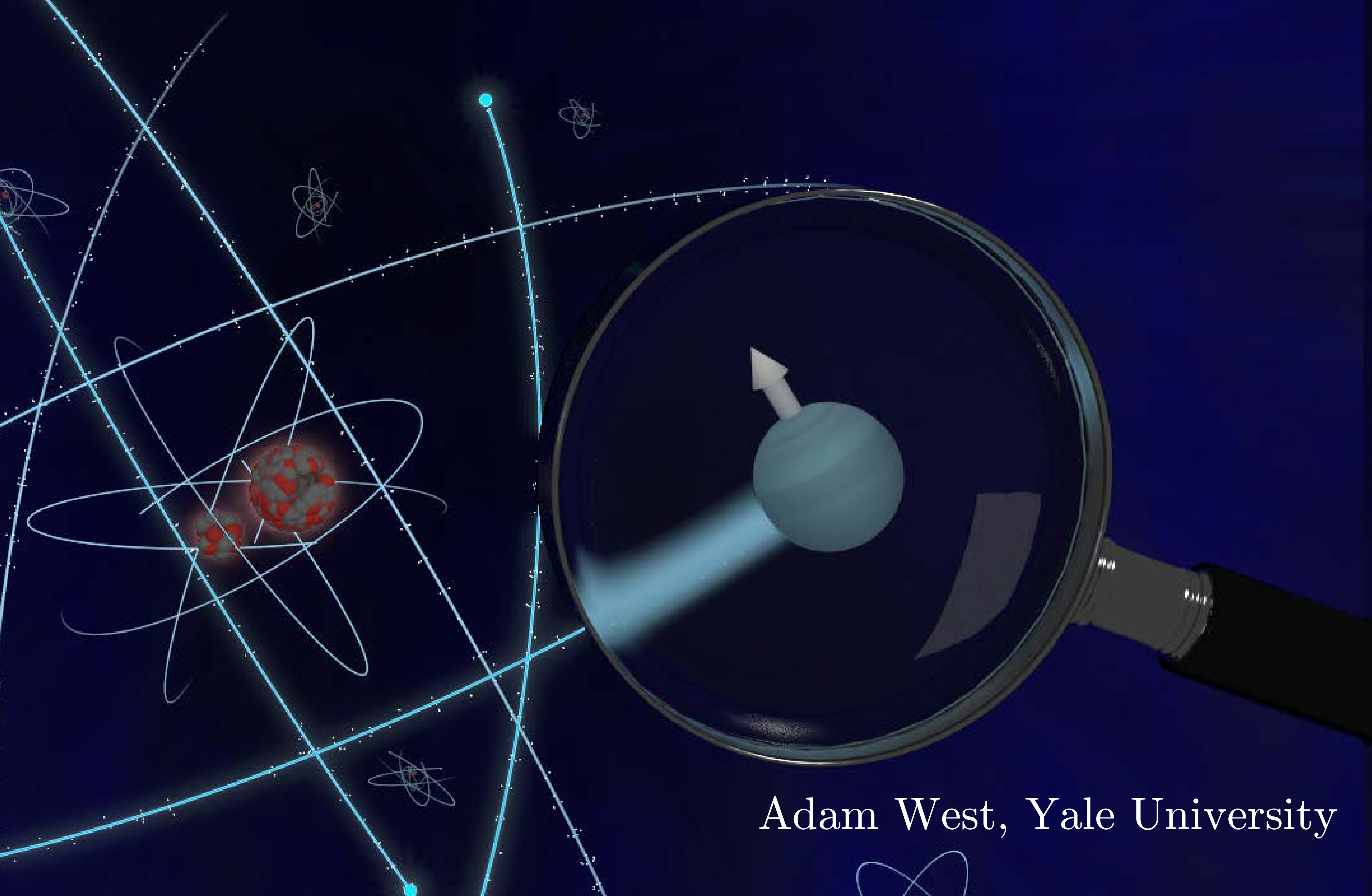
Lepton Dipole Moments



Adam West, Yale University

Outline:

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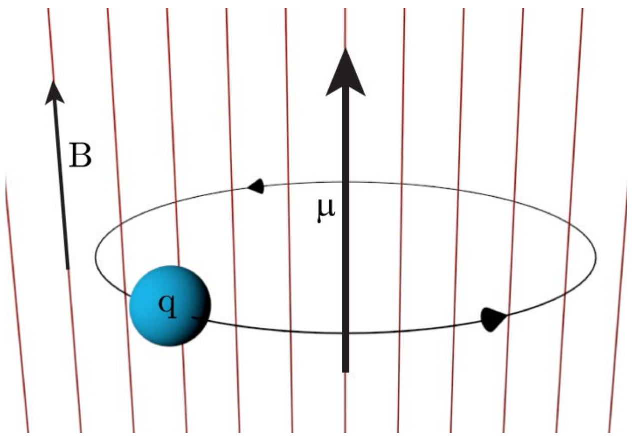
- Introduction
- MDMs (g-2)
    - Motivation
        - Test of fundamental theories
    - Electron
        - Penning traps
    - Muon
        - Storage ring technique
    - Tau
        - Collider results
    - Neutrinos



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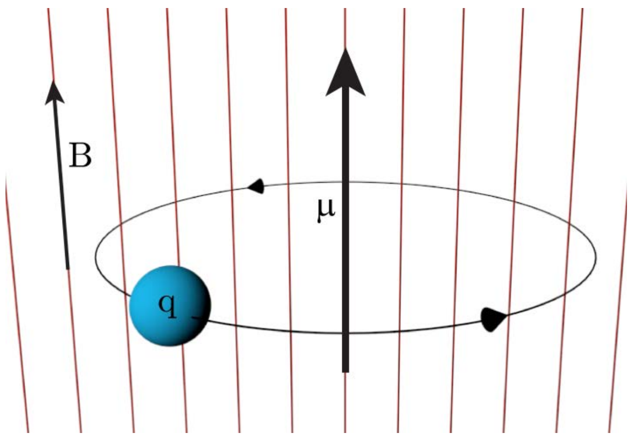

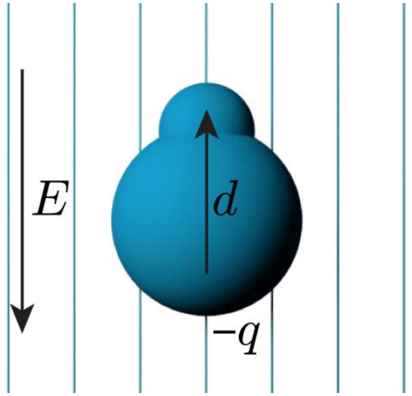

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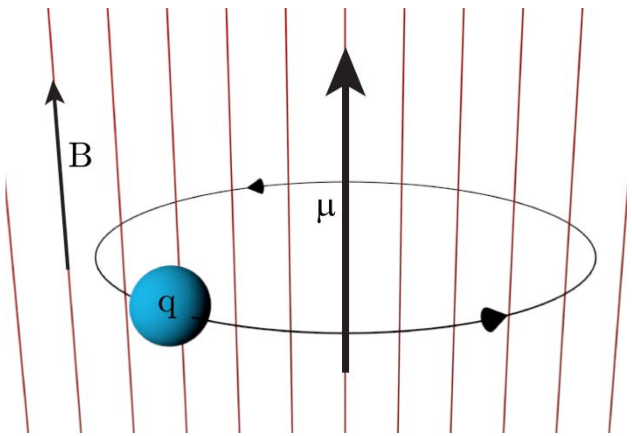

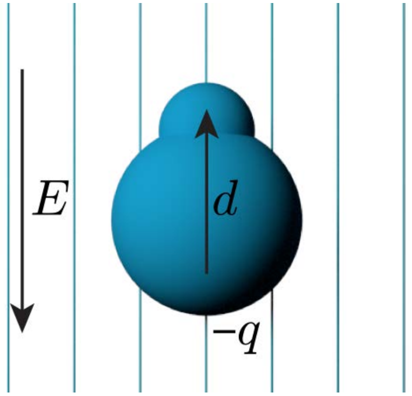

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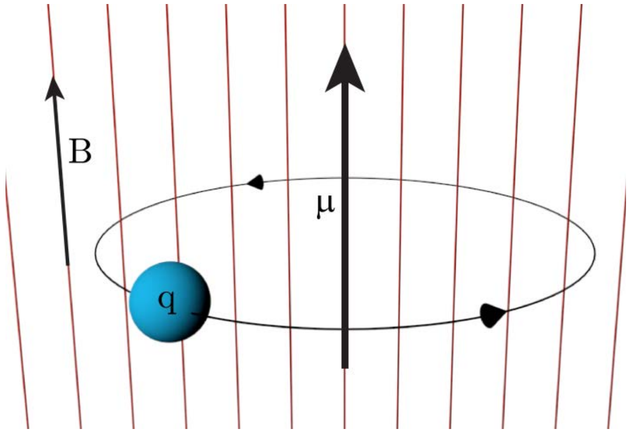

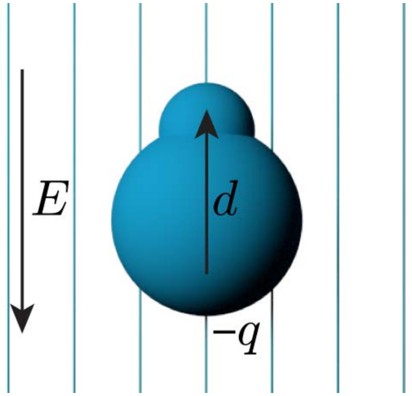

All of these experiments exemplify **precision measurement**

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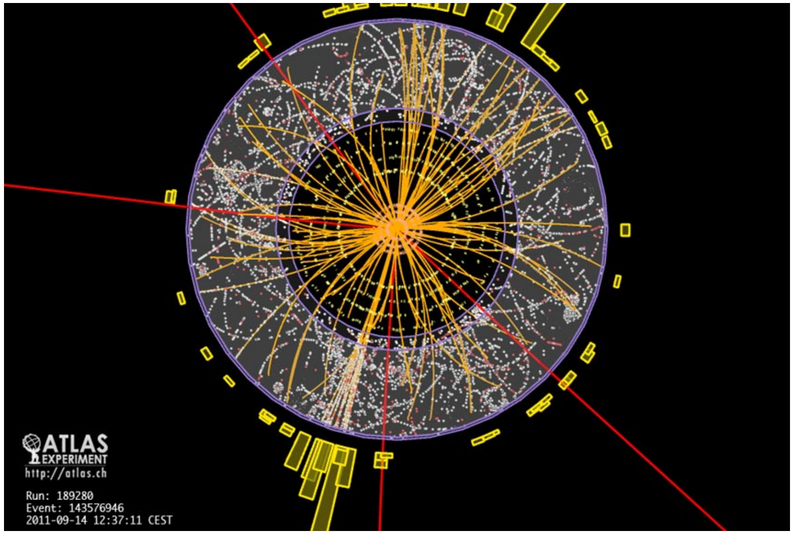
LHC:

New physics through observations of new particles



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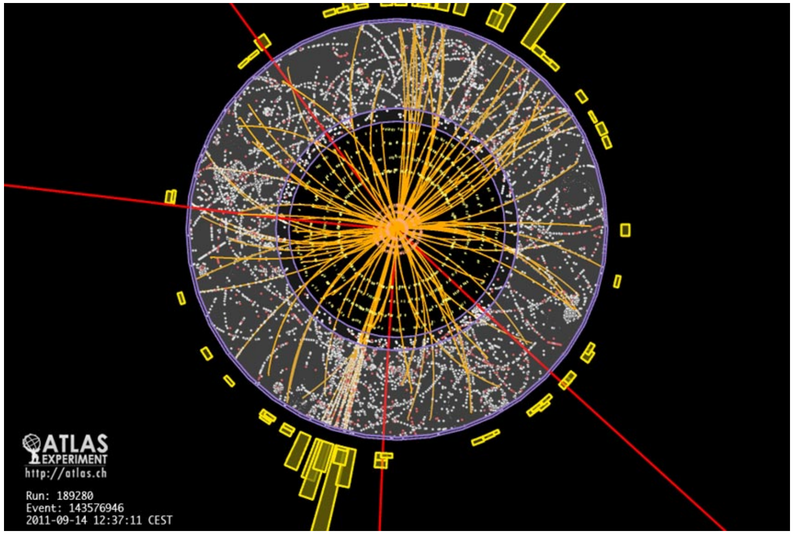
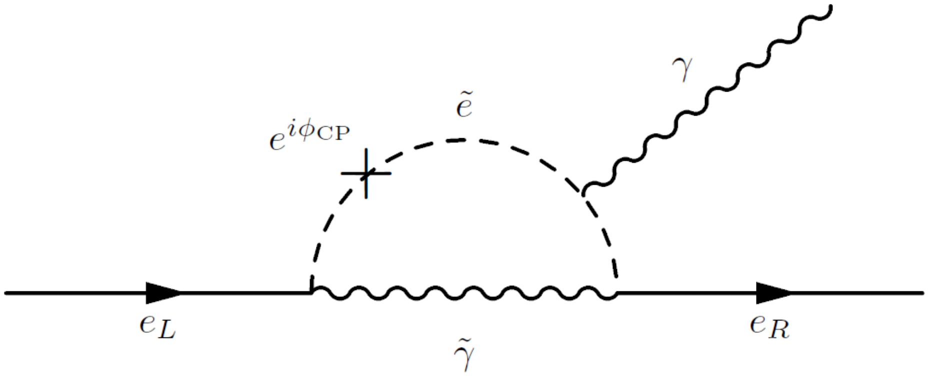


Dipole moments:
New physics through observations of the effects of virtual particles



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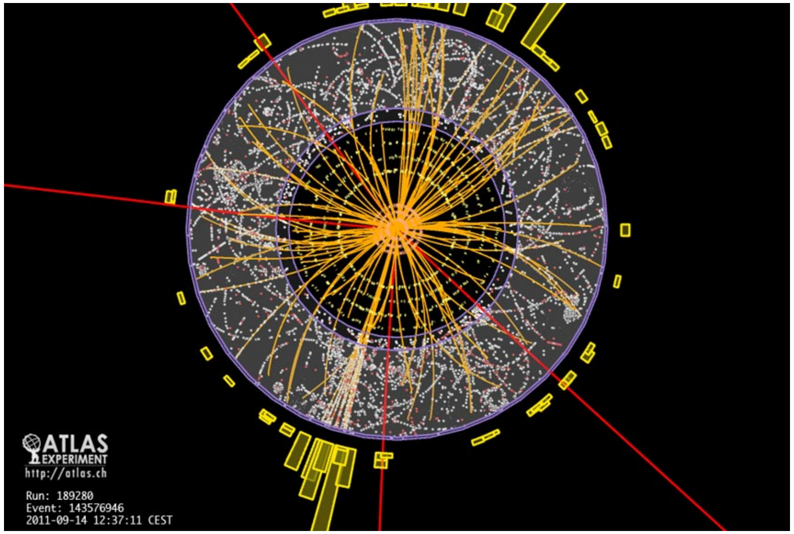

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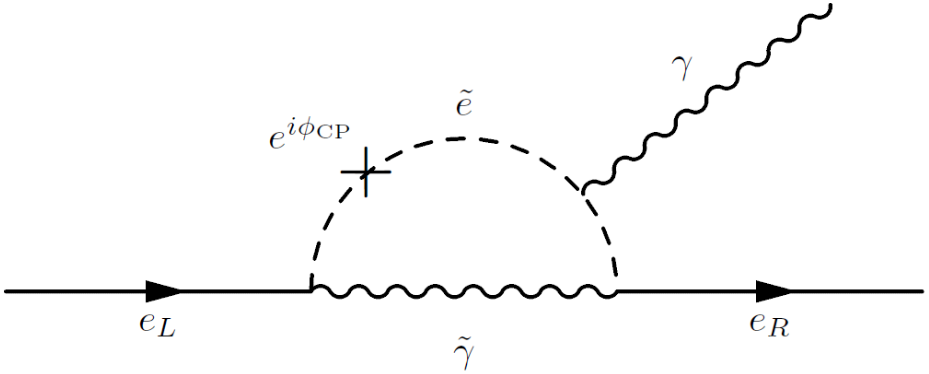

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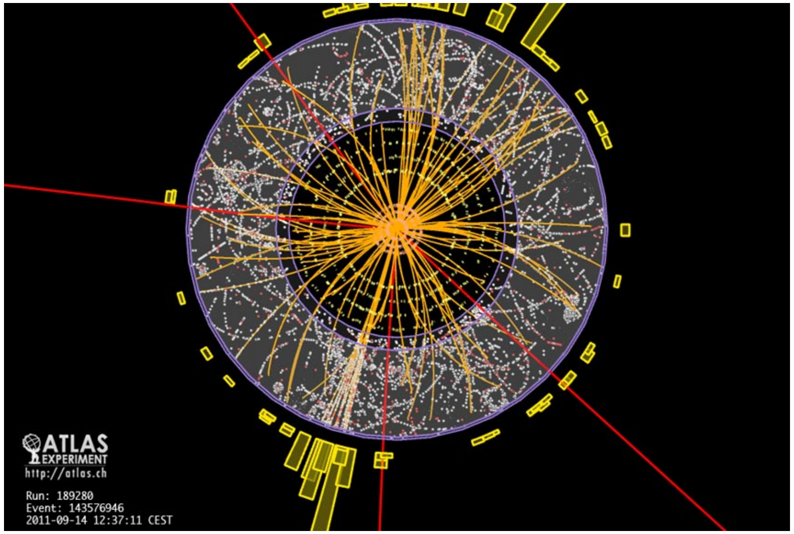

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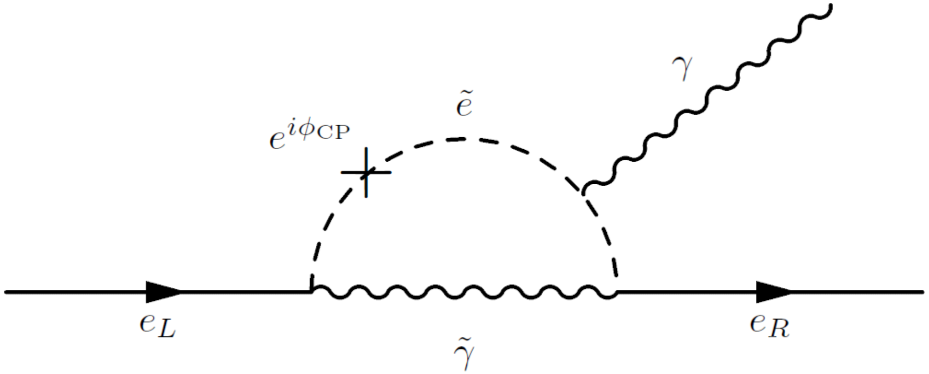

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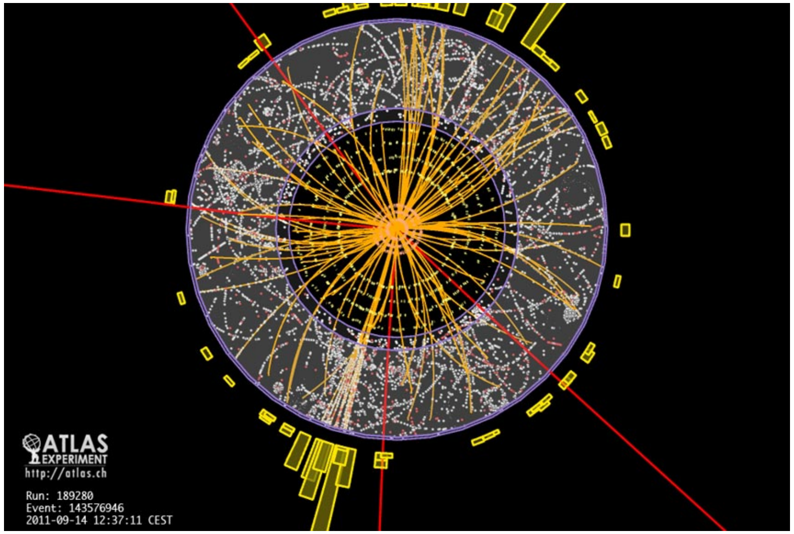

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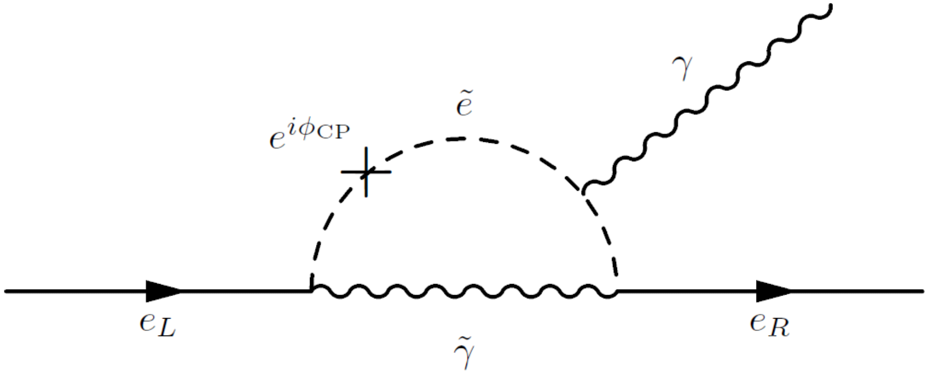

Sensitive to weakly interacting particles

Complementary approaches, allow discrimination

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EDMS:

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Probes of new physics

$$\Lambda^2 \sim e\frac{m_l}{d_l}\left(\frac{\alpha}{4\pi}\right)^n \sin\phi_{CP}$$

m_l = Lepton mass
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Muon EDM more sensitive to some types of new physics.

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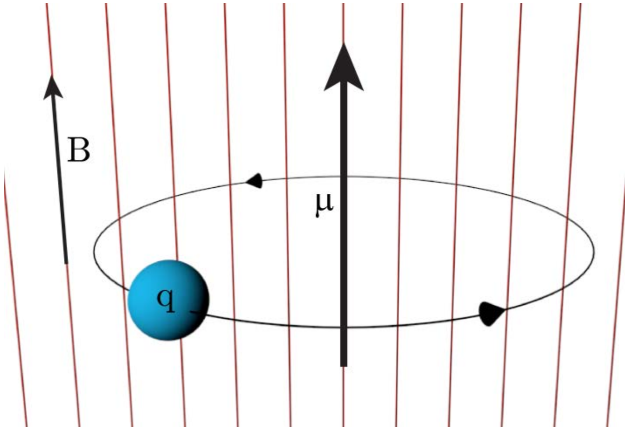
MDMs



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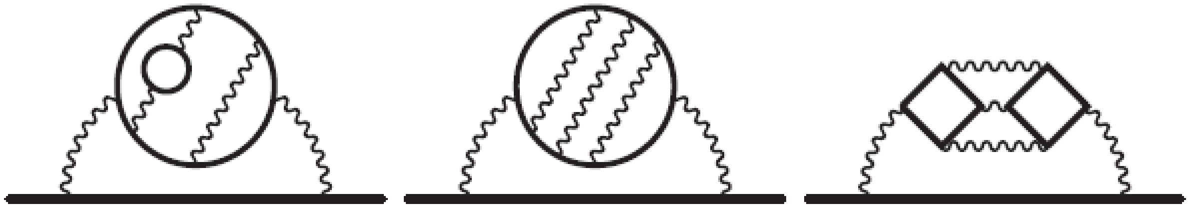
Tests of SM:

Comparisons against theory represent the most precise tests of SM predictions to date.[1]



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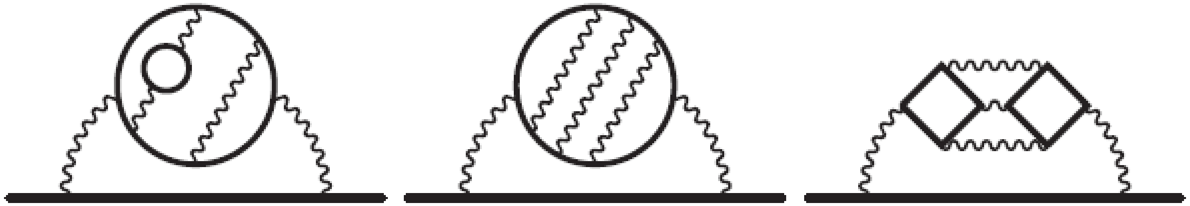
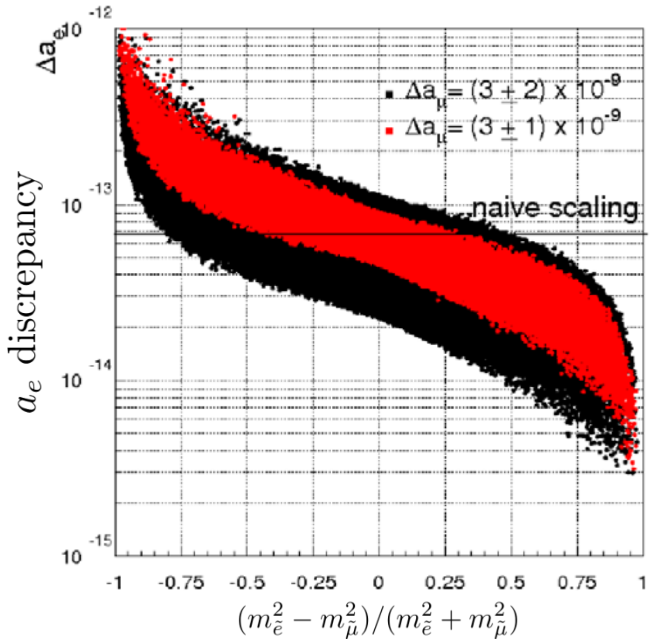


Discrepancies might indicate presence of internal structure or beyond SM physics.



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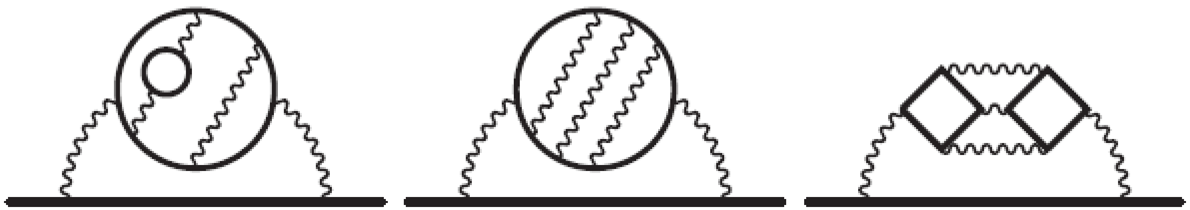

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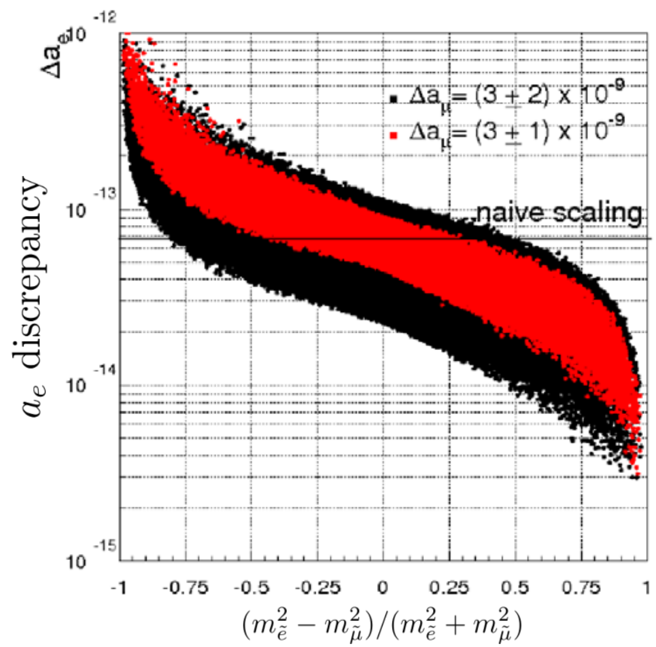
Multiple flavours are complementary, insight into lepton flavour violation.



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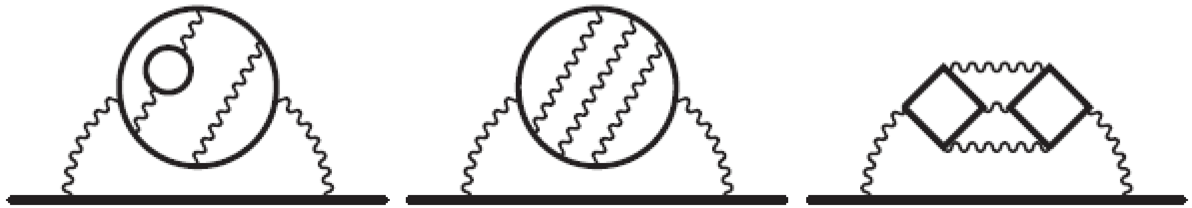

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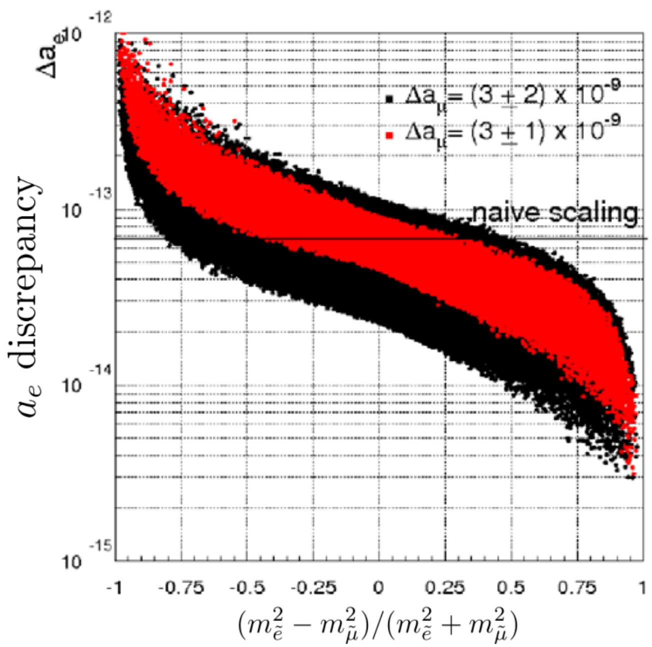
↓

Fri. 9:05: Charged Lepton Flavour Physics

Mark Lancaster



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Theory:

$$\vec{\mu} = g\frac{e}{2m}\vec{S}$$

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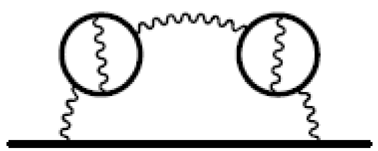

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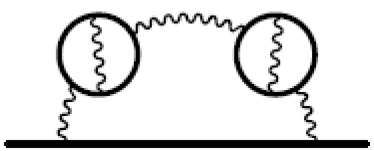

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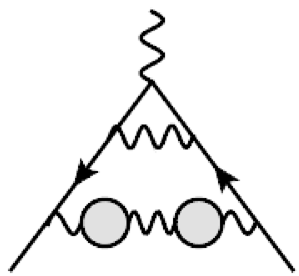

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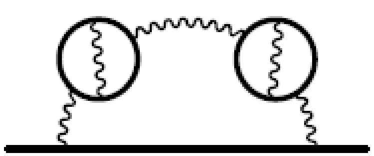

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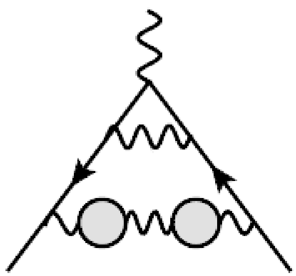

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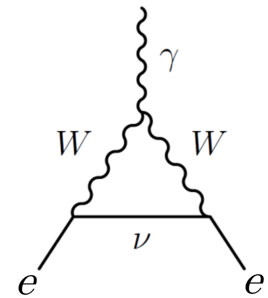


Weak interactions[3]

[1]PRL **109**, 111807 (2012), [2]PLB **734**, 144 (2014), [3]PRD **67**, 073006 (2003), [4]PRD **88**, 053005 (2013)

Electron g-2:

Theory:

$$\vec{\mu} = g\frac{e}{2m}\vec{S}$$

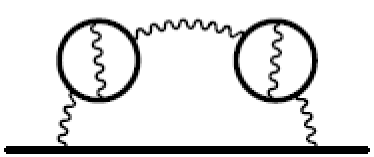
- Classical mechanics/non-relativistic QM: $g_e = 1$
- Dirac combined QM and special relativity to show: $g_e = 2$
- Detailed (perturbative) QED calculations tell us: $g_e = 2.002319304363286$

'Anomalous magnetic moment':

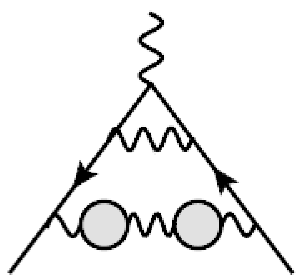
$$a_e = \frac{g-2}{2}$$

$$a_l = a_l^{\mathrm{QED}} + a_l^{\mathrm{Hadron}} + a_l^{\mathrm{Weak}} + \ldots$$

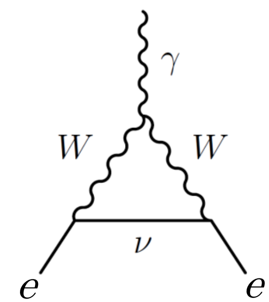
Calculations of a_e draw from many aspects of SM:



QED interactions[1]



Hadron interactions[2]



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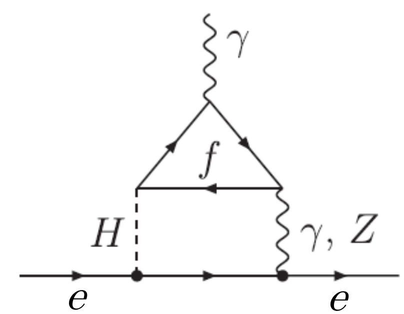
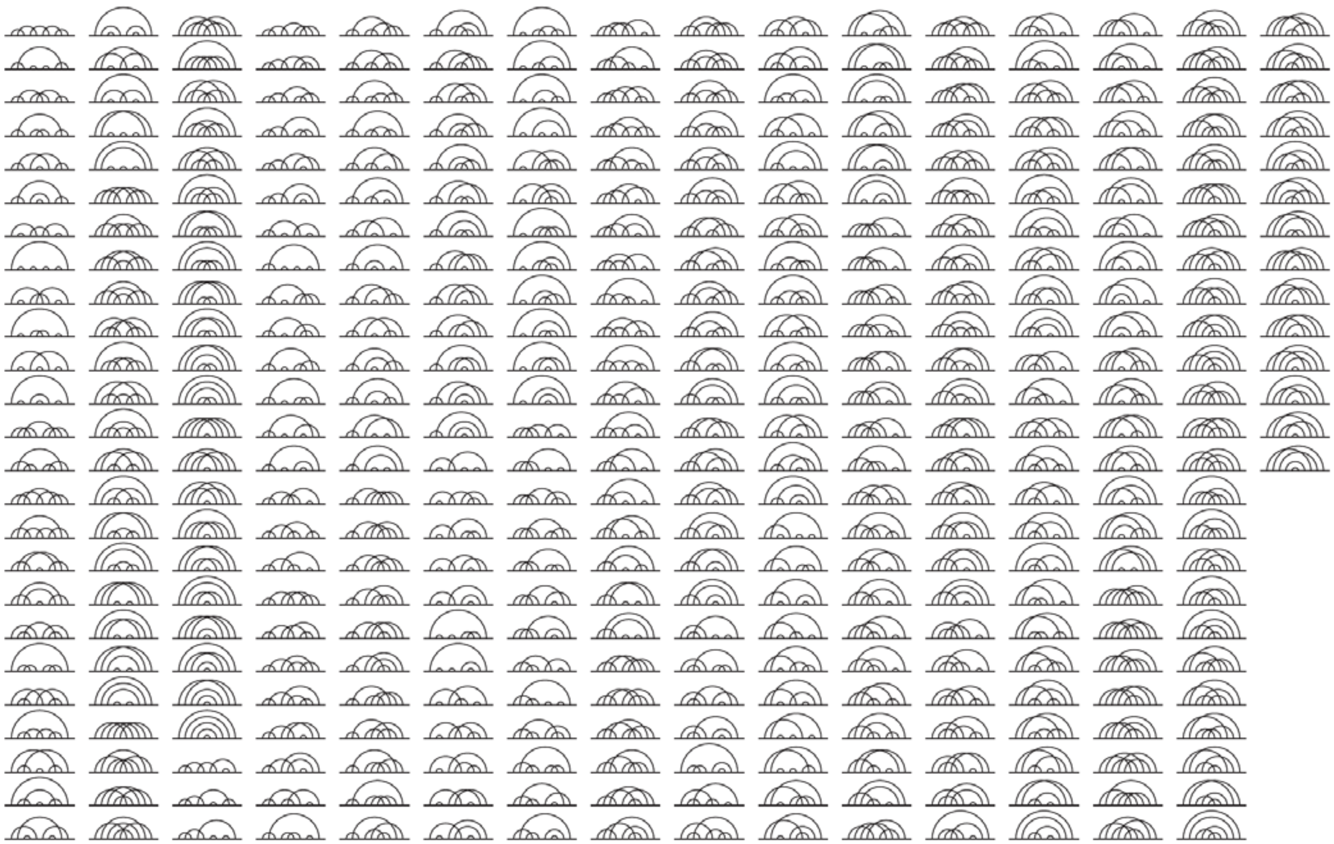


Loop contributions with Higgs[4]

[1]PRL **109**, 111807 (2012), [2]PLB **734**, 144 (2014), [3]PRD **67**, 073006 (2003), [4]PRD **88**, 053005 (2013)

Electron g-2:

Current state of the art: 5th order in QED



Subset of the 12,672 5th order diagrams contributing to a_e[1]

[1]Phys. Rev. D **91**, 033006 (2015)

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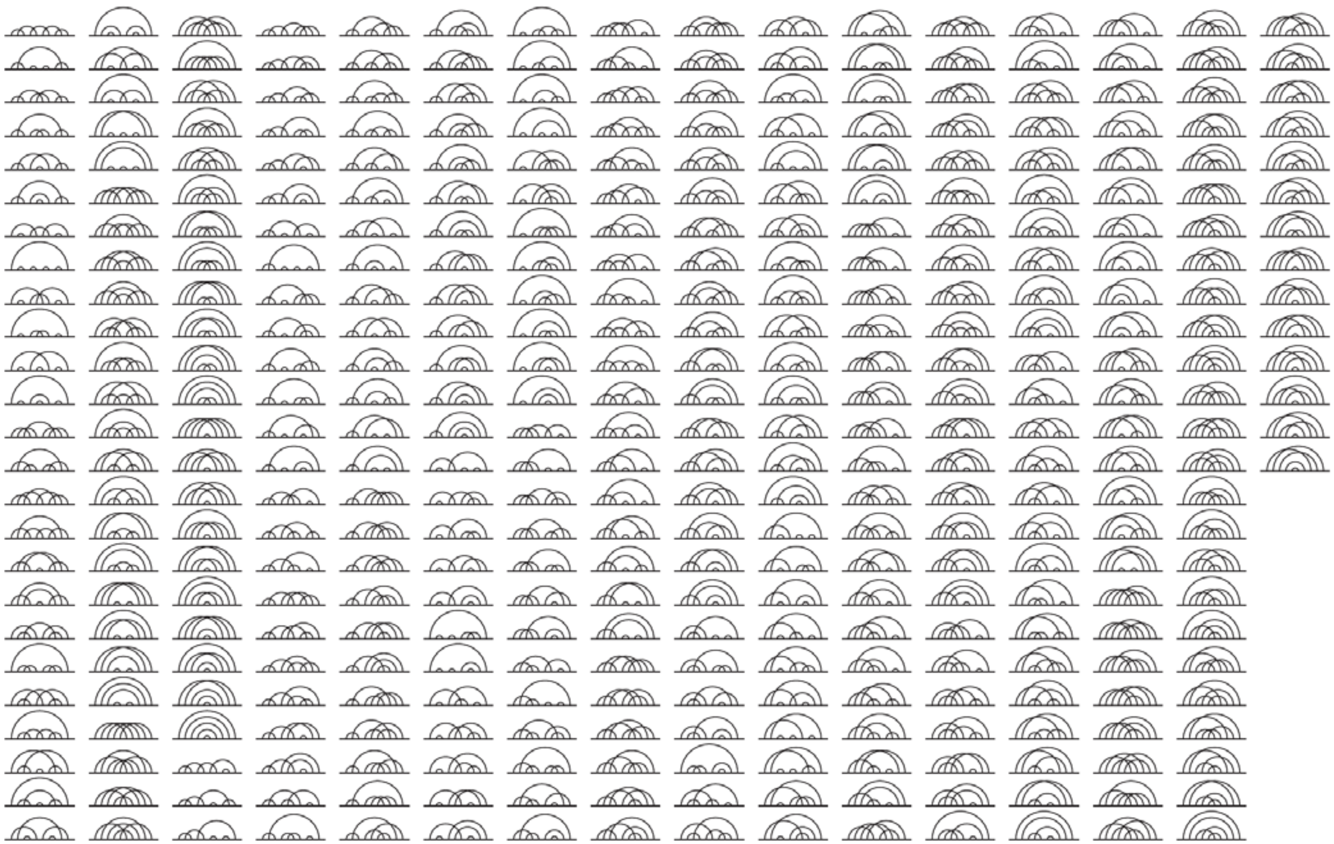

Subset of the 12,672 5^{th} order diagrams contributing to a_e[1]

$$a_e = 1\ 159\ 652\ 181.643(25)(23)(16)(763) \times 10^{-12}$$

[1]Phys. Rev. D **91**, 033006 (2015)

Electron g-2:

Experiment:

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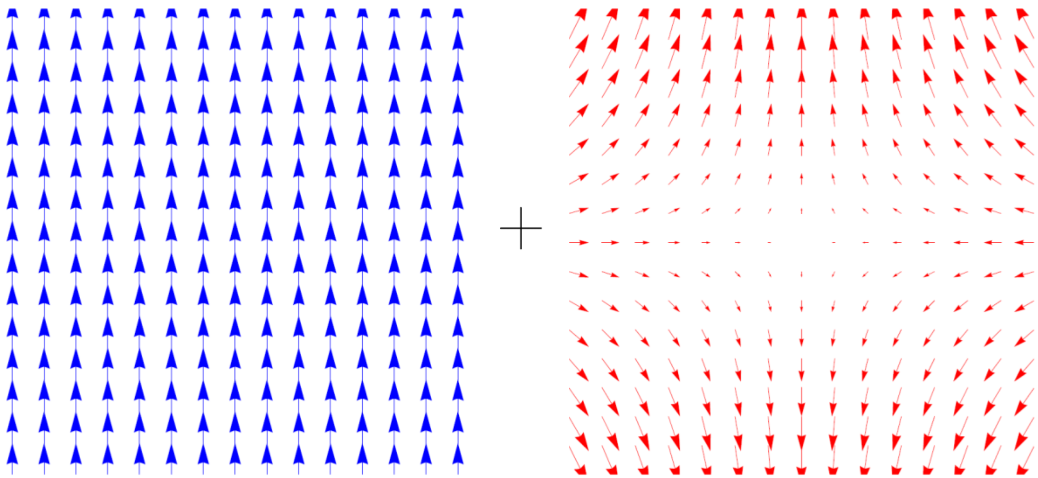
Electrons are confined by a Penning trap:



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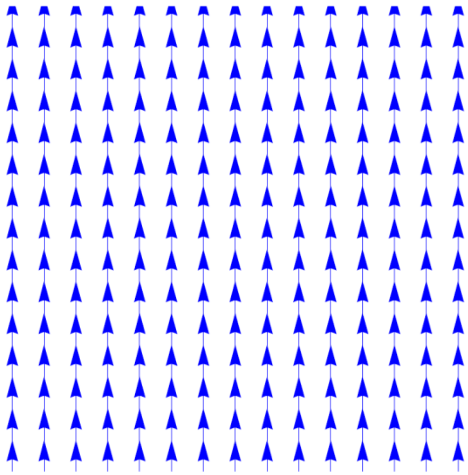
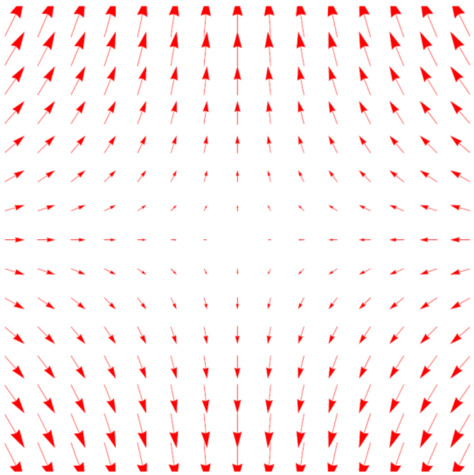


Uniform magnetic field

$\vec{B} = B_z \hat{z}$

Radial confinement

$+$



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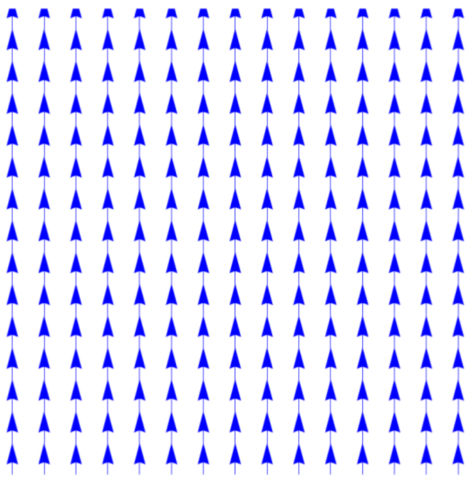

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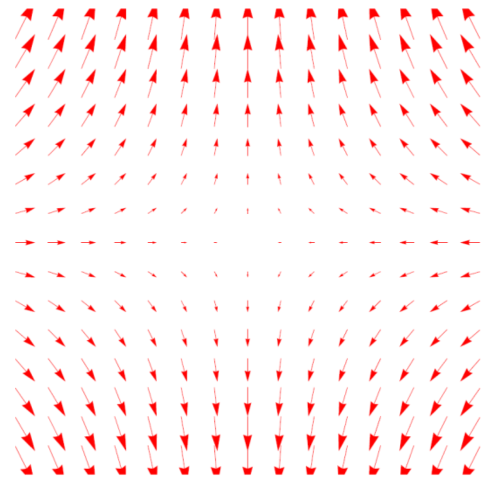

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Quadrupole electric field

$\vec{E} = E_0(-x\hat{x} - y\hat{y} + 2z\hat{z})$

Axial confinement

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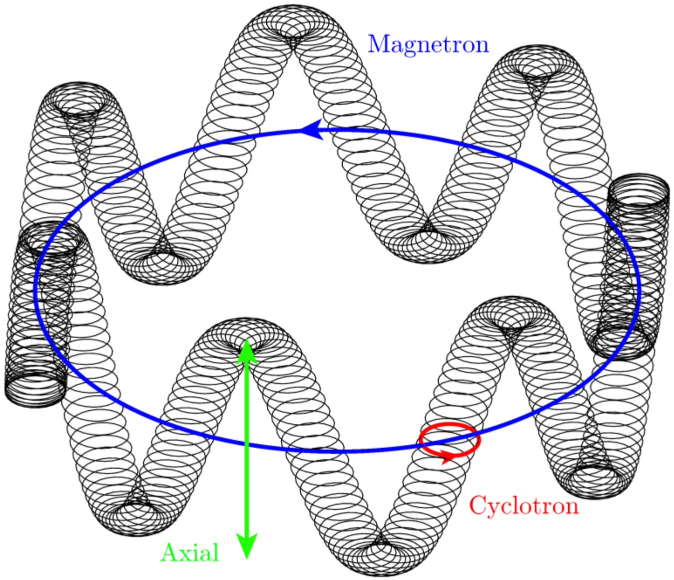

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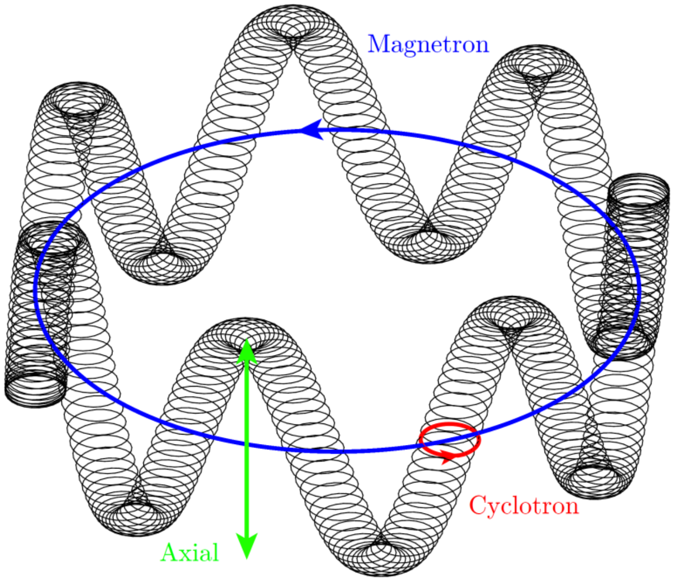

3 types of motion, each with characteristic frequency[1]

f_s = spin-flip frequency
f_c = cyclotron frequency

$$f_s = f_c\, g/2 \approx f_c$$

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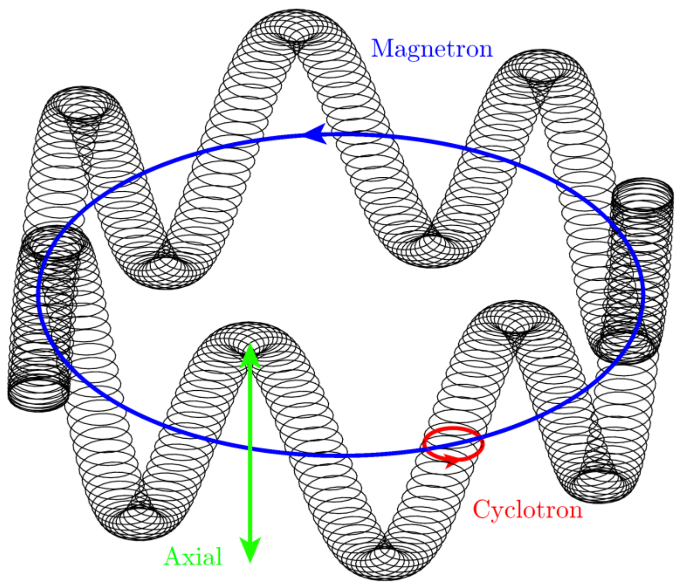

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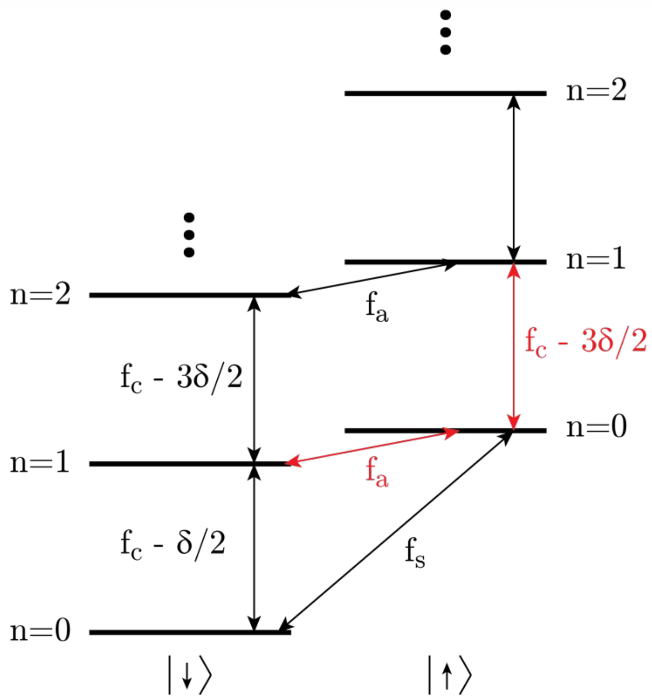

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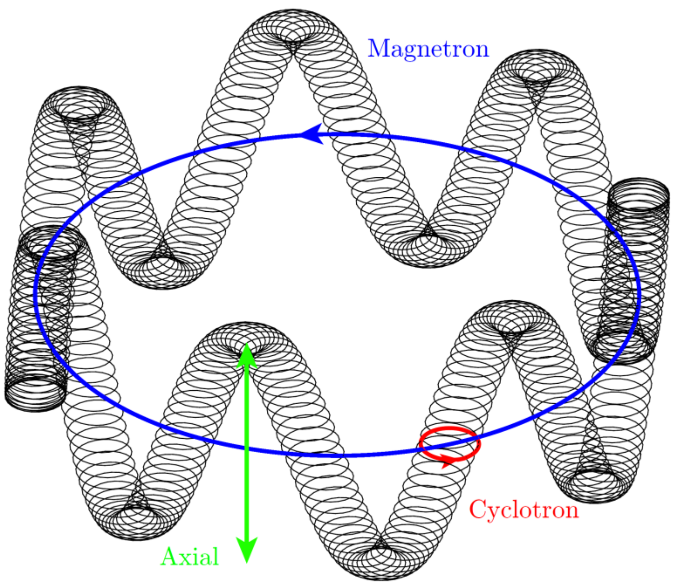

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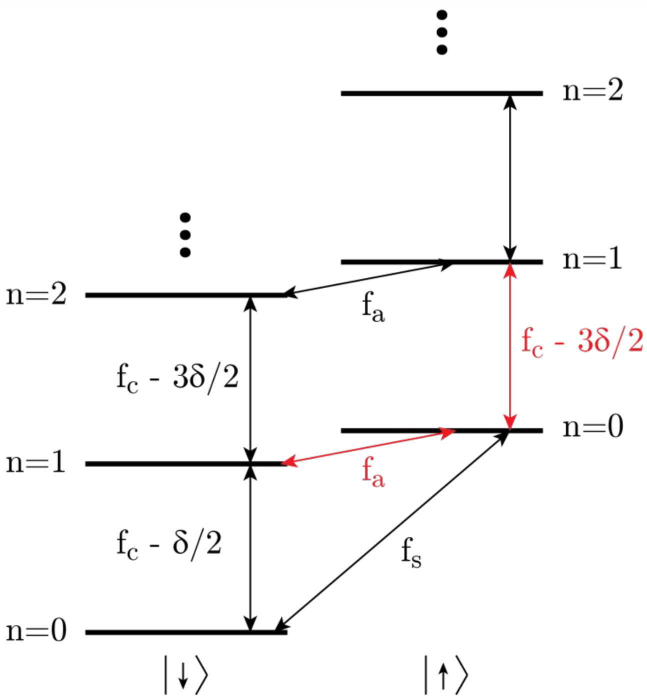

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Cyclotron level and spin state are coupled to the axial motion by adding a ‘magnetic bottle’.

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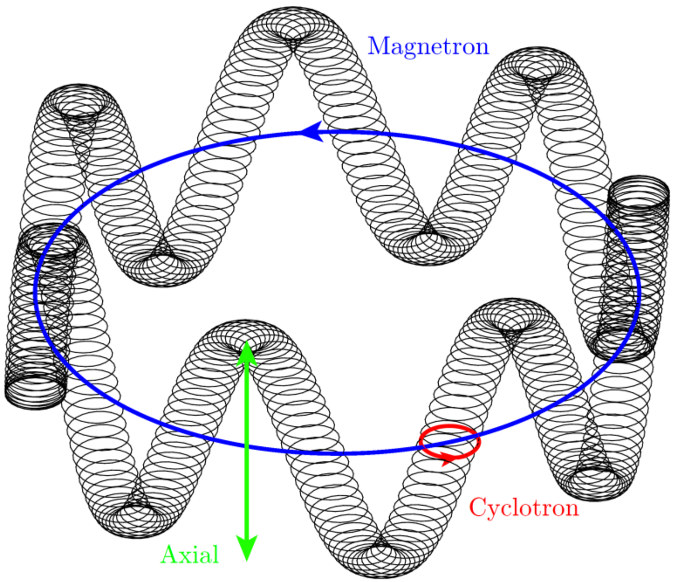

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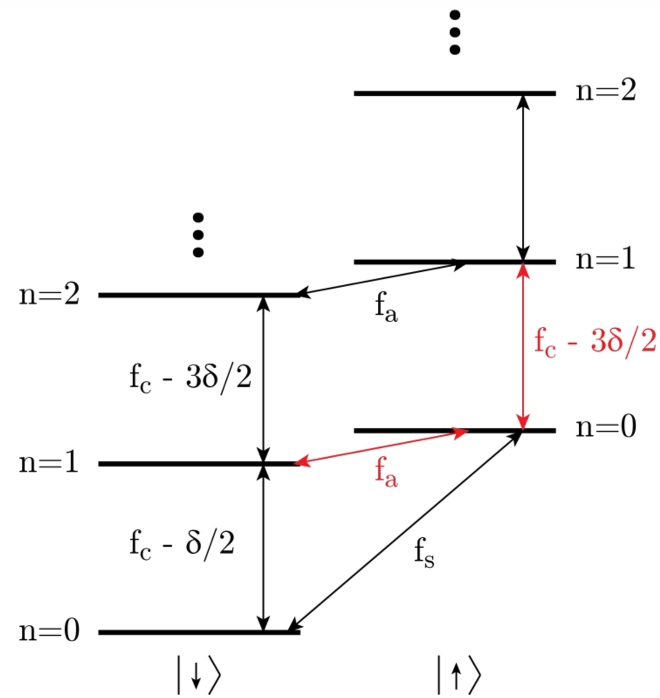

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100 mK cavity inhibits spontaneous emission and allows ground state electrons.

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Electron's axial motion produces an image current in the electrodes which is amplified and detected.

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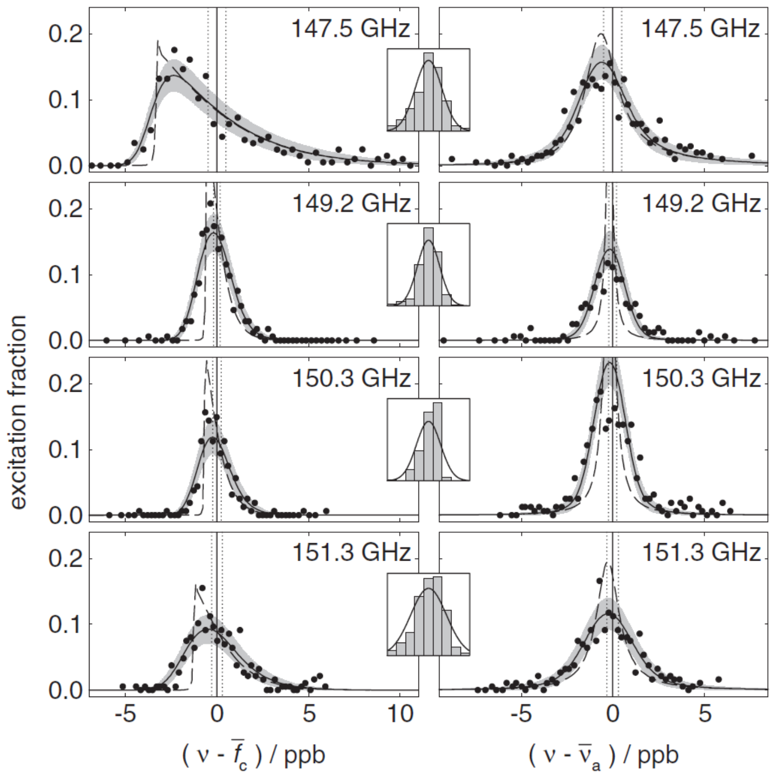

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Phys. Rev. Lett. **100**, 120801 (2008), Phys. Rev. D **91**, 033006 (2015)

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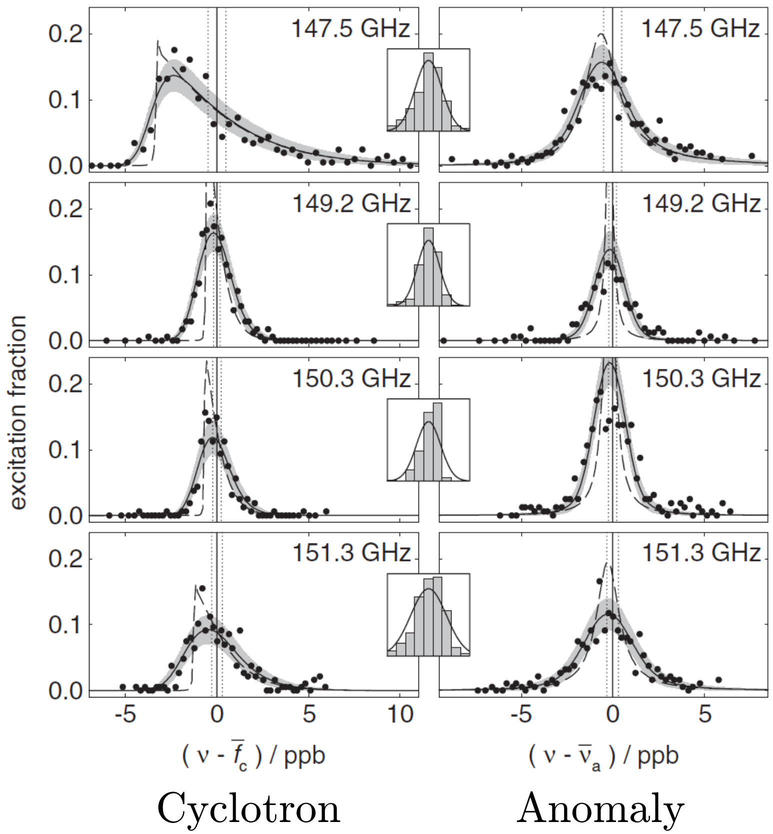

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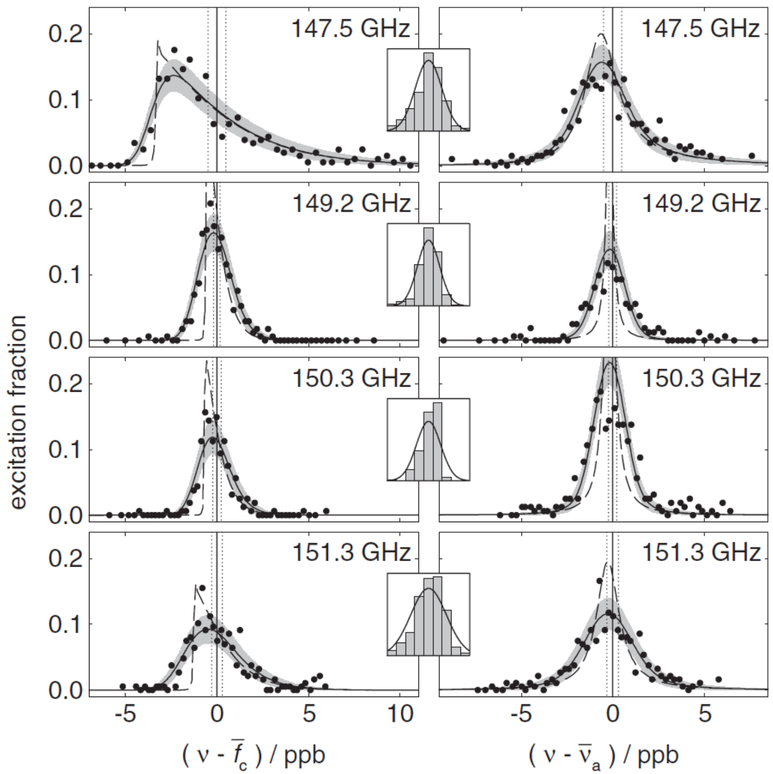

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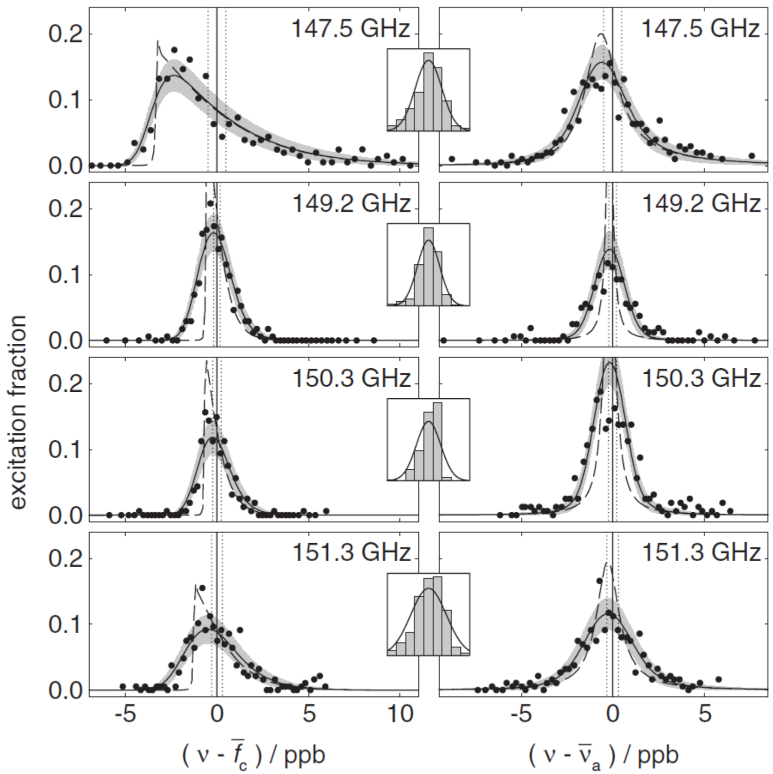

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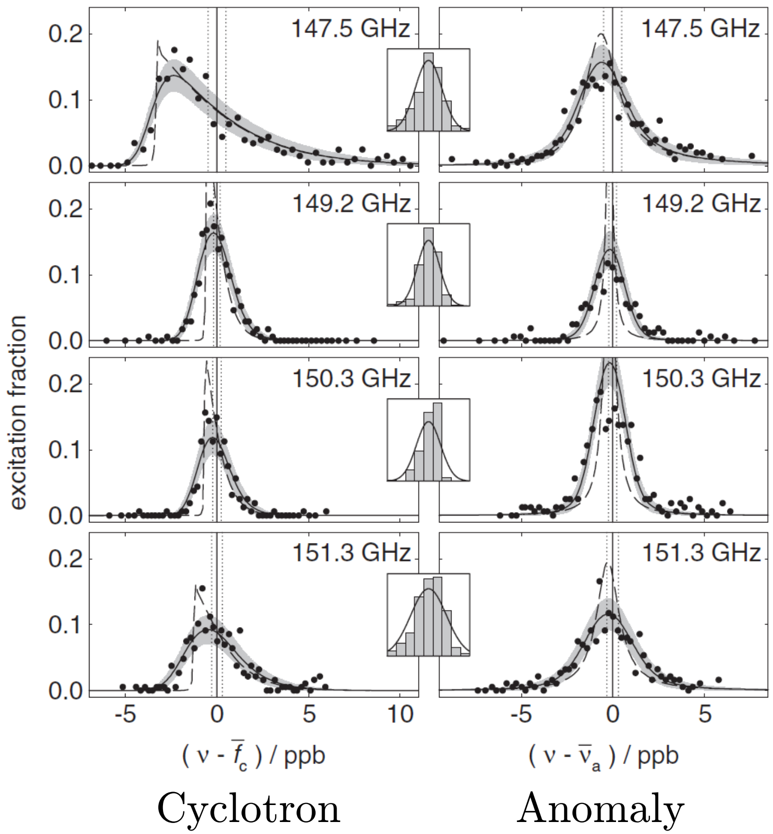

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Work is underway to apply the method to positrons and perform the best test of CPT in leptons.

Phys. Rev. Lett. **100**, 120801 (2008), Phys. Rev. D **91**, 033006 (2015)

Muon g-2:

Ion traps unsuitable:
Cyclotron radius = 2 m, impossible to load, require relativistic speeds (lifetime = 2 us).

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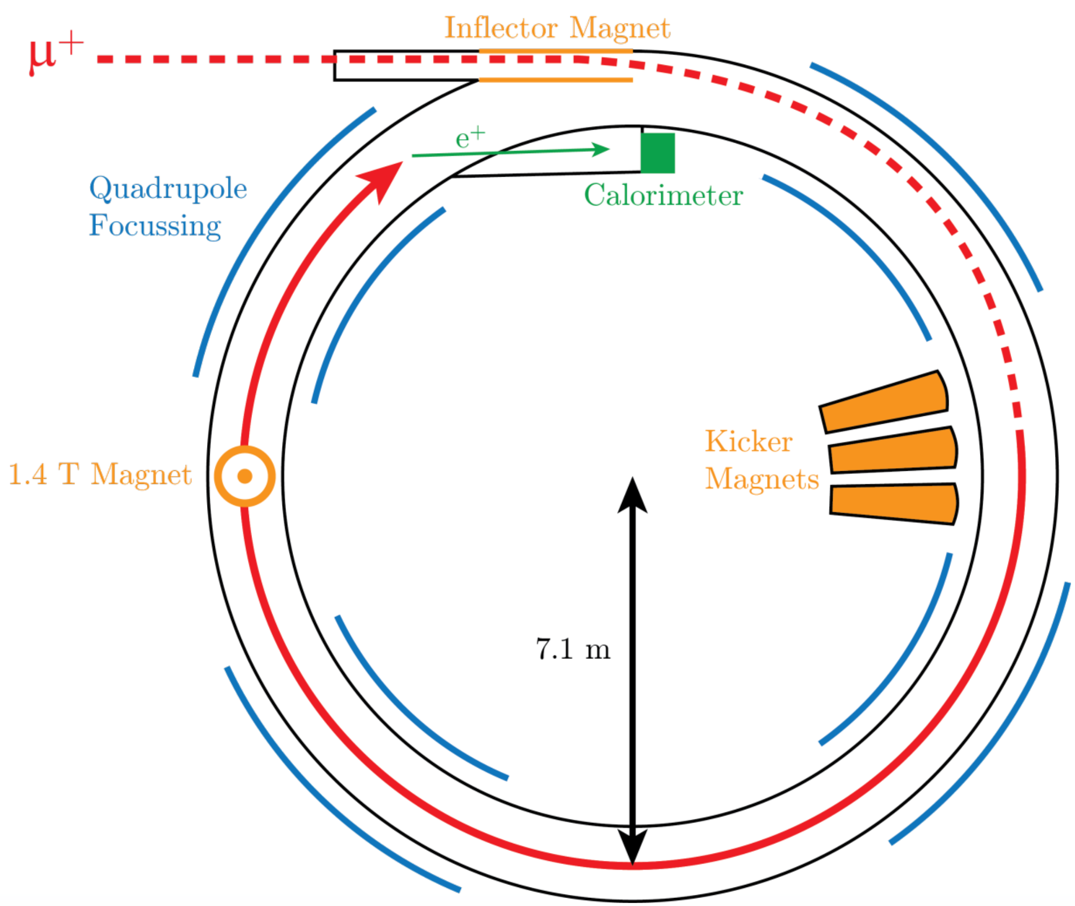

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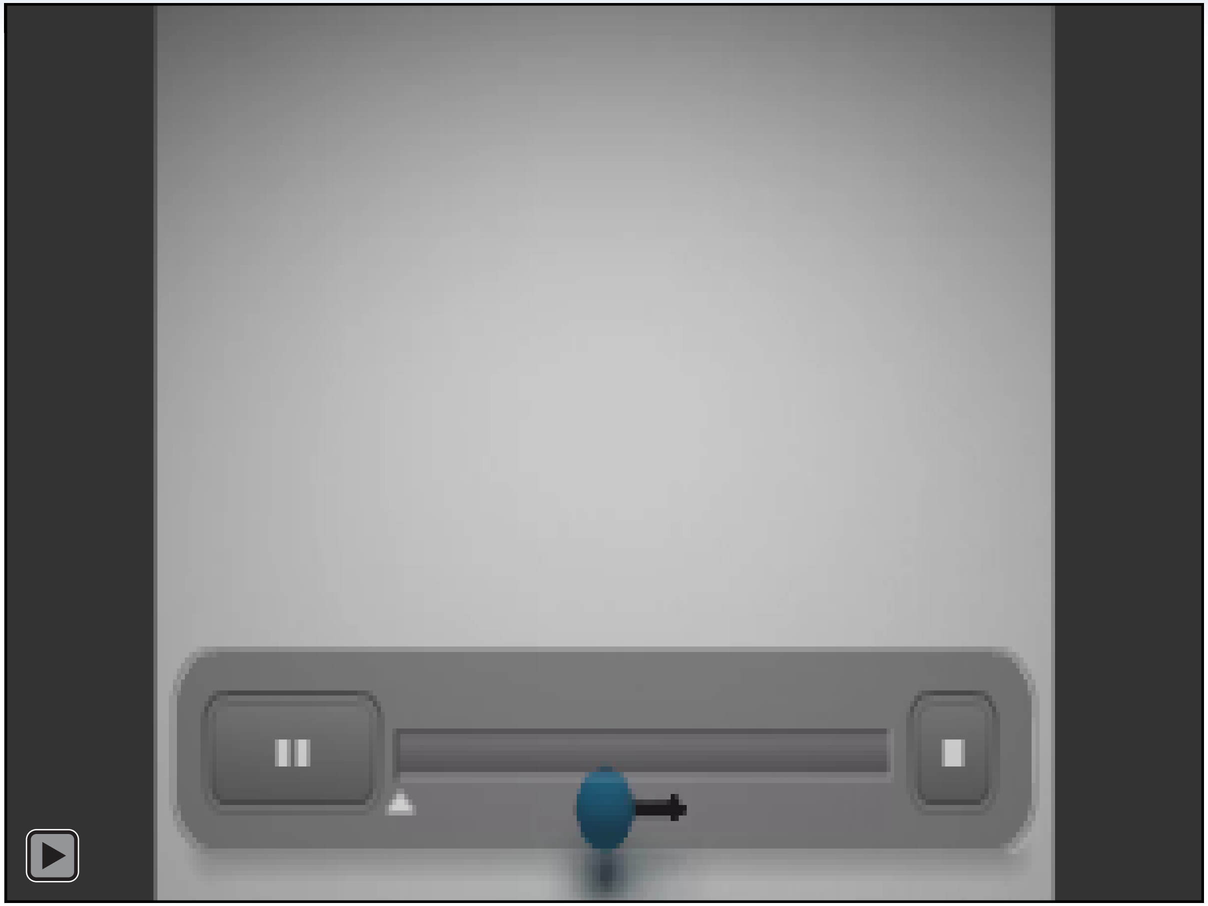

Spin Precession	Cyclotron Orbit	Anomaly Frequency
$\omega_s = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$	$\omega_c = \frac{eB}{mc\gamma}$	$\omega_a = \omega_s - \omega_c = a\frac{eB}{mc}$

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$$\vec{\omega}_a = \frac{e}{mc}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E}\right] = \frac{ea\vec{B}}{mc}$$

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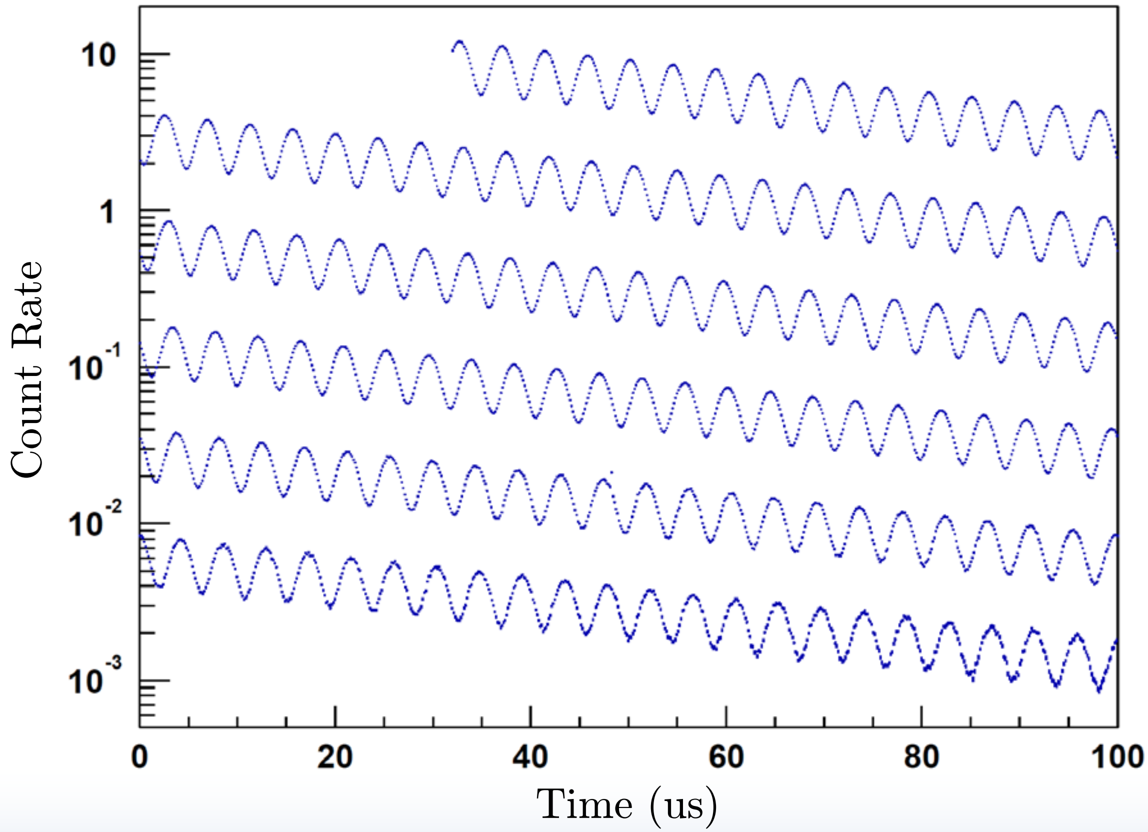

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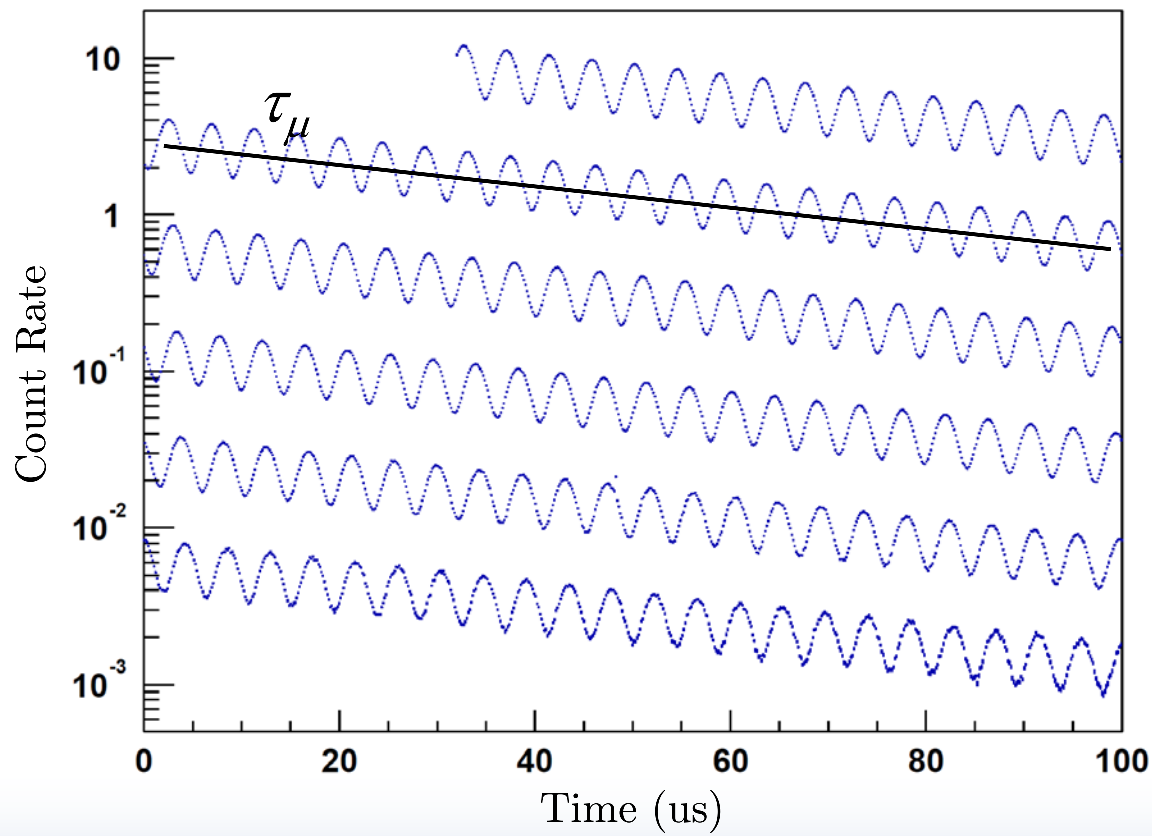

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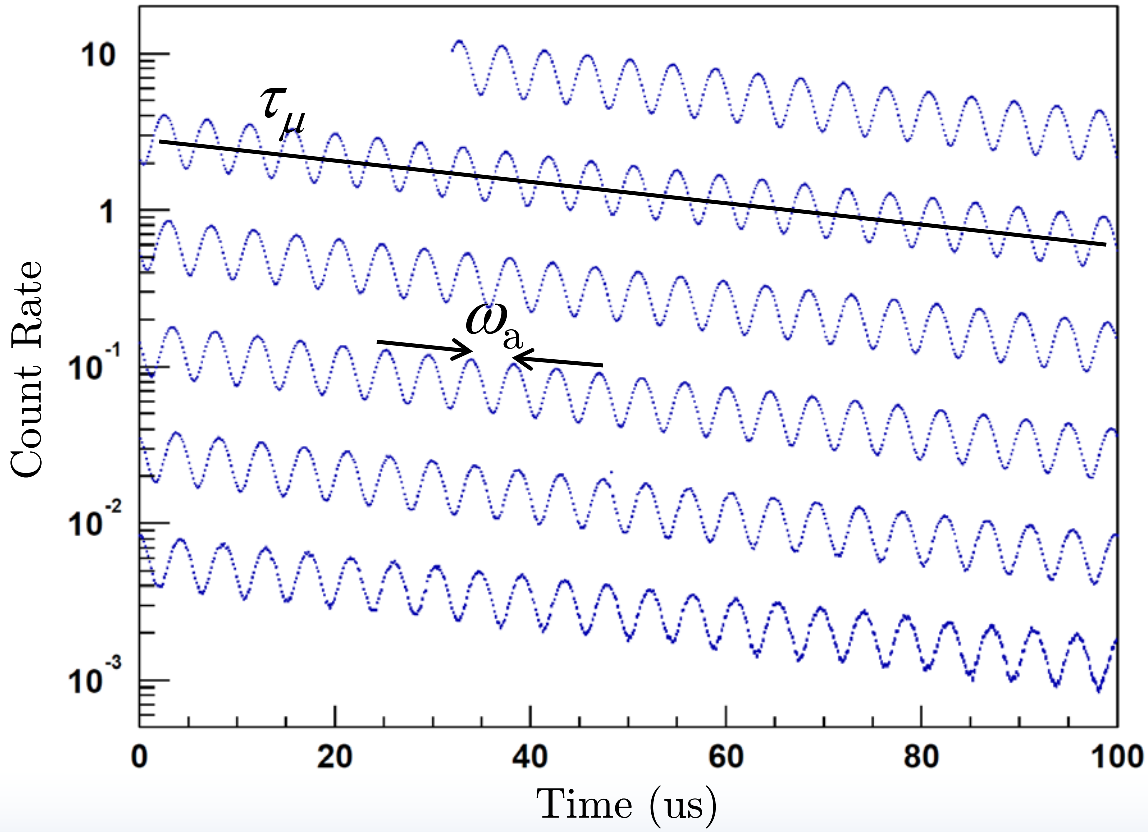
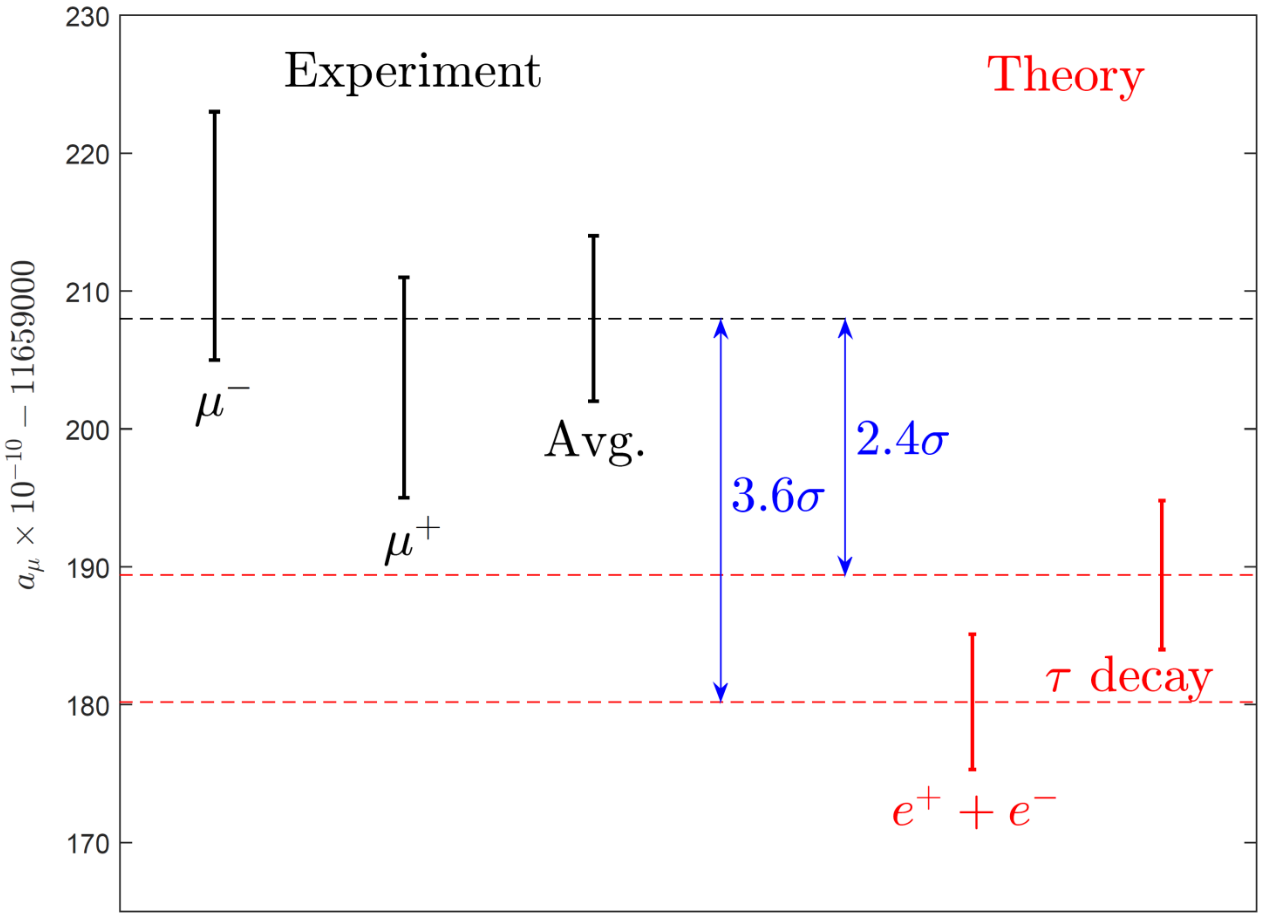


Muon g-2:

Significant discrepancy – may be explained by BSM theory.



Phys. Rev. Lett. **100**, 120801 (2008),

Muon g-2:

Assuming naive scaling we can make correspondences with other lepton moments.

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[1]JHEP11 (2012) 113

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In terms of EDMs[1]

$$
\begin{aligned}
d_\mu \approx 7 \times 10^{-14} \Delta a_\mu \tan\phi_\mu \; e \cdot \mathrm{cm} \quad &\approx \quad 2 \times 10^{-22} \; e \cdot \mathrm{cm} \\
d_e \approx 1 \times 10^{-11} \Delta a_\mu \frac{m_e^2}{m_\mu^2} \tan\phi_e \; e \cdot \mathrm{cm} \quad &\approx \quad 7 \times 10^{-25} \; e \cdot \mathrm{cm} \; (!) \\
d_\tau \approx 5 \times 10^{-15} \Delta a_\mu \frac{m_\tau^2}{m_\mu^2} \tan\phi_\tau \; e \cdot \mathrm{cm} \quad &\approx \quad 4 \times 10^{-21} \; e \cdot \mathrm{cm}
\end{aligned}
$$

[1]JHEP11 (2012) 113

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$$a_l = a_l^{\mathrm{QED}} + a_l^{\mathrm{Hadron}} + a_l^{\mathrm{Weak}}$$

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$$a_{\mathrm{l}} = a_{\mathrm{l}}^{\mathrm{QED}} + \underbrace{a_{\mathrm{l}}^{\mathrm{Hadron}} + a_{\mathrm{l}}^{\mathrm{Weak}}}_{\sim m_{\mathrm{l}}^2 \Rightarrow \text{ 40,000 times bigger for } \mu}$$

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Muon more sensitive than electron to new physics at electroweak scale.

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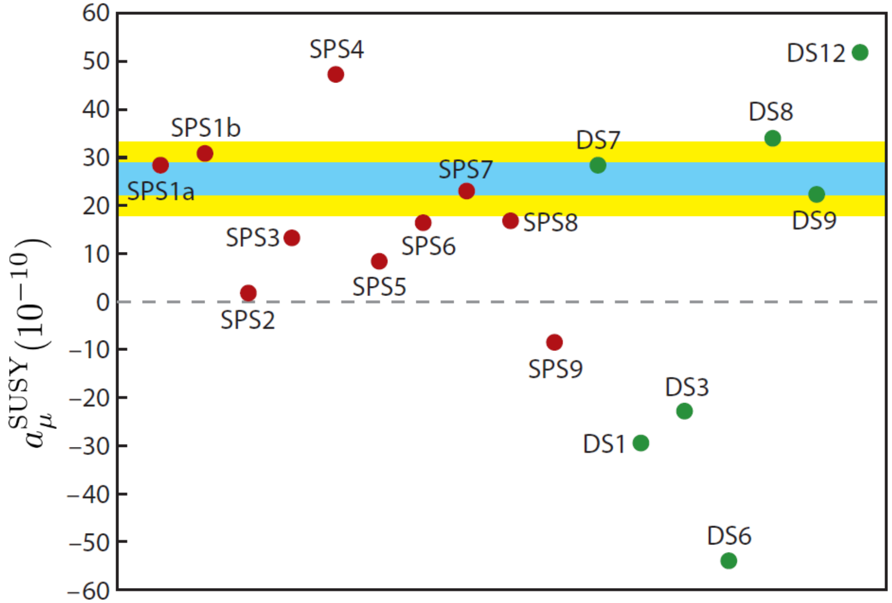
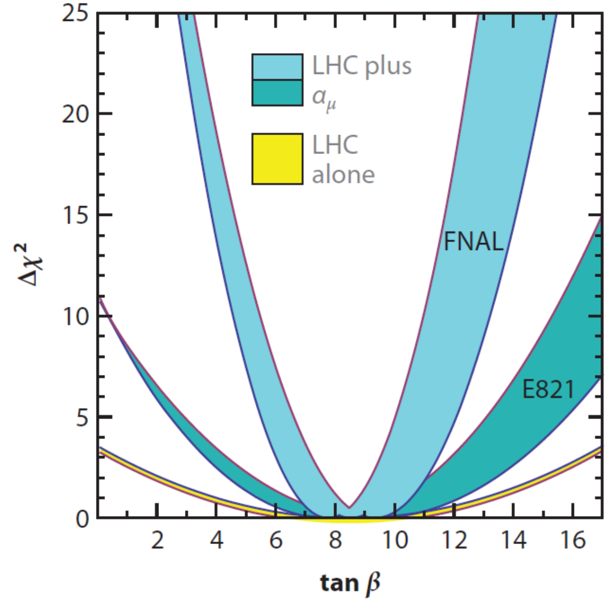
Already distinguishing between some theories better than the LHC[1]:





$$\Delta\chi^2 = \left[(a_\mu^{\text{SUSY}}(\tan\beta) - \Delta a_\mu)/\delta a_\mu\right]^2$$

tanβ = ratio of Higgs VEVs

[1]Annu. Rev. Nucl. Part. Sci. **62**, 237 (2012)

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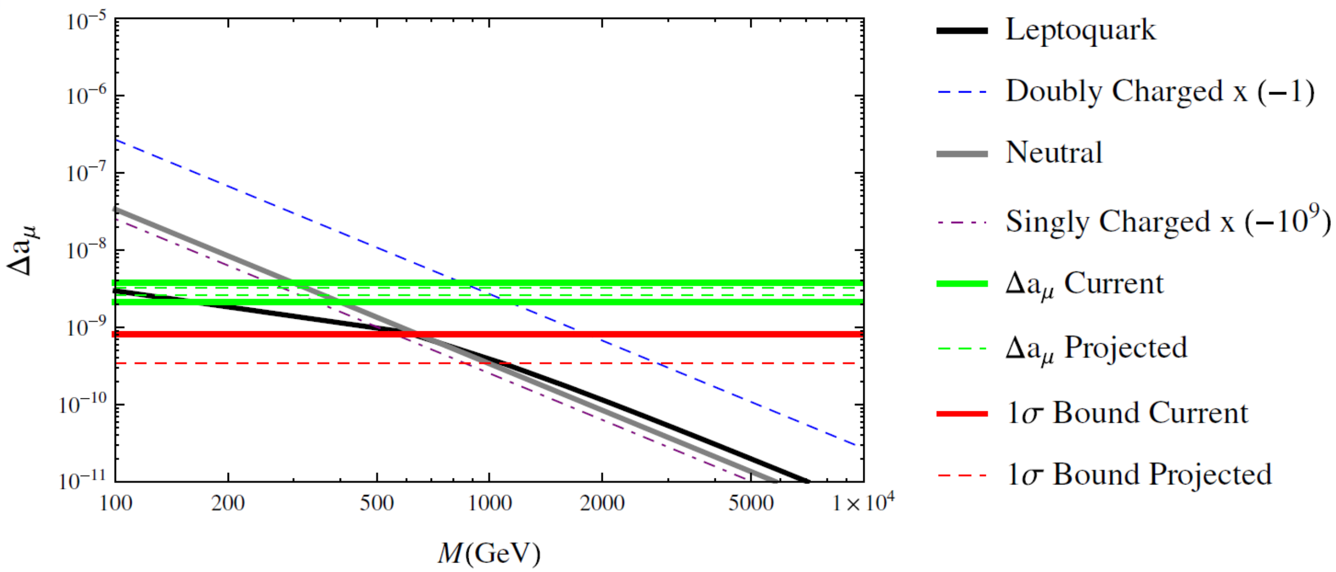

Phys. Rev. D **89**, 095024 (2014)

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New experiment at FNAL

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Aiming for fourfold increase in precision

Data taking 2016-2017…

Tau g-2:

$m_\tau/m_\mu = 17$ → 300 times more sensitive to new physics

[1]Eur. Phys. J. C **35** 159-170 (2004)

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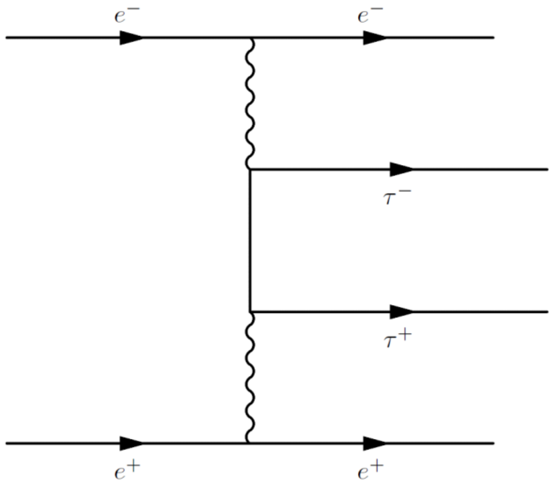

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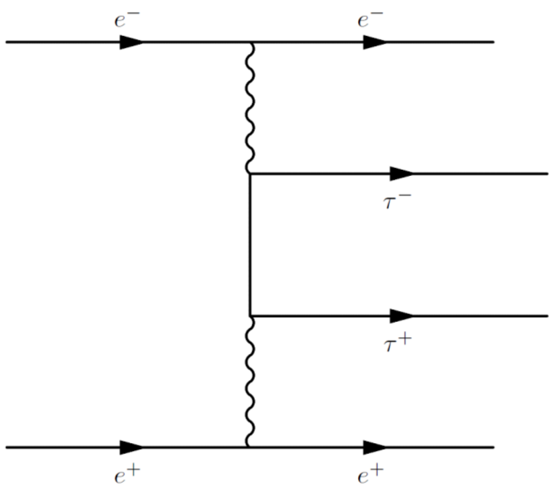

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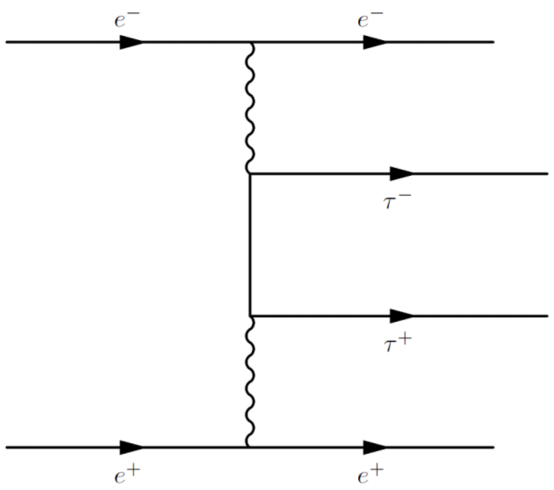
$$\underbrace{F_2(q^2)}_{a_\tau}\sigma^{\mu\nu}\frac{q_\nu}{2m_\tau} + i\underbrace{F_3(q^2)}_{d_\tau}\gamma^5\sigma^{\mu\nu}\frac{q_\nu}{2m_\tau}$$



[1]Eur. Phys. J. C **35** 159-170 (2004)

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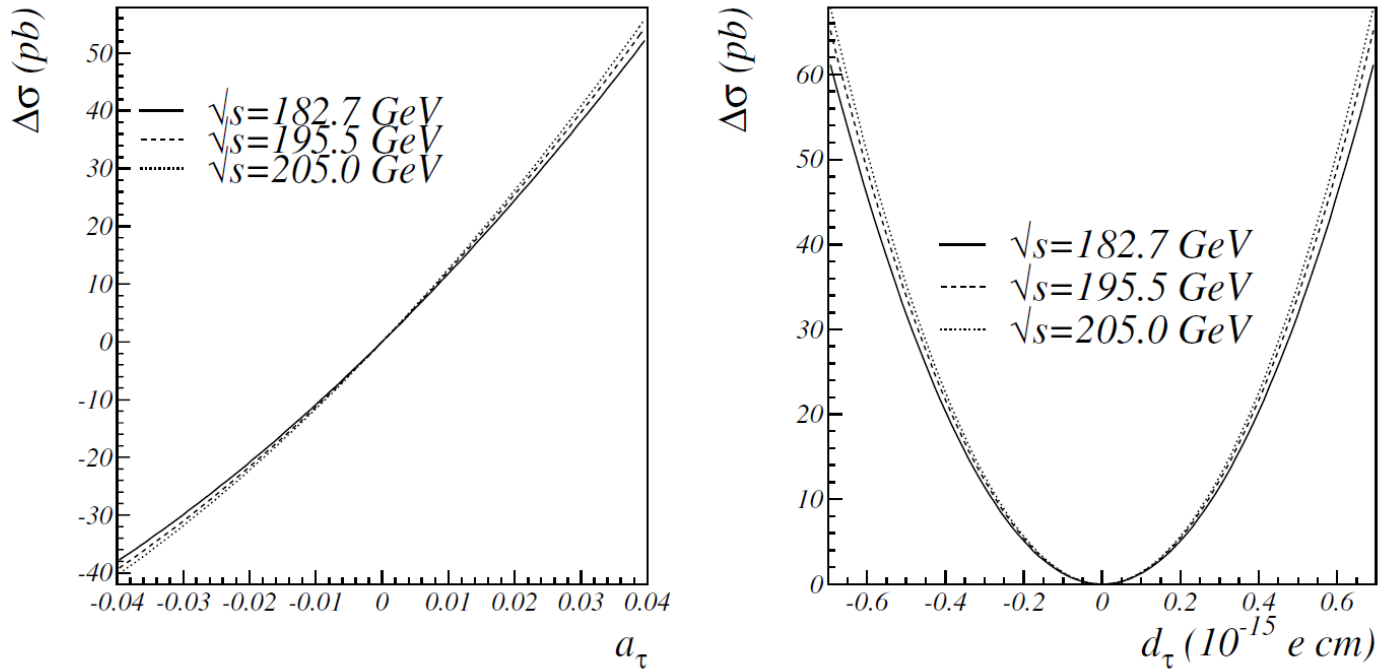

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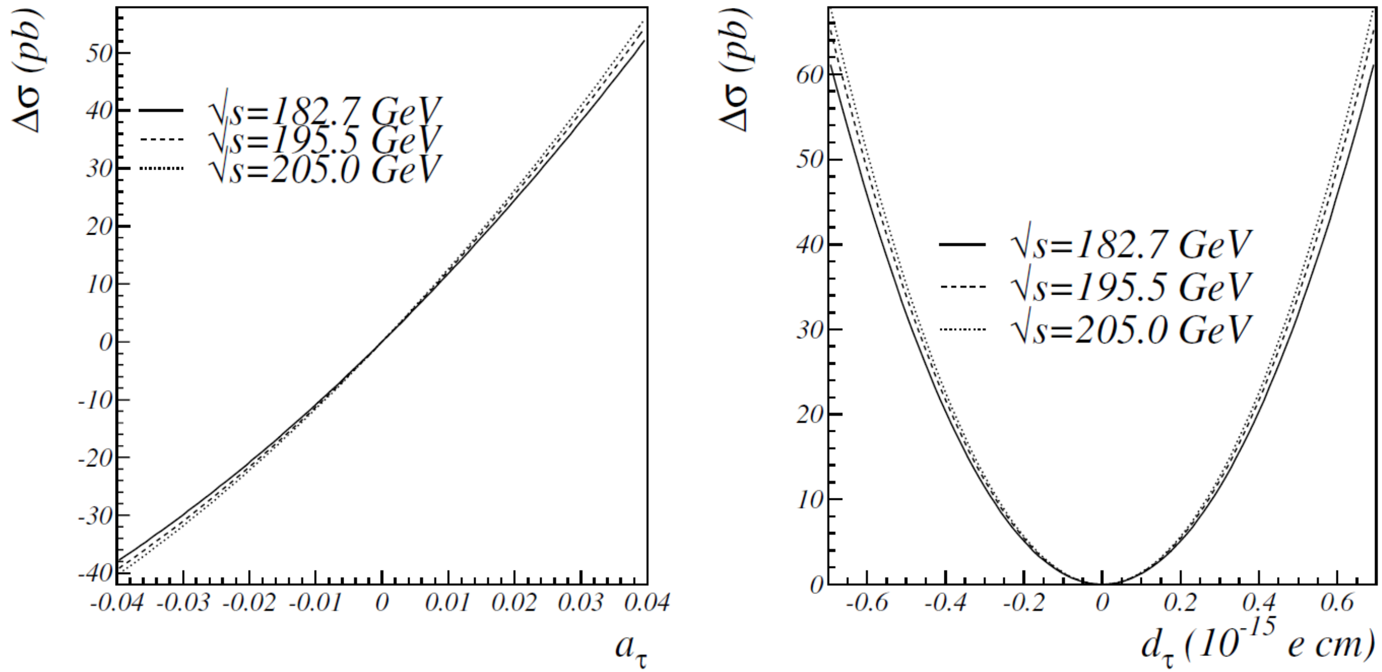

Current limit from DELPHI at LEP2 (95% C.L.)[1]: $-0.052 < a_\tau < 0.013$

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$$\omega_s^\tau = \frac{eB}{mc}\left(a_\tau + \gamma^{-1}\right)$$

Direct measure of spin precession using polarised taus in a bent crystal + strong electric field. Method used to determine MDM of Σ^+ hyperon[3]

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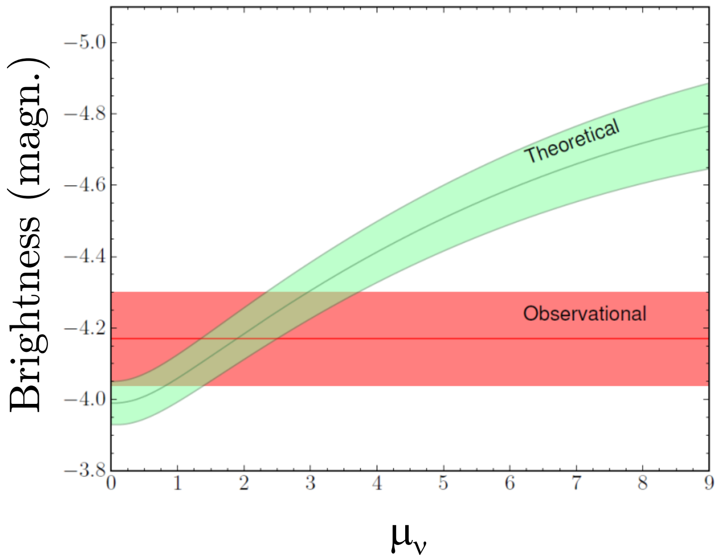

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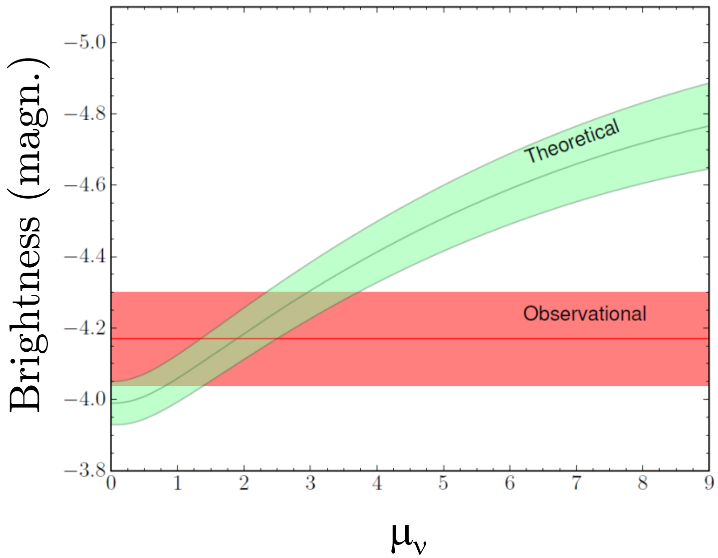

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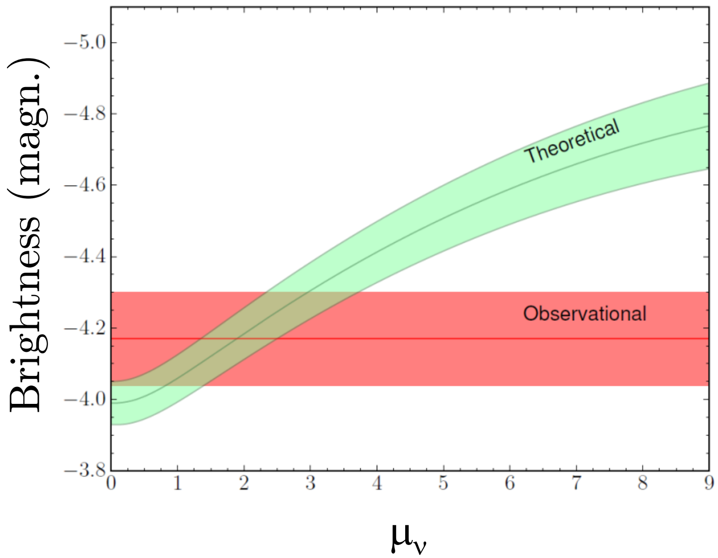

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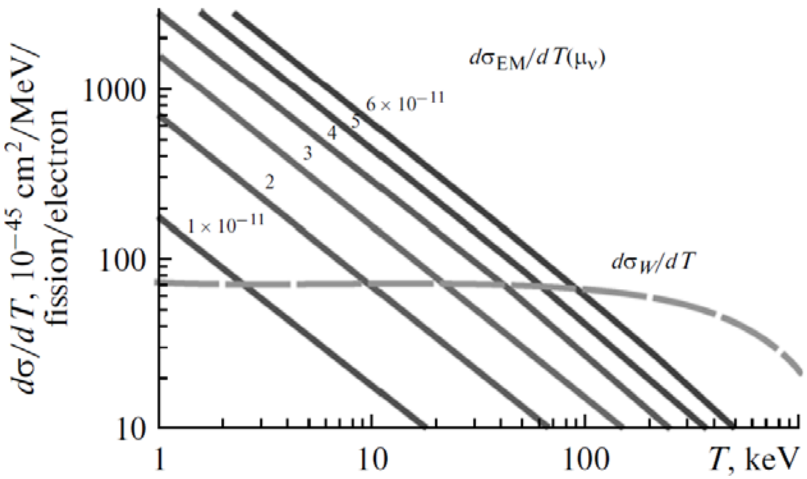

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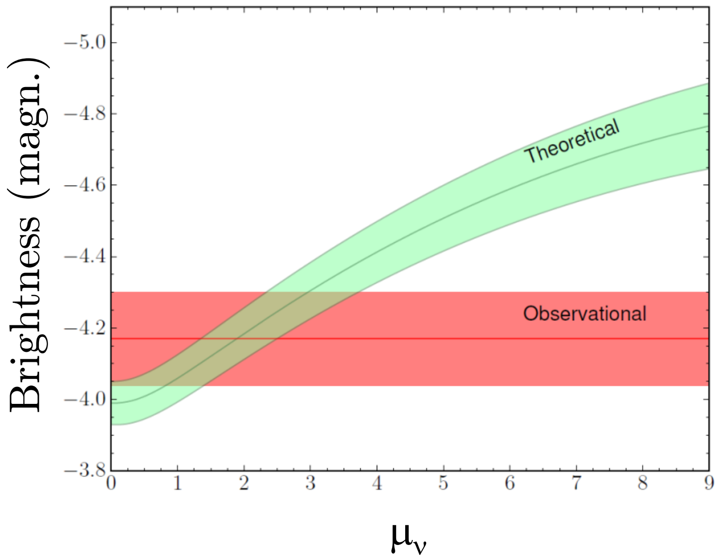

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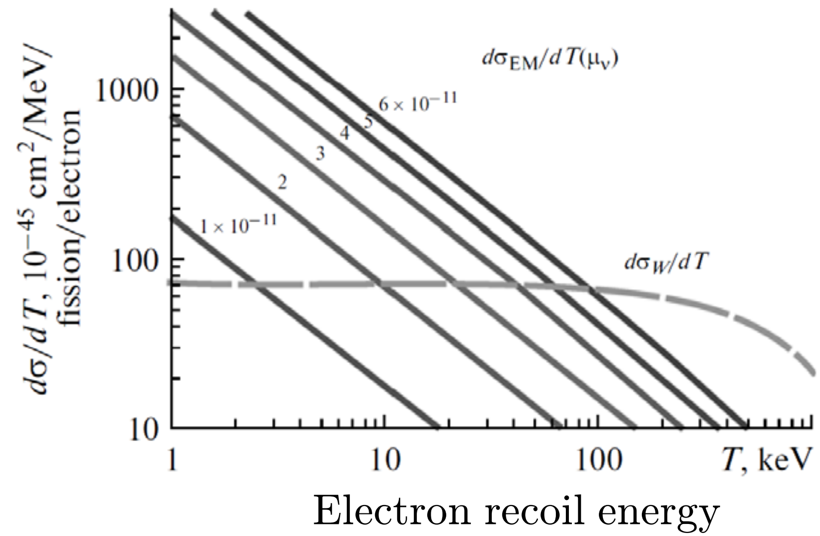

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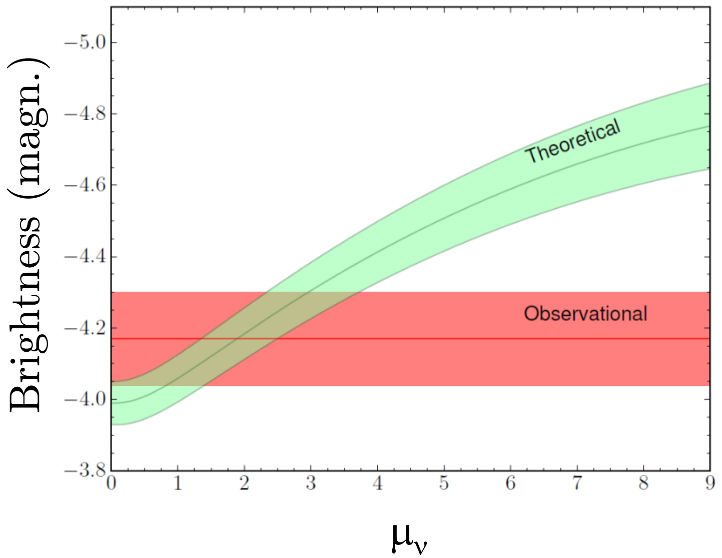

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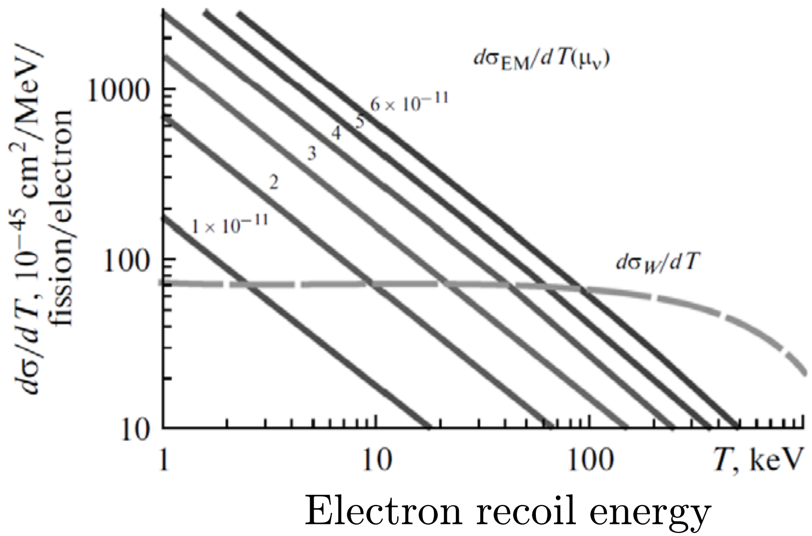

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Can recast as limits on EDM: 1.5 x 10^{-22} e.cm, 1.0 x 10^{-21} e.cm

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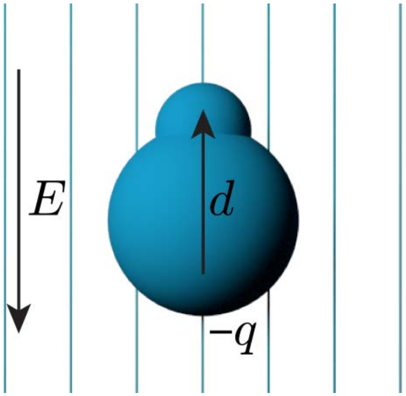
EDMs



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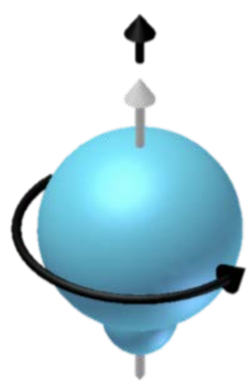

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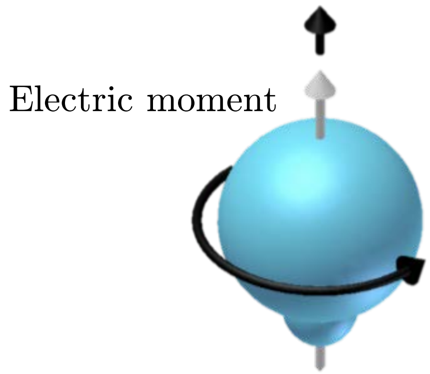

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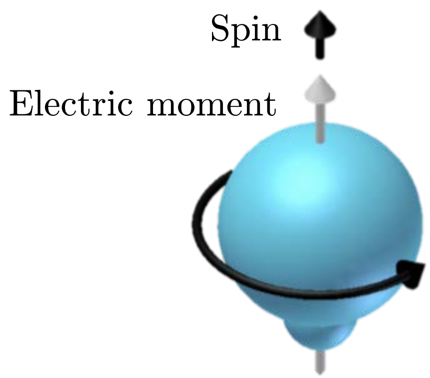

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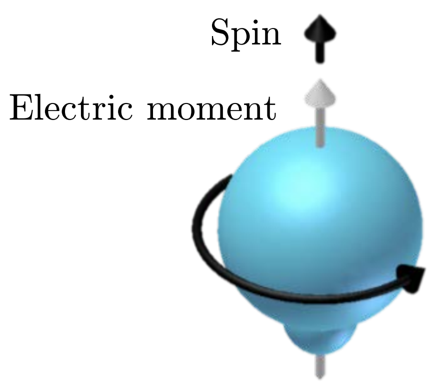

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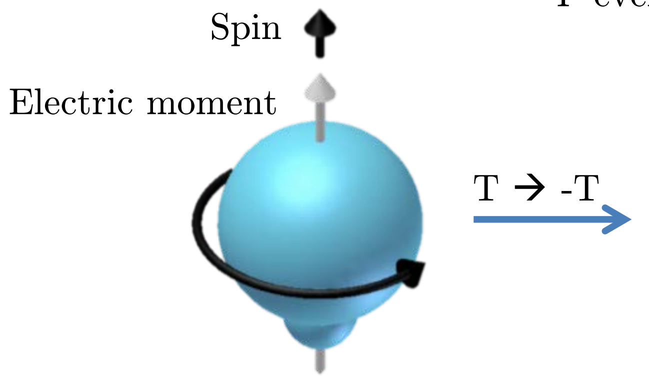

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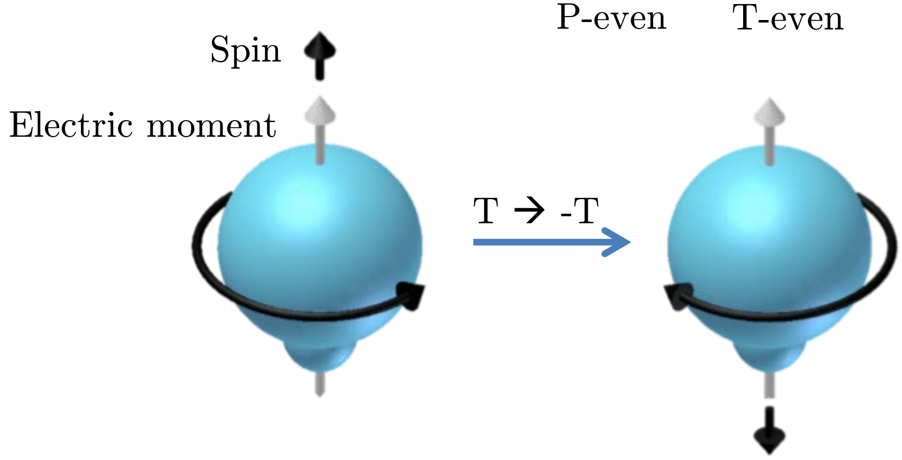

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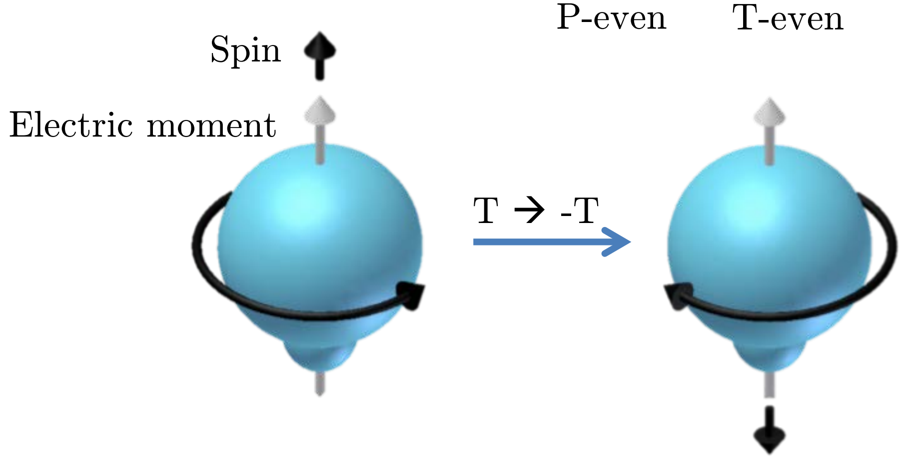

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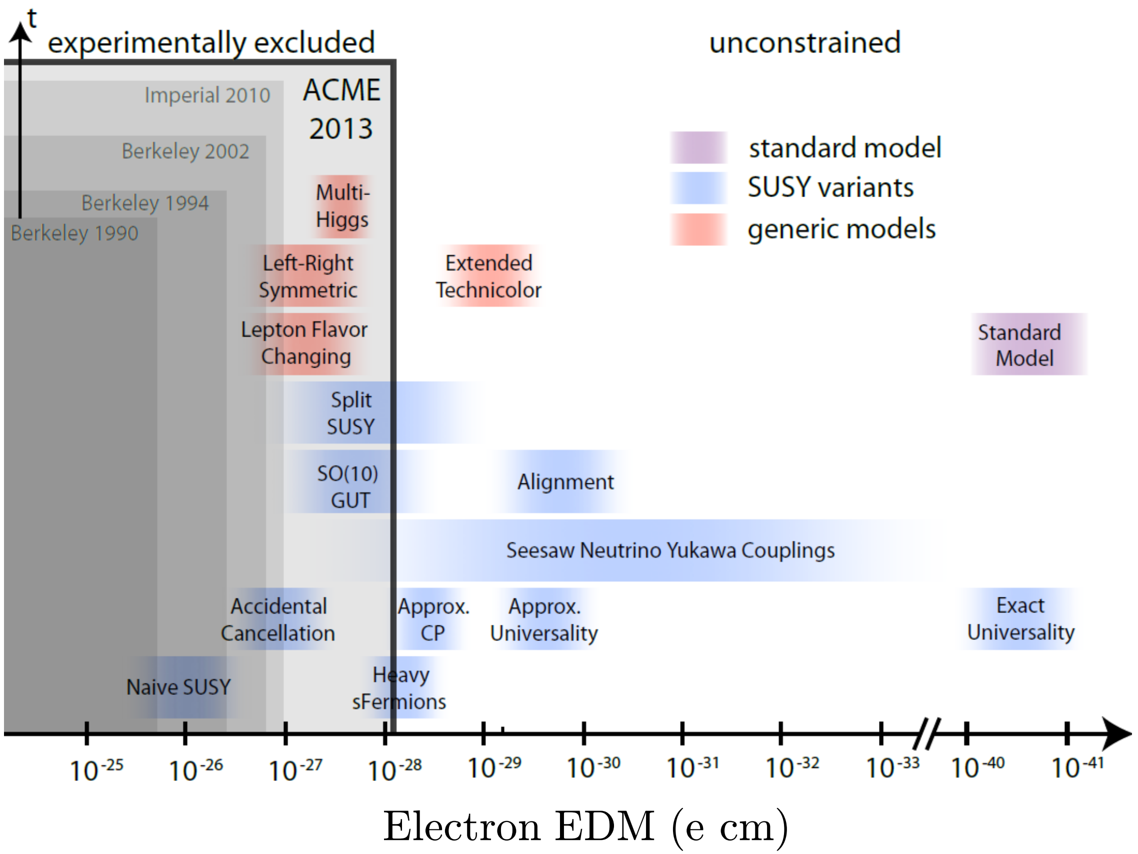

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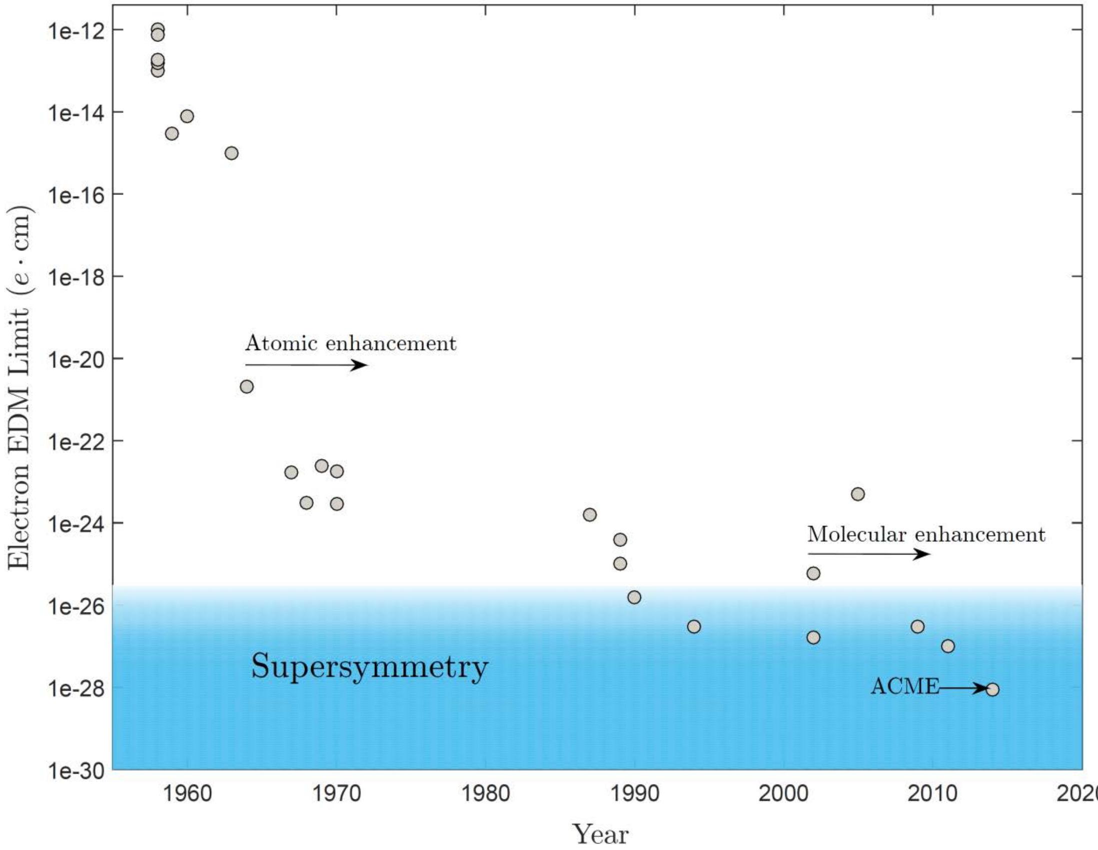
57 years of searching…



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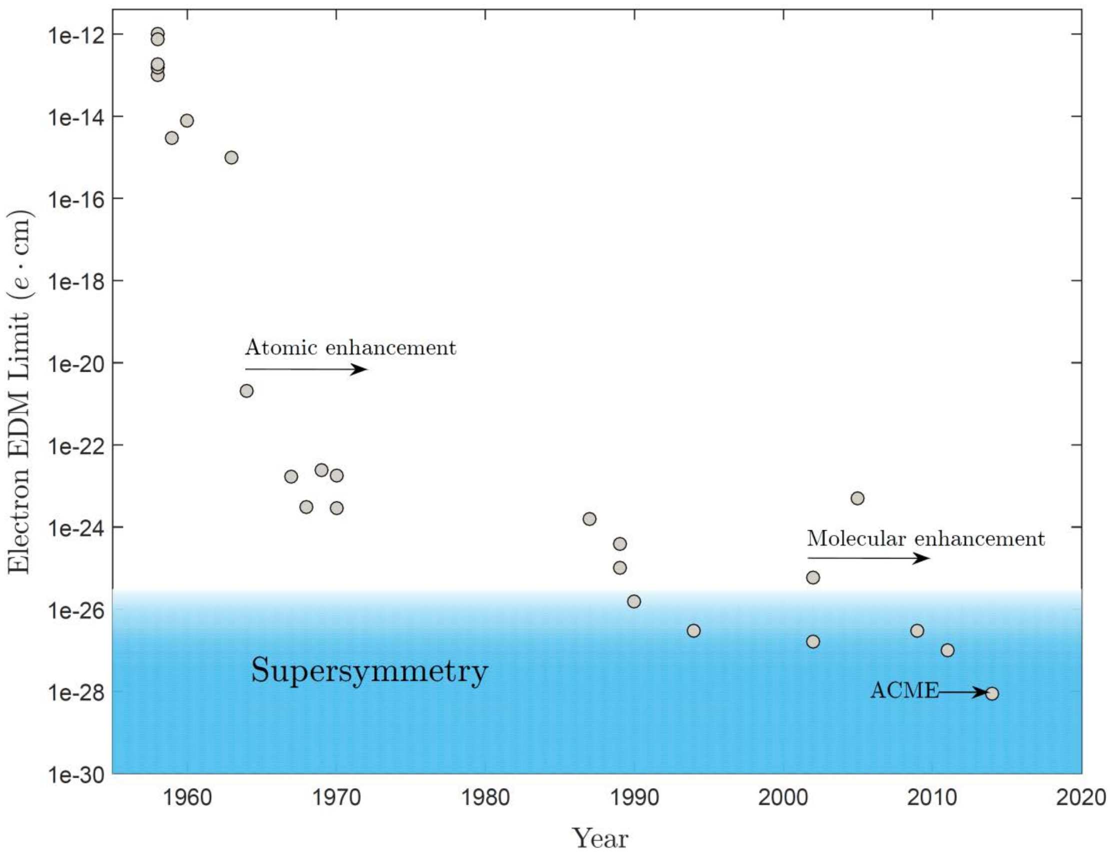

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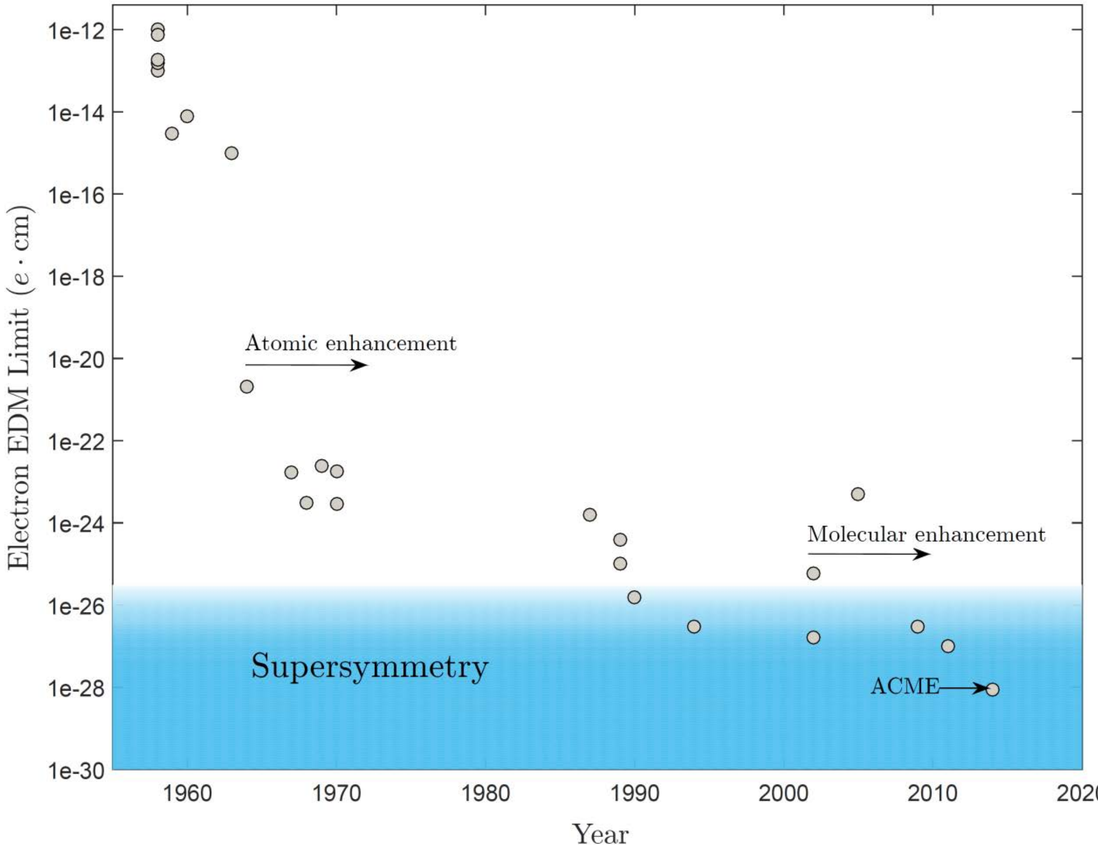

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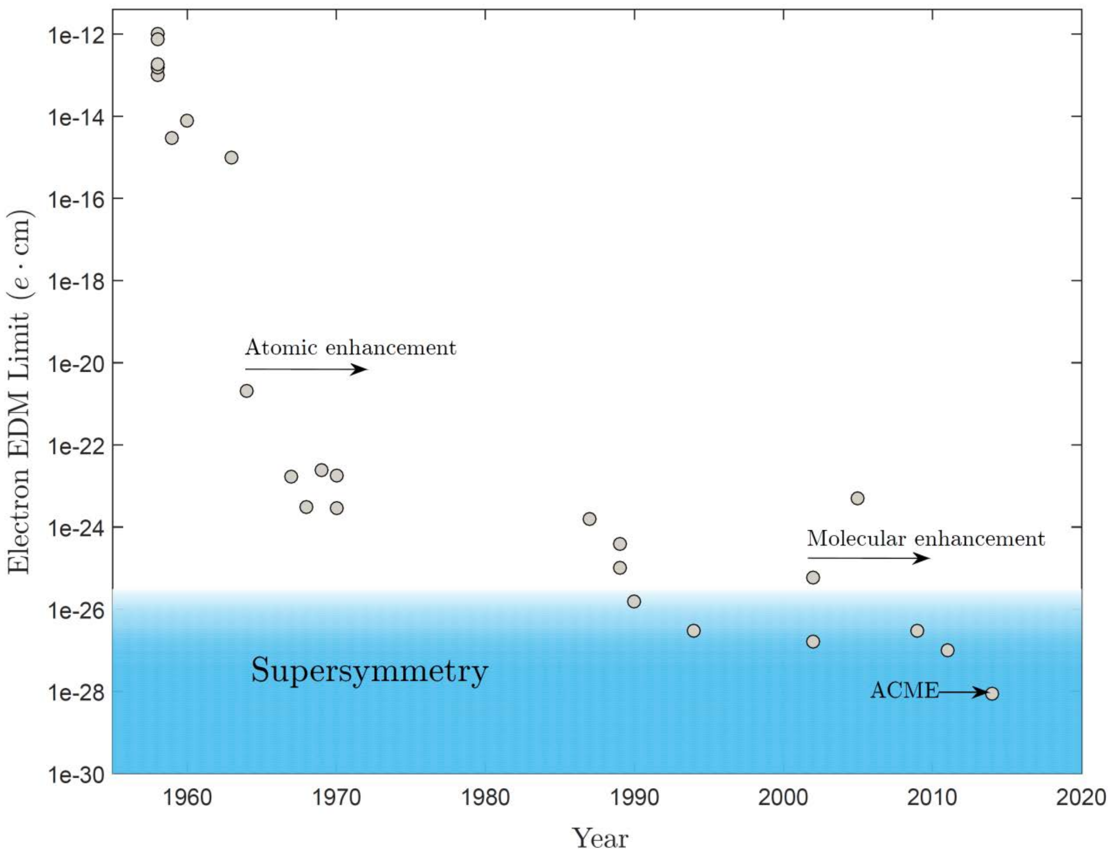

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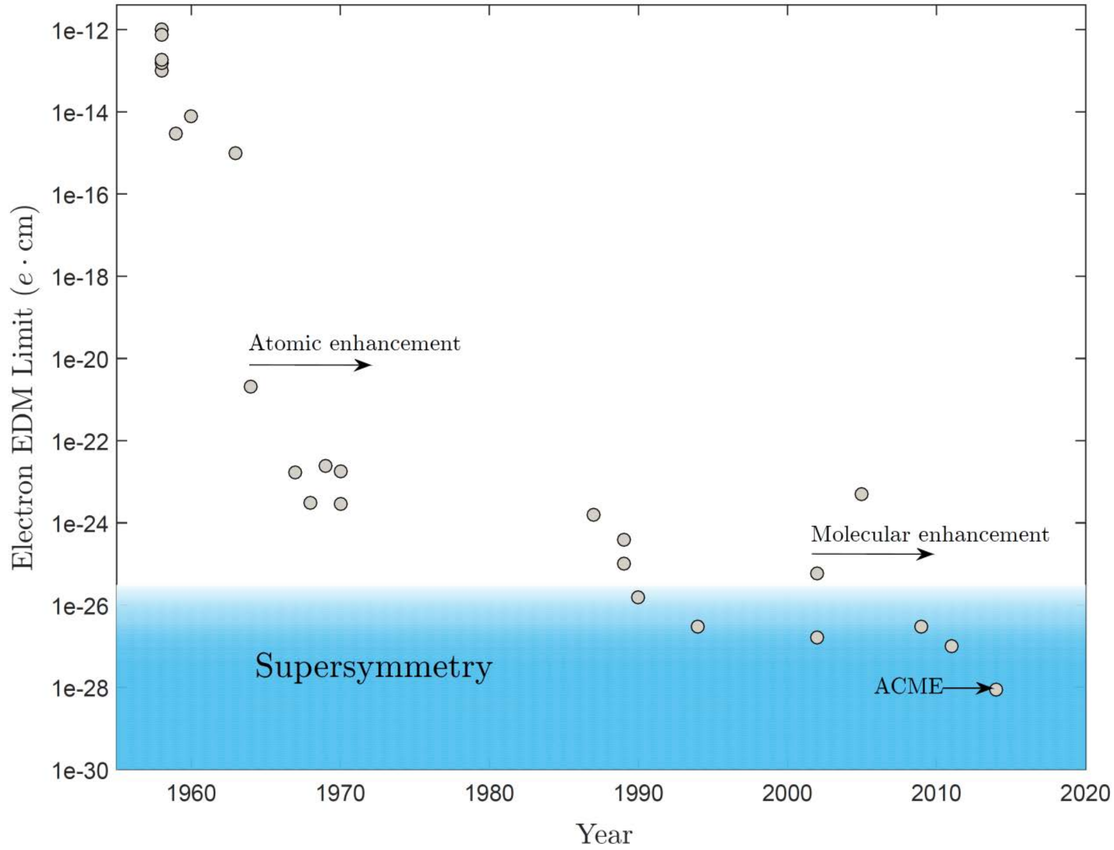

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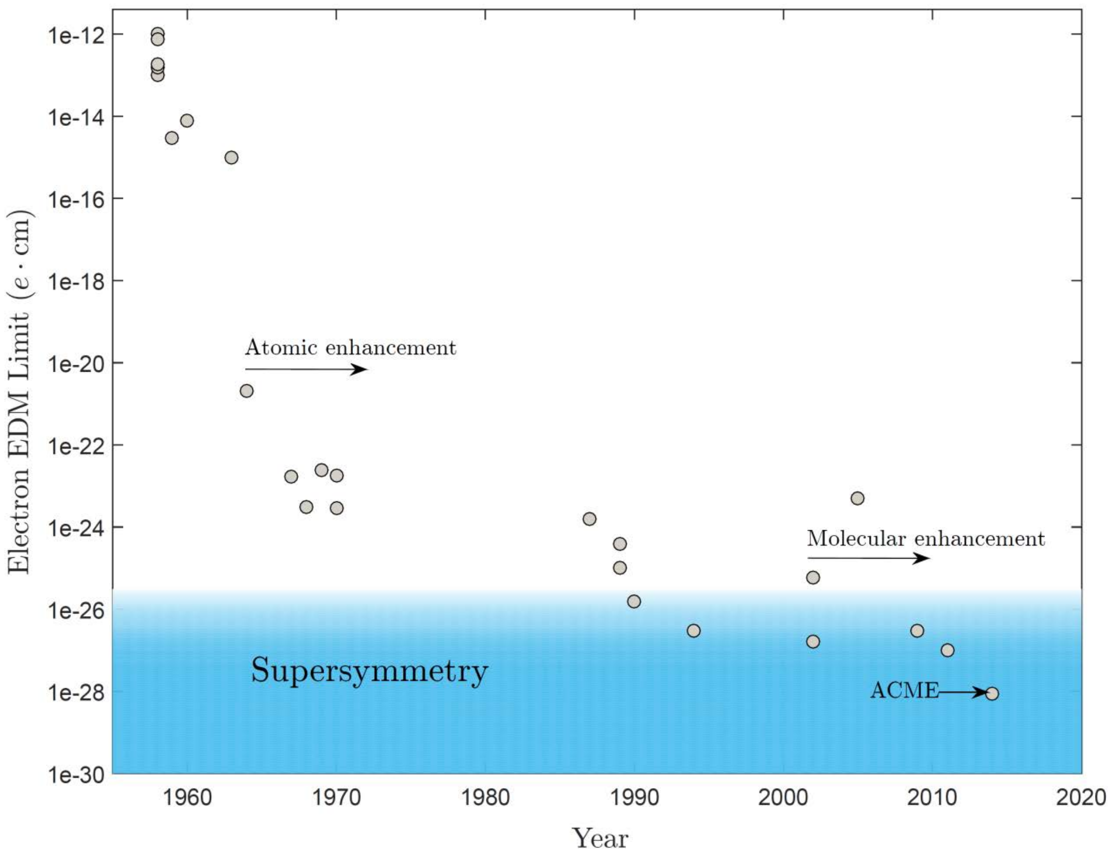

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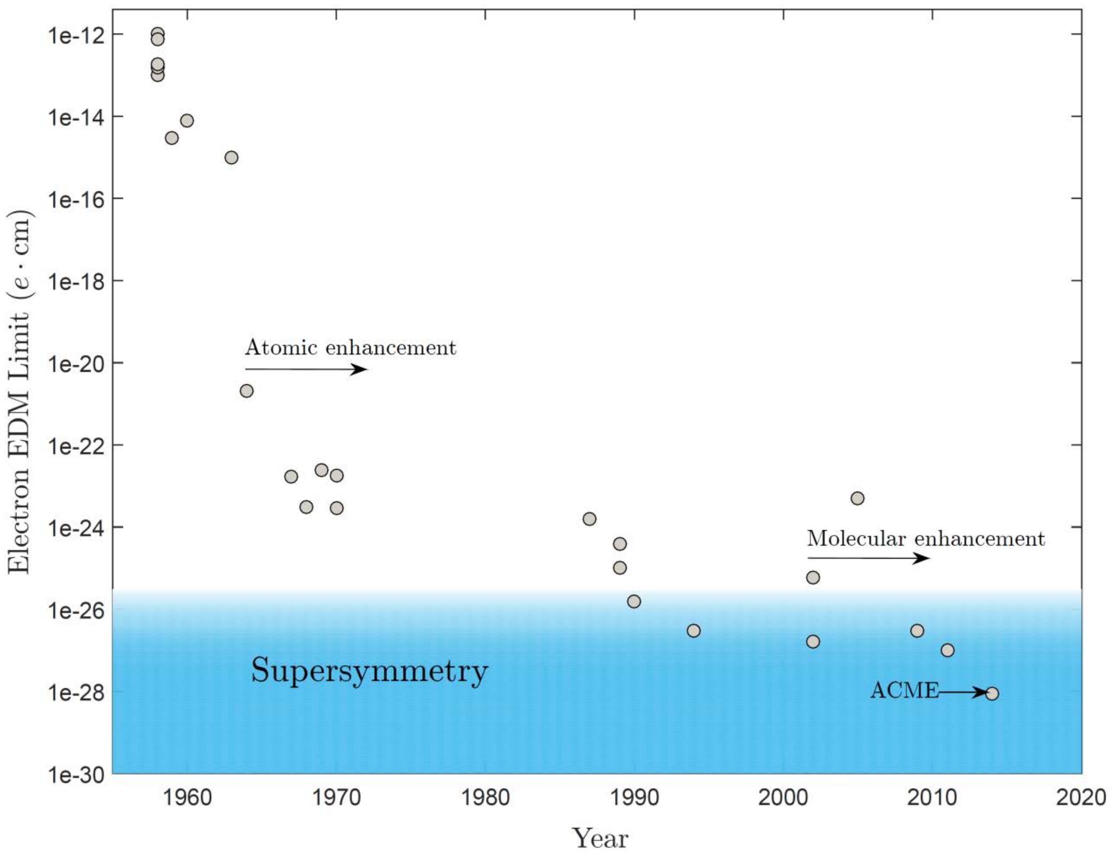

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$0.0044\ \mu_{\text{B}}$

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10^4 s^{-1}

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$$\mathcal{H} = -d\vec{\sigma}\cdot\vec{\mathcal{E}}_{\text{eff}} - \mu\vec{\sigma}\cdot\vec{\mathcal{B}}$$

$$\mathcal{H}(-\mathcal{E}_{\text{lab}}) - \mathcal{H}(+\mathcal{E}_{\text{lab}}) = 2d\vec{\sigma}\cdot\vec{\mathcal{E}}_{\text{eff}} + \mu\mathcal{B}^{\mathcal{E}}$$

$0.0044\ \mu_{\text{B}}$

We switch:

- $\mathcal{E}$ electric field direction/magnitude
- $\mathcal{B}$ magnetic field direction/magnitude
- $\mathcal{N}$ molecule orientation
- $\mathcal{G}$ global laser polarisation
- $\mathcal{R}$ relative laser polarisation
- $\mathcal{P}$ molecule excited state
- $\hat{k}$ laser beam direction
- molecule beam extent
- …

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From this we can extract the phase:
$$\mathcal{A} = \frac{S_+ - S_-}{S_+ + S_-} = \cos 2\phi$$

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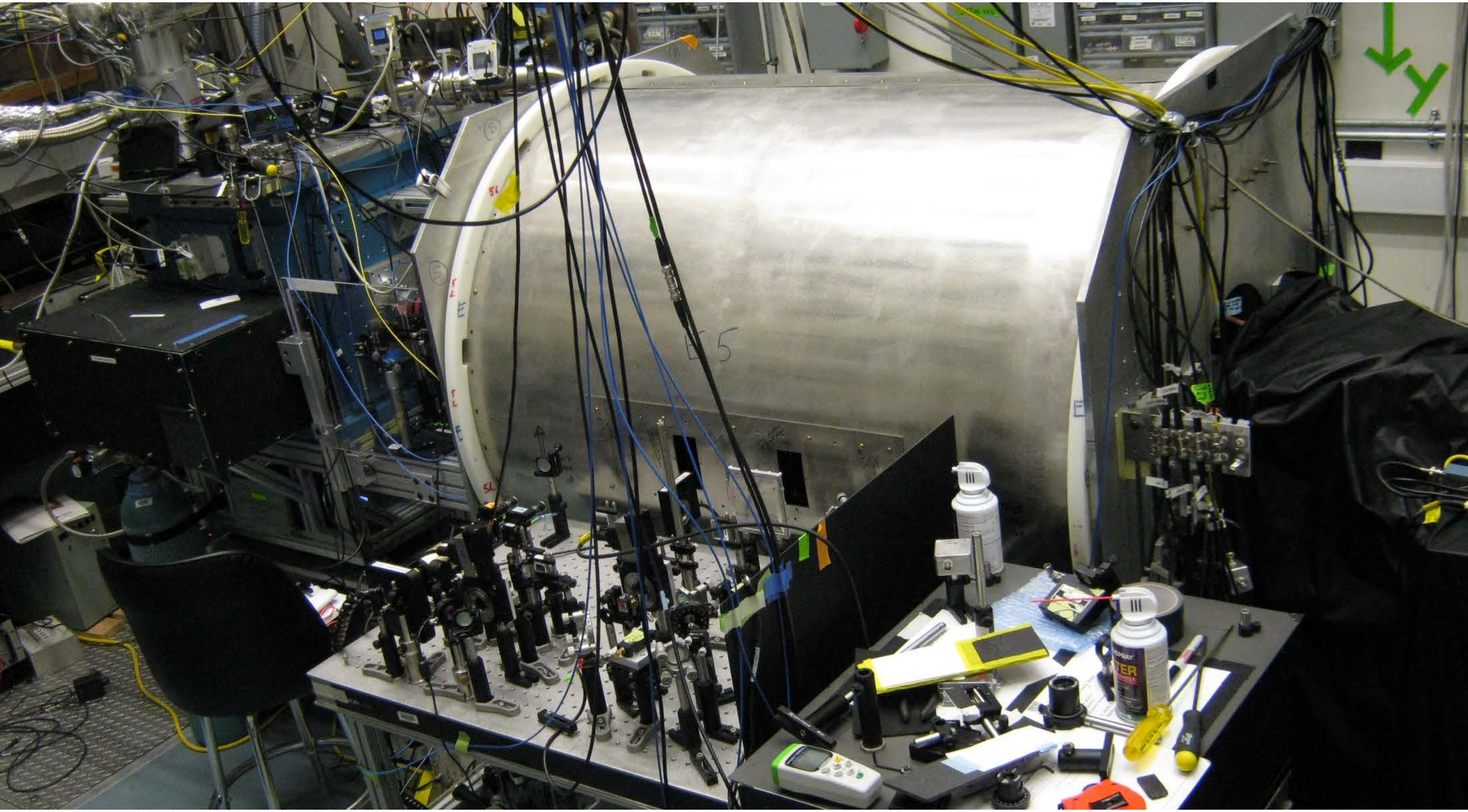

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[1]Nature **473**, 493 (2011), [2]Science **343** 269 (2014), [3]J. Mol. Spectrosc. **300**, 16 (2014), [4]J. Chem. Phys. **142** (2015) 024301
[5]Hyperfine Interact. **214**, 87 (2013)

Electron EDM:

2011: $$d_e \leq 1.1 \times 10^{-27}\ e \cdot \mathrm{cm}$$ 90% CL[1]

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Electron EDM:

2014: $$d_e \leq 9.3 \times 10^{-29}\ e \cdot \mathrm{cm}$$ 90% CL[2-4]

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$$\Lambda^2 = e\frac{m_e}{d_e}\left(\frac{\alpha}{4\pi}\right)^n \sin\phi_{CP}$$

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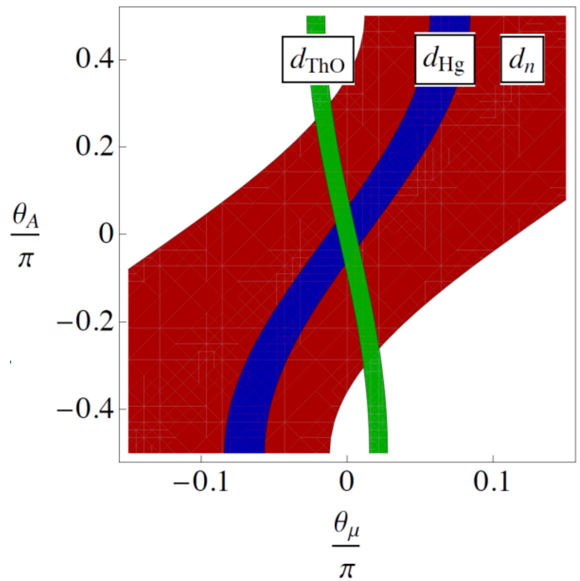
$M_{\mathrm{SUSY}} = 2$ TeV

Constrain either sparticle mass or supersymmetric phases.[5]

Complementary to LHC.



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ACME II:

- Improve molecule state preparation (STIRAP)
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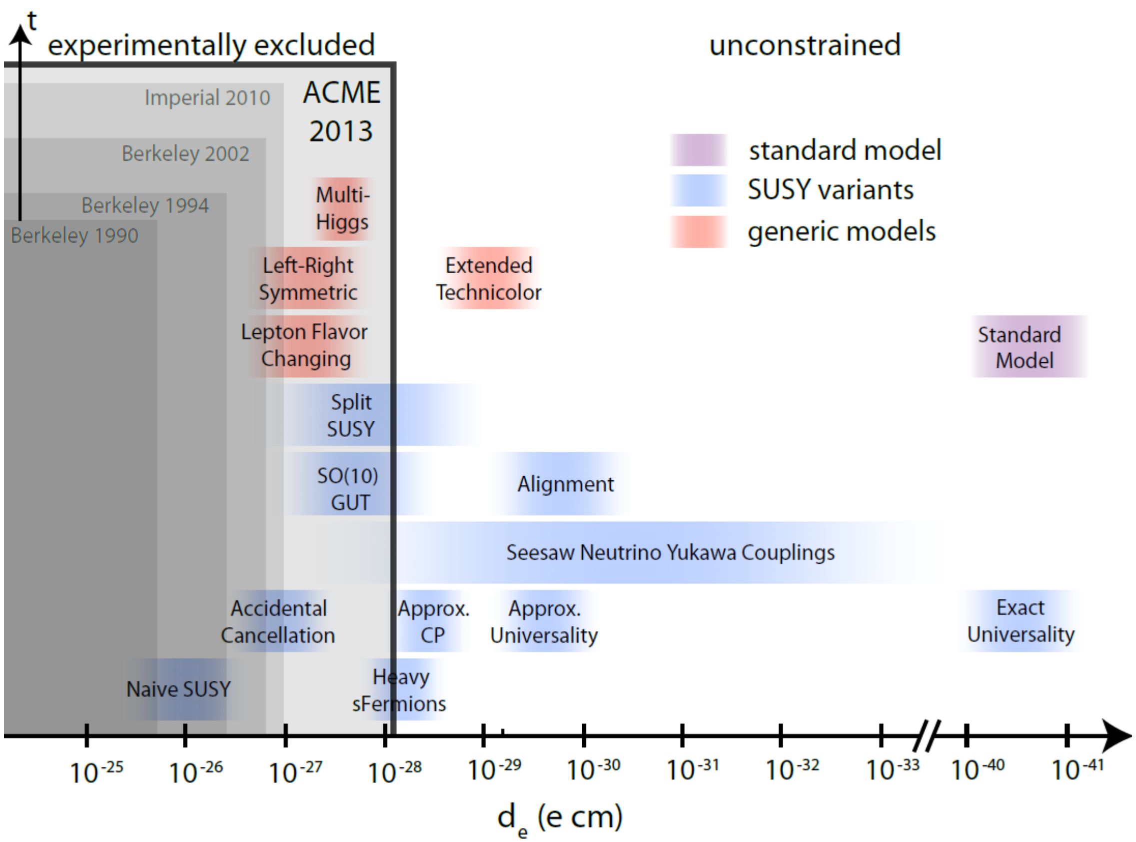

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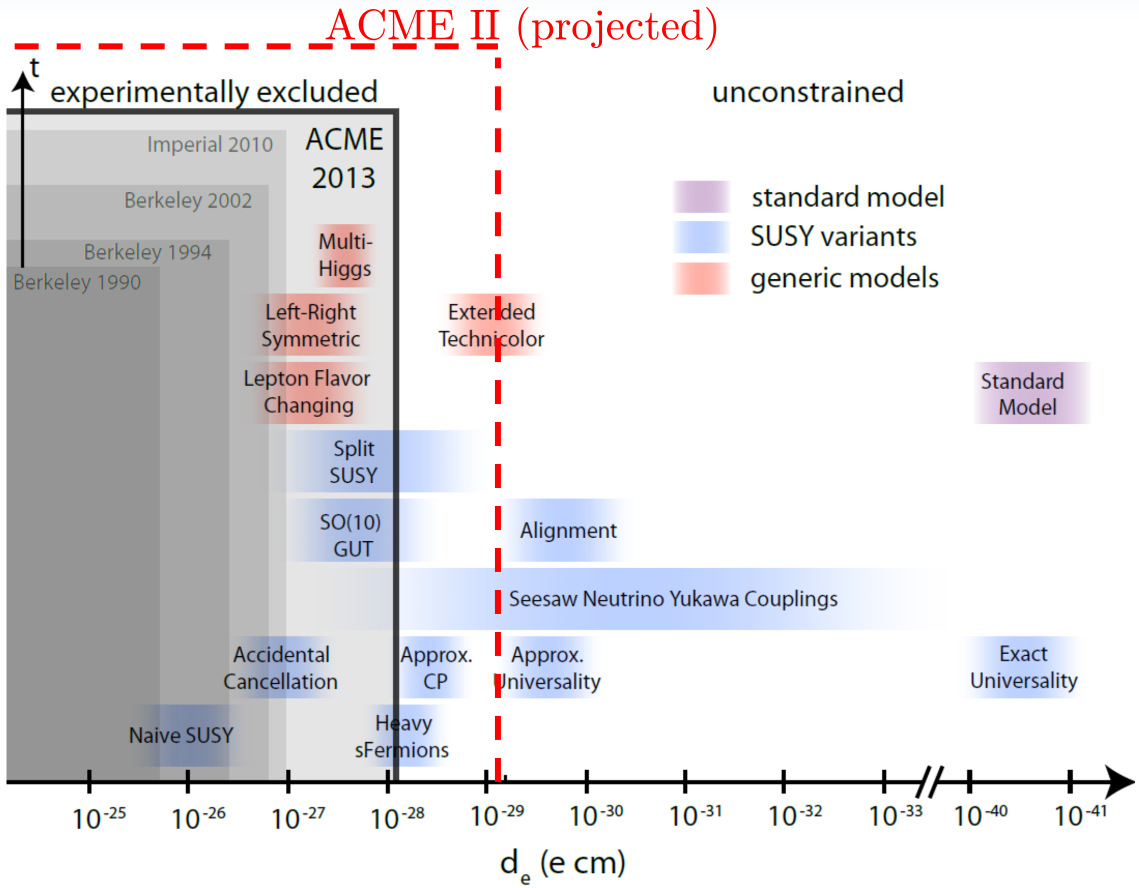

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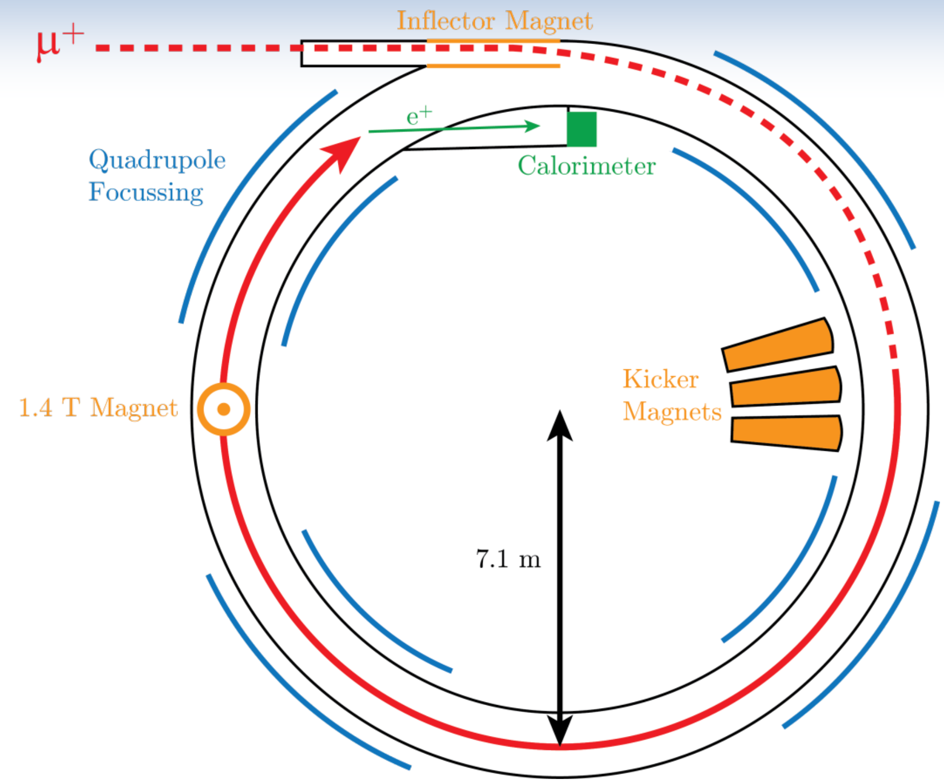

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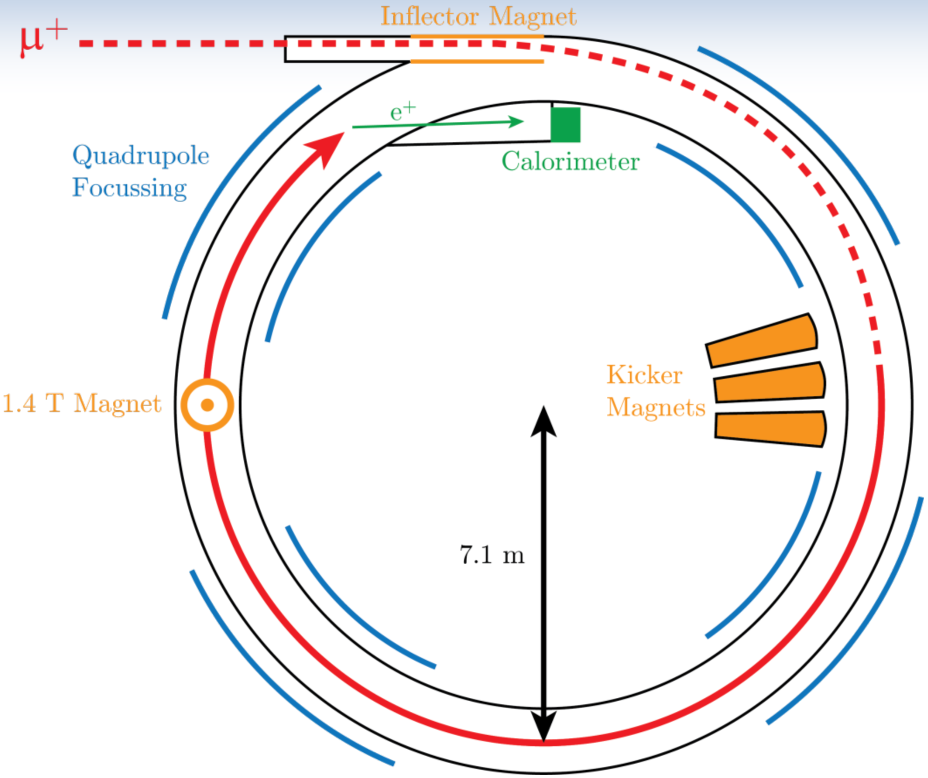

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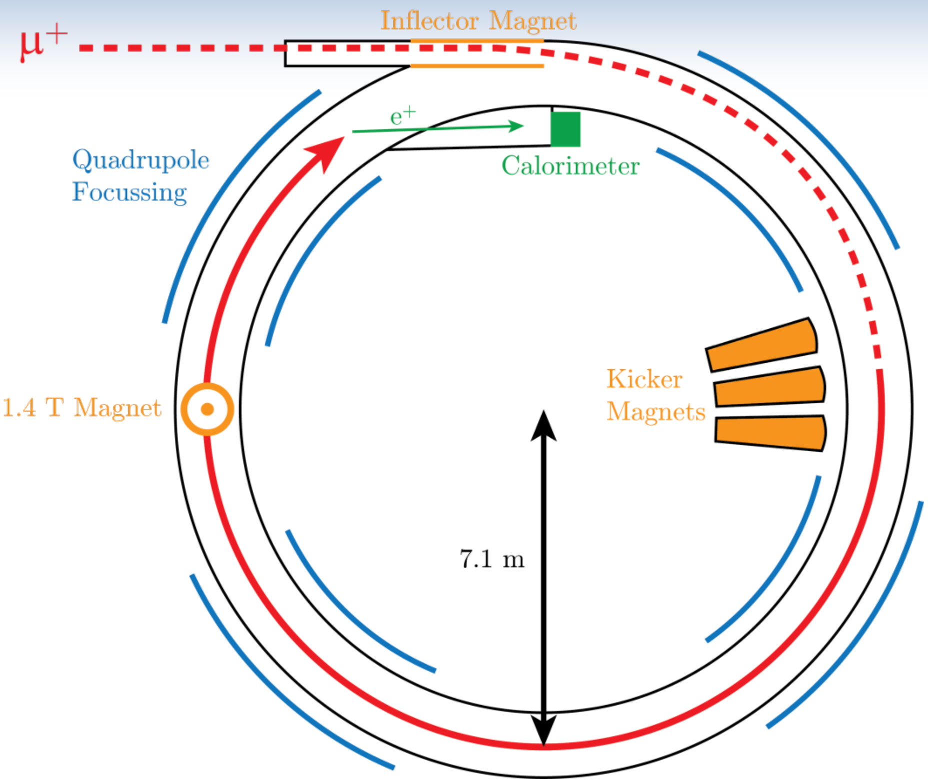

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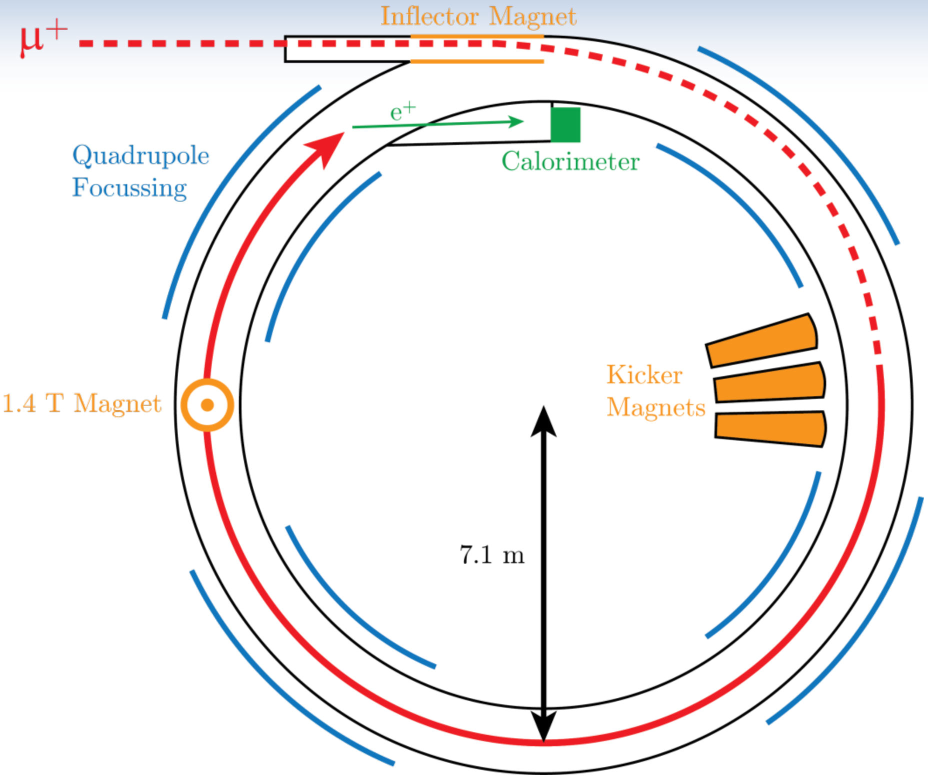

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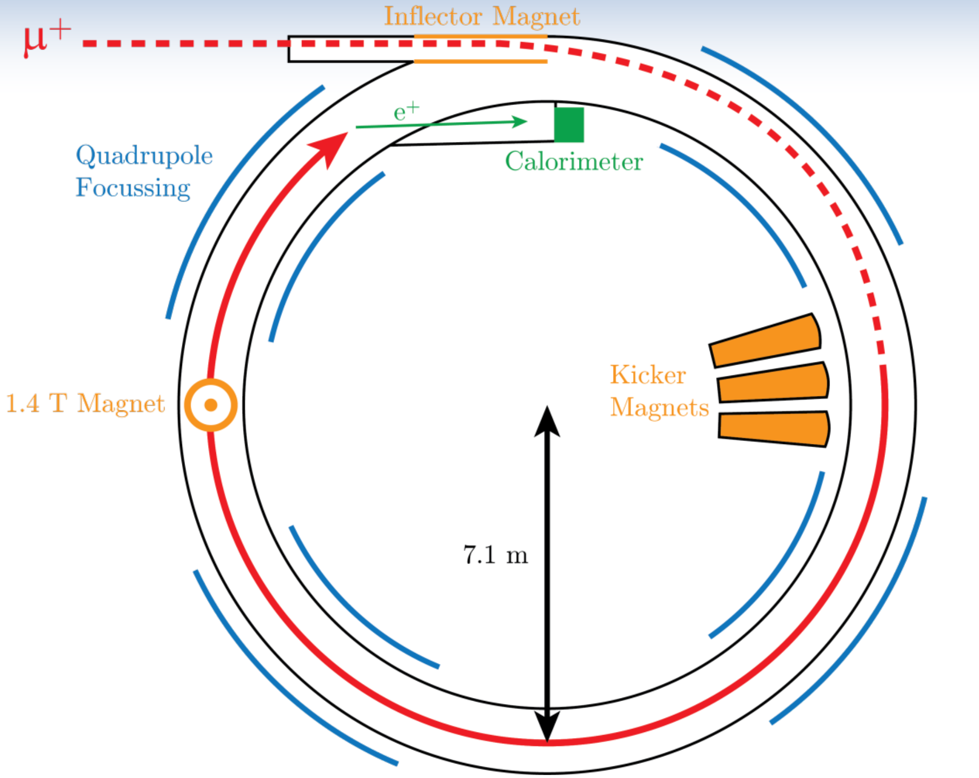
$$|d_\mu| < 1.9\times 10^{-19}\ e\cdot\text{cm}$$ [1] 95% C. L.



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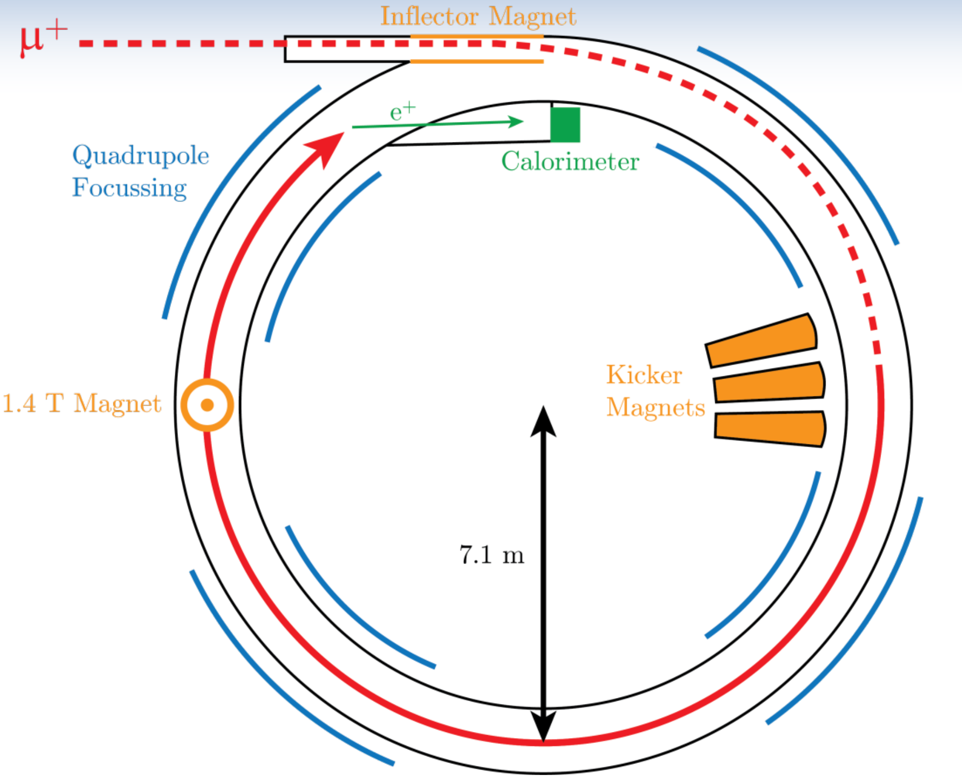

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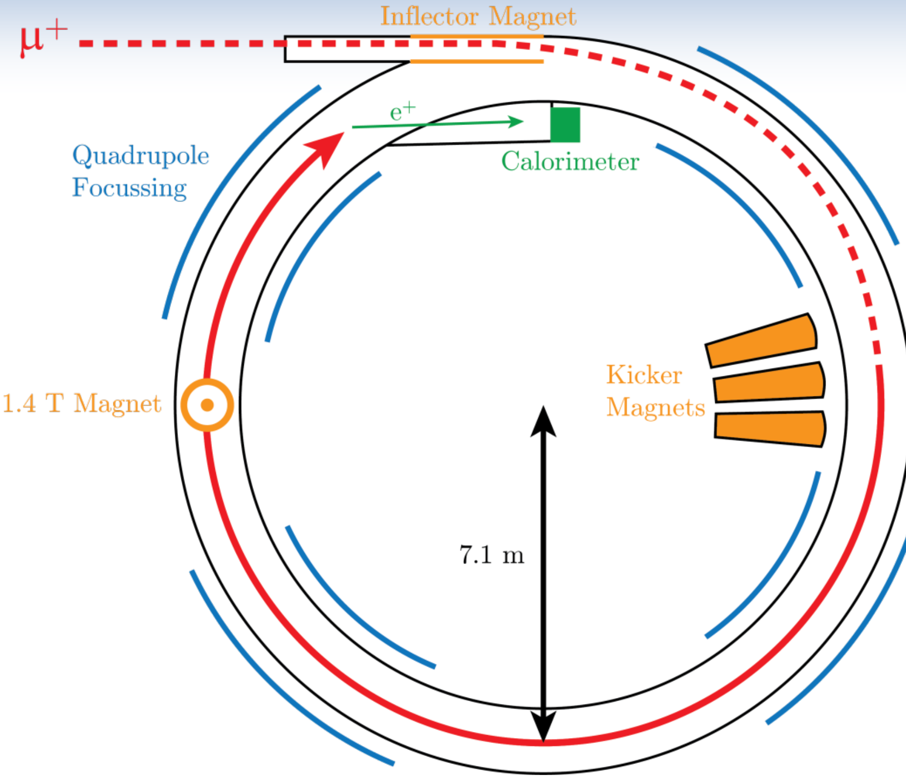

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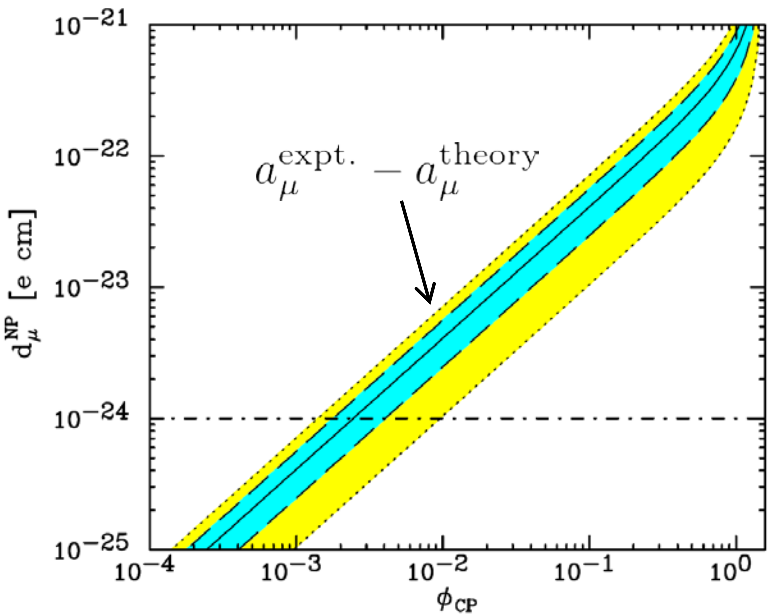
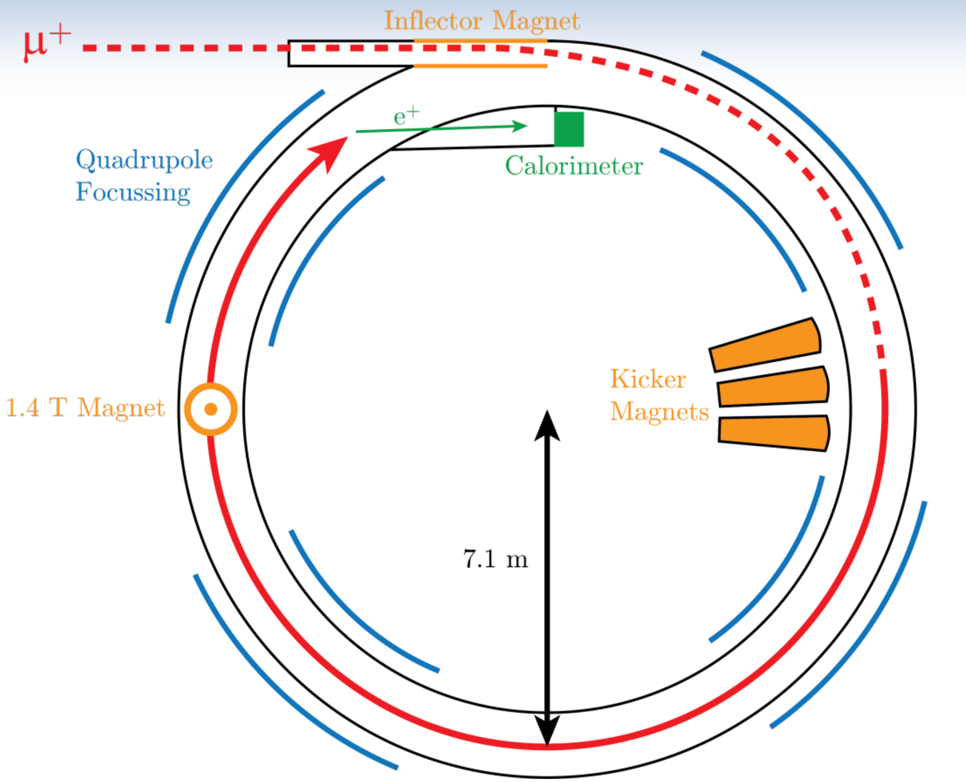
Better sensitivity would help constrain CP violating phases in some models:[2]





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$$\tau^- \to l^- \bar{\nu}_l \nu_\tau \gamma$$

3000 fb^{-1} at SuperKEKB gives a sensitivity of 8 x 10^{-18} e.cm on d_τ

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Conclusion:

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EDMs

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e

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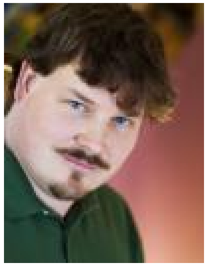
- All of these complementary to direct searches at LHC

ACME (electron EDM) Collaboration:





John Doyle Jerry Gabrielse David DeMille

Funding:

Elizabeth Petrik Cris Panda Zack Lasner

Jacob Baron Brendon O'Leary AW

Alumni:

Nick Hutzler (Harvard)
Ben Spaun (JILA)
Paul Hess (JQI)
Emil Kirilov (Innsbruck)
Amar Vutha (Toronto)
Yulia Gurevich (Heidelberg)
Wes Campbell (UCLA)
Ivan Kozyryev (Harvard)
Max Parsons (Harvard)

(Harvard / Yale)

Extra slides:

ACME

Advanced Cold Molecule Electron EDM

Harvard University

Yale University

Extra slides:

Muon g-2:

Assumption of 'magic momentum' not perfect → radial E-field correction.
Assumption of v.B = 0 not perfect → pitch correction.

Both of these contribute at the 0.3-0.4 ppm level (measurement precision = 0.7 ppm).

Theoretical uncertainty dominated by lowest-order hadronic vacuum polarisation.

Measured via e^-e^+ annihilation or from τ decay.

During negative muon decay, left handed electrons preferred.

If electron momentum maximal, it aligns antiparallel to the muon spin.

The general result: higher energy electrons anti-correlated with muon spin.

Extra slides:

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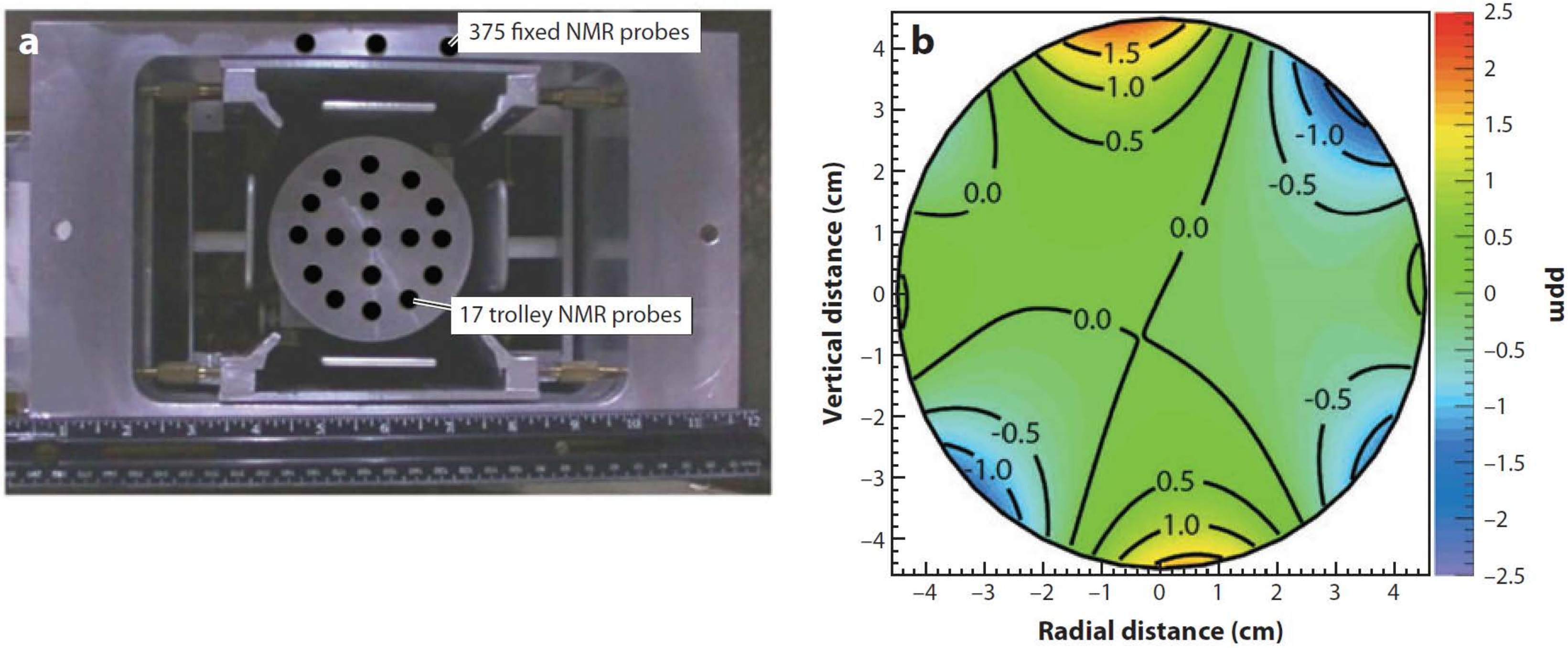

[1]Annu. Rev. Nucl. Part. Sci. **62**, 237 (2012)

Extra slides:

Muon EDM:

New method will use additional radial E-field to cancel out the g-2 effect.