

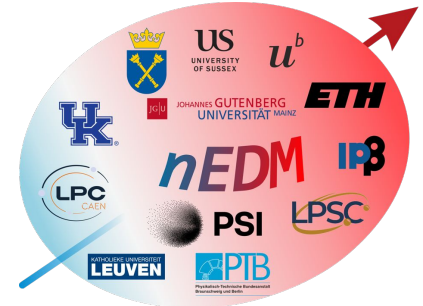
Offline data blinding for the n2EDM experiment

Junior seminar – 12/10/2026

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Context and experimental overview

1. Physics motivations
2. The n2EDM experiment at PSI
3. Measurement principle
4. The apparatus

Offline data blinding

1. Why blinding?
2. Blinding principle
3. A brief aside on UCN detection
4. Generating the blinded data
5. Testing the blinding algorithm

Conclusion

Context and experimental overview

1. Physics motivations

Physics motivations – The baryogenesis puzzle

Matter largely prevailed over antimatter

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10}$$

(CMB + elemt. abundances)

How?



Sakharov conditions (1967)

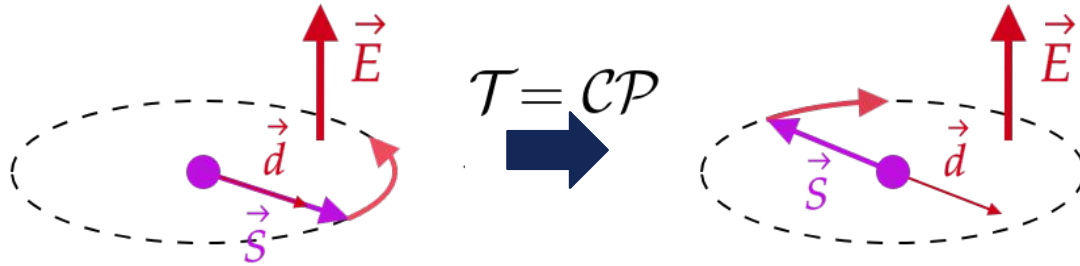
- **B violation** : processes can change the net baryon number
- **C and CP violation** : rates of a process and its conjugate differ (*C* alone is not enough : the *CP*-conjugate process, with $L \leftrightarrow \bar{R}$, compensates)
- **Departure from thermal equilibrium** : inverse processes (washout) are suppressed, so the asymmetry is not erased

From Standard Model

- **Electroweak sector** : CPV included in CKM phase
→ far too small to explain the baryon asymmetry
- **Strong sector** : no CPV observed yet, EDM measurements constrain $\theta < 10^{-10}$ (using $d_n < 1.8 \times 10^{-26} \text{ e} \cdot \text{cm}$)
→ strong CP problem

Physics motivations – EDM and CPV

How the EDM change under CP symmetry ?



EDM $\neq 0 \rightarrow$ CP violation

EDM Measurement

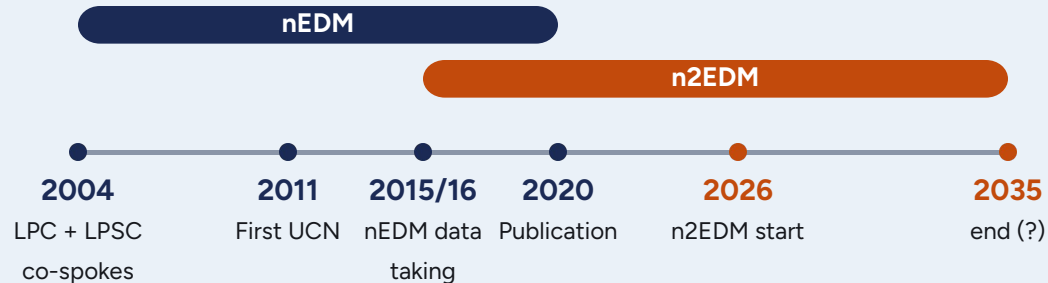
nEDM is non-zero $\rightarrow$ New Physics

compatible with zero $\rightarrow$ New constraints

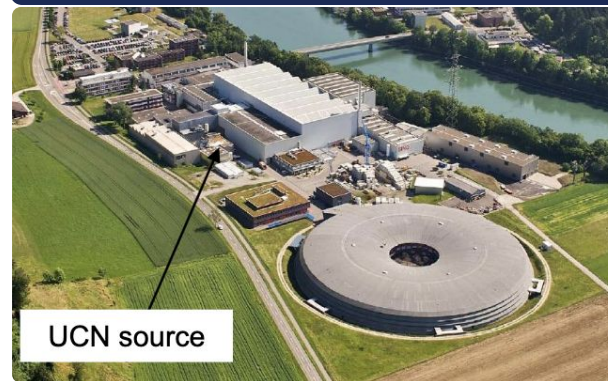
2. The n2EDM experiment at PSI

n2EDM experiment at PSI – From nEDM to n2EDM

Two decades of neutron EDM searches



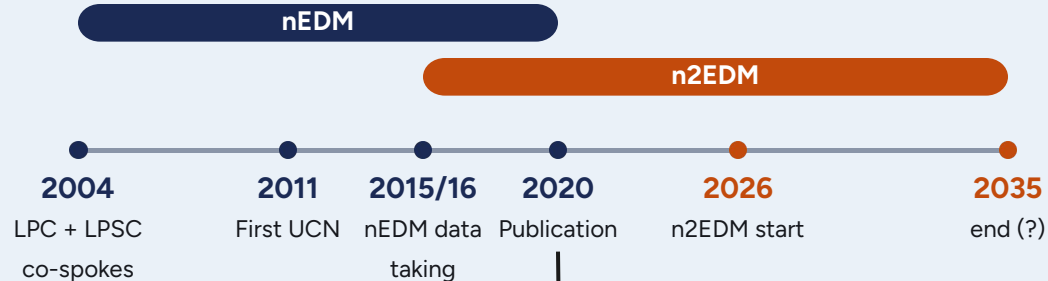
UCN source at PSI



Paul Scherrer Institute, Villigen (CH)

n2EDM experiment at PSI – From nEDM to n2EDM

Two decades of neutron EDM searches

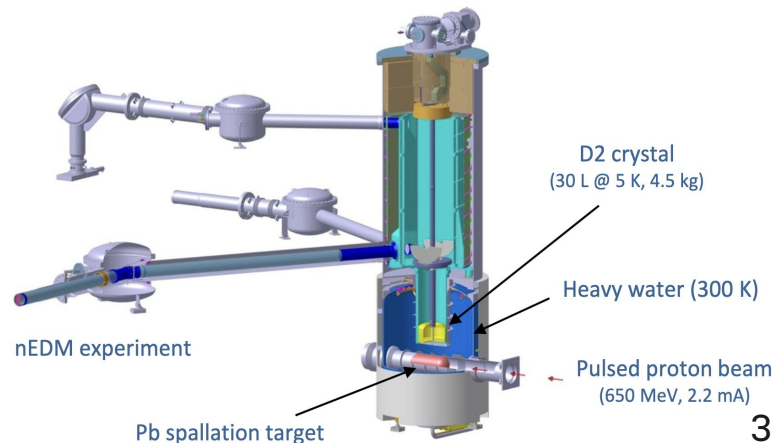
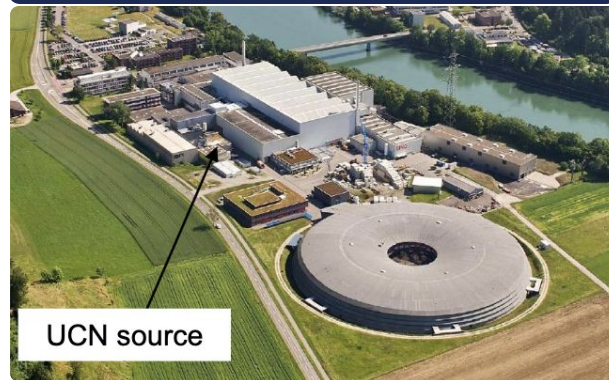


$$d_n < 1.8 \times 10^{-26} \text{ e cm} \quad (90\% \text{ C.L.})$$

A dedicated Ultracold neutrons (UCN) source for nEDM

- Built in **2001 – 2011** for the nEDM project
- Goal: **increase UCN production** by $\times 10 - 10^2$
- Driven by the **most intense proton beam** worldwide (2.4 mA)
- Most intense UCN source worldwide **until 2025**

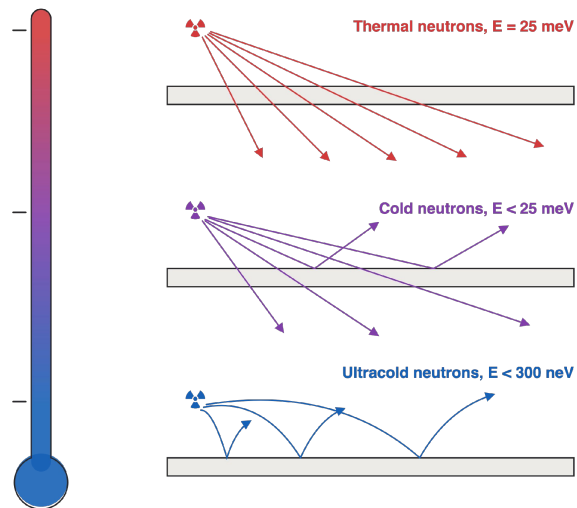
UCN source at PSI



n2EDM experiment at PSI – Ultracold Neutrons

Neutron optics

- **Fermi (pseudo-)potential** V_F : effective repulsive potential due to the coherent strong interaction with the nuclei of the material
- **Total reflection** : $E_n < V_F \rightarrow$ neutron reflected at any incident angle

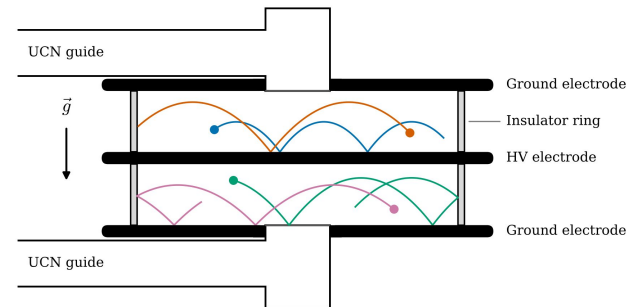


$$E \lesssim 300 \text{ neV} (v \lesssim 7.6 \text{ m/s})$$

We can guide and store UCN !
(with ballistic trajectories)

$$m_n g \simeq 103 \text{ neV/m}$$

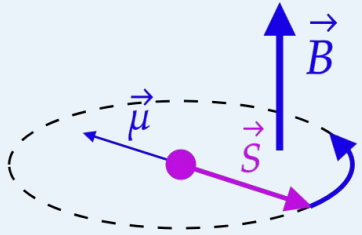
Material	Fermi potential (neV)
^{58}Ni	335
C (diamond)	305
Ni	252
Be	252
^{63}Cu	244
Fe	210
C (graphite)	194
Cu	168



*(not to scale; trajectories exaggerated for clarity)

3. The measurement principle

Magnetic Dipole Moment (MDM)



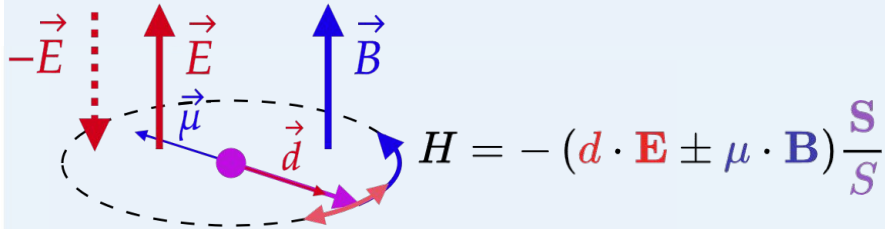
$$H = -\mu \cdot \mathbf{B} \frac{\mathbf{S}}{S}$$



Larmor precession

$$\nu_L = \frac{|\gamma_n|}{2\pi} B$$

MDM and EDM



$$\text{iff } \mathbf{B}_{\parallel} = \mathbf{B}_{\nparallel}$$

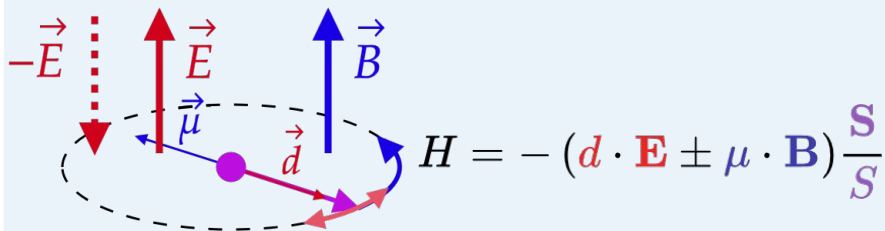
→

2 precession frequencies

$$\nu_{\parallel} = \frac{2}{h}(\mu B + dE)$$

$$\nu_{\nparallel} = \frac{2}{h}(\mu B - dE)$$

MDM and EDM



iff
 $\vec{B}_{\parallel} = \vec{B}_{\nparallel}$

2 precession frequencies

$$\nu_{\parallel} = \frac{2}{\hbar} (\mu B + dE)$$

$$\nu_{\nparallel} = \frac{2}{\hbar} (\mu B - dE)$$

In the end: $d = \frac{\hbar(\nu_{\parallel} - \nu_{\nparallel})}{4E}$

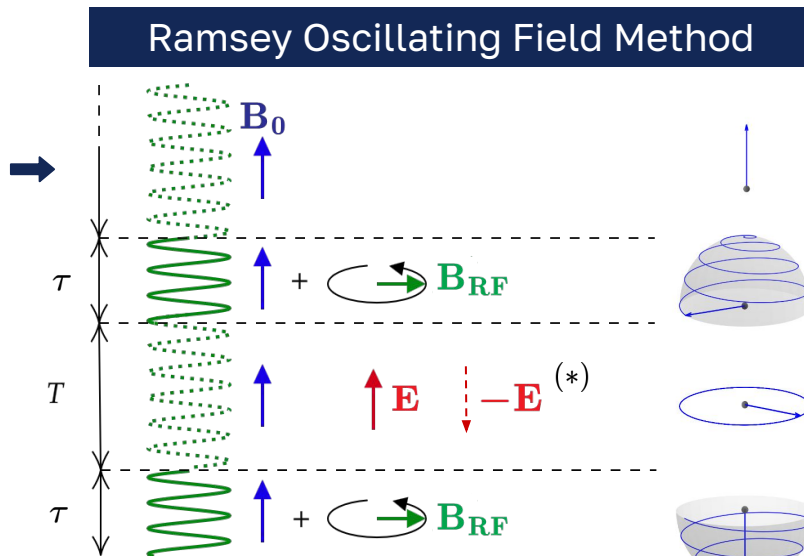
- Challenge:
- $B_0 = 1 \mu\text{T} : \nu_n \simeq 29 \text{ Hz}$
 - $E = 12 \text{ kV/cm}, d_n = 10^{-27} \text{ e} \cdot \text{cm} : \nu_n \simeq 6 \times 10^{-9} \text{ Hz}$
 $\rightarrow 1 \text{ turn} / 5 \text{ years}$

Control of the magnetic field is primordial !

Measurement principle – Asymmetry as a function of detuning

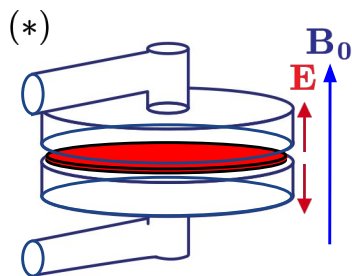
nEDM and Larmor precession

$$d_n = \frac{h(\nu_{\parallel} - \nu_{\parallel})}{4|\mathbf{E}|}$$

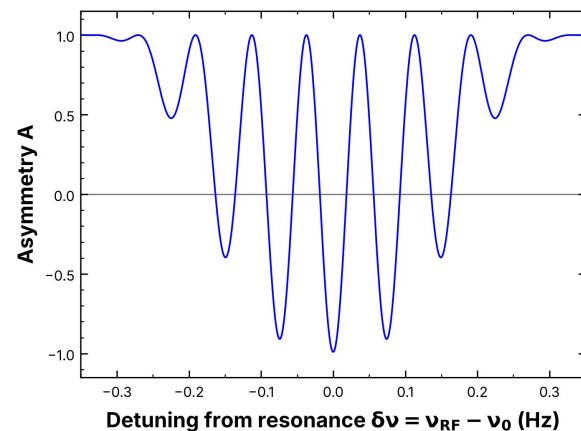


Get neutron frequency using Asymmetry

$$\mathcal{A}(\nu_{RF}) = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}}$$



Spin-flip probability is sensitive to the RF detuning from resonance



Measurement principle - Extracting neutrons frequency

Fitting function

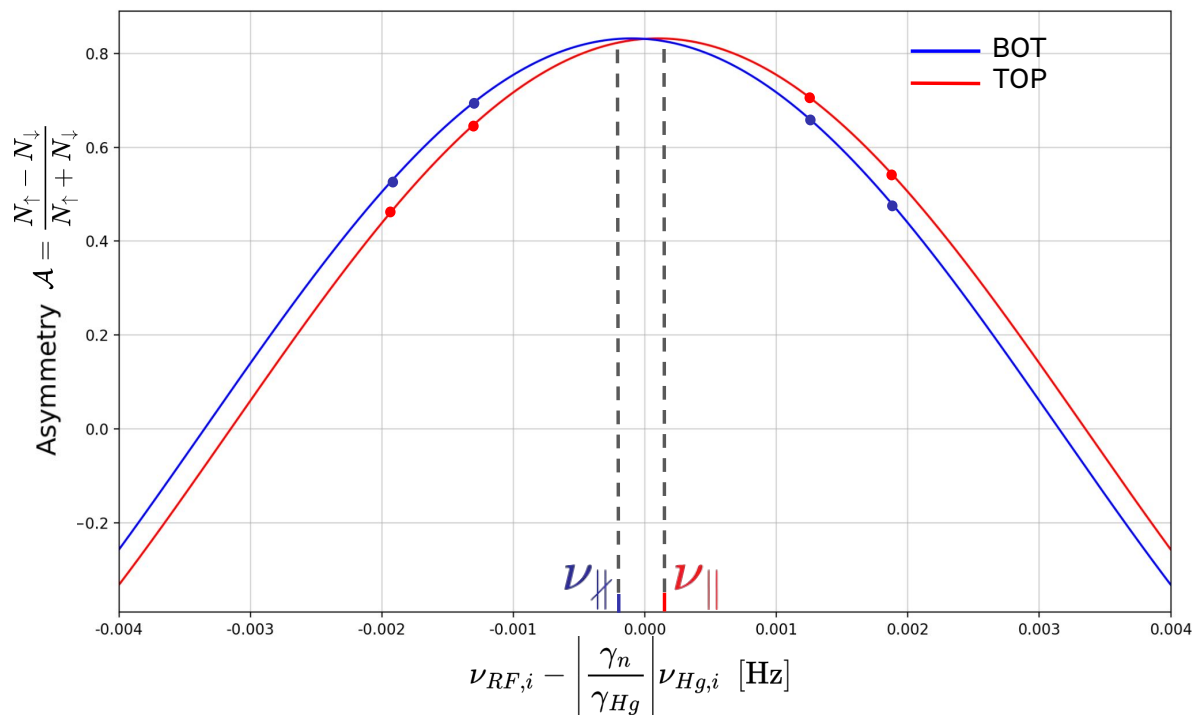
$$\mathcal{A}(\nu_{RF,i}) = \bar{A} - \alpha \cos\left(\frac{\pi}{\Delta\nu} x_i + \eta\right)$$

with the independent parameter (of ith cycle)

$$x_i = \nu_{RF,i} - \left| \frac{\gamma_n}{\gamma_{Hg}} \right| \nu_{Hg,i}$$

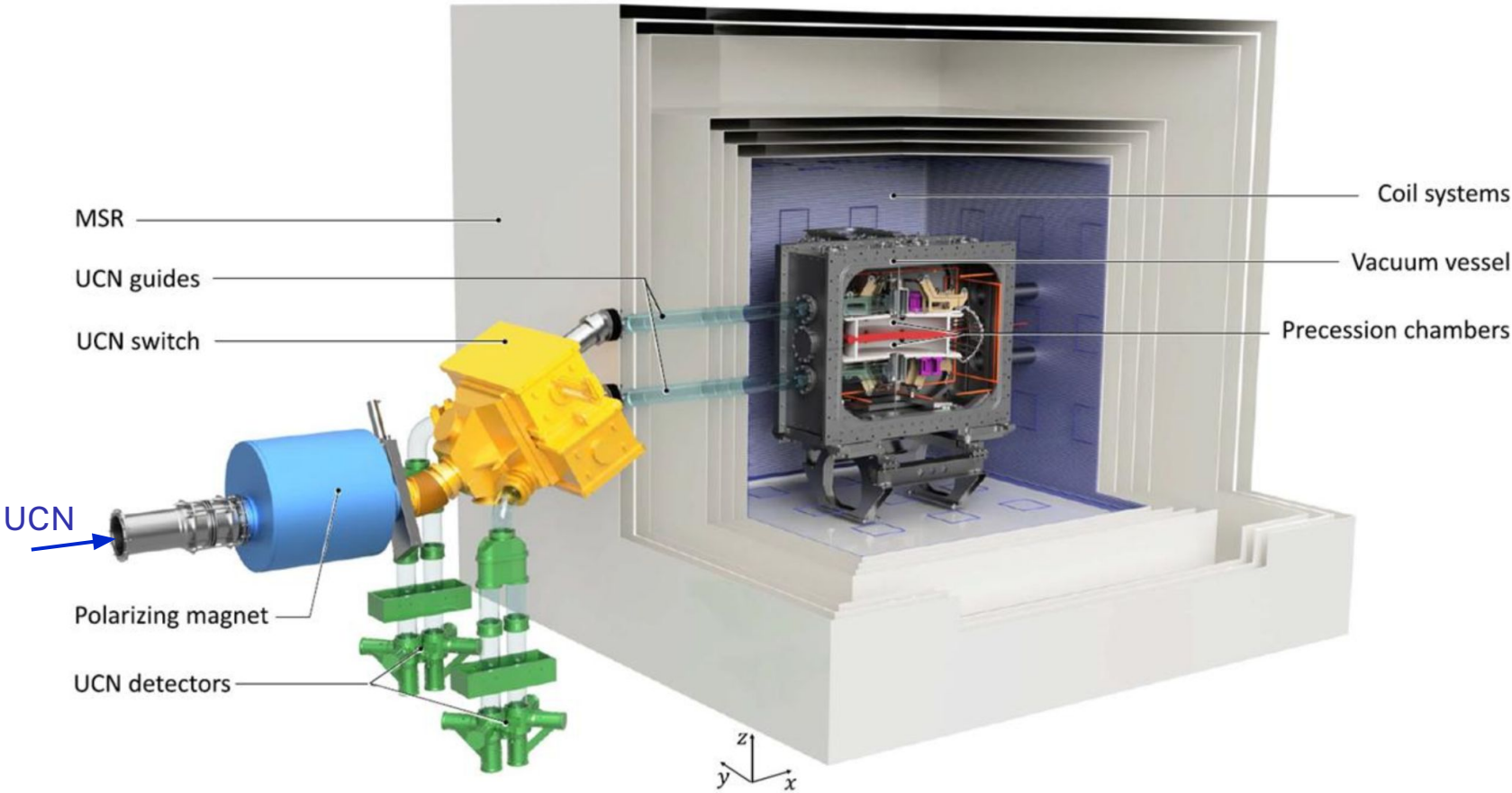
width of the central Ramsey fringe

$$\Delta\nu = \frac{1}{2(T + 4\tau/\pi)}$$



4. The apparatus

The apparatus – Full picture



The apparatus – Active & passive magnetic shielding

Passive – shielded room



- Footprint of **5.2 m × 5.2 m**
- Shielding factor **$10^6 - 10^9$** above 0.1 Hz

Active – magnetic shield system



- Active compensation with **55 km of wire**
- Power at the **kW** level, shielding down to the **mHz** range

Offline data blinding

1. Why do we need it ?

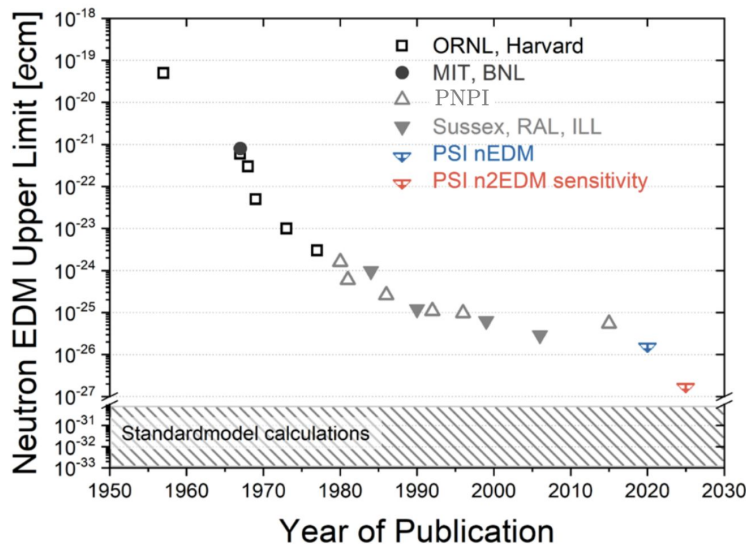
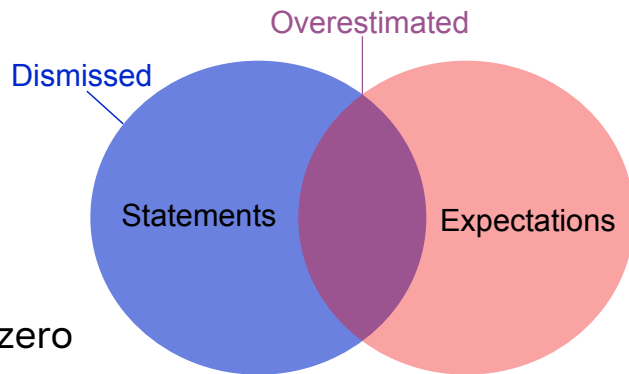
Data blinding – Why do we need it?

Confirmation bias:

Unconsciously nudging results toward what feels right

nEDM context:

nEDM have a long history of tighter limits, still compatible with zero



- steer choices toward the "expected" result
- stop analysis when we meet a "conform" outcome

Work with altered values

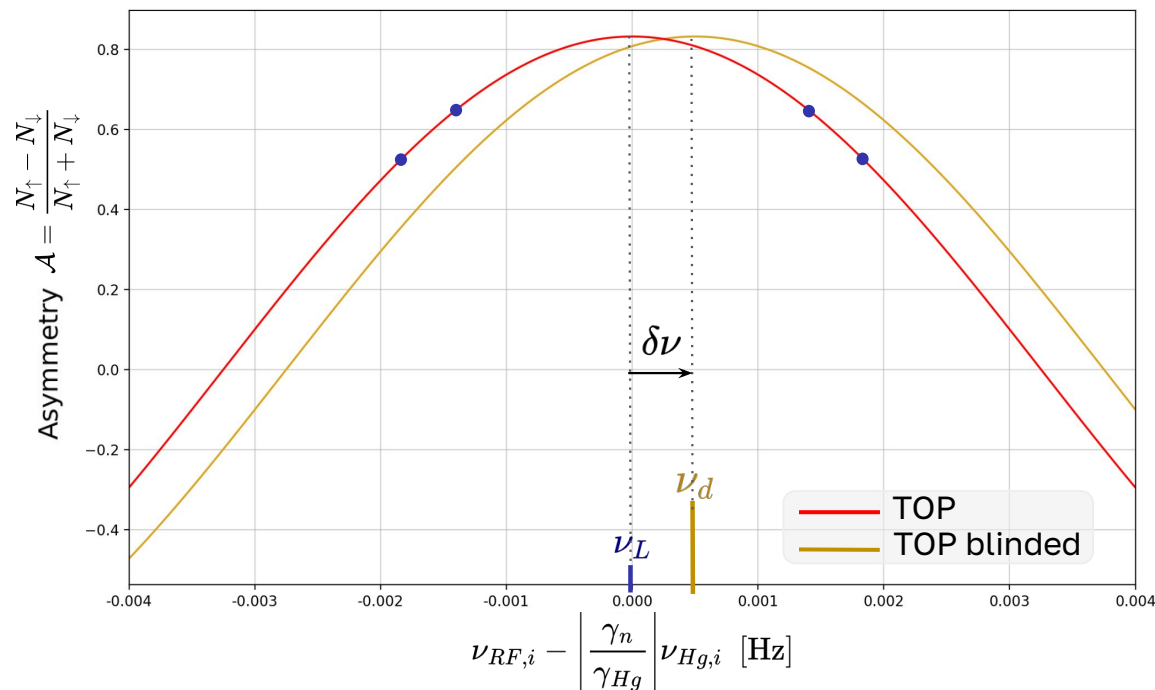
(behaving like the real one)

The blinding principle

The blinding principle – Shifting the measured Larmor precession frequency

Injected EDM

False EDM = Neutron frequency shift

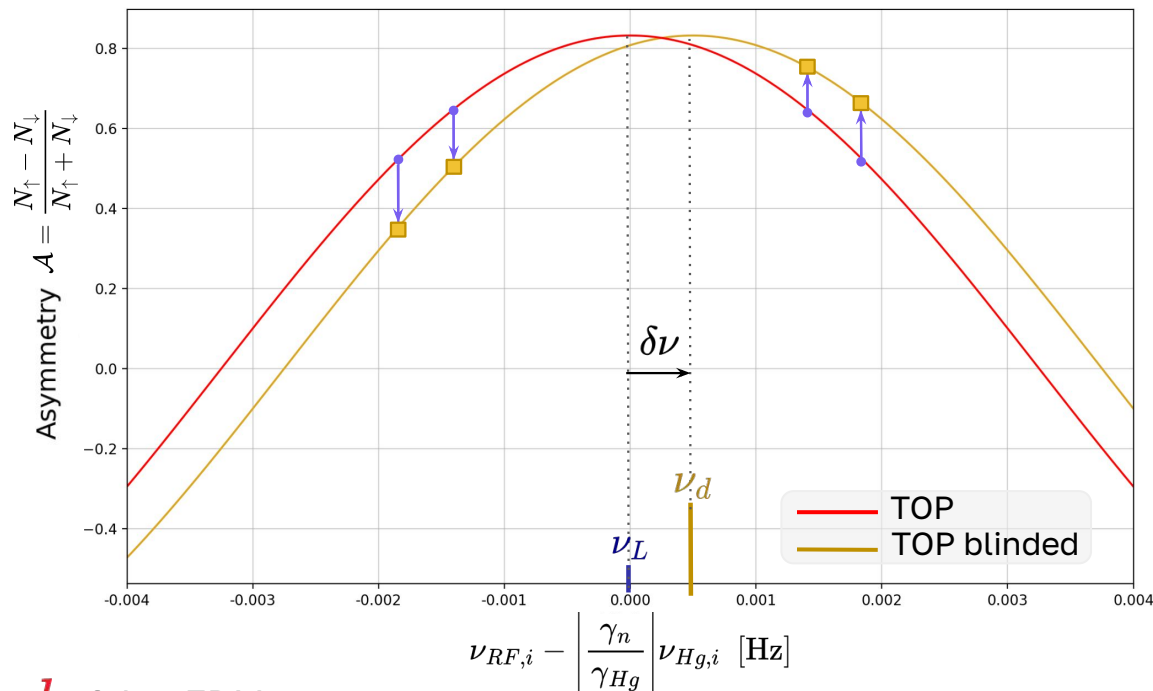


Realistic shift

Electric field dependent frequency shift:

$$\delta\nu = \frac{2d}{h} \frac{\mathbf{E} \cdot \mathbf{B}}{B}$$

The blinding principle – Shifting the measured Larmor precession frequency



d = false EDM

$$\delta N_{\uparrow, \downarrow; i} = \mp N_i \frac{\pi d}{h \Delta \nu} \frac{\mathbf{E} \cdot \mathbf{B}}{|\mathbf{B}|} \sin(\phi_i)$$

Realistic shift

Electric field dependent frequency shift:

$$\delta\nu = \frac{2d}{h} \frac{\mathbf{E} \cdot \mathbf{B}}{B}$$

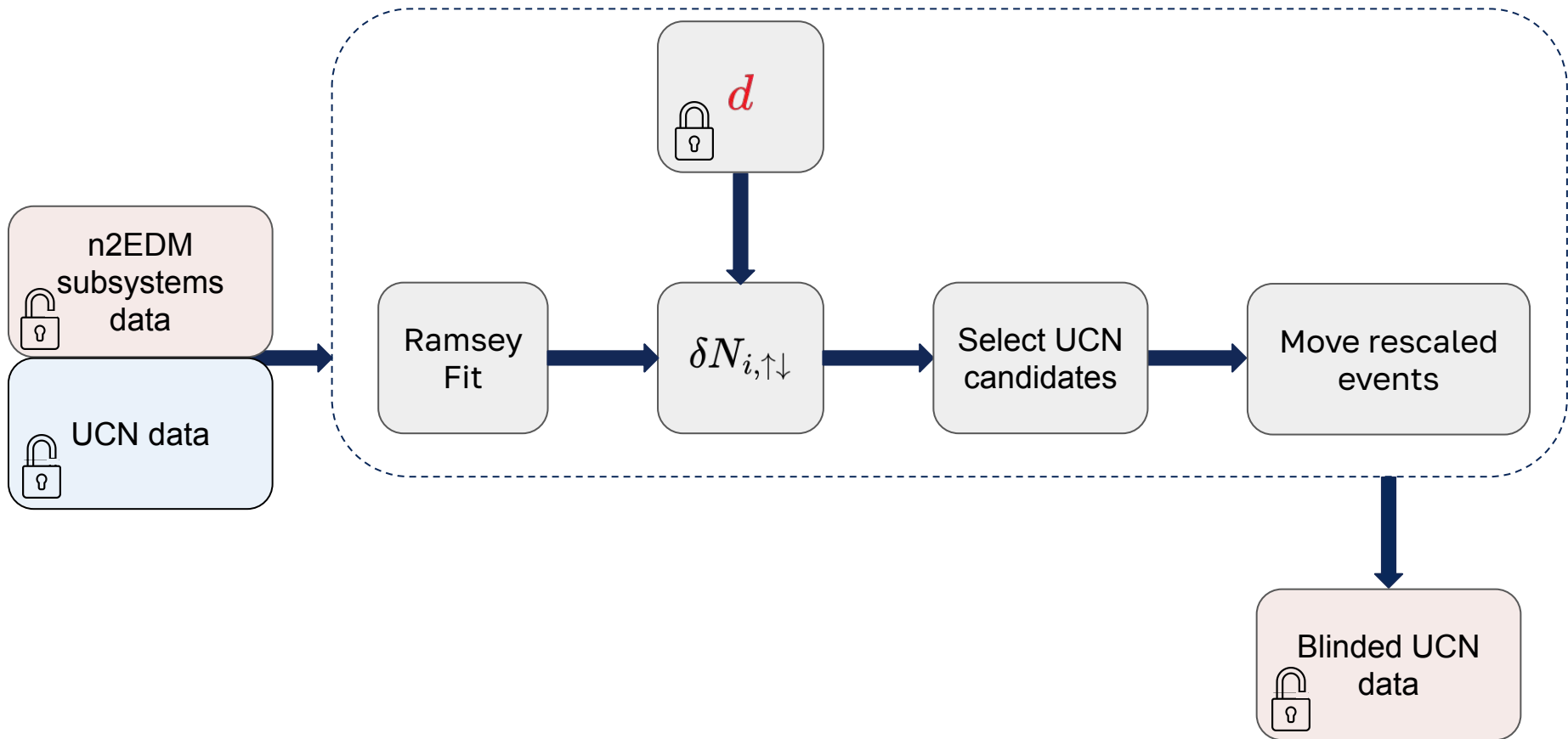


Transferring UCN count

Wrt spin component & position of working point (cycle wise)

How many ? $\delta N_{\uparrow, \downarrow; i}$

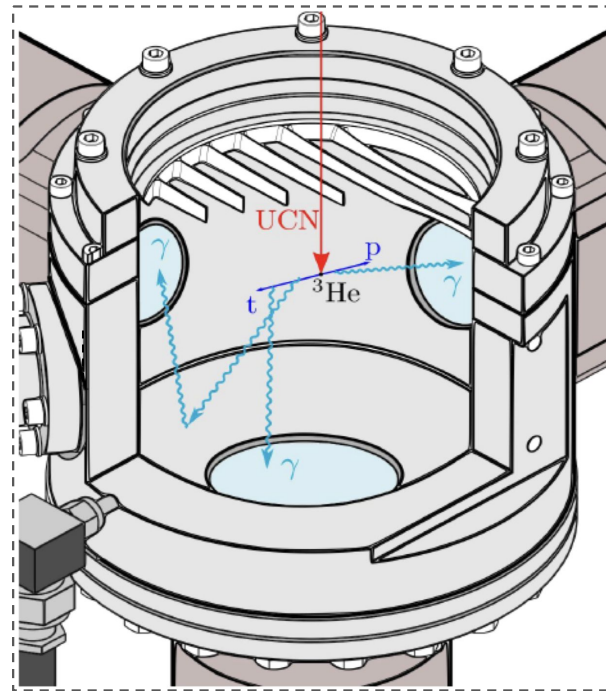
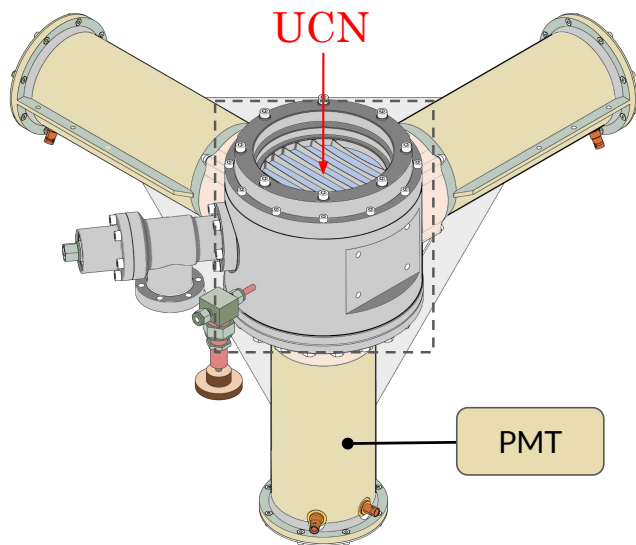
The blinding principle – Global vue



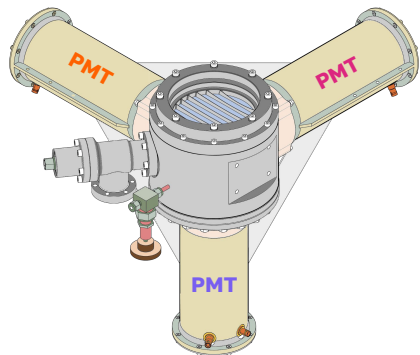
A brief aside on UCN detection

GADGET – Gaseous detector

- Al entrance window (Al-Mg)
- $^3\text{He} + n \rightarrow ^3\text{H} + p$ (+763 keV)
- Scintillator : CF_4 ($\tau^* \sim 6$ ns)
- 3 PMTs in coincidence (50 ns)



UCN detection – Sampling

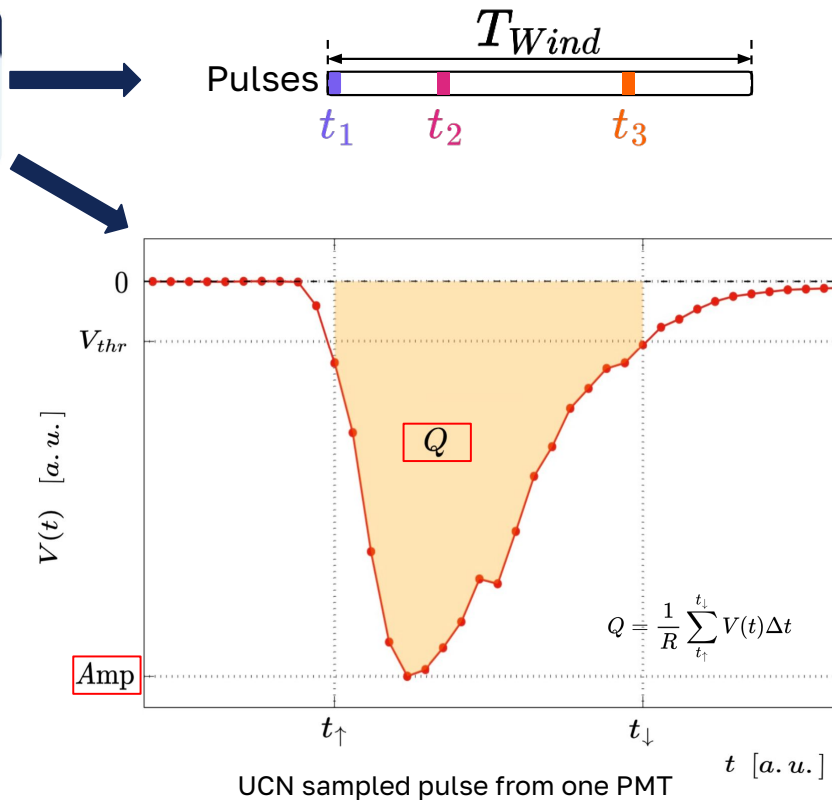


FASTER DAQ

- Groups events in coincidence
- Computes pulse parameters

Grouped pulse parameters

$$Q_{tot} = \sum_{i=1}^3 Q_i$$
$$Amp_{tot} = \sum_{i=1}^3 Amp_i$$

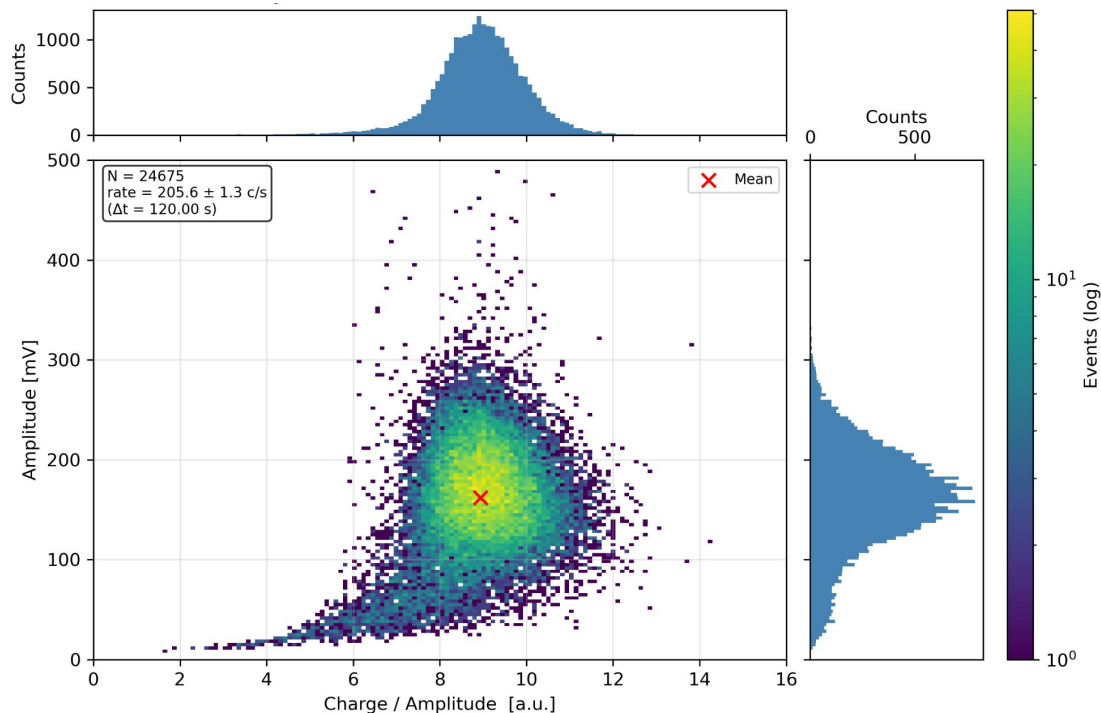


Selection of the UCN pulses

$$\text{Amp}_{tot} = f\left(\frac{Q_{tot}}{\text{Amp}_{tot}}\right)$$

Pulse Shape Analysis

Goal → discriminates events types :
UCN, Electronic noise, Cherenkov



Back to the blinding procedure

Blinding procedure – Selecting UCN candidates

Problem: How to avoid non-UCN events ?

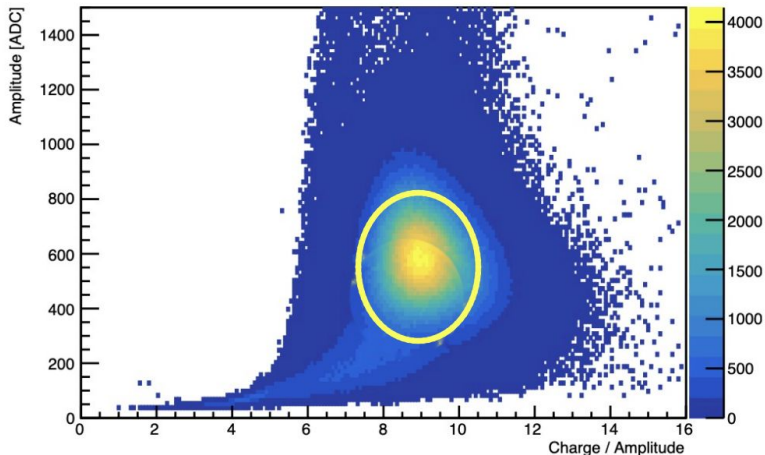
Define an elliptic region for each detector:

$$\frac{\overline{\text{Amp}}_{tot,i}}{\sigma(\text{Amp}_{tot,i})} \quad \frac{\overline{Q}_{tot,i} / \overline{\text{Amp}}_{tot,i}}{\sigma(Q_{tot,i} / \text{Amp}_{tot,i})}$$

Selected events (S=2)

$$\sum_{j=1}^2 \left(\frac{x_j - \bar{x}_j}{s \sigma(\bar{x}_j)} \right)^2 \leq 1$$

Det 1



Event	Timestamp (ns)				Charge Q	Amplitude A
1	41	873	208	520	1351	1014
2	41	873	214	258	6185	1864
3	41	873	220	510	5357	2142
4	41	873	228	615	1517	689
5	41	873	233	946	5342	1845
6	41	873	240	994	2490	671
7	41	873	248	546	2076	548
8	41	873	250	805	5563	1814
9	41	873	251	588	5609	1856
10	41	873	254	499	1668	162
11	41	873	257	279	6063	2188
12	41	873	265	178	2475	352
13	41	873	273	417	6388	2123
14	41	873	273	762	5734	2166
⋮	⋮	⋮	⋮	⋮	⋮	⋮

UCN-like event (selected)

← random choice

Blinding procedure – Transferring rescaled events

Problem: Detectors response is different → must be taken into account

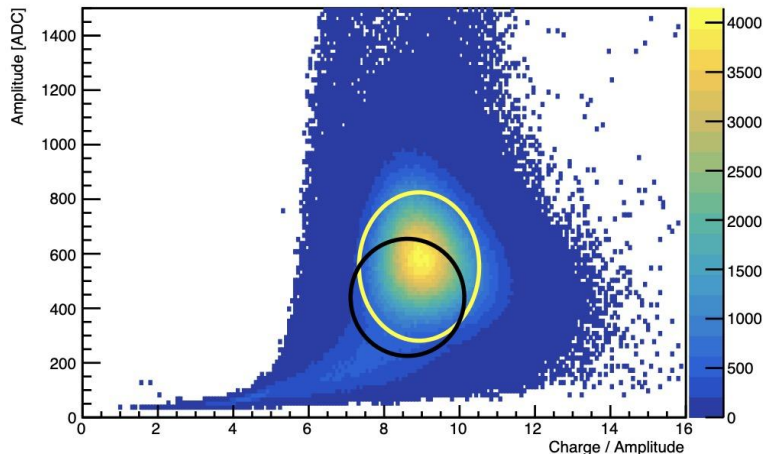
Define an elliptic region for each detector:

$$\frac{\overline{\text{Amp}}_{tot,i}}{\sigma(\text{Amp}_{tot,i})} \quad \frac{\overline{Q}_{tot,i} / \overline{\text{Amp}}_{tot,i}}{\sigma(Q_{tot,i} / \text{Amp}_{tot,i})}$$

Selected events (S=2)

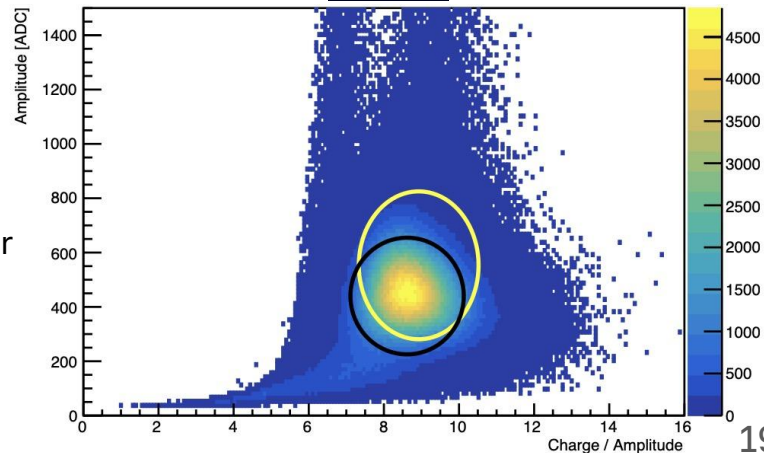
$$\sum_{j=1}^2 \left(\frac{x_j - \bar{x}_j}{s \sigma(\bar{x}_j)} \right)^2 \leq 1$$

Det 1

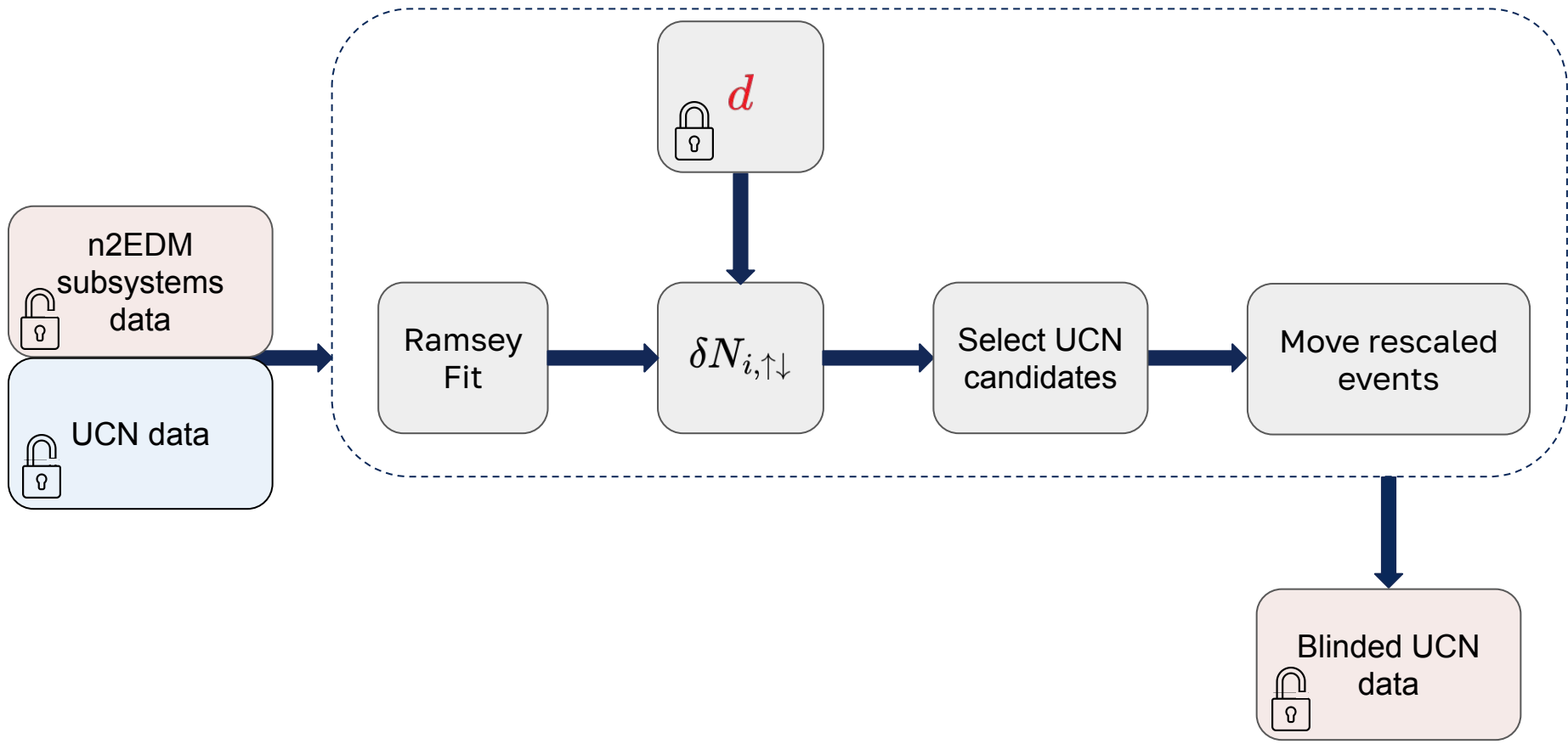


Transfer !
wrt to the response
of the **target** detector
(rescaling process)

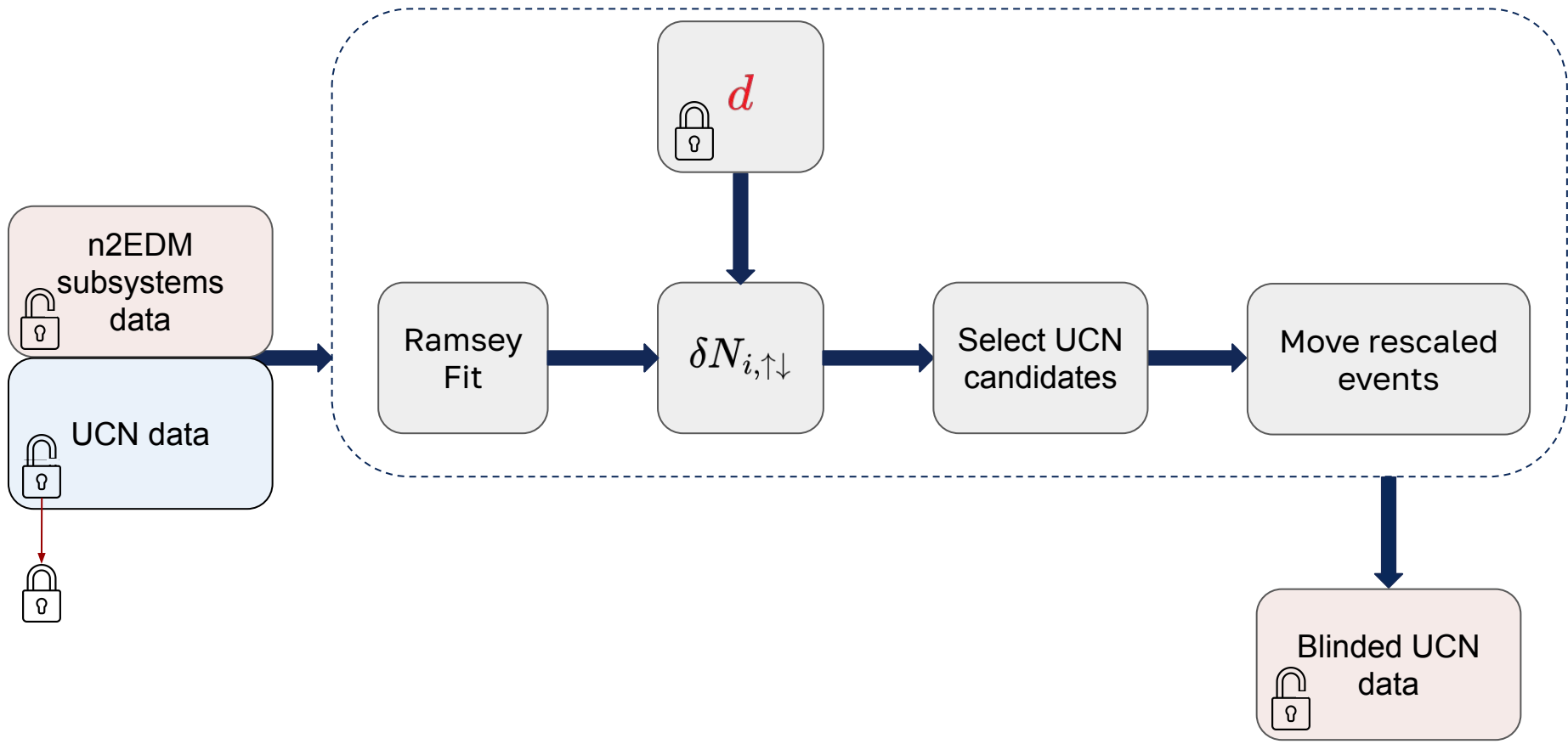
Det 2



Global vue of the blinding process

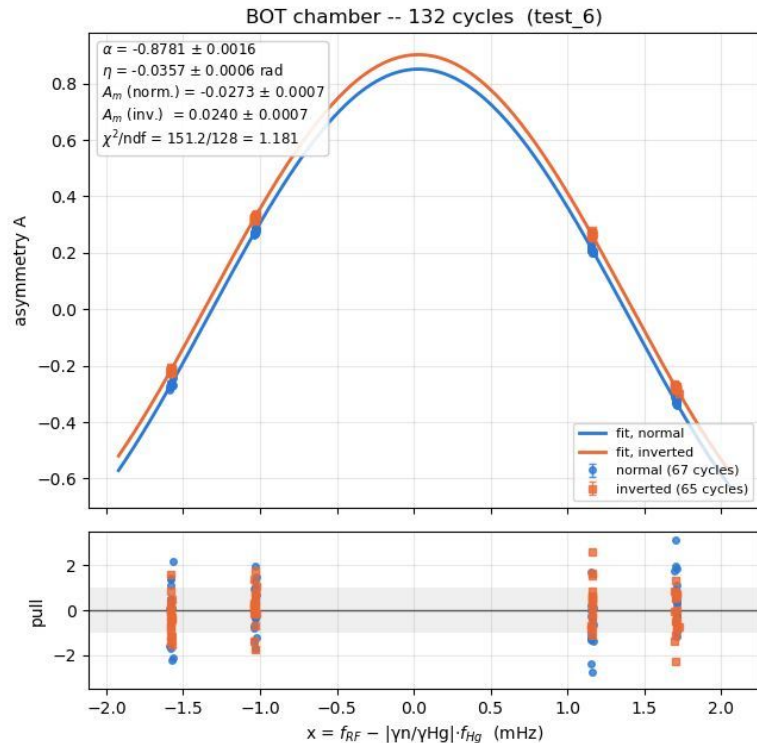
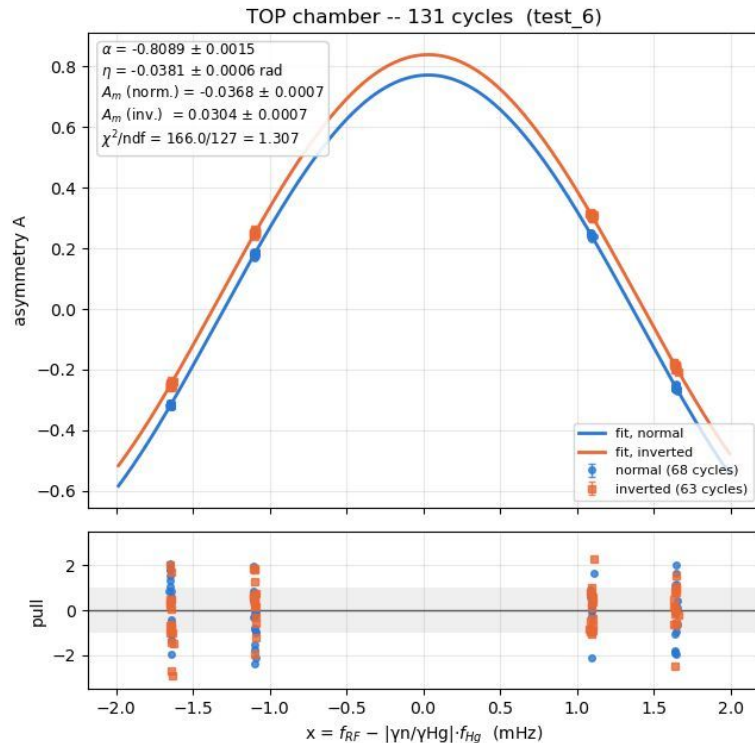


Global vue of the blinding process



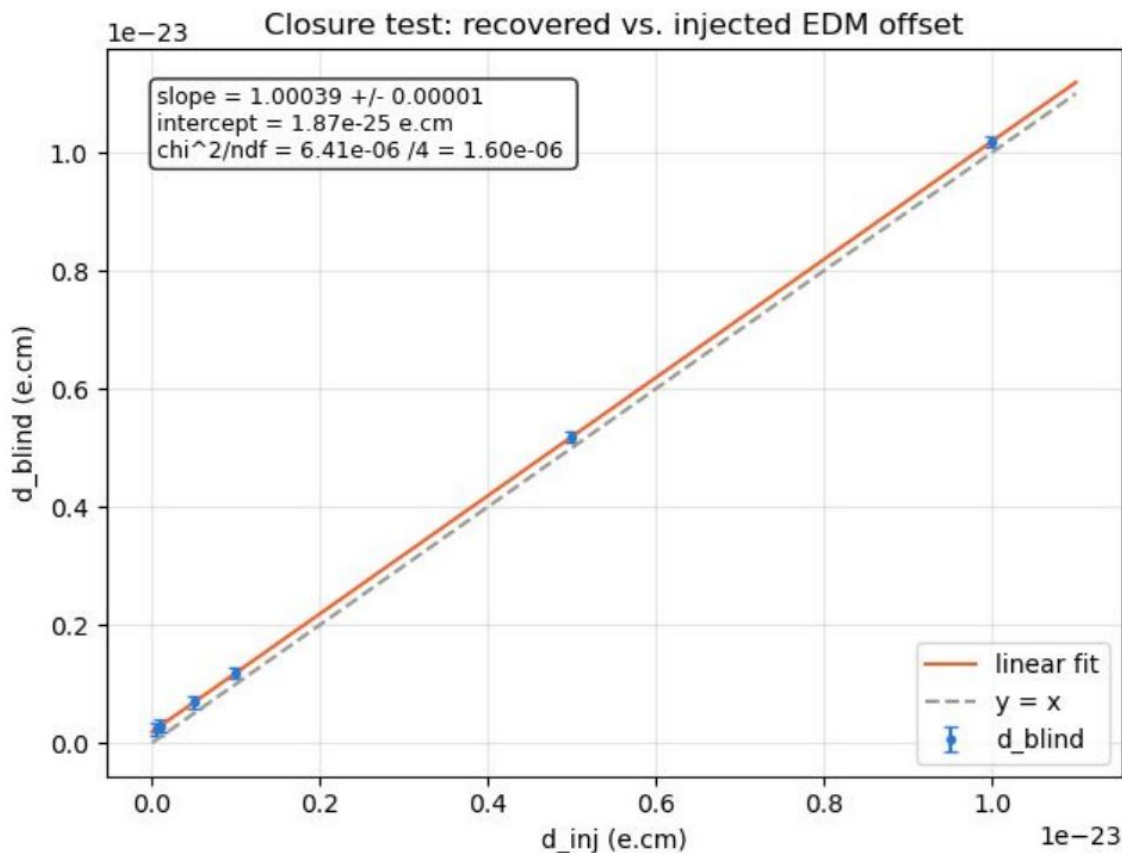
Testing the blinding algorithm

Testing the blinding algorithm – Fit result on a blinded run (12/2025)



- Blinding shifts only η in opposite directions: $|\eta|$ TOP $0.0377 \rightarrow 0.0381$, BOT $0.0361 \rightarrow 0.0357$ (expected $\pm 4.3 \times 10^{-4}$ rad for $d = 10^{-25}$ e·cm); α and $\bar{A}$ unchanged compared to raw data.
- Pulls centred on 0 at the 4 working points, no visible structure

Testing the blinding algorithm – recovered vs. injected offset



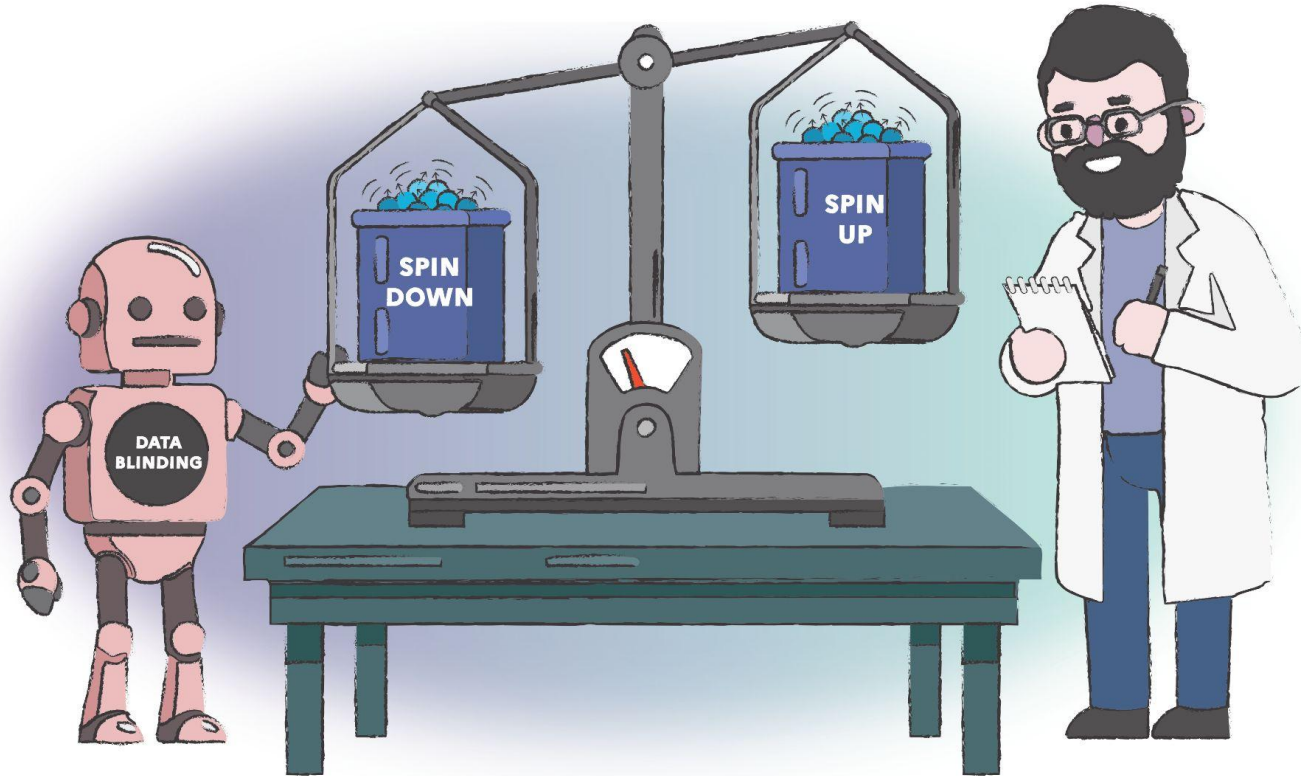
Observations

- ▶ **Linear response:** slope = 1.0004
offset recovered at the 4×10^{-4} level
- ▶ **Intercept** 1.87×10^{-25} e.cm
= unblinded value
 $\bar{d}_{\text{raw}} = (1.84 \pm 0.99) \times 10^{-25}$
 $\Rightarrow$ already in the raw data
- ▶ $\chi^2/\text{ndf} \approx 10^{-6}$: same neutrons and same seed in all tests $\Rightarrow$ fully correlated points, common fluctuation absorbed by the intercept
- ▶ **Paired difference**
 $\bar{d}_{\text{blind}} - \bar{d}_{\text{raw}} - d_{\text{inj}} \simeq 3 \times 10^{-27}$ e.cm
= blinding noise ($\sim 0.03\%$ sensitivity loss)

- Injected EDM recovered linearly (slope = $1 \pm 4 \times 10^{-4}$)
- Deviation from injection $\sim 3 \times 10^{-27}$ e·cm, i.e. ~ 3 % of σ_{stat} (run 7992) $\Rightarrow \lesssim 0.05$ % sensitivity loss
- Generation of blinded UCN files : Operational
- Sanity check : On going
- Implementation on n2EDM DAQ : On going

Goal: Check that we are able to recover the injected EDM on the last nEDM runs (switching polarity)

Thank you for listening ! Any questions ?



Measurement principle - Extracting neutrons frequency

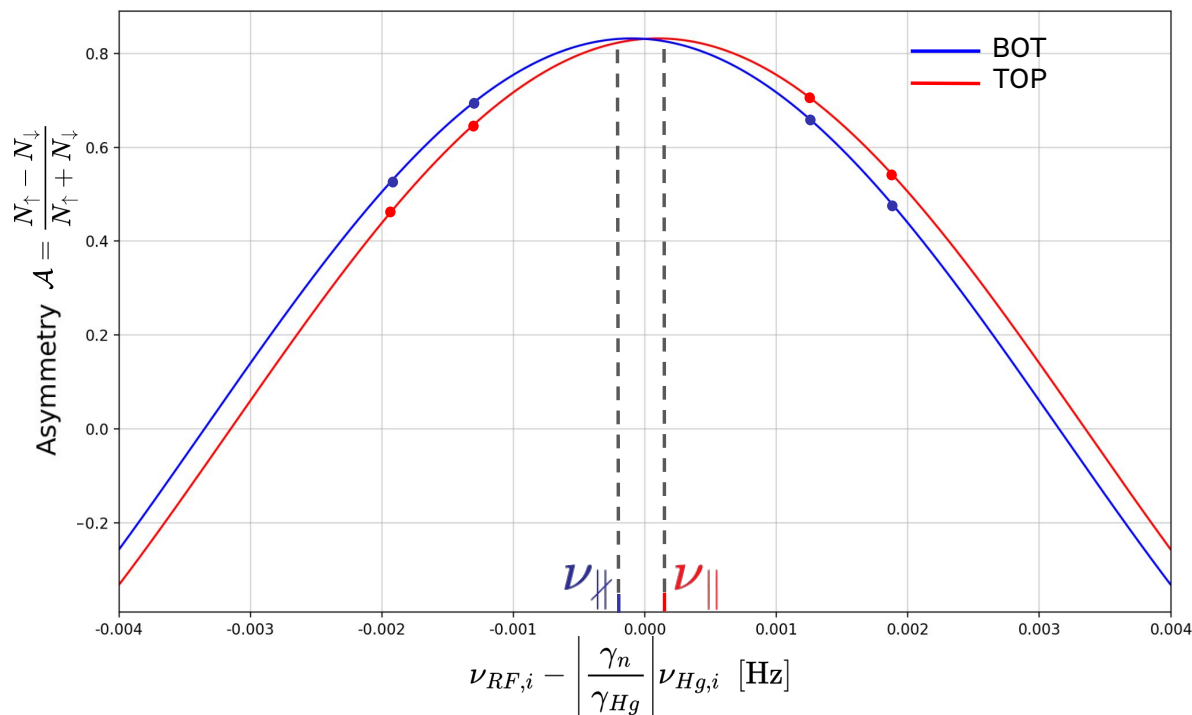
Fitting function

$$\mathcal{A}(\nu_{RF,i}) = \bar{A} - \alpha \cos\left(\frac{\pi}{\Delta\nu} x_i + \eta\right)$$

with the independent parameter (of ith cycle)

$$x_i = \nu_{RF,i} - \left| \frac{\gamma_n}{\gamma_{Hg}} \right| \nu_{Hg,i}$$

$$\Delta\nu = \frac{1}{2(T + 4\tau/\pi)}$$



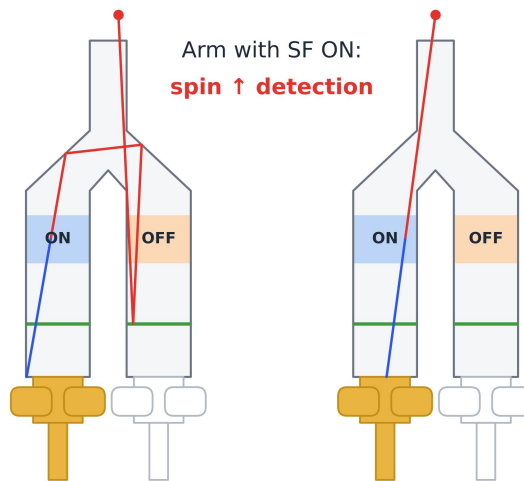
Measurement principle – How the asymmetry is measured

Analyzing foil

- Magnetized iron coating
- Spin down $\rightarrow$ transmitted
- Spin up $\rightarrow$ reflected

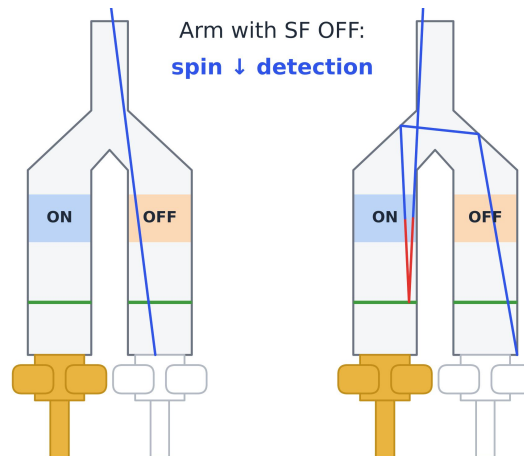
UCN trajectories

- Correct arm $\rightarrow$ transmitted directly
- Wrong arm $\rightarrow$ reflected to the other arm, then transmitted

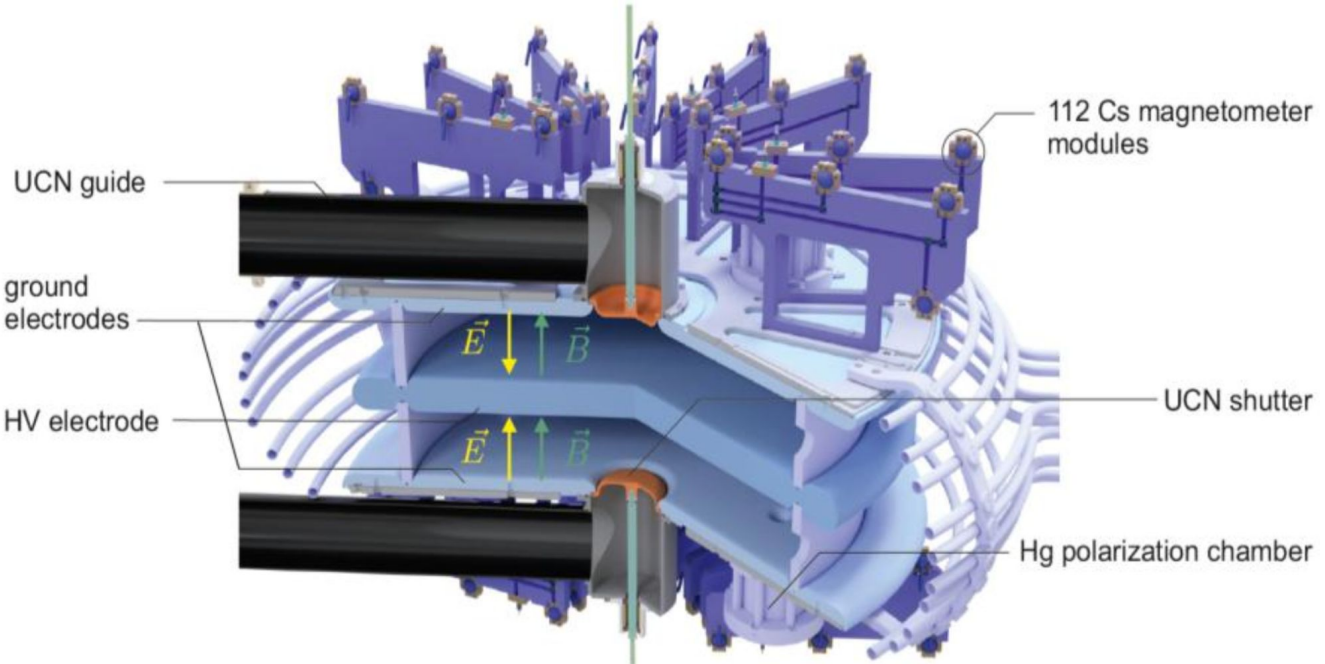


Switching spin-flippers

- Systematics effects
- 4 configurations in total



Double precession chamber – Full picture



The blinding principle – Moving the right number of neutrons

From config and data

- $\Delta\nu$ fringe width
- N_i UCN number at cycle i
- $\mathbf{E} \cdot \mathbf{B} / |\mathbf{B}|$ electric fields configurations
- ν_{Hg} mercury Larmor frequency
- ν_{RF} applied RF frequency

$$\delta N_{\uparrow, \downarrow; i} = \mp N_i \frac{\pi \alpha d}{h \Delta \nu} \frac{\mathbf{E} \cdot \mathbf{B}}{|\mathbf{B}|} \sin(\phi_i)$$

Fitting the central Ramsey fringe (run level)

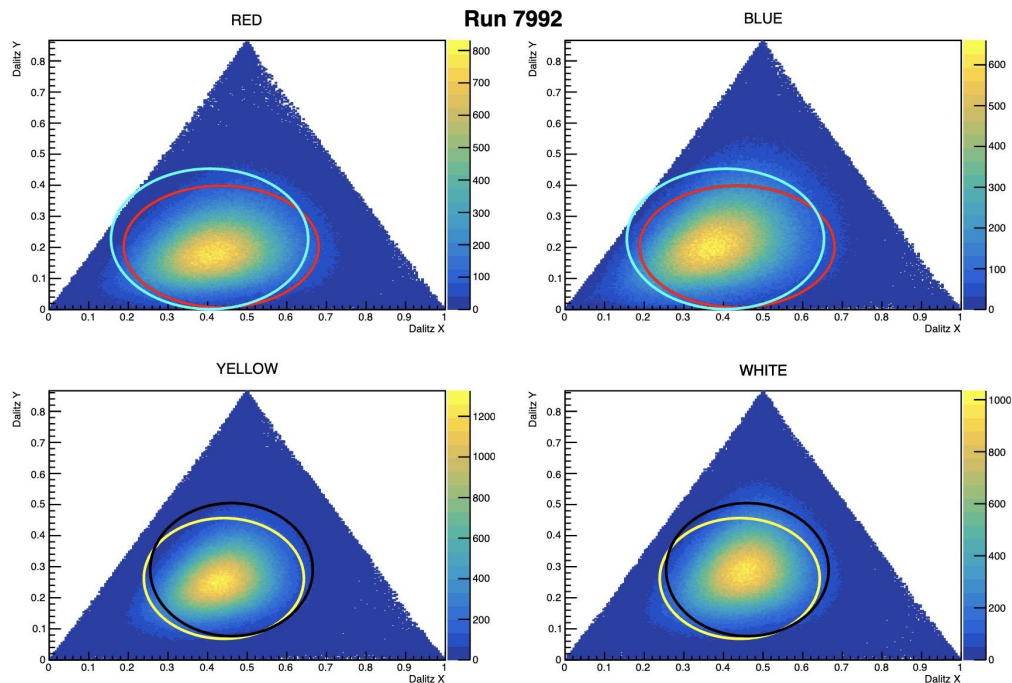
- α visibility
- η correction phase shift
- $\bar{A}$ mean asymmetry

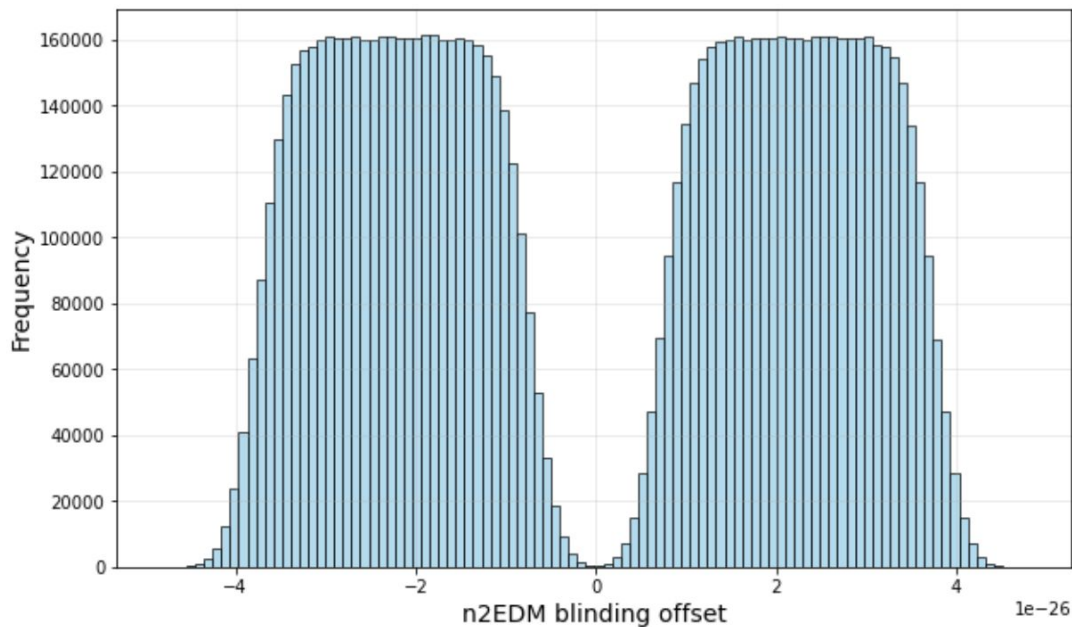
$$\mathcal{A}(\nu_{RF, i}) = \bar{A} - \alpha \cos\left(\frac{\pi}{\Delta \nu} x_i + \eta\right)$$

Working point position $\phi_i = \arccos \left[\frac{1}{\alpha} \left(\frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} - \bar{A} \right) \right]$

Backup slides - 4 parameters event selection

$$\{X_0, X_1, X_2, X_3\} = \left\{ \text{Amp}_{tot,i}, \frac{Q_{tot,i}}{\text{Amp}_{tot,i}}, D_{x,i}, D_{y,i} \right\} \quad \text{4D-ellipsoid: } \sum_{j=1}^4 \left(\frac{X_j - \overline{X_j}}{S \sigma(X_j)} \right)^2 \leq 1$$





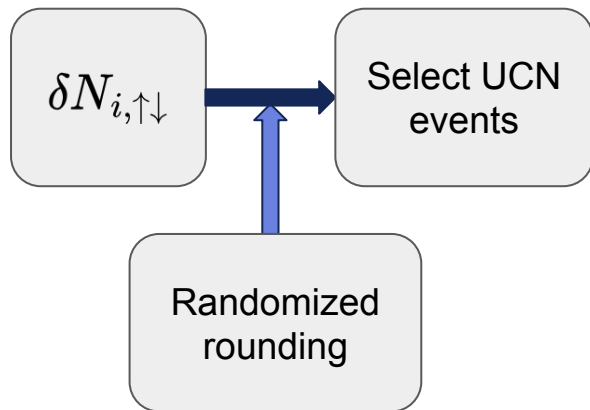
$$\left[-3.75 \times 10^{-26}, -0.75 \times 10^{-26}\right] \cup \left[0.75 \times 10^{-26}, 3.75 \times 10^{-26}\right] e \cdot \text{cm}$$

$$\phi_i = \arccos \left[\frac{1}{\alpha} \left(\frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} - \bar{\mathcal{A}} \right) \right]$$

sign ?

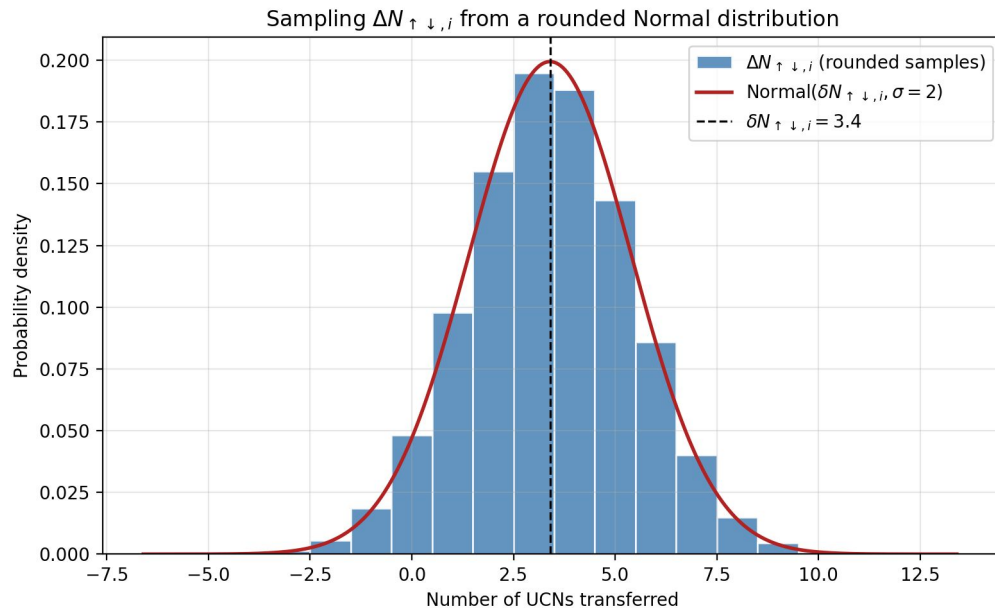
$$\phi_i = \frac{\pi}{\Delta\nu} \left(\nu_{RF,i} - \left| \frac{\gamma_n}{\gamma_{Hg}} \right| \nu_{Hg,i} \right) + \eta$$

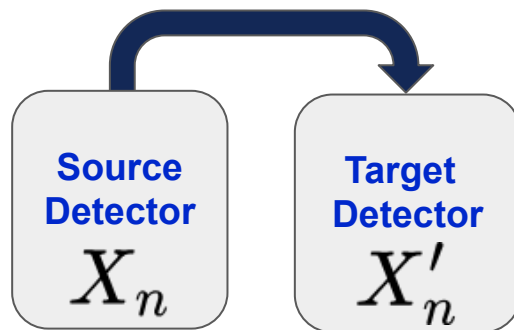
Backup slides - From float to integer



$$\Delta N_{\uparrow,\downarrow;i} = \lfloor \delta N_{\uparrow,\downarrow;i} + r + 0.5 \rfloor$$

with $r \sim \mathcal{N}(0, \sigma = 2)$





Mean-and-width matching condition:

$$X'_n = \overline{X_{n,t}} + \left(X_n - \overline{X_{n,s}} \right) \frac{\sigma_{X_{n,t}}}{\sigma_{X_{n,s}}}$$

with $X \in \{Q, Amp, W\}$ and $n \in \{1, 2, 3\}$

Neutron frequency extraction

Invert the fitted Ramsey curve cycle by cycle:

$$A_i = \bar{A} - \alpha \cos\left(\frac{\pi}{\Delta\nu}(f_{n,i} - f_{\text{RF},i})\right)$$
$$\longrightarrow f_{n,i} = \underbrace{f_{\text{RF},i} \pm \arccos\left(\frac{\bar{A} - A_i}{\alpha}\right) \frac{\Delta\nu}{\pi}}_{X_{\pm,i}} + 2k_{\pm,i} \Delta\nu$$

Choice of branch and fringe

f_0 as a reference for the resonance, $f_{n,i} \approx f_{0,i}$:

$$k_{\pm,i} = \text{round}\left(\frac{f_{0,i} - X_{\pm,i}}{2\Delta\nu}\right)$$

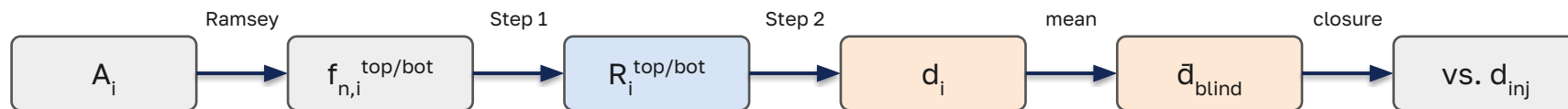
$\Rightarrow$ pick the solution closest to $f_{0,i}$

Uncertainty

$$\sigma_{f_{n,i}} \simeq \frac{\Delta\nu}{\pi} \frac{\sigma_{A_i}}{|\alpha \sin \varphi_i|} \simeq 6 \mu\text{Hz}$$

per cycle and per chamber

From the neutron frequency to the EDM: two steps



Step 1 – Hg comagnetometer ratio

Per cycle i and per chamber:

$$R_i = \frac{f_{n,i}}{f_{\text{Hg},i}}$$

$$\left(\frac{\sigma_R}{R}\right)^2 = \left(\frac{\sigma_{f_n}}{f_n}\right)^2 + \left(\frac{\sigma_{f_{\text{Hg}}}}{f_{\text{Hg}}}\right)^2$$

f_n and f_{Hg} are both $\propto B$

$\Rightarrow$ magnetic-field drifts cancel in R

Step 2 – Top/Bottom difference

Same B , opposite E ($E_{\text{bot}} = -E_{\text{top}}$):

$$d_i = \frac{\pi \hbar \bar{f}_{\text{Hg},i}}{2E_i} (R_i^{\text{top}} - R_i^{\text{bot}})$$

B terms cancel, EDM term doubles

Weighted mean over the run:

$$\bar{d} = \frac{\sum_i d_i / \sigma_{d_i}^2}{\sum_i 1 / \sigma_{d_i}^2}, \quad \sigma_{\bar{d}} = \left(\sum_i \sigma_{d_i}^{-2} \right)^{-1/2}$$

Closure: $\bar{d}_{\text{blind}} - \bar{d}_{\text{raw}}$ compared with d_{inj} for the 6 injected offsets (132 cycles).

Backup slides - Why the closure χ^2 is ≈ 0

All tests are built from the same raw neutrons:

$$\bar{d}_{\text{blind},j} = s d_{\text{inj},j} + \underbrace{\bar{d}_{\text{raw}}}_{\text{common}} + \underbrace{\delta_{\text{blind}}}_{\text{common}} + \eta_j, \quad |\eta_j| \sim 10^{-28} e \cdot \text{cm} \ll \sigma_{\bar{d}}$$

$$\text{Cov}(\bar{d}_{\text{blind},j}, \bar{d}_{\text{blind},k}) \simeq \sigma_{\bar{d}}^2 \Rightarrow \rho_{jk} \simeq \frac{1}{1 + \kappa^2} \simeq 0.9995$$

The standard χ^2 treats the points as independent:

$$\chi^2 = \sum_j \frac{(\bar{d}_{\text{blind},j} - s d_{\text{inj},j} - b)^2}{\sigma_{\bar{d}}^2} \simeq \sum_j \frac{\eta_j^2}{\sigma_{\bar{d}}^2} \sim 6 \times \left(\frac{10^{-28}}{10^{-25}} \right)^2 \sim 10^{-6}$$

$\Rightarrow$ relevant precision: paired differences $\sigma(\bar{d}_{\text{blind}} - \bar{d}_{\text{raw}}) \simeq \kappa \sigma_{\bar{d}} \simeq 2 \times 10^{-27} e \cdot \text{cm}$