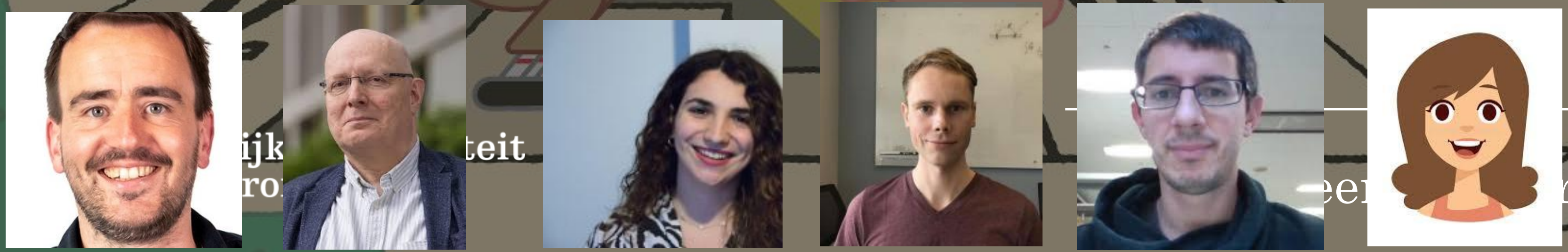
Probing hadronic CP violation with Electric Dipole Moments of paramagnetic molecules



Collaborators: Jordy de Vries, Rob Timmermans, Lemonia Gialidi, Wouter Dekens, Javier Menéndez, Beatriz Romeo

Contents

Our papers: 2502.06406, 2510.14933.

Earlier work: Flambaum, Pospelov, Ritz & Stadnik, 1912.13129v3.

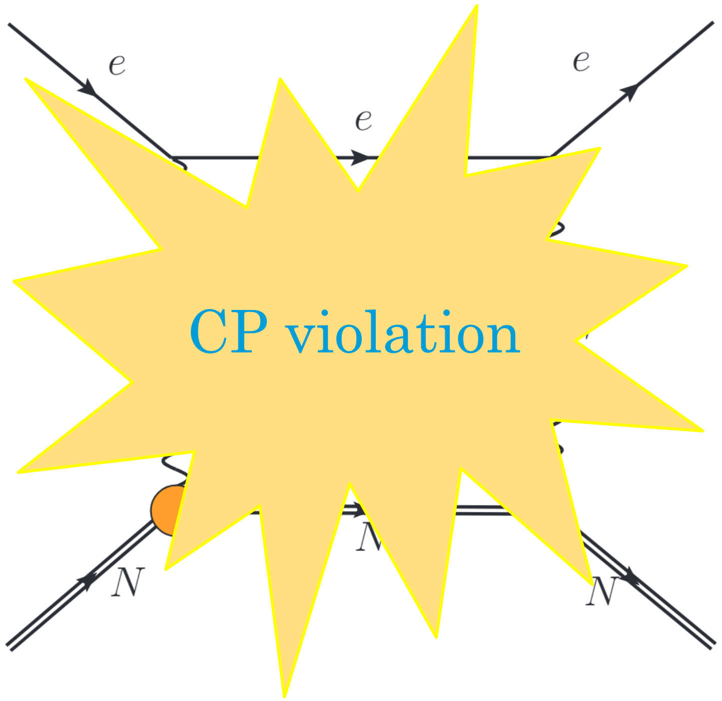
Part 1: hadronic CPV in paramagnetic EDMs

- Intro on **E**lectric **D**ipole **M**oments
- Sources of CP violation
- Precision development

Part 2: e-$\cancel{N}$ interactions

Nucleus

- Particle & nuclear physics
- Results: bound & disentangle

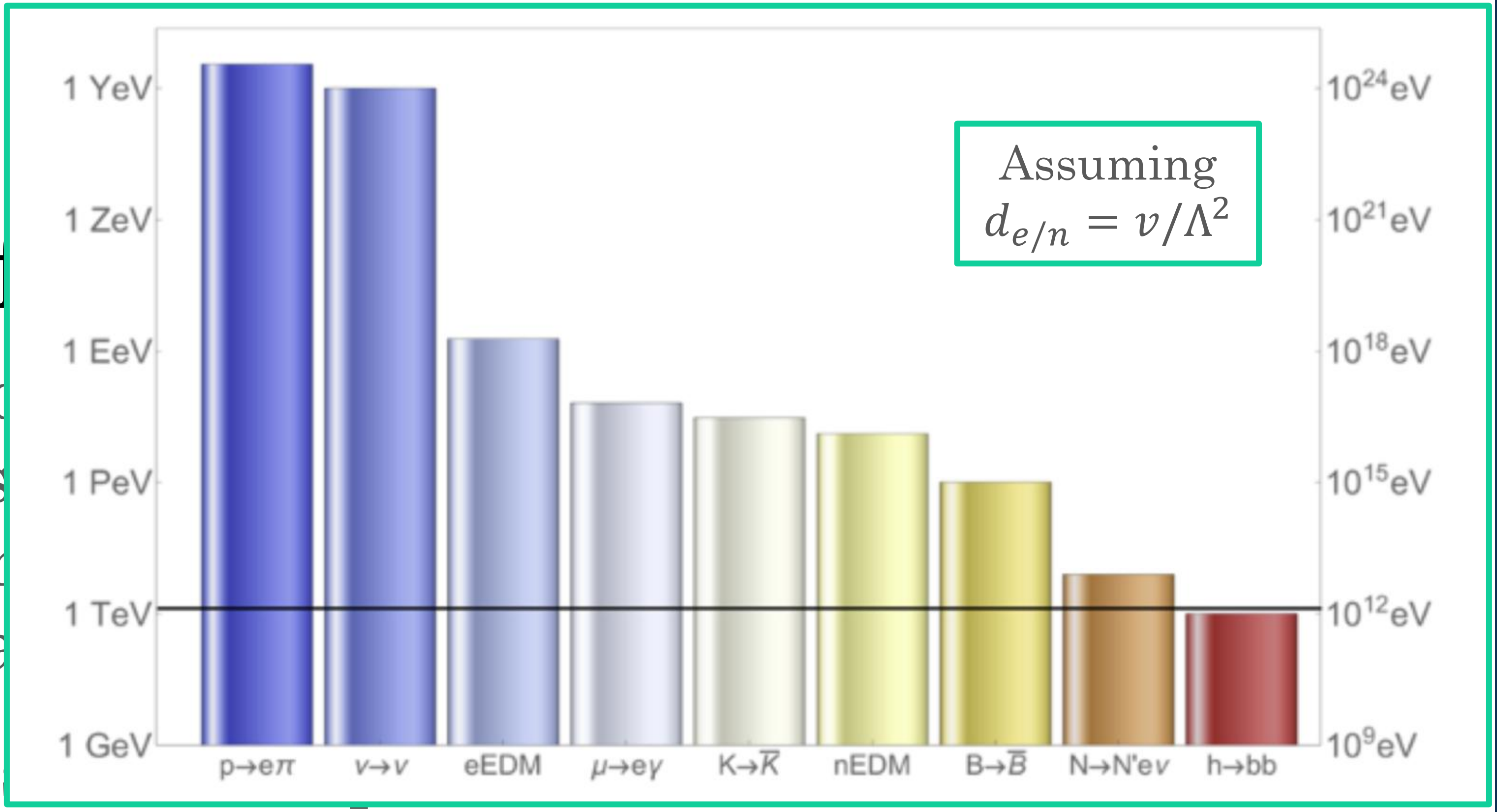


Part 1: hadronic CPV in paramagnetic EDMs

The state o

- Big problems: no
  neutrino masses
  anti-matter asy
  dark matter, gra

How can EDM re



Plot by Adam Falkowski

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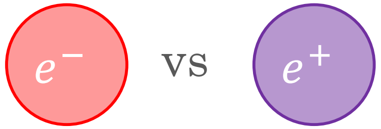
Probe of CP violation

- Need BSM CPV to explain matter anti-matter asymmetry



- EDMs probe this (in case of electroweak baryogenesis)

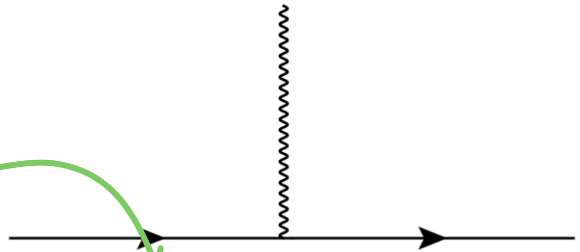
2

"Model killer"

- Many BSM scenarios predict larger EDMs than SM
- Precise EDM bounds rule out large part of parameter space
- Probe high NP energies Λ

Dipole moments: magnetic & electric

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



Magnetic dipole moment (MDM)

Non-relativistically: $H = -\mu\vec{S}\cdot\vec{B}$

Magnetic dipole moment   Spin   Magnetic field

Even under T: $-\mu\left(-\vec{S}\right)\cdot\left(-\vec{B}\right) = -\mu\vec{S}\cdot\vec{B}$

Electric dipole moment (EDM)

Non-relativistically: $H = -d\vec{S}\cdot\vec{E}$

Electric dipole moment   Electric field

Odd under T: $-d\left(-\vec{S}\right)\cdot\left(\vec{E}\right) = +d\vec{S}\cdot\vec{E}$

Through CPT-conservation:
EDM violates CP, MDM doesn't

Also: MDM comes in at tree-level in SM, EDM only at higher loop level → MDM much larger than EDM in SM

Pospelov & Ritz 0504231v2 (2005), Konstantin Gaul ECT*
4/3/24, Jordy de Vries SLAC 13/8/19

Paramagnetic: total electron spin non-zero
Diamagnetic: total electron spin = zero
Systems: atoms, molecules

Tracing the CP violation

hope to one day

We measure EDMs of:

Leptons | Nuclei | Neutron | Paramagnetic systems | Diamagnetic systems

Higher energy

Molecular, atomic, nuclear theory

C_{P} | C_{T} | C_{SP}

Heavy-baryon chiral perturbation theory (π, p, n, γ, e)

d_n | $\bar{g}_{\pi/\eta}$ | d_p

Quark EDM | Quark chromo-EDM | Gluon chromo-EDM | 4-quark operators | Lepton-quark operators | Lepton EDM (d_e)

Elementary particle level: SM, SMEFT, other BSM

From these fundamental sources of CPV:

CKM phase | QCD $\bar{\theta}$ term | * BSM sources *

Left-right symmetric models

SUSY

2-Higgs doublet models

?

Pospelov & Ritz 0504231v2 (2005), Konstantin Gaul ECT*
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Tracing the CP violation

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C_{P}

C_{T}

C_{SP}

Hadronic CPV

Heavy-baryon chiral perturbation theory (π, p, n, γ, e)

d_n

$\bar{g}_{\pi/\eta}$

d_p

Quark EDM

Quark chromo-EDM

Gluon chromo-EDM

4-quark operators

Lepton-quark operators

Lepton EDM (d_e)

Elementary particle level: SM, SMEFT, other BSM

From these fundamental sources of CPV:

CKM phase

QCD $\bar{\theta}$ term

* BSM sources *

Left-right symmetric models

SUSY

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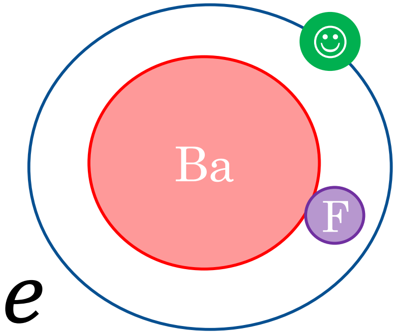
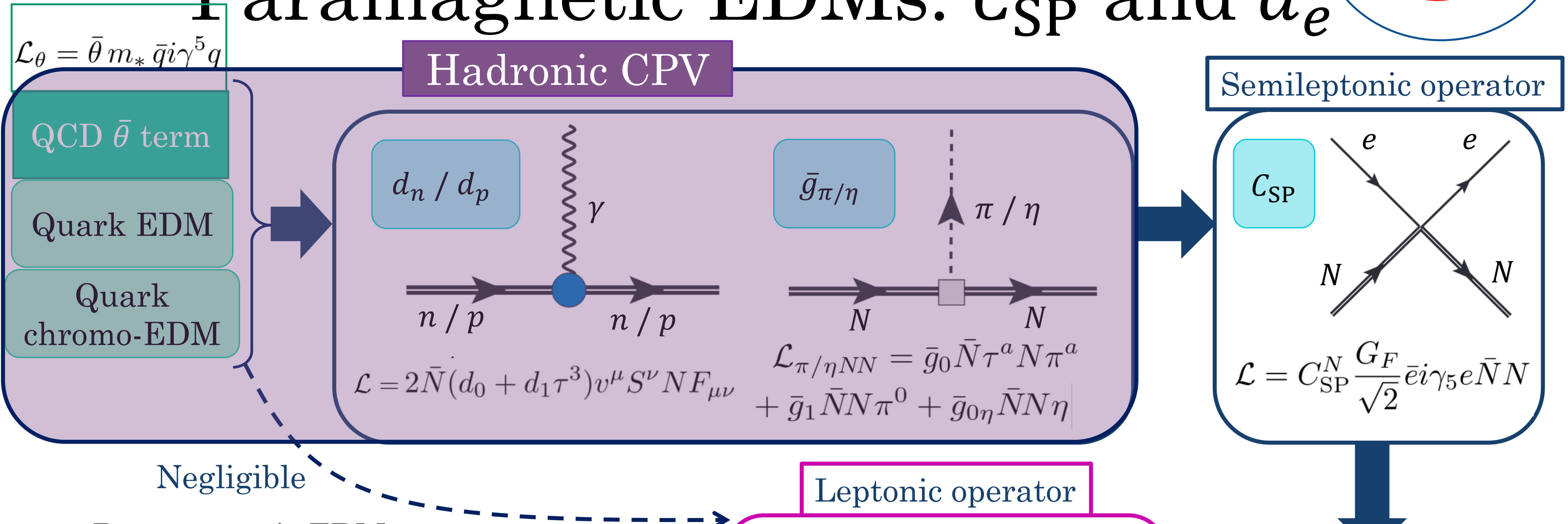
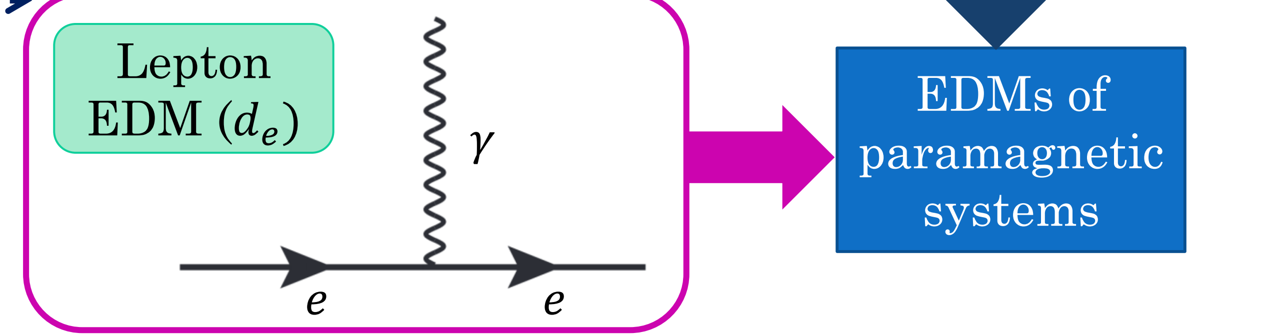
?

Paramagnetic EDMs: C_{SP} and d_e







- Paramagnetic EDM = $a\, C_{SP} + b\, d_e$
- Usually, bounds on paramagnetic EDMs are interpreted as bounds on d_e
- But! Paramagnetic EDM bounds are now so stringent, that we can derive relevant bounds on $\bar{\theta}, d_p, d_n$ from them too

Precision development

Plot by Kseniia Svirina, ECT* slides 6/3/24

Last ~20 years:

- nEDM bounds improved by factor ~4
- eEDM bounds (from paramagnetic systems) improved by factor ~400 → $\mathrm{HfF}^+, \mathrm{ThO}, \mathrm{YbF}, \mathrm{Tl}\ \ldots$

Diamagnetic atoms, e.g. ^{199}Hg and ^{225}Ra, improve slowly

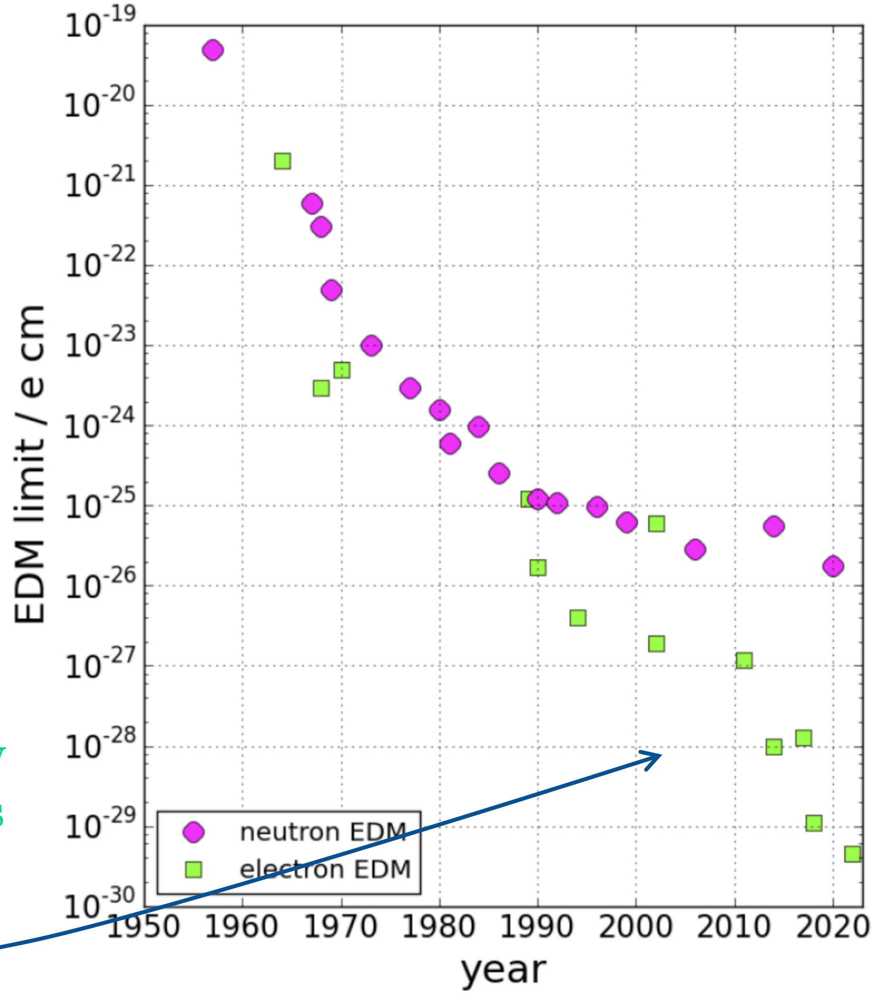
Currently:

- $|d_n| \lesssim 10^{-26}\ e$ cm
- $|\bar{\theta}|_{\mathrm{nEDM}} \lesssim 10^{-10}$

PSI 2020, J. Liang et al. 2301.04331

- $|d_p|_{\mathrm{Hg}} \lesssim 10^{-25}\ e$ cm

Graner et al. 2016, Dmitriev & Sen'kov 2003



Paramagnetic bounds are now 2 - 3 orders less stringent. But:

1

2 Disentangling → next slide…

Disentangling

or

Suppose: non-zero nEDM **and** paramagnetic EDM measurements.

What can we say about the underlying CPV?

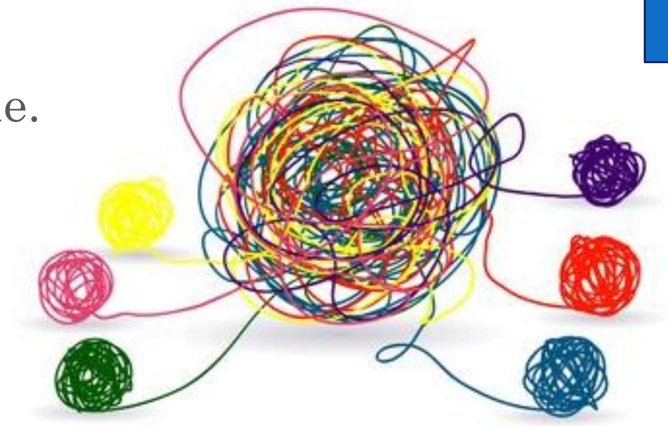
- We know $d_n = c_1\,\bar{\theta}$ and $\omega = c_2\,\bar{\theta}$ from theory
- Can check d_n/ω from theory against experiment
- Same for other CPV sources: $d_n = c_3\,d_q$ and $\omega = c_4\,d_q$, gives different d_n/ω

So: disentangle possible sources!

Also useful if precision is not (yet) the same.

$\omega = a\,C_{\mathrm{SP}} + b\,d_e$

Hadronic CPV:
$\bar{\theta}, d_q \ldots$



Recap slide

- EDMs are a powerful probe of CP-violation
- The EDM field spans over a wide range of energies, from fundamental CP-violating sources to experiments
- Measurable EDMs can be sourced by multiple CP-odd sources, through different 'avenues'
- Hadronic CP-violating sources are e.g. d_p, d_n, $\bar{\theta}$
- Paramagnetic EDM searches have improved a lot in sensitivity over the past decades
- We want to investigate hadronic CP violation in paramagnetic EDMs. Why?

as opposed to leptonic

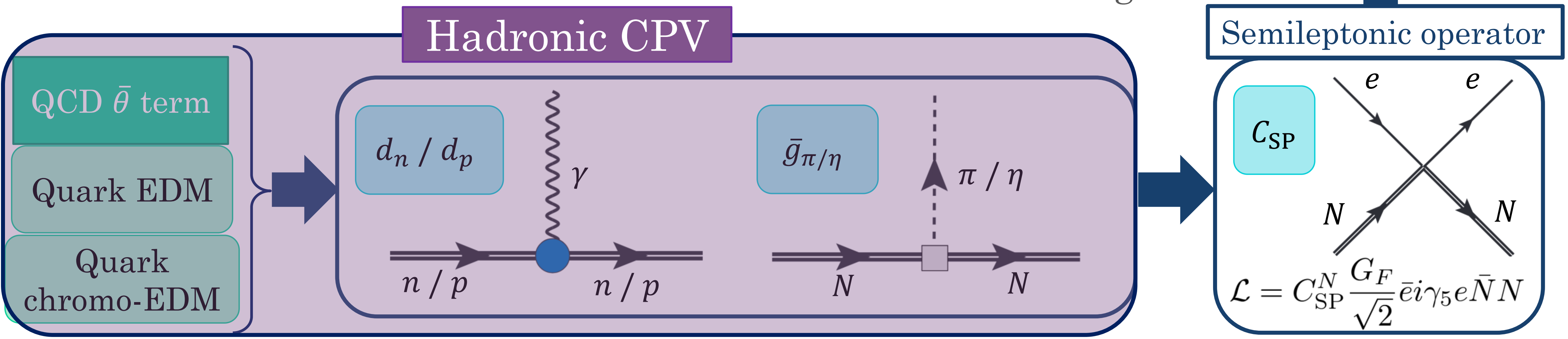
1. Bound d_p, d_n, $\bar{\theta}$...
2. Disentangle possible sources

Part 2: electron-nucleus interactions

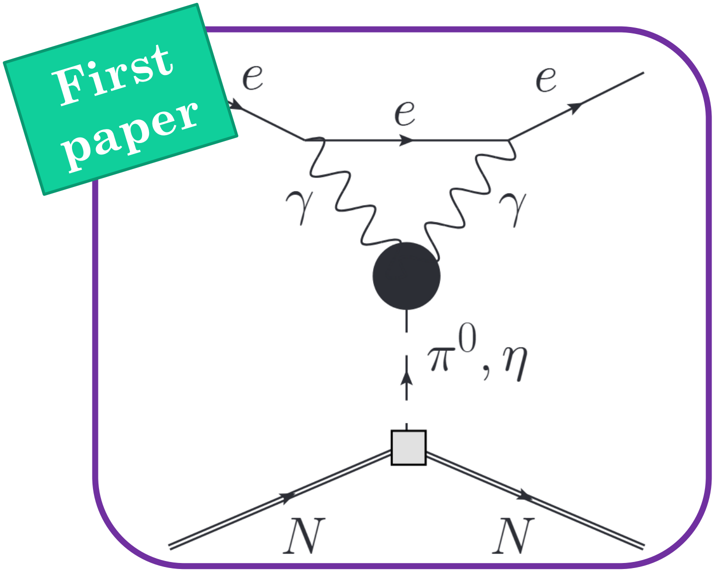
A closer look at C_{SP}

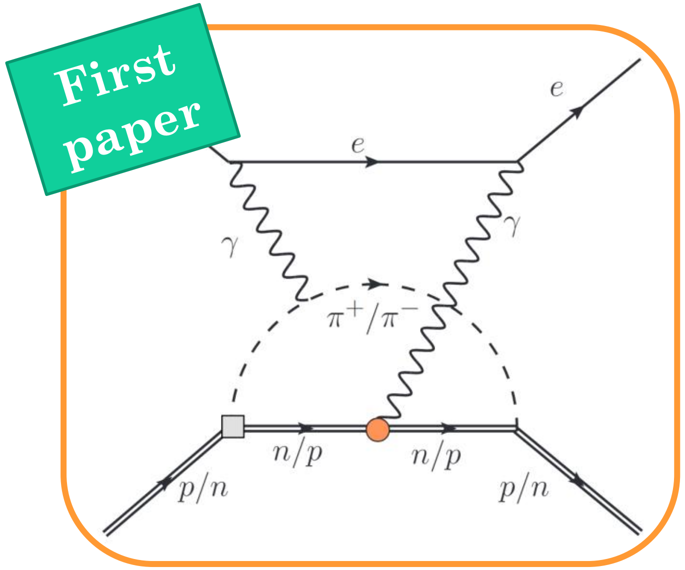
EDMs of paramagnetic systems

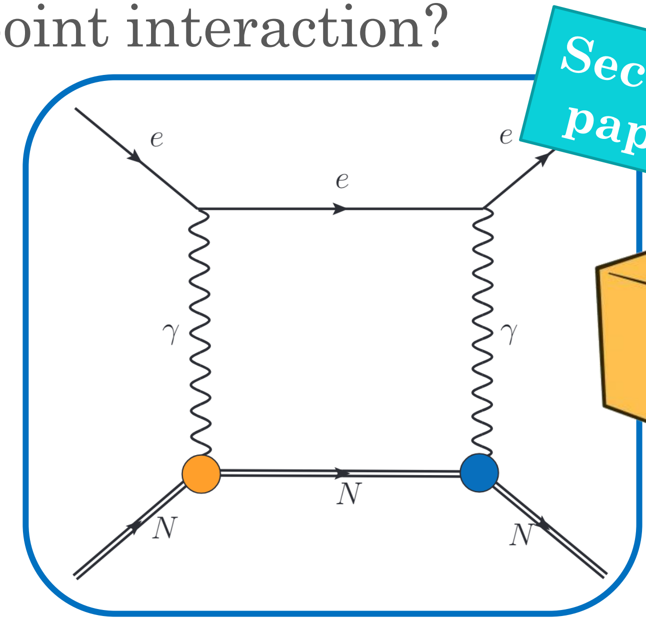
Recall the 'chain' of CP violation we want to investigate:

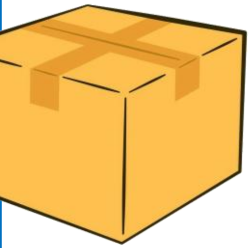


How do we build such an effective $eeNN$ 4-point interaction?





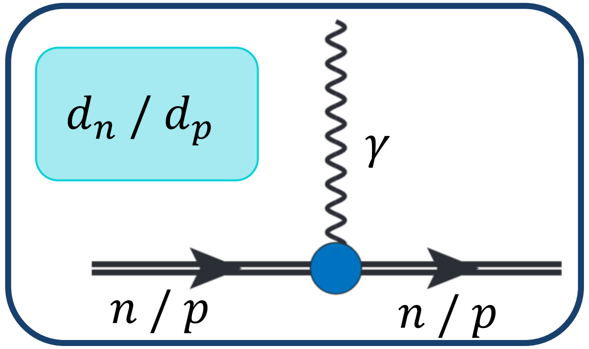


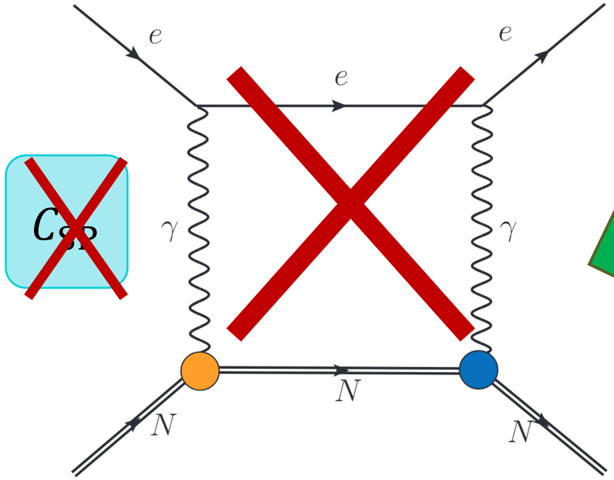


Simple?

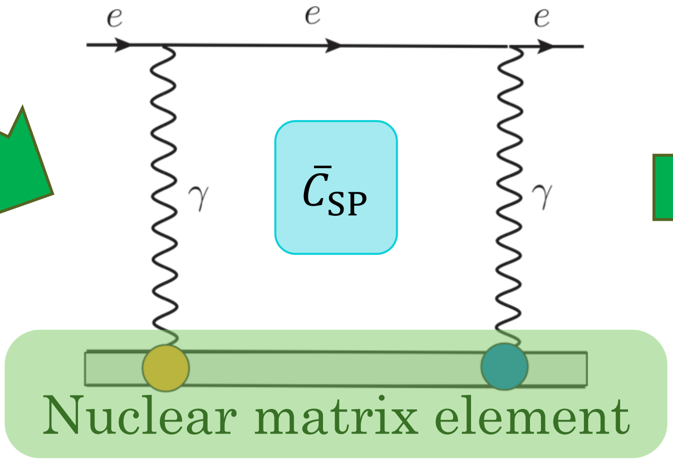
Tackling boxes

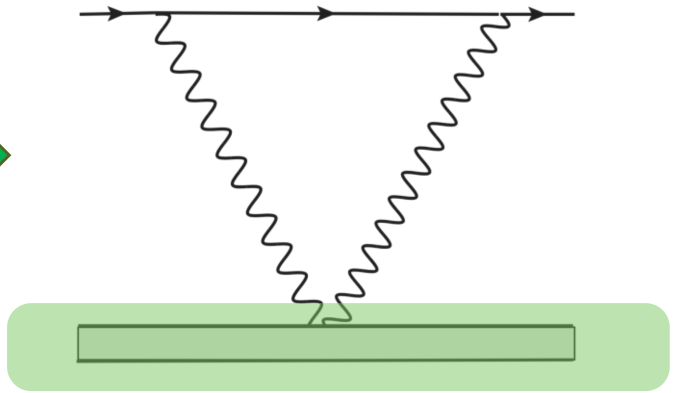
- **Ultrasoft** photon momenta $q_\gamma^0 \sim |\overrightarrow{q_\gamma}| \sim m_\pi^2/m_N$
- Probe **nuclear** structure

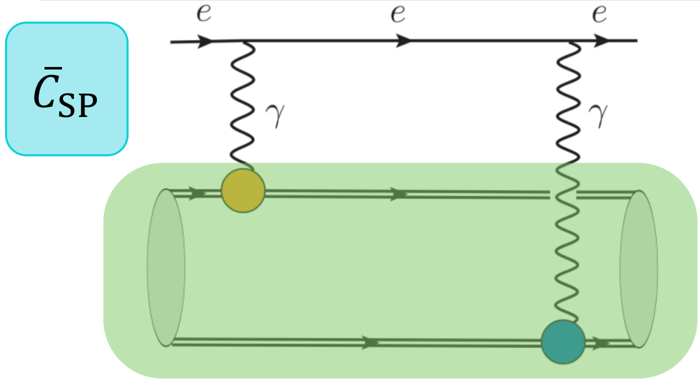




- Difficult integrals… use EFT: $E_n \gg m_e$
- Integrate out nuclear excited states





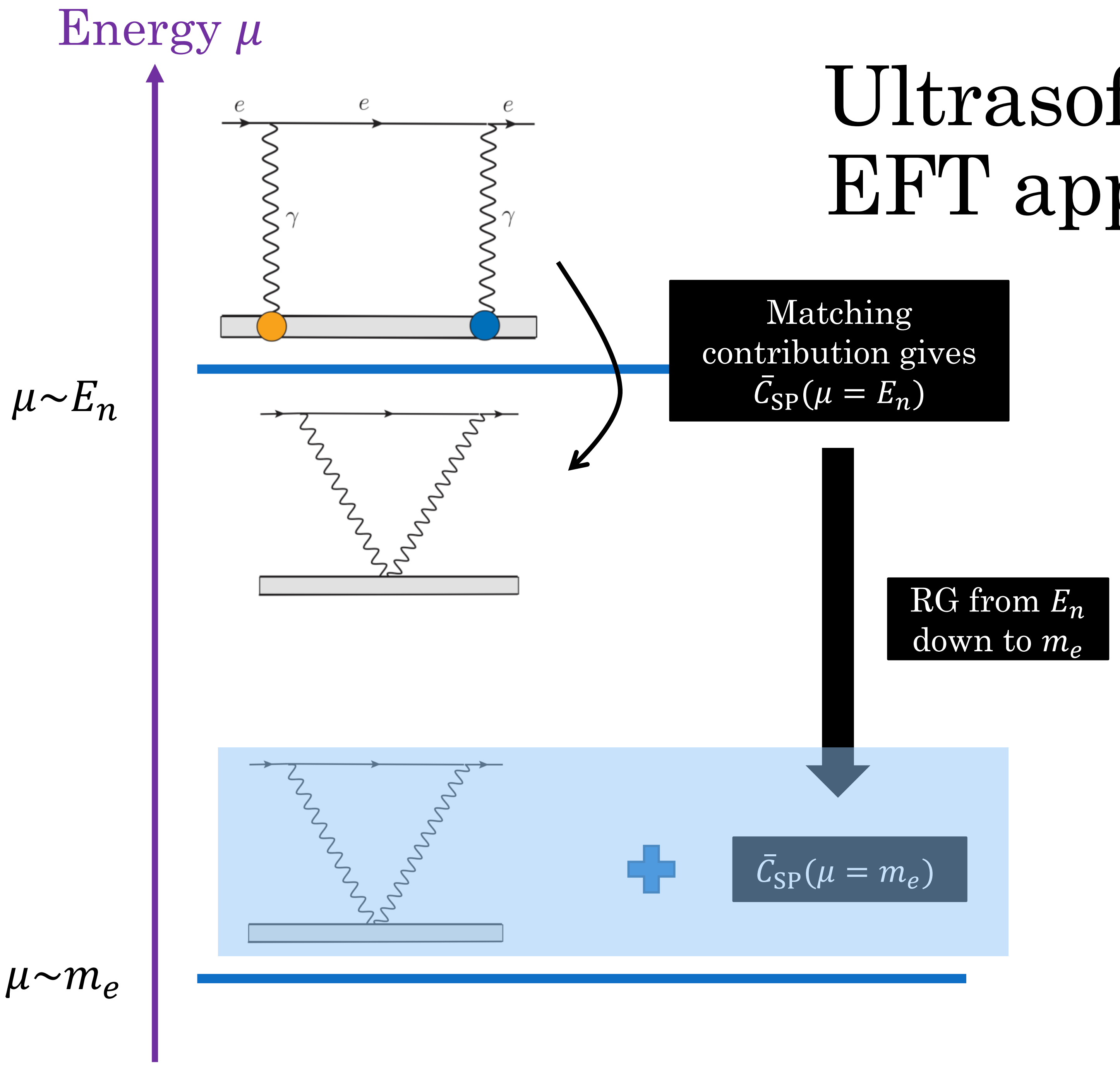


Another relevant momentum region:

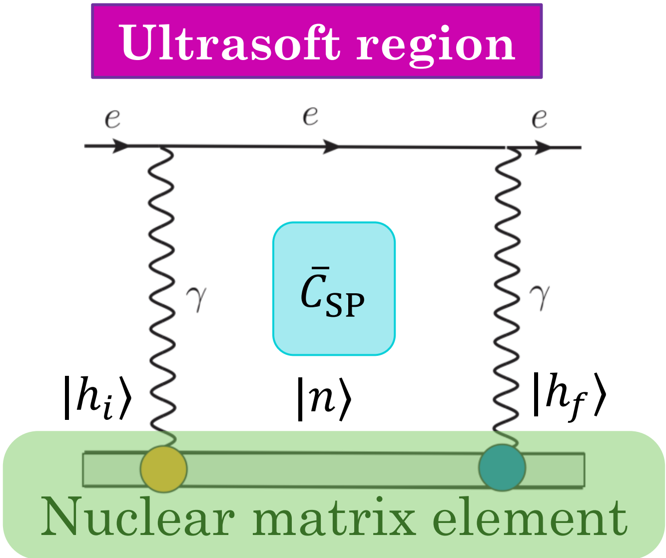
- **Potential** photon momenta $q_\gamma^0 \sim \overrightarrow{q_\gamma}^2/m_N$, $|\overrightarrow{q_\gamma}| \sim m_\pi$
- Expand in small scales like $q_\gamma^0/|\overrightarrow{q_\gamma}|$
- Only two-nucleon contributions

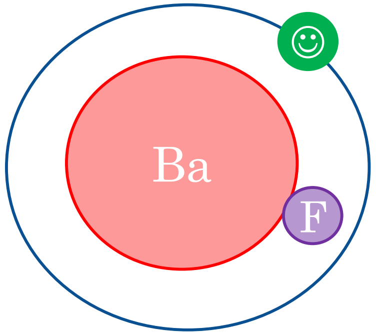
See chapter 5
in Manohar
1804.05863v1.

Ultrasoft region: EFT approach



Results from the nuclear side





We obtain:

$$\bar{C}_{SP}^{\rm usoft} = -\frac{\sqrt{2}\alpha^2 m_e}{3 m_N G_F} M_{SP}^{\rm usoft}$$

EDM

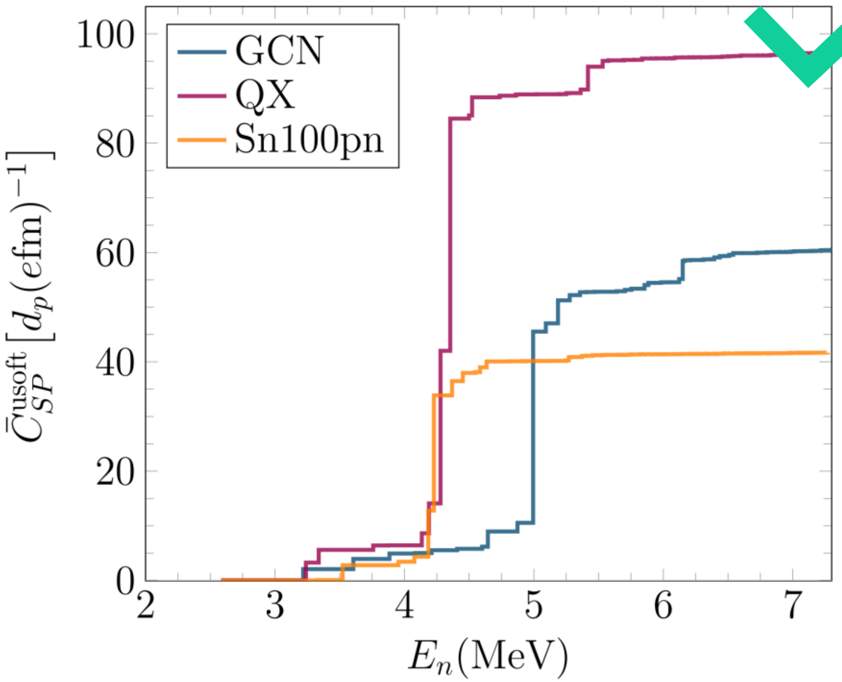
MDM

$\Delta_n = E_n - E_i$

$$M_{SP}^{\rm usoft} = \sum_n \frac{\langle h_f | D^{(i)} \vec{\sigma} | n \rangle \cdot \langle n | \mu^{(i)} \vec{\sigma} | h_i \rangle}{\Delta_n} \left(1 + 3 \ln \frac{4\Delta_n^2}{m_e^2} \right)$$

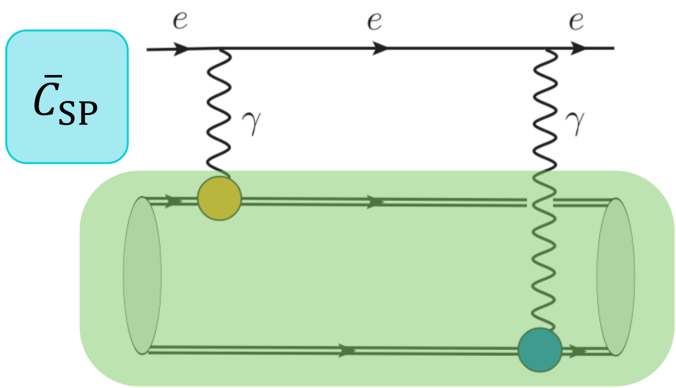
- Calculate $M_{SP}^{\rm usoft}$ and Δ_n for Ba-138 in nuclear shell model
- Check approximation $\Delta_n \gg m_e$
- Ba-138 has magic neutron number → only d_p contributes

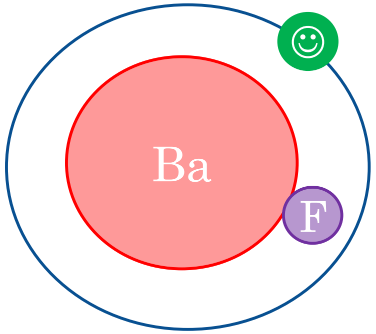
$$\boxed{\bar{C}_{SP}^{\rm usoft} = (67 \pm 28)\ d_p\,(e\,\mathrm{fm})^{-1}}$$



Results from the nuclear side

Potential region





We obtain:

$$\bar{C}_{SP}^{\rm pot} = -\frac{\sqrt{2}}{G_F}\langle h_i|V|h_i\rangle$$

$$V(\vec{r}) = -\frac{e^4 m_e}{18\pi m_N}\sum_{i\neq j}\mu^{(i)}D^{(j)}\,|\vec{r}|\left[\sigma^{(i)}\cdot\sigma^{(j)} + \cancel{\frac{1}{16}S^{(ij)}(r)}\right]$$

Small

Again: calculate NME for Ba-138 in nuclear shell model

- Valence **and** core nucleons contribute
- Coherence: count p and n pairs. Consequences:

1. NME ~ $c_1\, Z\, d_p + c_2\, N\, d_n$
2. Potential > ~~ultrasoft~~
3. Potential less dependent on nuclear structure → small error

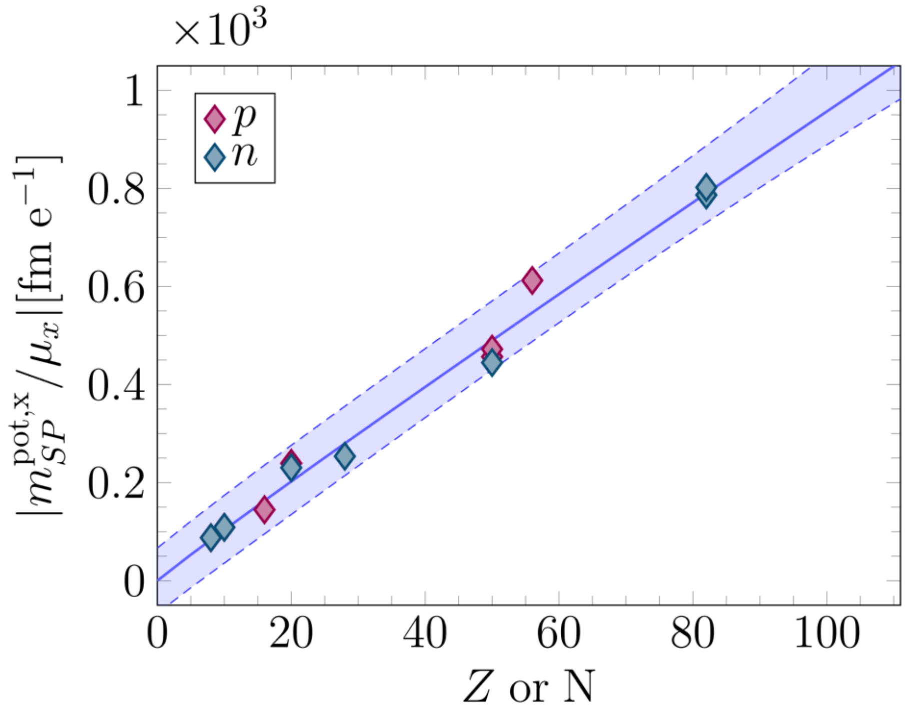
$$\boxed{\bar{C}_{SP}^{\rm pot} = \left[(-433\pm 5)\, d_p + (387\pm 0.4)\, d_n\right]\ (e\,{\rm fm})^{-1}}$$

Scaling!

- Explore scaling of potential NME with Z and N

$$M_{SP}^{\text{pot}} = m_{SP}^{\text{pot,p}}\, d_p + m_{SP}^{\text{pot,n}}\, d_n$$

- Lighter nuclei confirm scaling (up to ~20%)
- What about heavier nuclei: Th, Hf?



Connect to experiments:

$$\omega = a\,C_{\text{SP}} + b d_e \rightarrow \frac{\omega}{b} = d_e + \frac{a}{b}\,C_{\text{SP}}$$

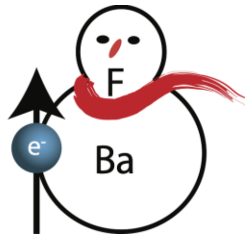
$$\boxed{d_e^{\text{equiv}} \equiv r_{\text{mol}}\bar{C}_{\text{SP}}/A}$$

$$\boxed{d_e^{\text{equiv}} = \frac{\sqrt{2}e^4 m_e}{18\pi G_F m_N}\,\frac{r_{\text{mol}}}{A}(-9.74)\left[\,Z\,\mu_p\,d_p + N\,\mu_n\,d_n\right]\frac{\text{fm}}{e}}$$

Extrapolate from BaF to HfF$^+$

P. Aggarwal et al. (NL-eEDM), 1804.10012
T. S. Roussy et al. (JILA), 2212.11841.

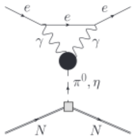
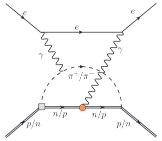
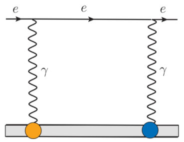
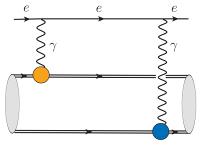
Results: bounds



d_p and d_n bounds

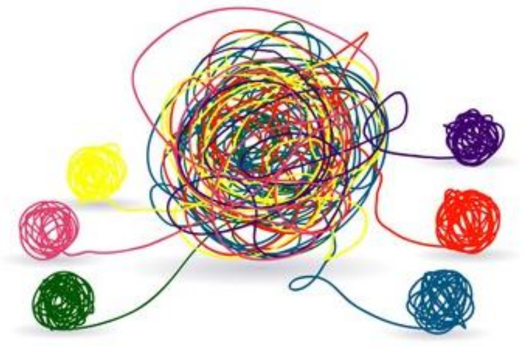
- Projected: $|d_e|_{\mathrm{BaF}} < 10^{-30}\ e$ cm $\begin{cases} |d_p|_{\mathrm{BaF}} < 8.4 \cdot 10^{-24}\ e \text{ cm} \\ |d_n|_{\mathrm{BaF}} < 8 \cdot 10^{-24}\ e \text{ cm} \end{cases}$
- With scaling function & $|d_e|_{\mathrm{HfF^+}} < 4.1 \cdot 10^{-30}\ e$ cm $\begin{cases} |d_p|_{\mathrm{HfF^+}} < 1.6 \cdot 10^{-23}\ e \text{ cm} \\ |d_n|_{\mathrm{HfF^+}} < 1.6 \cdot 10^{-23}\ e \text{ cm} \end{cases}$
- Recall current limits $\begin{cases} |d_p|_{\mathrm{Hg}} \lesssim 10^{-25}\ e \text{ cm} \\ |d_n| \lesssim 10^{-26}\ e \text{ cm} \end{cases}$

$\bar{\theta}$ bound

- Unfortunate cancellation between   and  

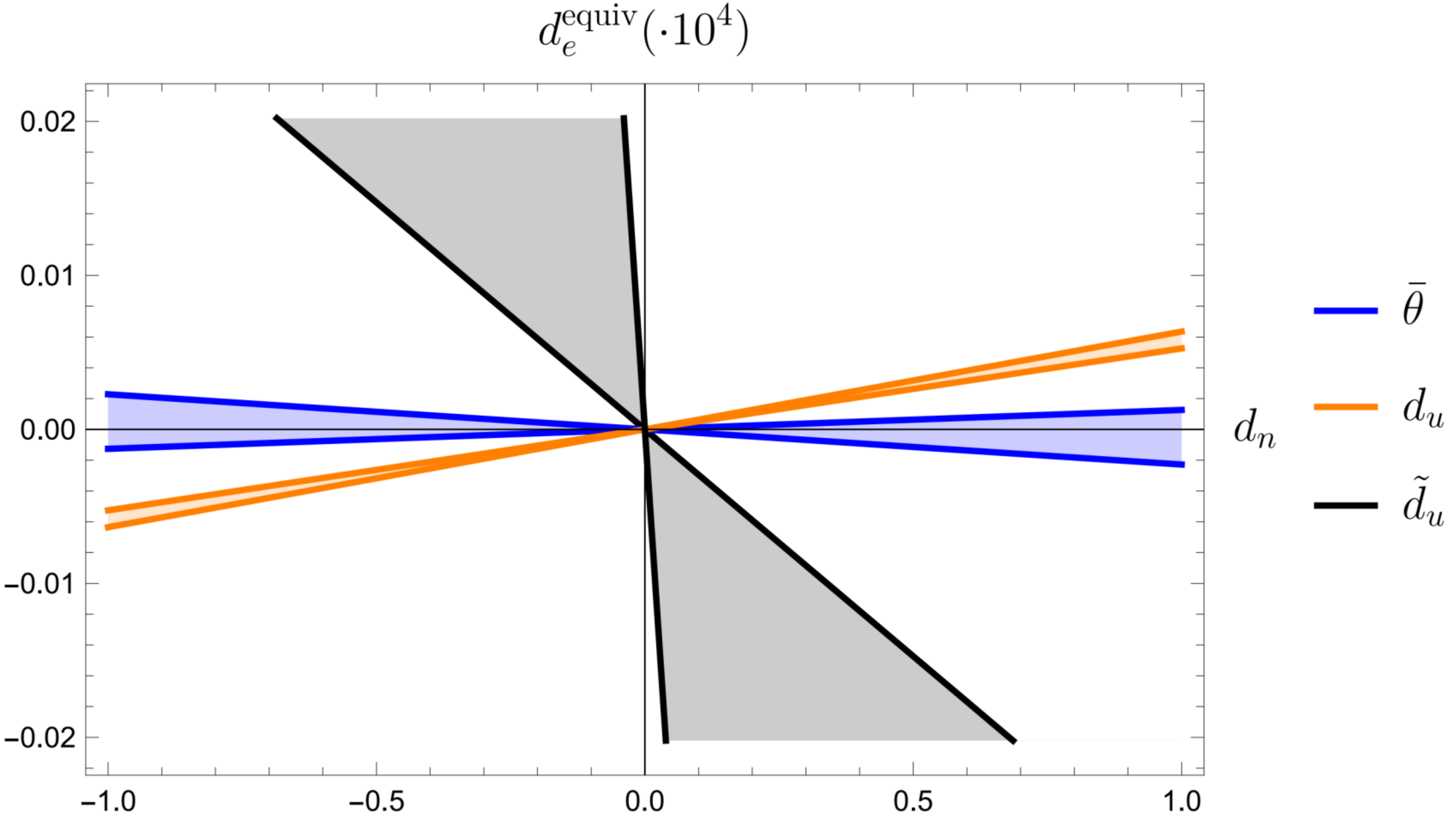
→ $\bar{\theta}$ limit weaker? More precision needed

Results: disentangle



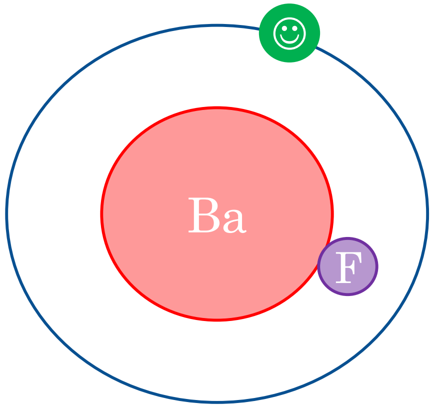
Recall:
$d_n = c_1\,\bar{\theta}$ and $\omega = c_2\,\bar{\theta}$
$d_n = c_3\,d_q$ and $\omega = c_4\,d_q$

d_n/ω
or actually d_n/d_e^{equiv}



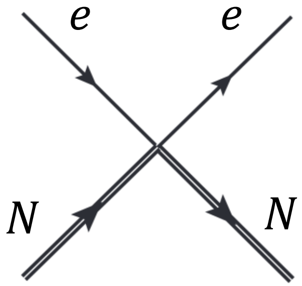
Summary

Part 1: hadronic CPV in paramagnetic EDMs



$$\omega = a\, C_{\rm SP} + b\, d_e$$

Hadronic CPV



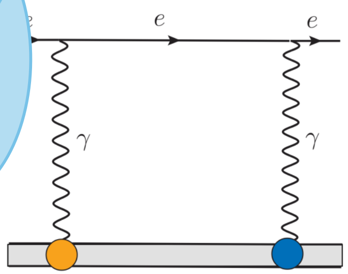
$$\mathcal{L} = C^N_{\rm SP}\frac{G_F}{\sqrt{2}}\bar{e}i\gamma_5 e\bar{N}N$$

- CP-odd e-N interactions → paramagnetic molecule EDMs probe hadronic CPV
- Paramagnetic experimental precision advance → independent bounds crucial for disentangling possible CP-odd sources

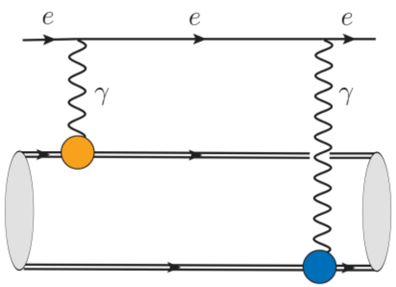
Outlook

- NME calculations in heavier systems (Th, Hf)
- Higher-order chiral corrections, e.g. to potential expression

Part 2: electron-nucleus interactions



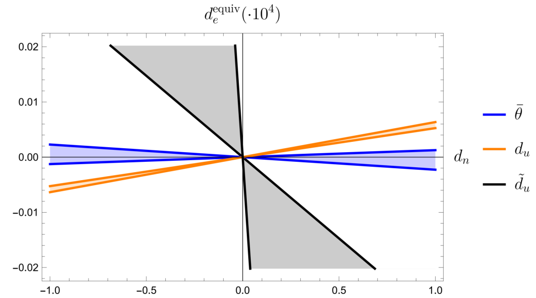
Ultrasoft: EFT without nuclear excited states



Potential: coherent scaling with Z & N → dominant

Results:

- Independent bounds on $d_p, d_n, \bar{\theta}$
- Disentangling of CP-odd sources



Thank you for listening!
Any questions?