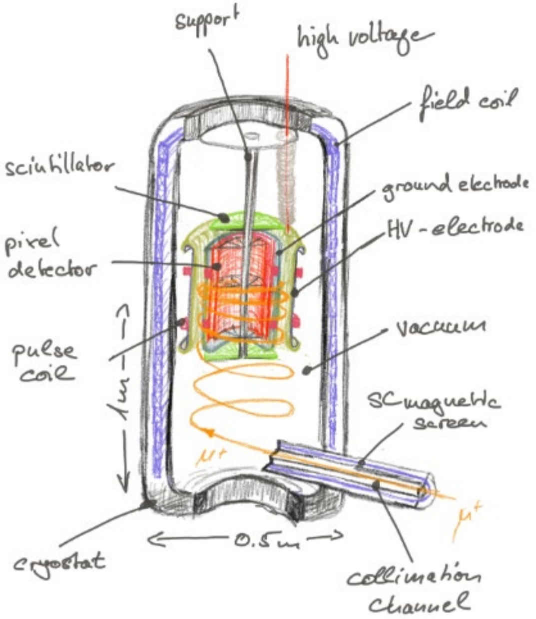
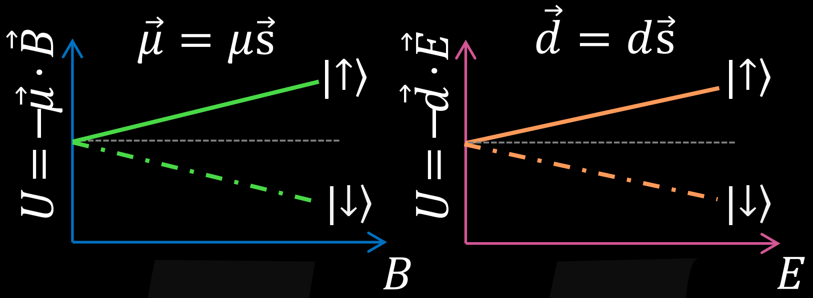


muon & neutron EDM searches at PSI

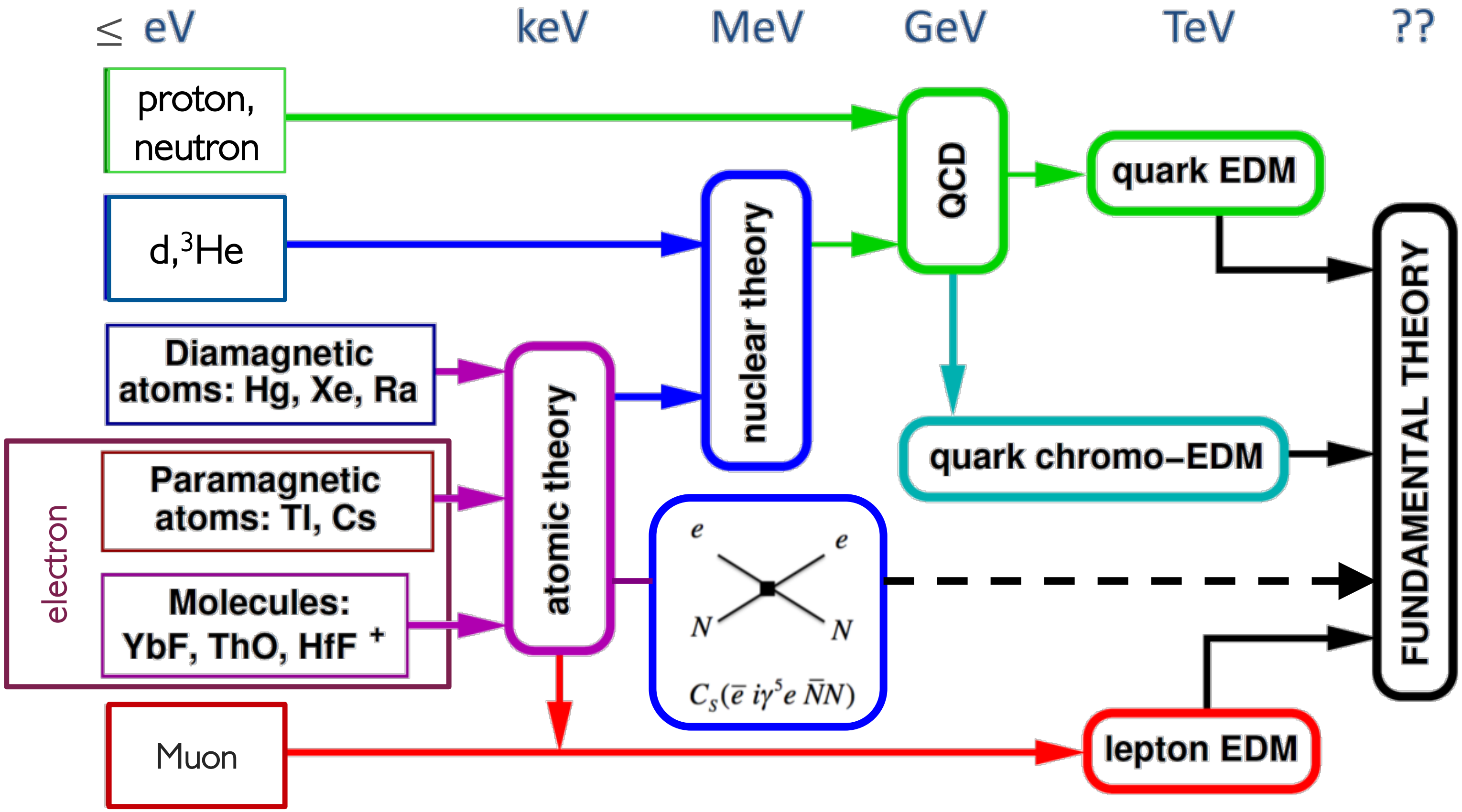
P. Schmidt-Wellenburg

Searches for electric dipole moments at PSI

CP violation & edm

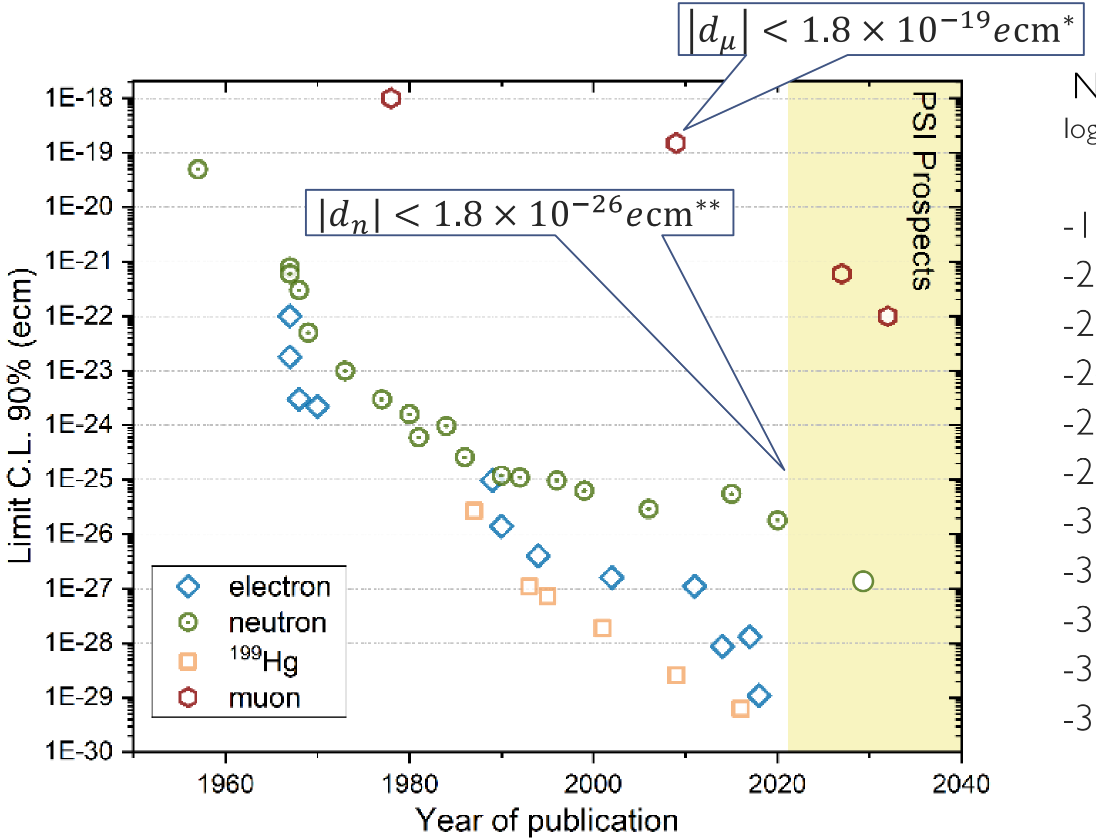


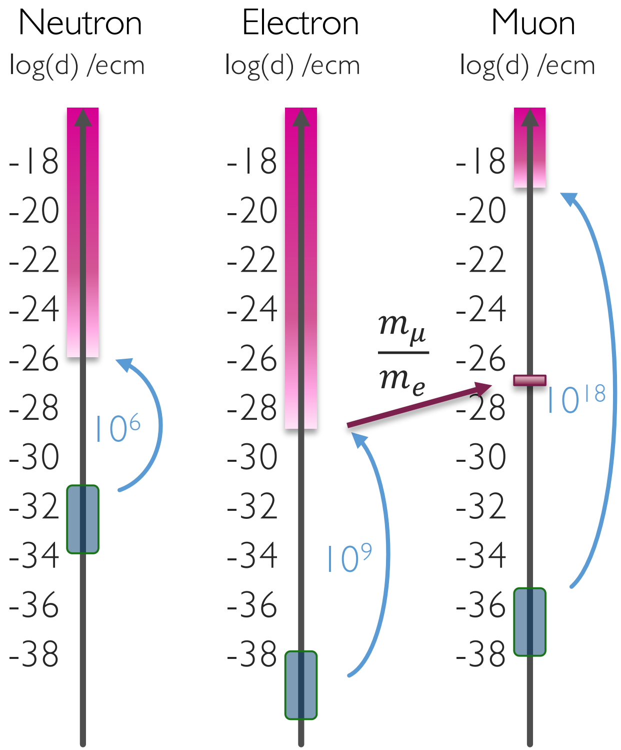
Complementarity of EDM searches



Scheme: adapted from Rob G. E. Timmermans

A brief history of EDM searches





*Bennett et al., PRD80(2009)052008

** Abel et al., PRL124(2020)081803

Sakharov criteria for baryogenesis

SM expectation:

not possible

vs.

Observed*:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} : \; 6\times10^{-10}$$

Sakharov criteria*	SM	BSM
1. *Baryon number violation*	✓	✓
2. *C and CP violation*		✓
3. *Thermal non-equilibrium*		✓

search for EDMs

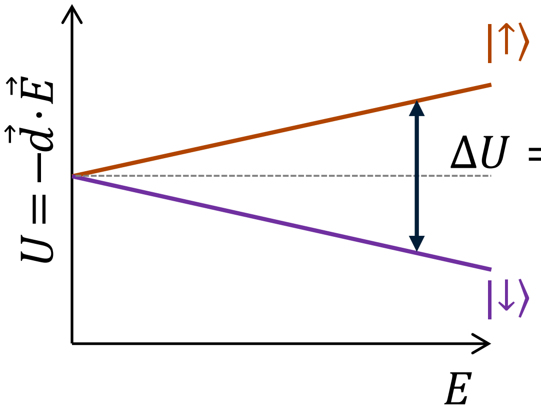
$(6.19 \pm 0.15) \times 10^{-10}$

*[A. D. Sakharov, JETP 5 (1967), 32]

*[E. Komatsu et al. ApJS(2011)192]

EDM measurement basics (neutron search)

Measure the energy splitting



$$\Delta U = \hbar\omega_e = 2dE$$

Best to measure the associated frequency ω_e

$$f_e = \frac{2dE}{h} \approx 53\text{nHz}$$

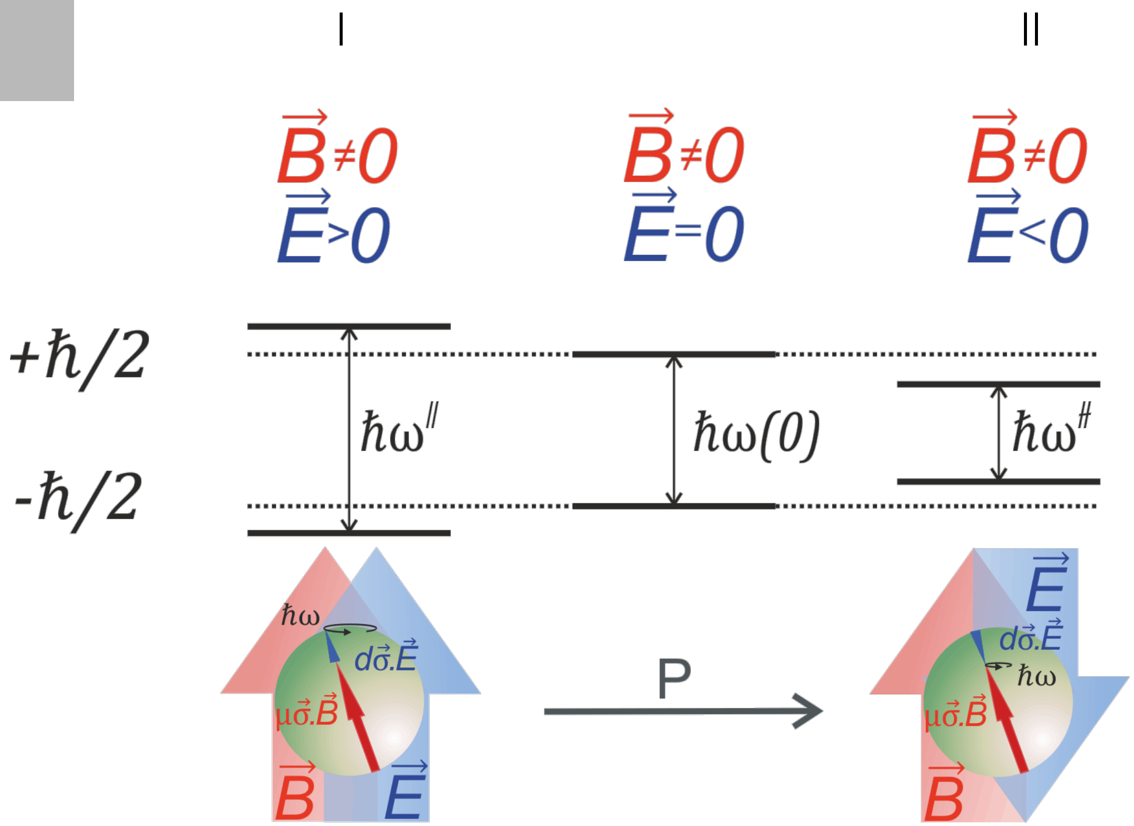
Corresponds to about 1 turn in a year

Systematic effect:
classical Larmor precession

$$f_L = \frac{2\mu B}{h} \approx 0.1\text{mHz}$$

Corresponds to 1 turn in 2.5 h in the best MSR

Use a magnetic offset field



I $f^{\uparrow} = \frac{2}{h}(\mu B + dE)$

II $f^{\downarrow} = \frac{2}{h}(\mu B - dE)$

II-I $\Delta f = \frac{2}{h}(\mu \Delta B - 2dE)$

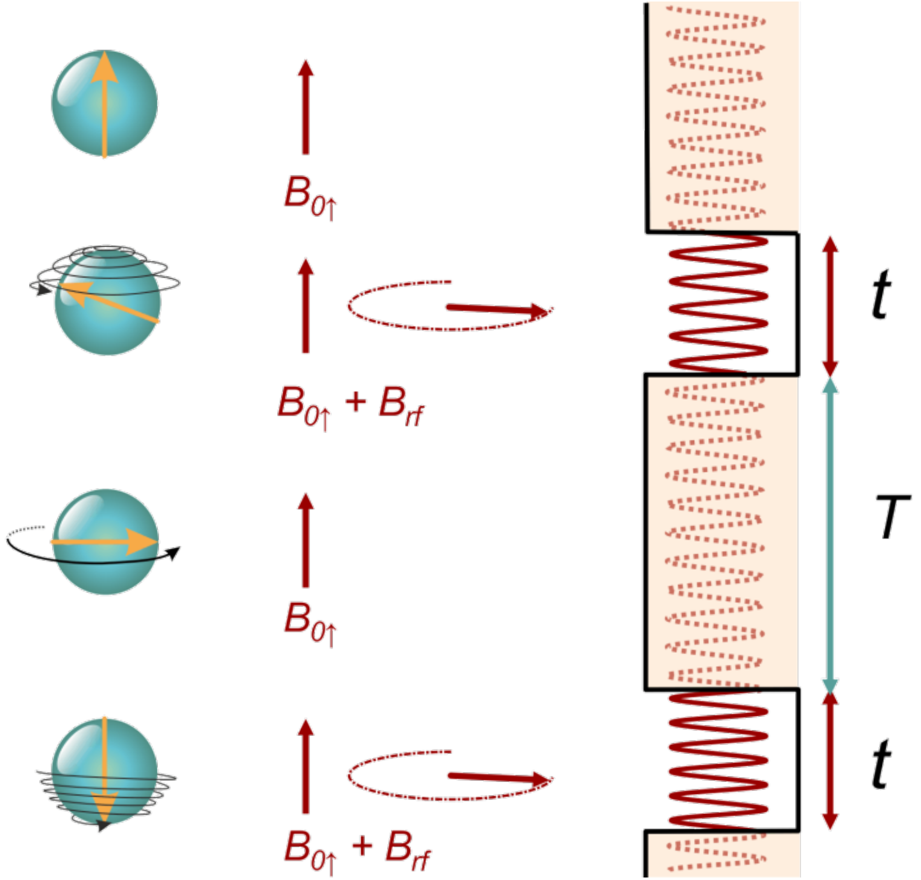
The Ramsey technique

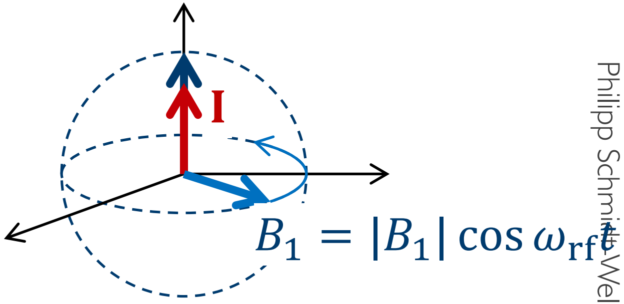
Spin "down" neutron...

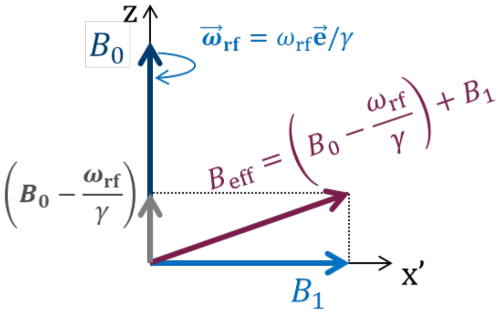
Apply π/2 spin flip pulse...

Free precession at ω_L

Second π/2 spin flip pulse.



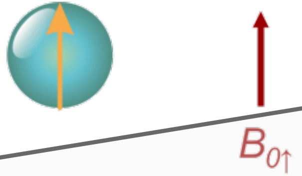


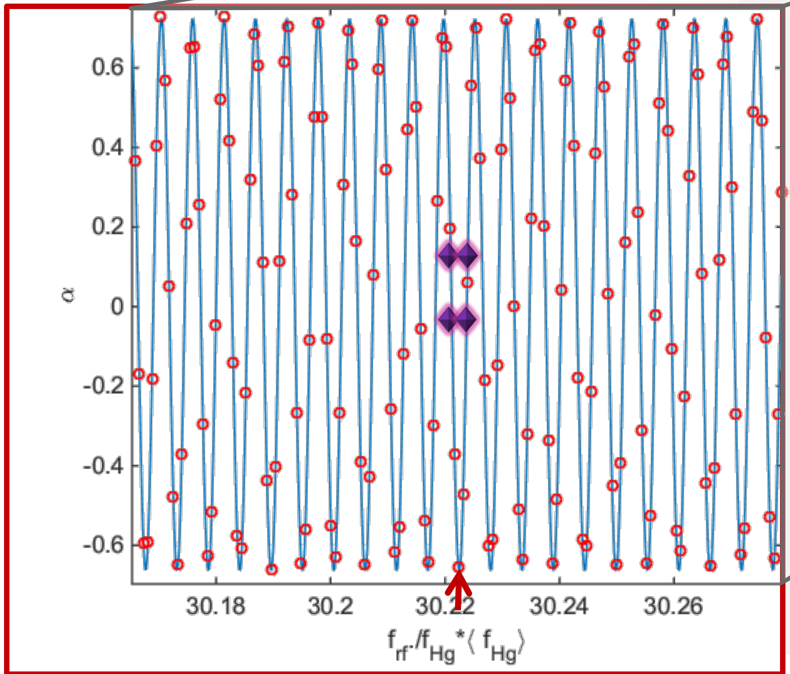


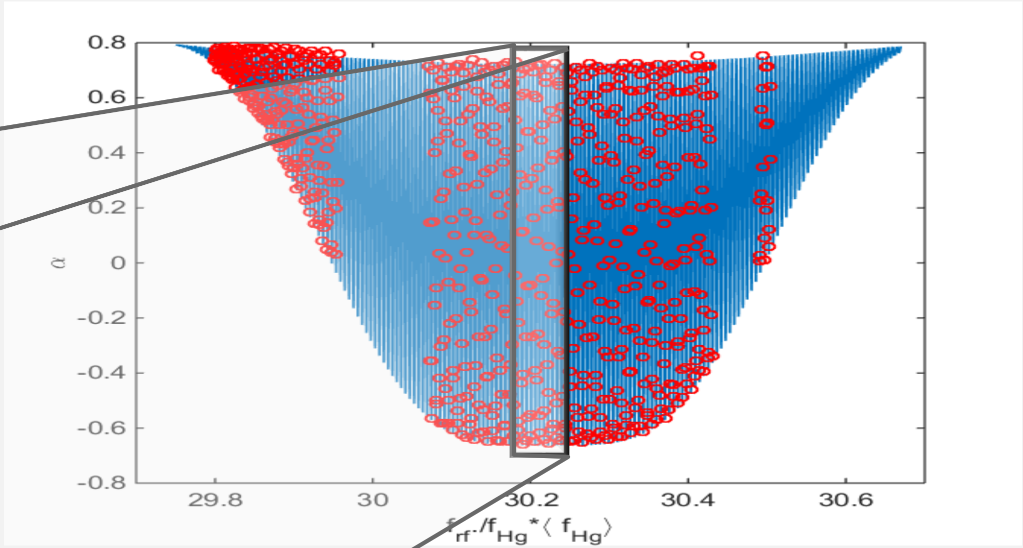
Effective field in rotating coordinate system

The Ramsey technique

Spin "down" neutron...





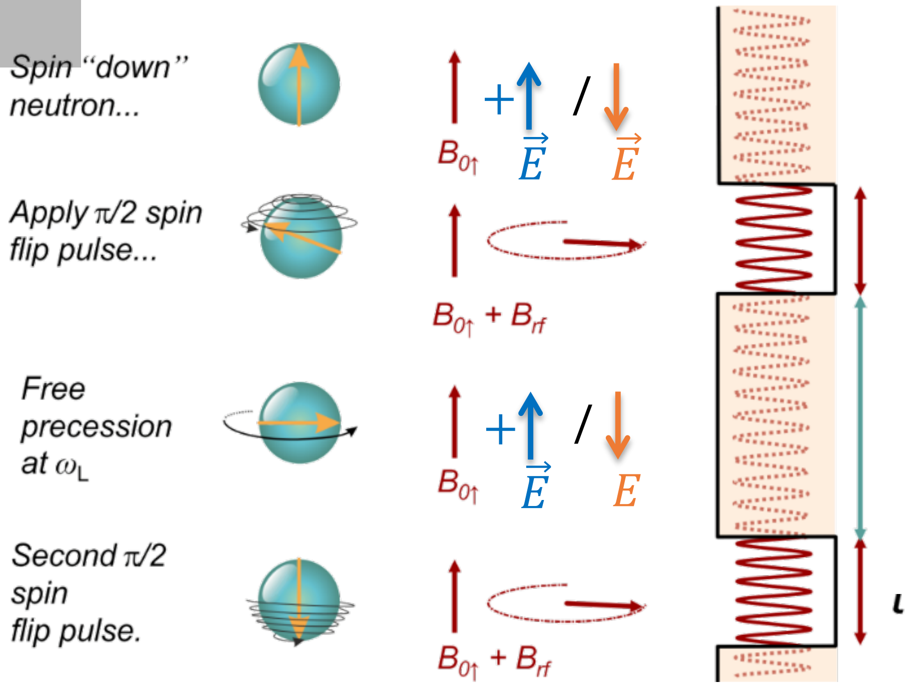


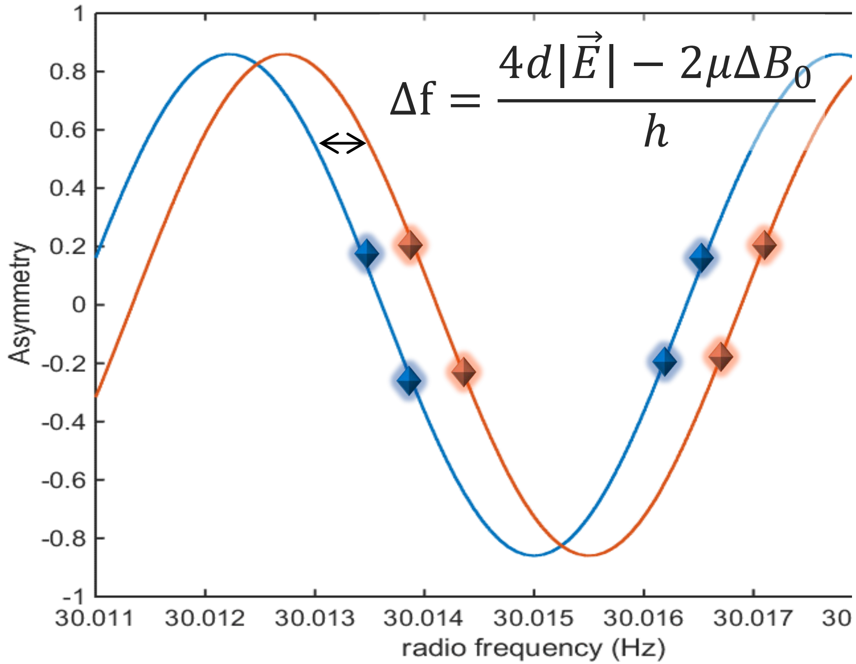
Sensitivity:

$$\sigma(f_{\mathrm{n}}) = \frac{1}{2\pi\alpha T\sqrt{N}}$$

α	Visibility of resonance
T	Time of free precession
N	Number of neutrons

Coupling of the spin to an electric field





$$\Delta f = \frac{4d|\vec{E}| - 2\mu\Delta B_0}{h}$$

$$\sigma(d_n) = \frac{\hbar}{2\alpha E T\sqrt{N}}$$

Sensitivity for an EDM

$$\sigma(d) \propto \frac{1}{PE\sqrt{NT}A}$$

P: Initial polarization

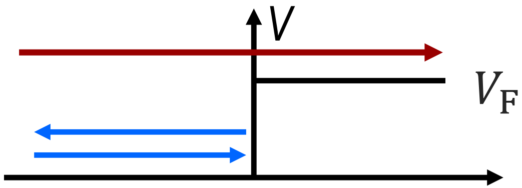
E: Electric field strength

N: Number of particles

T: *Observation time*

A: *Analyzing power*

Ultracold neutrons: good for $T\sqrt{N}$



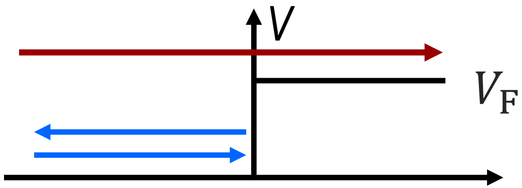
$$V_\mathrm{F} = \frac{2\pi\hbar}{m_\mathrm{n}}\, bN \leq 350\mathrm{neV}$$

(8m/s, 3mK)

Materials used at PSI:

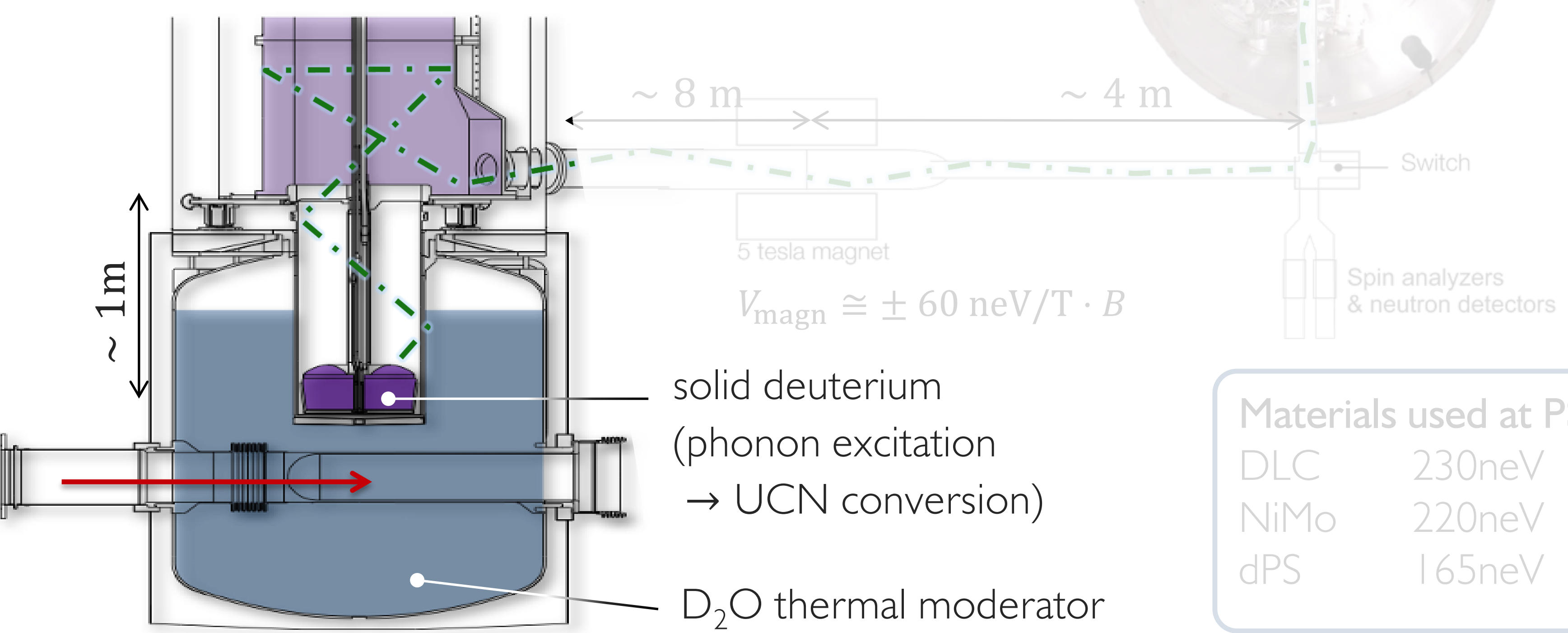
DLC	230neV
NiMo	220neV
dPS	165neV

Ultracold neutrons: good for $T\sqrt{N}$



$$V_F = \frac{2\pi\hbar}{m_n} bN \leq 350\text{neV}$$

$(8\text{m/s}, 3\text{mK})$



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DLC	230neV
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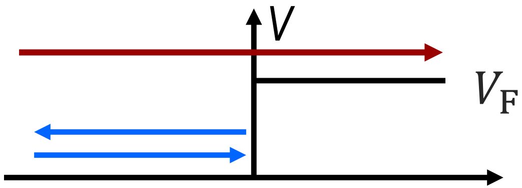
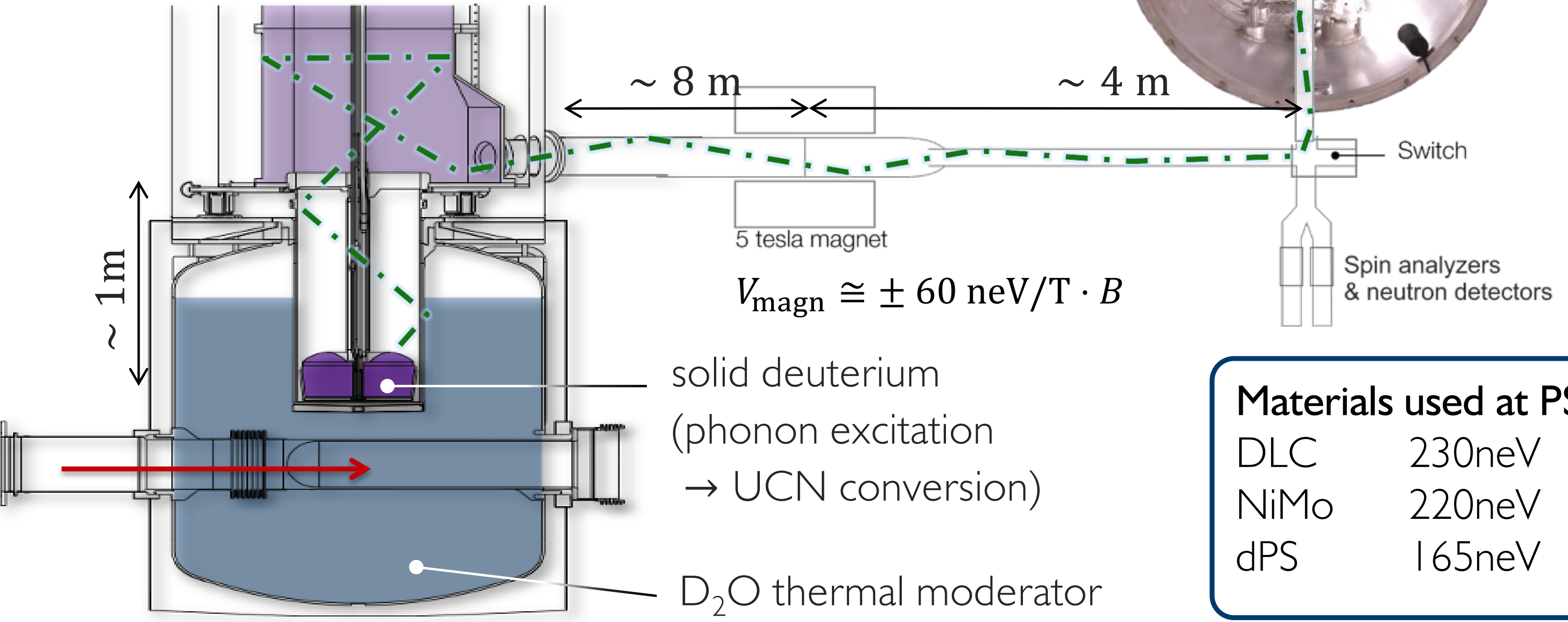
Ultracold neutrons: good for $T\sqrt{N}$



$$V_\mathrm{F} = \frac{2\pi\hbar}{m_\mathrm{n}}\, bN \leq 350\mathrm{neV}$$

(8m/s, 3mK)

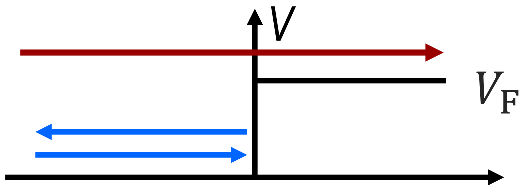


$$V_\mathrm{magn} \cong \pm\, 60\ \mathrm{neV/T} \cdot B$$

Materials used at PSI:

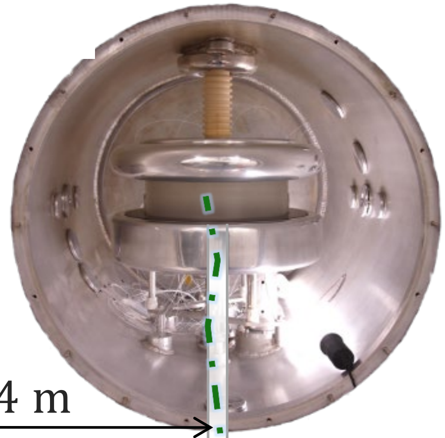
DLC	230neV
NiMo	220neV
dPS	165neV

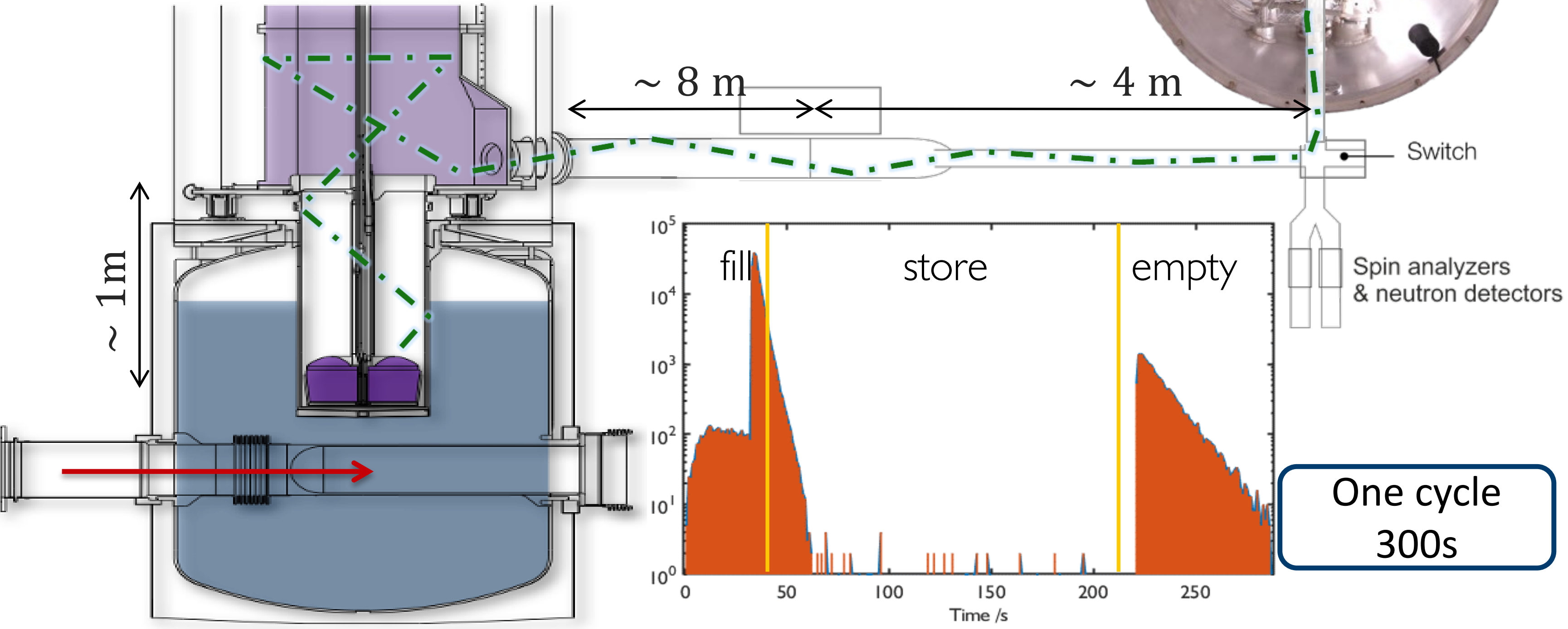
Ultracold neutrons: good for $T\sqrt{N}$



$$V_{\mathrm{F}} = \frac{2\pi\hbar}{m_{\mathrm{n}}} bN \leq 350\mathrm{neV}$$

(8m/s, 3mK)

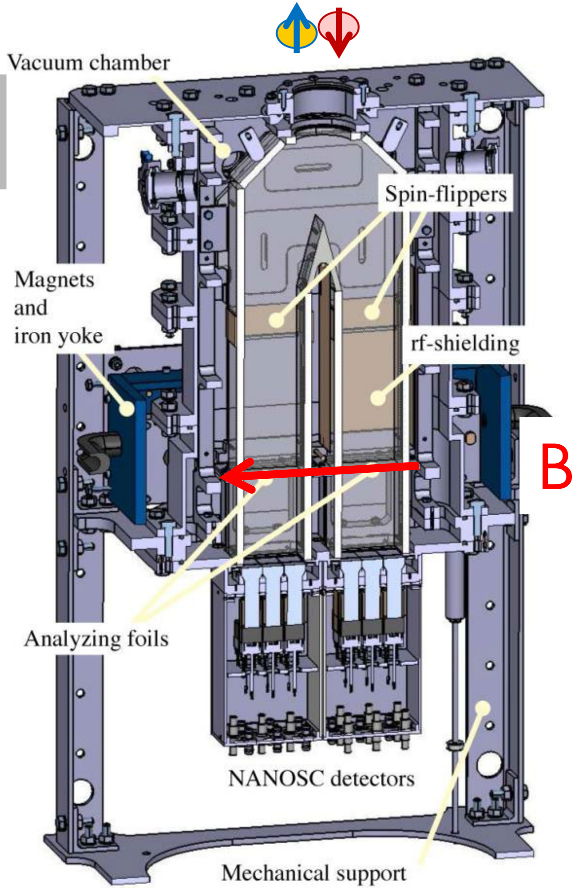




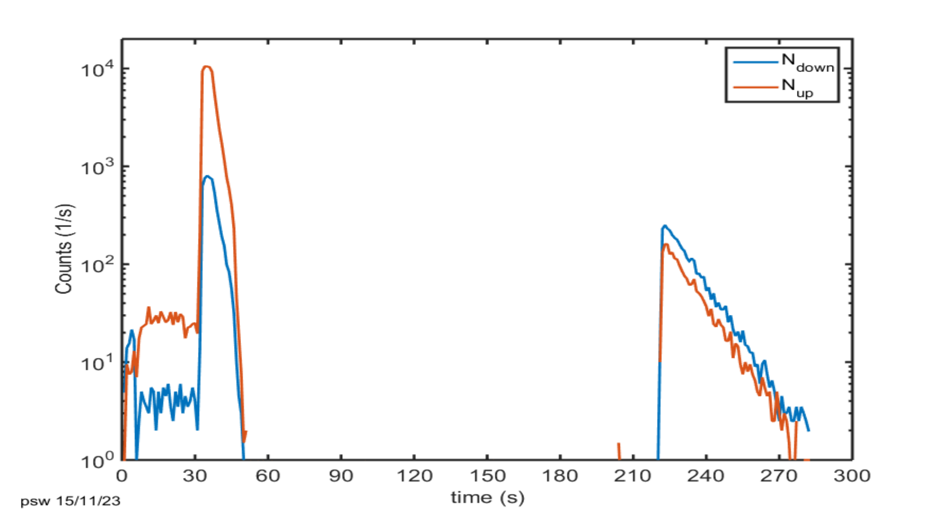
G. Bison et al. EPJA (2020) 56:33

Simultaneous spin detection

$$\sigma_{d_n} = \frac{\hbar}{2E\alpha T\sqrt{N}}$$



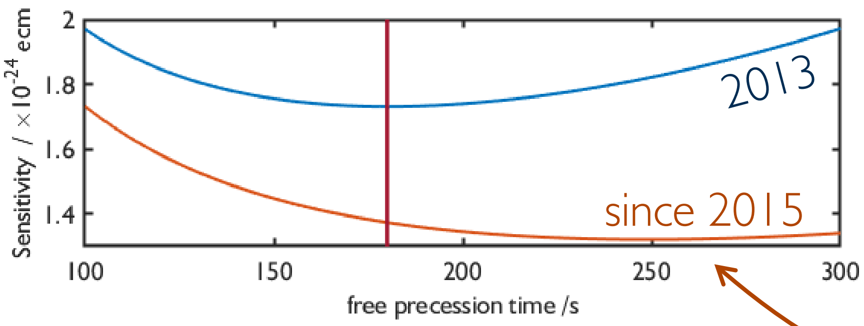
- Spin dependent detection
  - Adiabatic spinflipper
  - Iron coated foil
- ^{6}Li-doped scintillator GS20



S. Afach *et al.*, EPJA (2015)51: 143

Increasing sensitivity

One cycle 300s	Many cycle each 300s
$$\sigma(d_\mathrm{n}) = \frac{\hbar}{2\alpha T E\sqrt{N}}$$	$$\sigma(d_\mathrm{n}) = \frac{\hbar}{2\alpha T E\sqrt{NM}}$$



- $N_0 = 20000$
- $\tau_{s,f} = 180\mathrm{s},\ 80\mathrm{s}$
- $E = 11\ \mathrm{kV/cm}$
- $\alpha_0 = 0.99$

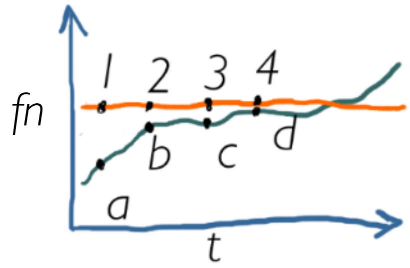
$T = 500\mathrm{s}, 1300\mathrm{s}$

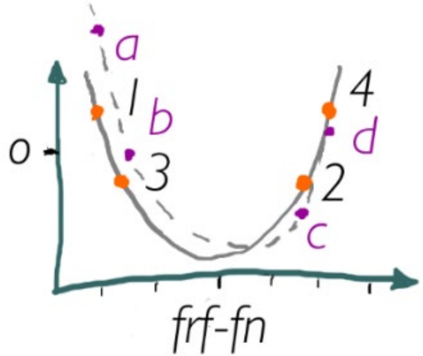
Sensitivity versus field drifts

- Sensitivity for many cycles ideal case:

$$\sigma(d_{\mathrm{n}}) = \frac{\hbar}{2\alpha T E \sqrt{NM}}$$

- Only if magnetic field is stable enough.
  (Good fit with orange,
  bad fit with purple)



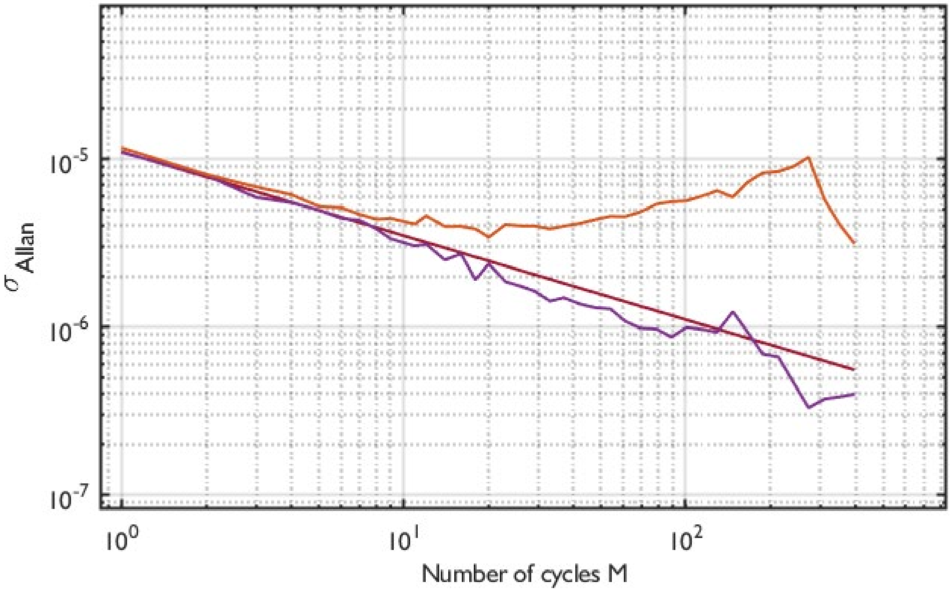


Stability and changing E-fields

$$\Delta f = \frac{4d_n|\vec{E}| - 2\mu\Delta B_0}{h}$$

Options with field changes:

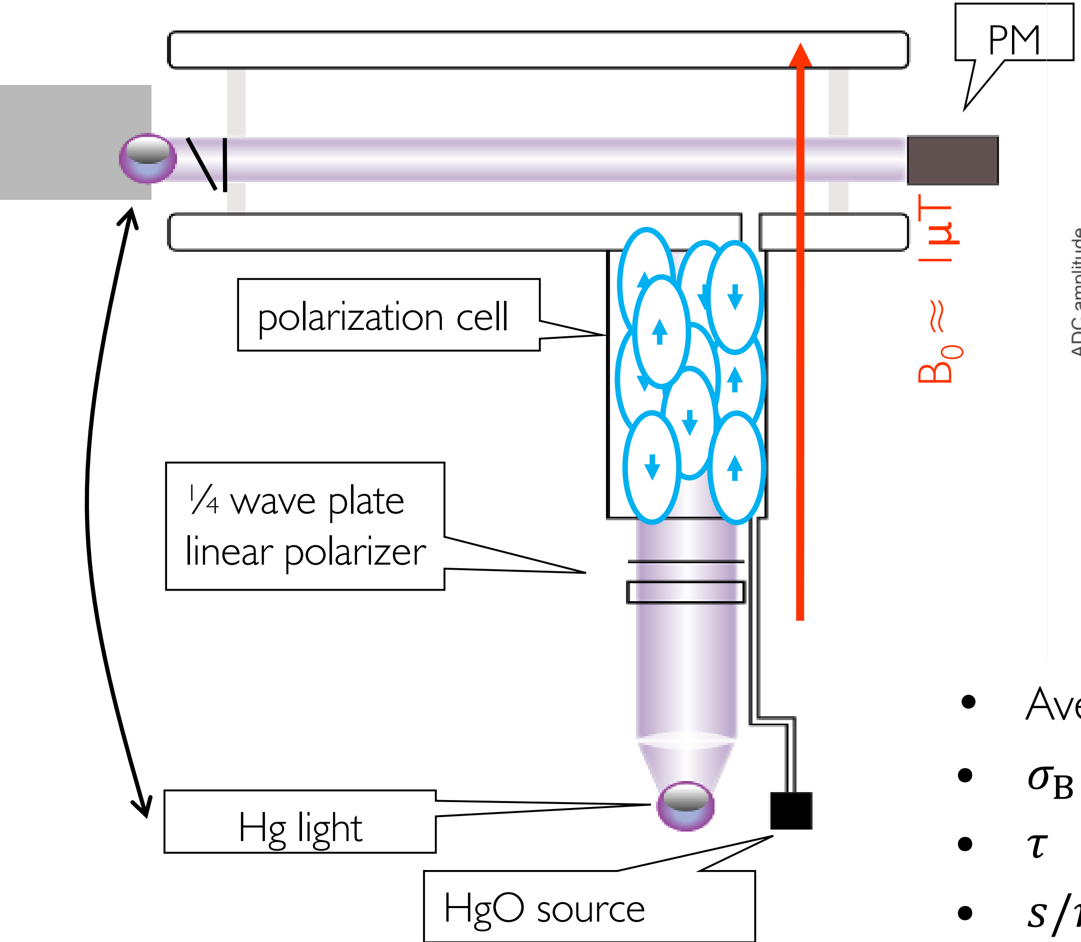
- Change E-field with adequate period (e.g. every 10 cycles) (loose time due to E ramps)
- Use a stack of two neutron precession chambers
- Use a comagnetometer

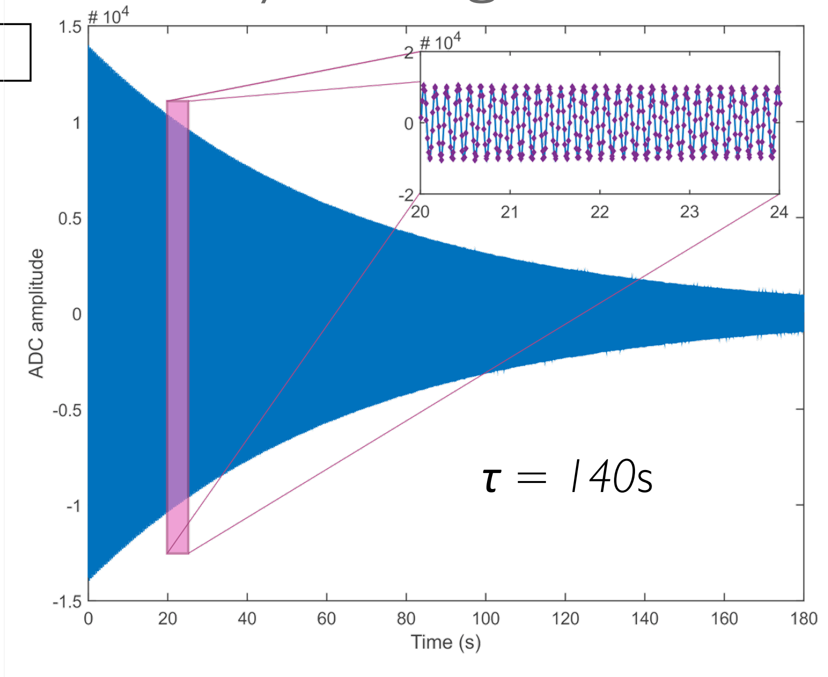


→ Gatchina's double chamber design

→ Sussex's co-magnetometer

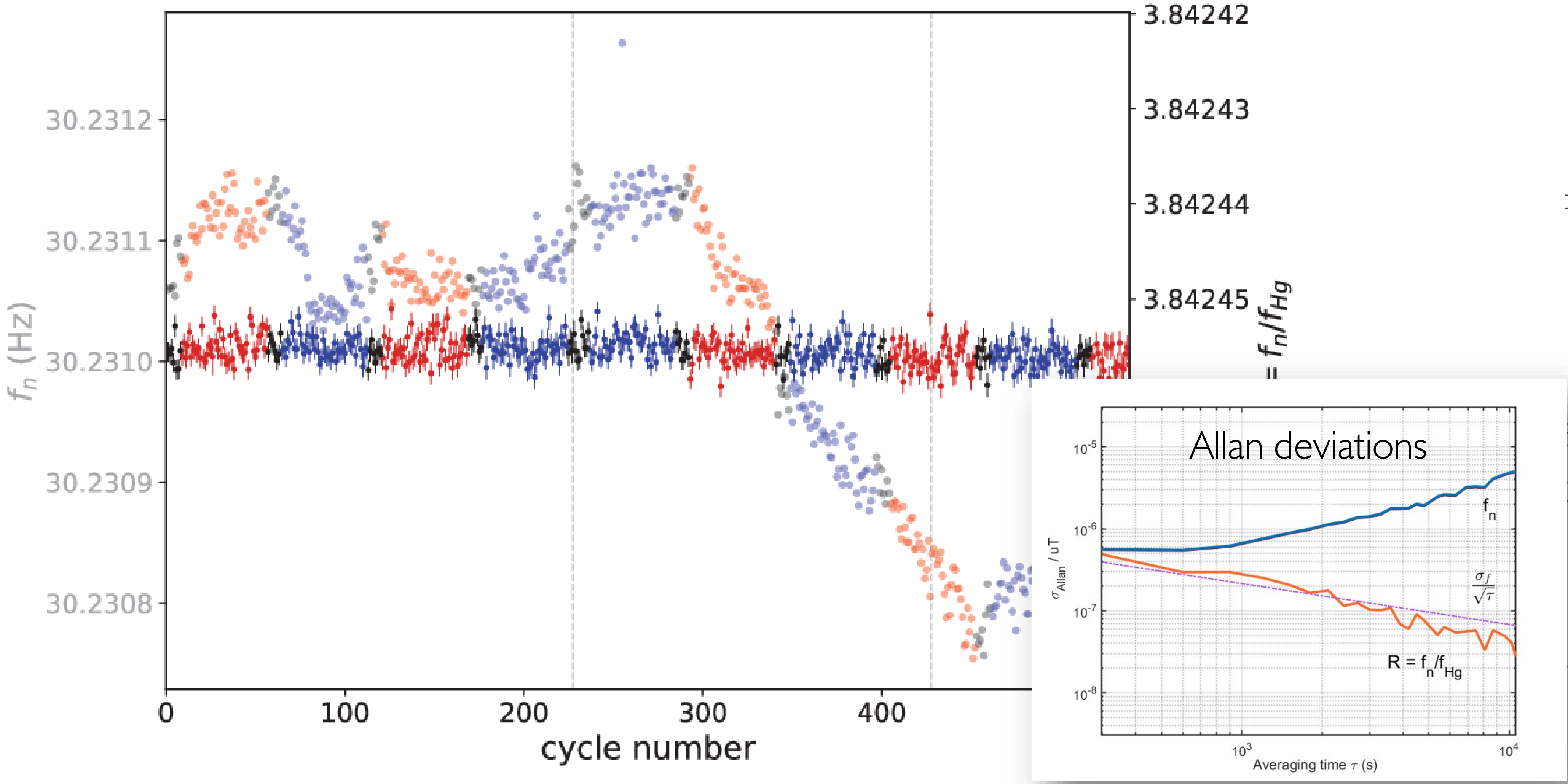
Mercury comagnetometer





- Average magnetic field (volume and cycle)
- $\sigma_B \leq 100$ fT (CR-limit)
- $\tau > 100$ s wo HV (with ~ 90 s)
- $s/n > 1000$

Real data example (stability)



Systematic effects

Table I: Summary of systematic effects in 10^{-28} $e$cm. The first three effects are treated within the crossing-point fit and are included in $d_\times$. The additional effects below the line are considered separately.

	Effect	shift	error
False Hg EDM	Error on $\langle z \rangle$	-	7
	Higher order gradients $\hat{G}$	69	10
	Transverse field correction $\langle B_T^2 \rangle$	0	5
Other effects	Hg EDM[8]	-0.1	0.1
	Local dipole fields	-	4
	$v \times E$ UCN net motion	-	2
	Quadratic $v \times E$	-	0.1
	Uncompensated G drift	-	7.5
	Mercury light shift	-	0.4
	Inc. scattering ^{199}Hg	-	7
	TOTAL		

Systematic effects (no free meals)

Express EDM with ratios:

$$\boldsymbol{d_{\mathrm{n}}} = \frac{\hbar\langle\boldsymbol{\omega_{\mathrm{Hg}}}\rangle}{\boldsymbol{4E}}(\boldsymbol{R_{+}} - \boldsymbol{R_{-}})$$

$$R_{\pm} = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}} = \left|\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\right|\left(1 \pm \delta_{\mathrm{EDM}} \pm \delta_{\mathrm{EDM}}^{\mathrm{false}} + \delta_{\mathrm{Q}} + \delta_{\mathrm{G}} + \delta_{\mathrm{T}} + \delta_{\mathrm{E}} + \delta_{\mathrm{LS}} + \delta_{\mathrm{I}} + \delta_{\mathrm{P}} + \delta_{AC}\right)$$

E-field | B-field | Secondary effects

- nEDM
- HgEDM

Linear effect $(v \times E)$
- "geometric phase"
- Ordered motion

Quadratic effect (neutron and Hg, random motion)

e.g. for $E = 0$ all E-field term are zero.
e.g. for B uniform all B-field terms are zero.

Secondary effects cancel unless correlated with E-field.

$v \times E$ the dominant systematic

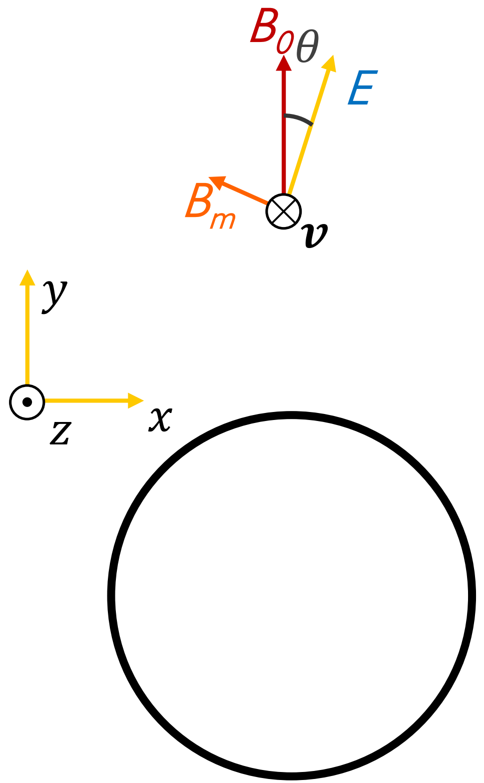
- Motional magnetic field from $B_\mathrm{m} = -\frac{v \times E}{c^2}$
- Naively no contribution as $\bar{v} = 0$ for UCN?
- In non-uniform B-field and E-field:

Rabi: Spin rotation due to oscillating horizontal field. This leads to a shift (Ramsey, Bloch, Siegert) of the resonance frequency by

$$\Delta\omega = \frac{(\gamma_n B_\perp)^2}{2(\gamma_\mathrm{n} B_0 - \omega_r)}$$

with

$$B_\perp = \frac{\partial B_z}{\partial z}\frac{r}{2} + \frac{v_r E}{c^2}$$



and the oscillation ω_r is a result of rapidly changing trajectories, e.g. $\omega_r = v_r/2R$

J.M. Pendlebury et al., **PRA** 70 (2004) 032102
G. Pignol and S. Roccia, **PRA** 85 (2012) 042105

$v \times E$ the dominant systematic

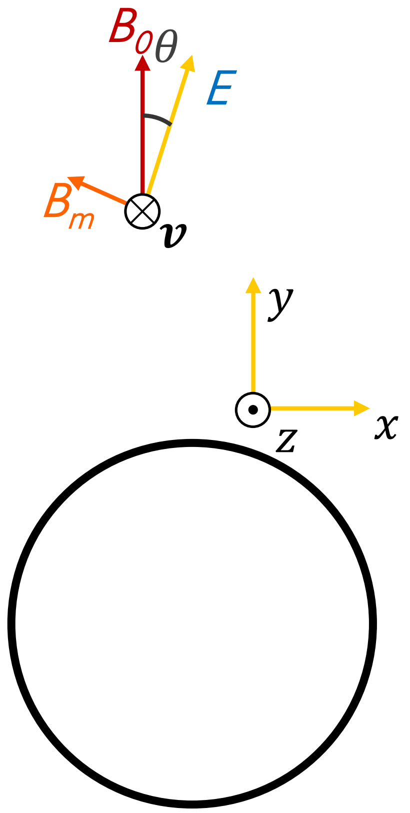
- Motional magnetic field from $B_\mathrm{m} = -\frac{v \times E}{c^2}$
- In non-uniform B-field and E-field:

$$B_\perp^2 = \left(\frac{\partial B_z}{\partial z}\frac{r}{2}\right)^2 + r\frac{\partial B_z}{\partial z}\frac{v_r E}{c^2} + \left(\frac{v_r E}{c^2}\right)^2$$

- The term linear in E will lead to a electric field induced shift of precession frequency, **an EDM like signal.**

$$\Delta\omega_\mathrm{f} = r\frac{\partial B_z}{\partial z}\frac{v_r E}{2c^2(\gamma_\mathrm{n} B_0 - \omega_r)}$$

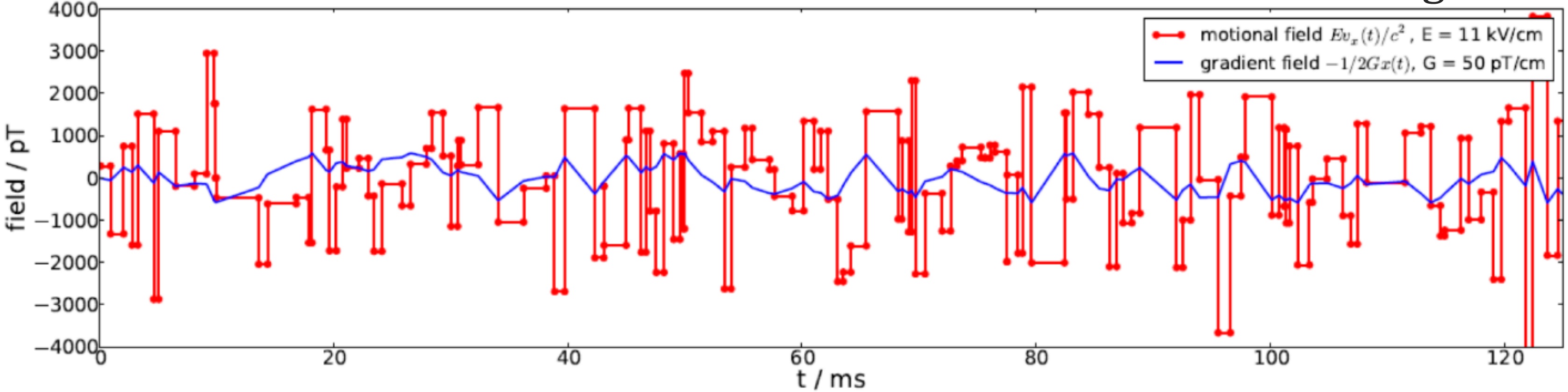
Different for neutrons (adiabatic), and mercury (ballistic/non-adiabatic)



J. M. Pendlebury et al., PRA 70 (2004) 032102

Motional false effect from ^{199}Hg

The dominant effect is transferred from ^{199}Hg to neutron: $d^{\text{false}}_{\text{n}\leftarrow\text{Hg}}$



$$d^{\text{false}}_{\text{n}\leftarrow\text{Hg}} = \frac{\hbar\gamma_{\text{n}}\gamma_{\text{Hg}}}{2c^2}\langle xB_x + yB_y\rangle$$
$$= \frac{\hbar\gamma_{\text{n}}\gamma_{\text{Hg}}}{32c^2} D^2 G_{1,0}$$

with
D = 47cm

$$d^{\text{false}}_{\text{n}\leftarrow\text{Hg}} = G_{1,0}\, 4.4\times 10^{-27} e\,\frac{\text{cm}^2}{\text{pT}}$$

G. Pignol and S. Roccia, **PRA** 85 (2012) 042105
Guillaume Pignol, **PLB** 793 (2019) 440

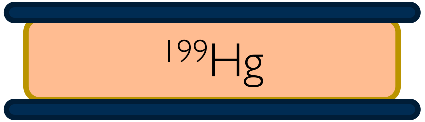
PAUL SCHERRER INSTITUT PSI

Use R-value as proxy for $G_{1,0}$

- Center of mass offset
- Non-adiabaticity

$$R_{\pm} = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}} = \left|\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\right| \left(1 \pm \delta_{\mathrm{EDM}} \pm \delta_{\mathrm{EDM}}^{\mathrm{false}} + \delta_{\mathrm{Q}} + \delta_{\mathrm{G}} + \delta_{\mathrm{T}} + \delta_{\mathrm{E}} + \delta_{\mathrm{LS}} + \delta_{\mathrm{I}} + \delta_{\mathrm{P}} + \delta_{AC}\right)$$

$\frac{\gamma_{\mathrm{Hg}}}{2\pi} \approx 8$ Hz/μT

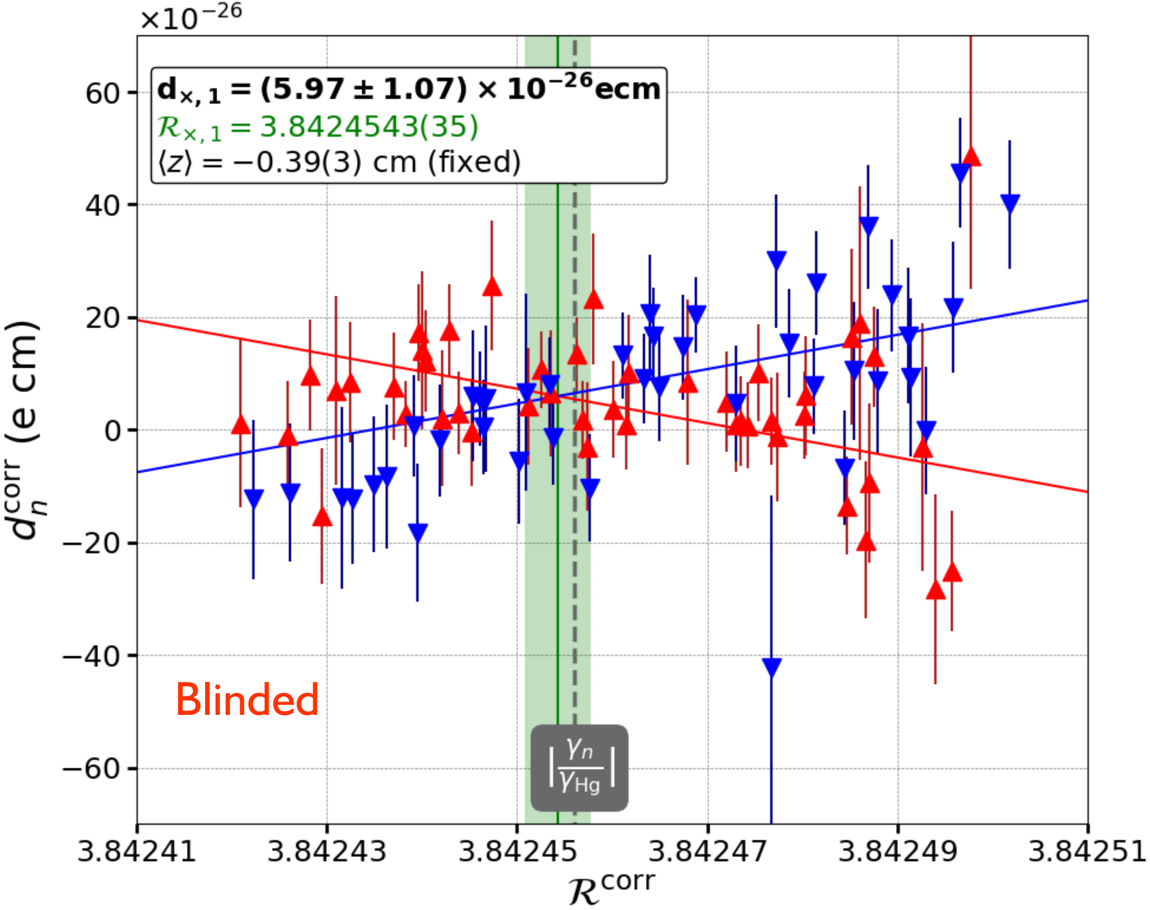


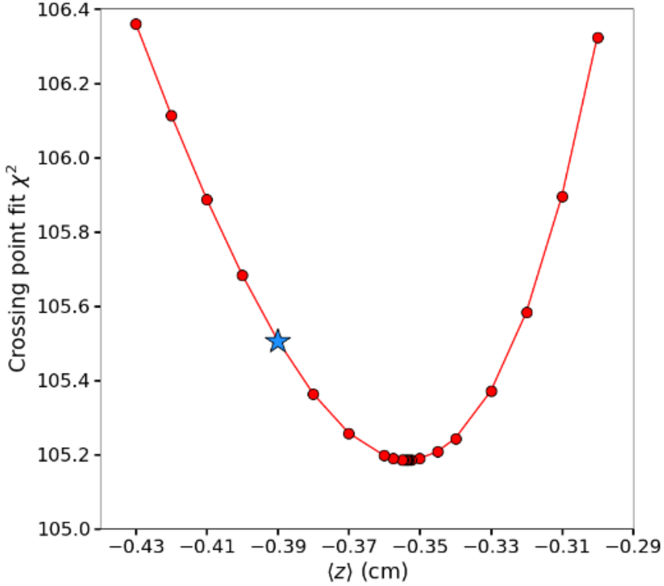
$\frac{\gamma_{\mathrm{n}}}{2\pi} \approx 30$ Hz/μT

$\overline{v_{\mathrm{Hg}}} \approx 160$ m/s vs. $\overline{v_{\mathrm{UCN}}} \approx 3$ m/s

$$R \cdot \left|\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\right| - 1 = \delta_{\mathrm{G}} = \pm \frac{\langle z \rangle G_{1,0}}{B_0}$$

Crossing point analysis





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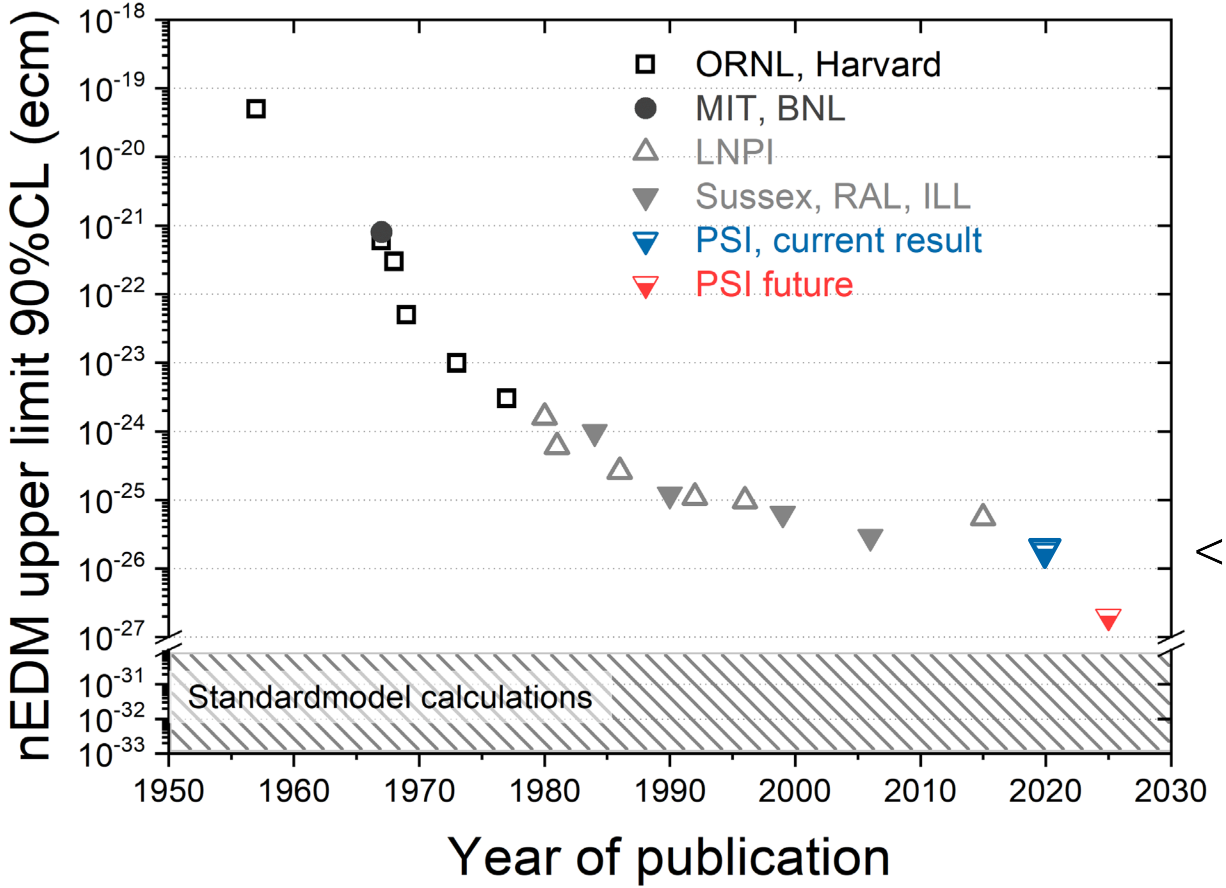
New Result (PSI)

Previous result (ILL), J.M. Pendlebury *et al*, Phys. Rev. D **92** 092003 (2015)

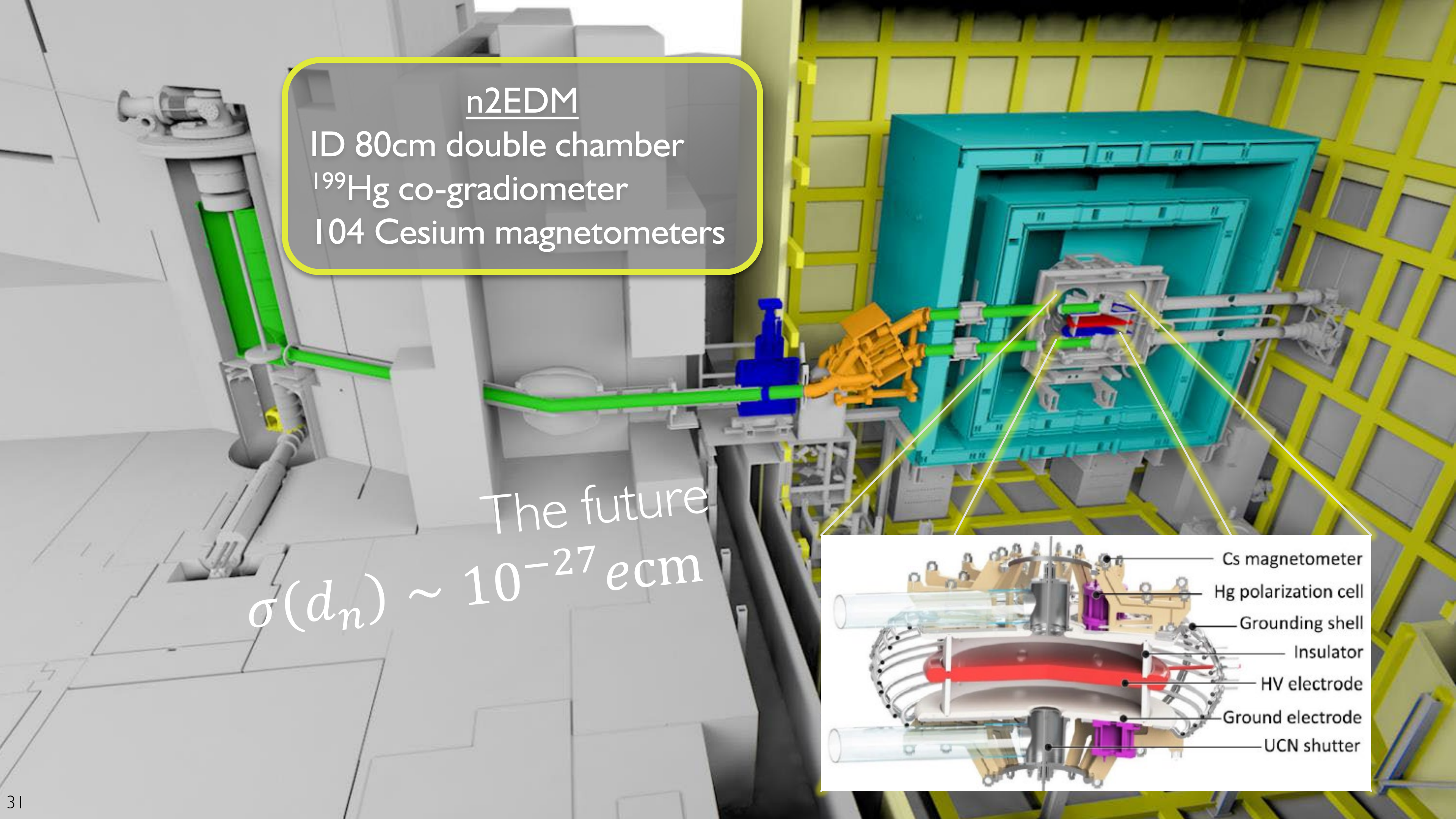
$$d_n = \left(-0.2 \pm 1.5_{\text{stat}} \pm 1.0_{\text{syst}}\right) \times 10^{-26}\ e\text{cm}$$

$$d_n = \left(\ 0.0\ \pm\ 1.1_{\text{stat}}\ \pm\ 0.2_{\text{syst}}\right) \times 10^{-26}\ e\text{cm}$$

The new limit



$< 1.8 \times 10^{-26} e\text{cm}$



n2EDM

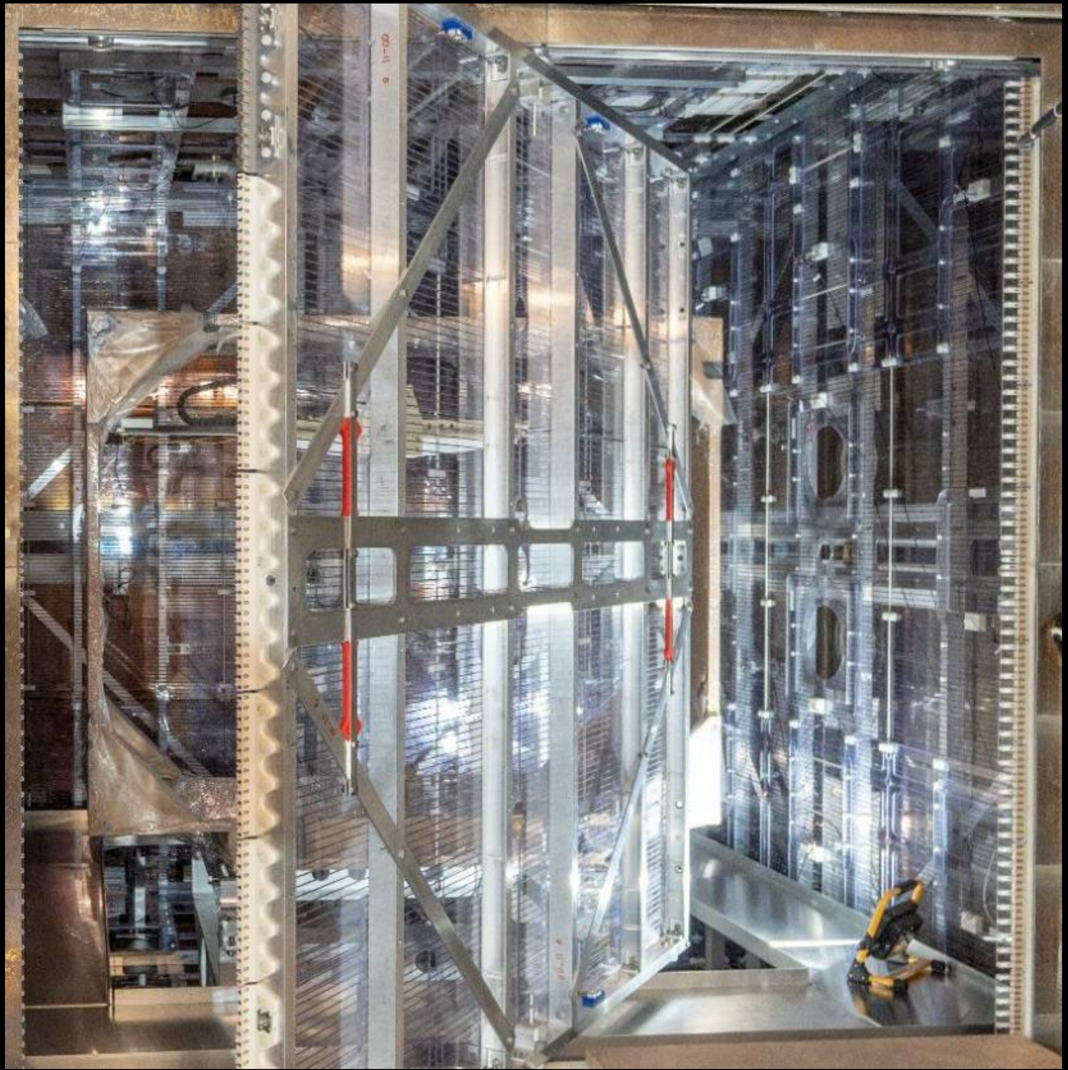
ID 80cm double chamber

^{199}Hg co-gradiometer

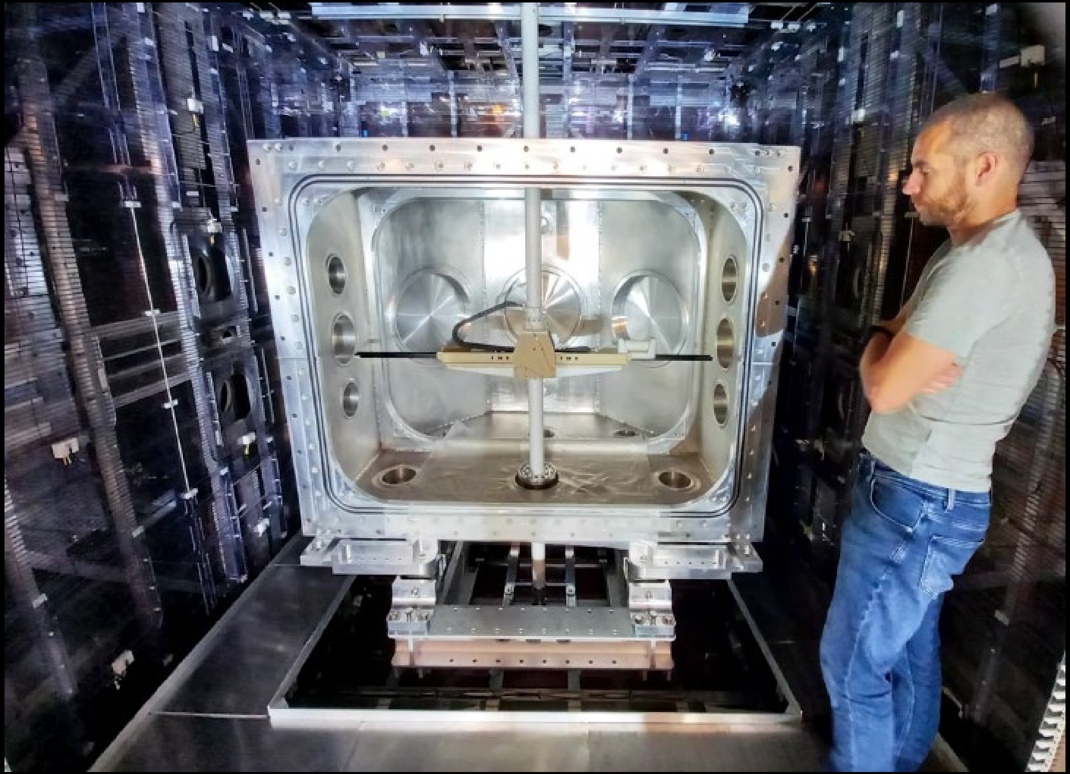
104 Cesium magnetometers

The future

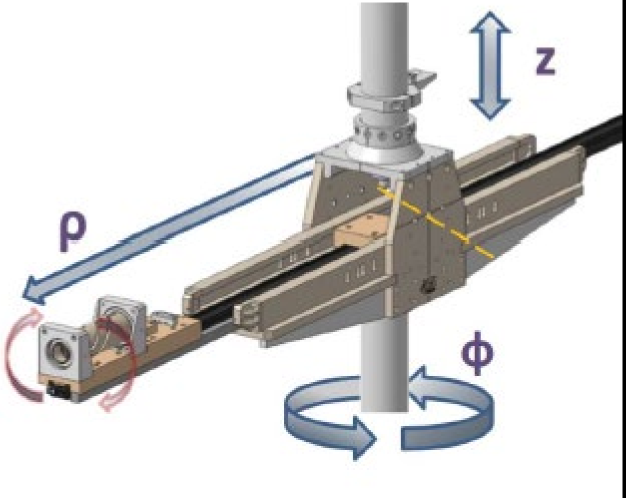
$\sigma(d_n) \sim 10^{-27}\, ecm$



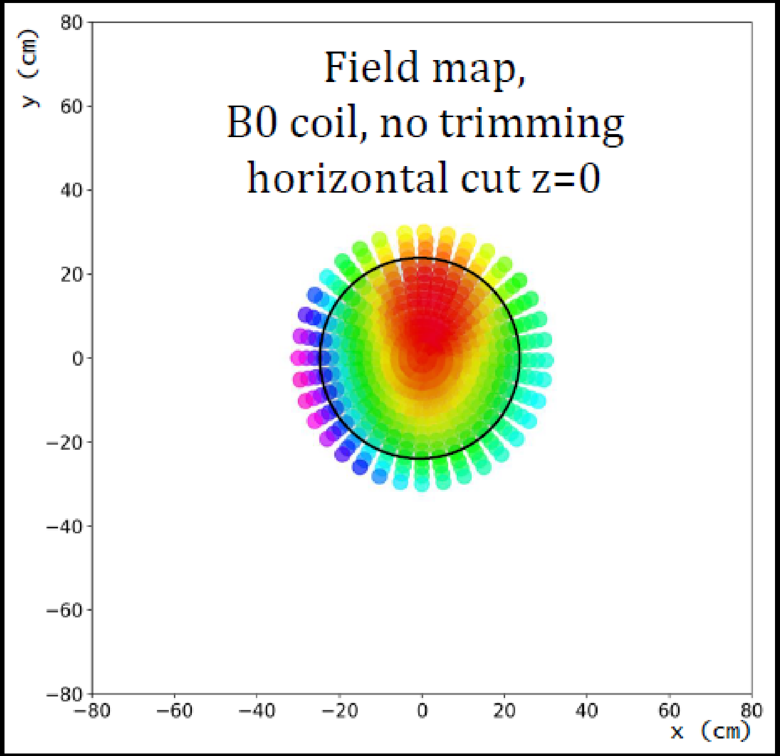
Commissioning of the magnetic field

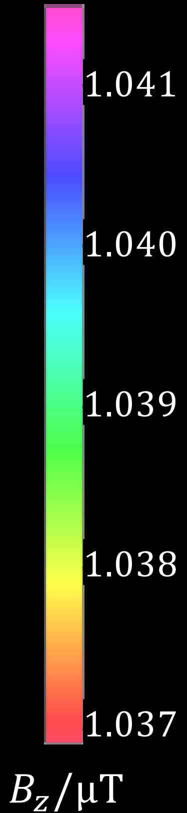


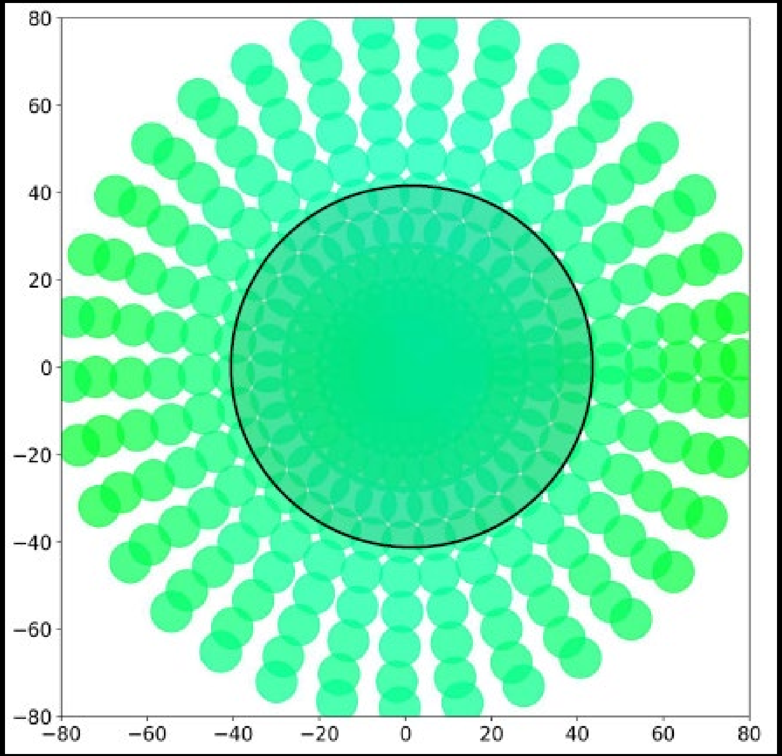
High precision magnetic field mapping using a fluxgate sensor mounted on a three axis robot.



Excellent magnetic-field uniformity







nEDM 2017 $\sigma(B_z) = 900\text{pT}$

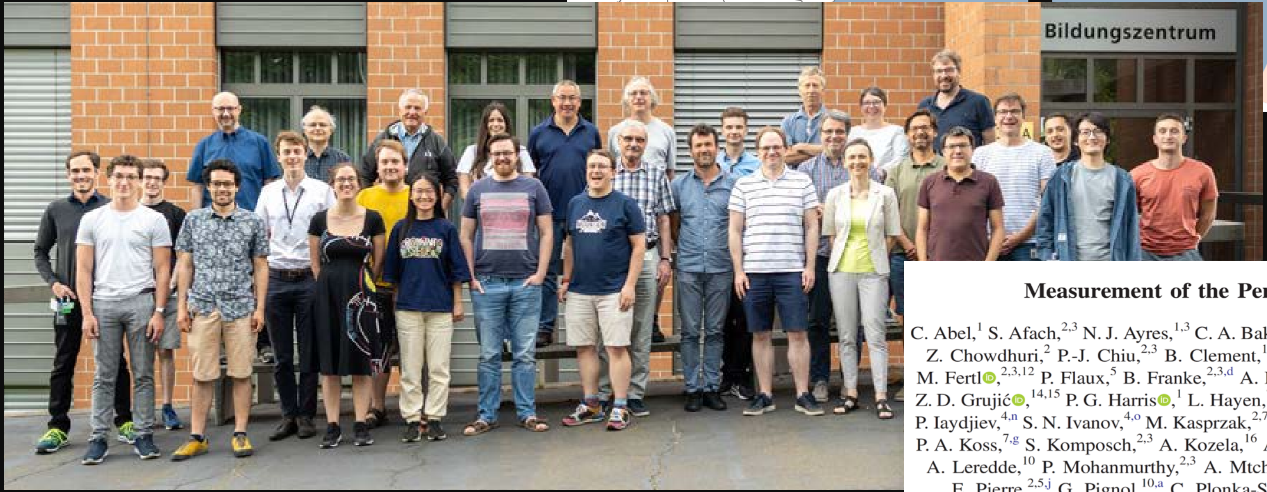
In the precession chamber Ø 47 cm

n2EDM 2022 $\sigma(B_z) \leq 60\text{pT}$

In the precession chamber Ø 80 cm

The collaboration

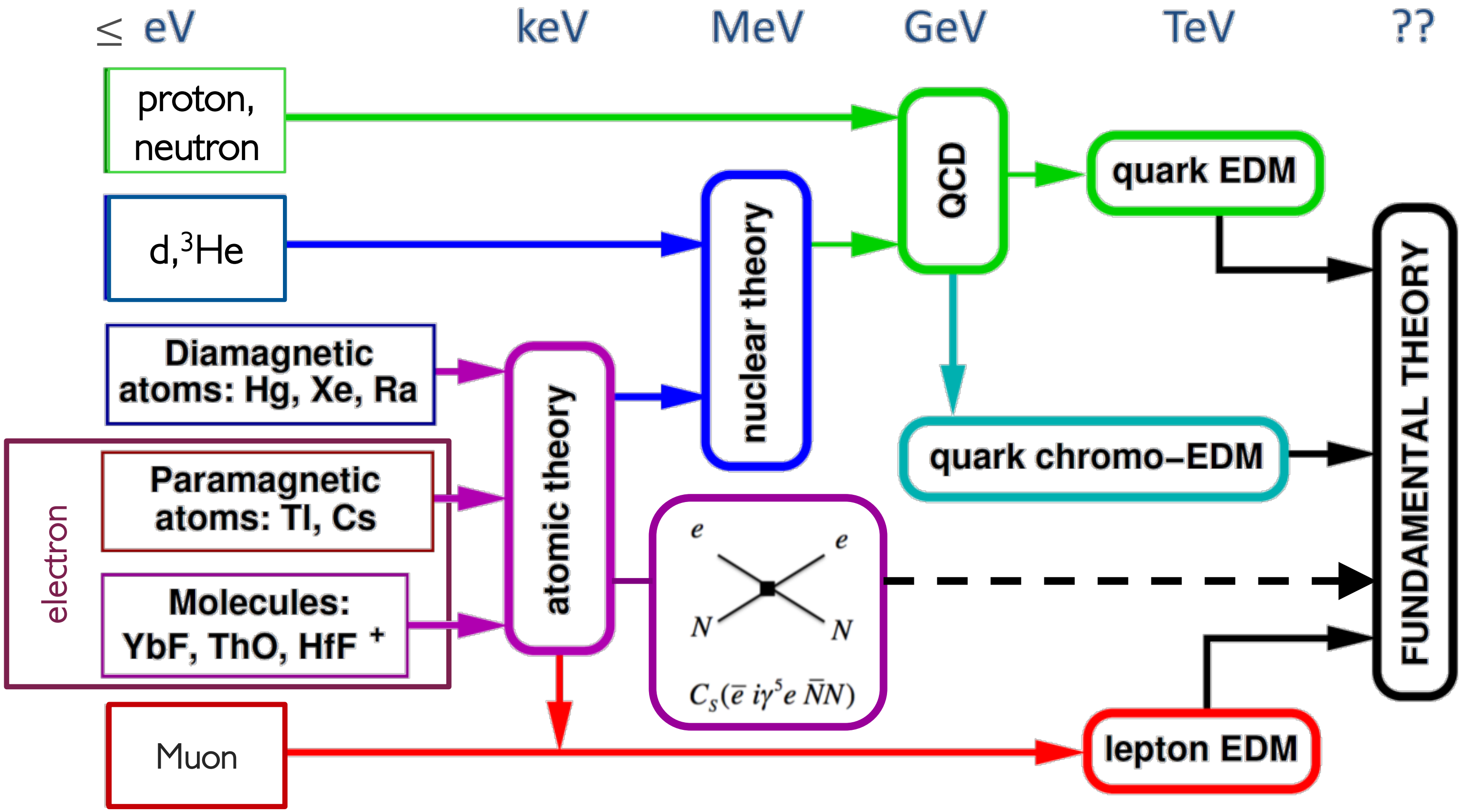
- 16 Institutions
- 8 Countries
- 84 authors
- 34 PhD degrees



Measurement of the Permanent Electric Dipole Moment of the Neutron

C. Abel,[1] S. Afach,[2,3] N. J. Ayres,[1,3] C. A. Baker,[4] G. Ban,[5] G. Bison,[2] K. Bodek,[6] V. Bondar,[2,3,7] M. Burghoff,[8] E. Chanel,[9] Z. Chowdhuri,[2] P.-J. Chiu,[2,3] B. Clement,[10] C. B. Crawford,[11] M. Daum,[2] S. Emmenegger,[3] L. Ferraris-Bouchez,[10] M. Fertl,[2,3,12] P. Flaux,[5] B. Franke,[2,3,d] A. Fratangelo,[9] P. Geltenbort,[13] K. Green,[4] W. C. Griffith,[1] M. van der Grinten,[4] Z. D. Grujić,[14,15] P. G. Harris,[1] L. Hayen,[7,e] W. Heil,[12] R. Henneck,[2] V. Hélaine,[2,5] N. Hild,[2,3] Z. Hodge,[9] M. Horras,[2,3] P. Iaydjiev,[4,n] S. N. Ivanov,[4,o] M. Kasprzak,[2,7,14] Y. Kermaidic,[10,f] K. Kirch,[2,3] A. Knecht,[2,3] P. Knowles,[14] H.-C. Koch,[2,14,12] P. A. Koss,[7,g] S. Komposch,[2,3] A. Kozela,[16] A. Kraft,[2,12] J. Krempel,[3] M. Kuźniak,[2,6,h] B. Lauss,[2] T. Lefort,[5] Y. Lemière,[5] A. Leredde,[10] P. Mohanmurthy,[2,3] A. Mtchedlishvili,[2] M. Musgrave,[1,i] O. Naviliat-Cuncic,[5] D. Pais,[2,3] F. M. Piegsa,[9] E. Pierre,[2,5,j] G. Pignol,[10,a] C. Plonka-Spehr,[17] P. N. Prashanth,[7] G. Quéméner,[5] M. Rawlik,[3,k] D. Rebreyend,[10] I. Rienäcker,[2,3] D. Ries,[2,3,17] S. Roccia,[13,18,b] G. Rogel,[5,l] D. Rozpedzik,[6] A. Schnabel,[8] P. Schmidt-Wellenburg,[2,c] N. Severijns,[7] D. Shiers,[1] R. Tavakoli Dinani,[7] J. A. Thorne,[1,9] R. Virot,[10] J. Voigt,[8] A. Weis,[14] E. Wursten,[7,m] G. Wyszynski,[3,6] J. Zejma,[6] J. Zenner,[2,17] and G. Zsigmond[2]

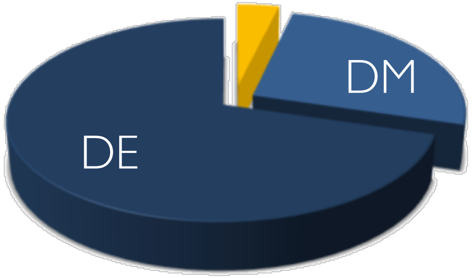
Complementarity of EDM searches



Scheme: adapted from Rob G. E. Timmermans

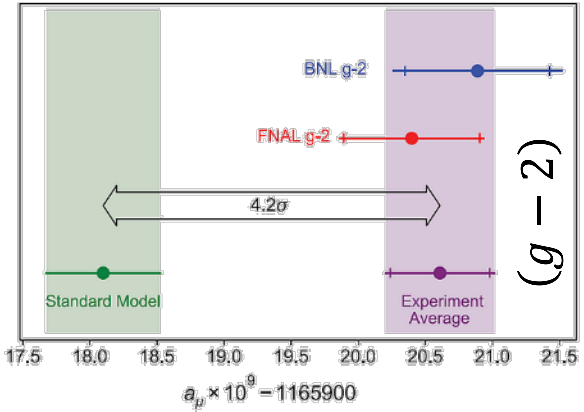
CP violation

– Matter/Antimatter imbalance (BAU)
– Constituencies of dark matter (axions)
– Natural in many BSM theories



Laboratory hints for NP

- Muon g-2 $4.2\ \sigma$
- LFUV in B decays
  – Semileptonic decays combined: $> 5\sigma$



Possible evidence for NP in muons ?

EFT analysis of contributions to F2 and F3

magnetic-dipole

Anapole - moment

$$\langle p'|J_\mu^{\mathrm{EM}}|p\rangle = \bar{\Psi}(p')\left[F_1\gamma_\mu + \frac{iF_2}{2M}\sigma_{\mu\nu}q^\nu + \frac{iF_3}{2M}\sigma_{\mu\nu}\gamma_5 q^\nu + \frac{F_4}{M^2}(q^2\gamma_\mu - \gamma^\mu q_\mu q_\mu)\right]\Psi(p)$$

charge

electric-dipole

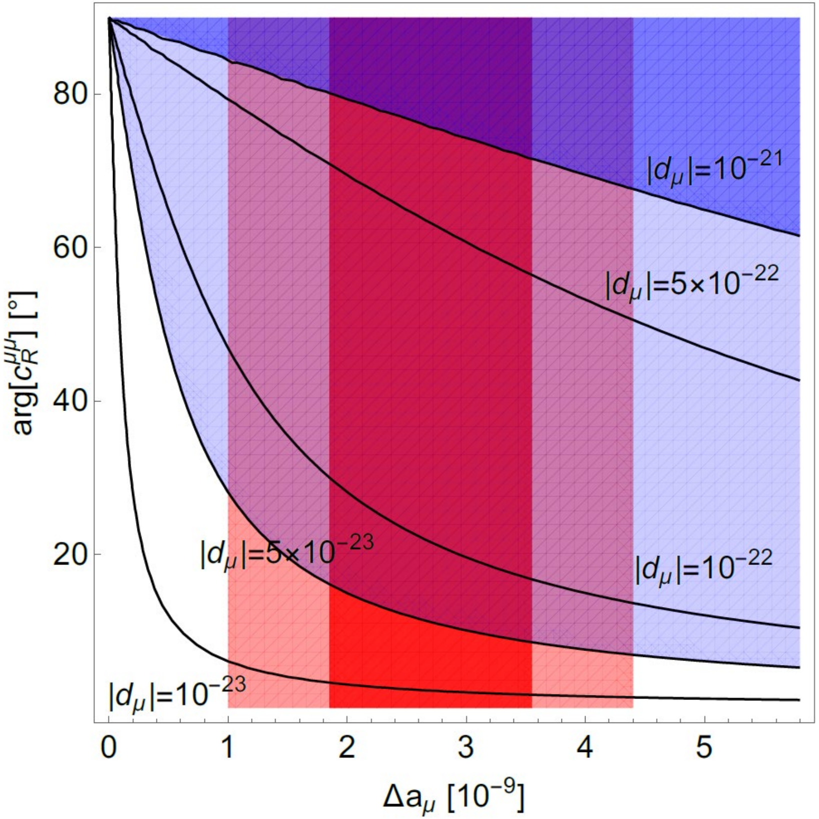
Effective Hamiltonian:

$$\mathcal{H}_{\mathrm{eff}} = c_R^{\ell_f\ell_i}\,\bar{\ell}_f\sigma_{\mu\nu}P_R\ell_i F^{\mu\nu} + \mathrm{h.c.}$$

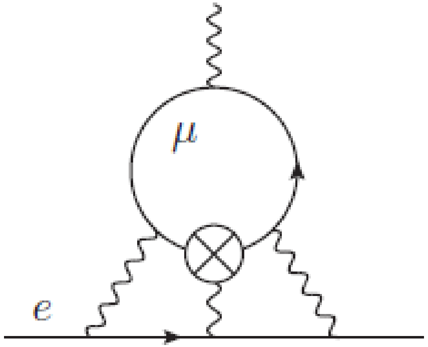
$$\delta F_2 = a_{\ell_i} = -\frac{2m_{\ell_i}}{e}\left(c_R^{\ell_i\ell_i} + c_R^{\ell_i\ell_i*}\right) = -\frac{4m_{\ell_i}}{e}\,\mathrm{Re}\,c_R^{\ell_i\ell_i}$$

$$F_3 = d_{\ell_i} = i\left(c_R^{\ell_i\ell_i} - c_R^{\ell_i\ell_i*}\right) = -2\,\mathrm{Im}\,c_R^{\ell_i\ell_i},$$

General limits on μEDM in flavor violating models



- EFT phase of Wilson parameter $c_R^{\mu\mu}$ hardly constraint



- μEDM contribution in electron EDM allows for large value: $d_\mu \leq 7.5 \times 10^{-19}\, e\mathrm{cm}$

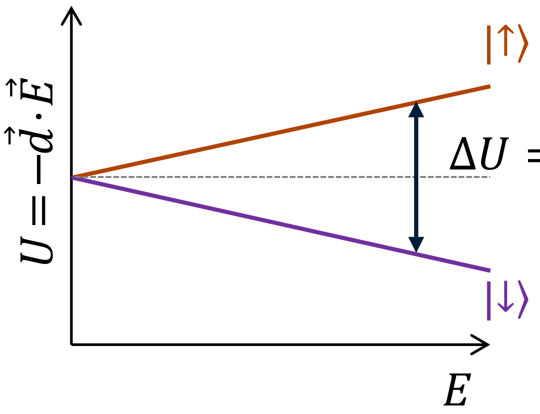
A.Crivellin, M. Hoferichter, PSW PRD 98(2018) 113002

PAUL SCHERRER INSTITUT PSI

Frequencies, state of the art, and the frozen spin

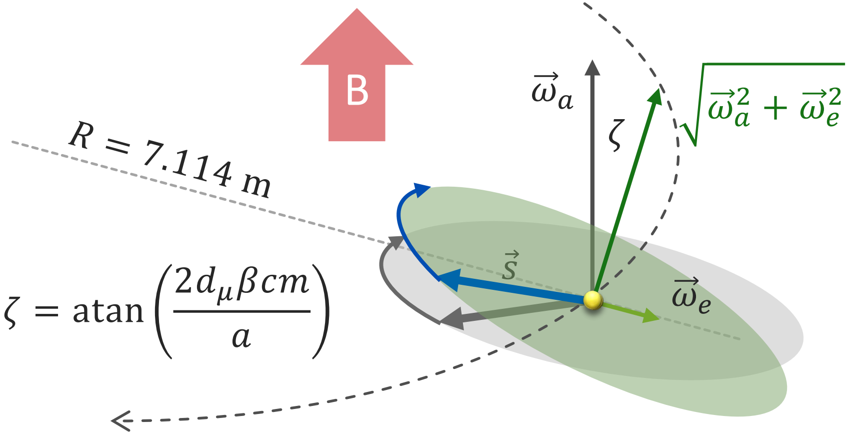
$$\vec{\omega} = \vec{\omega}_c - \vec{\omega}_L = -\frac{q}{m}\left[a\vec{B} + \left(\frac{1}{\gamma^2 - 1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

g-2 term ω_a



$\sigma(d_\mu) \approx 10^{-21} e\text{cm}$

FNAL* & JPARC**



$\zeta = \text{atan}\left(\frac{2d_\mu\beta cm}{a}\right)$

[*Chislett et al., EPJConf.**118** 01005(2016), **Abe et al., PTEP053C02 (2019)]

State of the art and the frozen spin*

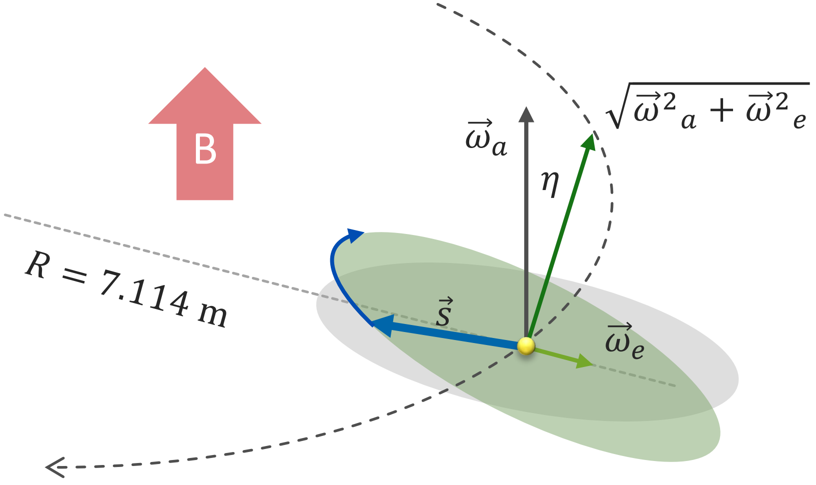
$$\vec{\omega} = -\frac{q}{m}\left[a\vec{B} + \left(\frac{1}{1-\gamma^2} - a\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{2d_\mu mc}{q\hbar}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right]$$

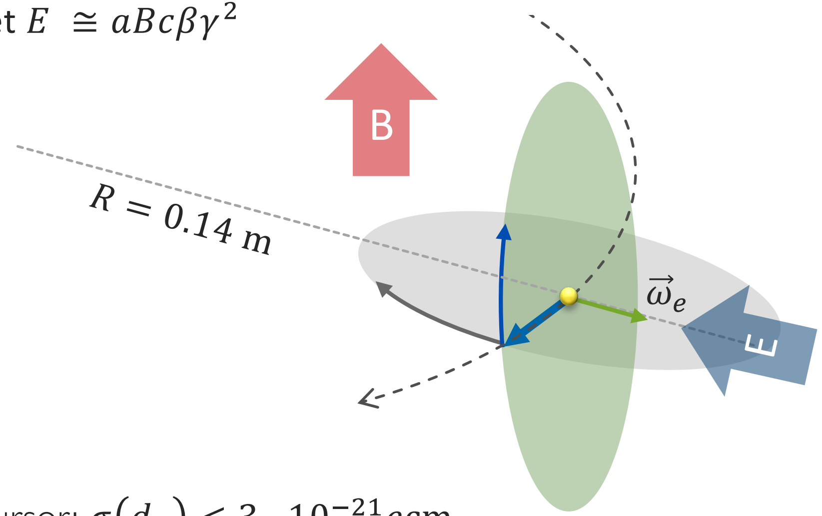
g-2 term ω_a EDM term ω_e

FNAL & JPARC $\sigma(d_\mu) \approx 10^{-21} ecm$

Frozen spin at PSI: $\sigma(d_\mu) < 6 \cdot 10^{-23} ecm$

set $E \cong aBc\beta\gamma^2$

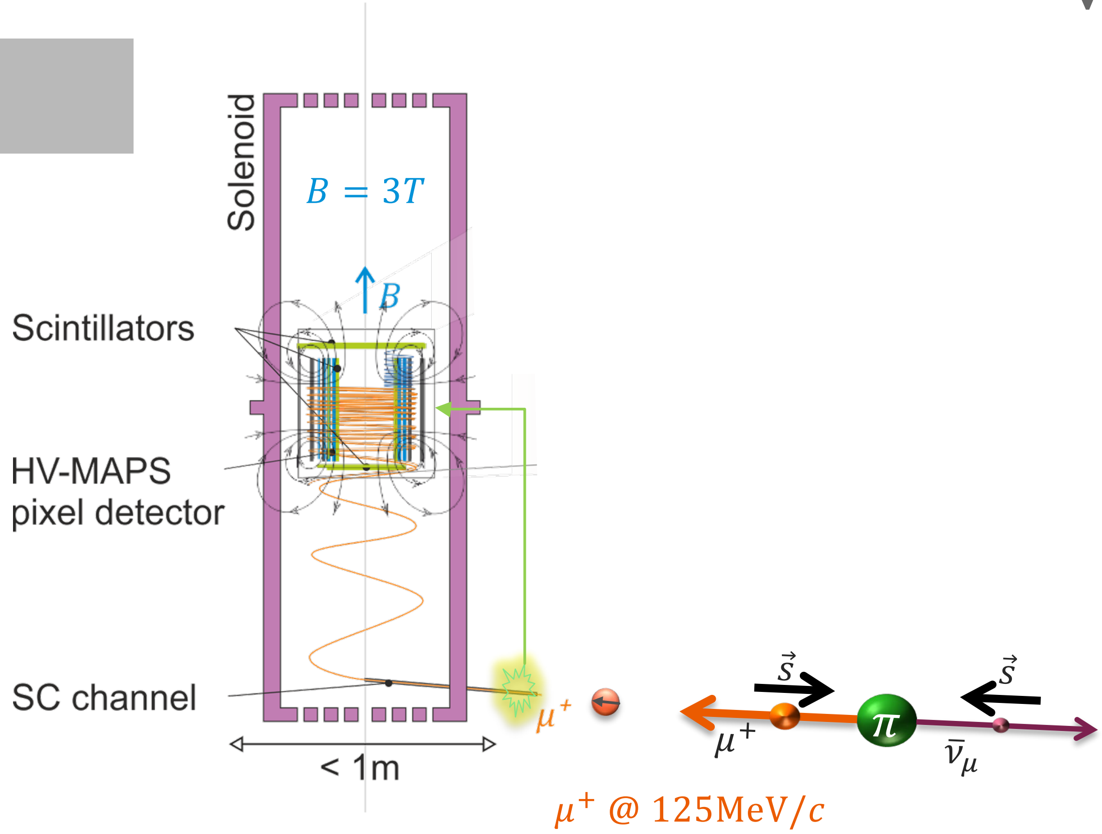




Prescursor: $\sigma(d_\mu) < 3 \cdot 10^{-21} ecm$

[*Farley et al,, PRL93 042001 (2004)] ,

Search for a muEDM using the frozen spin with longitudinal injection

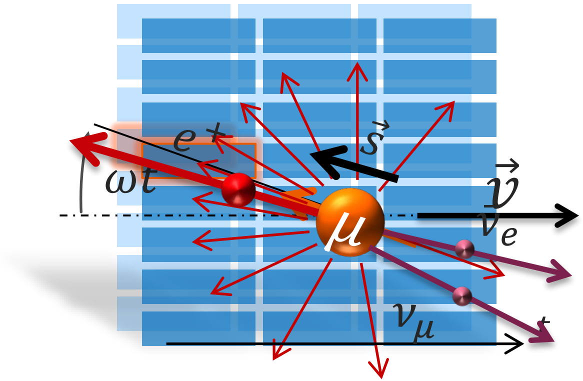


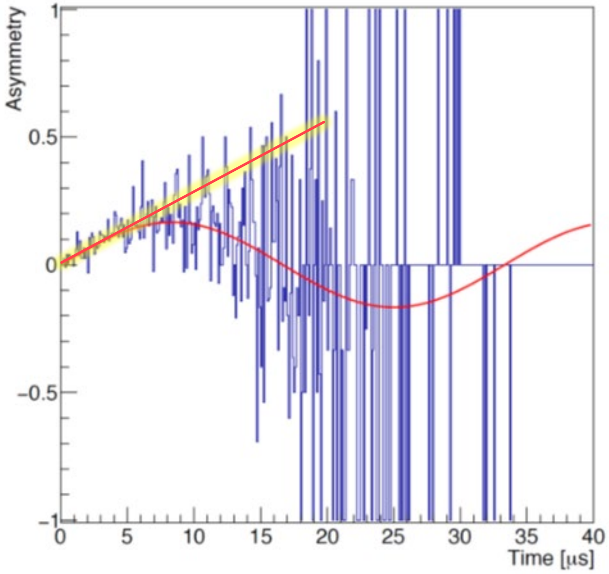
- μ^+ from Pion-decay → high polarization $p \approx 95\%$
- Injection through superconducting channel
- Fast scintillator triggers pulse
- Magnetic pulse stops longitudinal motion of μ^+
- Weakly focusing field for storage
- Thin electrodes provide electric field for frozen spin
- Pixelated detectors for e^+- tracking

Signal: asymmetry up/downwards tracks with time

Positrons are emitted dominantly along the spin direction

$$A(t) = \frac{N_{\uparrow}(t) - N_{\downarrow}(t)}{N_{\uparrow}(t) + N_{\downarrow}(t)} = \alpha p \sin\left(\frac{2d_{\mu}}{\hbar} t\right) \approx \alpha p \frac{2d_{\mu}}{\hbar} t$$





The slope gives the sensitivity of the measurement:

$$\sigma(d_{\mu}) = \frac{\hbar \gamma^2 a_{\mu}}{2 p E_{f} \sqrt{N}\, \gamma \tau_{\mu}\, \alpha}$$

p := initial polarization
E_f := Electric field in lab
$\sqrt{N}$:= number of positrons
τ_{μ} := lifetime of muon
α := mean decay asymmetry

A phased approached

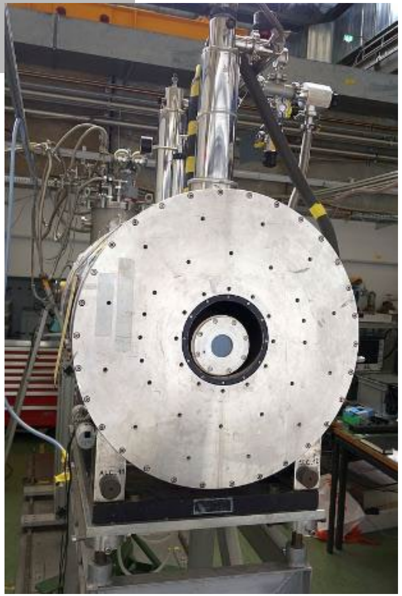
- Existing solenoid at PSI, max 5T
- Bore diameters 200mm
- Field was measured in 2022 found suitable for injection

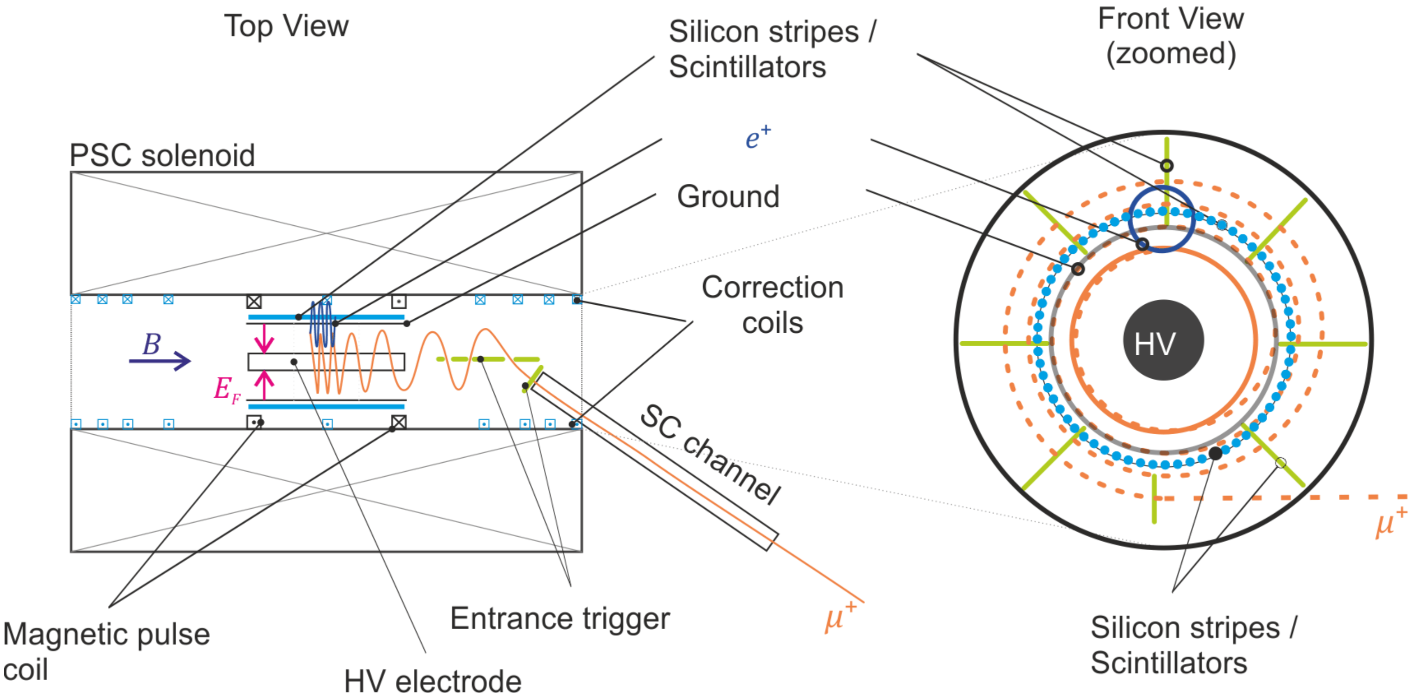
Phase 2 (dedicated magnet muon momentum $\geq 125\mathrm{MeV}/c$)

- Large bore (up to 900 mm diameter)
- High Temporal field stability (10ppb/h)
- Excellent spatial field uniformity (<1 ppb/mm)

The muEDM phase I on piE1

Test bed and frozen spin demonstrator





muEDM measurement $< 3 \cdot 10^{-21} ecm$

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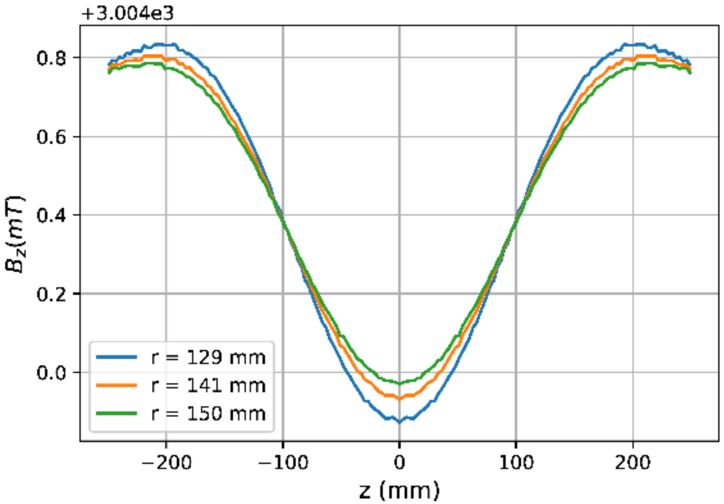
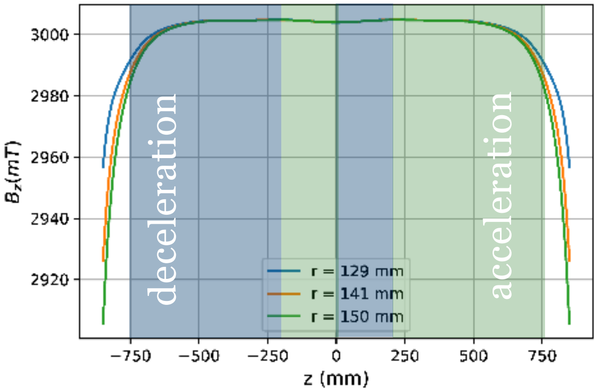
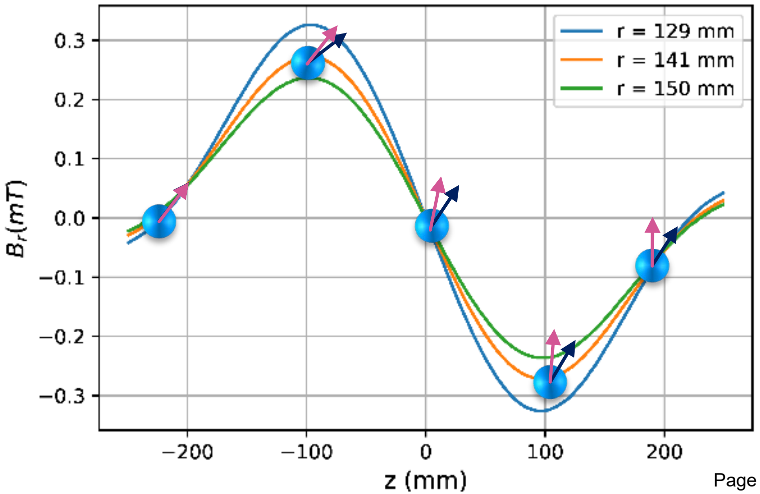
Storage and injectio

- Strength of weakly focusing field in the center region defines “depth” of storage
- The deeper / stronger the weakly focusing field the stronger needs to be the pulse

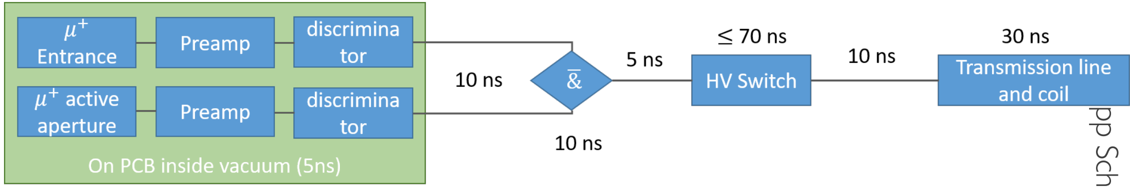


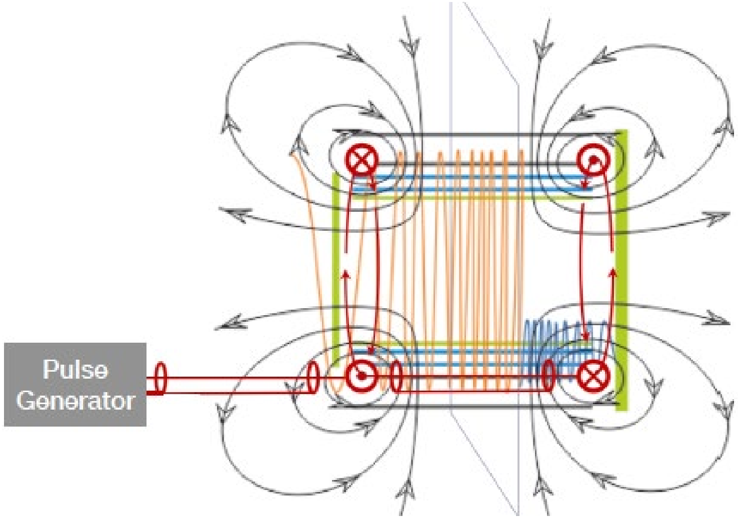


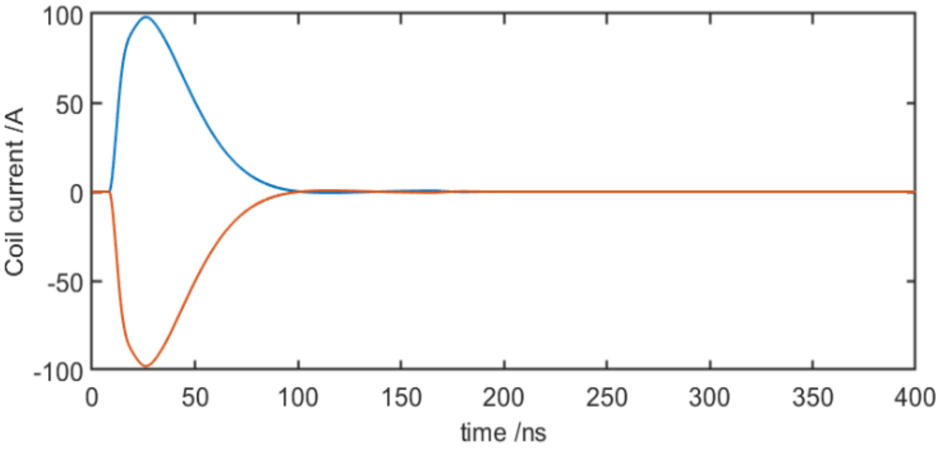


Radial magnetic field pulse to kick muons

- Pulse width $\Delta t \approx 100\text{ ns}$
- Delay between trigger and pulse peak $\Delta t_d \approx 100\text{ns}$
- Peak current 100A
- Eddy current damping by electrodes?

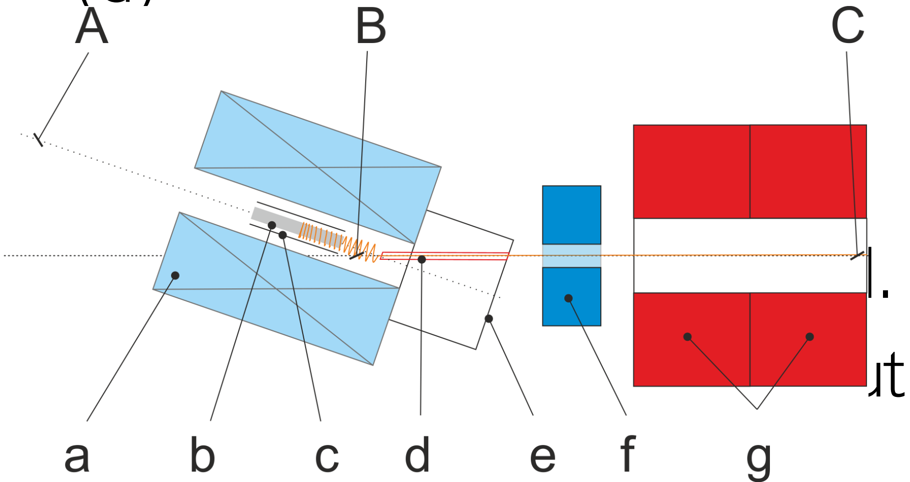






Injection and statistical sensitivity

- Large phase space at exit of beam collimated by passage through a collimation channel (d)



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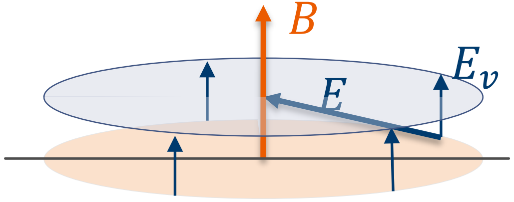
$$\sigma(d_\mu) = \frac{\hbar \gamma a_\mu}{2pE_\mathrm{f}\sqrt{N}\,\tau_\mu\,\alpha}$$

	πE1	μE1
Muon flux (μ^+/s)	4×10^6	1.2×10^8
Channel transmission	0.03	0.005
Injection efficiency	0.017	0.60
Muon storage rate (1/s)	2×10^3	360×10^3
Gamma factor γ	1.04	1.56
e^+ detection rate (1/s)	500	90×10^3
Detections per 200 days	8.64×10^9	1.5×10^{12}
Mean decay asymmetry A	0.3	0.3
Initial polarization P_0	0.95	0.95
Sensitivity in one year ($e\cdot$cm)	$<3 \times 10^{-21}$	$< 6 \times 10^{-23}$

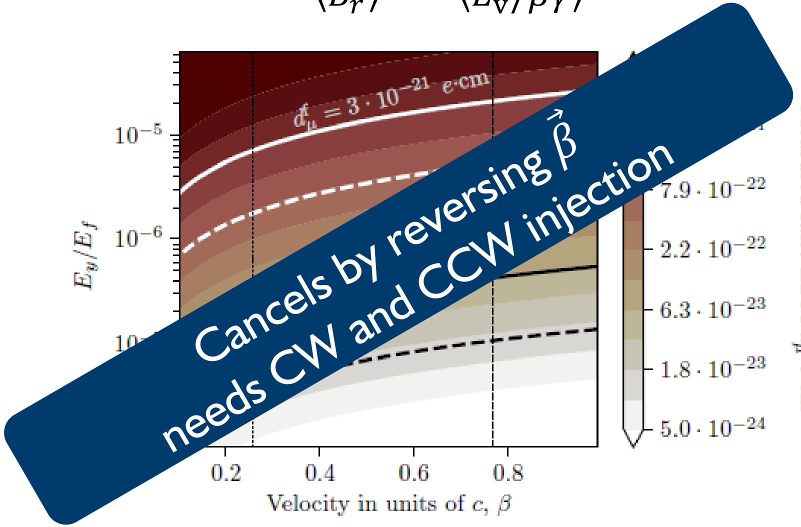
Systematic studies (example)

- Systematic effects: all effects that lead to a ***real*** or ***apparent*** precession of the spin around the radial axis that are not related to the EDM
- Major sources of systematic effects in the frozen spin technique:
  - Coupling of the magnetic moment with the EM fields of the experimental setup (**real**)
  - Early to late variation of detection efficiency of the EDM detectors (**apparent**)



Will move orbit out of central plane until:

$$\langle B_r^* \rangle = -\langle E_\text{v}/\beta\gamma \rangle$$



Systematic study - overview

- Systematic effects are studied using analytic expressions
- Comparison with GEANT4 spin tracking Monte Carlo for verification
- Deduce specifications for experiment

Next steps:

- Parametrization of magnetic-field non-uniformity
- Deduce magnetic-field requirements

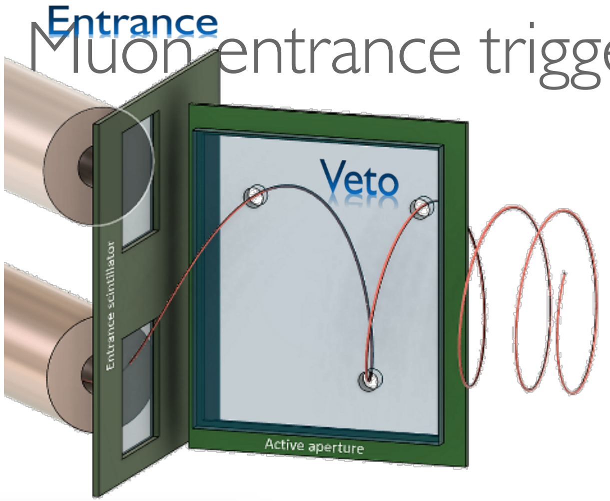
Systematic effect	Constraints	Phase I	
		Expected value	Syst. ($\times 10^{-21}$ e·cm)
Cone shaped electrodes (longitudinal E-field)	Up-down asymmetry in the electrode shape	$\Delta_R < 30$ µm	0.75
Electrode local smoothness (longitudinal E-field)	Local longitudinal electrode smoothness	$\delta_R < 3$ µm	0.75
Residual B-field from kick	Decay time of kicker field	< 50 ns	$< 10^{-2}$
Net current flowing muon orbit area	Wiring of electronics inside the orbit	< 10 mA	$< 10^{-2}$
Early-to-late detection efficiency change	Shielding and cooling of detectors	–	
Resonant geometrical phase accumulation	Misalignment of central axes	Pitch < 1 mrad Offset < 2 mm	2×10^{-2}
TOTAL			1.1

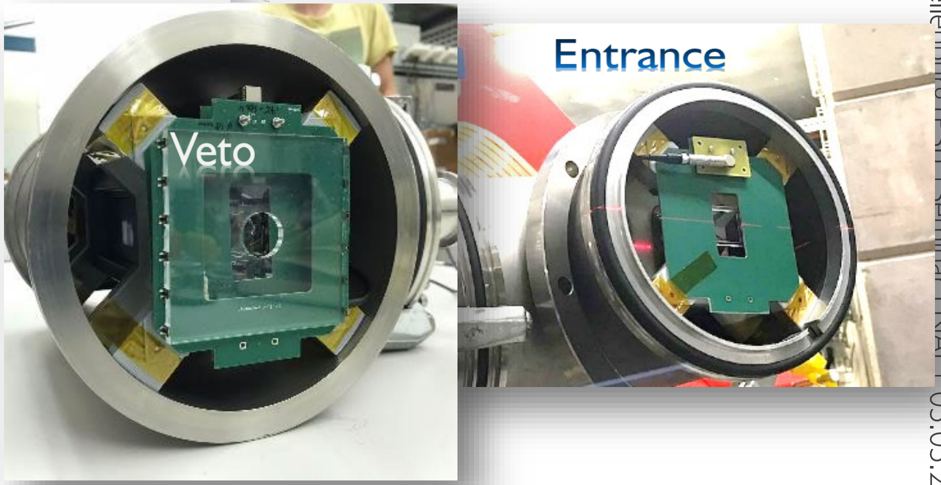
Muon entrance trigger

- Magnetic pulse needs to be triggered by incident muon
- Only about 2% of muons passing through the collimation channel are within the acceptance phase space
- Scattering in scintillators increase beam divergence

⬇

- Combine thin ($\leq 100\mu m$) entrance scintillator with
- Active aperture as veto





Positron detection – figure of merit

Detection of g-2 precession ω_a

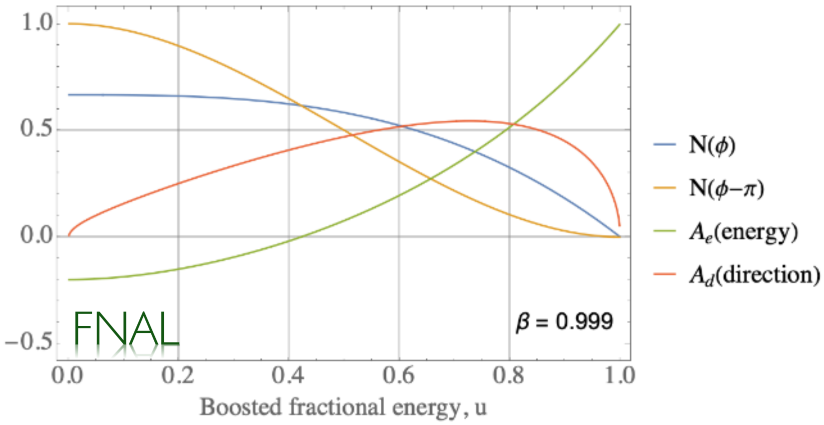
- Measurement of mean magnetic field $\langle B \rangle$
- Measure $\omega_a(E)$ to tune electric field to frozen-spin condition

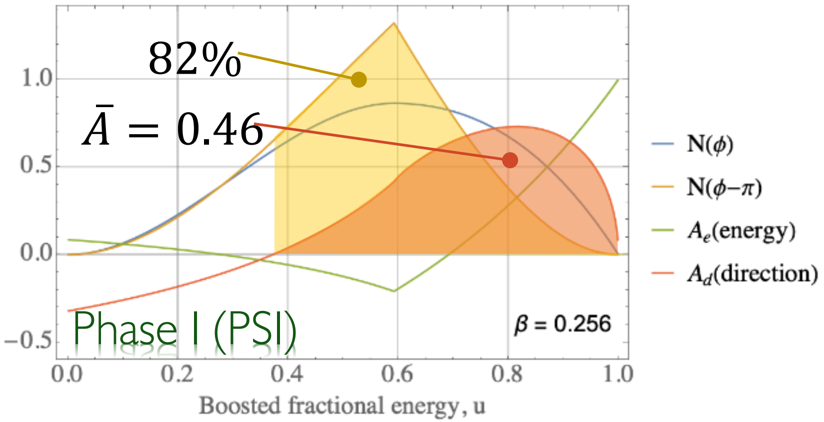
Requires momentum resolution

Detection of EDM polarization

- Measurement of Asymmetry as function of time $A(t)$

Requires spatial resolution along cylinder

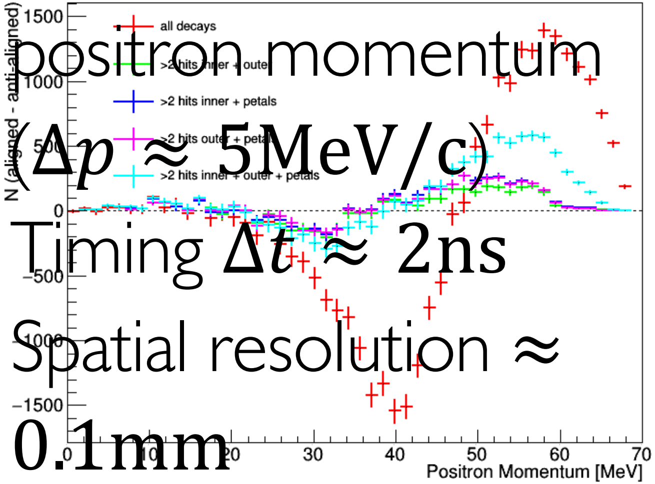




Silicon strip detector for g-2 detection

Silicon strip detector for g-2 detection

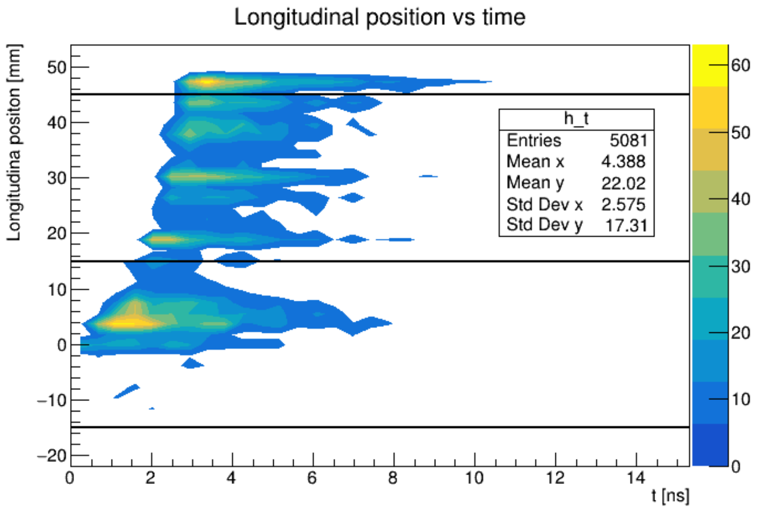
- Reconstruction of transverse positron momentum ($\Delta p \approx 5\mathrm{MeV/c}$)
- Timing $\Delta t \approx 2\mathrm{ns}$
- Spatial resolution $\approx 0.1\mathrm{mm}$

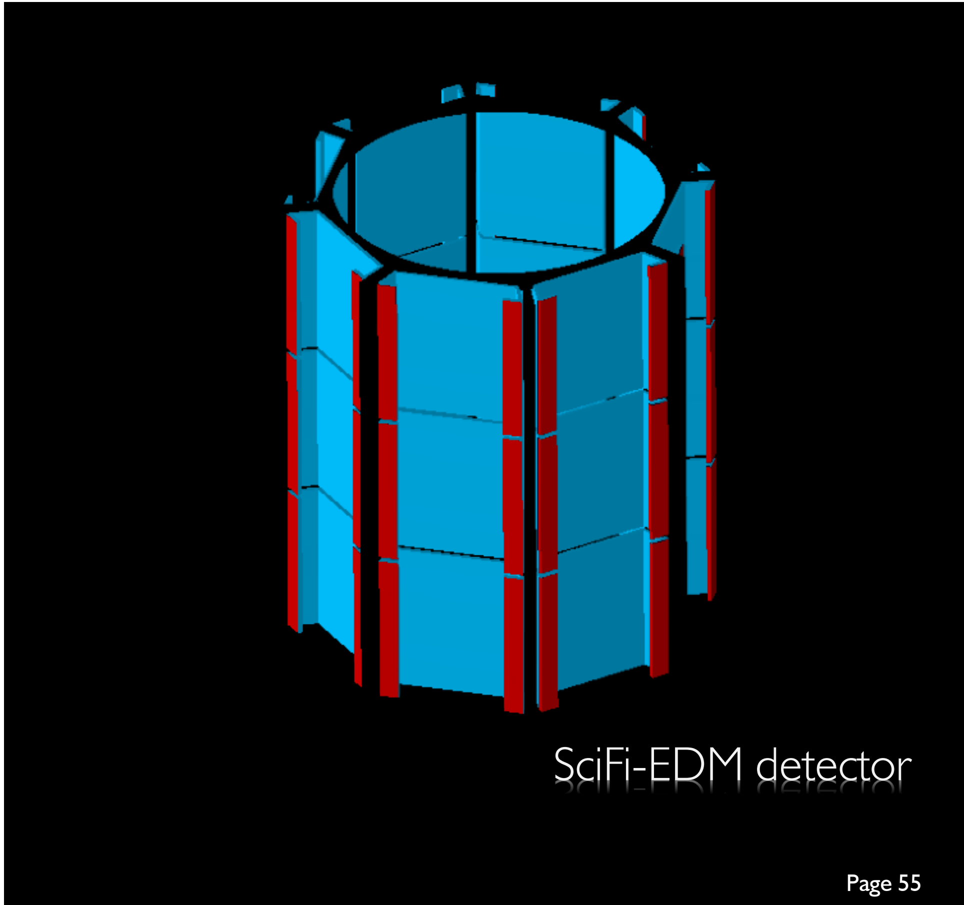


Scintillating fiber detector for EDM-signal

Scintillating fiber detector for EDM asymmetry measurement and timing

- Horizontal fiber ribbons with $250\mu m$ pitch and $100\mu m$ resolution
- Timing resolution $< 2ns$
- Reconstruction of longitudinal momentum





Conclusions

- EDM are excellent probes to search for new physics
- PSI is currently preparing two experiments to improve the current best limits of the neutron and muon EDM in the next decade to better than:

$$\sigma(d_{\mathrm{n}}) \sim 1 \times 10^{-27} e\mathrm{cm}$$

and

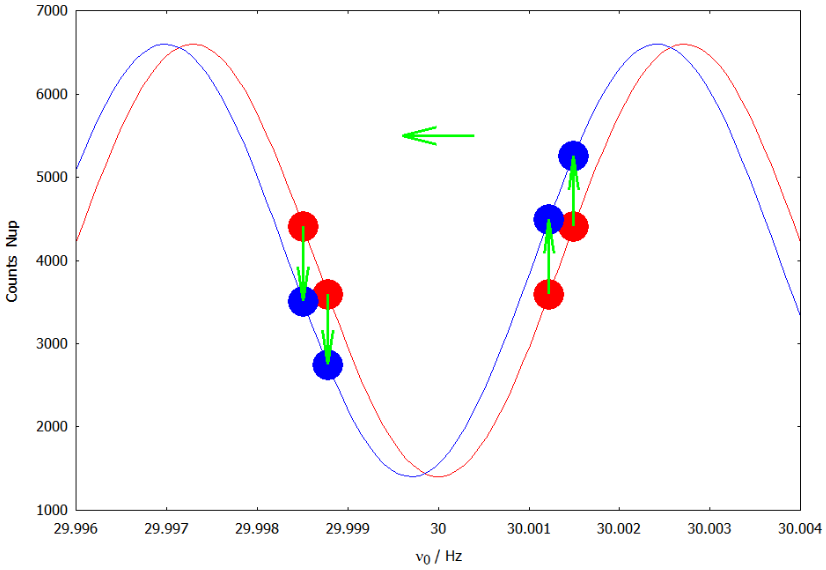
$$\sigma(d_{\mu}) \sim 6 \times 10^{-23} e\mathrm{cm}$$

- Shift the central value by adding an unknown offset EDM of **-1.5** to **1.5E-25** ecm to the data

$$\delta N_{\uparrow,\downarrow;i} = \mp \bar{N} \frac{\pi\alpha}{\Delta\nu} \frac{d \cdot E}{h} \sin\phi_i$$

with $$\phi_i = \frac{(\nu_i - \nu_0)}{\Delta\nu}\pi$$

- Keep un-blinded data in a safe place (encrypted)
- Two blinding levels
  - Primary blinding same for both analysis groups
  - Secondary blinding layer different for both groups



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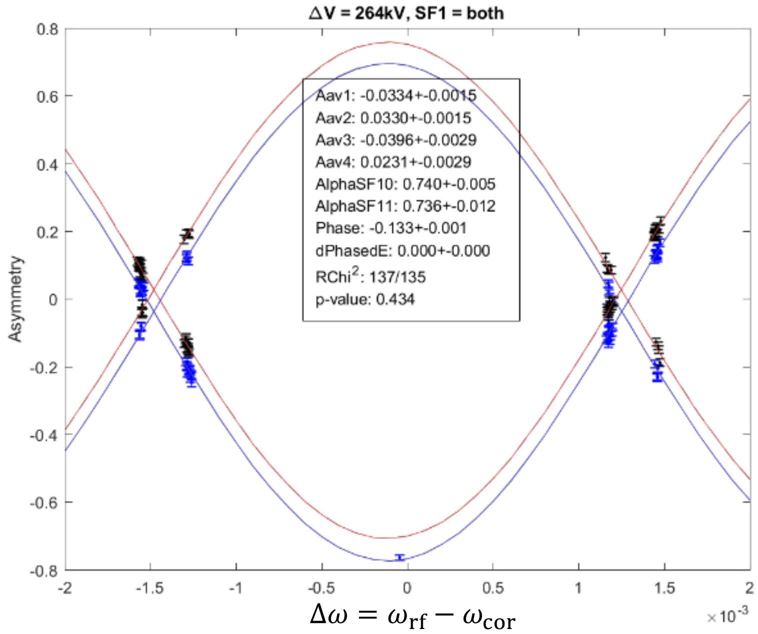
Single Ramsey fit

- One fit per subsequence: combine all E-field states SF2 ans SF1 states
  - A total of 8 fit parameters
  - Parameter errors are small due to high number of **dof.**



$$A_i = \underbrace{A_{\mathrm{av}(1-4)}}_{4} - \underbrace{\alpha}_{2} \cos\left(\frac{\omega_{\mathrm{rf}} - \omega_{\mathrm{cor}}}{\Delta\nu} - \Phi_1 - E\frac{\mathrm{d}\phi_2}{\mathrm{d}E}\right)$$

depends on initial and final spin flipper

one for each initial state

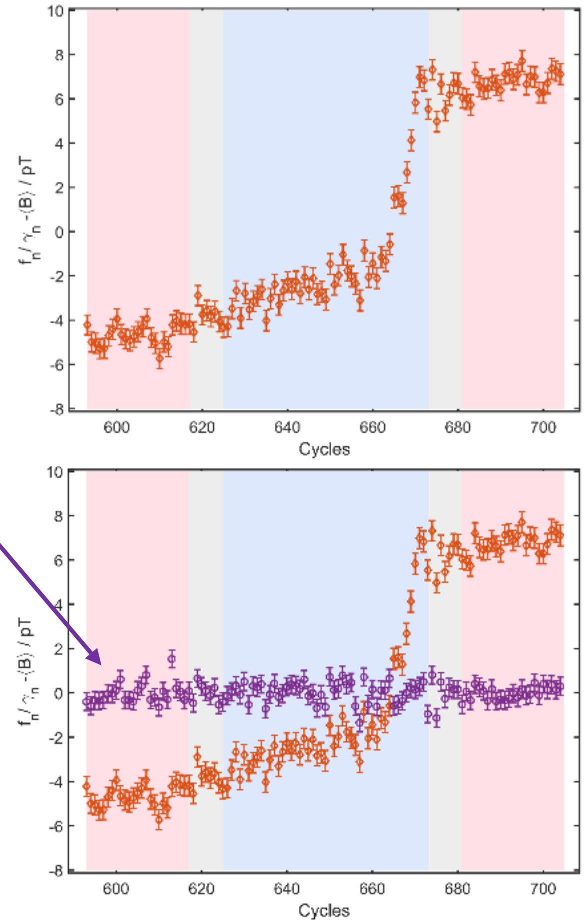
blinding

Single point fit to obtain f_{n}

- Fix all parameters of the fit but ϕ_1^i for each cycle *i*, and solve cosine equation for ϕ_1^i.

$$f_{\mathrm{n}}^i = \frac{\phi_1^i}{2\pi T} \Rightarrow R^i = \frac{f_{\mathrm{n}}^i + \langle z \rangle \Delta g}{f_{\mathrm{Hg}}^i}$$

- As we use the same parameters from the original Ramsey fit for each cycle, a full covariant error propagation is required in the next step.



Obtain d_n from R

Remaining drifts in R required to employ an R vs (t, E) fit:

$$R(t) = \frac{\mathrm{d}R}{\mathrm{d}t}(t - \langle t \rangle) + E(t) \cdot a + R_{\mathrm{sub}}$$

Philipp S.

Minimize

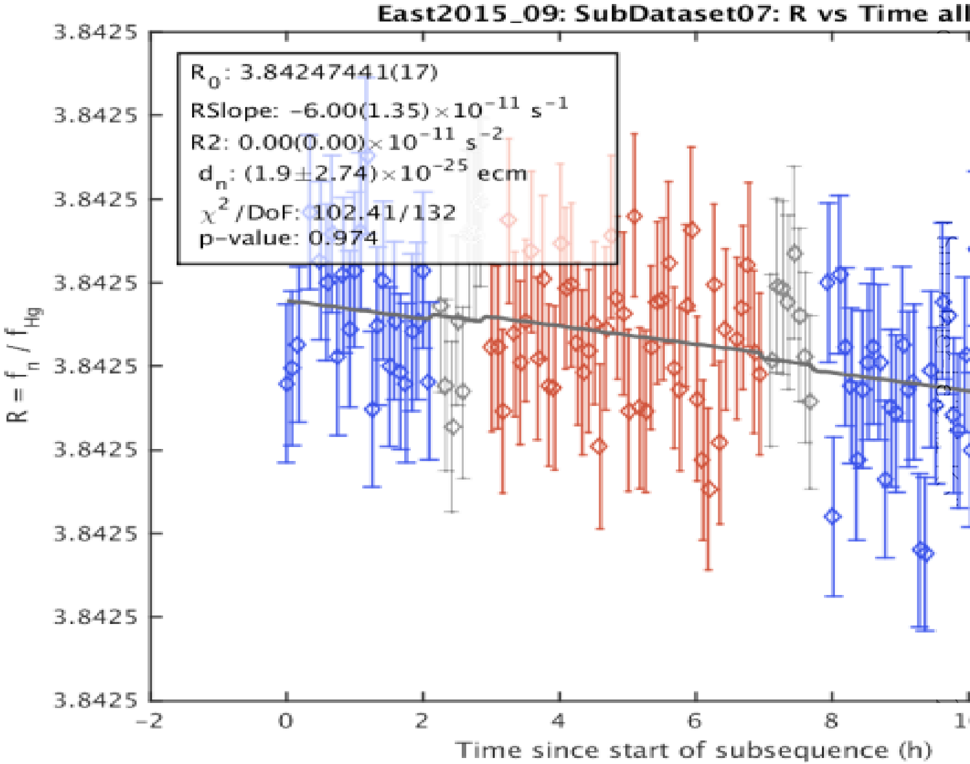
$$(R - Ax)^{-1} C^{-1} (R - Ax)$$

with

$$Ax = \begin{bmatrix} 1 & t_1 - \langle t \rangle & E_1 \\ 1 & t_2 - \langle t \rangle & E_2 \\ \vdots & \vdots & \vdots \\ 1 & t_n - \langle t \rangle & E_3 \end{bmatrix} \begin{pmatrix} R_{\mathrm{sub}} \\ \mathrm{d}R/\mathrm{d}t \\ a \end{pmatrix}.$$

From a we deduce the EDM for each subset:

$$d_{\mathrm{n}} = \mp a \frac{h}{\langle f_{\mathrm{Hg}} \rangle}$$



Effect of higher order gradients

$$R_\pm = \frac{f_\mathrm{n}}{f_\mathrm{Hg}} = \left|\frac{\gamma_\mathrm{n}}{\gamma_\mathrm{Hg}}\right|\left(1 \pm \delta_\mathrm{EDM} \pm \delta_\mathrm{EDM}^\mathrm{false} + \delta_\mathrm{Q} + \delta_\mathrm{G} + \delta_\mathrm{T} + \delta_\mathrm{E} + \delta_\mathrm{LS} + \delta_\mathrm{I} + \delta_\mathrm{P} + \delta_{AC}\right)$$

$$\delta_\mathrm{G} = \pm\frac{\langle z\rangle G_{1,0}}{|B_0|}$$

and

$$d_{\mathrm{n}\leftarrow\mathrm{Hg}}^\mathrm{false} = \frac{\hbar\gamma_\mathrm{n}\gamma_\mathrm{Hg}}{32c^2}D^2 G_{1,0}$$

is not the full story, but… … neither.

But instead:

$$\delta_\mathrm{G} = \frac{\langle z\rangle G_\mathrm{g}}{|B_0|}$$

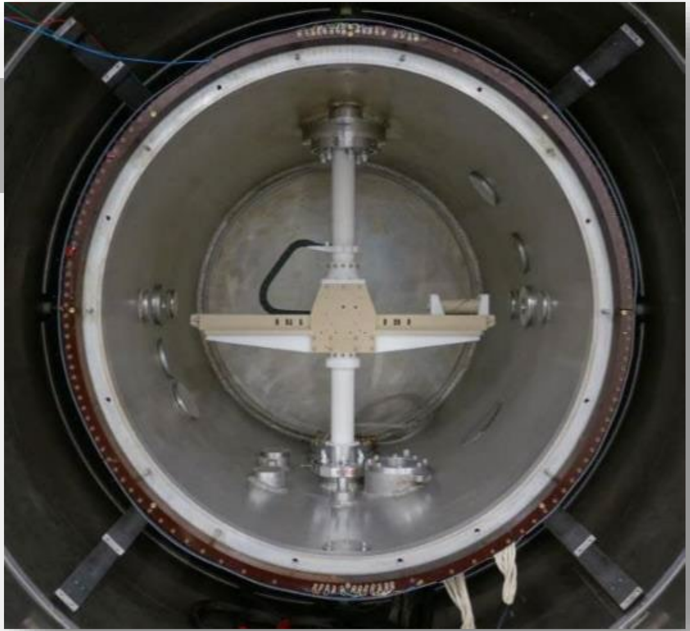
with

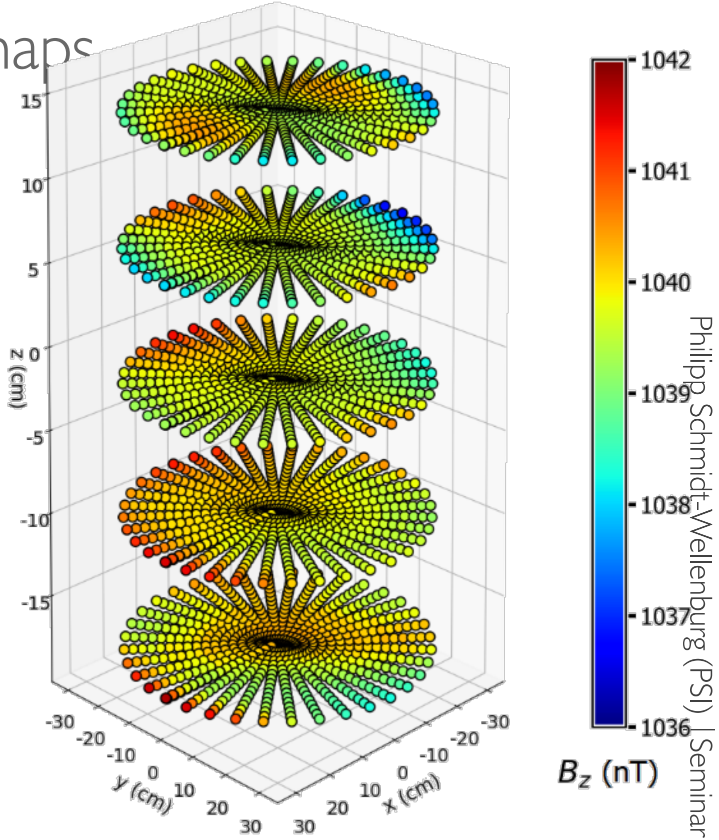
$$G_\mathrm{g} = \mathrm{G}_{10} + \mathrm{G}_{30}\left(\frac{3H^2}{20} - \frac{3D^2}{16}\right) + \cdots$$

$$d_{\mathrm{n}\leftarrow\mathrm{Hg}}^\mathrm{false} = -\frac{\hbar\gamma_\mathrm{n}\gamma_\mathrm{Hg}}{32c^2}\sum_{l\ \mathrm{odd}} G_{l0}\langle\rho\Pi_{\rho l m}\rangle$$

$$= \frac{\hbar\gamma_\mathrm{n}\gamma_\mathrm{Hg}}{32c^2}D^2\left[G_{10} - G_{30}\left(\frac{D^2}{8} - \frac{H^2}{4}\right)\right.$$

Magnetic field maps





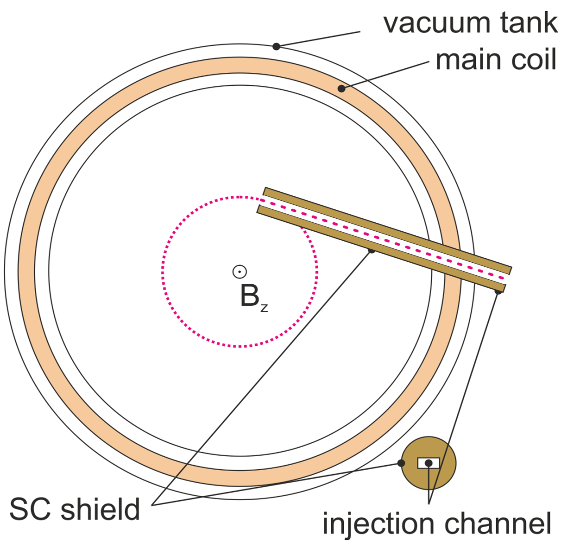
Mapping with fluxgate

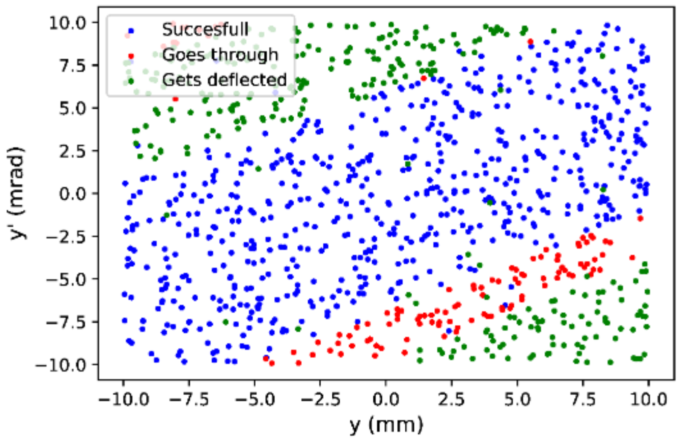
- -20<z<20,
- -10<r<30,
- Δϕ = 5°

- Fit to order $l = 7$
- Extract $\langle B_T^2 \rangle$ for each base configuration
- Extract $\delta_G(\hat{G})$ for each base configuration

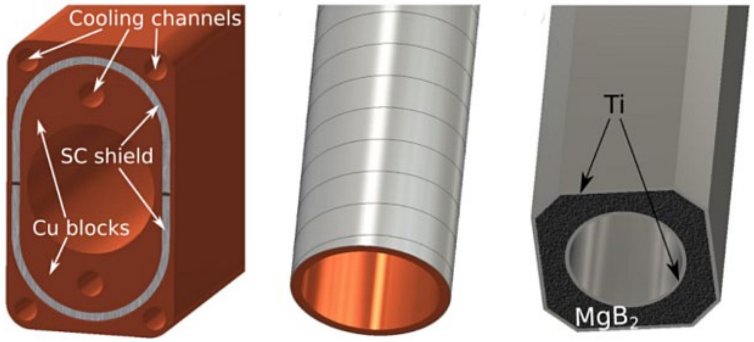
Injection channel

- Injection channel with SC magnetic shield
- Defines vertical and horizontal divergence

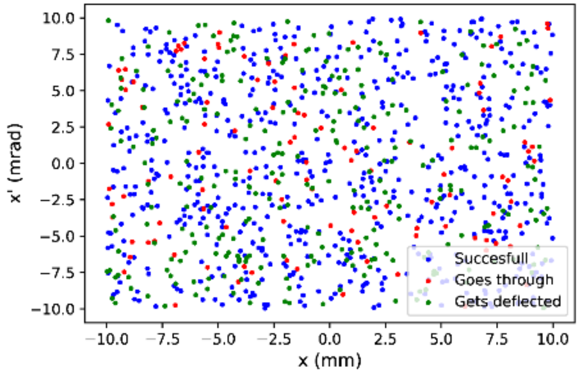




vertical



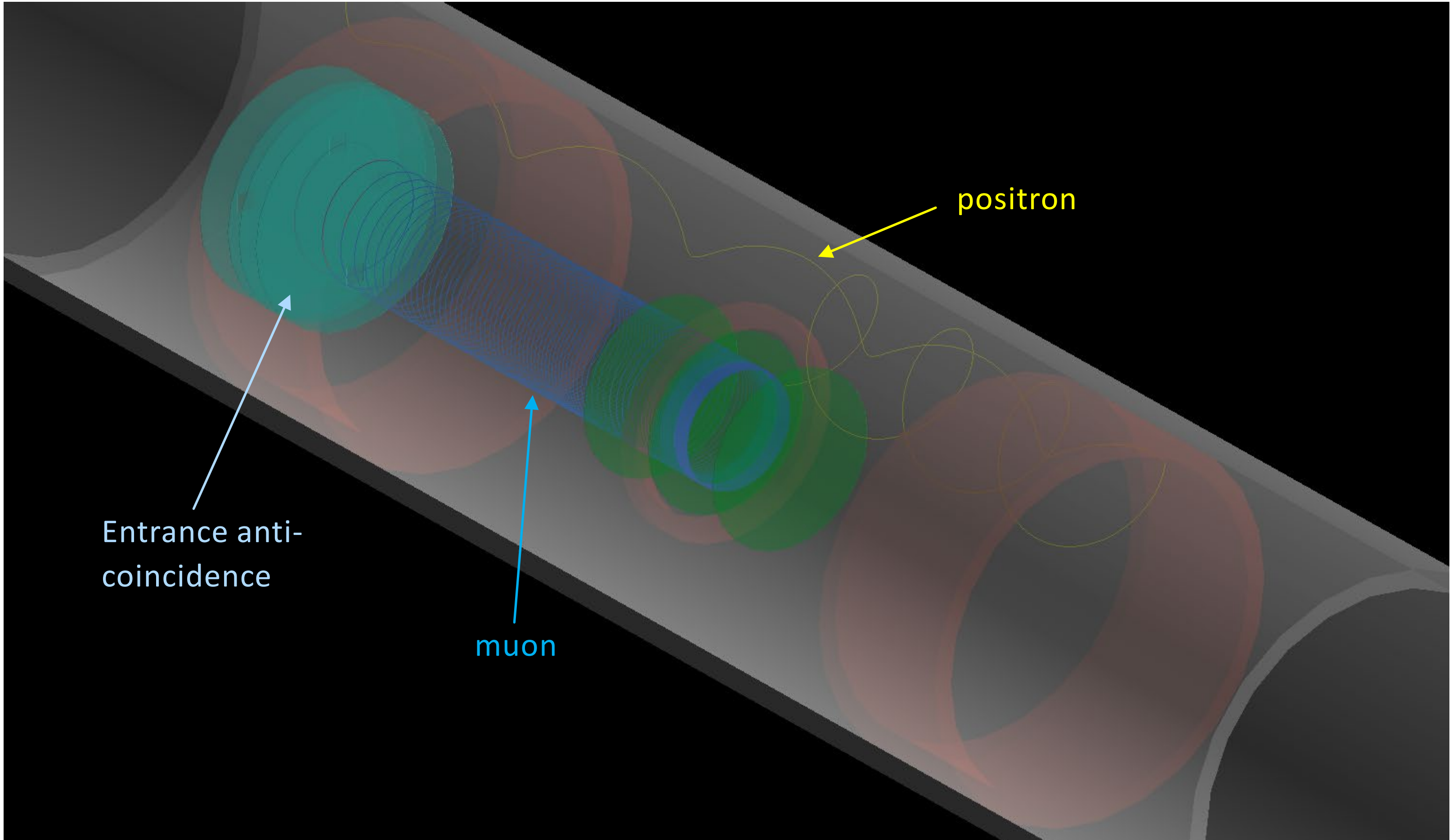
horizontal



D. Barna et al., PR Acc. B 20 (2017) 041002
D. Barna et al., IEEE Trans. Appl. Supercond. 29 (2018) 4900108.
D. Barna et al., IEEE Trans. Appl. Supercond. 29 (2018) 4101310.

Philipp Schmidt-Wellenburg

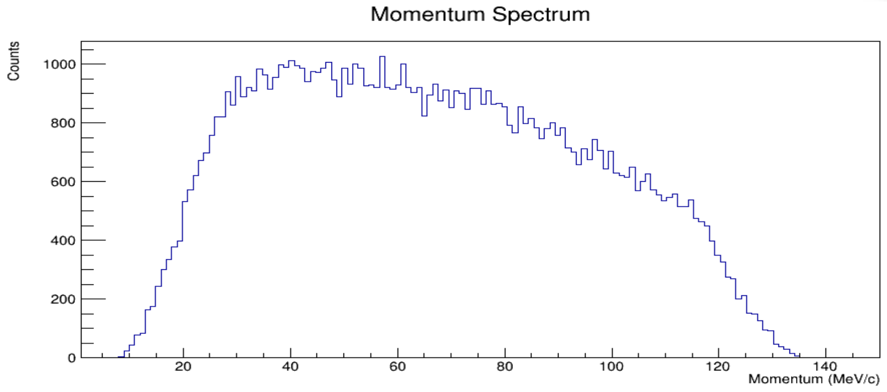
Entrance trigger and storage simulation

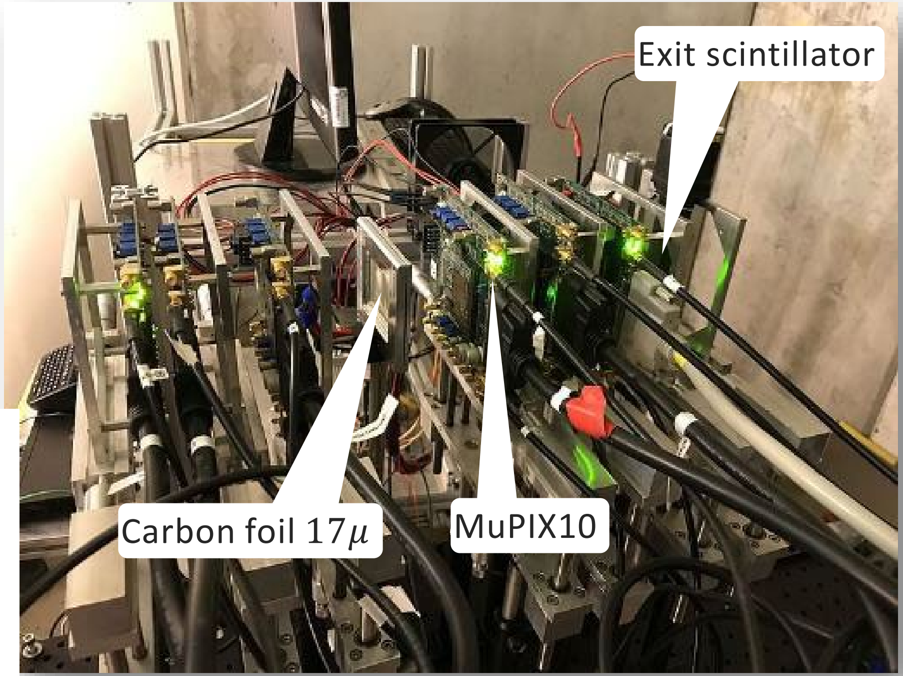


Ongoing muEDM activities

- Characterization of potential electrode material with positrons and muons

$$50\ \mathrm{MeV}/c < p < 145\ \mathrm{MeV}/c$$





Systematic effects

- Systematic effects: all effects that lead to the real or apparent precession of the spin around the radial axis that are not related to the EDM
- Sources of systematic effects currently studied in analytically and in simulations
  - Imperfections in the storage ring (electric and magnetic fields, local dipoles)
  - Variation of detection efficiency of the EDM detectors
  - Non-uniformity of initial injection
  - gravity?
  - …. unthought-of problems

→ Derive specifications for all features of the experiment

Courtesy: Chavdar Dutsov