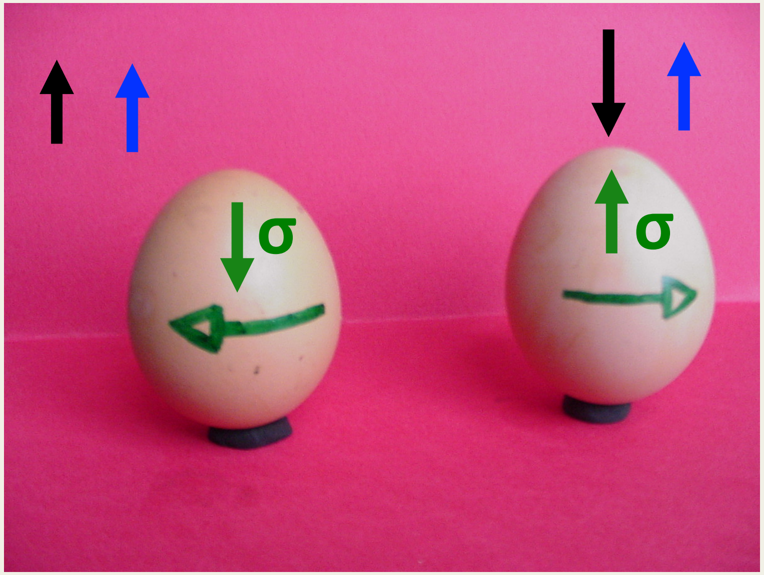
Electric Dipole Moments and the search for new CP violation



Jordy de Vries, Nikhef, Amsterdam

Topical Lectures on electric dipole moments, Dec. 14-16

Goals

- **Goal 1:** A crash course in Electric Dipole Moments
  - What are EDMs and why do people bother to find them?
  - Overview of EDM theory and experimental landscape (I'm a theorist…)
- **Goal 2:** Put EDMs in a broader context (LHC/flavor/….)
  - How do EDM measurements complement other searches ?
- **Goal 3:** Discuss outstanding issues/challenges/opportunities

A rough outline …

- Part 1: **What are Magnetic and Electric Dipole Moments ?**
    - General introduction
    - EDMs and the CKM mechanism
- Part 2: **EDMs and 'strong' CP violation**
    - The QCD theta term and the strong CP problem
- Part 3: **Classes of EDM experiments**
    - Why are there so many experiments ??
- Part 4: **EDMs in the era of the LHC**

Magnetic dipole moments

- Let's remind ourselves about magnetic dipole moments
- A particle with spin (i.e. electron) in a magnetic field is described by

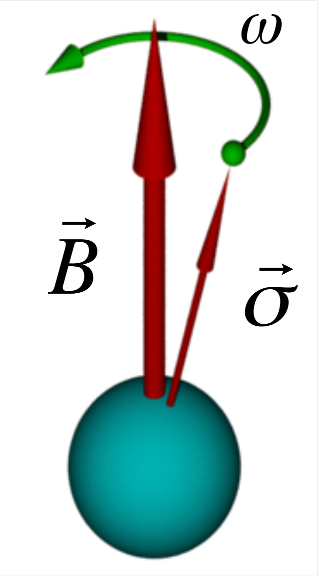
$$H = -\mu(\vec{S} \cdot \vec{B}) \qquad \vec{S} = \vec{\sigma} / 2$$

Hamiltonian

Spin

Magnetic Field

Magnetic dipole moment



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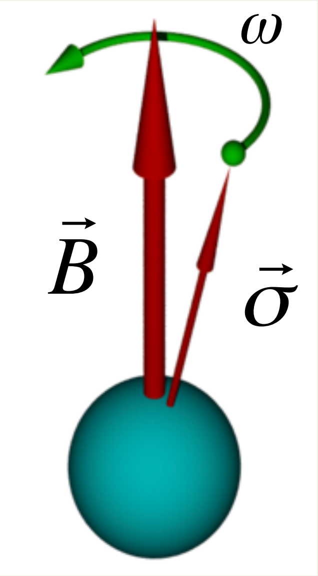


- The B-field puts a torque on the system → spin precession

$$\omega = 2\mu B \sin\theta$$

- How large is the magnetic dipole moment ?

Magnetic dipole moments

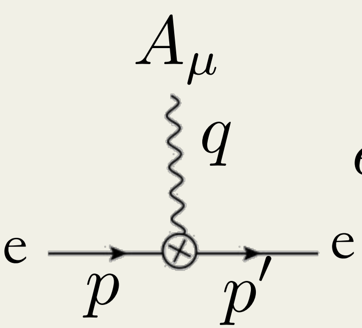
- Magnetic moment from Dirac Equation (DE):

$$(i\gamma^\mu D_\mu - m)\,\Psi_e(p) = 0$$

$$D_\mu = \partial_\mu + ieA_\mu$$

- In the non-relativistic limit, the solution to DE becomes:

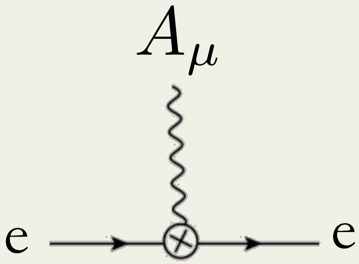
$$\Psi_e(p) \sim \begin{pmatrix} \chi \\ \frac{\vec{\sigma}\cdot\vec{p}}{2m}\chi \end{pmatrix}$$



$$e\bar{u}(p')\gamma^\mu u(p)A_\mu \to e\left[(\chi^\dagger\chi)A_0 + \frac{i}{2m}\chi^\dagger\sigma^k\chi\,\underbrace{\epsilon^{klm}q^l A^m}_{B^k}\right]$$

$$q = p - p'$$

Magnetic dipole moments



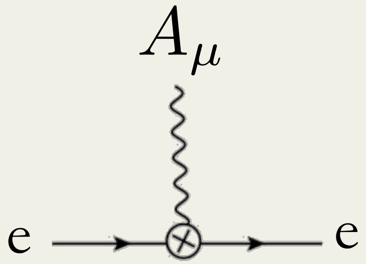
$$e\bar{u}(p')\gamma^\mu u(p)A_\mu \to e\left[(\chi^\dagger\chi)A_0 - \frac{1}{2m}\chi^\dagger\sigma\cdot B\chi\right]$$

- So Dirac predicts: $H = -\frac{\mu}{2}(\vec{\sigma}\cdot\vec{B})$ $\qquad \mu = \frac{eg}{2m}$ $\qquad g = 2$

- g is the gyromagnetic ratio, triumph of Dirac and QM !

- Electron magnetic moment ~ e/m_e ~ 10^{-11} e cm ~ 100 e fm
- Nucleon magnetic moment ~ e/m_N ~ 10^{-13} e cm ~ 1 e fm
- **By the way: do we expect for the nucleon g=2 as well ?**

Magnetic dipole moments



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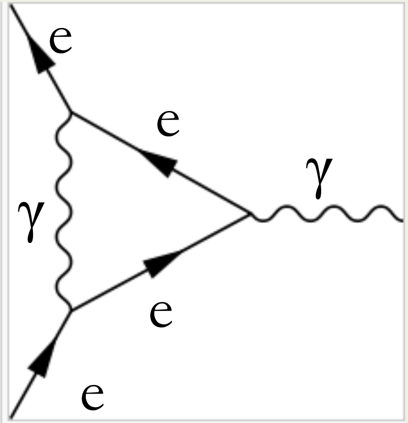
  (g = -3.826 for neutron and g = 5.58 for proton)

- Measurements in 1940's: g_e = 2*(1.00118+-0.00003)…..
- **Enter Quantum Field Theory**

Anomalous magnetic moments



- Anomalous magnetic moment defined as a=(g-2)/2
- Calculate from loop diagrams:

$$a_e = \frac{\alpha_{em}}{2\pi} + \mathcal{O}(\alpha_{em}^2)$$

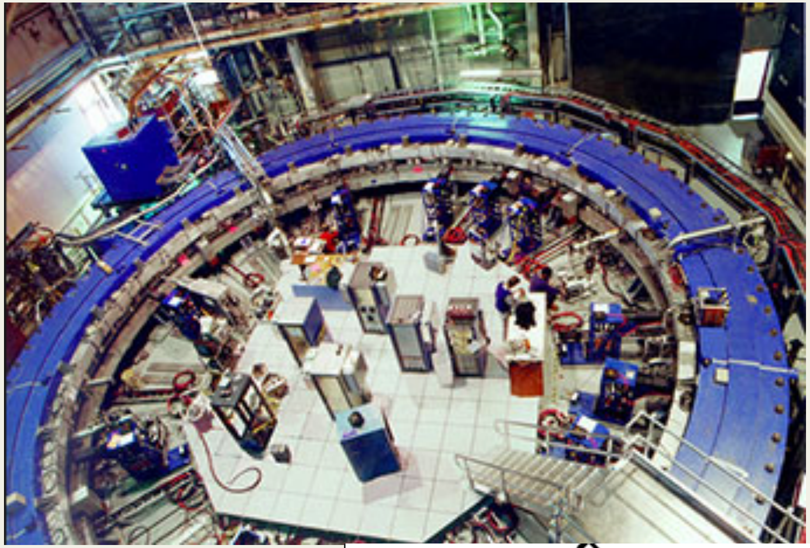
- Nowadays calculated up to **5 loops** in QED, 2 loops in electroweak
- **Measurement so precise (Harvard group) that it is used to determine the fine-structure constant $\boldsymbol{\alpha}_{em}$**

- Alternatively: take α_{em} from somewhere else (atomic spectroscopy)

$$\Delta a_e = a_e^{\mathrm{exp}} - a_e^{\mathrm{SM}} = -1.05(0.82) \times 10^{-12}$$

- Agreement up to 12 digits…. Quite remarkable.

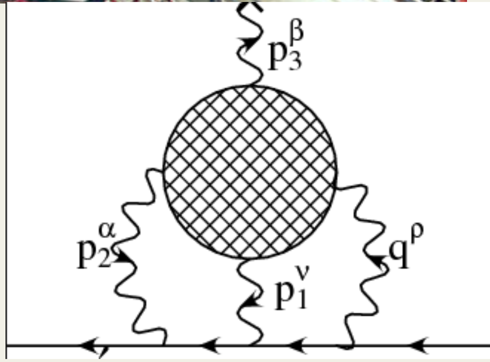
Trouble in paradise



- The muon is elementary too !
- Measure its g-2 as well @ Brookhaven

$$\Delta a_\mu = a_\mu^{\exp} - a_\mu^{\mathrm{SM}} = 2.88(0.63)(0.49) \times 10^{-9}$$

- **Some tension with SM predictions ~ 3 sigma**



- Larger theory uncertainties from hadronic effects…

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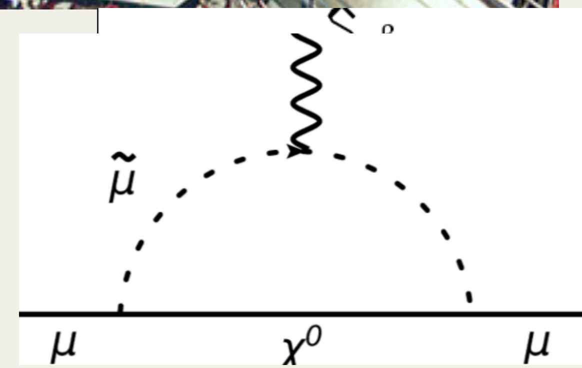


- Larger theory uncertainties from hadronic effects…
- Say it is true, what does it mean? A new term in the QED Lagrangian !

$$\mathcal{L} = \bar{\Psi}_\mu(i\gamma^\mu D_\mu - m_\mu)\Psi_\mu - C_\mu m_\mu \bar{\Psi}_\mu \sigma^{\mu\nu}\Psi_\mu F_{\mu\nu}$$

- 'new physics' contribution $\Delta a_\mu = m_\mu^2 C_\mu \qquad C_\mu \sim \alpha_{em}\dfrac{1}{\Lambda_{BSM}^2}$

$$\Lambda_{BSM} \sim \frac{m_\mu\sqrt{\alpha_{em}}}{\sqrt{\Delta a_\mu}} \sim 100\,\mathrm{GeV}$$

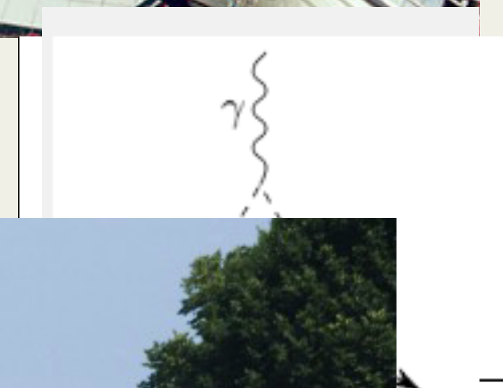
A bit low…..

Trouble in paradise

o !

Brookhaven

$3)(0.49) \times 10^{-9}$



redictions ~ 3 sigma

- Larger theory uncert
- Say it is true, what d

$$\mathcal{L} = \bar{\Psi}_\mu($$

- 'new physics' contrib

$$\Lambda_{BSM} \sim \frac{m_\mu \sqrt{\alpha_e}}{\sqrt{\Delta a_\mu}}$$

~~Magnetic~~ Electric dipole moments

- Let's remind ourselves about **electric** dipole moments
- A particle with spin (i.e. neutron) in an **electric** field is described by

$$H = -d(\vec{S}\cdot\vec{E}) \qquad \vec{S} = \vec{\sigma}/2$$

Hamiltonian

Spin

Electric Field

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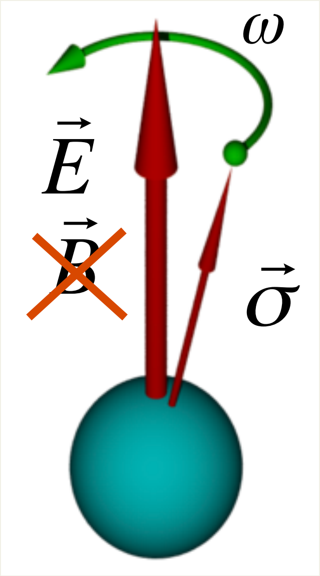

- The **E-field** puts a torque on the system → spin precession

$$\omega = 2\cancel{\mu B}\sin\theta \qquad \omega = 2dE\sin\theta$$

- How large is the **electric** dipole moment ?

Electric dipole moments

- We already exhausted the Dirac equation… No EDM there ?
- Can we understand this ?

$$H = -\mu(\vec{S}\cdot\vec{B}) - d(\vec{S}\cdot\vec{E})$$

Electric dipole moments

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$$H = -\mu(\vec{S}\cdot\vec{B}) - d(\vec{S}\cdot\vec{E})$$

- Perform a Time-reversal (T) transformation

$$\vec{S} \longrightarrow -\vec{S}$$

Spin like angular momentum ~ $\vec{L} \sim \vec{r} \times \vec{p}$

$$\vec{B} \longrightarrow -\vec{B}$$

$$\vec{B} \propto \varepsilon^{ijk} F_{jk} \sim \partial_j A_k \longrightarrow (+\partial_j)(-A_k)$$

$$\vec{E} \longrightarrow \vec{E}$$

$$\vec{E} \propto F_{0i} \sim \partial_0 A_i \longrightarrow (-\partial_0)(-A_i)$$

$$H = -\mu(\vec{S}\cdot\vec{B}) + d(\vec{S}\cdot\vec{E})$$

Electric dipole moments

- We already exhausted the Dirac equation… No EDM there ?
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$$H = -\mu(\vec{S}\cdot\vec{B}) - d(\vec{S}\cdot\vec{E})$$

- Perform a Parity (P) transformation

$\vec{S} \to \vec{S}$ Spin like angular momentum ~ $\vec{L} \sim \vec{r}\times\vec{p}$

$\vec{B} \to \vec{B}$ $\vec{B} \propto \varepsilon^{ijk} F_{jk} \sim \partial_j A_k \to (-\partial_j)(-A_k)$

$\vec{E} \to -\vec{E}$ $\vec{E} \propto F_{0i} \sim \partial_0 A_i \to (+\partial_0)(-A_i)$

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Electric dipole moments

- We already exhaustes the Dirac equation… No EDM there ?
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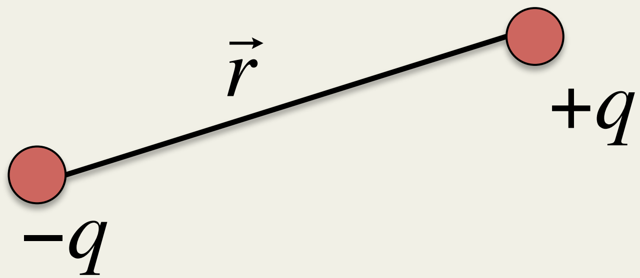
$$H = -\mu(\vec{S}\cdot\vec{B}) - d(\vec{S}\cdot\vec{E})$$

- EDMs violate T and P symmetry ! But QED is P-invariant !
- CPT theorem: **T-violation = CP violation** !

- So if we measure a nonzero EDM this means CP (or CPT…) violation!
- Two major questions should pop up:
  1. Uuuuh, what about H_2O or NH_3 molecules. HUGE EDMs. ~ 10^{-8} e cm
  2. What about CP violation in the SM ?

Other electric dipole moments

- Take a classical dipole configuration
- Electric dipole ~ d ~ q r
- Does not violate **anything**



- So we mean with an EDM: the coupling of **spin** and the **E-field**.

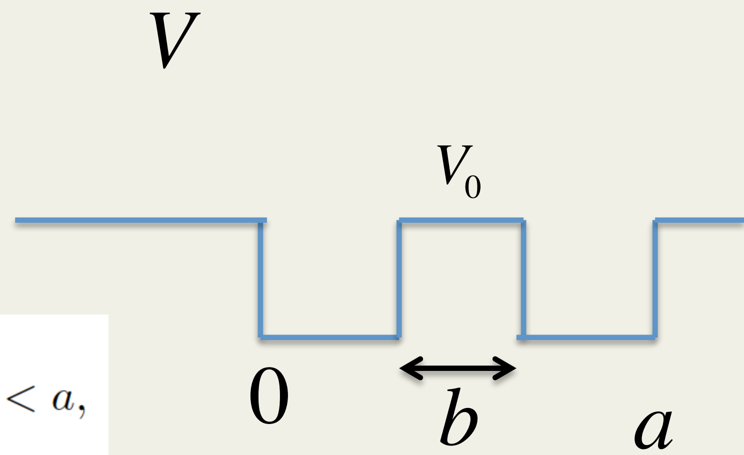
- For electron, neutron, atom, the only quantity available is the spin.
  So there is no 'r' around

- So where does the non-CPV EDM of molecules come from ?

Double-well potential

- Analogy take a double-well potential
- If V_0 is very small, get usual solutions

$$\psi_n(x) = \begin{cases} \sqrt{\frac{2}{a}} \sin\left(\frac{n\pi x}{a}\right) & \text{if } 0 < x < a, \\ 0 & \text{otherwise,} \end{cases}$$



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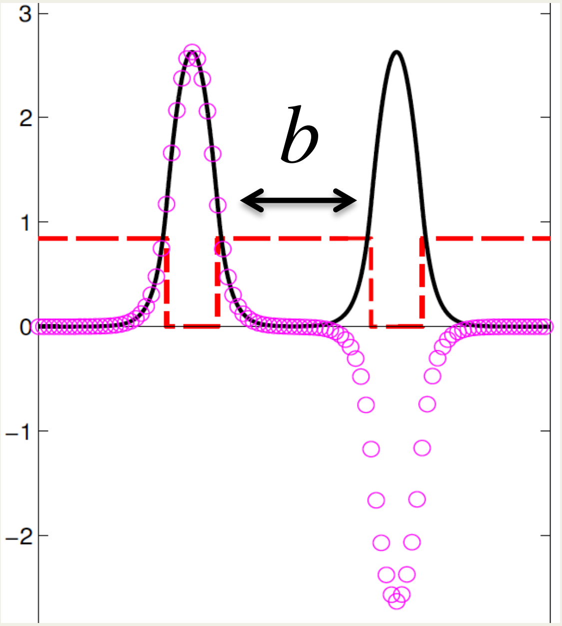

- With nonzero V_0 , two solutions appear with different parity and a small enery difference (tunneling effect !). **$E_+ - E_- \sim b$**

- A molecule like water has indeed **a nearly-degenerate** ground state with opposite parity

Fake EDMs

- So we have 2 states which we call $|\pm\rangle$
- Turn on Electric Field E (mixing of states)

$$H = \begin{pmatrix} \mathcal{E}^+ & 0 \\ 0 & \mathcal{E}^- \end{pmatrix} + \begin{pmatrix} 0 & Eb \\ Eb & 0 \end{pmatrix}$$

- Diagonalize matrix to get energy eigenvalues

$$\mathcal{E}_{1,2} = \frac{1}{2}(\mathcal{E}_+ + \mathcal{E}_-) \pm \sqrt{(\mathcal{E}_+ - \mathcal{E}_-)^2/4 + E^2b^2}$$

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- If the E field is smaller than the energy gap

$$\mathcal{E}_{1,2} = \frac{1}{2}(\mathcal{E}_+ + \mathcal{E}_-) \pm \frac{1}{2}(\mathcal{E}_+ - \mathcal{E}_-)\left(1 + \frac{2E^2 b^2}{(\mathcal{E}_+ - \mathcal{E}_-)^2}\right)$$

- The energy shift is quadratic in the E field !! So no P or T violation
- If the E field is larger than the gap: **degenerate ground state**

$$\mathcal{E}_{1,2} = \frac{1}{2}(\mathcal{E}_+ + \mathcal{E}_-) \pm Eb$$

EDM theorem

- Nonzero EDMs imply P and T (and CP) violation if the system has a **nondegenerate ground state**
- Note: all subatomic particles are non-degenerate

1. Uuuuh, what about H_2O or NH_3 molecules. HUGE EDMs. ~ 10^{-8} e cm

   Degenerate ground states, no signal for CP violation !

2. What about CP violation in the Standard Model (SM) ?
   How large are EDMs expected to be ?

CP violation in the Standard Model

- **Two** sources of CPV in the Standard Model

$$L_{CPV} = L_{CKM} + L_{theta}$$

$$V_{CKM} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{bmatrix}$$

- Three real (CP-conserving) mixing angles and one CPV phase
- Appears in charged weak interactions. In diagonal-mass basis

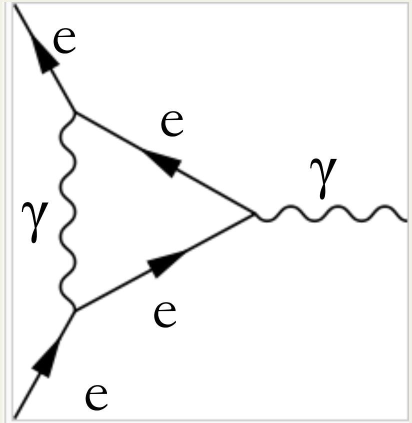
$$\frac{-g}{\sqrt{2}}(\bar{u}_L,\, \bar{c}_L,\, \bar{t}_L)\gamma^\mu V_{CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} W_\mu^+ + \text{h.c.}$$

- Note, CPV phase is not small at all: Sin(δ_{13}) ~ O(1)
- But the off-diagonal elements are small: $s_{13} \sim 10^{-3}$ (not understood)

SM CKM EDMs (too many acronyms!)

- Analogously to g-2 magnetic moment corrections we can calculate SM EDMs.

$$L_{dip} = -\frac{1}{2}\bar{\Psi}\sigma^{\mu\nu}(\mu + i\gamma^5 d)\Psi F_{\mu\nu}$$



$$\mu = \frac{e}{2m_e}\frac{\alpha_{em}}{2\pi} \qquad d = 0$$

Why ?

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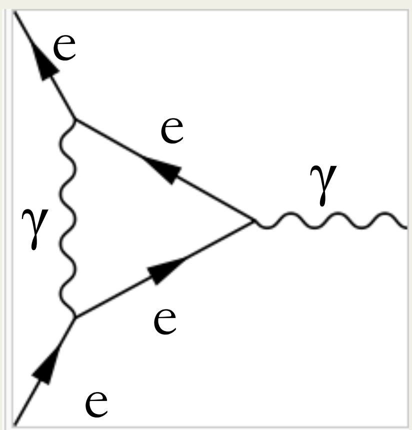

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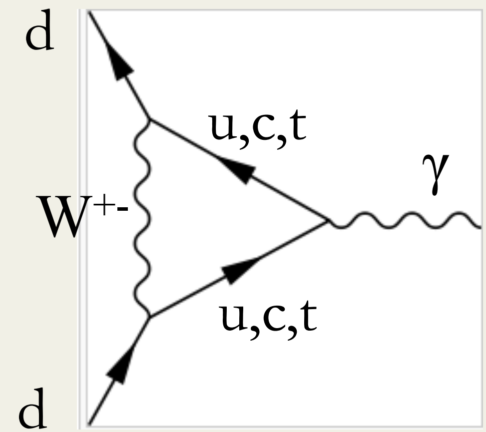


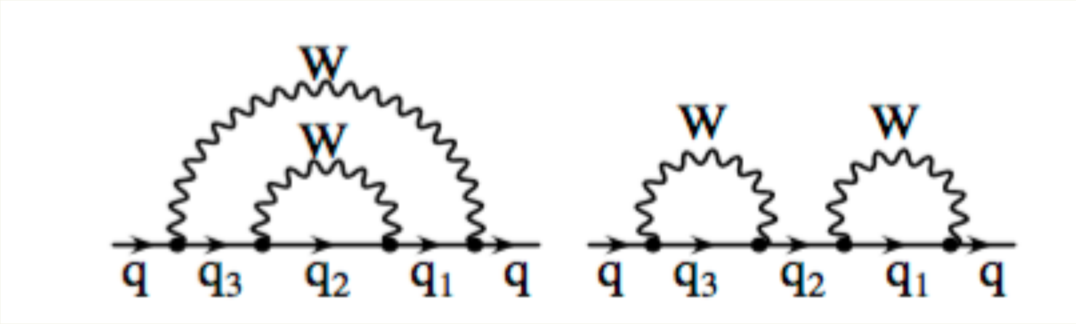
$$\mu \propto \frac{m_d}{m_W^2}\frac{\alpha_{weak}}{2\pi}(V_{qd}V_{qd}^*)$$

$$d = 0$$

Why ?

SM CKM EDMs (too many acronyms!)

- At two loops: individual diagrams contribute but the sum vanishes
- d_q (2 loops) = 0, this was unexpected !



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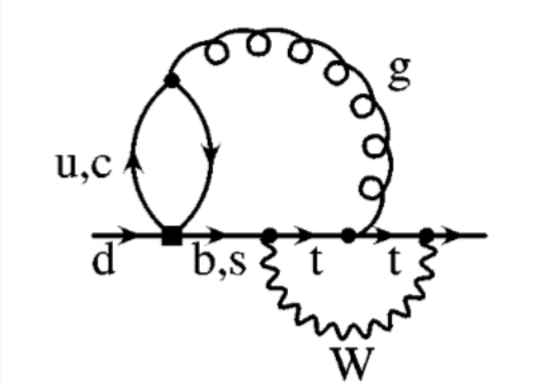


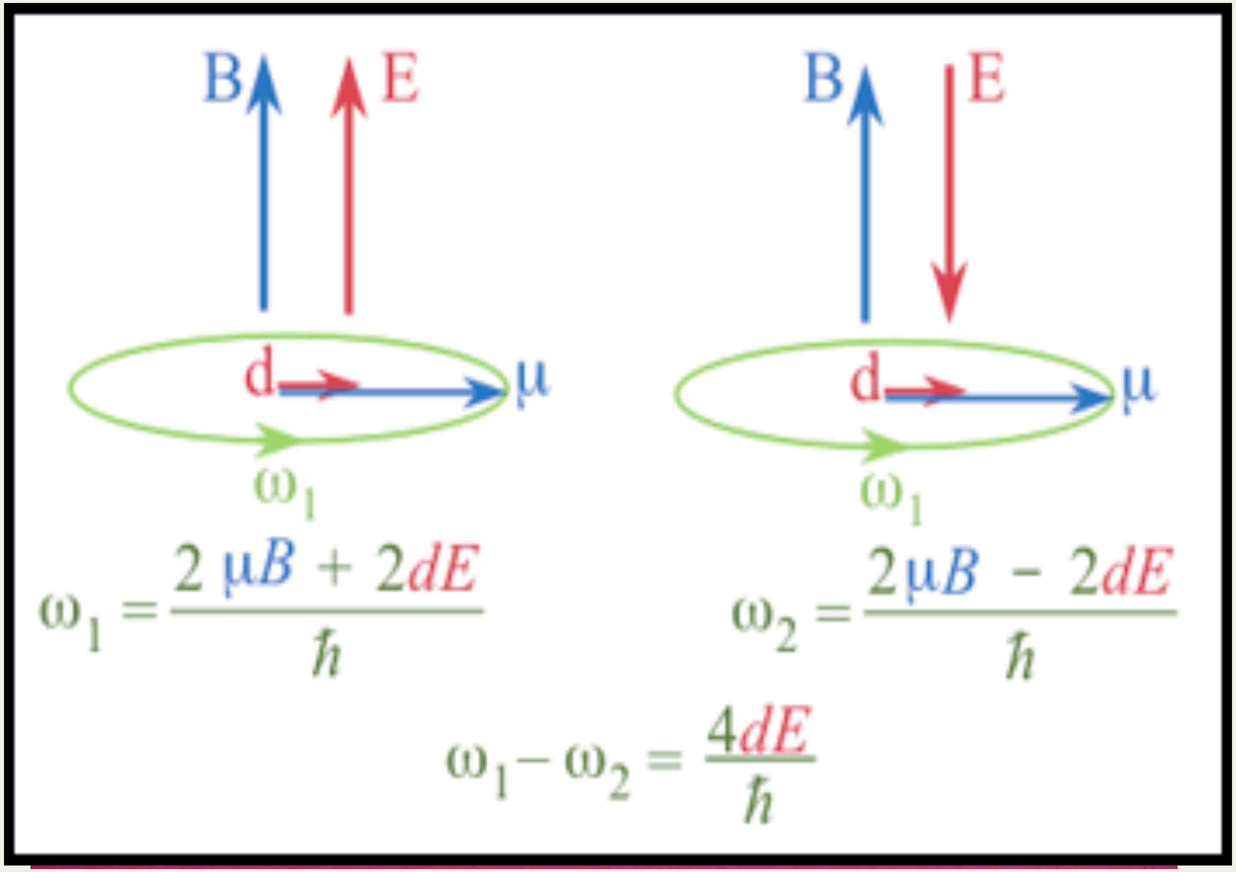
- At three loops: $$d_d \simeq m_d \frac{m_c^2 \alpha_s G_F^2}{108\pi^5} \mathcal{J}_{CP} \simeq 10^{-21}\, e\,\mathrm{fm}$$

$$\mathcal{J}_{CP} = c_{12} c_{23} c_{13}^2 s_{12} s_{23} s_{13} \sin\delta \simeq 3 \cdot 10^{-5}$$

- Electron EDM at 4 loops $\quad d_e \simeq 10^{-26}\, e\,\mathrm{fm}$
- Compare with magnetic moment: $\mu_e \simeq 100\, e\,\mathrm{fm}$
- CKM EDMs are really **very very very very** small

Measuring EDMs

- General idea now. Later more.



$$\delta d(stat) \sim \frac{1}{E * T * \sqrt{N}}$$

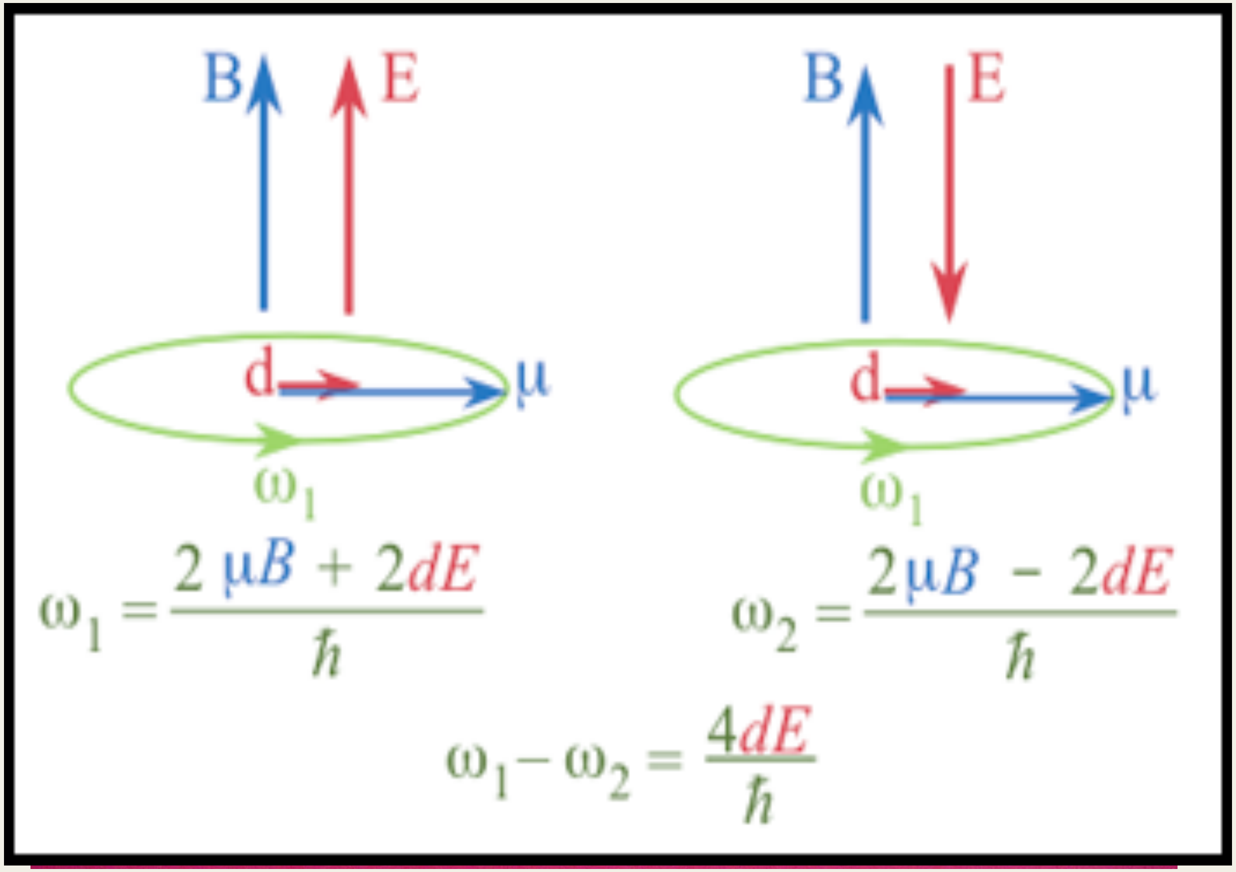
E ~ electric field,

T ~ coherence time,

N ~ number of particles

Measuring EDMs

- General idea now. Later more.



- Note

$$d = 10^{-28}\, e\ cm \qquad E = 100\ kV / cm$$

$$\delta\omega \sim 10^{-7}\ rad / s \sim 1\ rad / year$$

It’s hopeless…..

System	Current limit	CKM contribution
Neutron	$< 10^{-26}$ e cm	$10^{-31,-32}$ e cm
^{199}Hg	$< 10^{-29}$ e cm	$10^{-33,-35}$ e cm
Electron	$< 10^{-28}$ e cm	$10^{-38,-39}$ e cm

- Systems with strongest experimental limits
- CKM contributions are many **orders of magnitude** away

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- Systems with strongest experimental limits
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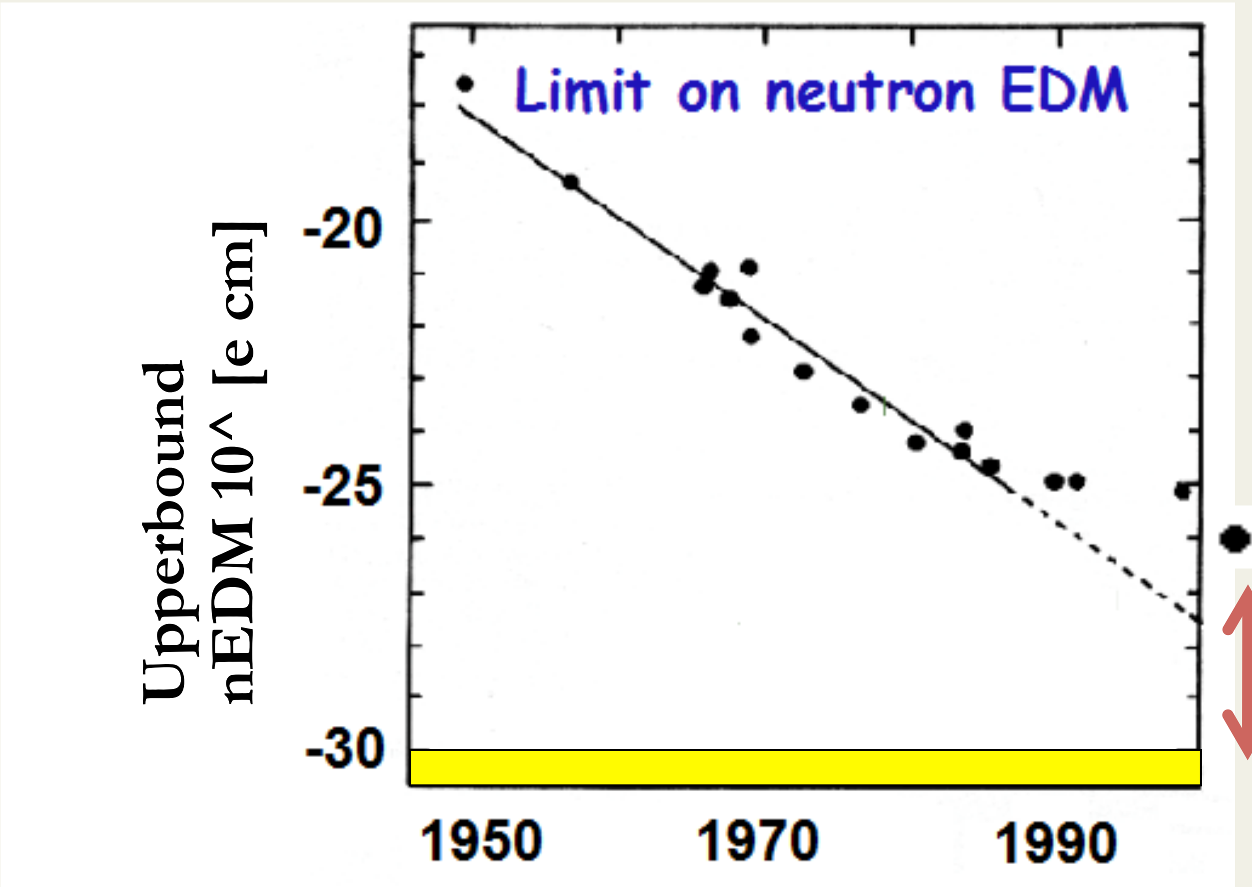
- **Some questions for later**: why neutron, Hg, and electron ?
- Why is the CKM contribution to Hg smaller than to neutron ?
- What do these bounds mean for BSM CP violation ?

Standard Model suppression



Baker et al '06 '15

"Here be dragons"

5 to 6 orders **below** upper bound ⟷ **Out of reach!**

With linear extrapolation: CKM neutron EDM in 2075….

Other sources of CP violation

- Another SM source of CP violation (QCD theta term)
- Discussed in next lecture

- CKM EDMs are small because of the peculiar SM flavor structure
- Only CPV in flavor-changing transitions + 3 loops .....
- **NOT GENERAL** at all. In many BSM models, EDMs at tree- or one-loop level. Much larger EDMs !

- These lectures will not discuss BSM models in any detail, **but just to illustrate**

The MSSM

The MSSM can contain many new sources of CP violation

Higgsino and Higgs masses
$\to$ 2 phases

$$\mu \tilde{H}_u \tilde{H}_d + B\mu H_u H_d + m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2$$

squark and slepton masses
$\to$ 15 phases

$$m_Q^2 \tilde{Q}_L^\dagger \tilde{Q}_L + m_U^2 \tilde{U}_R^\dagger \tilde{U}_R + m_D^2 \tilde{D}_R^\dagger \tilde{D}_R$$
$$+ m_L^2 \tilde{L}_L^\dagger \tilde{L}_L + m_E^2 \tilde{E}_R^\dagger \tilde{E}_R$$

gaugino masses
$\to$ 3 phases

$$m_1 \tilde{B}\tilde{B} + m_2 \tilde{W}\tilde{W} + m_3 \tilde{g}\tilde{g}$$

trilinear couplings
$\to$ 27 phases

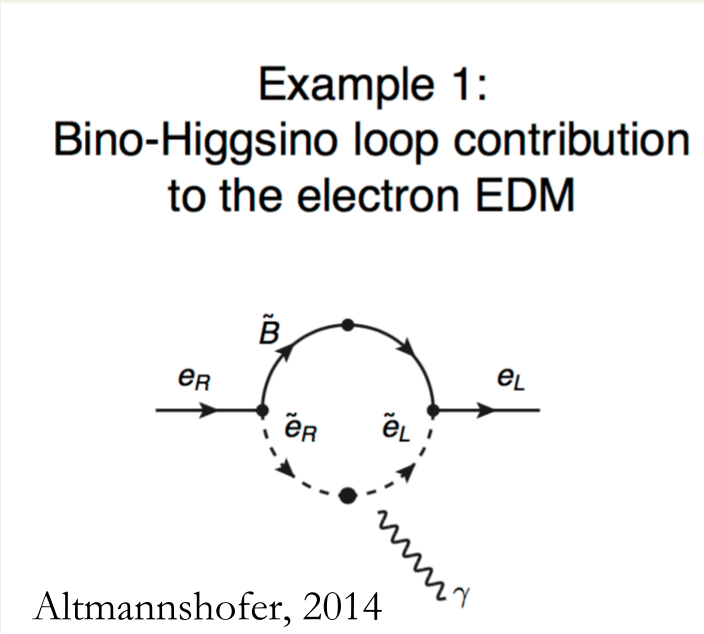
$$A_u\, H_u \tilde{Q}_L^\dagger \tilde{U}_R + A_d\, H_d \tilde{Q}_L^\dagger \tilde{D}_R + A_\ell\, H_d \tilde{L}_L^\dagger \tilde{E}_R$$

not all phases are physical! (like in the case of the CKM matrix)

2 phases can be rotated away...

Slide from Altmannshofer, 2014

The SUSY CP problem



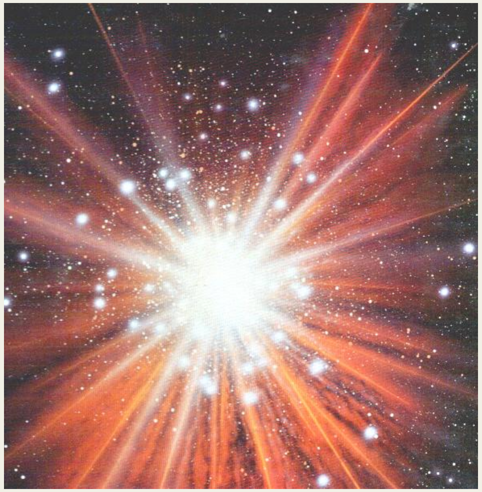
- CPV phase already at one-loop !
- **Typical size of EDM**

$$d_e \sim \left(\frac{\alpha_{em}}{\pi}\right)^n \frac{m_e}{\Lambda^2} \sin\phi$$

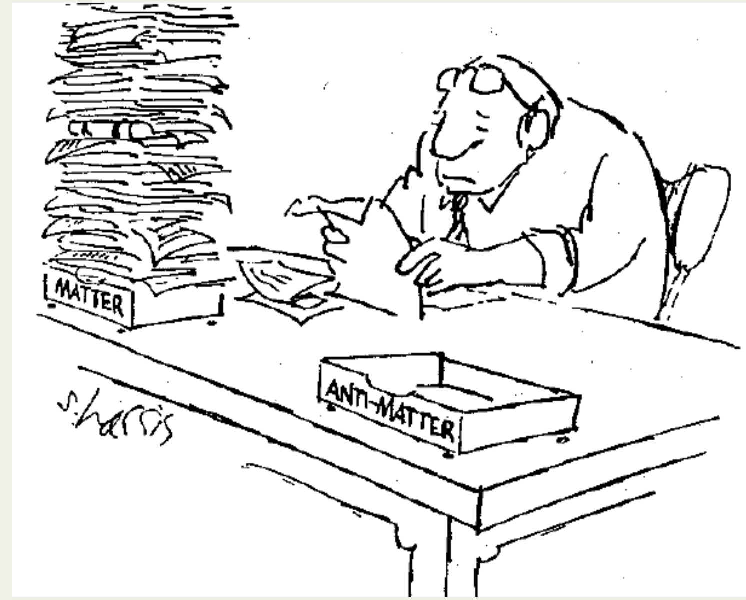
If phase = O(1): Λ > 10 TeV (n=1)

- MSSM was pushed above 1 TeV well before the LHC was turned on
- **Usual solution: ignore CPV phases… (pMSSM, cMSSM, ...)**
- 'Solutions' to the problem exist (decouple sfermions, cancellations, ...)

Matter-Antimatter asymmetry



13.7 billion years →

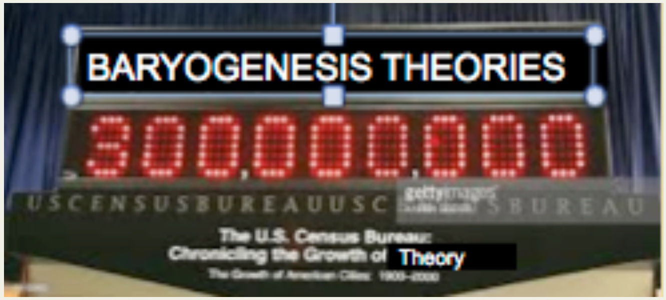


Observed: $$\frac{n(b)}{n(\gamma)} \approx 10^{-9}, \quad n(\bar{b}) \approx 0$$

Expected: $$\frac{n(b)}{n(\gamma)} \approx \frac{n(\bar{b})}{n(\gamma)} \approx 10^{-18}$$

Sakharov Conditions

	Standard Model
• Baryon number violation :	Yes ! (sphalerons)
• C & CP violation:	**Yes, but too small**
• Out of equilibrium (or CPT violation)	**No**



Some BSM required to understand asymmetry !

One number…. 100000 explanations…..

Scenarios: Leptogenesis, **Electroweak baryogenesis**, Affleck-Dine, Asymmetric Dark Matter, whatever-you-can-come-up-with-genesis

- In many models, EDMs are not linked to the asymmetry

It’s hopeless….. But that is nice !

Why are EDMs interesting to measure?

A search for new physics which is

‘background free’
CKM too small

Many beyond-the-SM models predict large EDMs:

Complementary to LHC search

Matter/Antimatter asymmetry requires more CPV:

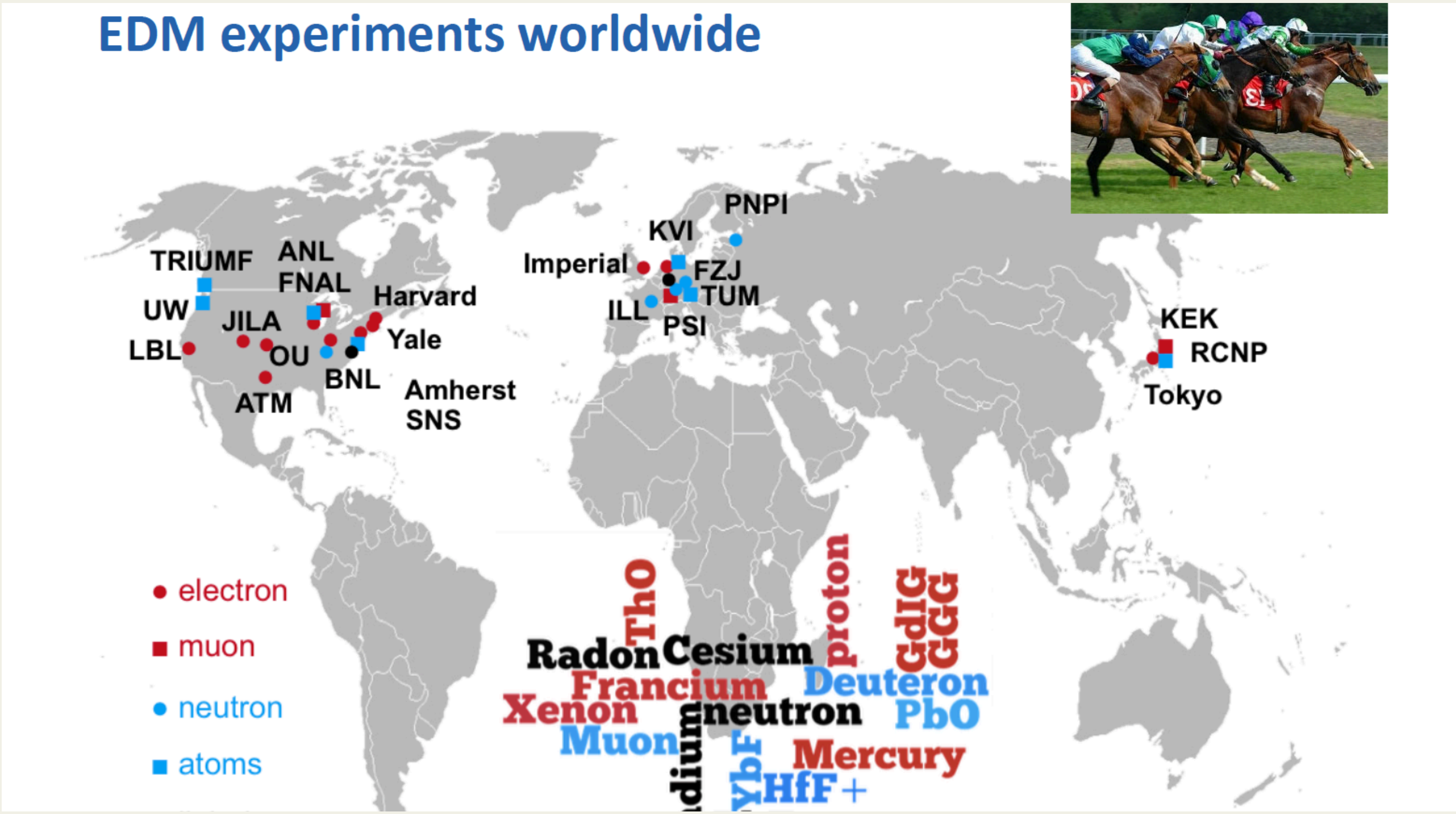
EDMs are good probes, but NO direct link

Very active experimental field

	System	Group	Limit	C.L.	Value	Year
	^{205}Tl	Berkeley	1.6×10^{-27}	90%	$6.9(7.4) \times 10^{-28}$	2002
e	YbF	Imperial	10.5×10^{-28}	90	$-2.4(5.7)(1.5) \times 10^{-28}$	2011
	ThO	ACME	8.7×10^{-29}	90	$-2.1(3.7)(2.5) \times 10^{-29}$	2014
	n	Sussex-RAL-ILL	3.0×10^{-26}	90	$0.2(1.5)(0.7) \times 10^{-26}$	2006
	^{129}Xe	UMich	6.6×10^{-27}	95	$0.7(3.3)(0.1) \times 10^{-27}$	2001
	^{199}Hg	UWash	7.4×10^{-30}	95	$-2.2(2.8)(1.5) \times 10^{-30}$	2016
	^{225}Ra	Argonne	1.4×10^{-23}	95	$-0.5(1.5)(0.01) \times 10^{-23}$	2016
	muon	E821 BNL g−2	1.8×10^{-19}	95	$0.0(0.2)(0.9) \times 10^{-19}$	2009

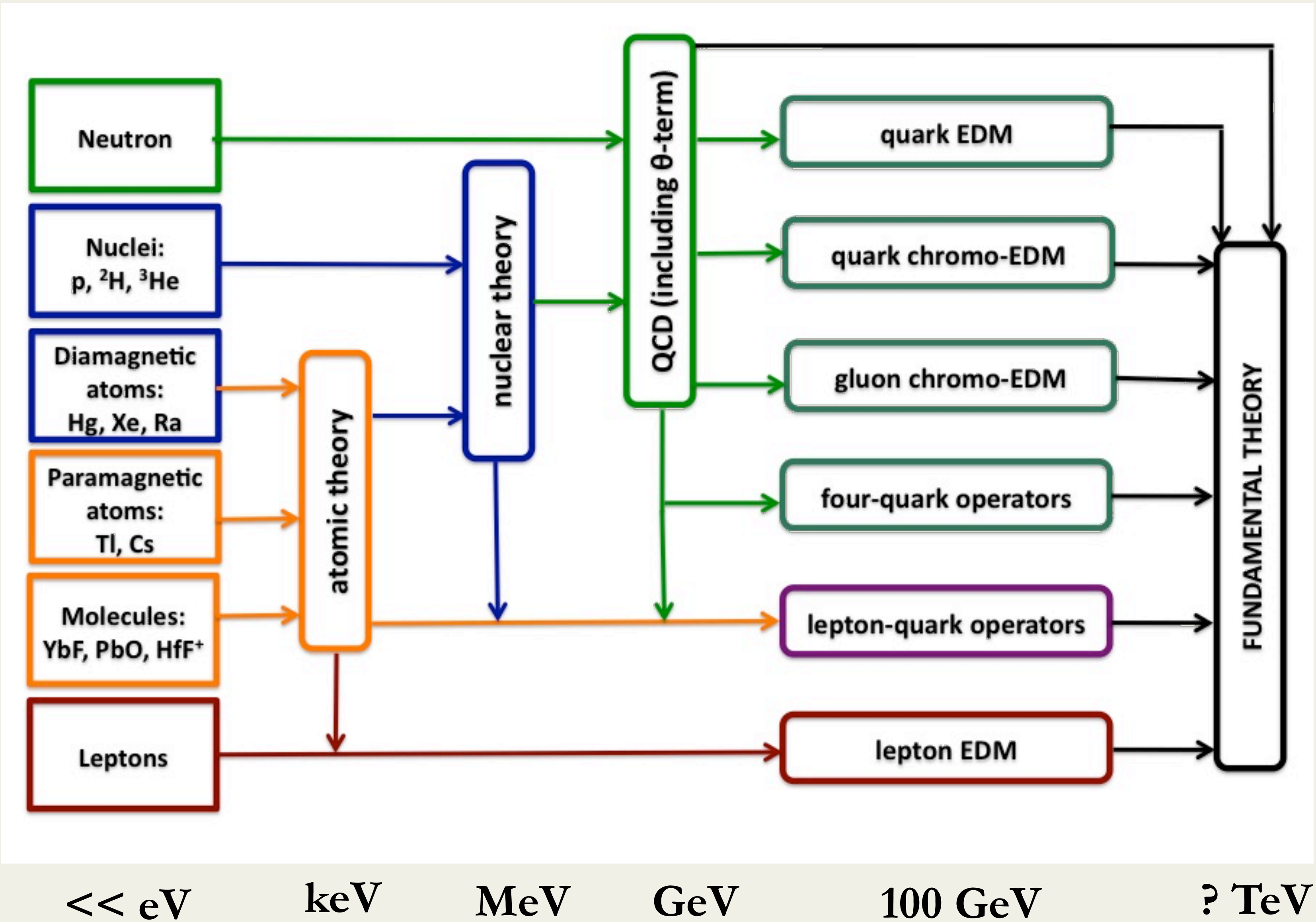
- Why do experiments on all these systems?
- How do the experiments compare? What does dn/dHg $\sim 10^{-3,-4}$ imply?
- Are there new systems that would be interesting to study ?

Race for an EDM



- And new experiment at Groningen/Nikhef using BaF molecule

EDMs are a multi-scale problem



Intermediate summary

- Electric dipole moments are probes of P and T and CP violation

$$H = -\mu(\vec{S}\cdot\vec{B}) - d(\vec{S}\cdot\vec{E})$$

- CP-violating analogue of magnetic dipole moments
- 'structural' EDMs of molecules like H2O are **unrelated (no CPV)**
- CPV in CKM is not 'small' but **just very inefficient** in creating EDMs
- 3 or 4 loops: **orders of magnitude below experiments**

- CPV beyond-the-SM is **very well motivated**
- In most BSM models EDMs are created much more efficiently
- Possible connection to **baryogenesis** (but no 1-to-1 link !)

- Forseeable future: **nonzero EDM = new CP violation**