PAUL SCHERRER INSTITUT

Philipp Schmidt-Wellenburg :: Scientist :: Paul Scherrer Institute

Storage ring searches for EDM of charged particle

CP2023 in Les Houches

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
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Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
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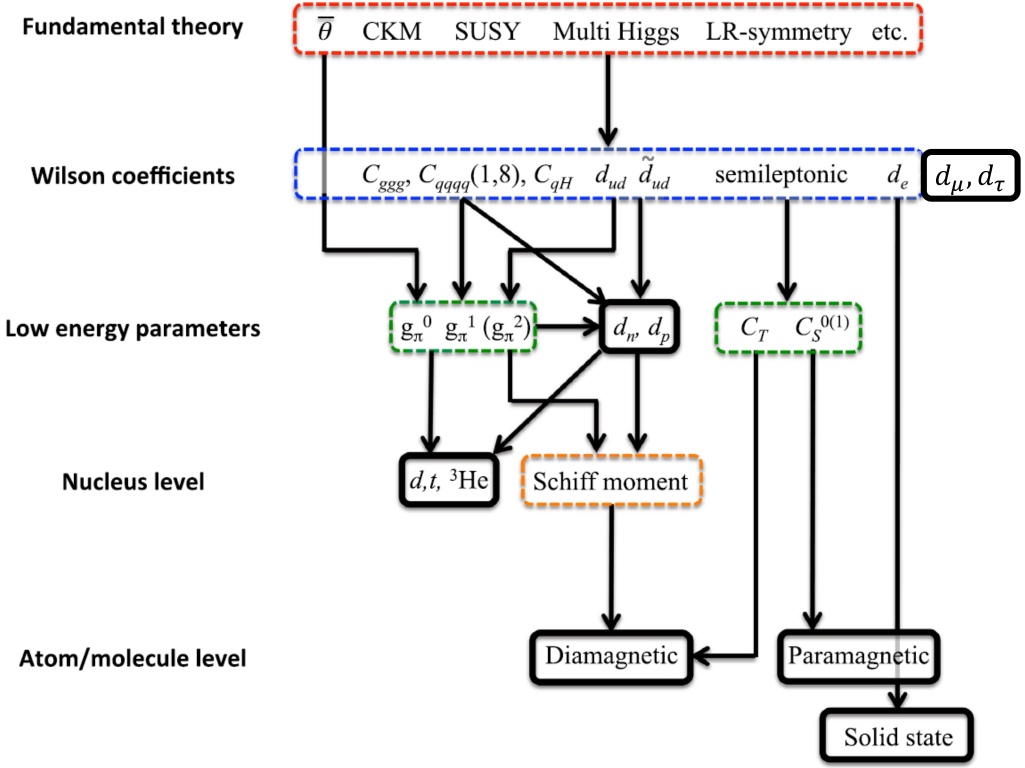
FNSNF
SWISS NATIONAL SCIENCE FOUNDATION

Complications when using atoms and molecules

In general, when measuring the EDM of an atom or molecule we face the situation that a possible signal could be generated by many different operators at higher energy.

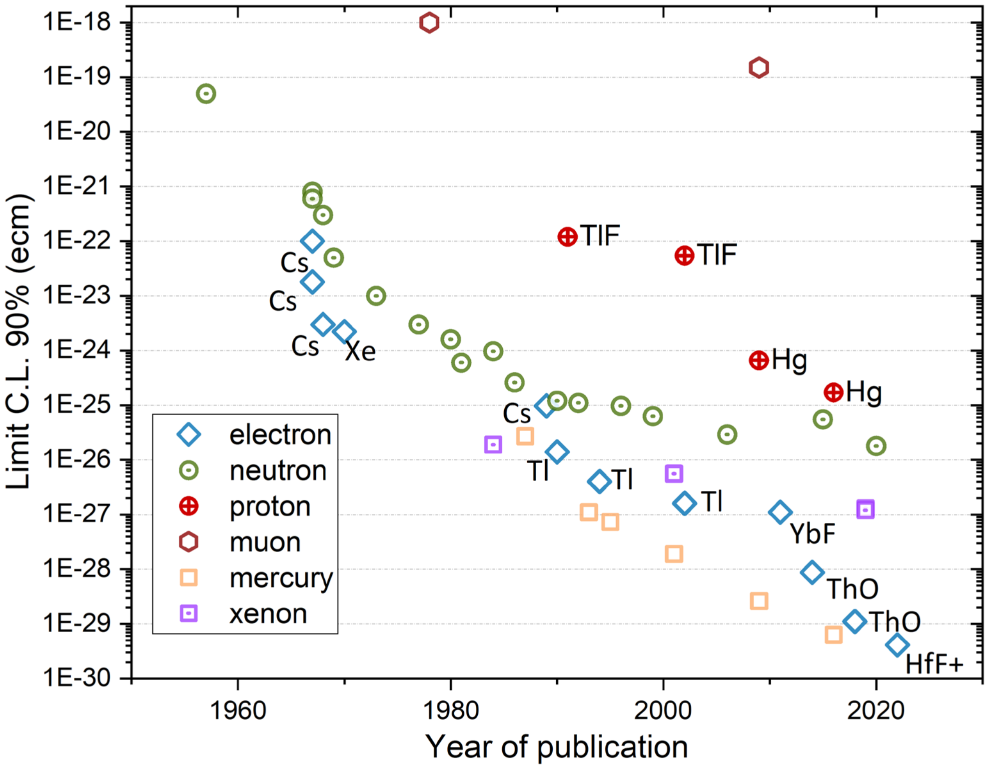
In general: $d_{\mathrm{A}} = \sum_i \alpha_{ij} C_j$,

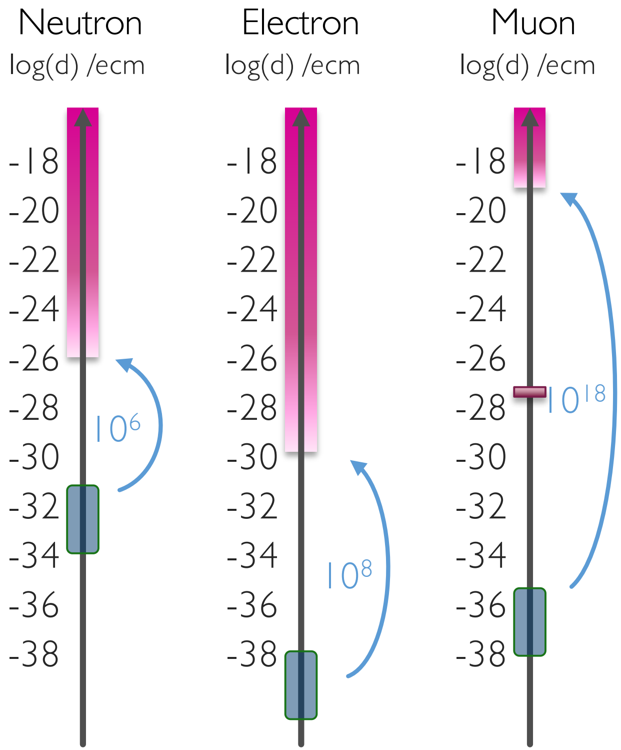
where α_{ij} is the sensitivity of the specific system to the CP violating operator C_j.



[from Chupp et al., RMP91, 015001,2019]

A not so brief history of EDM searches





*Bennett et al., PRD80(2009)052008

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

Only limits:

Particle	Limit /ecm 90%CL	System	Reference
n	1.8×10^{-26}	Ultracold neutrons	[Abel et al., PRL124, 081808, 2020]
Hg	6.3×10^{-30}	Hg vapor	[Graner et al., PRL116, 161601, 2016]
↳p	2.0×10^{-25}	Assuming all others zero	
↳n	1.2×10^{-26}		
↳e	6.0×10^{-28}		
HfF+			[Roussy et al., arXiv:2212.11841v3]
↳e	4.1×10^{-30}	Assuming all others zero	
Muon	1.5×10^{-19}	Storage ring (g-2)	[Bennett et al, PRD80, 052008, 2009]
^{129}Xe	1.5×10^{-19}	^{3}He- Comagnetometer	[Sachdeva et al., PRL123,143003, 2019] [Allmendinger et al, PRA100, 022505, 2019]
↳p	3.2×10^{-22}	Assuming all others zero	
↳n	6.4×10^{-23}		
↳e	1.9×10^{-24}		

What can we do to measure only the EDM of the particle?

The generic idea of all EDM experiments:

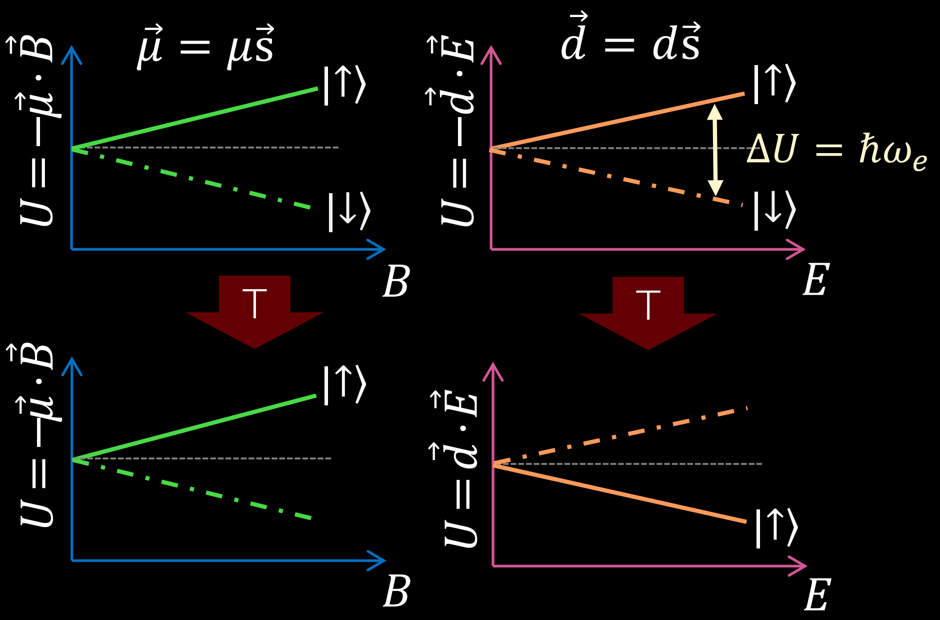
Preparation of a spin polarized particle ensemble

Interaction with electric field

Measurement of evolution of angular momentum

$$\frac{d\vec{I}}{dt} = \underbrace{\left(\mu\vec{B} + d\vec{E}\right)}_{\vec{\Omega}} \times \vec{I}$$

CP violation & edm

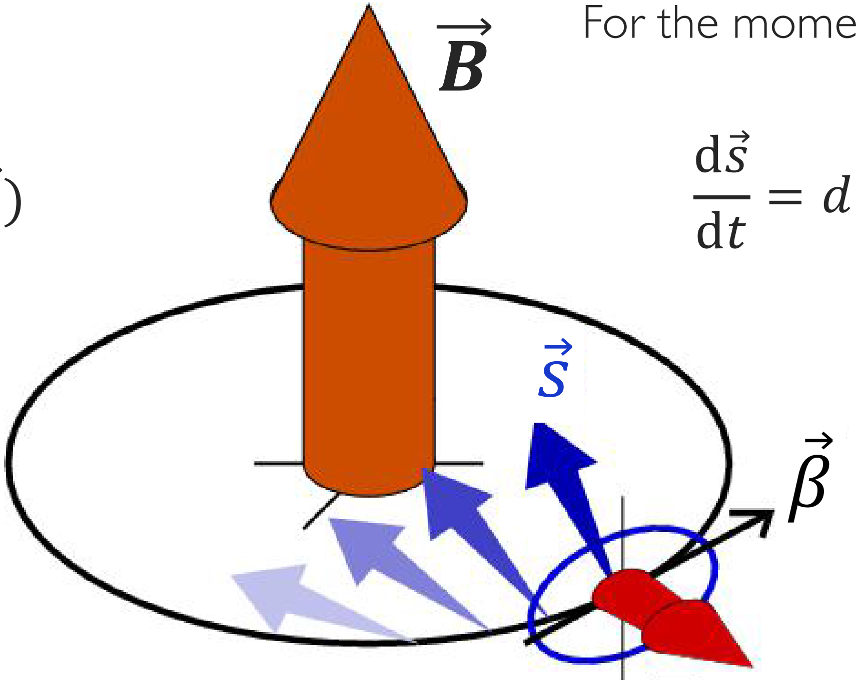


Measure the spin evolution in a storage ring

For the moment assume $\mu = 0$

$$\frac{\mathrm{d}\vec{p}}{\mathrm{d}t} = \mathrm{q}(\vec{\mathrm{v}} \times \vec{B})$$

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = d\ \vec{s}(\vec{\beta} \times \vec{B})$$



The relativistic E-field in the rest frame of the particle can be very large!

$$\vec{E} = \vec{\beta} \times \vec{B} \approx O(\mathrm{GV/m})$$

Lepton spin precession and motion in a B-field

Relativistic lepton spin precession in a perpendicular magnetic field

$$\vec{\omega}_L = \frac{gq\vec{B}}{2m} + (1-\gamma)\frac{q\vec{B}}{\gamma m} = \frac{aq\vec{B}}{m} + \frac{q\vec{B}}{\gamma m}$$

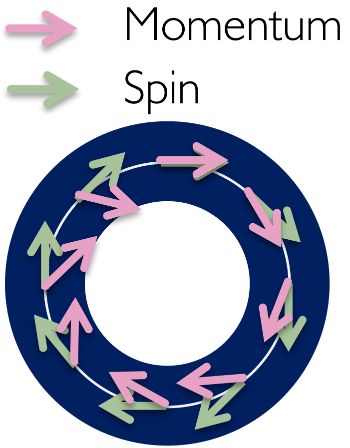
$$a = \frac{g-2}{2}$$

Cyclotron frequency of a lepton in a perpendicular magnetic field

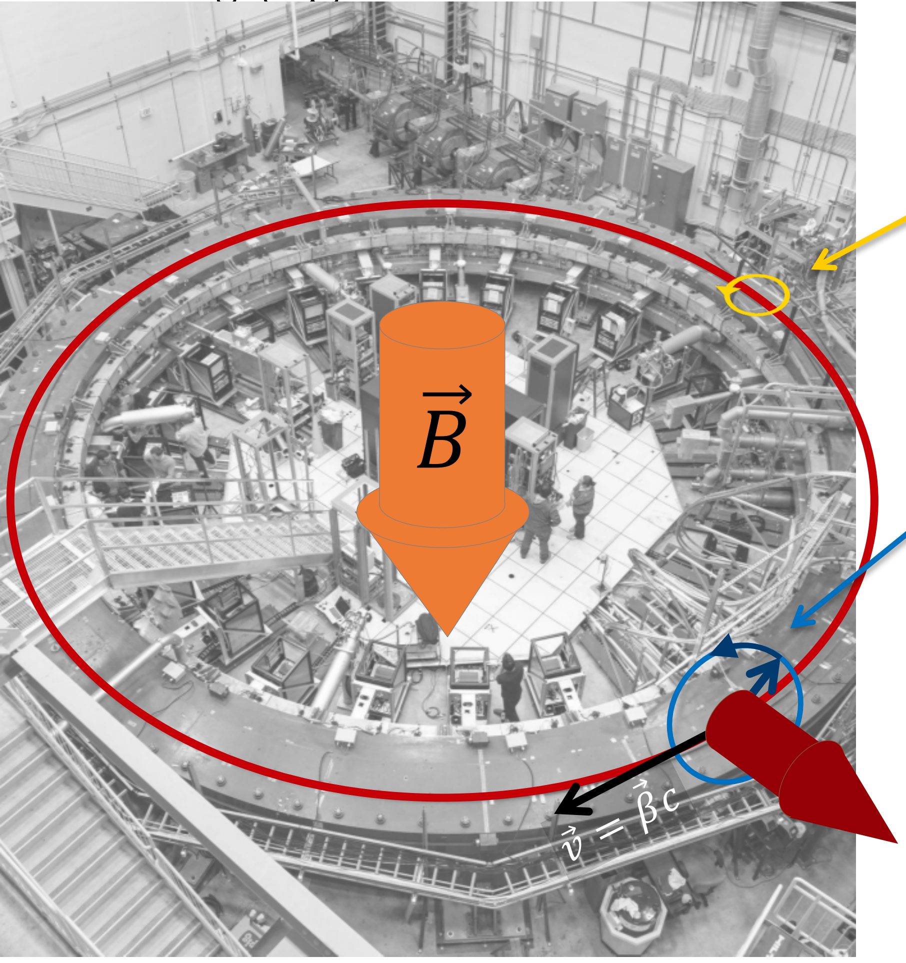
$$\vec{\omega}_C = \frac{q\vec{B}}{\gamma m}$$

Measurement of the anomalous magnetic moment by observing relative precession

$$\vec{\omega}_a = \vec{\omega}_C - \vec{\omega}_L = -\frac{q}{m}a\vec{B}$$



Spin precession in $\vec{B}$ and $\vec{E}$ fields of a storage rings:



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

Spin precession in orbital plane

$$\left(a = \frac{g-2}{2}\right)$$

$$\vec{\omega}_d = -\frac{q}{m}\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)$$

Spin precession out of orbital plane: "EDM signal"

$$\left(\eta = \frac{4mcd}{q\hbar}\right)$$

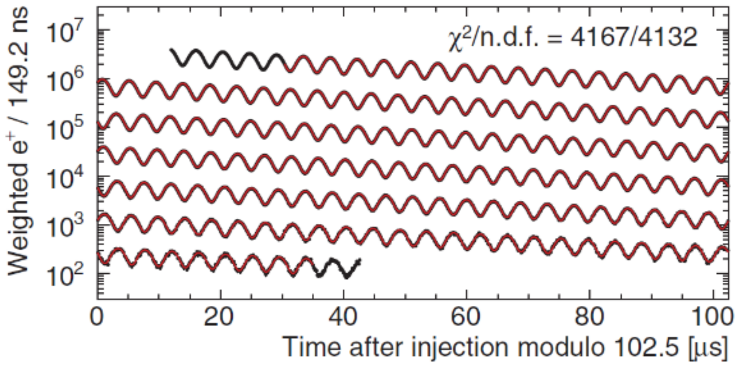
Sum $\vec{\omega} = \vec{\omega}_a + \vec{\omega}_d$ dilutes the EDM signal and increases systematic effects

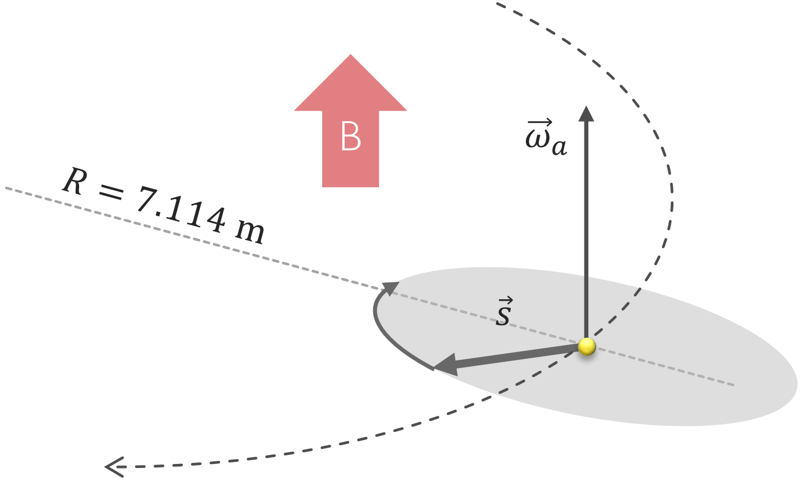
$$\vec{E} = \vec{\beta}\times\vec{B} \approx O(1\mathrm{GV/m})$$

Muon dipole moments and frequencies

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

g-2 term ω_a





[Abi et al., PRL126 141801(2021)]

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The g-2 experiment: measuring with magic momentum

$$\begin{pmatrix}\omega_x\\ \omega_y\\ \omega_z\end{pmatrix} = -\frac{q}{m}\left[\begin{pmatrix}0\\ aB_y\\ 0\end{pmatrix} + \left(\frac{1-a-a\gamma}{c(1-\gamma)}\right)\begin{pmatrix}-\beta_z E_y\\ \beta_z E_x\\ 0\end{pmatrix} + \frac{\eta_d}{2c}\begin{pmatrix}E_x - v_z B_y\\ E_y\\ E_z\end{pmatrix}\right]$$

- Run at "magic-moment" $p_\mu = 3.1\mathrm{GeV}/c$
  → can use E-fields to steer the beam
- Assume η small
  → direct access to a_μ from

$$\vec{\omega}_a = -qa\vec{B}/m$$

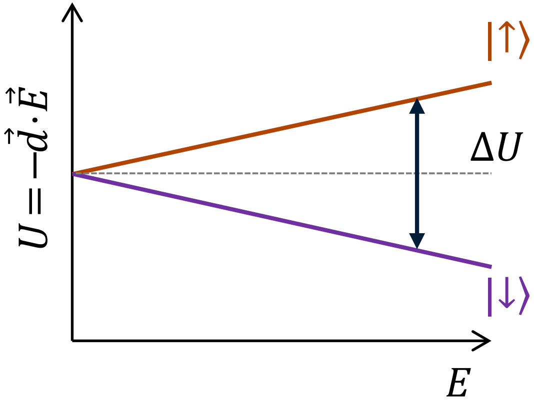
- An EDM signal would be visible as up/down oscillation

Muon dipole moments and frequencies

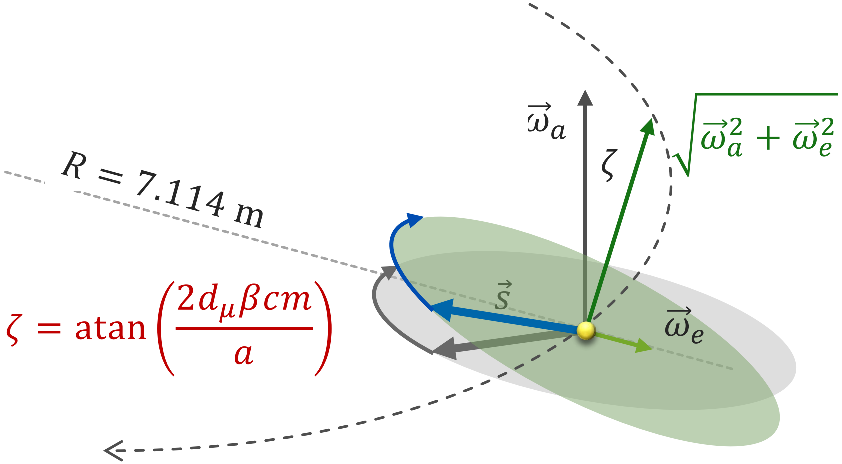
$$\vec{\omega} = -\frac{q}{m}\left[a\vec{B} + \left(\frac{1}{\gamma^2-1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] - \frac{2d_\mu mc}{q\hbar}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)$$

g-2 term ω_a

EDM term ω_e



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



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

FNAL* & JPARC**: $\sigma(d_\mu) \approx 10^{-21} e\text{cm}$

[*Chislett et al., EPJConf. 118 01005(2016), Abi et al., PRL126 141801(2021), **Abe et al., PTEP053C02 (2019)]

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Statistical sensitivity of the g-2 EDM extraction

$$A_v(t) = \frac{N_u(t) - N_d(t)}{N_u(t) + N_d(t)}$$

A_v: amplitude in detector

ℓ: distance between decay and detector

$$A_v(t) = \zeta \cdot \ell \cdot \sin(\omega t + \phi)$$

$$dA = \frac{2N_n N_d}{(N_u + N_d)^2} \sqrt{\frac{1}{N_u} + \frac{1}{N_d}} \approx \sqrt{\frac{1}{N_{tot}}}$$

$$\frac{dA}{d\zeta} = \ell \cdot \sin(\omega t + \phi)$$

$$d\zeta = \frac{1}{\ell \sin(\omega t + \phi)\sqrt{N_{tot}}}$$

$$\zeta = \operatorname{atan}\left(\frac{\omega_e}{\omega_a}\right) = \operatorname{atan}\left(\frac{\eta\beta}{2a}\right) \approx \frac{\eta\beta}{2a}$$

Time averaged sine

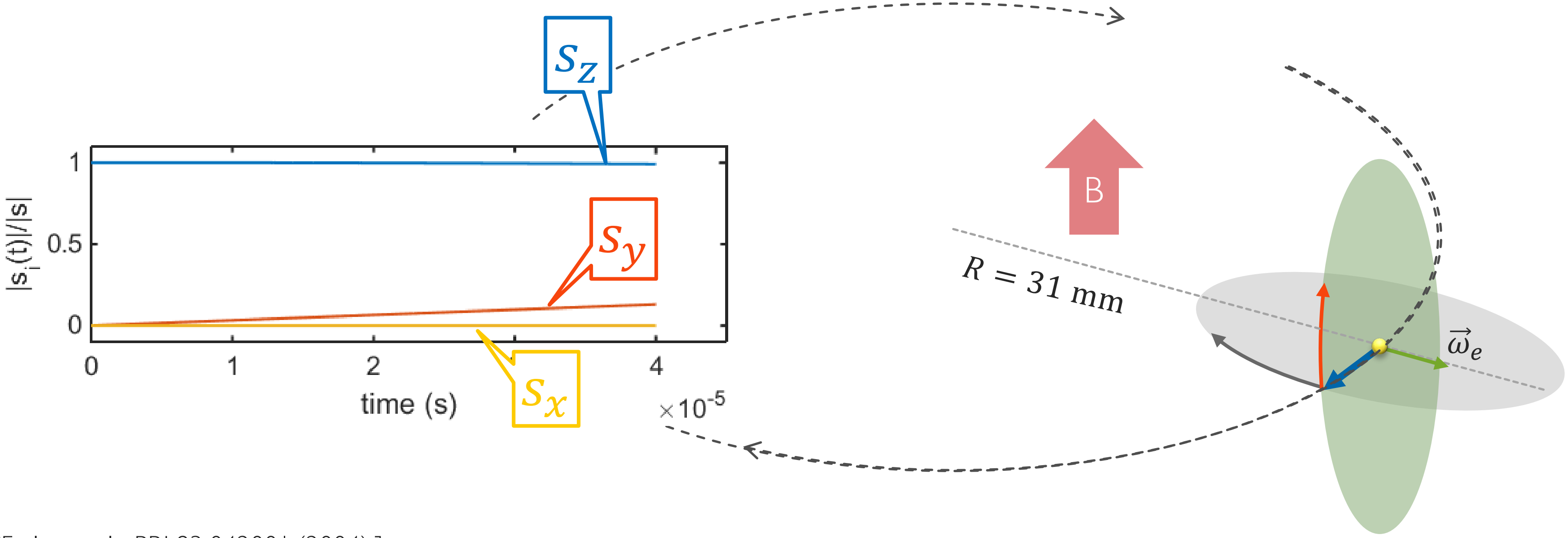
$$\sigma(\eta) = \frac{2a\sqrt{2}}{\beta\ell\sqrt{N}}$$

Statistical sensitivity depends only on $\sqrt{N}$

Muon dipole moments –freezing the spin at PSI

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

g-2 term ω_a EDM term ω_e



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

Statistical sensitivity of the frozen spin technique

$$A_v(t) = \frac{N_u(t) - N_d(t)}{N_u(t) + N_d(t)}$$

$$A_v(t) = \alpha P \sin\left(\frac{2d_\mu E t}{\hbar} + \phi\right)$$

A_v: amplitude in detector

P: initial polarization

α: analysis power

t: mean observation time

$$\mathrm{d}A = \frac{2N_n N_d}{(N_u + N_d)^2}\sqrt{\frac{1}{N_u} + \frac{1}{N_d}} \approx \sqrt{\frac{1}{N_{\mathrm{tot}}}}$$

$$\sigma(d_\mu) = \frac{\hbar}{2PE\sqrt{N}t\alpha}$$

$$\left.\frac{\mathrm{d}A}{\mathrm{d}d_\mu}\right|_{max} = \frac{2\alpha P d_\mu E t}{\hbar}$$

Statistical sensitivity increases linear with E-field and observation time

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The frozen spin method

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

Two options to cancel g-2 signal:

- Select radial electric field E_f to cancel g-2 term
- All electric storage ring and magic momentum

$$a\vec{B} = \left(a - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}$$

$$E_f = \frac{aBc\beta}{(a\beta^2 - (1 - \beta^2))}$$

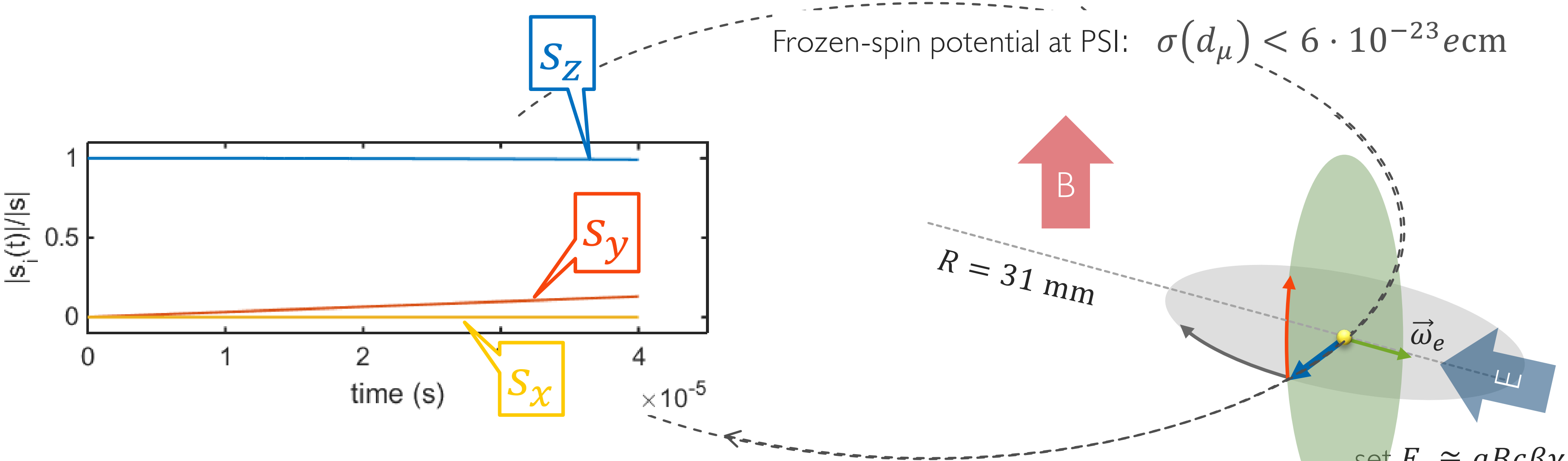
$$E_f \cong -aBc\beta\gamma^2$$

Muon dipole moments –freezing the spin at PSI

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

g-2 term ω_a EDM term ω_e

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



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

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

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

PAUL SCHERRER INSTITUT PSI

The frozen spin method

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

Proton EDM search with $a_P = 1.793$

Two options to cancel g-2 signal:

- Select radial electric field E_f to cancel g-2 term
- All electric storage ring and magic momentum

$$\vec{B} = 0$$

$$\gamma = \sqrt{(1 + a)/a} \approx 1.25$$

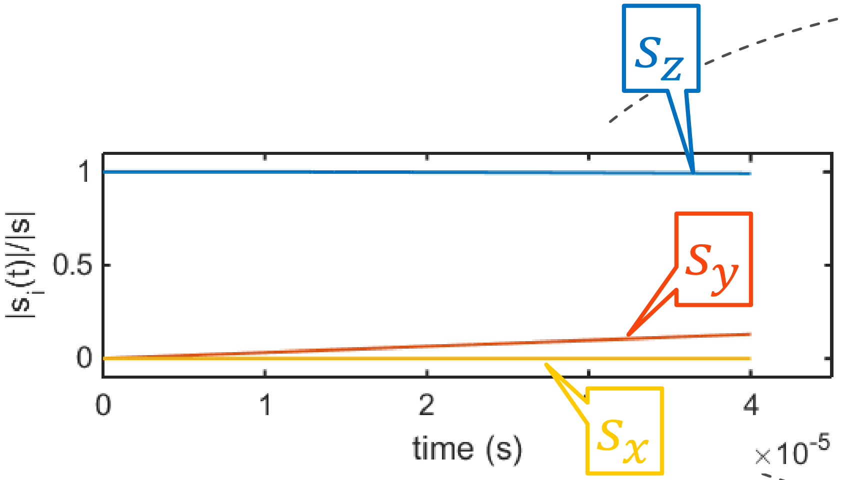
$$p_{\mathrm{magic}} = 0.7\ \mathrm{GeV}/c$$

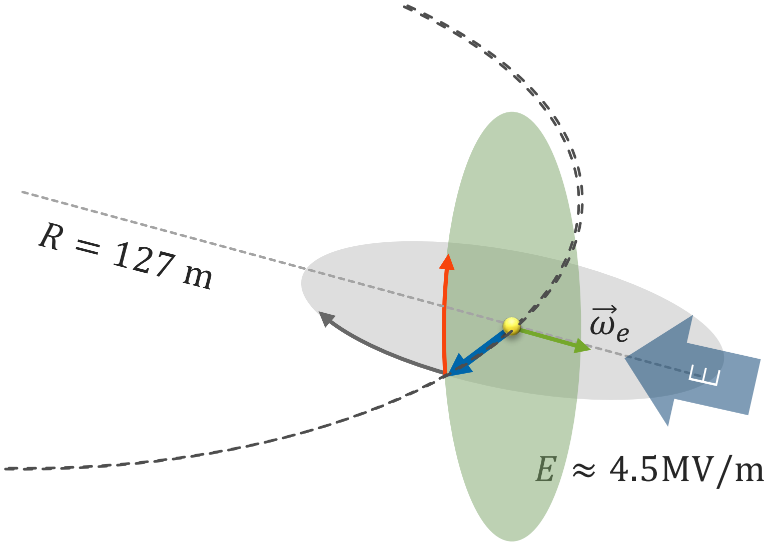
Muon dipole moments –freezing the spin at PSI

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

EDM term ω_e

$\sigma(d_\mu) \approx 10^{-29}\,e\text{cm}^*$





[*arXiv:2205/00830v1] ,

When to use which variant?

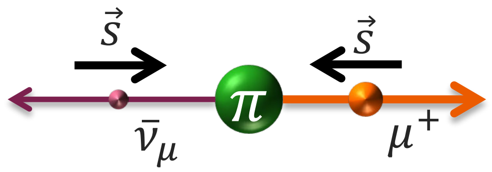
Frozen-spin sensitivity: $$\zeta = \frac{E_x + v_z B_y}{E_x} = \frac{a+1}{a\gamma^2}$$

Particle	μ/μ_N	a	$\zeta\gamma^2$
μ	-8.891	0.001166	858
p	-1.913	1.793	1.56
^{2}H	0.857	-0.143	-5.99
^{3}H	2.979	7.918	1.13
^{3}He	-2.128	-4.184	0.76

- The higher $\zeta\gamma^2$ the better the frozen-spin sensitivity
- Negaitve a does not permit a "magic momentum" scheme

Muon polarization and analysis

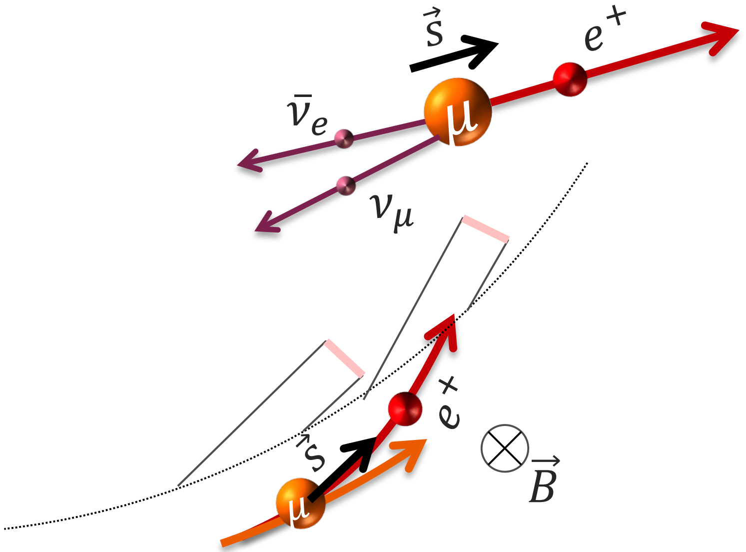
- Weak decay $\pi^+ \rightarrow \mu^+ + \bar{\nu}_\mu$ result in $P_\mu \approx 95\%$ for $p_\pi \sim 220\text{MeV}/c^2$ backward decay in $P_\mu \approx 95\%$



- Weak decay $\mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu$ results in decay asymmetry

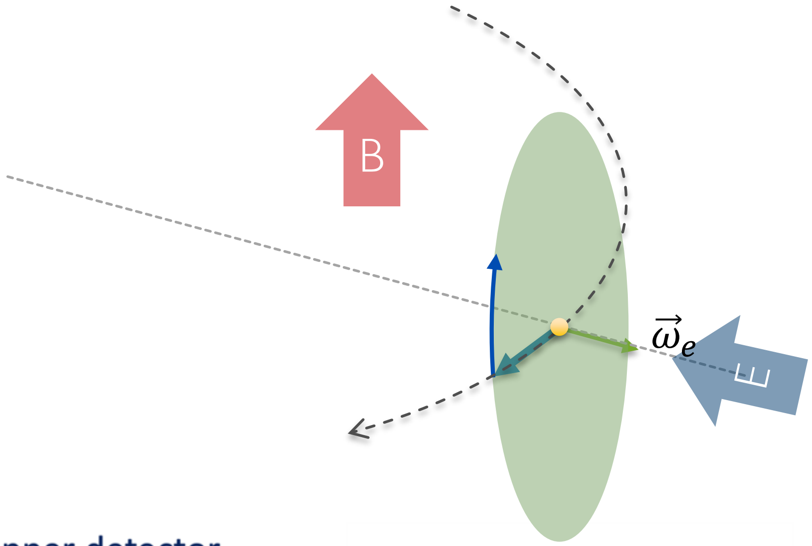
$$\bar{\alpha} \approx 0.3$$

- Detection of e^+ of decay (for EDM vertical resolution)

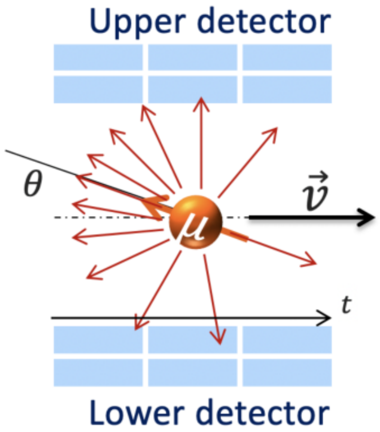


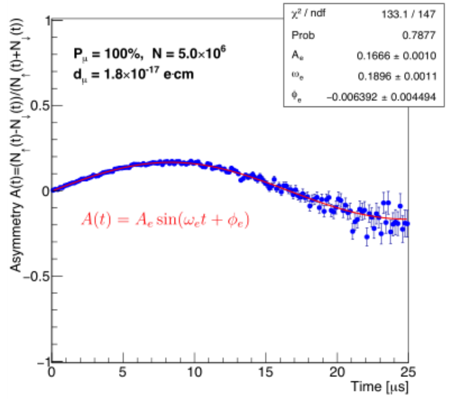
The general experimental idea for a muon EDM

- If the EDM $\neq 0$, then there will be a vertical precession out of the plane of the orbit
  - An asymmetry increasing with time will be observed recording decay positrons
- If the EDM $= 0$, then the spin should always be parallel to the momentum asymmetry should be zero



More details in talk by Chavdar





Current storage ring EDM projects

An all electric storage ring to search for the pEDM

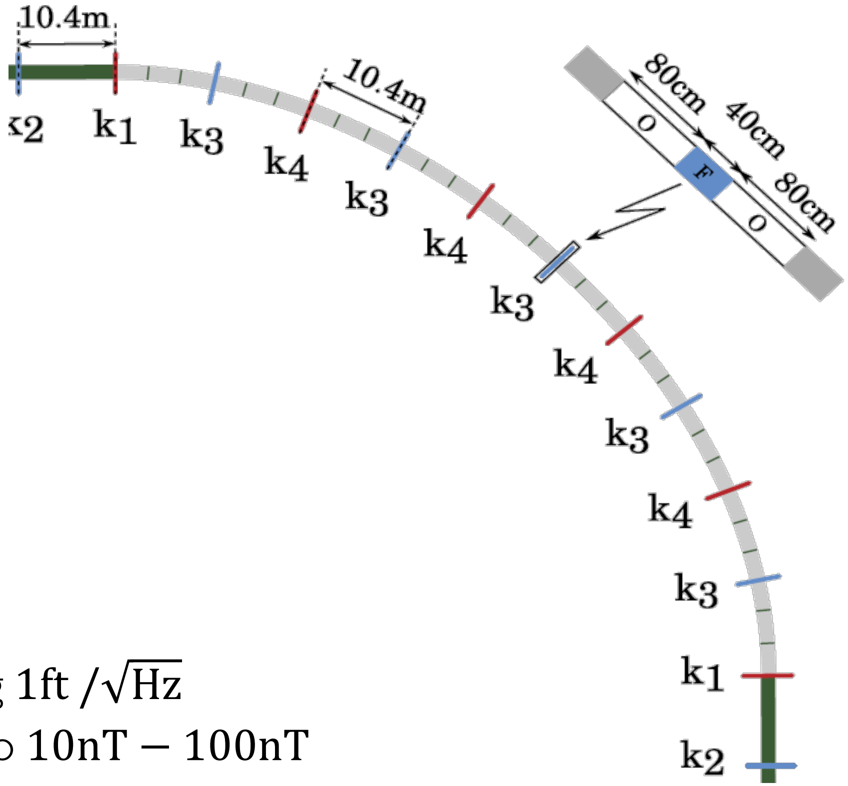
Magic momentum $\mathrm{p} = \frac{0.7\mathrm{GeV}}{c}$,

$\mathrm{E} = 8\mathrm{MV/m}, \rho = 50, \ell = 500\mathrm{m}$

$\tau_c > 1000s$

$\sigma \approx 2 \times 10^{-29} e\mathrm{cm}$

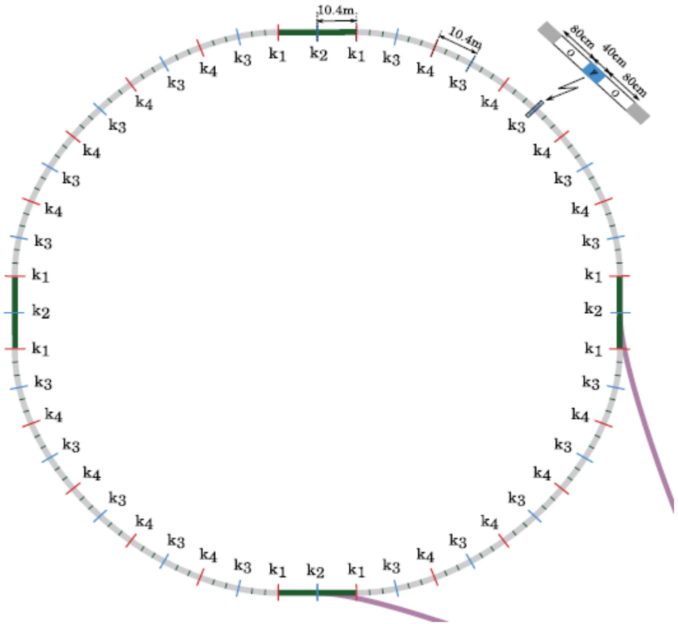
Polarimetry uses scattering on target



Systematic challenges:

- Radial B-field $\langle B_r \rangle < 10\mathrm{aT}$
- Can be detected by separation of CW and CCW beams by 1pm
- This requires BPM based on Squids resolving $\mathbf{1ft}/\sqrt{\mathbf{Hz}}$
- Magnetic shield to reduce background field to $\mathbf{10nT - 100nT}$

Hybrid storage ring high priority in SNOWMASS

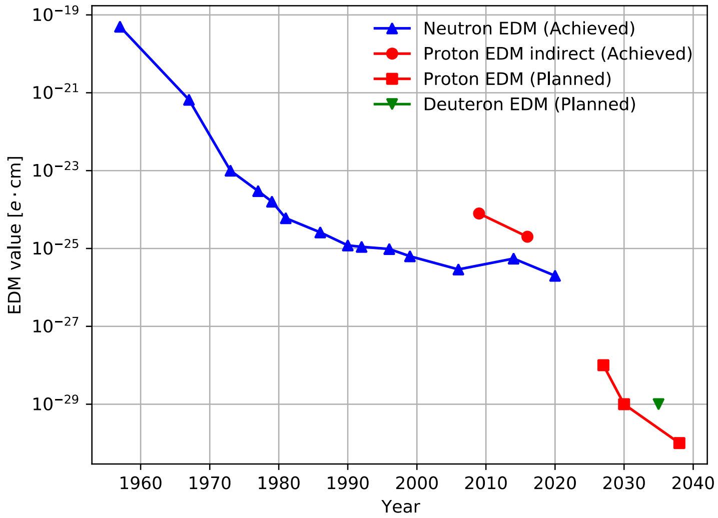


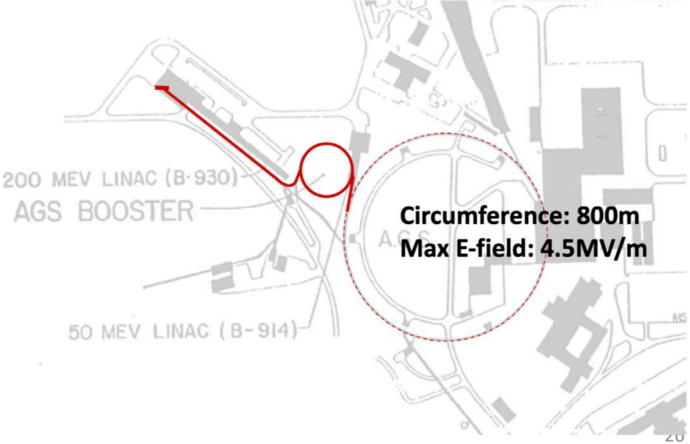
- EDM physics is must do, exciting and timely, CP-violation, $\sim 10^3$ TeV New-Physics reach, axion physics, DM/DE.

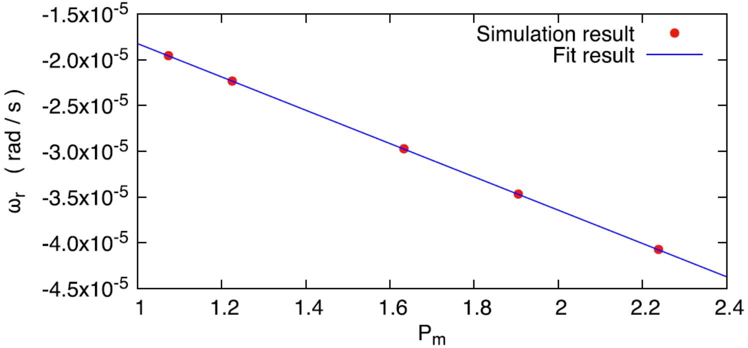
- Hybrid, symmetric ring lattice and spin-based alignment. Minimized systematic error sources. Statistics and systematics of pEDM to better than 10^{-29}e-cm.
- Simultaneous storage of clockwise and counterclockwise proton beams
- Snowmass encouraged BNL and the srEDM collaboration to come up with a technically strong proposal for a storage ring proton EDM. BNL is currently funding the cost estimate of the storage ring EDM experiment

Hybrid SR

- Replace electrostatic quadrupoles by magnetic ones and use “quadrupole tuning” to extrapolate to true EDM
- CW and CCW within $\mathbf{0.1\ \mu m}$ for all quadrupole strengths
- Cost estimation currently at BNL
- Circumference 500m
  E-field 45kV/cm







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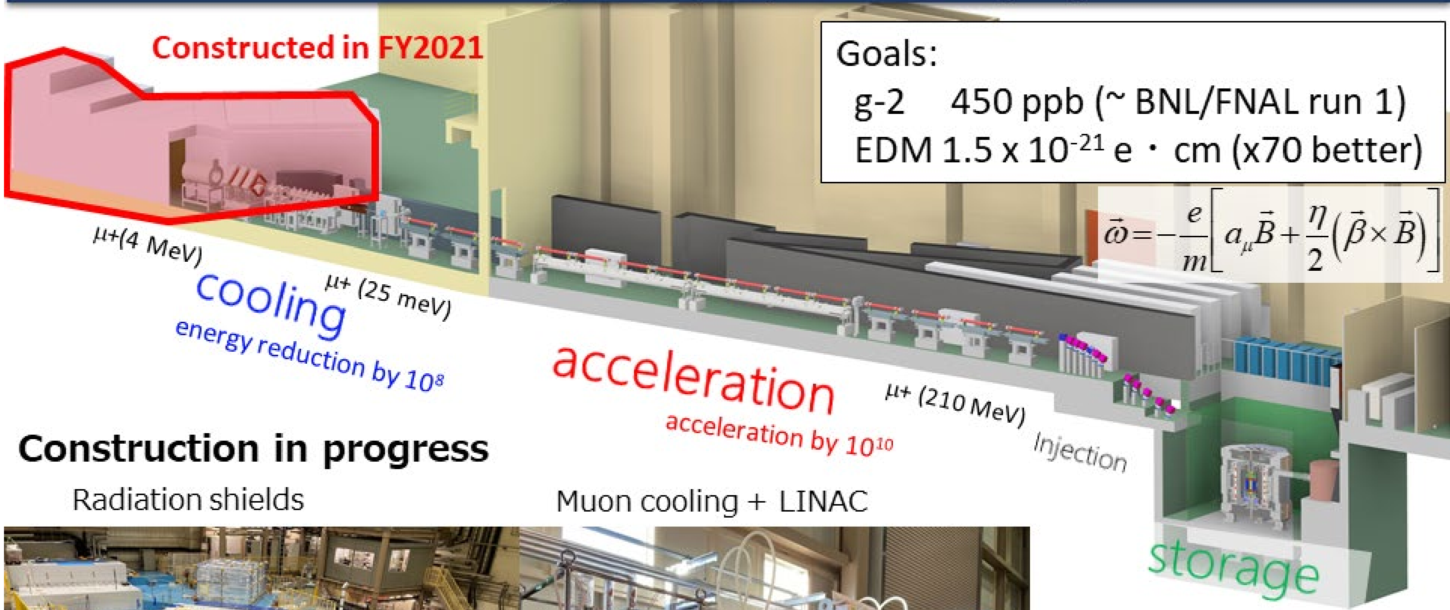
J-PARC muon g-2/EDM Experiment

Prog. Theor. Exp. Phys. **2019**, 053C02 (2019)

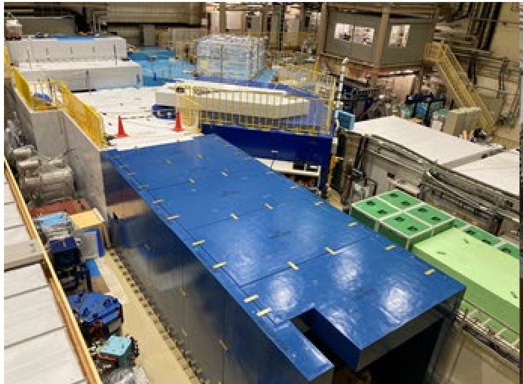
Goals:
g-2 450 ppb (~ BNL/FNAL run 1)
EDM 1.5 x 10^{-21} e・cm (x70 better)

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

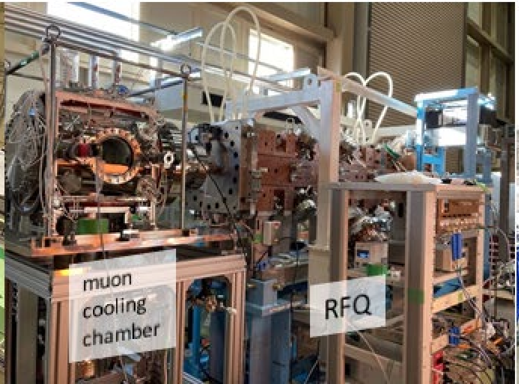


Construction in progress

Radiation shields



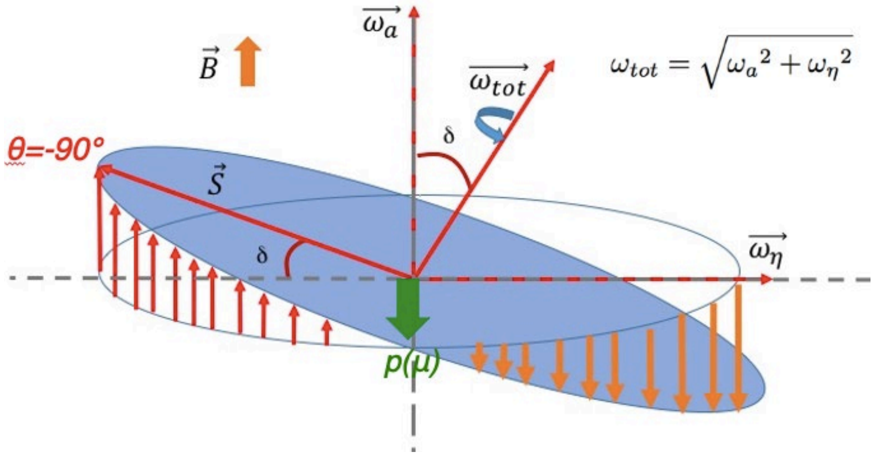
Muon cooling + LINAC



Magnetic field tests

Muon EDM @ FNAL

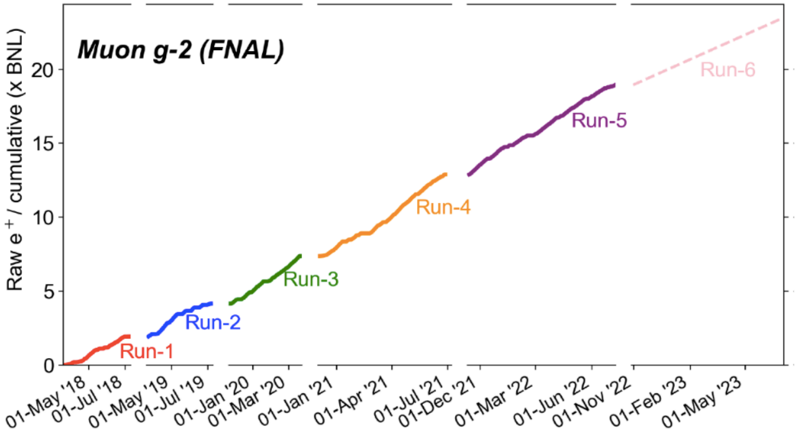
- Muon EDM causes tilt in precession plane
- Asymmetry in vertical decay angle of positrons
- Vertical angle measured by tracking detectors
- Momentum binned analysis for maximum sensitivity



- Run 1 analysis still blinded. Assuming zero signal expecting limit of:

  $|d_\mu| < 2.0 \times 10^{-19}$e.cm (95% C.L.)

- Still statistically limited in tracker analysis
- Factor of **~10 improvement** for statistics accumulated so far, with tracking improvements



Joe Price – on behalf of g-2 collaboration

EDM at FNAL

- Data taking concluded
- EDM analysis ongoing
- First result expected in … years

Frozen-spin in a compact SR for beta-decay ions

Feasibility of search for nuclear electric dipole moments at ion storage rings

I.B. Khriplovich [1]

Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia, and Novosibirsk University, Novosibirsk, Russia

Received 8 September 1998; revised 21 October 1998
Editor: P.V. Landshoff

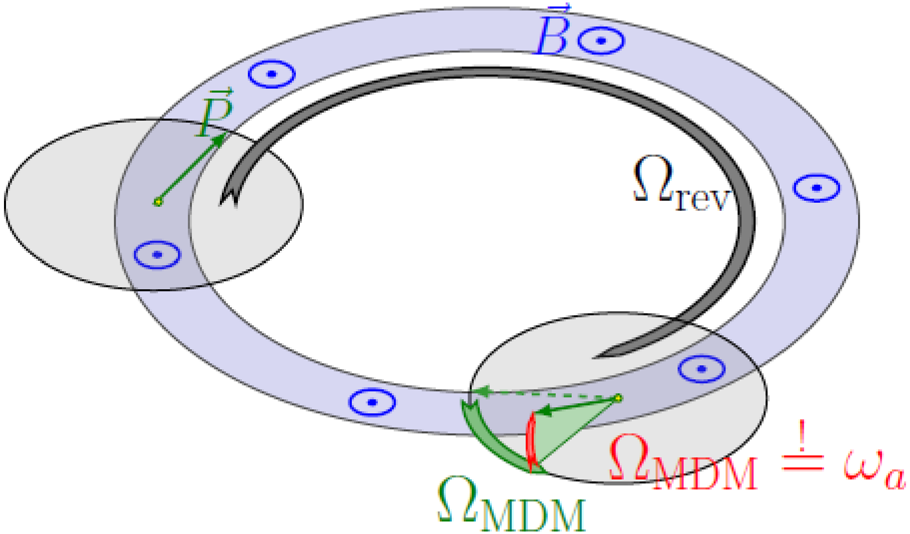
Advantages compared to muon:

- Much longer beta decay life time
- Sensitive to QCD-theta term
- Ideally magnetic momentum with $a \approx a_\mu$
- Input from theory and nuclear physics needed to identify ideal isotop

Ion	$J^\pi \to J^{\pi\prime}$	μ	z	$a \cdot 10^3$	$t_{1/2}$	Q (barn)	Branching
$^{24}_{11}$Na	$4^+ \to 4^+$	1.6903(8)	5	15.1(0.5)	15 h		99.944%
$^{60}_{27}$Co	$5^+ \to 4^+$	3.799(8)	23	−8(2)	5.3 y	0.44	99.925%
$^{82}_{35}$Br	$5^- \to 4^-$	1.6270(5)	13	27.2(0.3)	35 h	0.75	98.5%
$^{93}_{37}$Rb	$5/2^- \to 5/2^+$	1.4095(16)	27	−28.1(1.1)	5.8 s	0.18	43%
$^{94}_{37}$Rb	$3^- \to 3^-$	1.4984(18)	23	21.5(1.2)	2.7 s	0.16	30.6%
$^{110}_{47}$Ag*	$6^+ \to 5^+$	3.607(4)	33	3(1)	250 d	1.4	66.8%
$^{118}_{49}$In*	$8^- \to 7^-$	3.321(11)	25	−19(3)	8.5 s	0.44	1.4%
$^{120}_{49}$In*	$(8^-) \to 7^-$	3.692(4)	27	26(1)	47 s	0.53	84.1%
$^{121}_{50}$Sn	$3/2^+ \to 5/2^+$	0.6978(10)	28	6(1)	27 h	−0.02(2)	100%
$^{125}_{51}$Sb	$7/2^+ \to 5/2^+$	2.630(35)	47	0 ± 13	2.8 y		40.3%
$^{131}_{53}$I	$7/2^+ \to 5/2^+$	2.742(1)	51	7.0(0.4)	8.0 d	−0.40	89.9%
$^{133}_{53}$I	$7/2^+ \to 5/2^+$	2.856(5)	53	25(2)	21 h	−0.27	83%
$^{133}_{54}$Xe	$3/2^+ \to 5/2^+$	0.81340(7)	36	2.58(9)	5.2 d	0.14	99%
$^{134}_{55}$Cs	$4^+ \to 4^+$	2.9937(9)	51	−16.0(0.3)	2.0 y	0.39	70.11%
$^{136}_{55}$Cs	$5^+ \to 6^+$	3.711(15)	51	−9(4)	13 d	0.22	70.3%
$^{137}_{55}$Cs	$7/2^+ \to 11/2^-$	2.8413(1)	55	11.9(0.1)	30 y	0.051	94.4%
$^{139}_{55}$Cs	$7/2^+ \to 7/2^-$	2.696(4)	53	11(1)	9.3 m	−0.075	82%
$^{141}_{55}$Cs	$7/2^+ \to 7/2^-$	2.438(10)	49	3(4)	25 s	−0.36	57%
$^{143}_{55}$Cs	$3/2^+ \to 5/2^-$	0.870(4)	41	12(5)	1.8 s	0.47	24%
$^{140}_{57}$La	$3^- \to 3^+$	0.730(15)	17	3 ± 21	1.7 d	0.094	44%
$^{160}_{65}$Tb	$3^- \to 2^-$	1.790(7)	47	16(4)	72 d	3.8	44.9%
$^{170}_{69}$Tm	$1^- \to 0^+$	0.2476(36)	21	2.2 ± 14.5	129 d	0.74	99.854%
$^{177}_{71}$Lu	$7/2^+ \to 7/2^-$	2.239(11)	57	- 6(5)	6.7 d	3.4	78.6%
$^{183}_{73}$Ta	$7/2^+ \to 7/2^-$	(+)2.36(3)	61	12(13)	5.1 d		92%
$^{192}_{77}$Ir	$4(^+) \to 3^+,4^+$	1.924(10)	47	−17(5)	74 d	2.3	42%,54%
$^{196}_{79}$Au	$2^- \to 2^+$	0.5906(5)	29	−1.1(8)	6.2 d	0.81	8%
$^{198}_{79}$Au	$2^- \to 2^+$	0.5934(4)	29	13.9(7)	2.7 d	0.68	98.99%
$^{203}_{80}$Hg	$5/2^- \to 3/2^+$	0.84895(13)	34	14.71(15)	47 d	0.34	100%
$^{222}_{87}$Fr	$2^- \to 3^-$	0.63(1)	35	0 ± 20	14 m	0.51	55%
$^{223}_{87}$Fr	$3/2(^-) \to 3/2^-$	1.17(2)	87	0 ± 20	22 m	1.2	67%
$^{224}_{87}$Fr	$1(^-) \to 1^-$	0.40(1)	45	−3 ± 25	3.3 m	0.52	42%
$^{242}_{95}$Am	$1^- \to 0^+,2^+$	0.3879(15)	47	−0.5 ± 3.9	16 h	−2.4	37%,46%

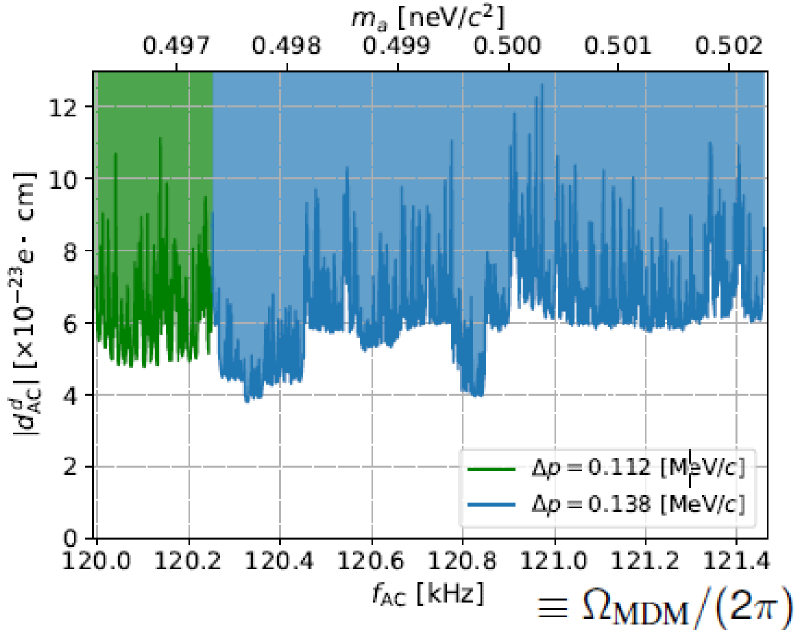
JEDI – Jülich EDM Investigations

- Measurement of Axions using deuterons



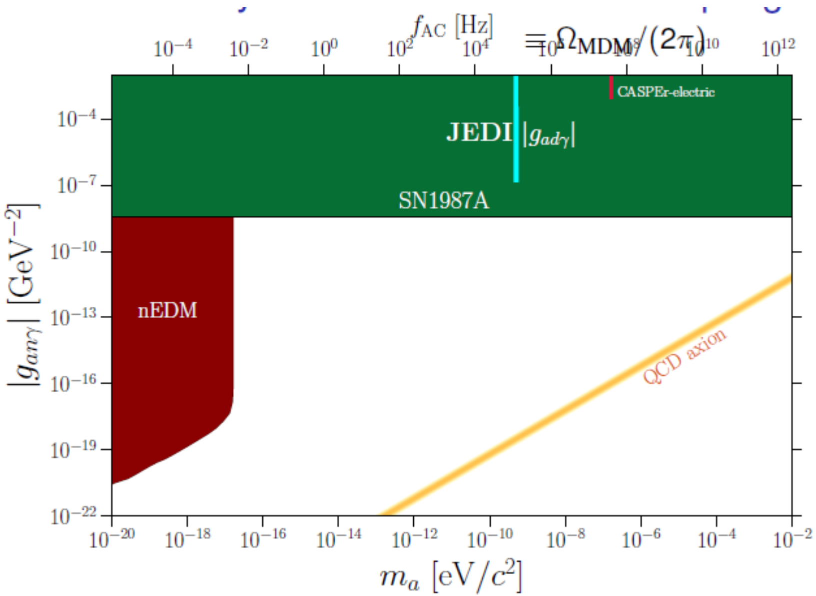
- Let spins precess in horizontal plane
- Axion/ALP will lead to a build-up of a vertical polarization resonance condition: $\hbar\omega_a = m_a c^2$

First results: ALPS at JEDI



https://arxiv.org/abs/2208.07293

- d_{AC}: Oscillating part of electric dipole moment
- a few days of beam time
- $f_{AC} = \frac{1}{2\pi}\frac{m_a c^2}{\hbar} = \gamma G f_{\text{rev}}$



Conclusions

- Storage rings exploiting the frozen-spin technique could provide a new window to CP violation manifesting in EDM of charged particles

- At PSI a compact muon EDM experiment is being setup for demonstration

- The international storage ring EDM collaboration proposed a new lattice for, e.g. BNL to search with a sensitivity of better than

$$\sigma(d_p) \approx 10^{-29} e\mathrm{cm}$$