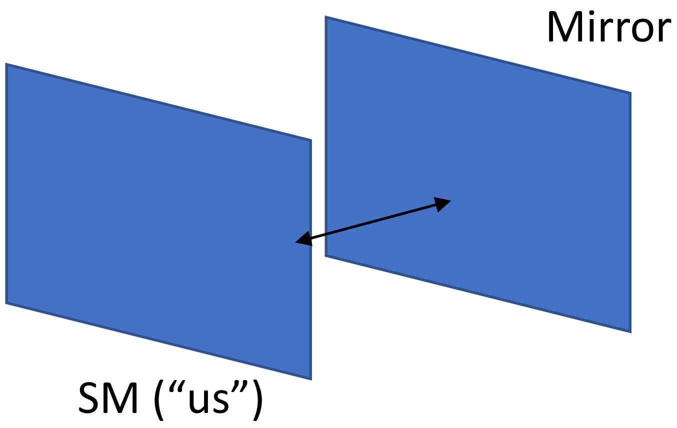
“Mirror” neutron oscillation

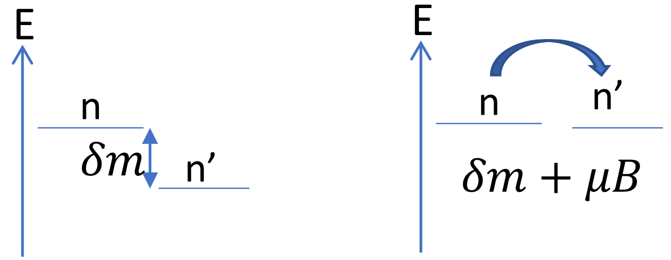
There exist a number of models either
- « mirror » universe
- two-brane extradimension models (ADD,…)
- generic $\mathbb{Z}_2$ symmetry
- …



Intially this kind of symmetry was suggested by Yang and Lee to restore parity conservation in weak interactions.

In each case there is a hidden sector and neutral particles can oscillate between SM and Mirror states.
As such oscillation aren’t observed, the symmetry must be broken and $m_n \neq m_{n'} \Rightarrow m_{n'} = m_n + \delta m$

We use coupling to the magnetic field to change the energy
Two-level hamiltonian :



$$\mathcal{H}'_{nn} = \begin{pmatrix} E_n & \tau_{nn}^{-1} \\ \tau_{nn}^{-1} & E_{n'} \end{pmatrix} = \begin{pmatrix} m_n + \mu B & \tau_{nn}^{-1} \\ \tau_{nn}^{-1} & m_{n'} + \delta m \end{pmatrix}$$

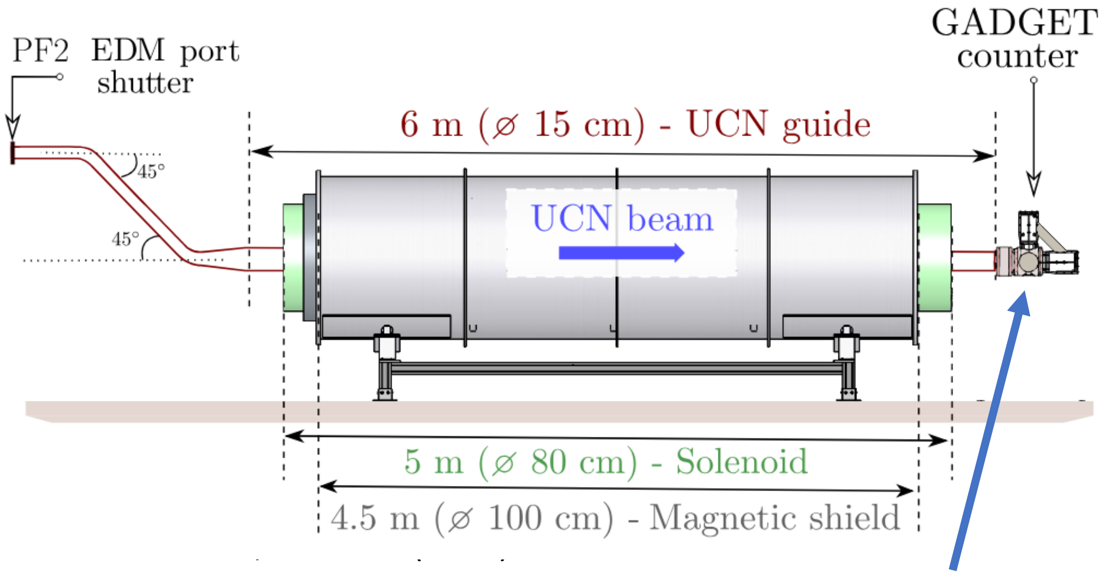
Two parameters : τ_{nn}^{-1} (mixing parameter) and δm (mass splitting)

PHYSICAL REVIEW LETTERS 131, 191801 (2023)

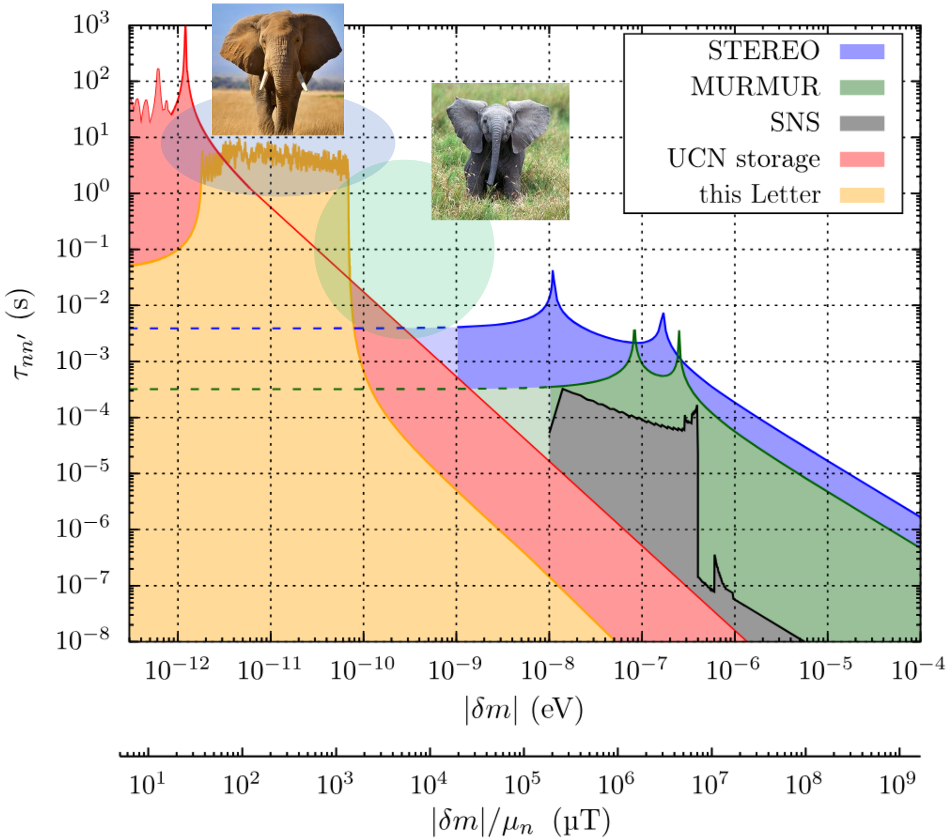
LPSC + LPC Caen + PSI/ETH + ILL

Elephant

UCN flow-through experiment
Scan magnetic field and look for a reduction of neutron flux (disappearance experiment)
2021 experiment, 50 days at ILL PF2,
Scan region from 30 to 1143 µT by 3µT (6mA) steps



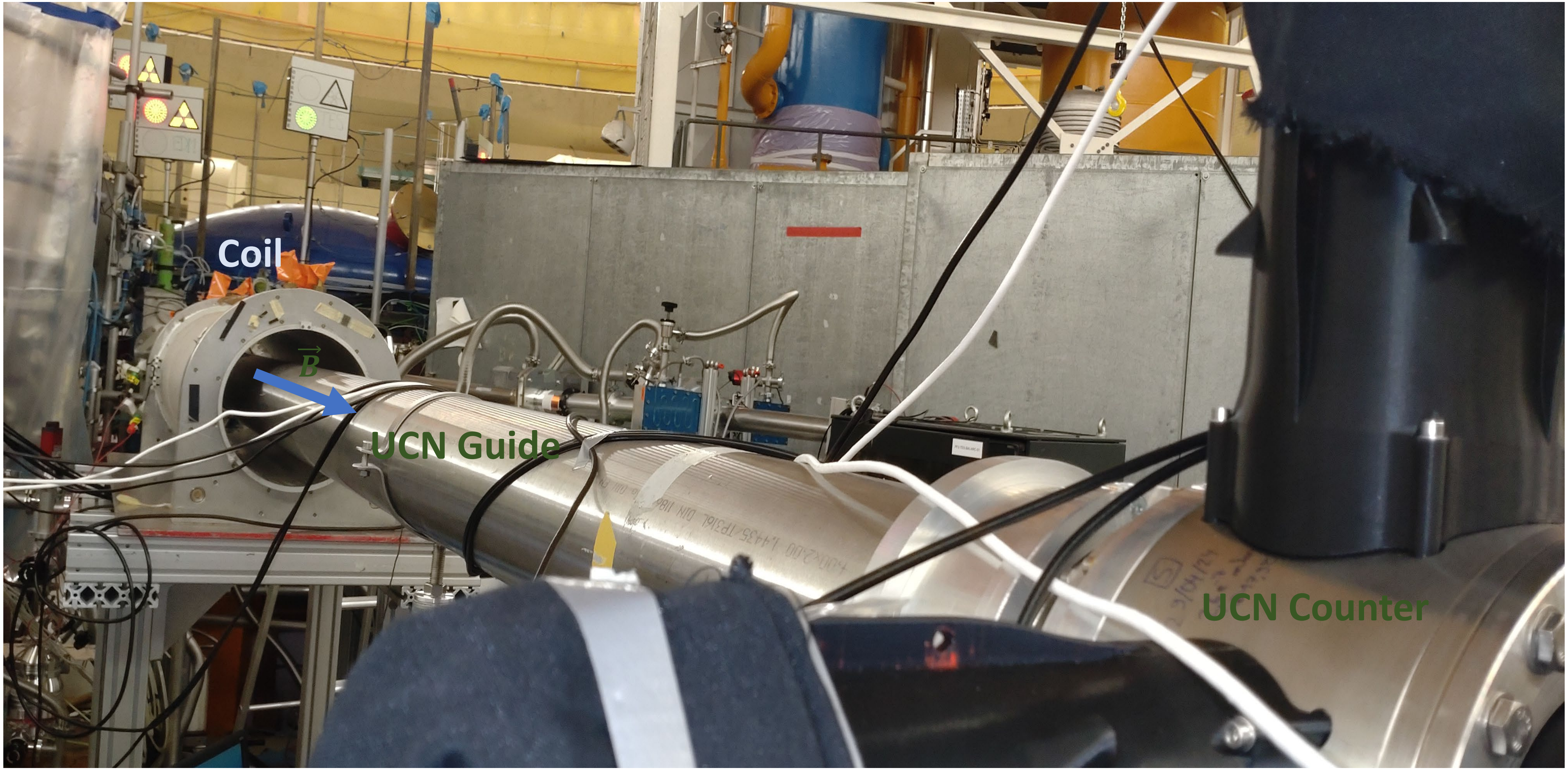
n2EDM detectors
(LPC Caen)



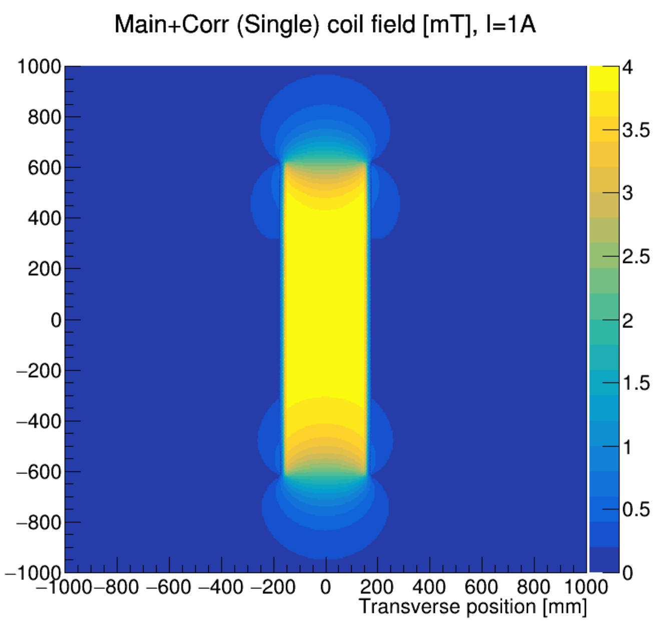
How to extend the limit in the higher mass splitting region ?

Low cost experiment : need to find a coil that can cover the 1mT-30mT range
need to cover a much larger field range : larger steps

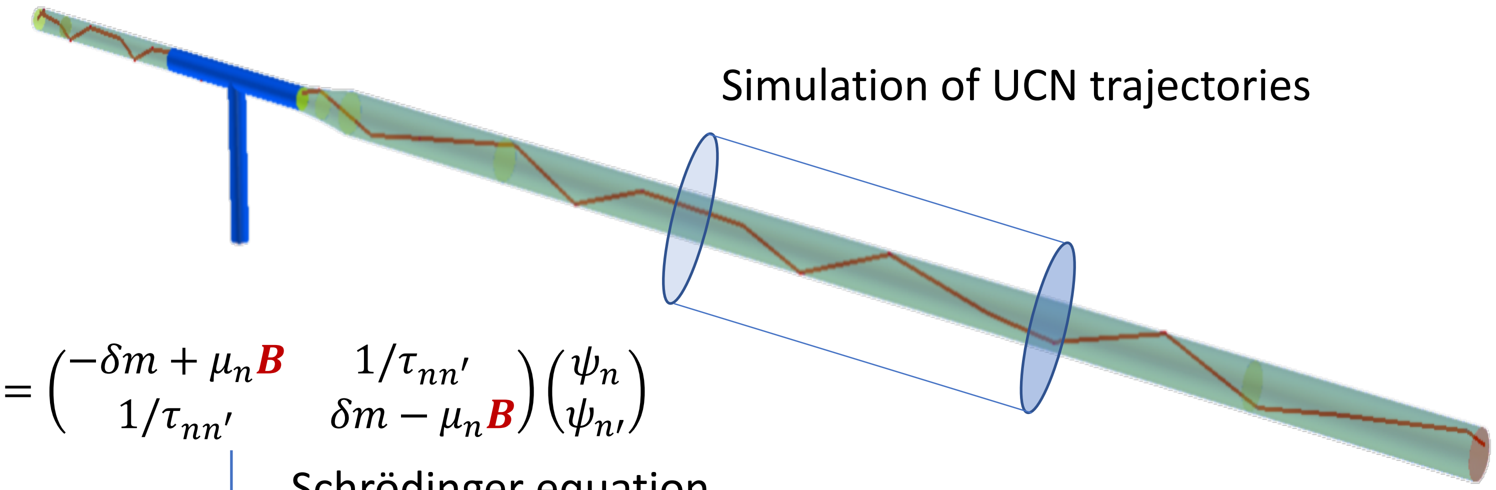
Baby elephant in the ILL savannah



Computing probabilites



Magnetic field map



Simulation of UCN trajectories

$$i\frac{d}{dt}\begin{pmatrix}\psi_n\\ \psi_{n'}\end{pmatrix} = \begin{pmatrix}-\delta m + \mu_n \boldsymbol{B} & 1/\tau_{nn'}\\ 1/\tau_{nn'} & \delta m - \mu_n \boldsymbol{B}\end{pmatrix}\begin{pmatrix}\psi_n\\ \psi_{n'}\end{pmatrix}$$

Schrödinger equation

Solve Schrödinger equation over many segments of simulated trajectories for $\tau_{nn} = 1$

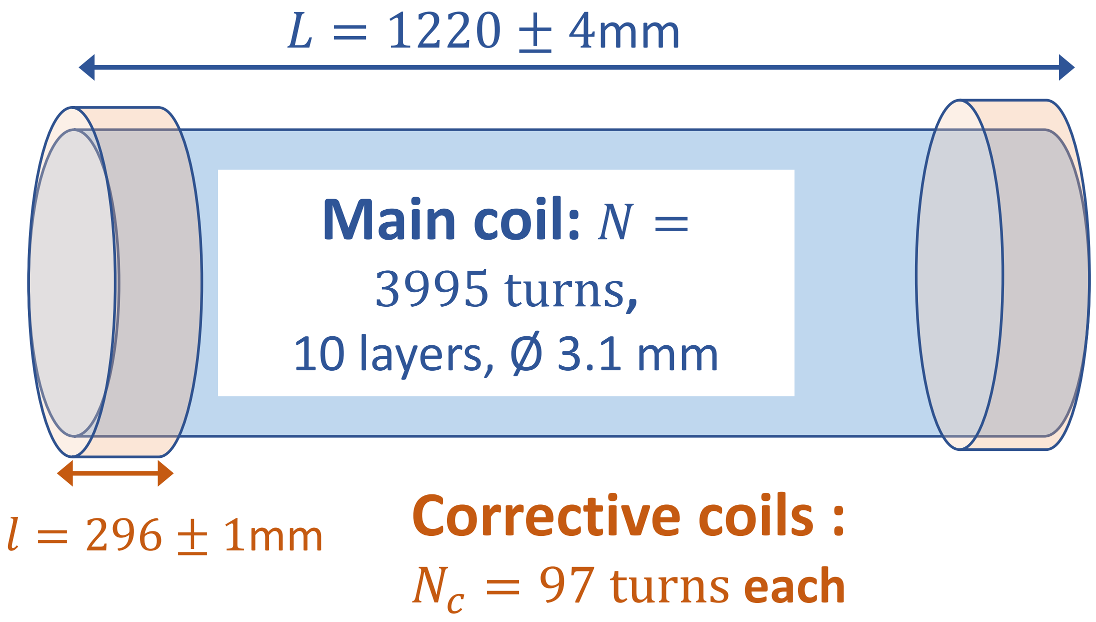
Compute transition probabilies over segments of trajectories

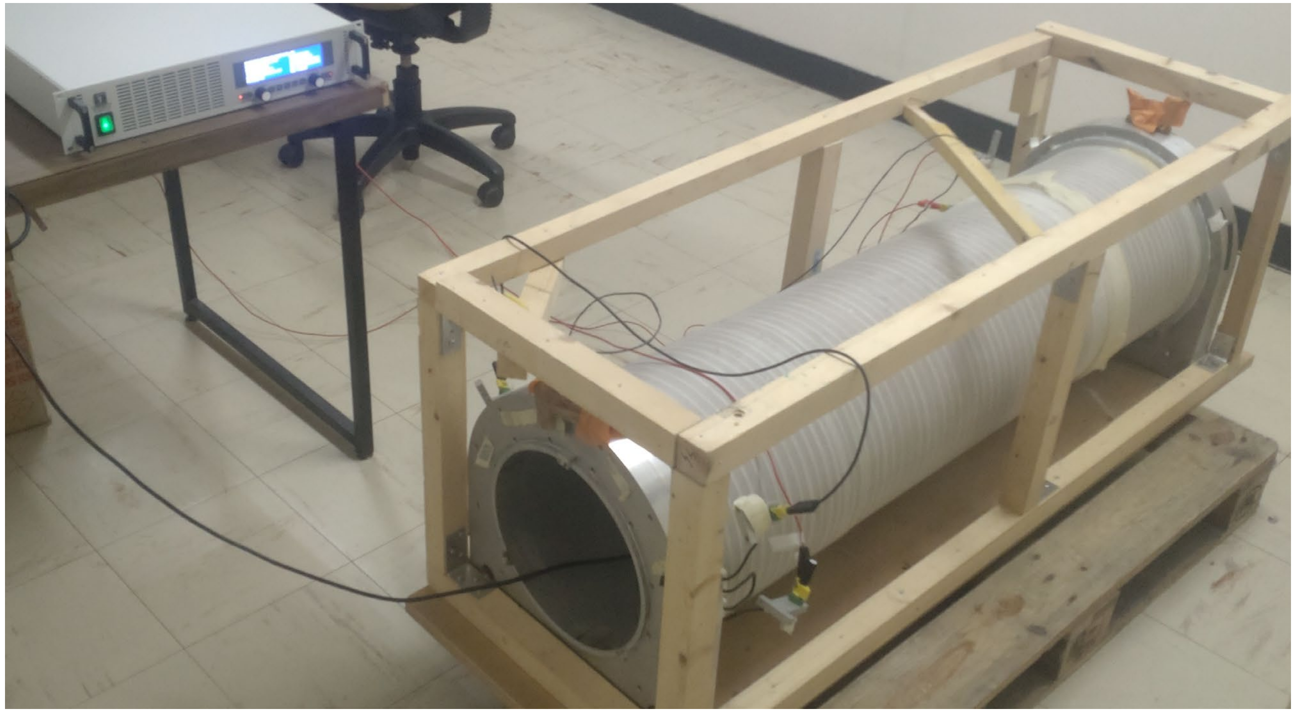
Average over many trajectories

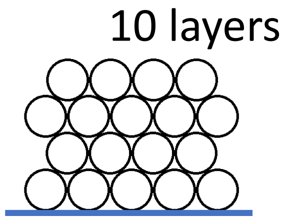
$$P_{oscill}(\delta m, I) \approx \frac{1}{N}\sum_{t}^{N}\sum_{s(t)}\left|\psi_{n'}(\tau(s))\right|^2$$

Free solenoid from LKB

Coil used for 3He polarization studies at LKB, gifted to us by P.-J. Nacher
Designed for : 100mA – 10A -> B=0,4-40mT (with water cooling above 25 mT)



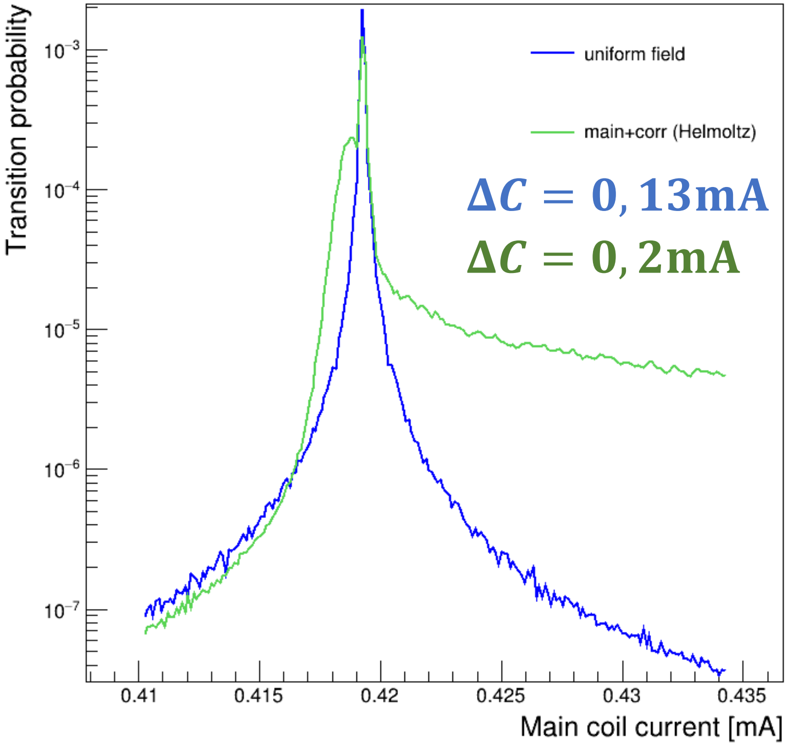


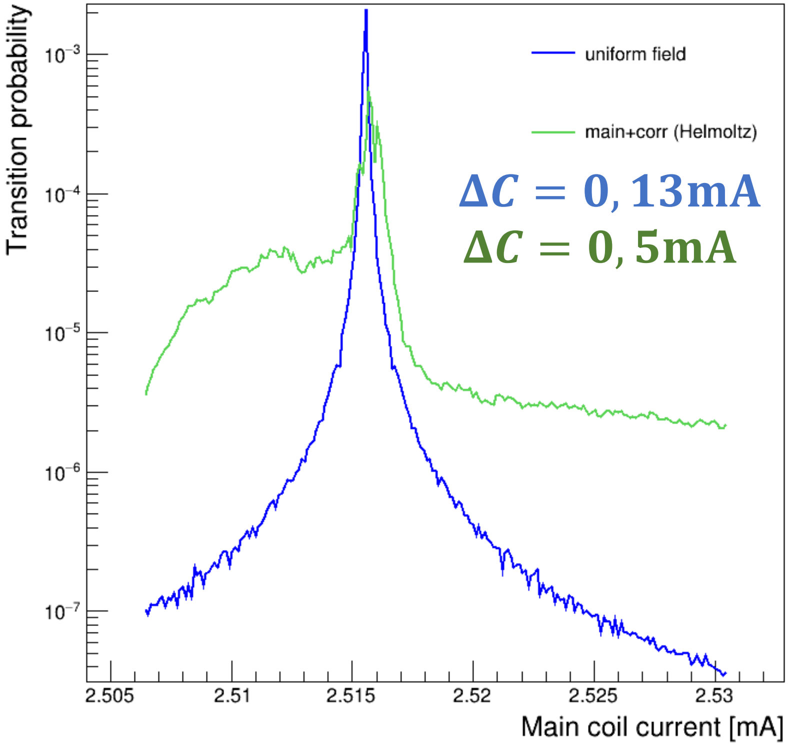


Use both given specs and calibration data to create a realistic model of the coil and compute the magnetic field

True uniform vs realistic uniform Field

$\delta m = 100 \text{ peV}, B = 1{,}6\text{mT}$ $\delta m = 600 \text{ peV}, B = 9{,}6\text{mT}$



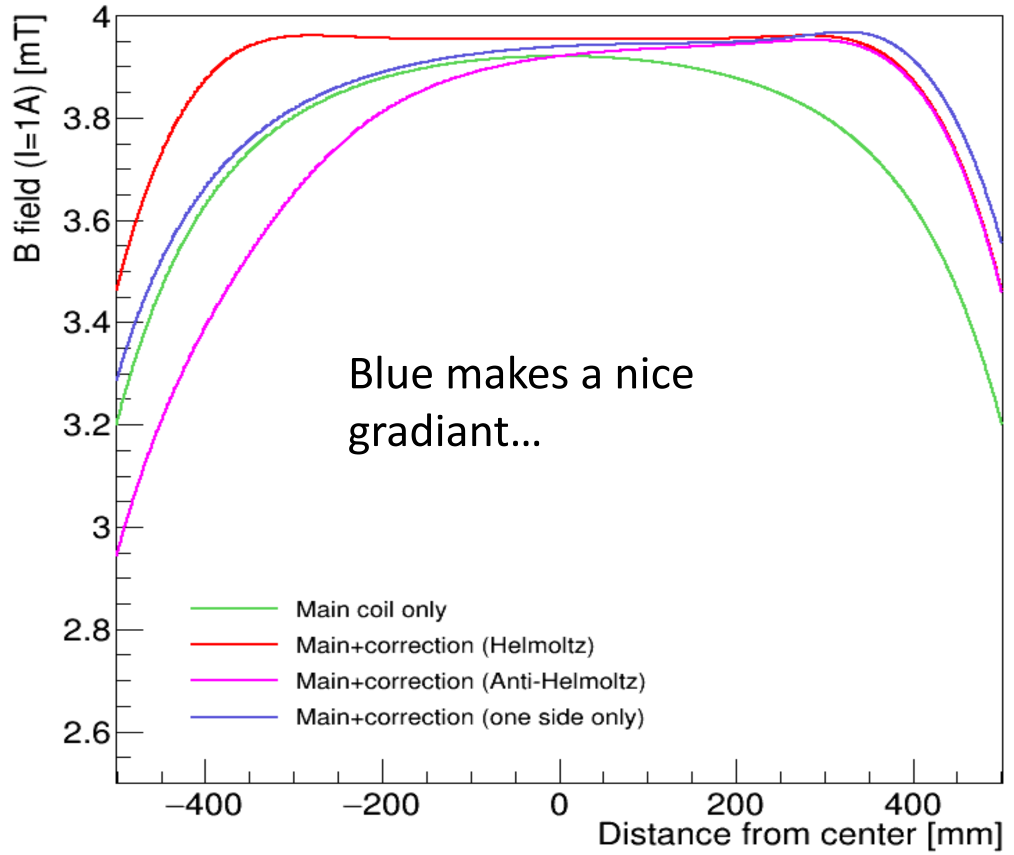


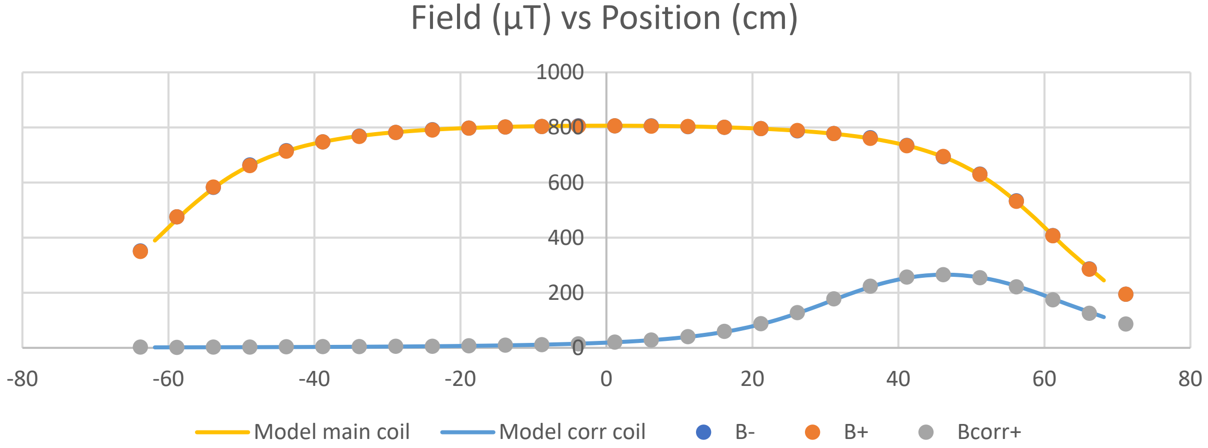
Transition probability vs Main coil current

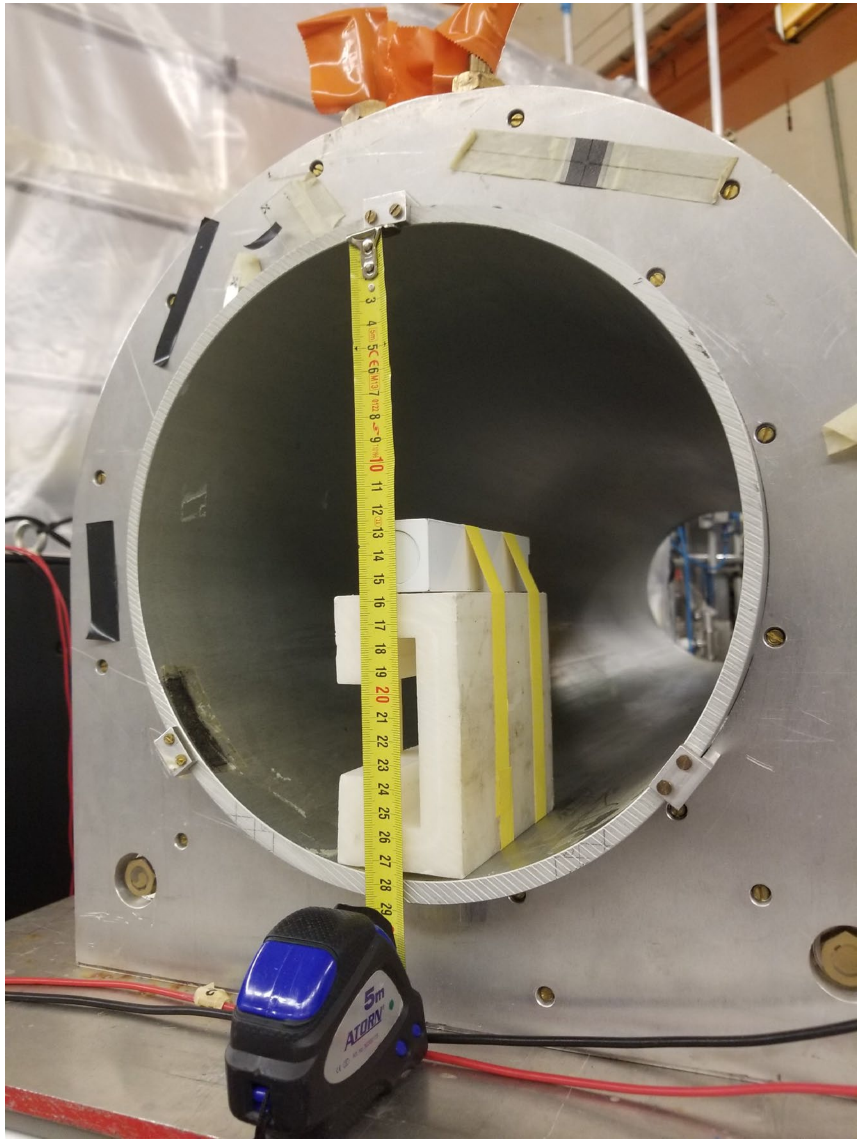
- The available power supply cannot go reliably below 2.3 mA steps (i.e. 9µT)
- Even if we could go to lower steps, it would reduce the sensitivity

Idea : use a magnetic gradient to widen the resonance

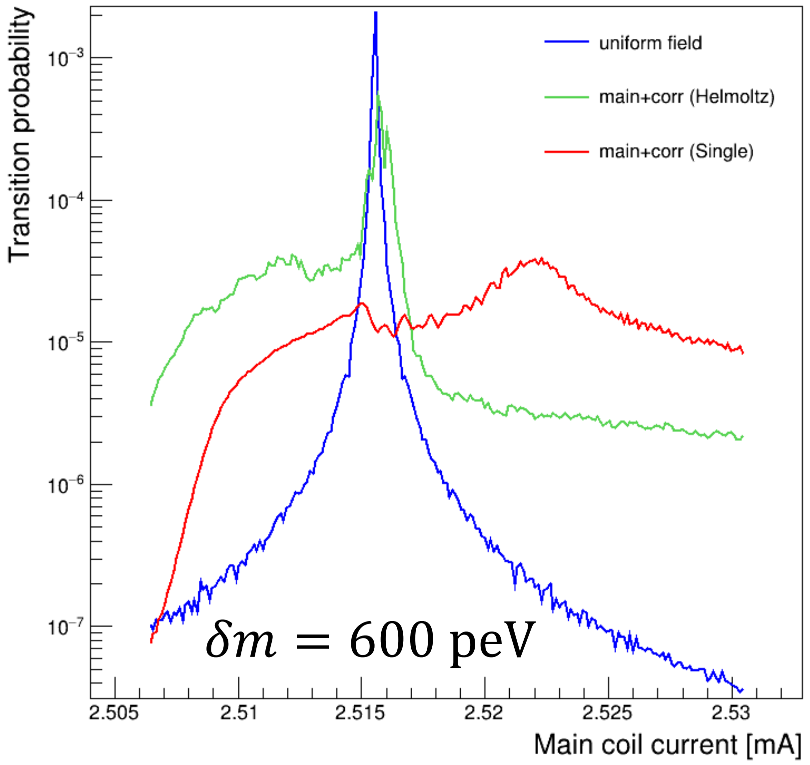
The correction coils

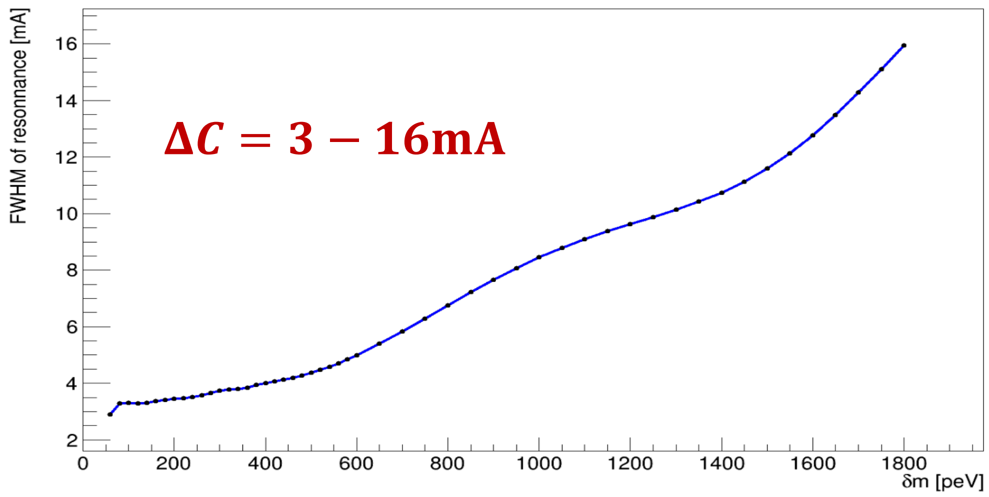






Gradient mode – Resonance width





2 phases scan strategy

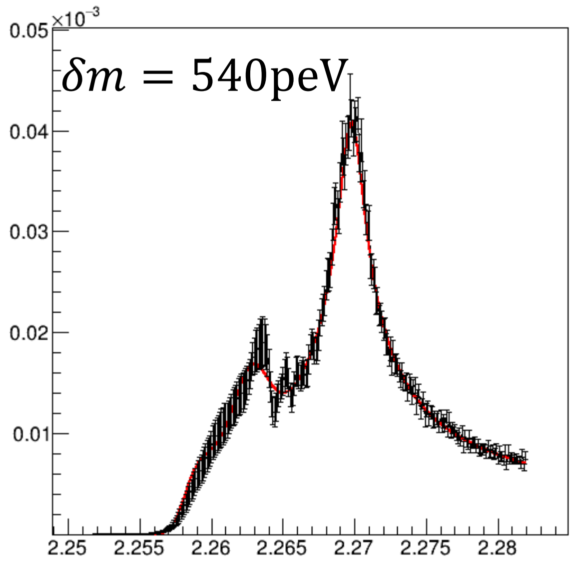
Main scan : May 22 – June 20

- Scan steps : 2,29mA
- 8 scans from 0,28 to 2,12 A (60-500 peV)
- 30 days of data

Extra scan : June 20 – July 5

- Scan steps : 6,87mA (3 times larger)
- 4 scans from 1,999 to 6,6 A (470-1550 peV)
- 14 days of data

Analytical model

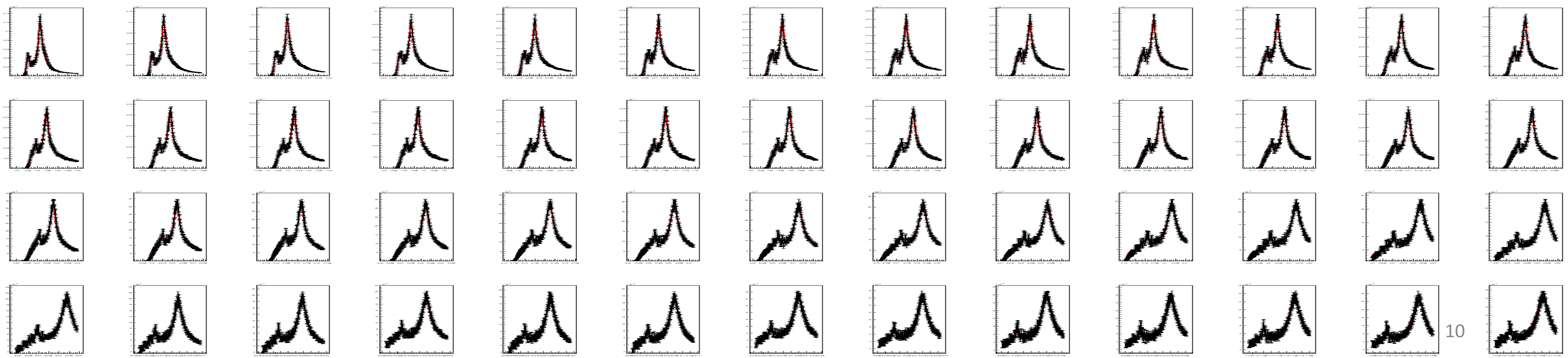


To compute the limit, one needs : $p(I;\delta m,\tau_{nn'}) = \frac{1s^2}{\tau_{nn'}^2} P(I;\delta_m;\tau = 1s)$

ie to solve the Schrödinger equation and average for any $(I,\delta m)$ couple

Far too time (and computer resources) consuming

Compute every 20 peV (60-600 peV) or 50 peV (600-1800 peV), fit with ad-hoc model and interpolate !



The 3 currents method

200000 UCN/s

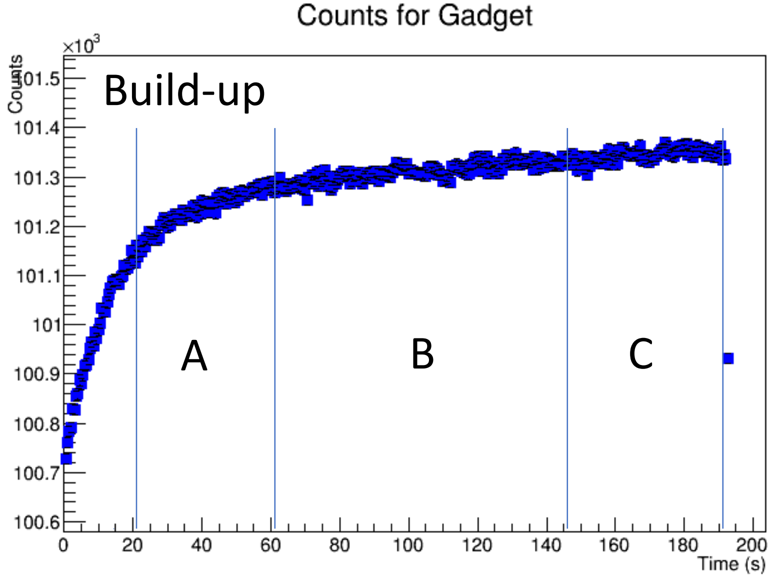
For one magnetic configuration, record

40 s at current $I - 30$ mA N_A

80 s at current I N_B

40 s at current $I + 30$ mA N_C

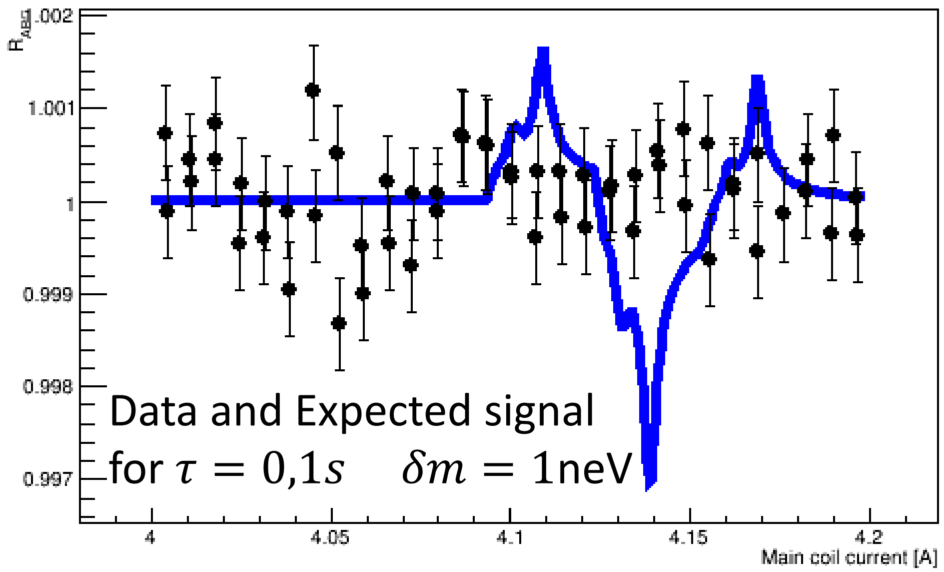
and compute $R_{ABC} = \frac{N_B}{\alpha N_A + N_C}$



Without oscillation and only linear shifts in the neutron rate $R = 1$

R will differ from 1 if neutrons disappear in A, B or C regions

α corrects for build up effects at early times (UCN storage in the guide)



No significant fluctuation is observed within the error bars

Error bars include

- statistical errors
- non statistical fluctuation (power fluctuation of the reactor, temperature fluctuation of the cold neutron source…) that are estimated looking at the RMS of the R_{ABC}

Limit setting

The 2 magic numbers

$$\alpha = \begin{cases} 1 & \text{if no qbounce} \\ 1{,}000384 & \text{if build} - \text{up} \end{cases}$$

$\xi = 1{,}5$: non Poisson fluctuation

Variation of the ambiant field

- measured at the same time
- Reject bad magnetic runs
- treated as a nuisance parameter

Magnetic precision

(very conservative)

Shift in $1\mu\mathrm{T} \equiv$ Shift in $250\mu\mathrm{A}$

$\Delta^{-} = \Delta^{+} = \mathbf{3}\ \mu\mathrm{T}$

Effect is small

$$R_{ABC} = \frac{N_B}{\alpha N_A + N_C} \qquad \Delta R_{ABC} = \xi R_{ABC} \sqrt{\frac{1}{N_B} + \frac{1}{\alpha^2 N_A + N_C}}$$

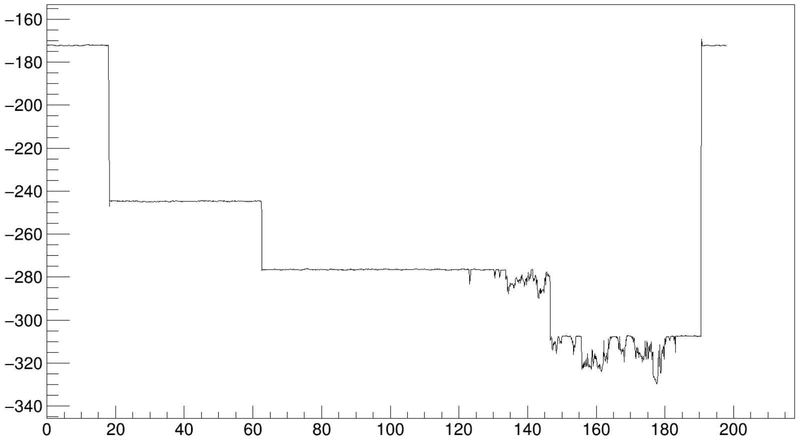
$$R_{ABC}^{model}(I, B^{off}) = \frac{2 - 2p\left(I, B^{off}; \delta m, \tau_{nn'}, \delta_B^{sign(I)}\right)}{2 - p\left(I - \delta I, B_x^{off}; \delta m, \tau_{nn'}, \delta_B^{sign(I)}\right) - p\left(I + \delta I, B_x^{off}; \delta m, \tau_{nn'}, \delta_B^{sign(I)}\right)}$$

For a fixed δm :

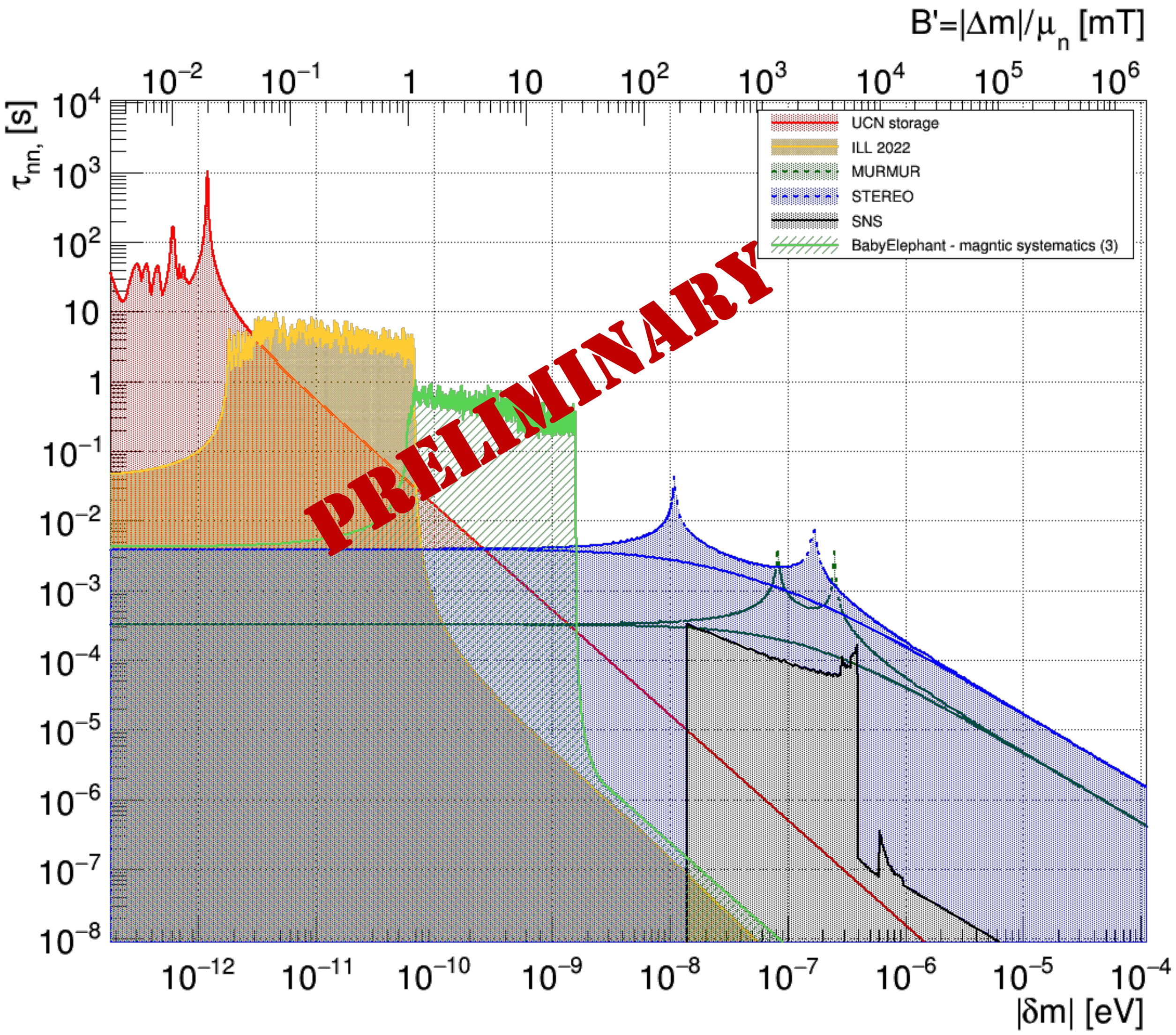
$$\chi^2(\tau_{nn'}, \delta_B^-, \delta_B^+) = \sum_k \left(\frac{R_{ABC}^k - R_{ABC}^{model}(I_k, B_{x,k}^{off})}{\Delta R_{ABC,k}}\right)^2 + \left(\frac{\delta_B^-}{\Delta^-}\right)^2 + \left(\frac{\delta_B^+}{\Delta^+}\right)^2$$

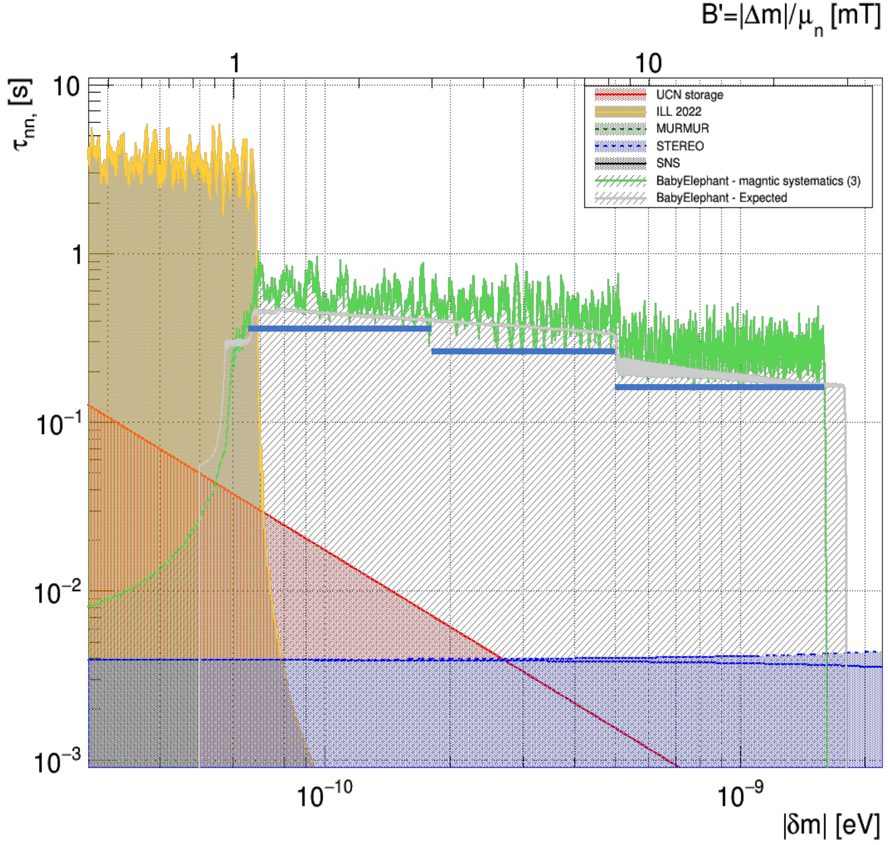
$$\chi^2(\tau_{nn'}) = \min_{\delta_B^-, \delta_B^+} \chi^2(\tau_{nn'}, \delta_B^-, \delta_B^+), \qquad \chi^2(\boldsymbol{\tau_{nn'}^{95\%}}) - \min_{\tau_{nn'}} \chi^2(\tau_{nn'}) = 3{,}84$$

...then plot $\tau_{nn'}^{95\%}$ vs δm



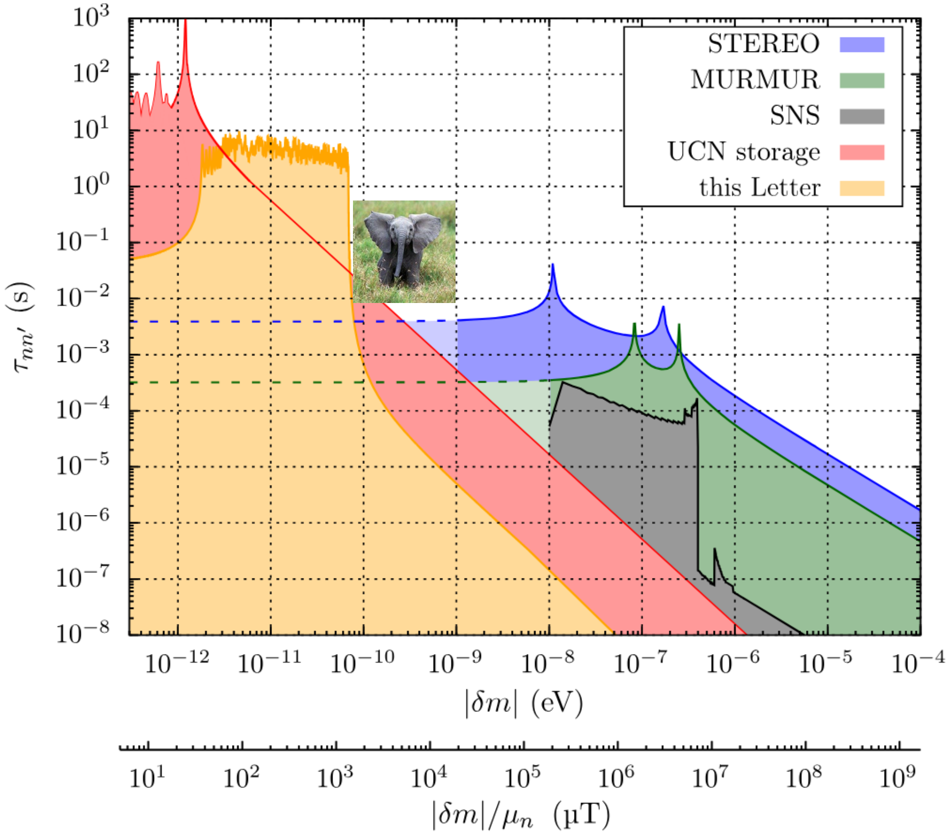
The optimistic limit





$70\text{peV} < \delta m$ $\delta m < 170\text{peV}$	$170\text{peV} < \delta m$ $\delta m < 510\text{peV}$	$510\text{peV} < \delta m$ $\delta m < 1550\text{peV}$
τ'_{nn} <350ms	τ'_{nn} <250ms	τ'_{nn} <150ms

Overview



We (LPSC+LPC+ILL) performed an experiment at ILL searching for neutron to mirror neutron oscillation.

Data were recorded from may to July 2024, probing the poorly constrained mass splitting region from 60 to 1550 peV

No significant deviation is observed and we will set a limit
Treatment of non statistical fluctuation is still under discussions
We expect to submit the paper early 2026.

Prospects

With the same coil and method, we could increase The range up to 3000peV, but it would require water cooling

Higher mass splitting would need larger fields (supra magnet ?) and bigger gradients… and therefore require different methods