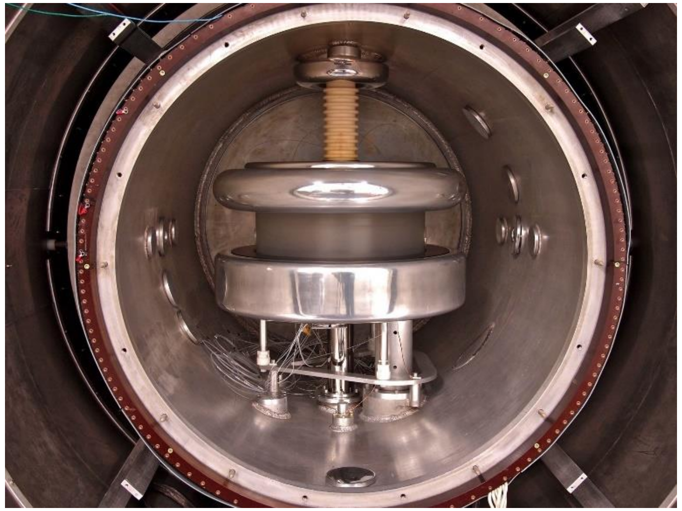
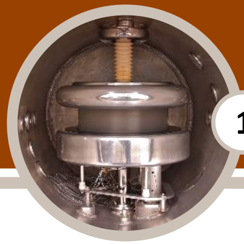
04/11/2019
GDR-InF

Systematic effects on measurement of the neutron electric dipole moment



Laura Ferraris-Bouchez

Introduction
Motivations



- Matter / antimatter asymmetry
  - No complex antimatter nuclei
  - No radiation excess (annihilation)

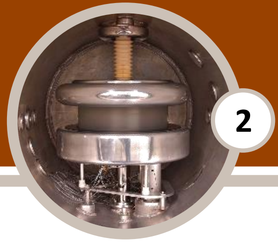
NECESSARY

- Sakharov conditions
  - Baryon number violation
  - Interactions out of thermal equilibrium
  - C and CP violations

Standard Model
CP violation
INSUFFICIENT

Fundamental particles
Electric Dipole Moment (EDM)

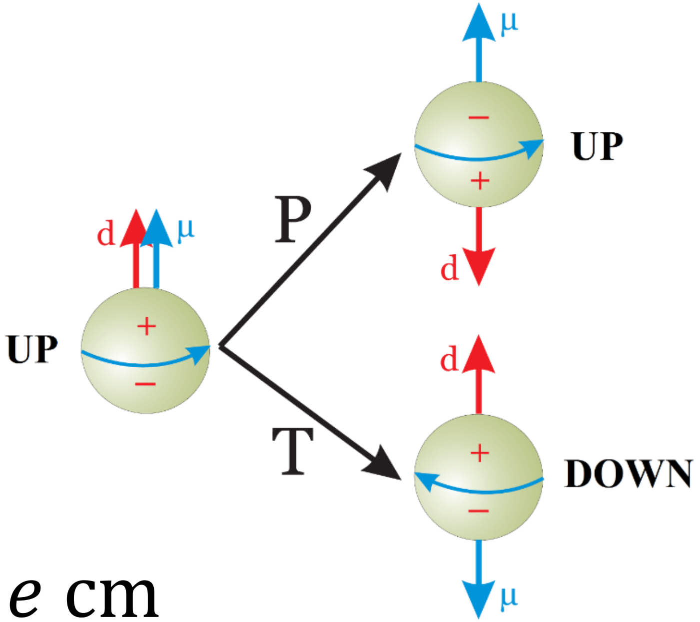
Introduction
Neutron Electric Dipole Moment

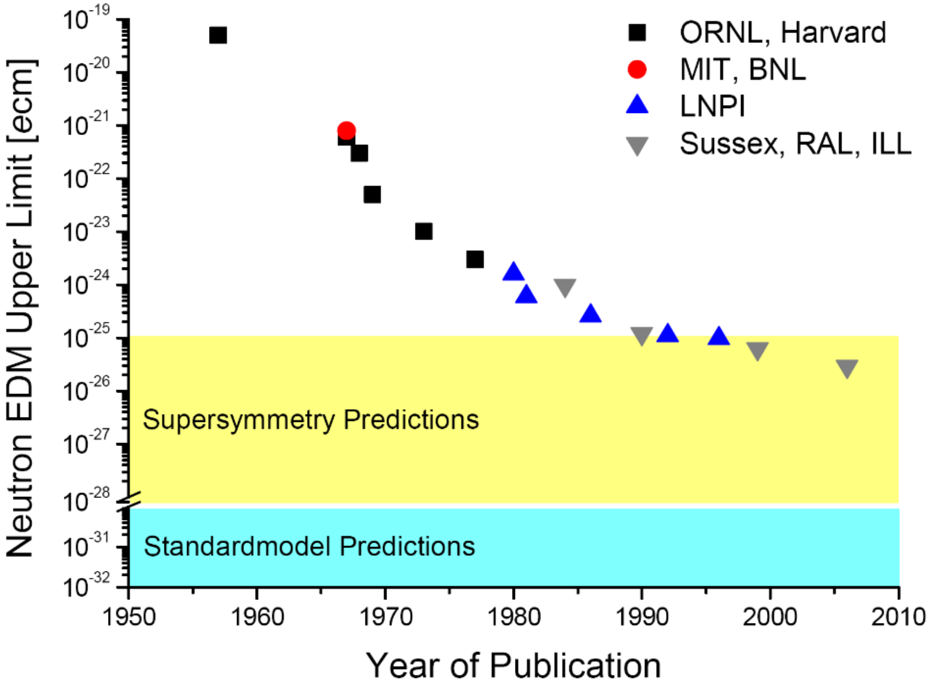


- Classically → Distance between **+** and **–** charges
- Spin / external electric field coupling

$$H = \mu_n \hat{\boldsymbol{\sigma}}_{\boldsymbol{z}} \cdot \boldsymbol{B} + d_n \hat{\boldsymbol{\sigma}}_{\boldsymbol{z}} \cdot \boldsymbol{E}$$

EDM → CP violation source



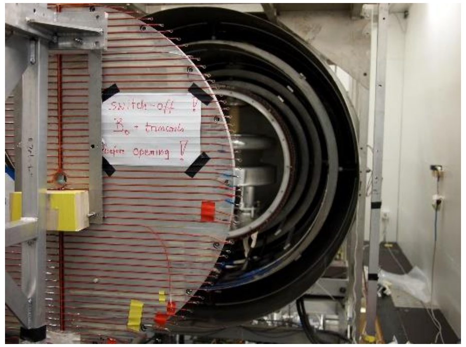


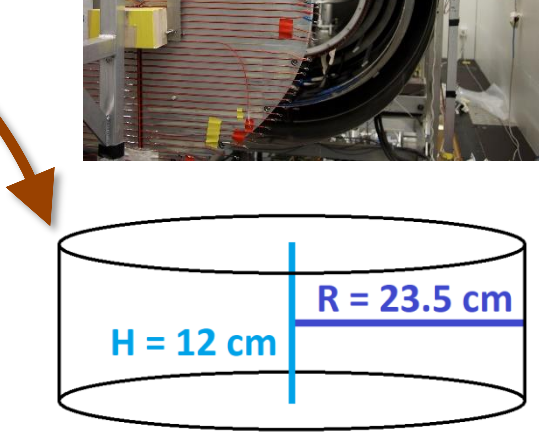
- SM: $10^{-32} e$ cm
- BSM: 10^{-25} à $10^{-29} e$ cm
  → Background free

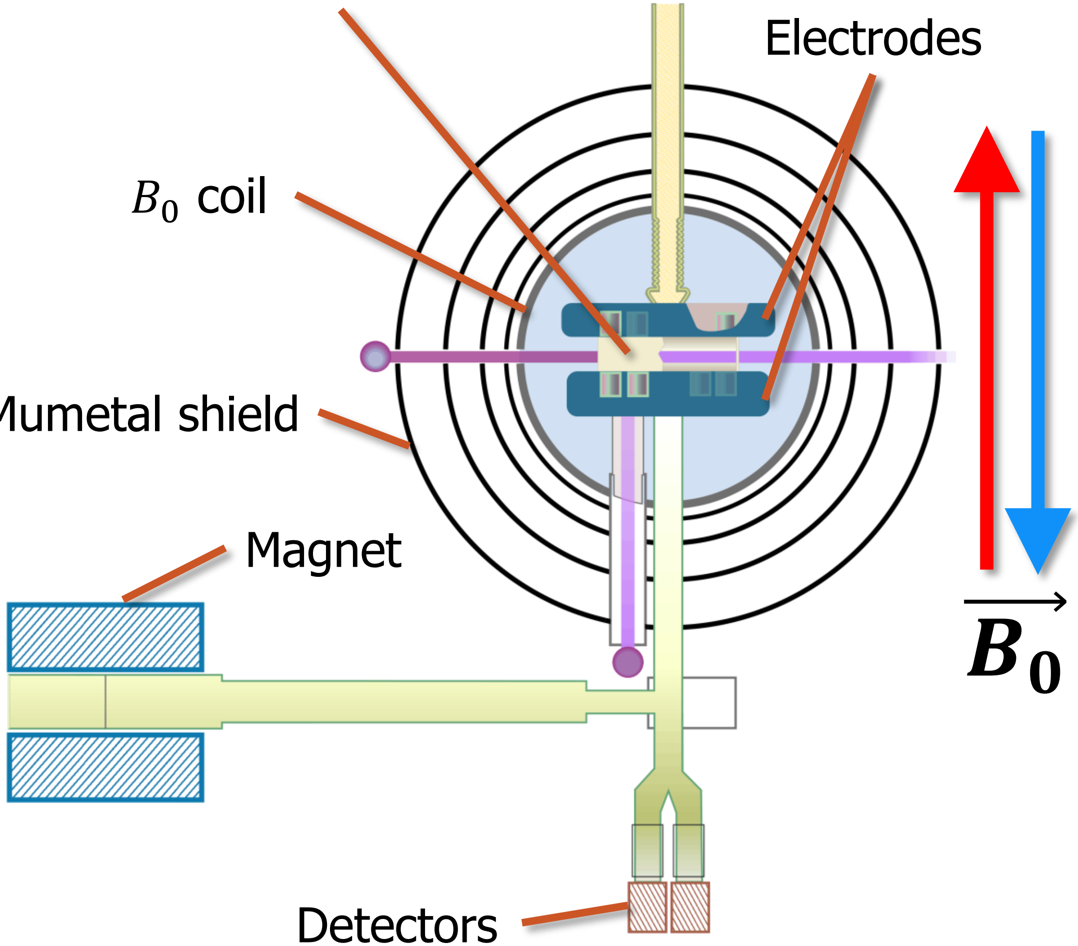
$$\boldsymbol{d_{\mathrm{n}} < 3,0 \times 10^{-26} e \ \mathrm{cm}\ (90\% \ \mathrm{CL})}$$

Paul Scherrer Institute nEDM experiment
General principle

$$f_n = \frac{2}{h}|\mu_n B \pm d_n E|$$

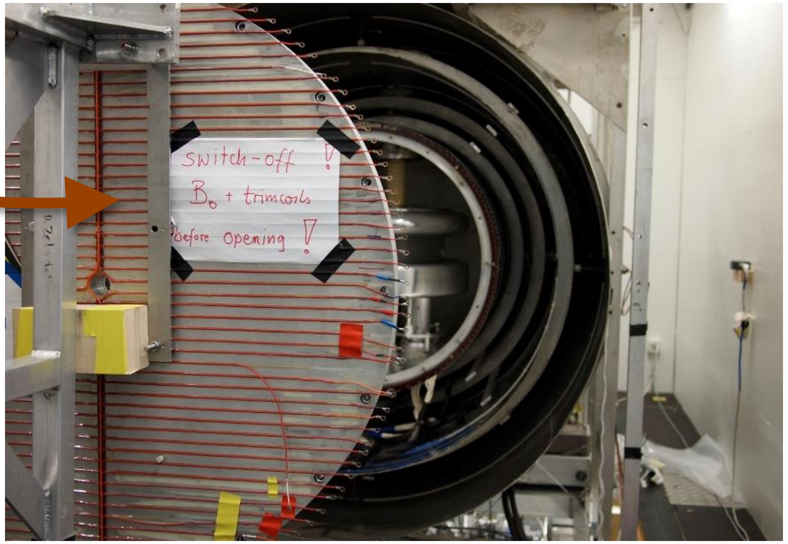




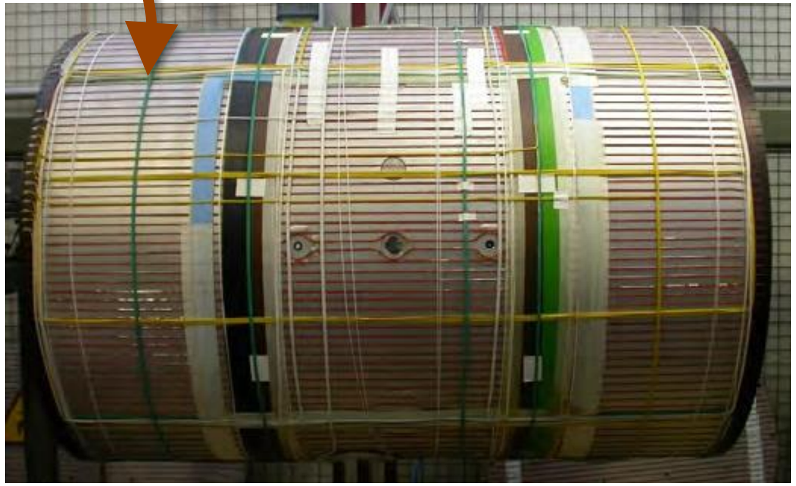


Statistical sensibility → $1.1 \times 10^{-26} e$ cm

- **1 μT** vertical field generated by B_0 coil
  - Very uniform → $\frac{\delta B_0}{B_0} \sim 10^{-3}$
- Non-uniformities reductions
  - 33 compensation coils (trimcoils)

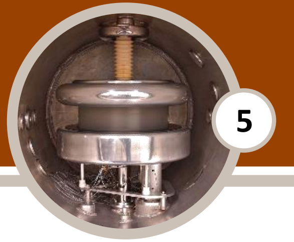


- **1 run nEDM :**
  - B_0 **up** / **down**
  - Set of currents i_c for the trimcoils
    - Minimization of non-uniformities
  - 1 fixed value for the vertical gradient



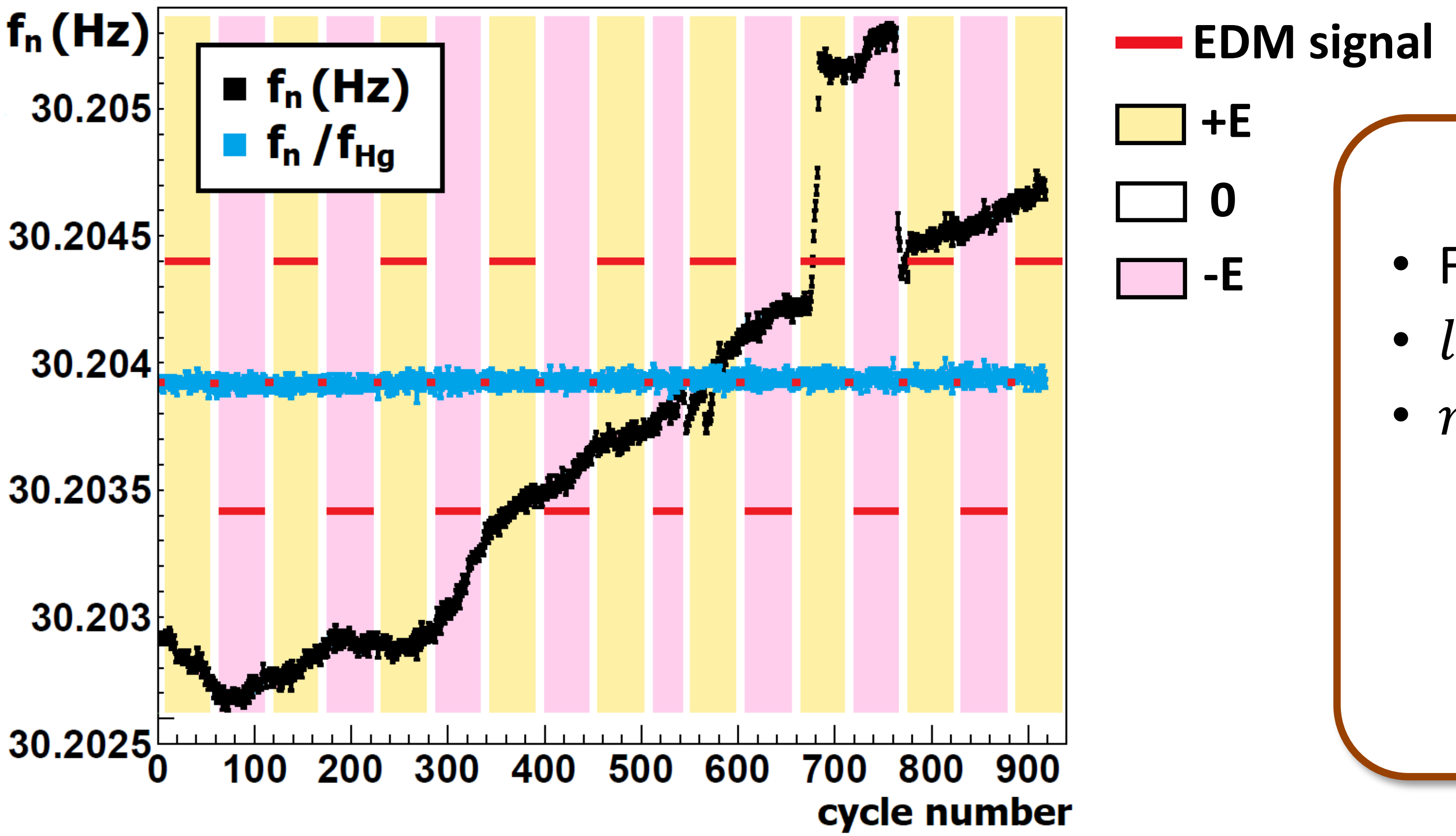
$\overrightarrow{\boldsymbol{B_0}}$

Paul Scherrer Institute nEDM experiment
Magnetic field



$$f_n = \frac{2}{h}|\mu_n B \pm d_n E|$$

- Magnetic field drifts
  - **Correction of f_n with Hg co-magnetometer**

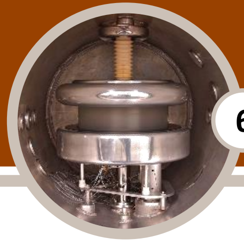


Field decomposition

- From spherical harmonics
- l → polynomial order in ρ, z
- m → order of the φ dependency

$$\vec{B} = \sum_{l\geq 0}\sum_{m} G_{l,m}\vec{\Pi}_{l,m}(\rho,\varphi,z)$$

$G_{l,m}$ → magnetic gradients



- Motional Hg false EDM
  - Relativistic field $\vec{v} \times \vec{E}/c^2$
  - Magnetic non-uniformities

$$d_{\text{n}} = d_{\text{n}}^{\text{true}} + d_{\text{n}\leftarrow\text{Hg}}^{\text{false}}$$

$$d_{\text{n}\leftarrow\text{Hg}}^{\text{false}} = \frac{\hbar\,\gamma_{\text{n}}\,\gamma_{\text{Hg}}\,R^2}{8\,c^2}\left(\boldsymbol{G}_{\textbf{grav}} + \widehat{\boldsymbol{G}}\right)$$

Gravitational gradient

$$\boldsymbol{G}_{\textbf{grav}} = G_{1,0} + AG_{3,0} + BG_{5,0} + \cdots$$

Residual gradient $\widehat{\boldsymbol{G}}$

$$\widehat{\boldsymbol{G}} = A'G_{3,0} + B'G_{5,0} + \cdots$$

- Gravitational shift $\langle z \rangle = -0.39(3)$ cm
  - Hg atoms: gas (uniformly distributed)
  - Very low energy UCNs (lower than Hg)

$$\mathcal{R} = \frac{f_{\text{n}}}{f_{\text{Hg}}} = \left|\frac{\gamma_{\text{n}}}{\gamma_{\text{Hg}}}\right| \cdot \left(1 \pm \frac{\langle z \rangle}{B_0}\boldsymbol{G}_{\textbf{grav}}\right)$$

Paul Scherrer Institute nEDM experiment

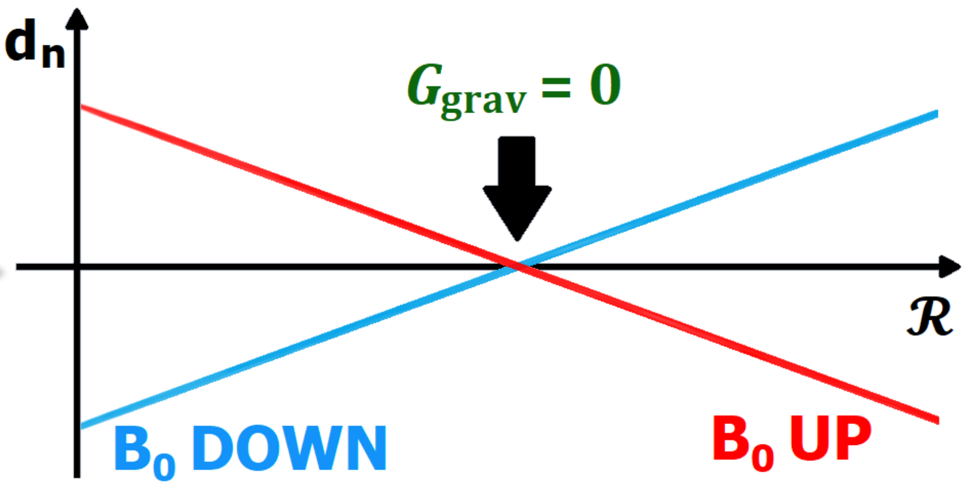
Magnetic non-uniformities effects

$$d_n = d_n^{true} + \frac{\hbar\, \gamma_n\, \gamma_{Hg}\, R^2}{8\, c^2}\left(G_{grav} + \hat{G}\right)$$

AND

$$\mathcal{R} = \frac{f_n}{f_{Hg}} = \left|\frac{\gamma_n}{\gamma_{Hg}}\right| \cdot \left(1 \pm \frac{\langle z \rangle}{B_0} G_{grav}\right)$$

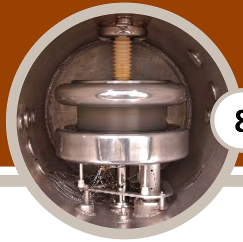
- 1 EDM run = B_0 up/down + 1 G_{grav} value
- $\hat{G}$ subtraction to d_n
- $d_n = d_\times \pm \eta(\mathcal{R} - \mathcal{R}_\times)$
- $\Delta\hat{G} \sim 0.6\,\mathrm{pT/cm} \Longrightarrow \Delta d_n \sim 3 \times 10^{-27} e\,\mathrm{cm}$



$d_n = d_\times = d_n^{true}$ at $G_{grav} = 0$

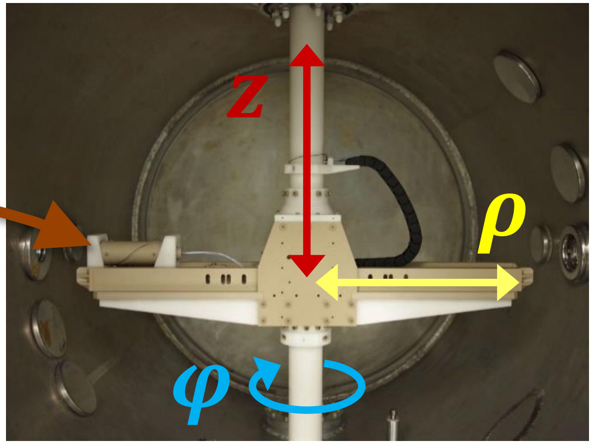
$\hat{G}$ must be measured per run
→ Offline magnetic field mapping

Magnetic field mapping
Panorama

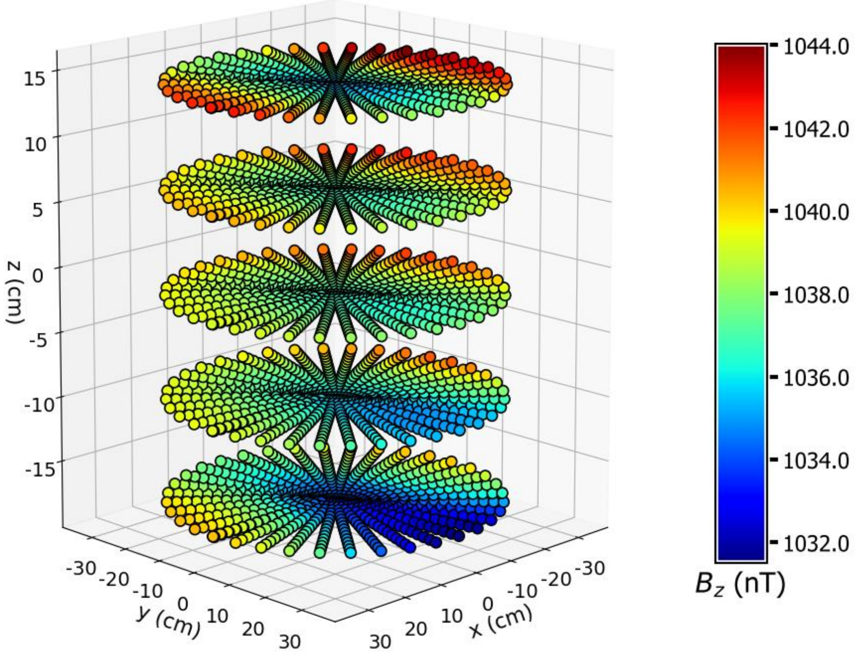


- **Goal:** $\hat{G}$ and $\langle B_T^2 \rangle$ per run

- **Mapper**
  - Fluxgate (3 axes magnetometer)
  - Radial motion on a rotating support

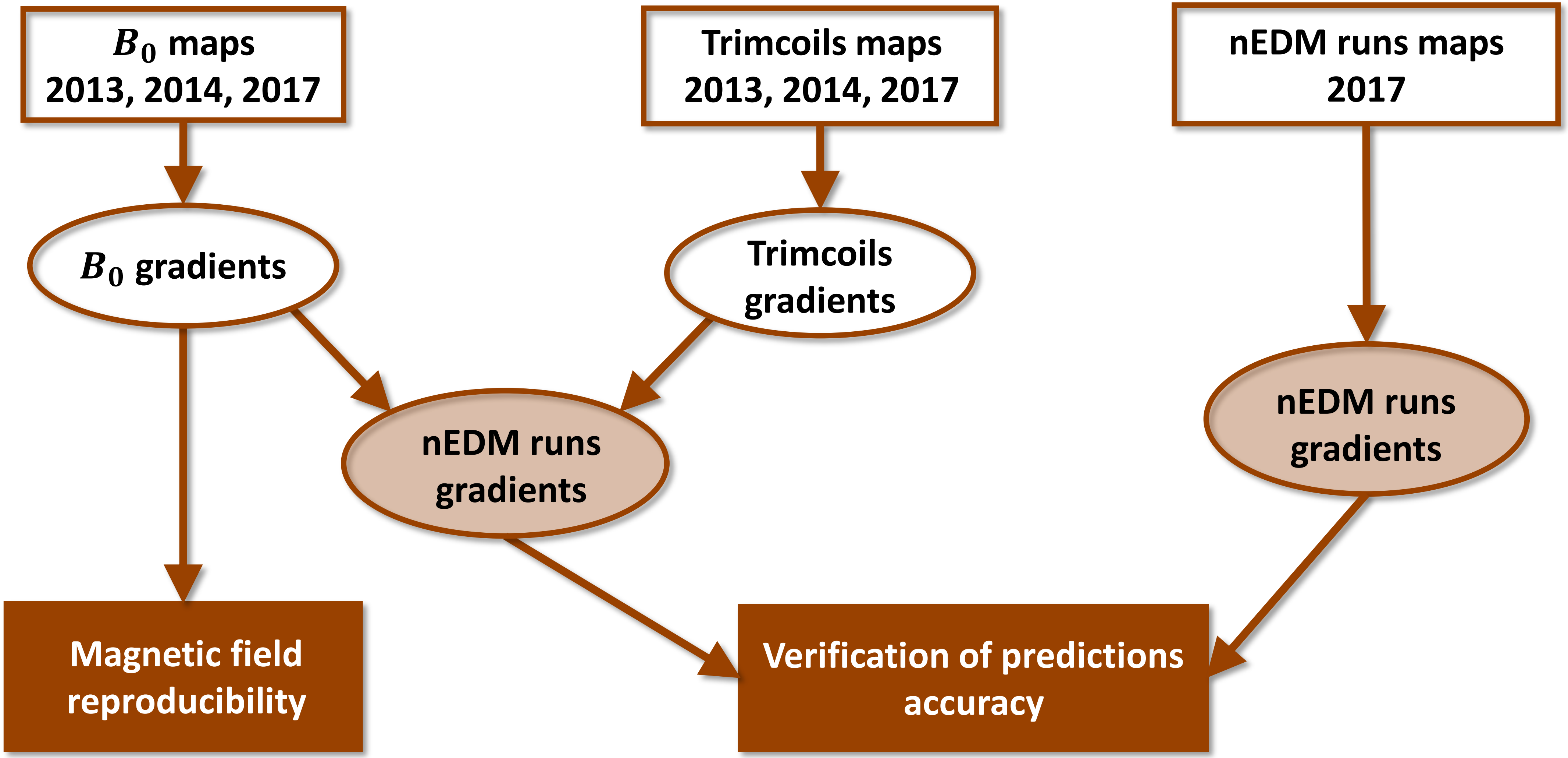


- 3 campaigns (2013, 2014 et 2017) ~ 300 maps
  - Remanent field
  - B0 up / down
  - Trimcoils
  - nEDM runs magnetic configuration

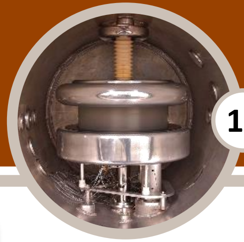


Mapping analysis

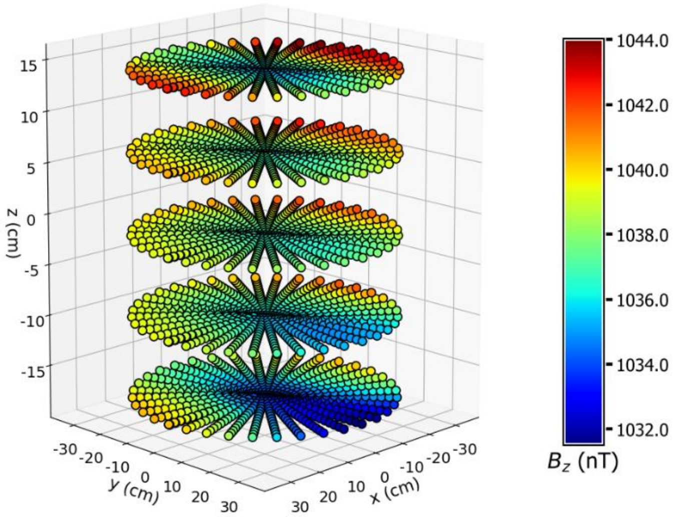
Global analysis



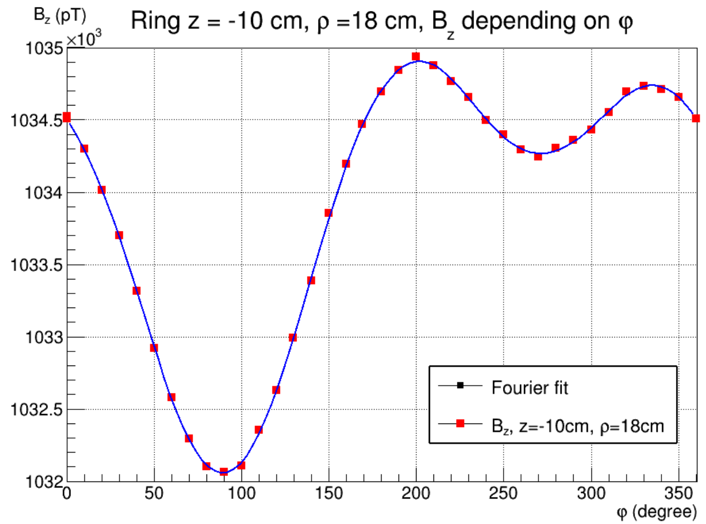
Mapping analysis
1 map analysis method



Rings set



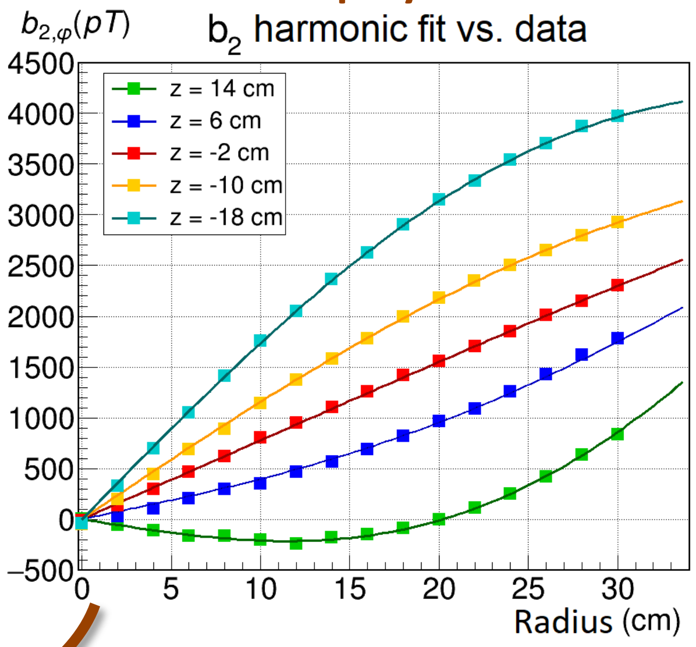
Ring by ring Fourier decomposition



$$B_z(\varphi) = \sum_{m\geq 0} a_{m,z}\cos(m\varphi) + b_{m,z}\sin(m\varphi)$$

Fourier coefficients set

Fourier coefficients fit with harmonic polynomials



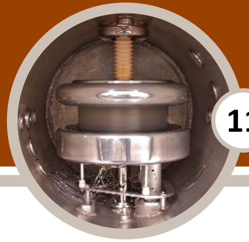
$$a_{m,z}(\rho, z) = \sum_{l\geq 0} G_{l,m}\widehat{\Pi}_{l,m}(\rho, z)$$

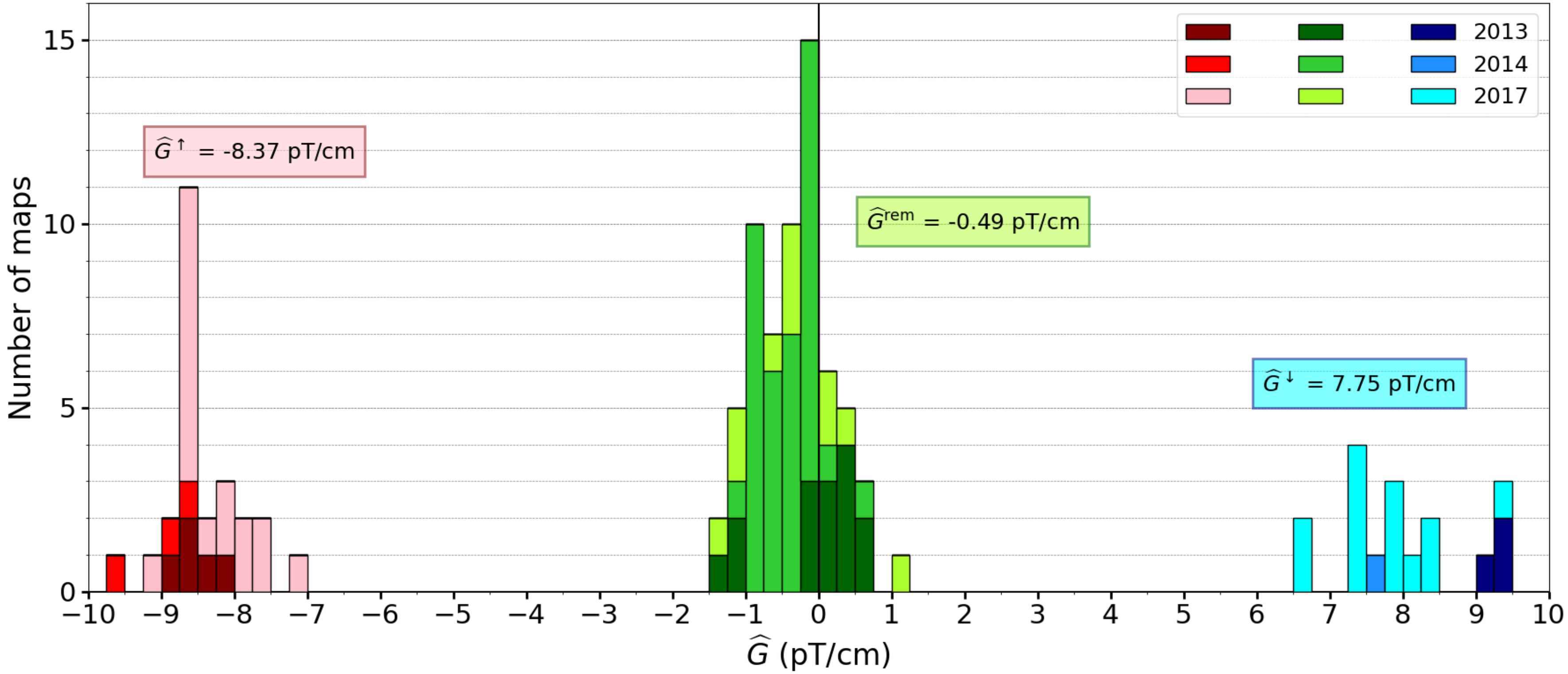
Gradients set $G_{l,m}$

Weighted combination of the 3 axes

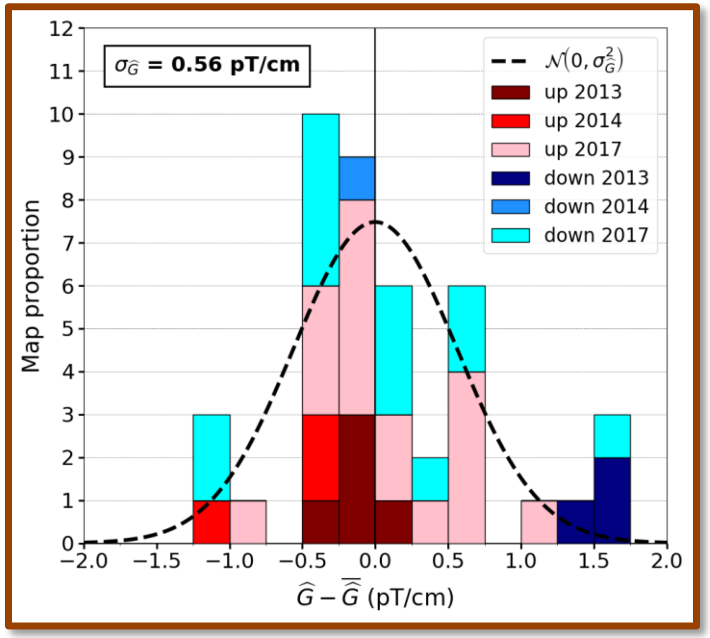
Per map: $\widehat{G},\ \langle B_T^2\rangle$

Mapping results
Field reproducibility





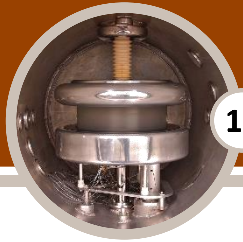
- B_0 maps :
  25 up / 17 down
- $\boldsymbol{\sigma_{\widehat{G}}} > \boldsymbol{\Delta\widehat{G}_{\mathrm{fit}}}$

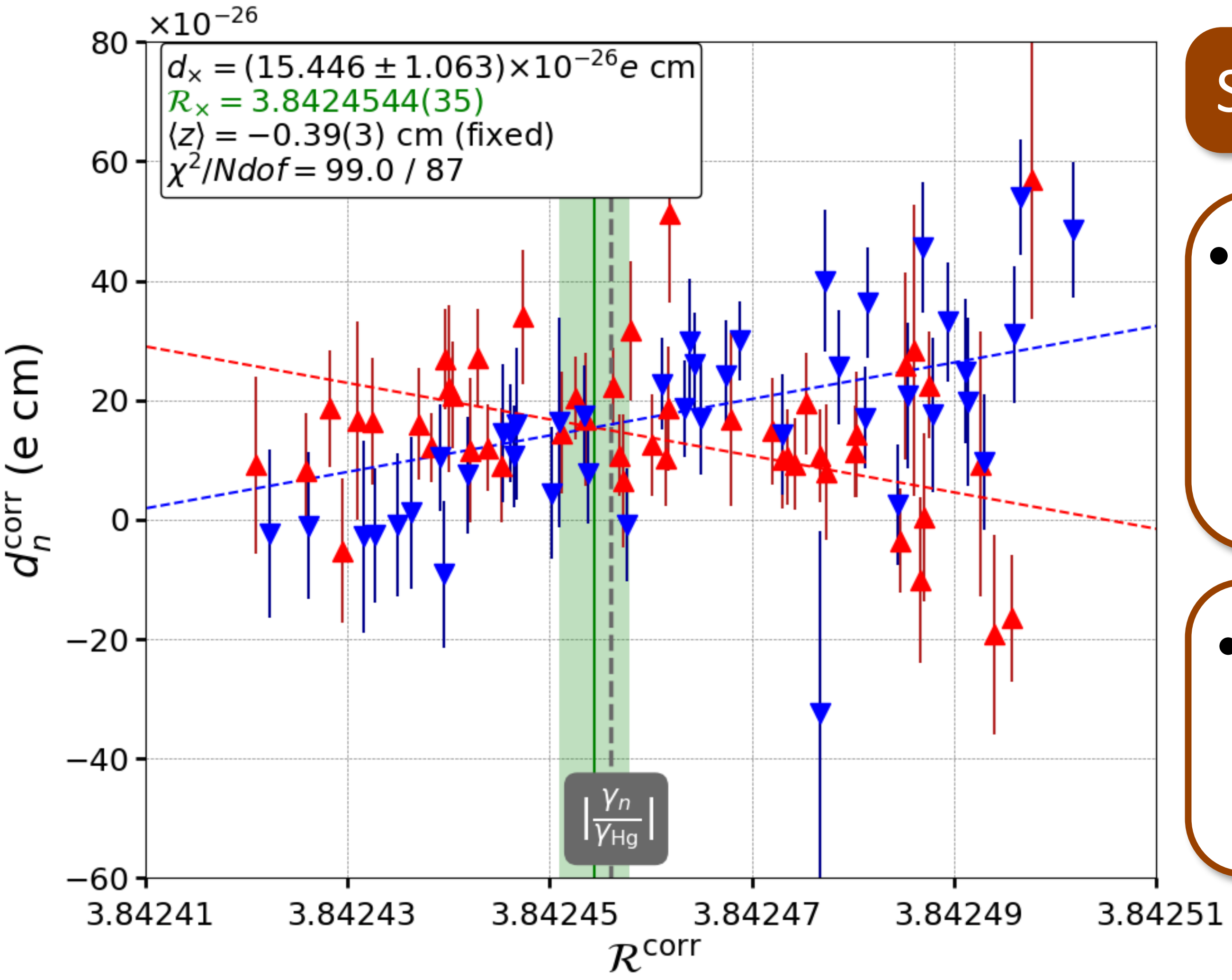


Per run:

- $\widehat{G} \sim 8\,\mathrm{pT/cm} \Longrightarrow$ correction of $\sim 3.5 \times 10^{-26} e$ cm
- $\sigma_{\widehat{G}} = 0.56\,\mathrm{pT/cm} \Longrightarrow \Delta d_{\mathrm{n} \leftarrow \sigma_{\widehat{G}}} = 25 \times 10^{-28} e\ \mathrm{cm}$

Crossing point analysis
Mapping corrections on double-blinded data



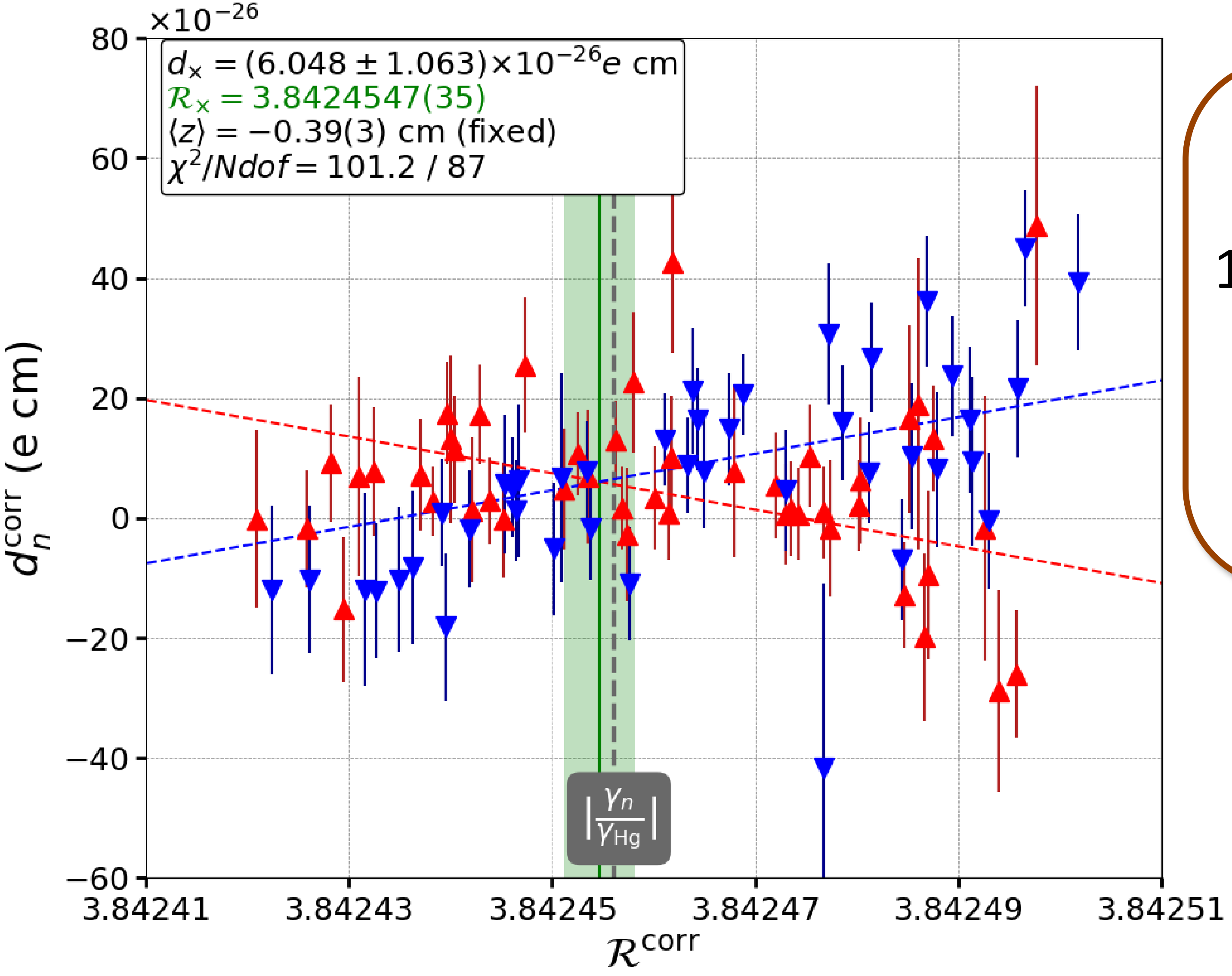


Statistical sensibility → $106 \times 10^{-28} e$ cm

- $\hat{G}$ correction run by run:
  - Correction to $d_\times \Longrightarrow -57 \times 10^{-28} e$ cm
    - → More than 50% of the error bar
  - Contribution to $\Delta d_\times \Longrightarrow 8 \times 10^{-28} e$ cm

- $\langle B_T^2 \rangle$ correction run by run:
  - Correction to $d_\times \Longrightarrow 1 \times 10^{-28} e$ cm
  - Contribution to $\Delta d_\times \Longrightarrow 5 \times 10^{-28} e$ cm

Crossing point analysis
Single-blinded data



2 independent analyzes with 2 different blinding factors

1st unblinding:

- Identical results (18% of the error bar)
- Identical statistical error
- Unchanged $\hat{G}$ correction
- Unchanged $\langle B_T^2 \rangle$ correction

Soon the results for non-blinded data …

Thank you!