muEDM in the landscape of storage ring EDM searches

– LTPhD Seminar (26 September 2023) –

Tim Hume, Muon Physics Group

Supervised by Dr. Philipp Schmidt-Wellenburg

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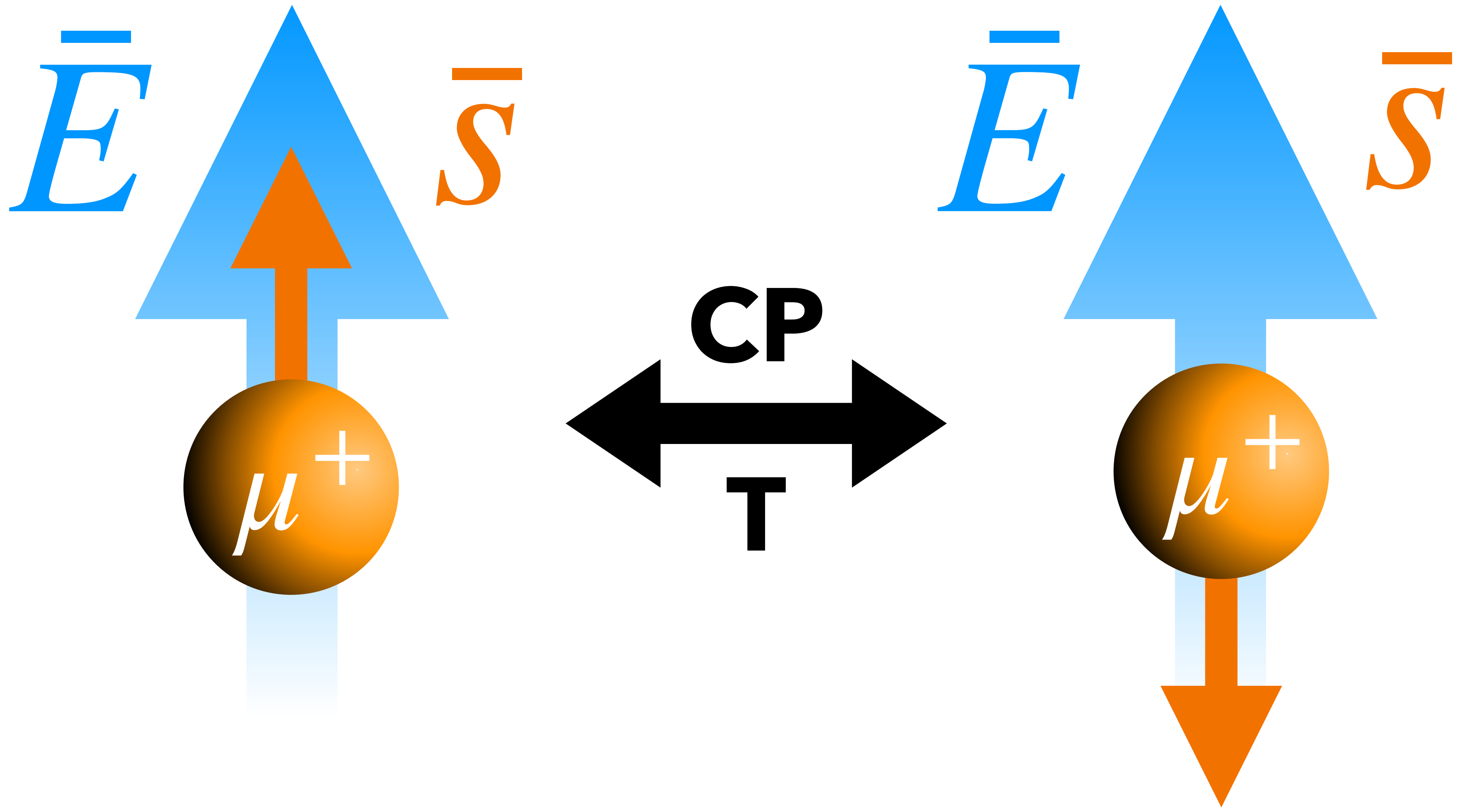
Muon Electric Dipole Moment

A permanent EDM requires T violation, equivalently CP violation by the CPT Theorem.



$$H_\mu^{EDM} \overset{\beta \to 0}{\propto} d_\mu \bar{\sigma} \cdot \bar{E}$$

Hamiltonian EDM term is CP violating

SM Prediction: $d_\mu^{SM} = 1.4 \times 10^{-38}\, e\,.\,\mathrm{cm}$

(Yamaguchi & Yamanaka, 2020)

Y. Yamaguchi & N. Yamanaka. *PRL*, 125:241802, 2020. DOI: 10.1103/PhysRevLett.125.241802.
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T.S. Roussy et al. Science, 381(6653):46–50, 2023. DOI: 10.1126/science.adg4084

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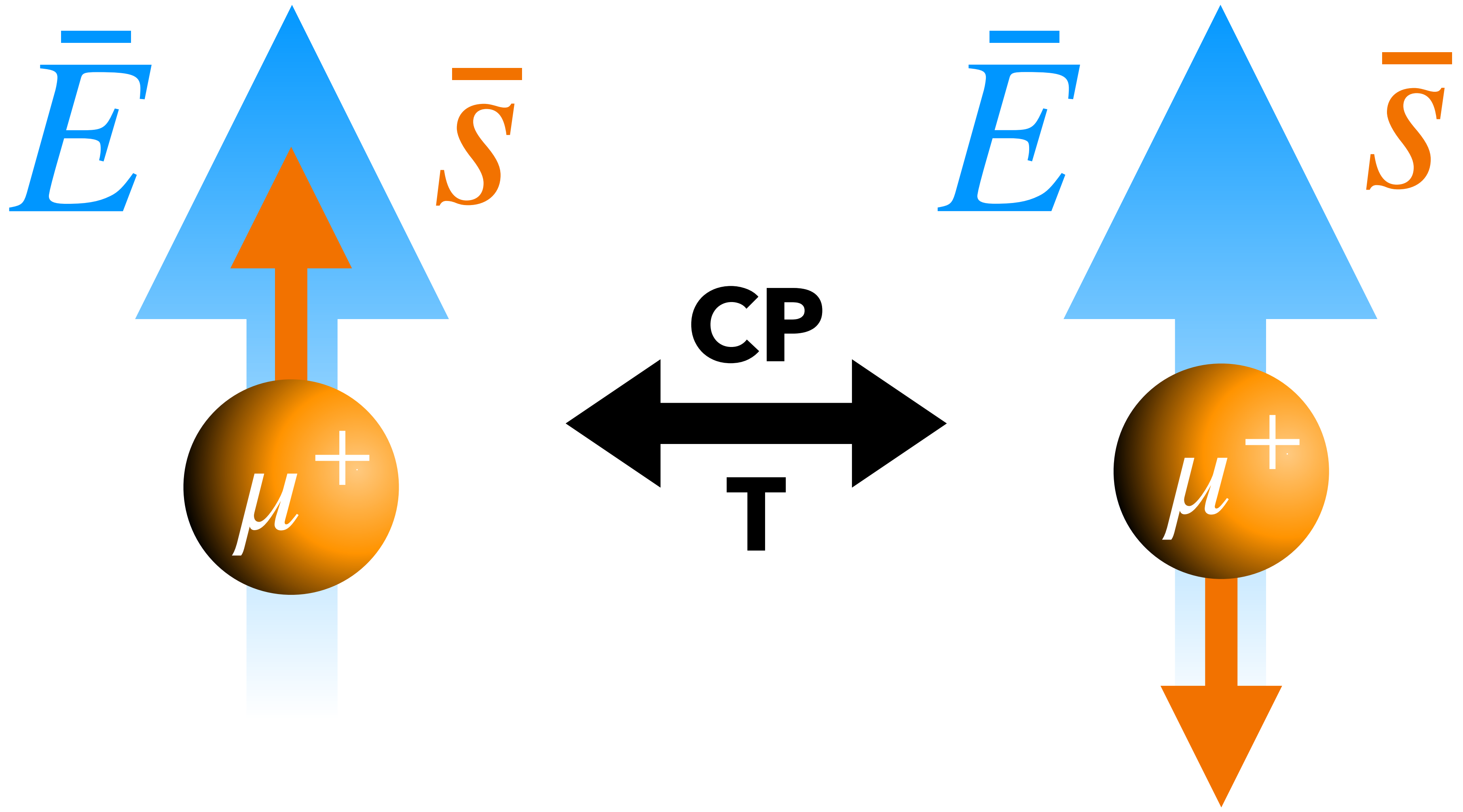

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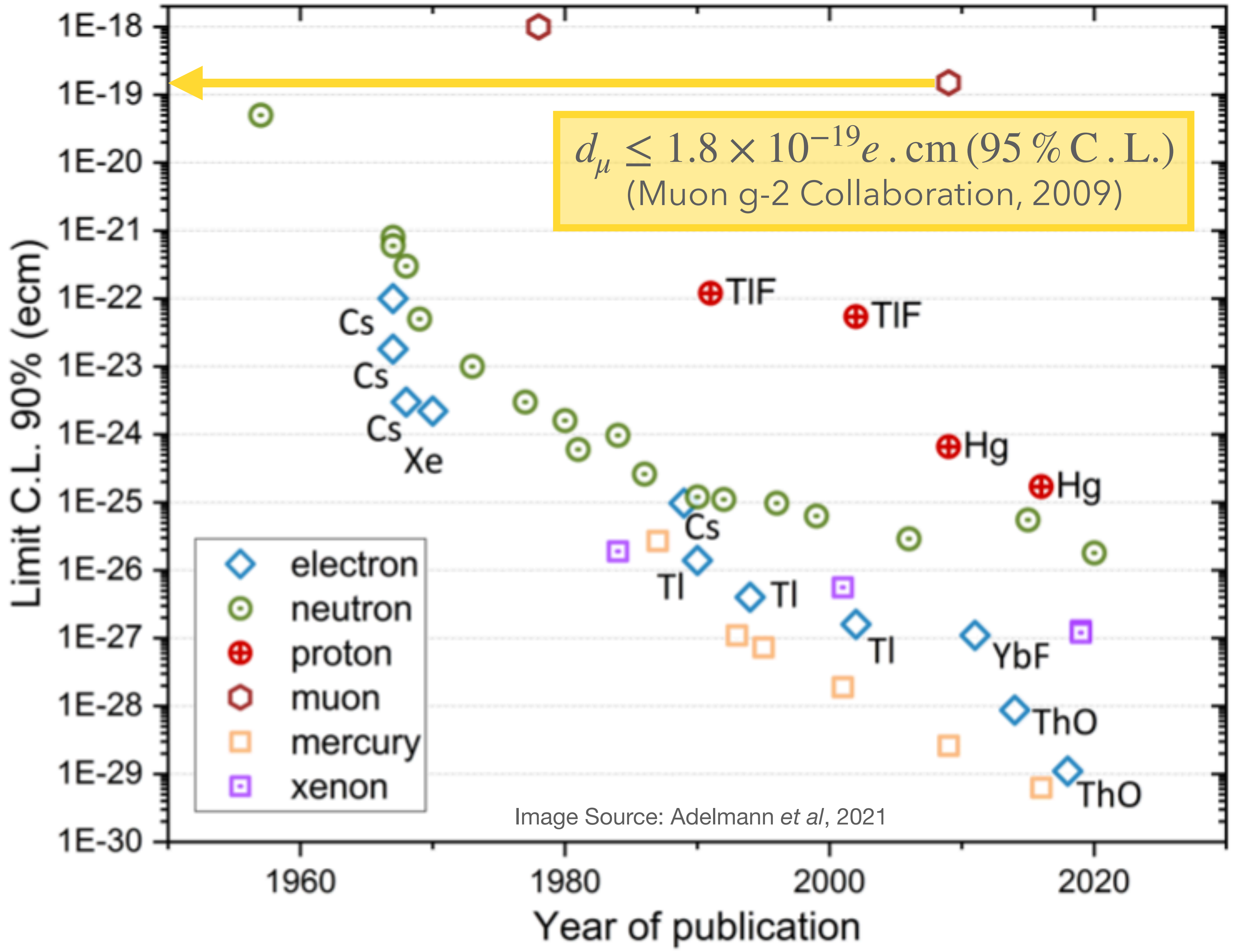

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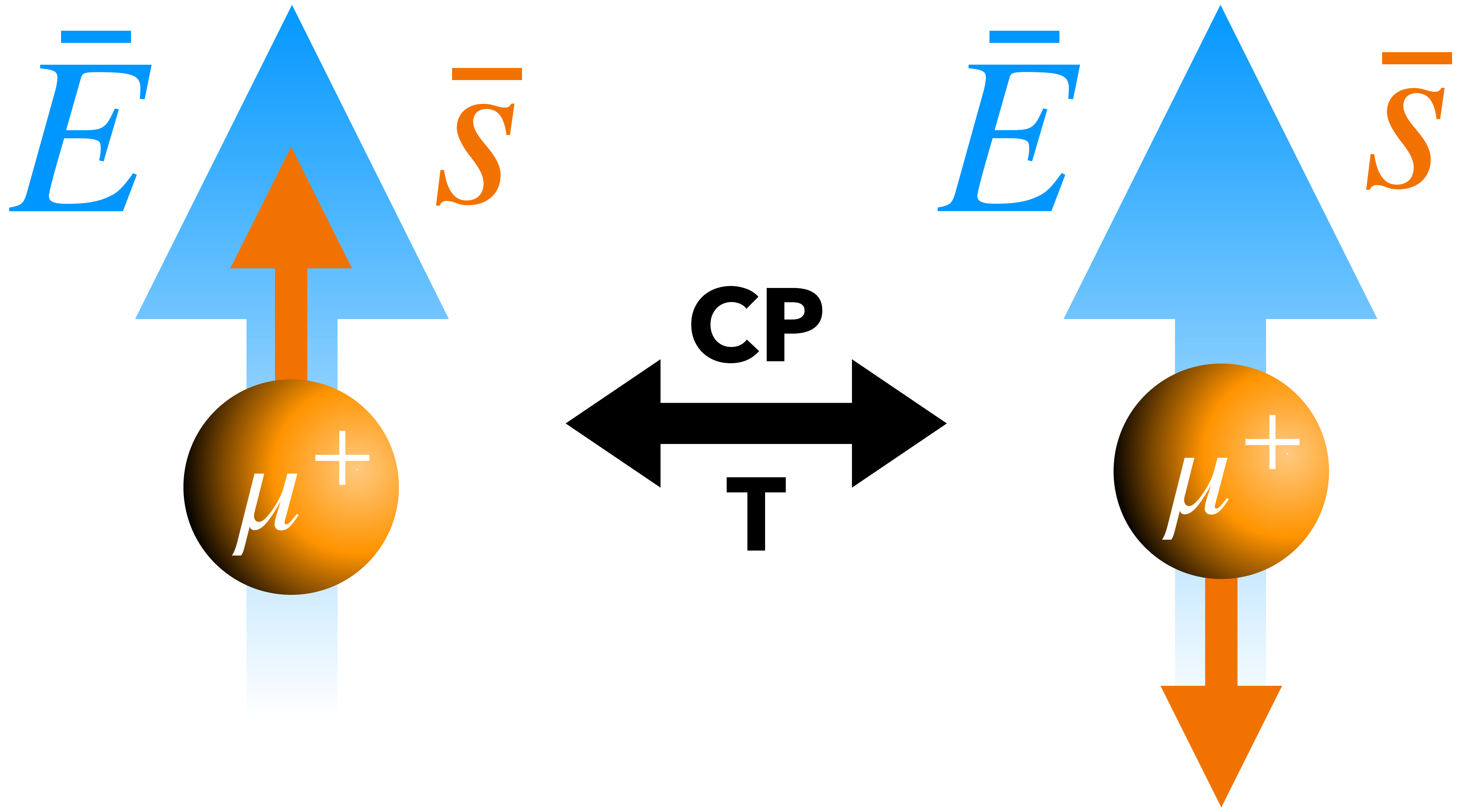
$$d_e \leq 4.1 \times 10^{-30} e\,.\,\mathrm{cm} \overset{LFU}{\Longrightarrow} ?\; d_\mu \leq \frac{m_\mu}{m_e} d_e = 6.0 \times 10^{-28} e\,.\,\mathrm{cm}$$

(Roussy et al., 2023)



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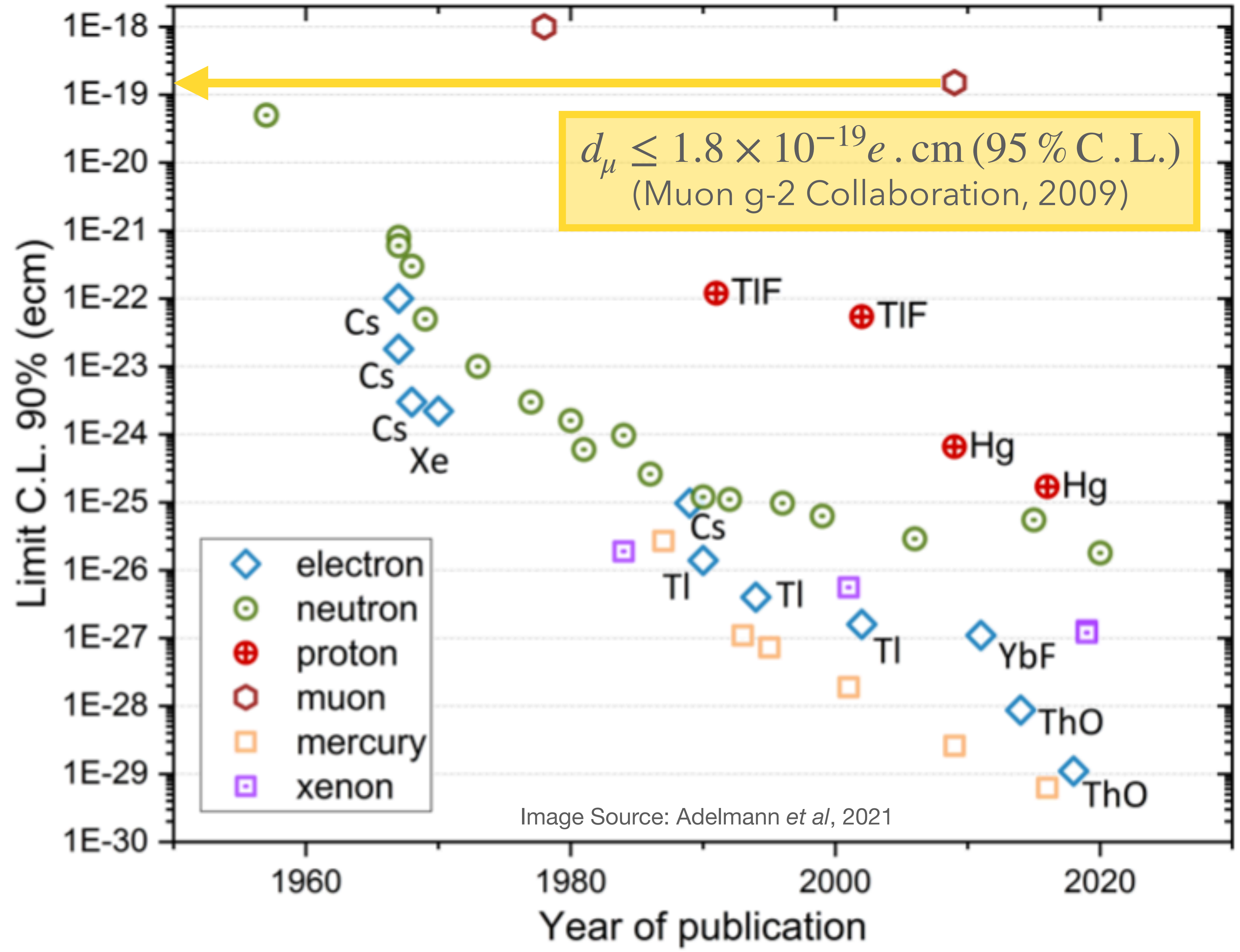

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Standard Model Prediction

The muon EDM is heavily suppressed in the SM.
With current sensitivity $\sim 10^{19}$ larger, we essentially perform a "background-free" search.

PHYSICAL REVIEW LETTERS 125, 241802 (2020)

Large Long-Distance Contributions to the Electric Dipole Moments of Charged Leptons in the Standard Model

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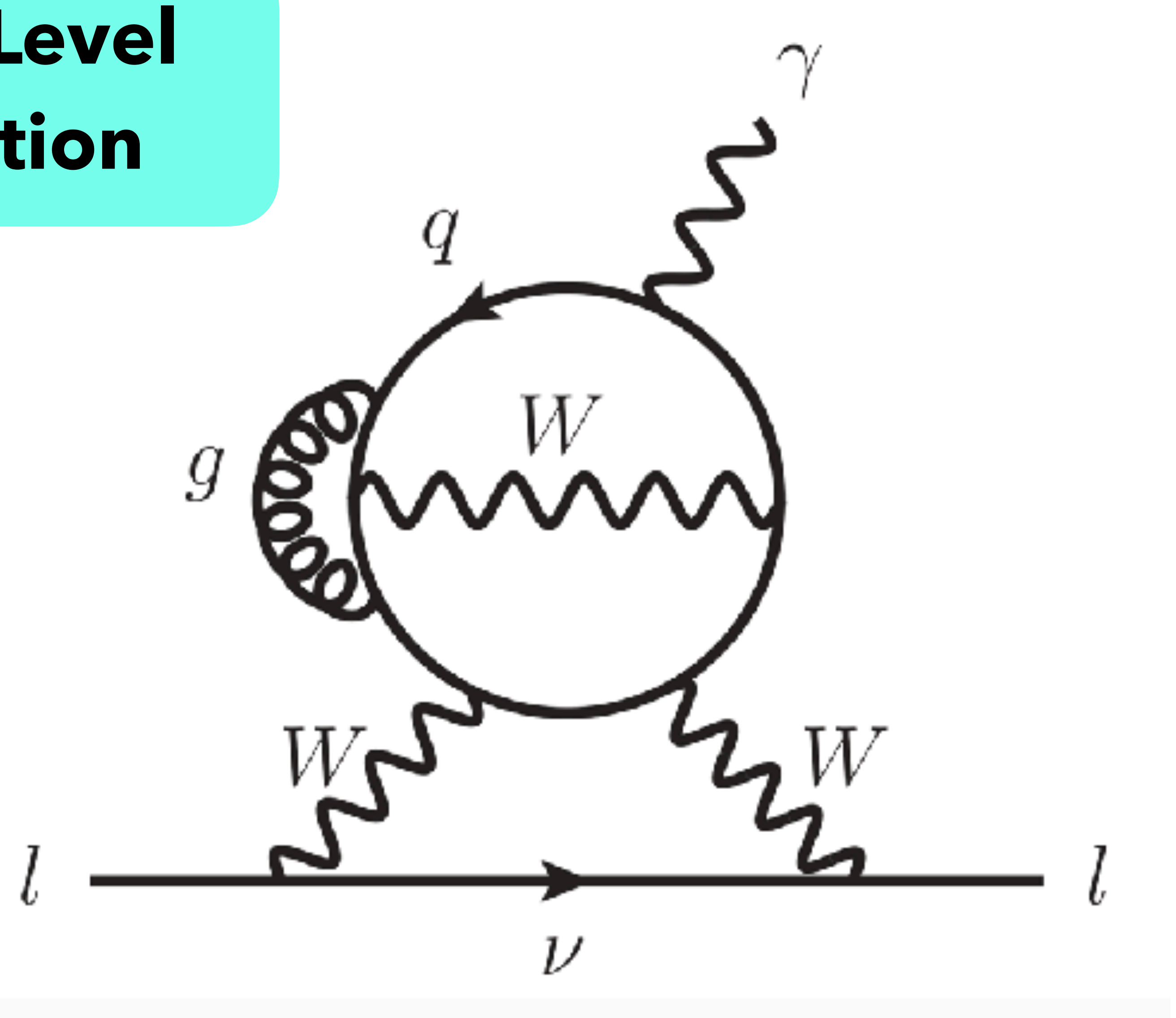
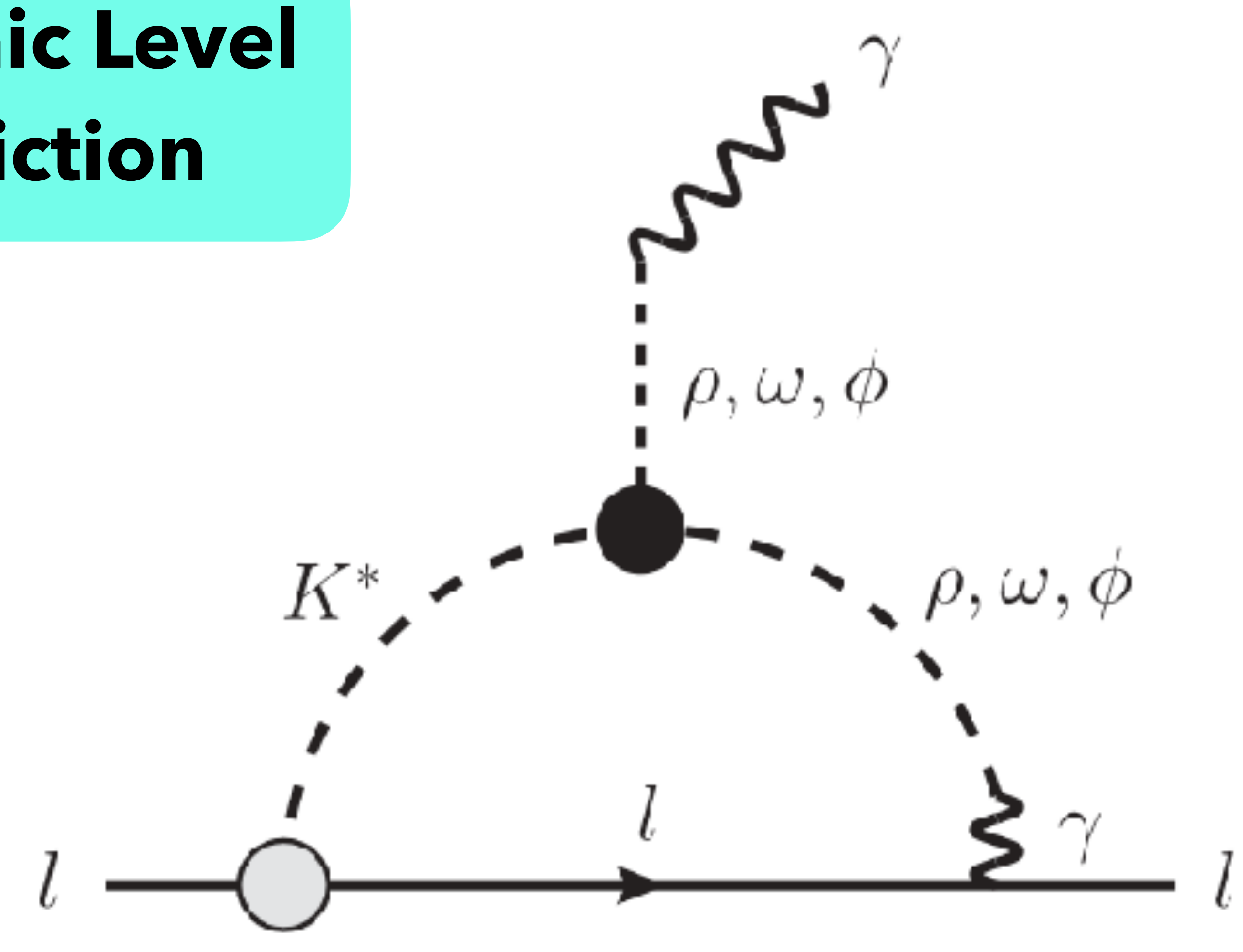
(Received 4 June 2020; accepted 9 November 2020; published 10 December 2020)

Quark Level Prediction



4-loop effect
Cancellation through GIM Mechanism
$d_\mu \sim \mathcal{O}(10^{-48}\, ecm)$

Hadronic Level Prediction



1-loop effect
Less cancellation due to different momenta
$d_\mu = 1.4 \times 10^{-38}\, ecm$

Lepton Flavour Violation

PHYSICAL REVIEW D 98, 113002 (2018)

Combined explanations of $(g-2)_{\mu,e}$ and implications for a large muon EDM

Andreas Crivellin,[1] Martin Hoferichter,[2] and Philipp Schmidt-Wellenburg[1]
[1]Paul Scherrer Institut, CH–5232 Villigen PSI, Switzerland
[2]Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195-1550, USA

(Received 3 August 2018; published 7 December 2018)

A BSM model assuming Minimal Flavour Violation (MFV) leads to a scaling of the lepton EDMS with mass, as expected with Lepton Flavour Universality (LFU):

$$d_e \leq 4.1 \times 10^{-30} e\,.\,\mathrm{cm} \overset{MFV}{\Longrightarrow} d_\mu \leq \frac{m_\mu}{m_e} d_e = 6.0 \times 10^{-28} e\,.\,\mathrm{cm}$$

(Roussy et al., 2023)

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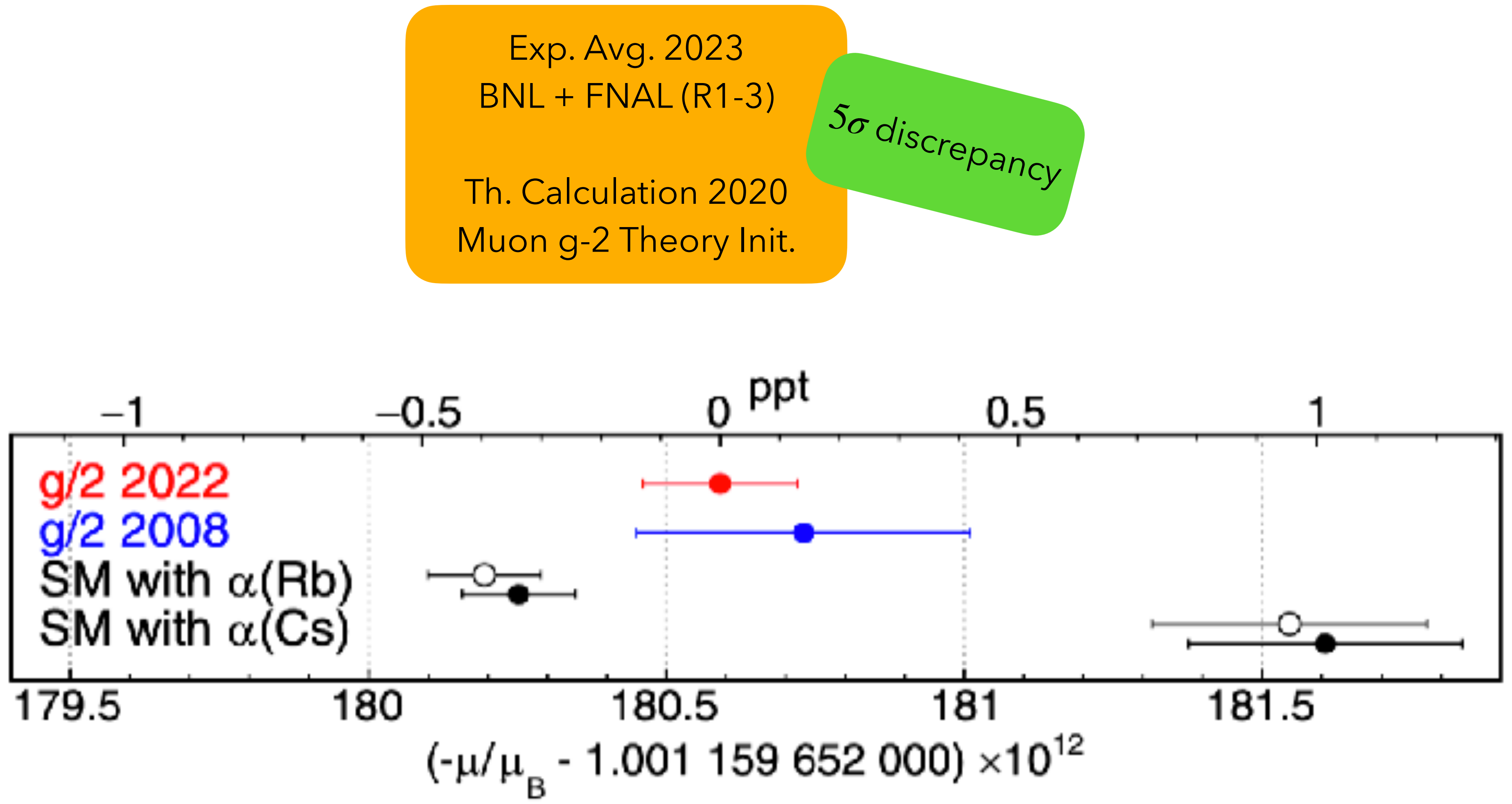
(Roussy et al., 2023) **?**

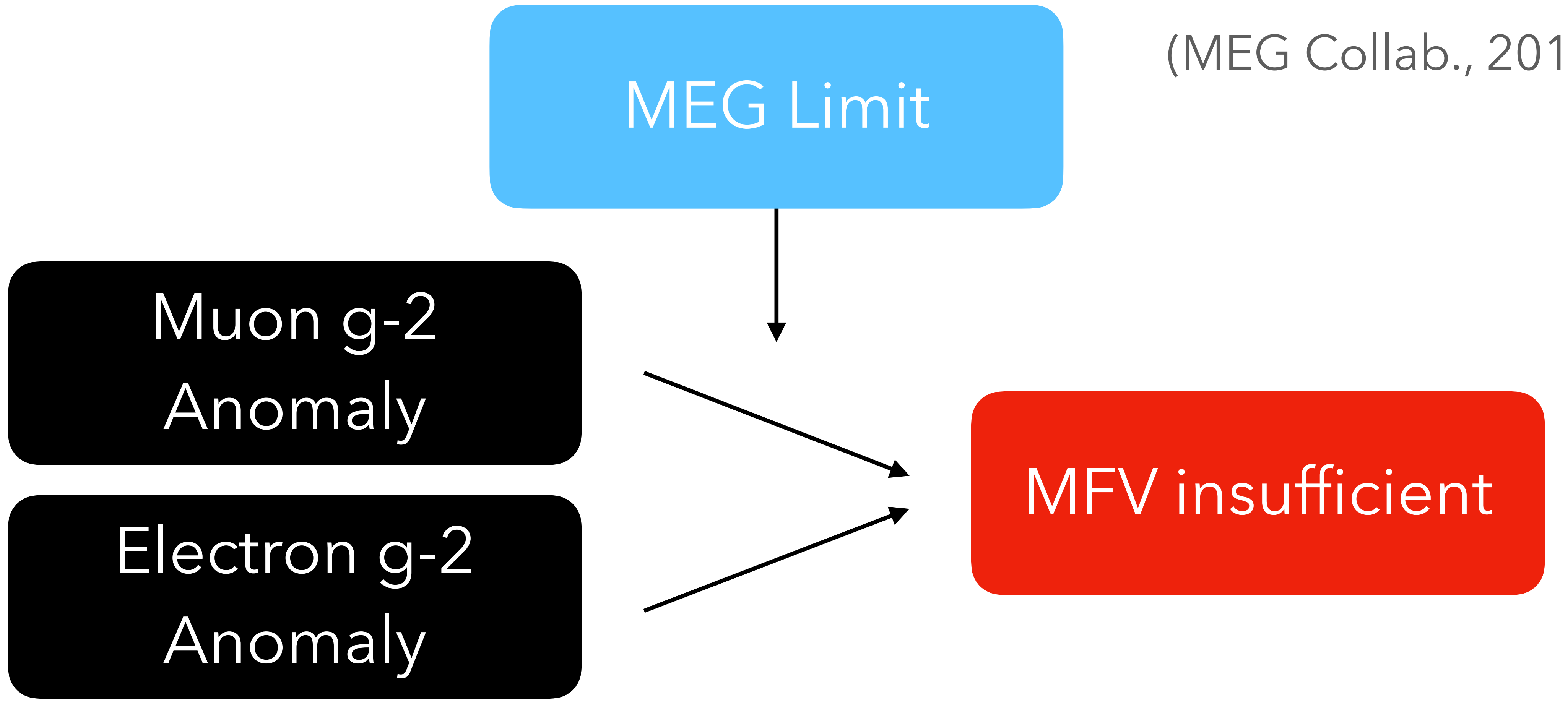
$$\mathrm{Br}[\mu \to e\gamma] < 4.2 \times 10^{-13}\ (90\,\%\ \mathrm{C.L.})$$

(MEG Collab., 2016)



$$\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}}$$

$$\Delta a_e = a_e^{\mathrm{exp}} - a_e^{\mathrm{SM}}$$



Given the constraints from MEG, and while the g-2 anomalies persist, a BSM theory addressing such anomalies should decouple e and μ sectors, accommodating a large muon EDM.

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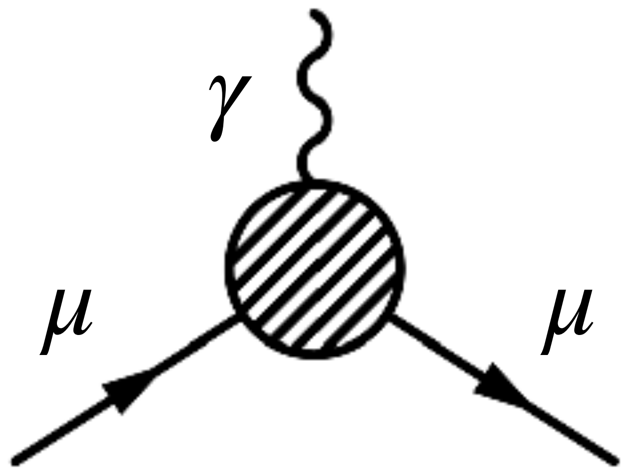
The EFT includes terms for the magnetic ($\sigma_{\alpha\beta}$) and electric ($\sigma_{\alpha\beta}\gamma^5$) dipole moments:

$$H_{\text{eff}} = c_R^{\ell_f \ell_i} \bar{\ell}_f \sigma_{\alpha\beta} P_R \ell_i F^{\alpha\beta} + \text{h.c.}$$



Expanding the terms ($P_R = \left(1+\gamma^5\right)/2$) and reducing to low energy limit (dipole form factors as $q^2 \to 0$), gives:

$$a_\mu^{(\text{eff})} = \frac{4m_\mu}{e}\text{Re}(c_R^{\mu\mu}) \qquad d_\mu^{(\text{eff})} = -2\text{Im}(c_R^{\mu\mu})$$

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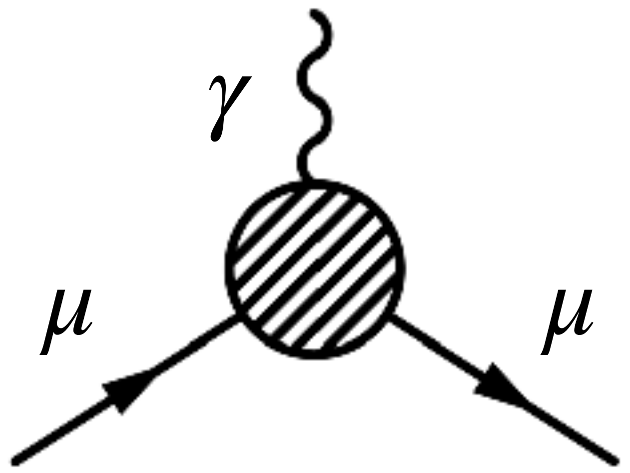

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Precision eEDM searches have constrained $\text{Im}(c_R^{ee})$, but that of the muon $\text{Im}(c_R^{\mu\mu})$ remains largely unconstrained:

$$\arg(c_R^{\mu\mu}) = \arctan\left(\frac{2m_\mu}{e}\frac{d_\mu^{(\text{eff})}}{a_\mu^{(\text{eff})}}\right)$$

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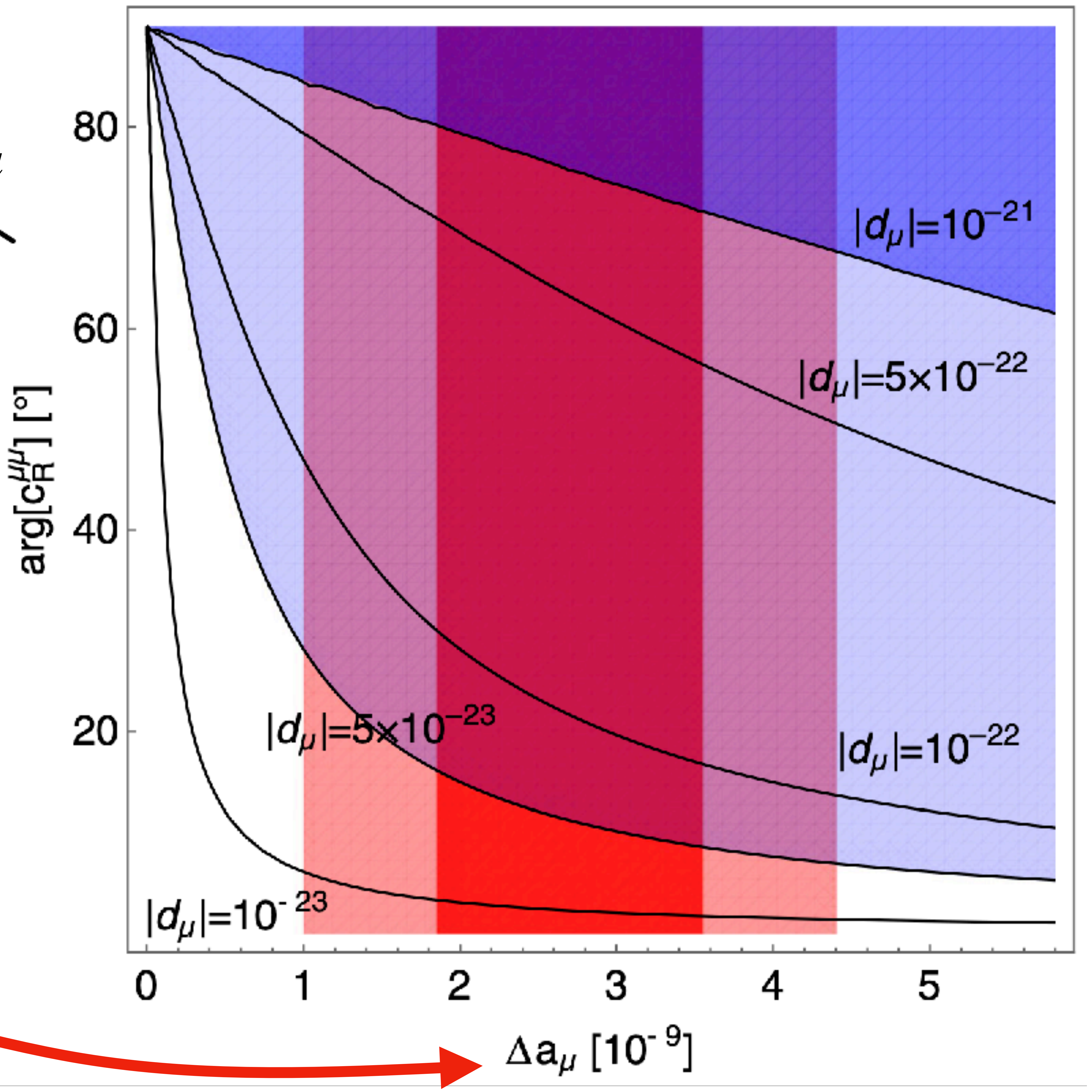

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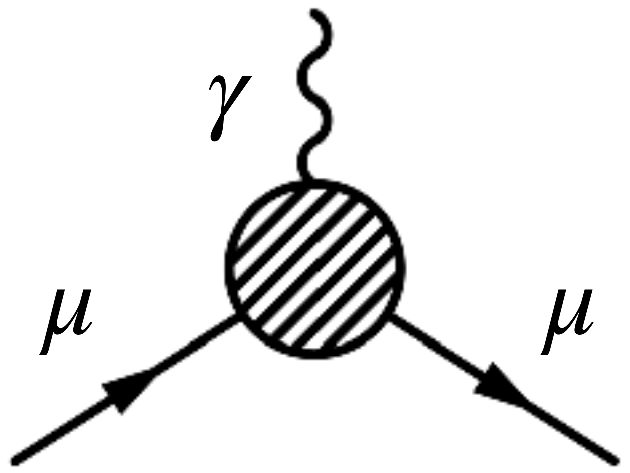

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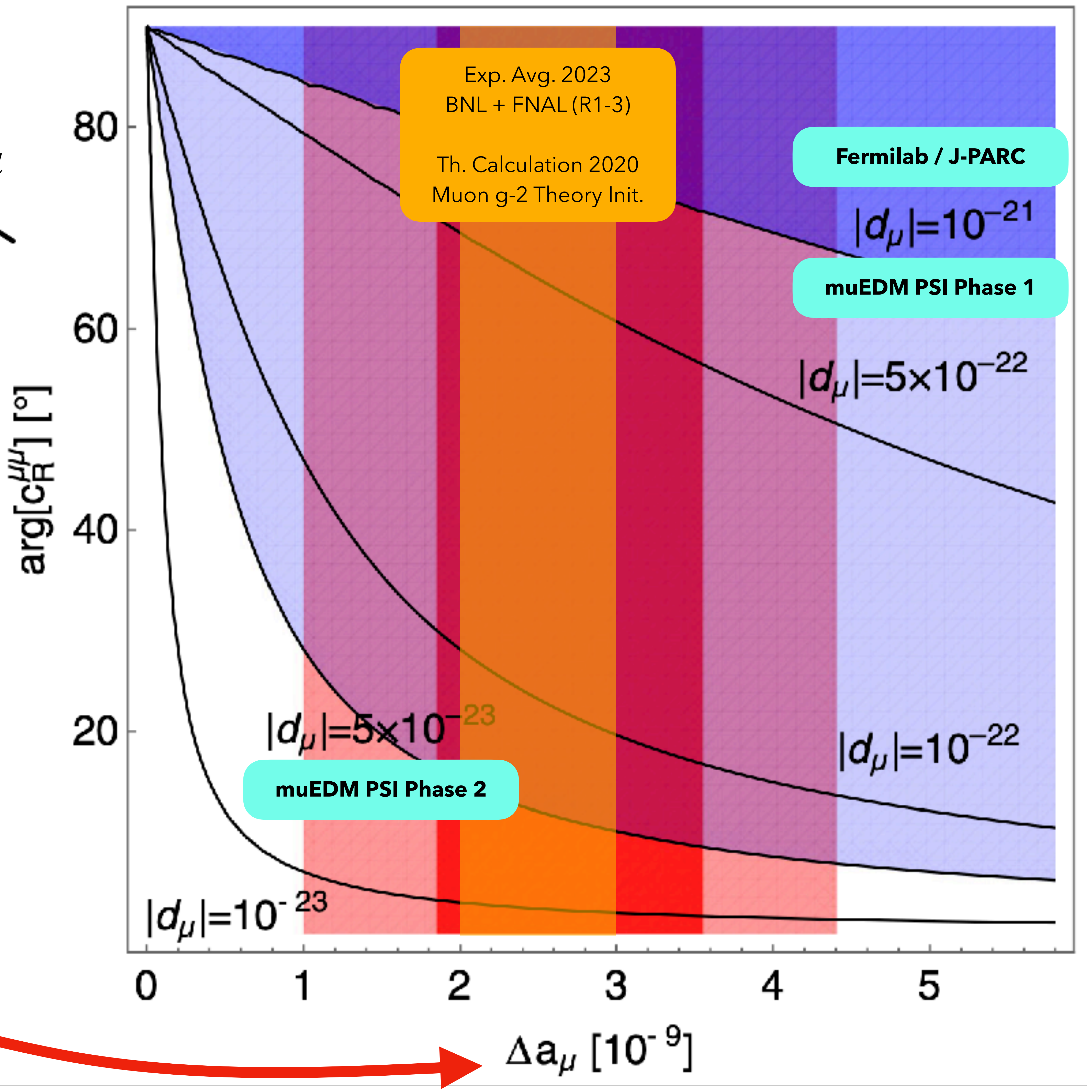

Indirect Limits

Atomic EDMs can also constrain CP-violating observables. The atomic EDM (due to relativistic corrections that counter the Schiff Theorem) is scaling as $d_{\text{atom}} \propto \alpha^2 Z^3$

PHYSICAL REVIEW LETTERS **128,** 131803 (2022)

Improved Indirect Limits on Muon Electric Dipole Moment

Yohei Ema,[1,*] Ting Gao,[2,†] and Maxim Pospelov[2,3,‡]

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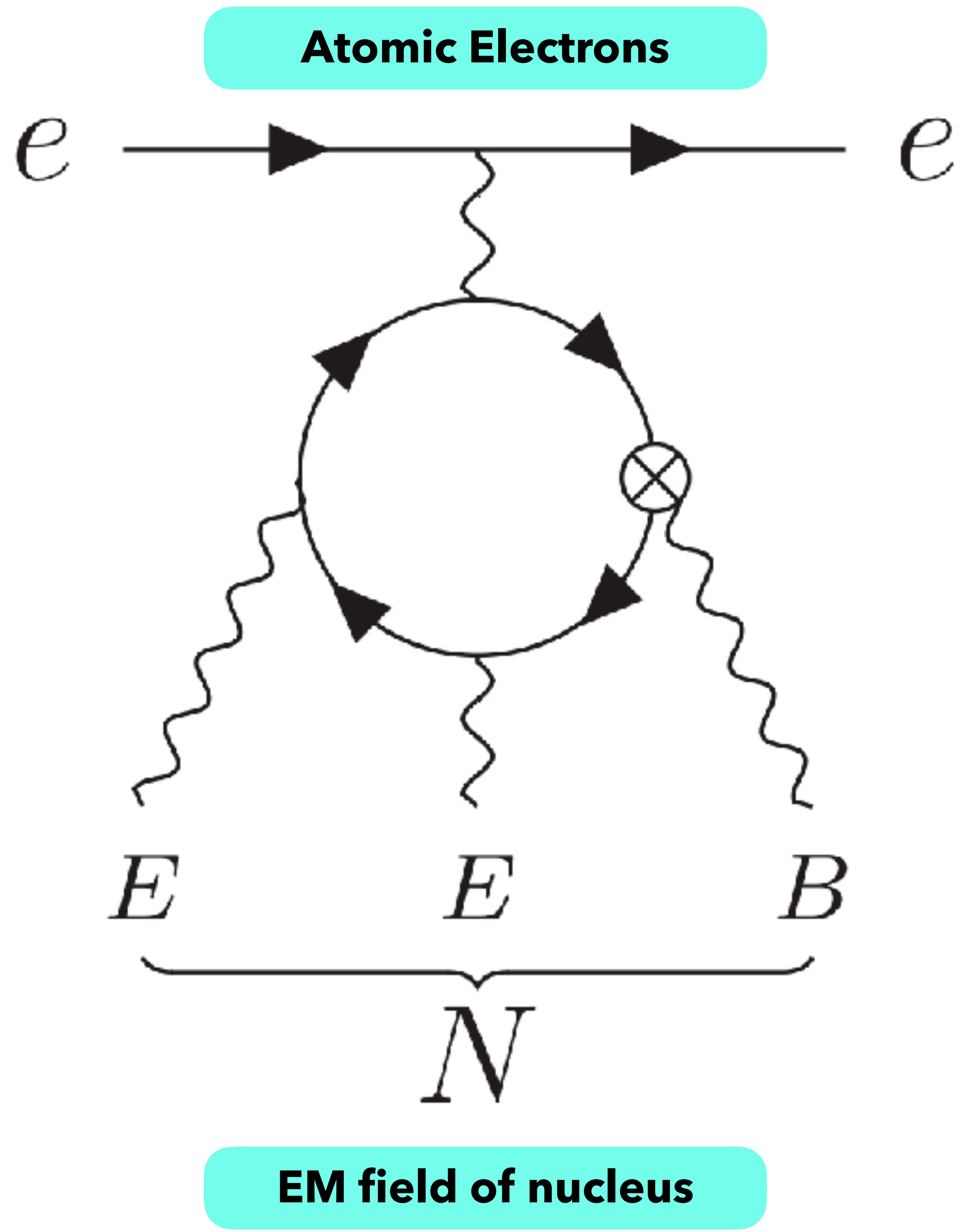
Low photon momenta inside nucleus: $q_\gamma \sim 30\,\text{MeV} < m_\mu$

Treat only the dominant $\mathbf{E}^3\mathbf{B}$ interaction inside the nucleus

$$\mathscr{L} = -\frac{d_\mu e^3}{12\pi^2 m_\mu^3}(\mathbf{E}\cdot\mathbf{B})(\mathbf{E}\cdot\mathbf{E} - \mathbf{B}\cdot\mathbf{B})$$

Nuclear $\mathbf{E}(r)$ field based on collective charge properties

Nuclear $\mathbf{B}(r, I)$ field estimated using shell model



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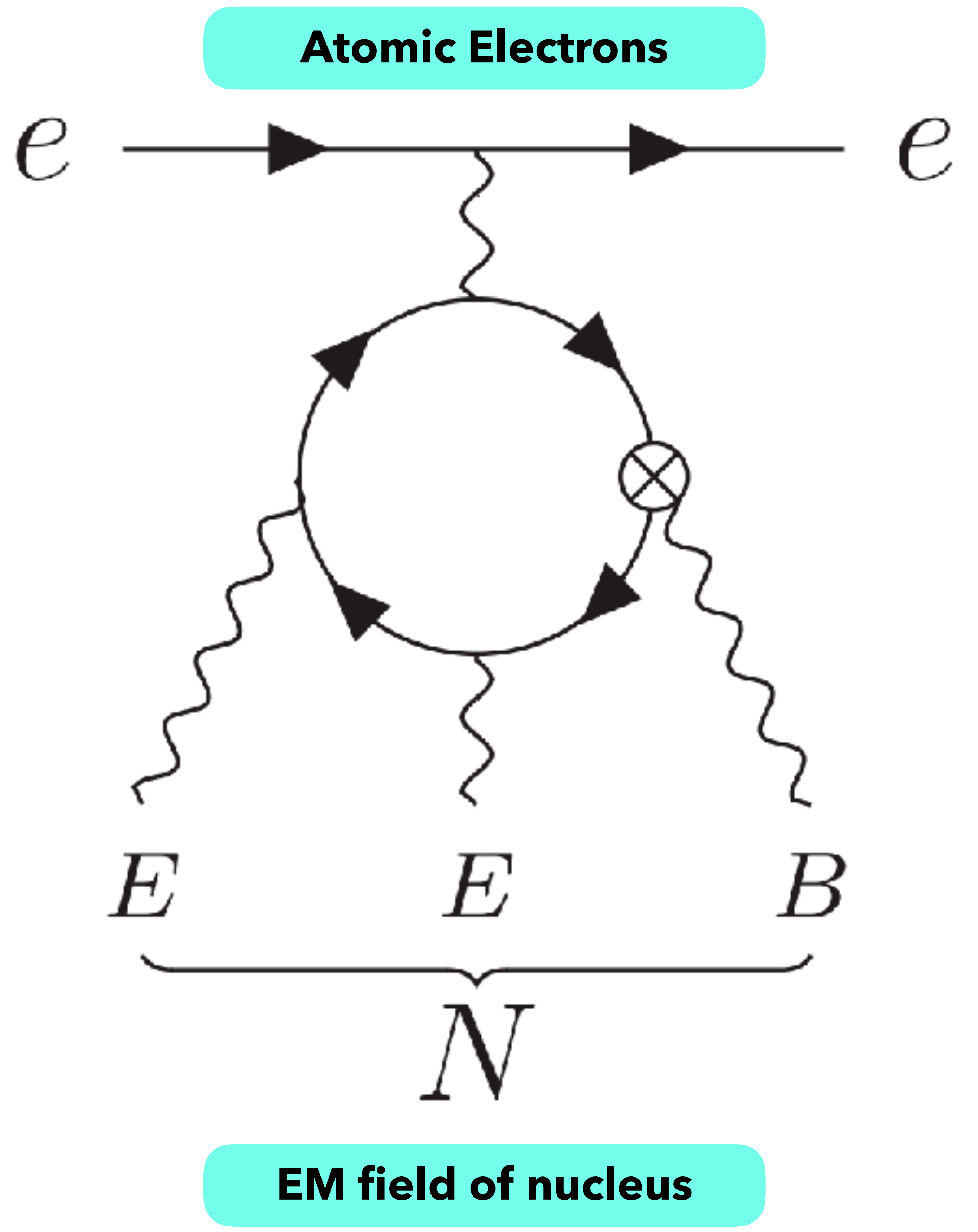


Calculate the Schiff moment S_N of the nucleus in terms of d_μ and compare to measurement.

$$S_N = (\text{Nuc. Struct.}) \times -\frac{d_\mu}{m_\mu^3}\frac{Z^2}{\alpha^3} m_p R_N^2$$

$$|S^{(\text{exp})}_{^{199}\text{Hg}}| < 3.1 \times 10^{-13}\, e\text{fm}^3 \implies d_\mu < 6.4 \times 10^{-20}\, e\text{cm}$$

Better than BNL direct limit

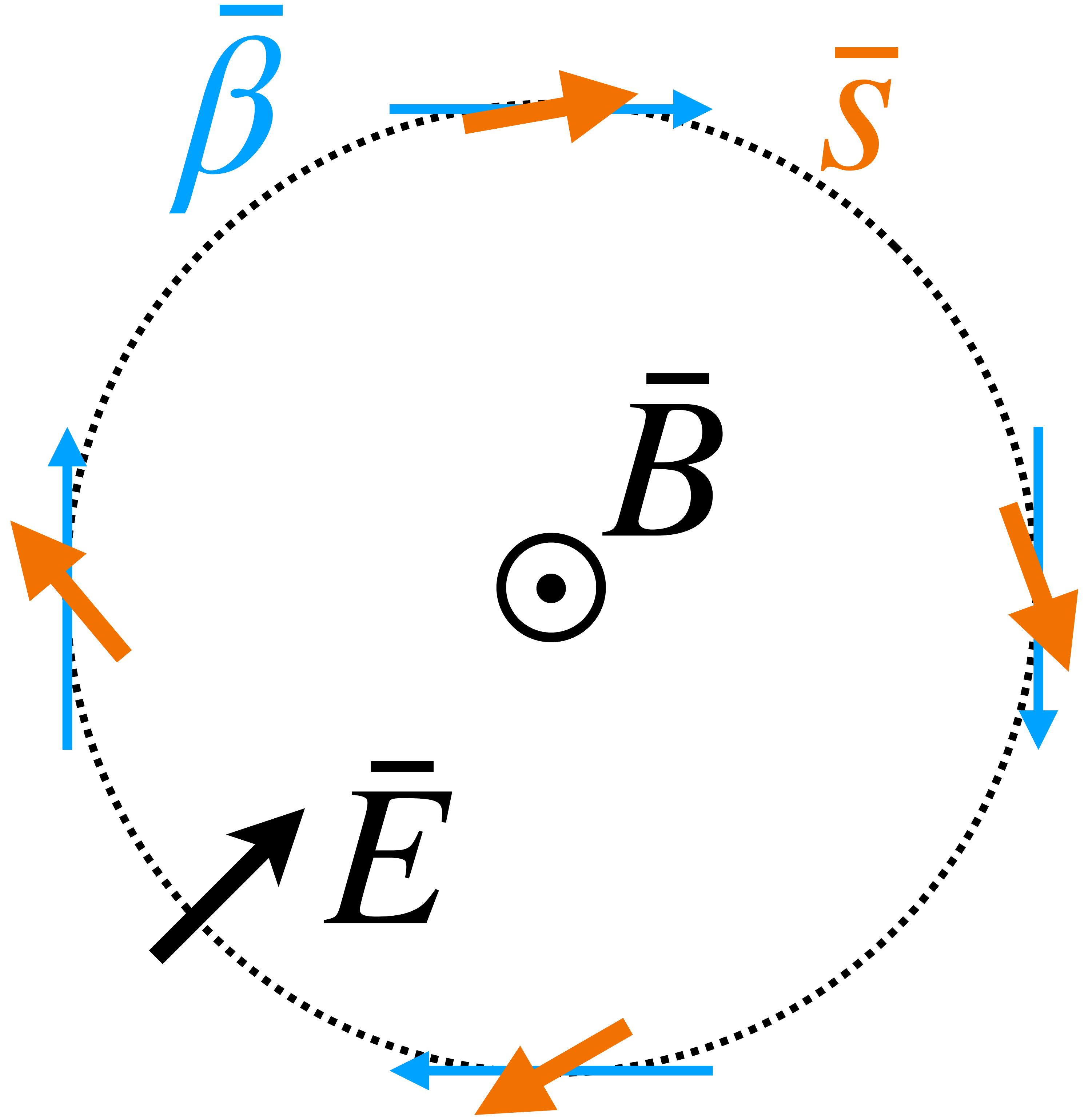
Spin Precession in a storage ring

$$\left(\vec{d}_\mu = \frac{\eta e}{2mc}\vec{s}\right)$$

Velocity : $\frac{\mathrm{d}\bar{\beta}}{\mathrm{d}t} = \bar{\Omega}_c \times \bar{\beta}$

$$\bar{\Omega} = \bar{\Omega}_0 - \bar{\Omega}_c$$

Spin : $\frac{\mathrm{d}\bar{s}}{\mathrm{d}t} = \bar{\Omega}_0 \times \bar{s}$



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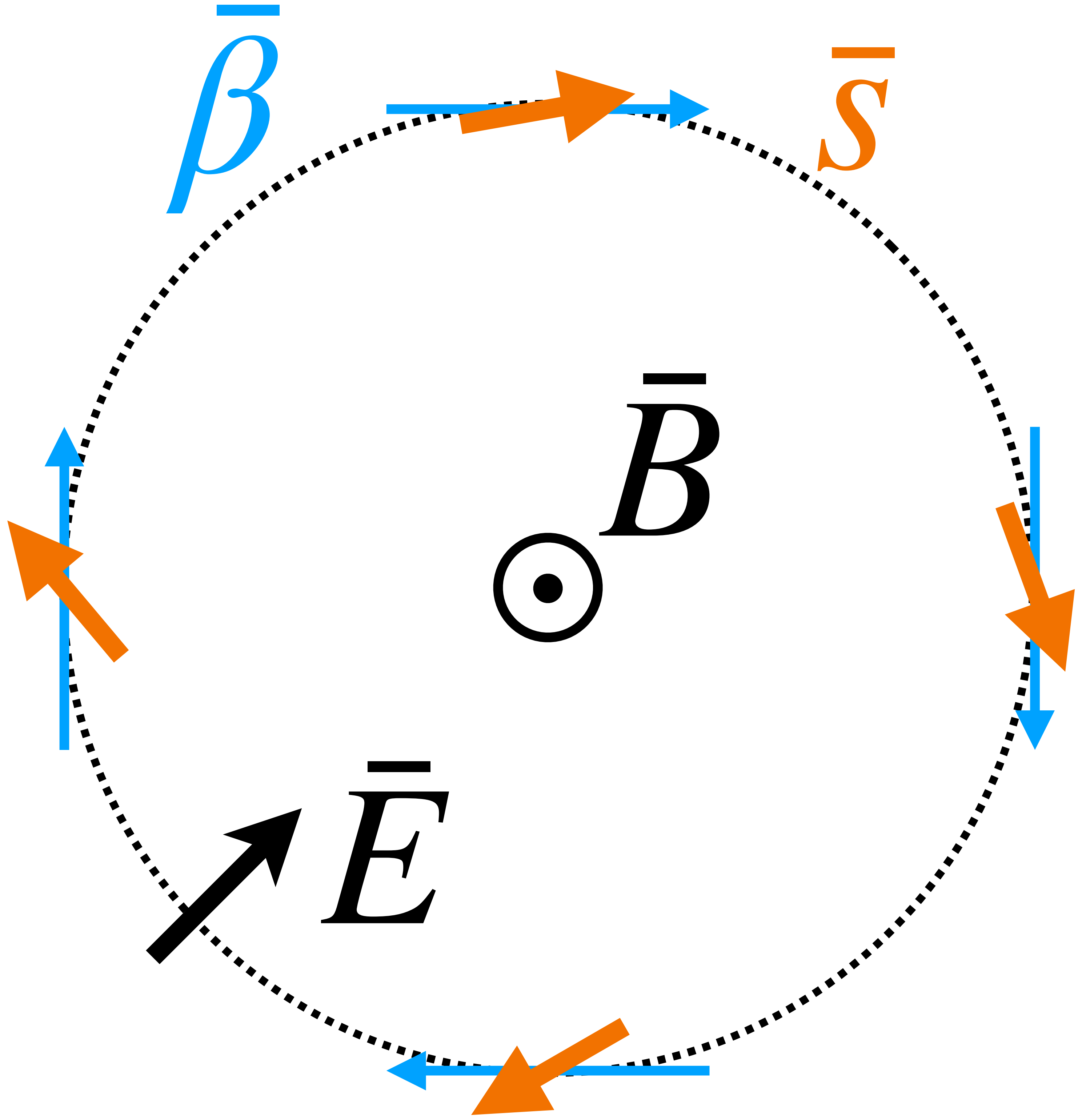
$$= \frac{aq}{m}\left(\bar{B} - \frac{\gamma}{\gamma+1}(\bar{\beta}\cdot\bar{B})\bar{\beta} - \left(1 + \frac{1}{a(1-\gamma^2)}\right)\frac{\bar{\beta}\times\bar{E}}{c}\right)$$

$$+ \frac{\eta q}{2m}\left(\bar{\beta}\times\bar{B} + \frac{\bar{E}}{c} - \frac{\gamma/c}{\gamma+1}(\bar{\beta}\cdot\bar{E})\bar{\beta}\right)$$



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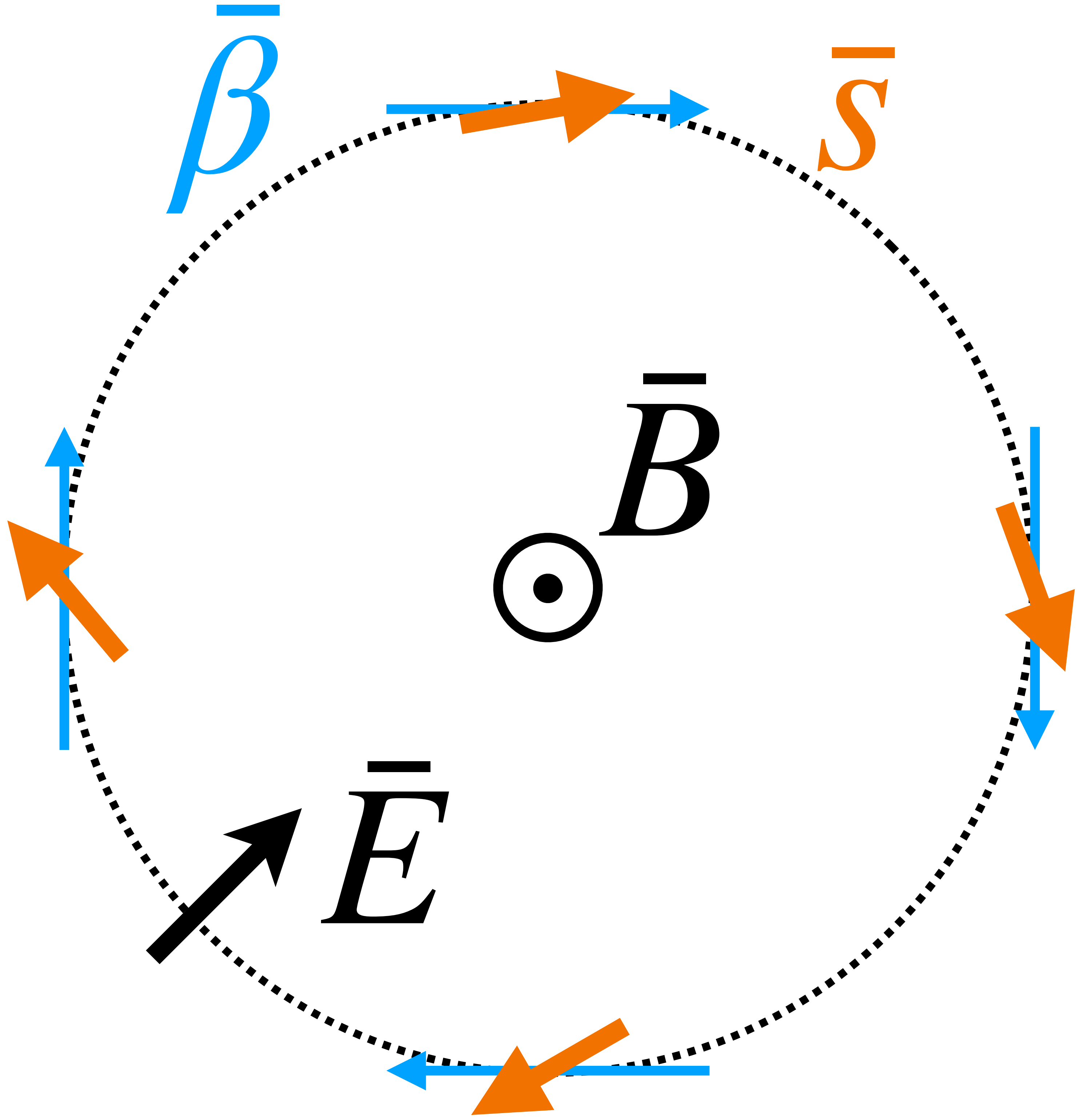

$$\bar{\Omega} = \frac{aq}{m}\left(\bar{B} - \left(1 + \frac{1}{a(1-\gamma^2)}\right)\frac{\bar{\beta}\times\bar{E}}{c}\right) + \frac{\eta q}{2m}\left(\bar{\beta}\times\bar{B} + \frac{\bar{E}}{c}\right)$$

Experimental Approaches

Fermilab

$$\bar{\Omega} = \frac{aq}{m}\left(\bar{B} - \left(1 + \frac{1}{a(1-\gamma^2)}\right)\frac{\bar{\beta}\times\bar{E}}{c}\right) + \frac{\eta q}{2m}\left(\bar{\beta}\times\bar{B} + \frac{\bar{E}}{c}\right)$$

"magic momentum"

J-PARC

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"E field shielding"

PSI

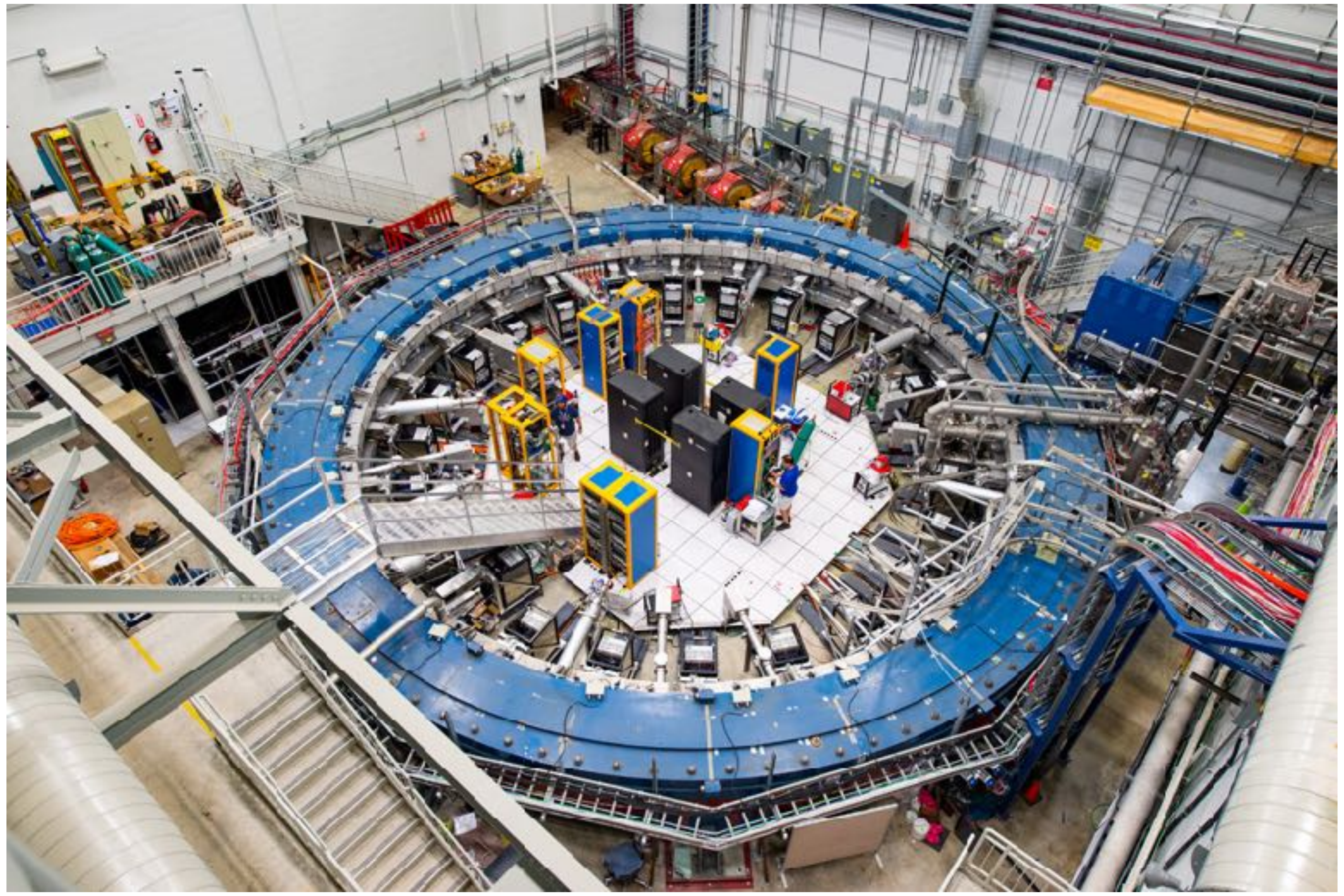
$$\bar{\Omega} = \frac{aq}{m}\left(\bar{B} - \left(1 + \frac{1}{a(1-\gamma^2)}\right)\frac{\bar{\beta}\times\bar{E}}{c}\right) + \frac{\eta q}{2m}\left(\bar{\beta}\times\bar{B} + \frac{\bar{E}}{c}\right)$$

"frozen spin"

Muon g-2 at BNL & Fermilab

Pulsed (avg. bunch freq. $11.4\,\mathrm{s}^{-1}$) muon beam with magic momentum $3.1\,\mathrm{GeV}/c$

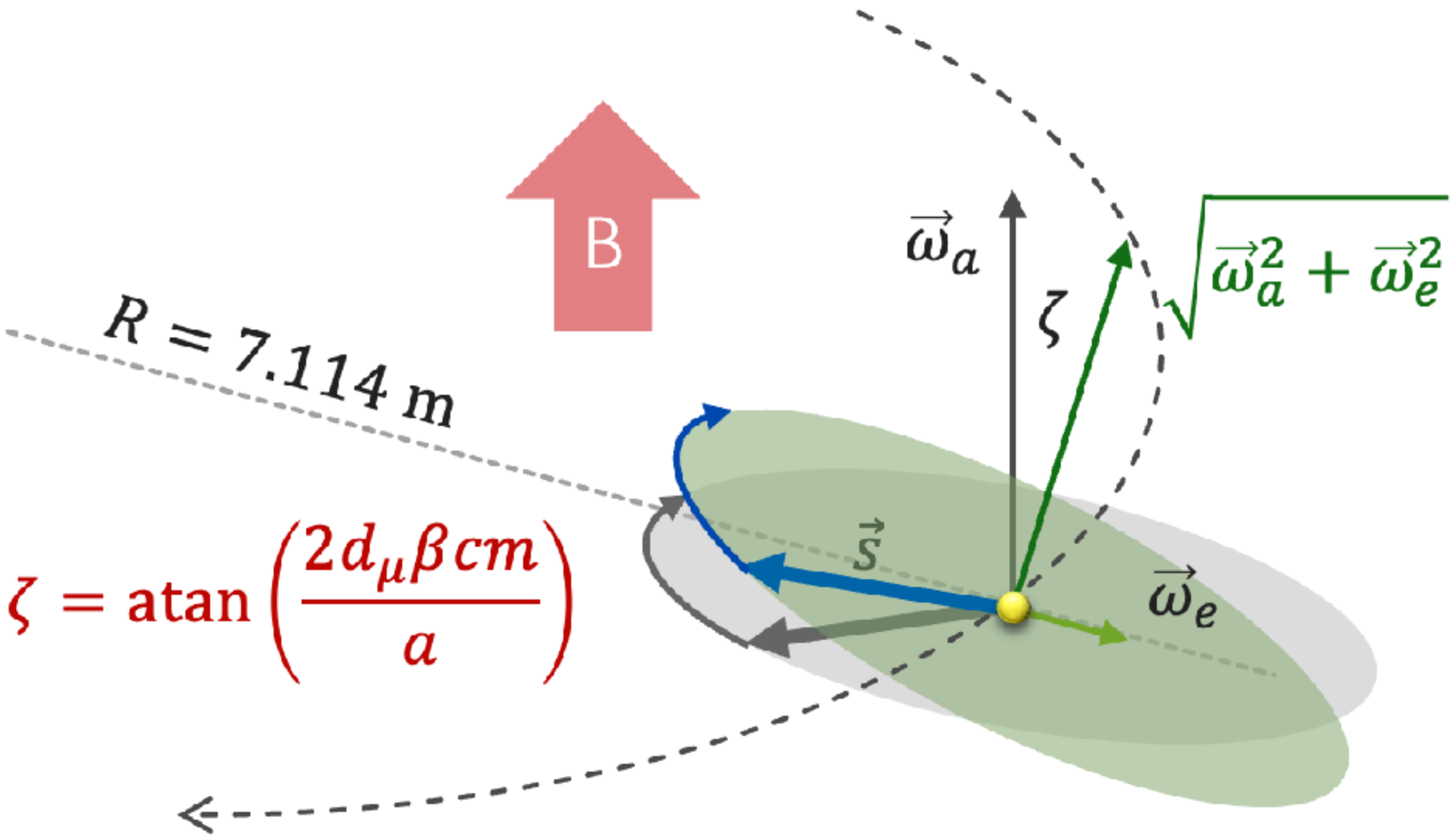
$$1 + \frac{1}{a_\mu(1-\gamma^2)} \stackrel{!}{=} 0 \implies \gamma = 29.3$$



Credit: FNAL, DoE muon-g-2.fnal.gov

$$\bar{\Omega} \approx \frac{aq}{m}\bar{B} + \frac{\eta q}{2m}\bar{\beta} \times \bar{B}$$

2 simultaneous precession axes!



Credit: P. Schmidt-Wellenburg

Frozen Spin Technique

Goal: Configure E, B fields such that spin follows velocity vector and EDM is the only inherent source of spin precession.

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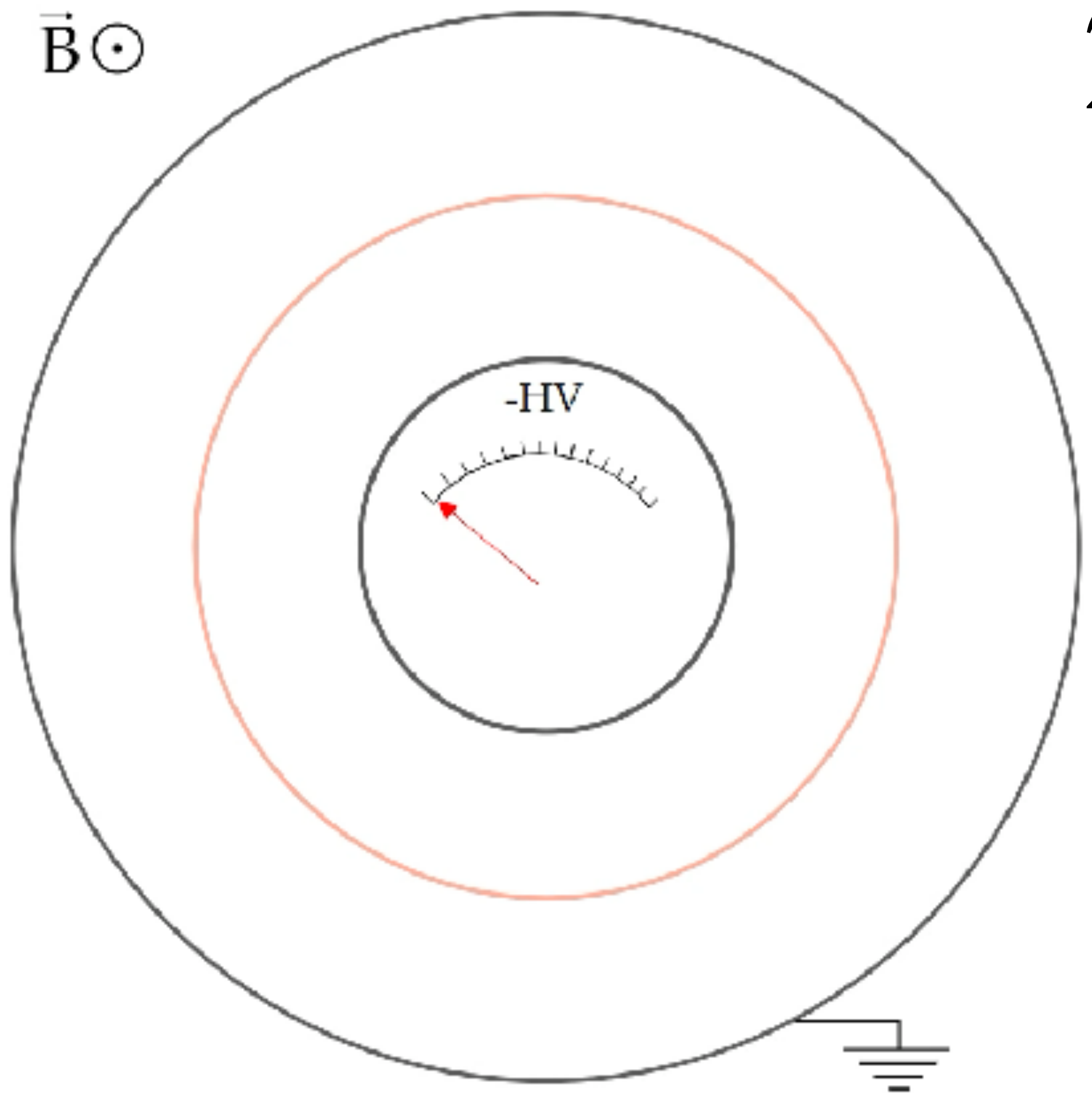


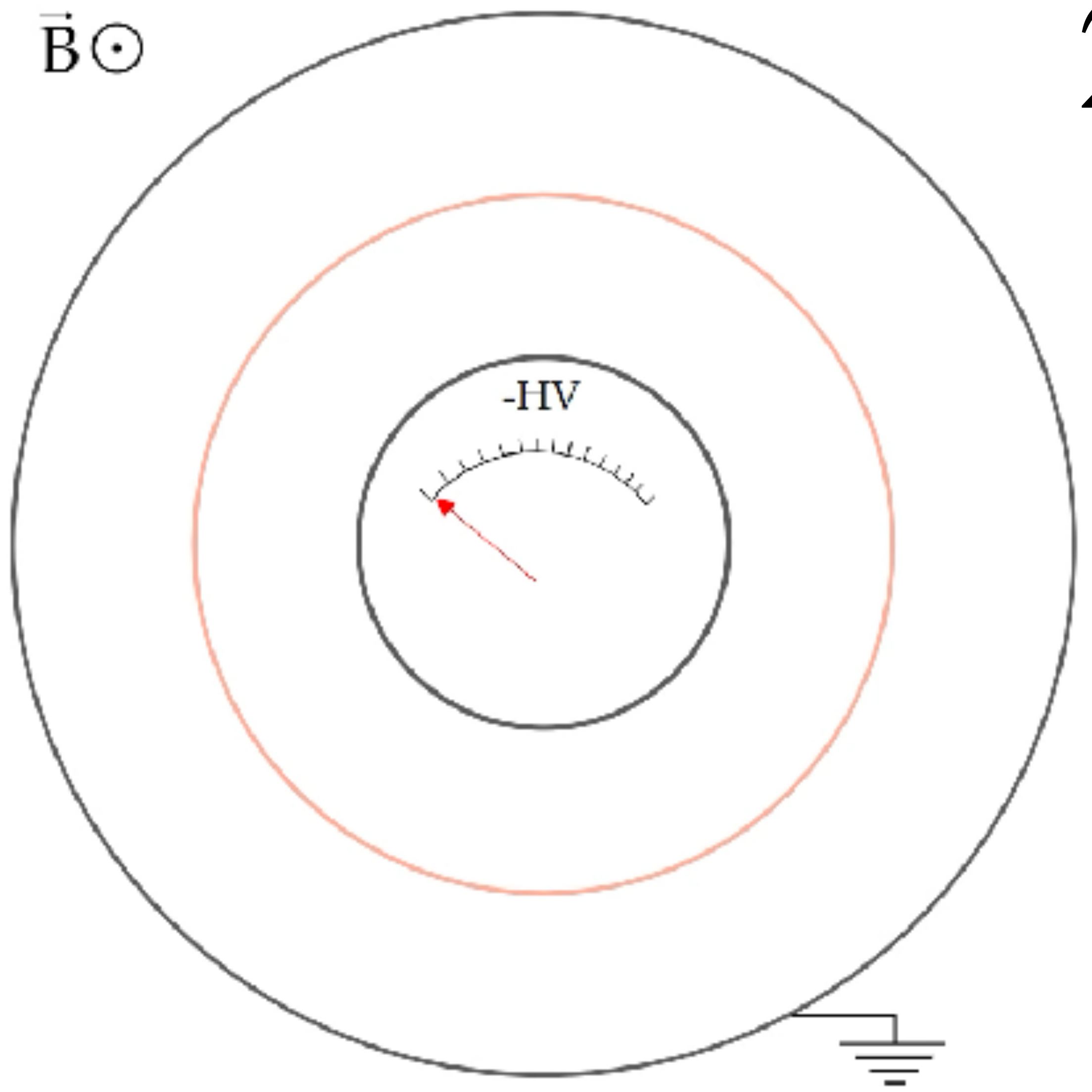
Frozen Spin Condition : $E_f \overset{a<<1}{\approx} aB\beta c\gamma^2$

Frozen Spin Technique

Goal: Configure E, B fields such that spin follows velocity vector and EDM is the only inherent source of spin precession.

$$\bar{\Omega} = \bar{\Omega}_0 - \bar{\Omega}_c = \frac{aq}{m}\left(\bar{B} - \frac{\gamma}{\gamma+1}(\bar{\beta}\cdot\bar{B})\bar{\beta} - \left(1 + \frac{1}{a(1-\gamma^2)}\right)\frac{\bar{\beta}\times\bar{E}}{c}\right)$$

$$+ \frac{\eta q}{2m}\left(\bar{\beta}\times\bar{B} + \frac{\bar{E}}{c} - \frac{\gamma/c}{\gamma+1}(\bar{\beta}\cdot\bar{E})\bar{\beta}\right)$$



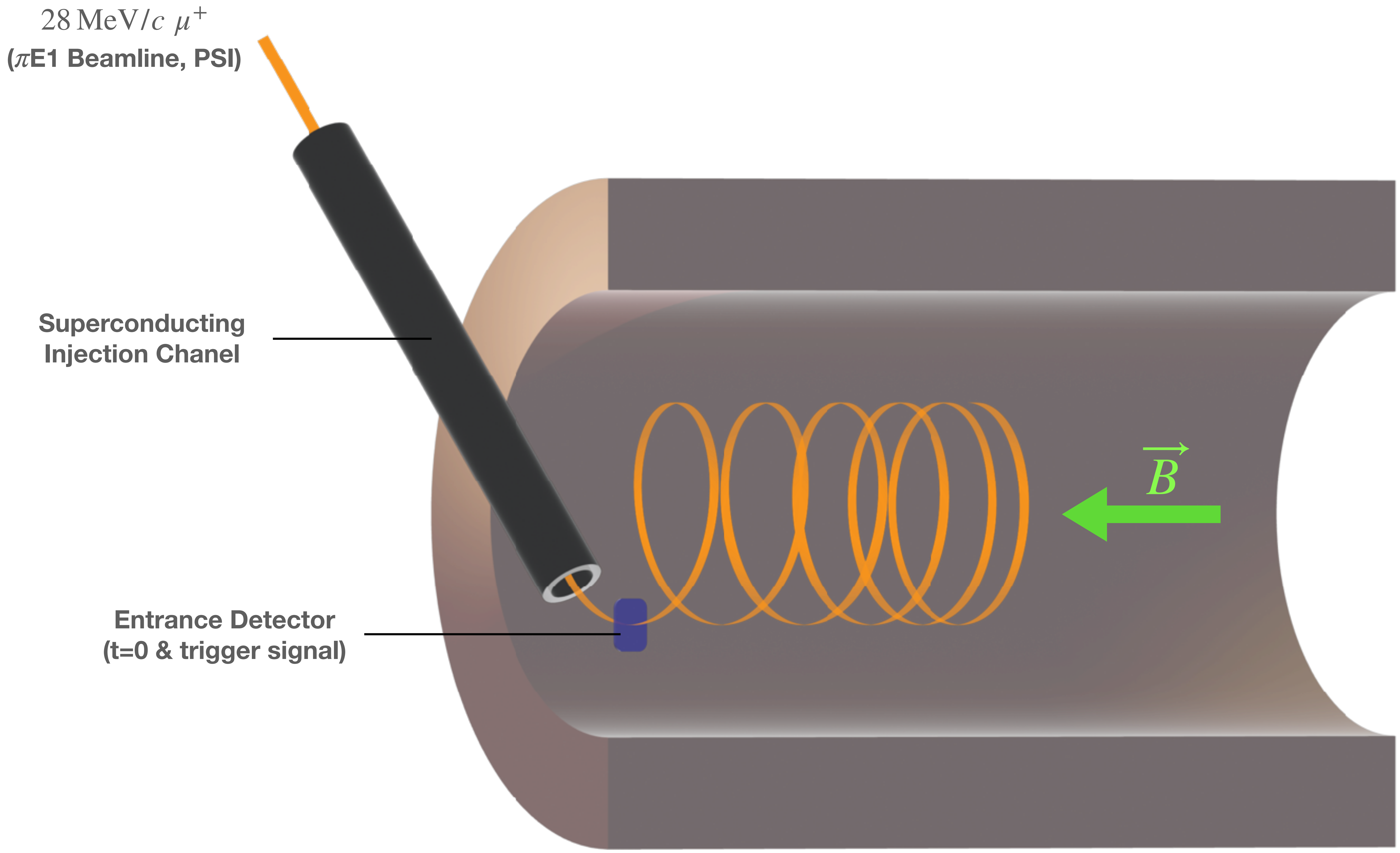
Frozen Spin Condition : $E_f \overset{a<<1}{\approx} aB\beta c\gamma^2$

Experimental Requirements:

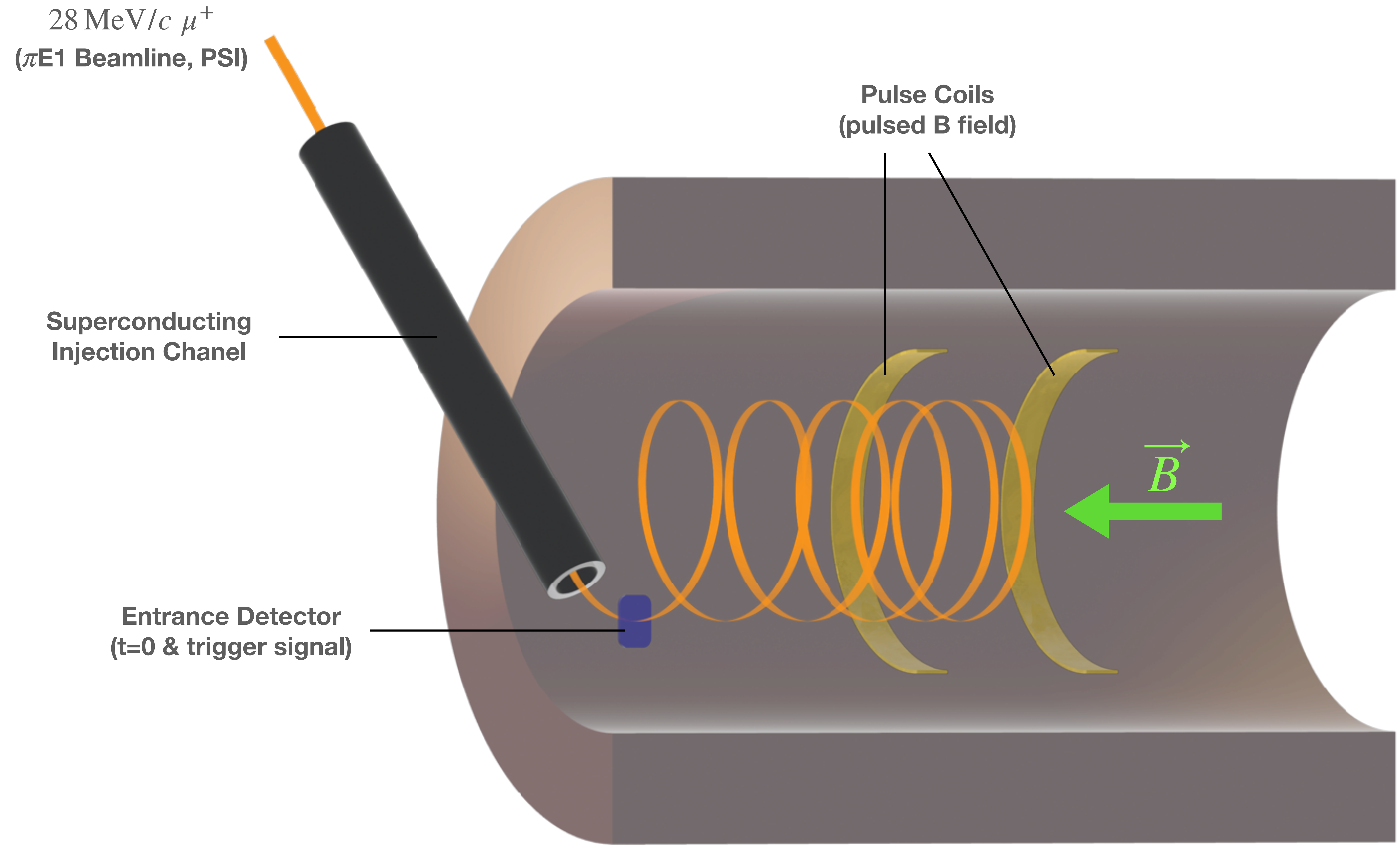
1. Fields ⊥ Velocity
2. Precisely tuned $E = E_f$
3. Constrained B_r (radial), E_z (axial)

Any periodic deviations must be stable over the timescale of τ_μ.

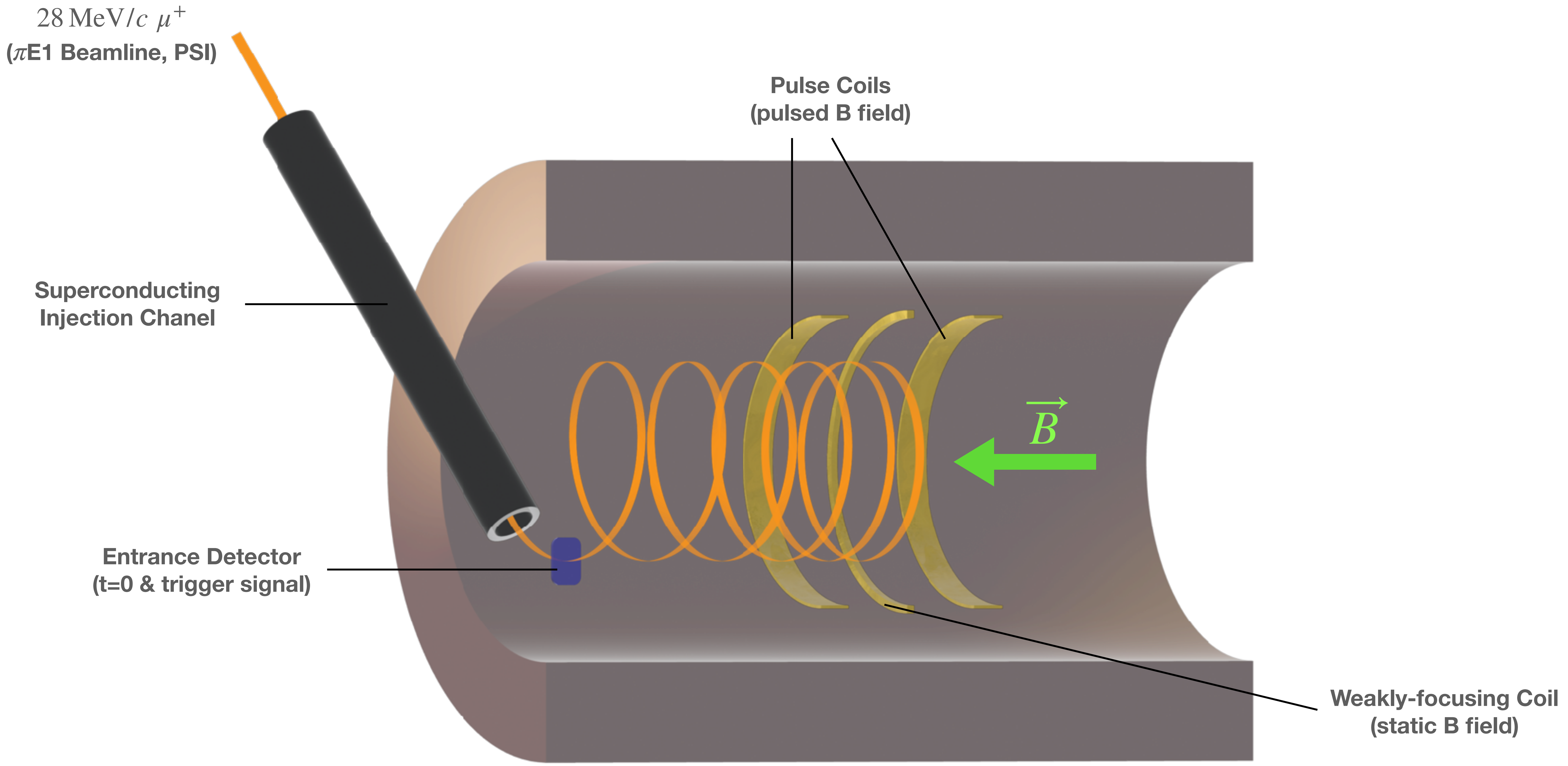
muEDM Experiment at PSI



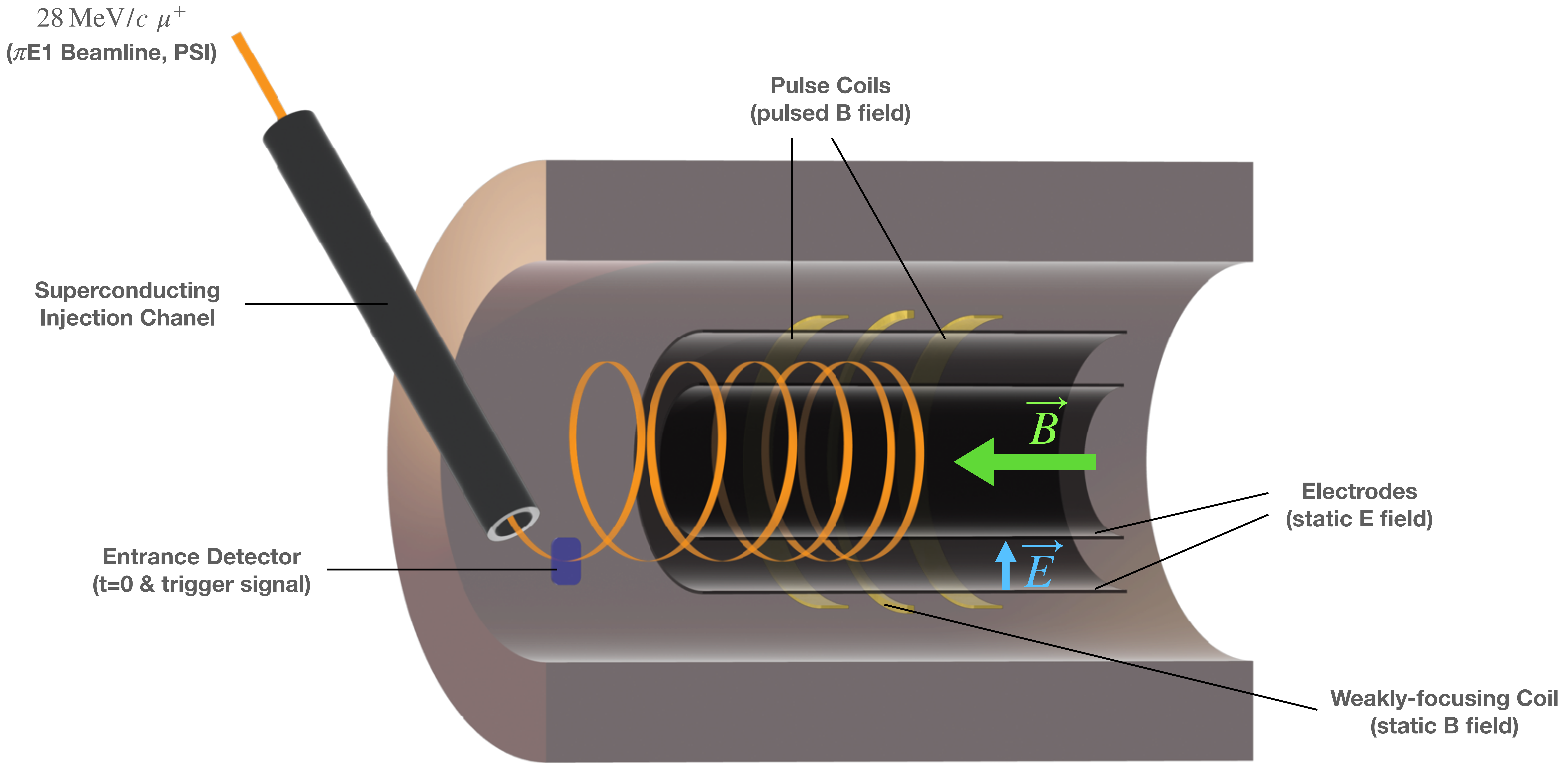
muEDM Experiment at PSI



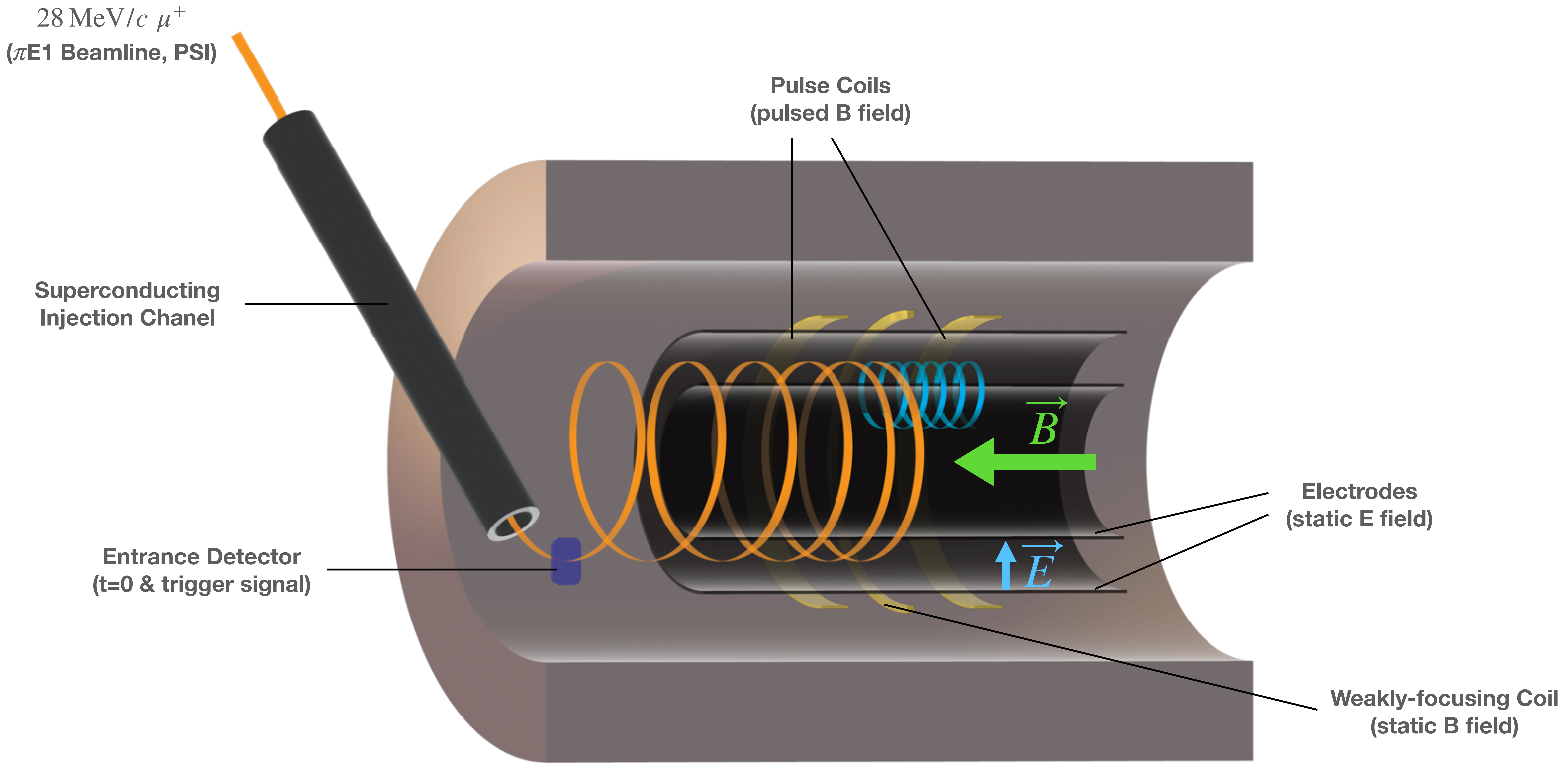
muEDM Experiment at PSI



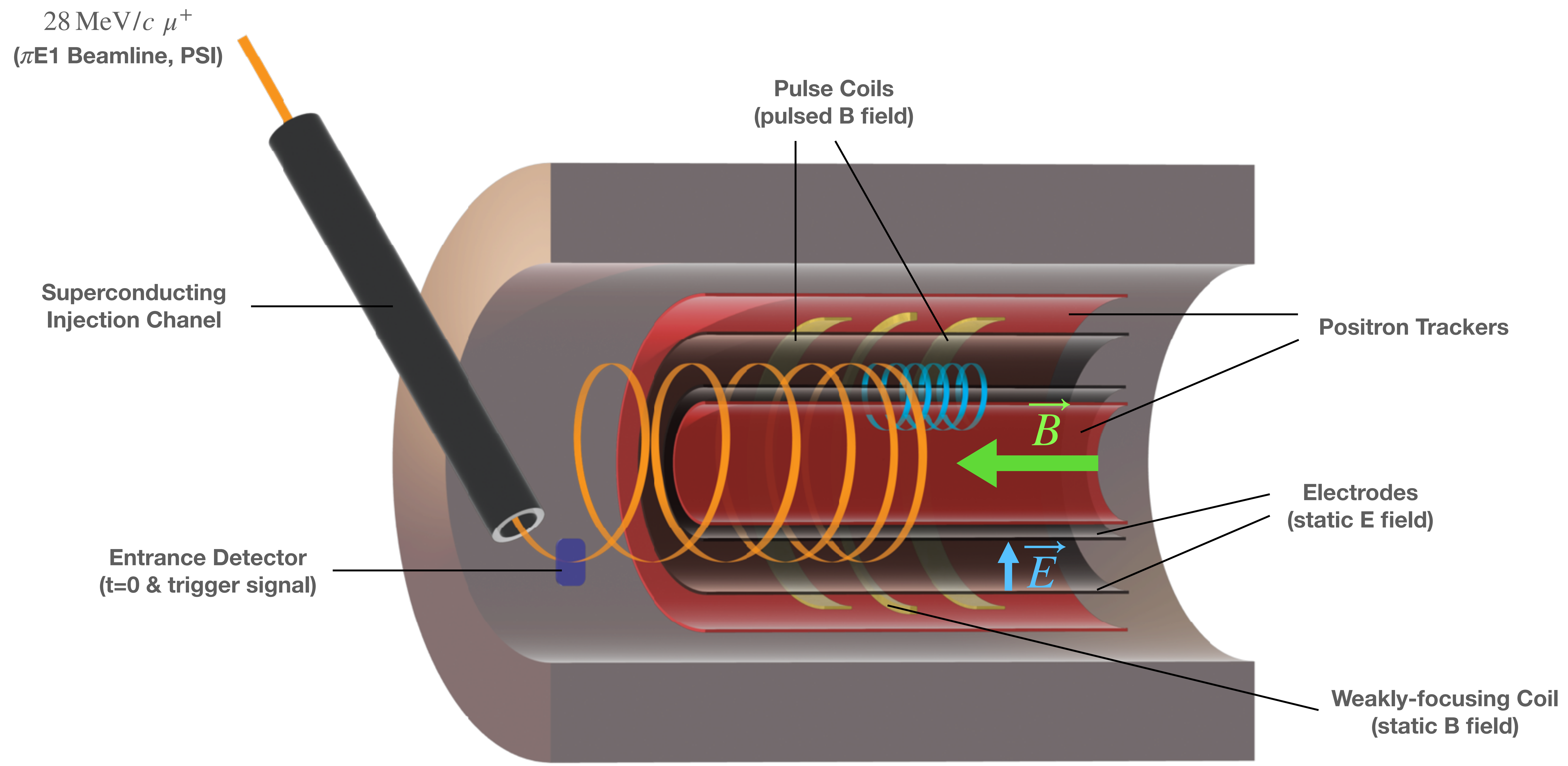
muEDM Experiment at PSI



muEDM Experiment at PSI

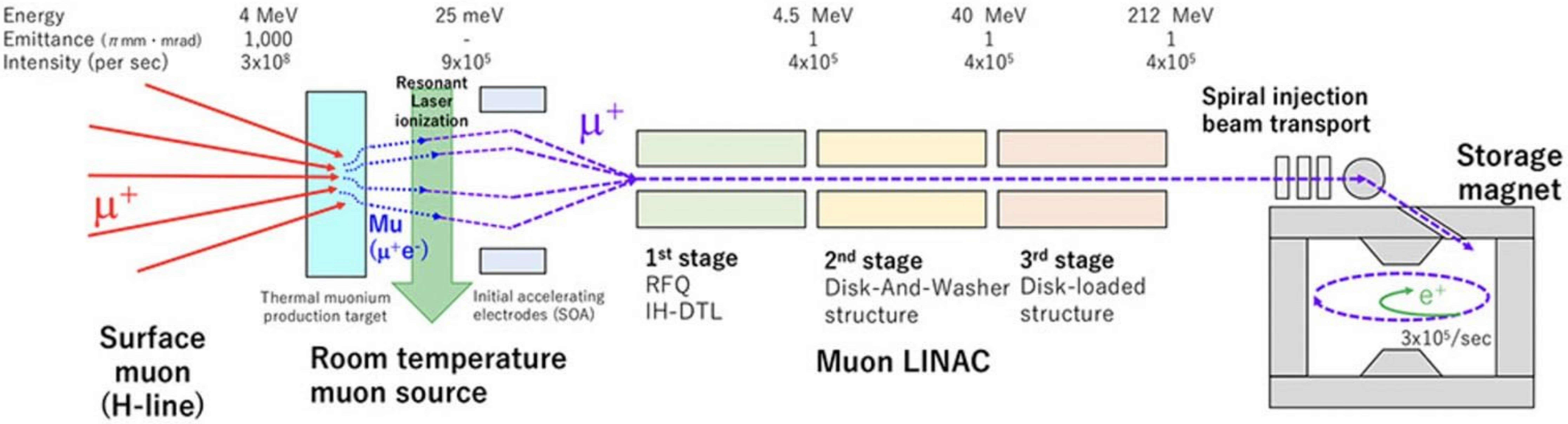


muEDM Experiment at PSI



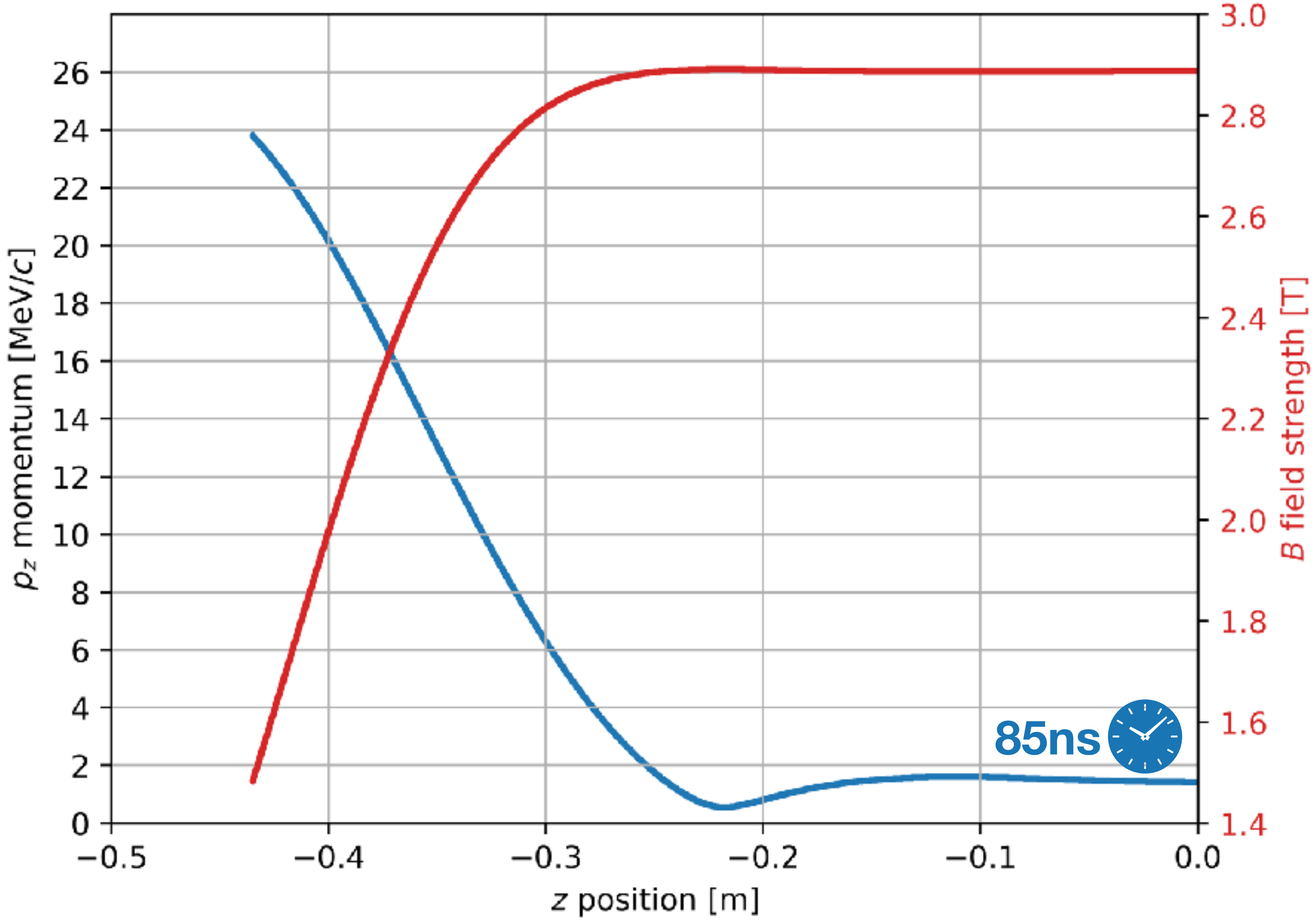
Muon g-2/EDM at JPARC

- Pulsed (bunch rate $25\,\mathrm{Hz}$) muon beam with momentum $30\,\mathrm{MeV}/c$.
- Longitudinal injection (similar to PSI)
- Electric field cancellation means narrow acceptance phase space.
- Pulsed beam demands bunched injection and measurement
- Ultra-cold muon beam developed for phase space compression.

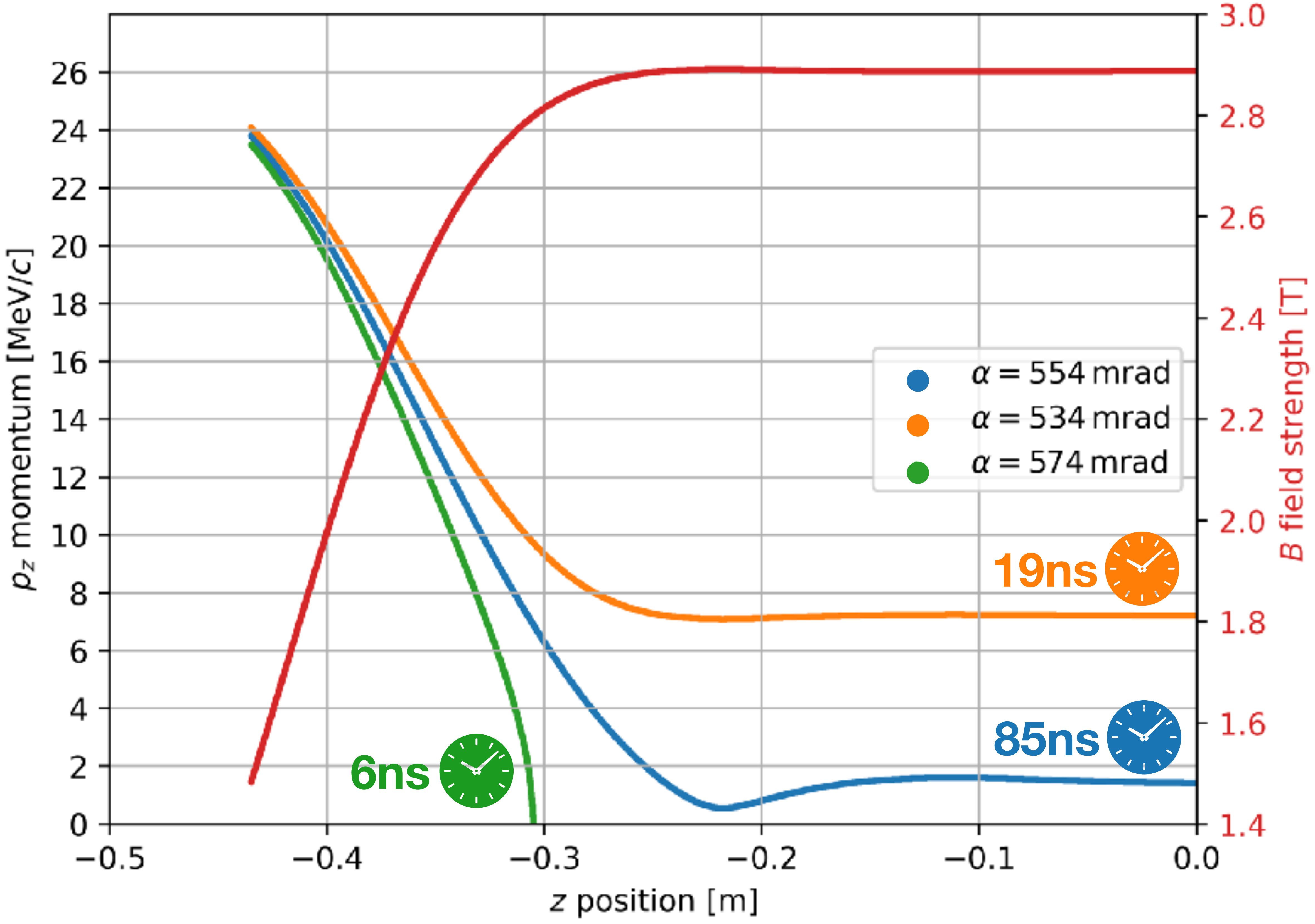


Credit: J-PARC g-2.kek.jp

Challenges: Injection & Storage



Challenges: Injection & Storage



Outlook for muEDM Phase I