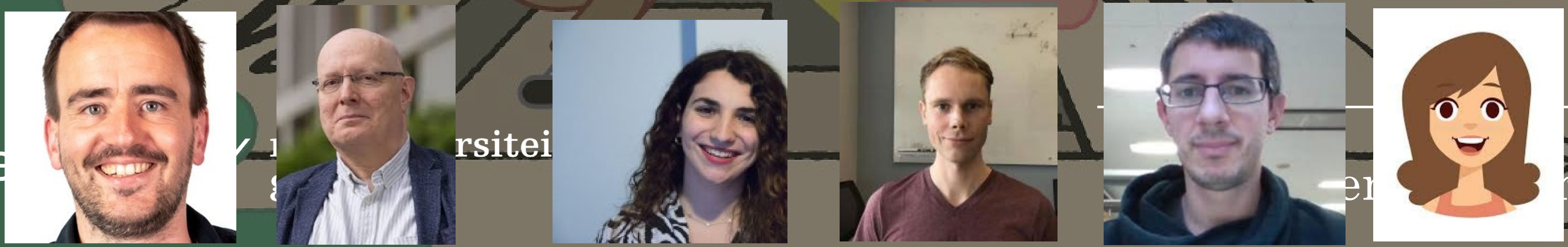
Probing hadronic CP violation with EDMs of paramagnetic molecules



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

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

Our papers: 2502.06406, 2510.14933.

Contents

Part 1: hadronic CPV in paramagnetic EDMs

- Sources of CP violation
- Precision development

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

Hadronic CPV

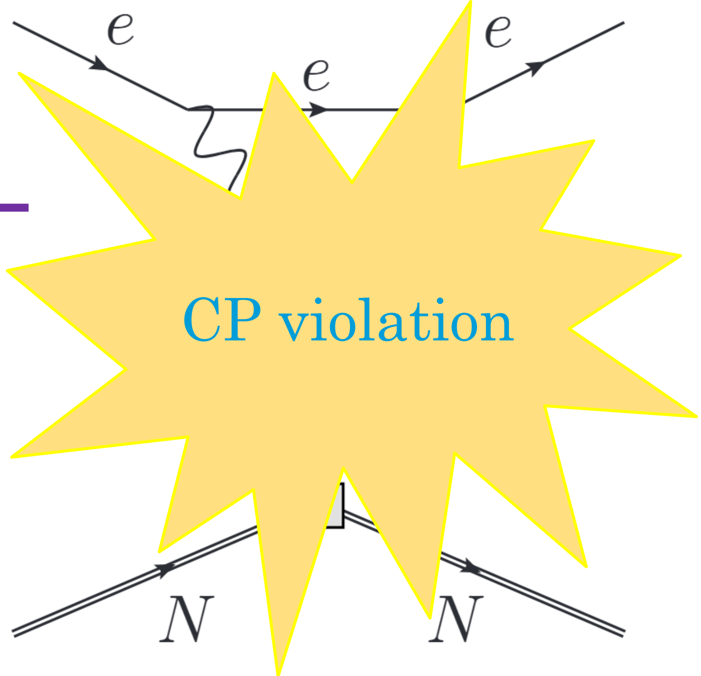
Part 2: e-N interactions

My talk

- Meson-nucleon interactions

Lemonia's talk

- Nucleon EDMs



Part 3: which source did it?

Part 1: hadronic CPV in paramagnetic EDMs

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

Tracing the CP violation

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

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

?

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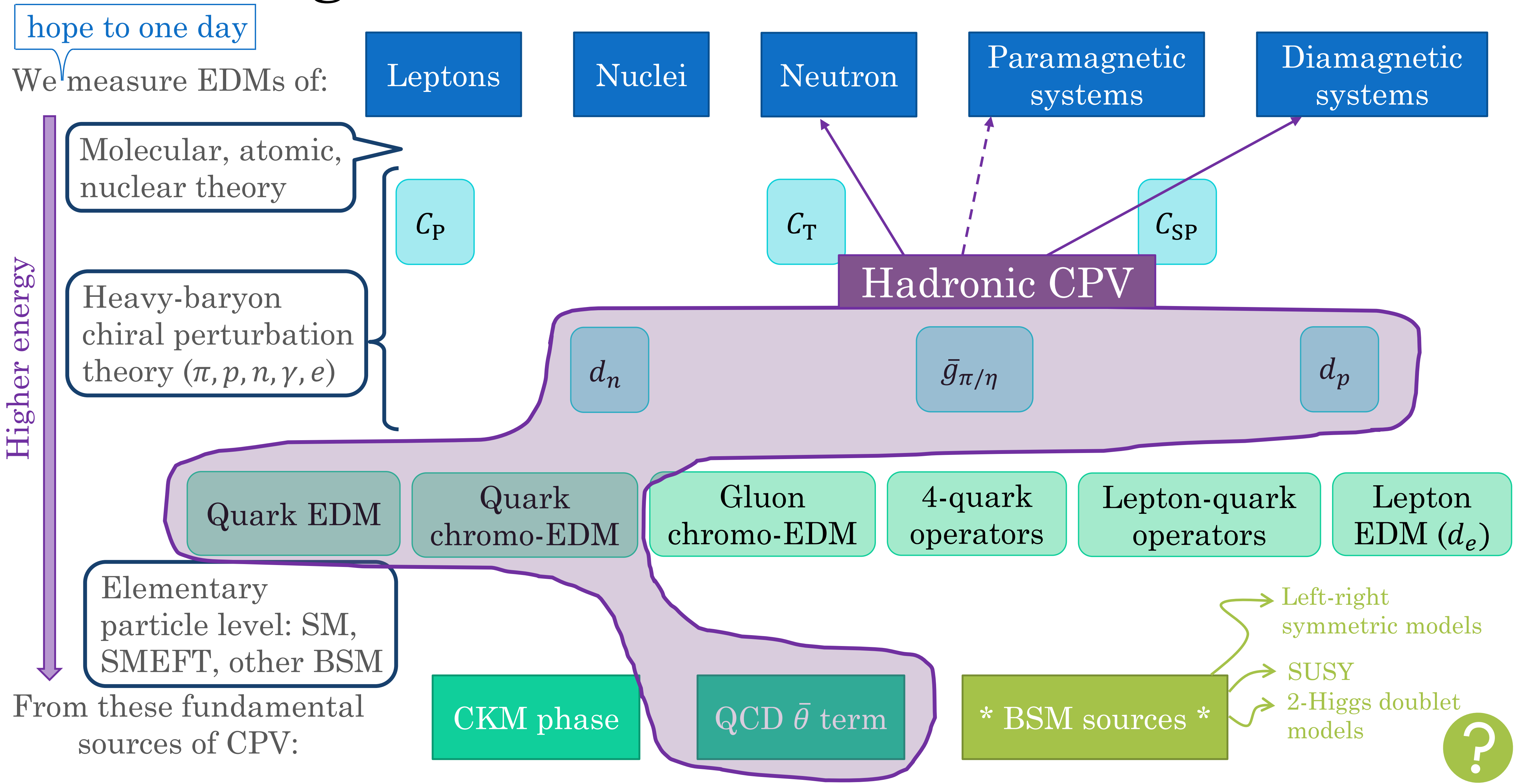
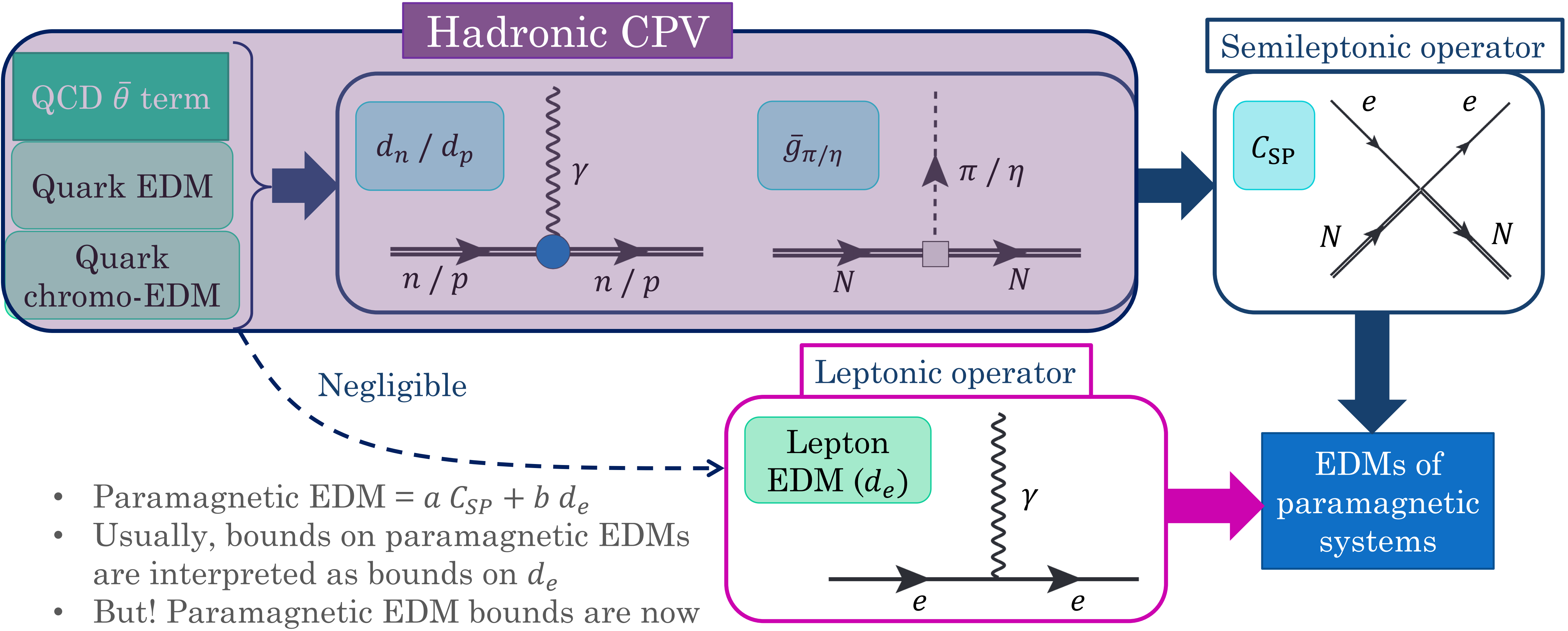


Paramagnetic EDMs: C_{SP} and d_e



- 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 & pEDM (from diamagnetic atoms): improvements within an order of magnitude
- eEDM bounds (from paramagnetic systems): improved by >2 orders

1-2 orders

2-3 orders

Projected improvements (next decade, 2203.08103)

Currently:

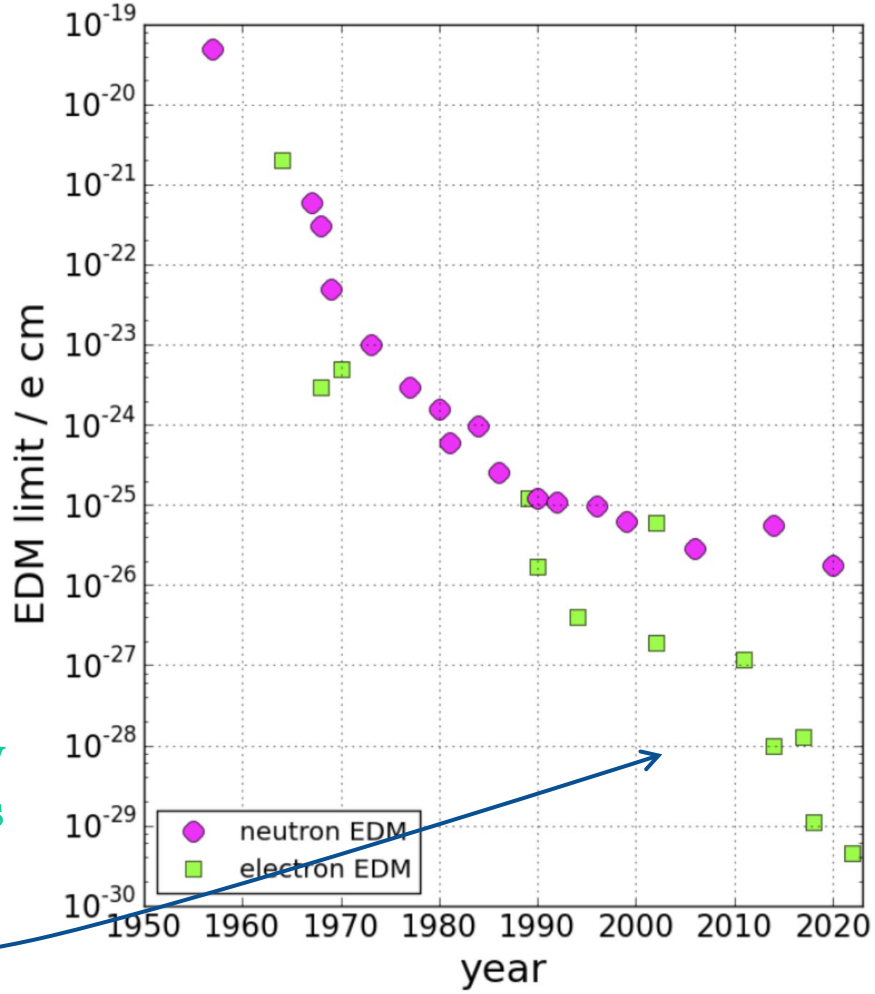
- $|d_n| \lesssim 10^{-26}$ e cm
- $|\bar{\theta}|_{\mathrm{nEDM}} \lesssim 10^{-10}$

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…

Sneak peek: which source did it?

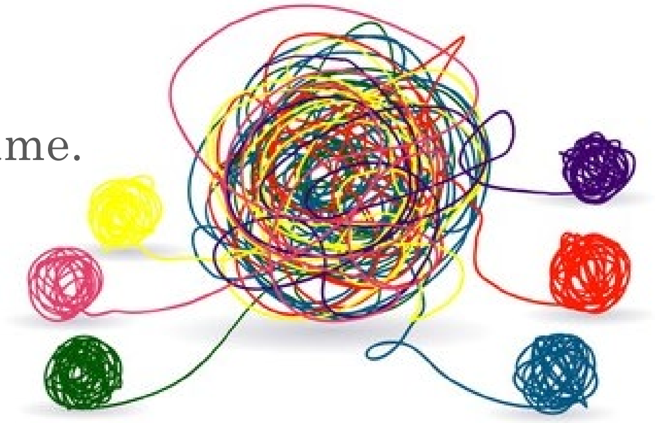
Suppose: non-zero nEDM **and** / **or** paramagnetic EDM measurements.

What can we say about the underlying CPV?

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

So: disentangle possible sources!

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



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

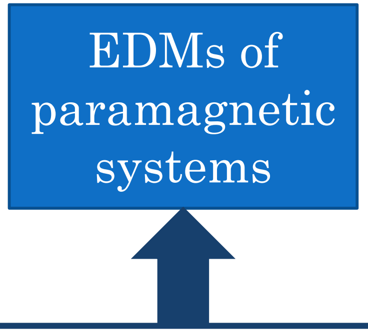
Hadronic CPV: $\bar{\theta}, d_q \ldots$

d_e^{equiv}

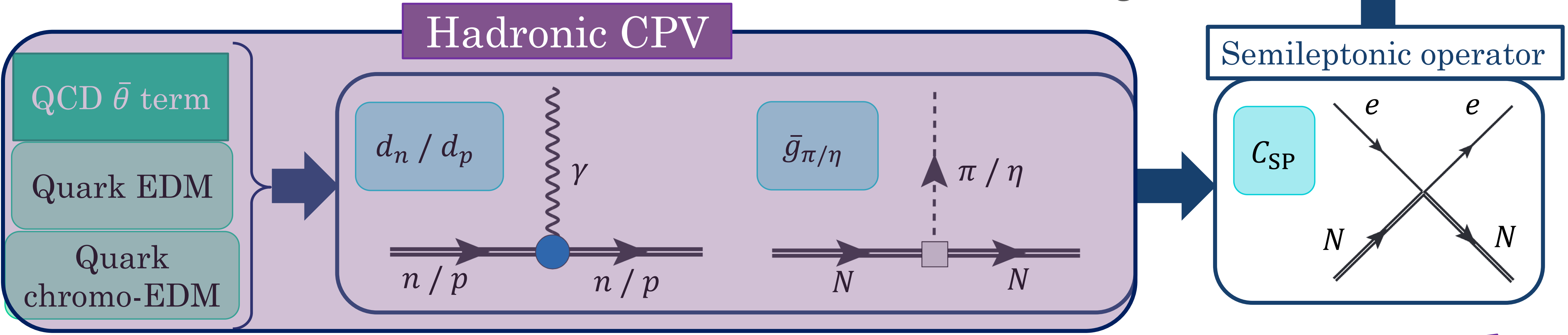
$$\frac{\omega}{b} = \frac{a}{b}\,C_{\text{SP}} + d_e$$

Part 2: e-N interactions

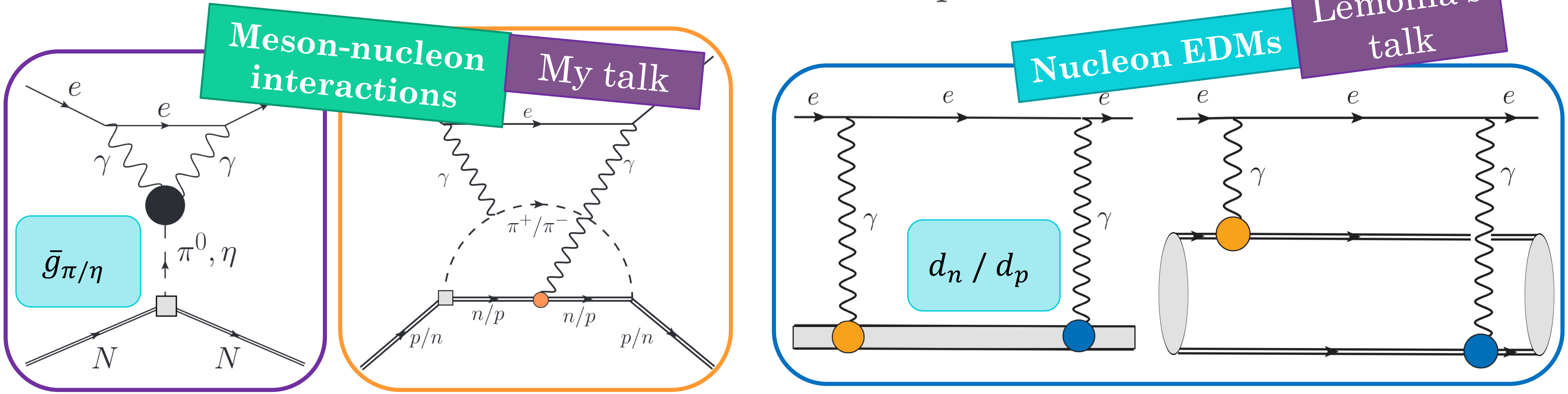
A closer look at C_{SP}



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



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



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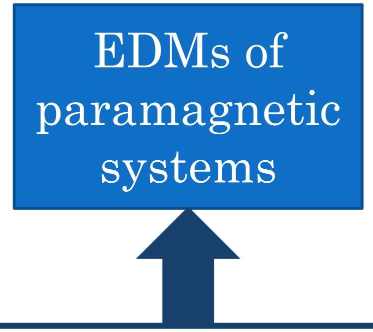

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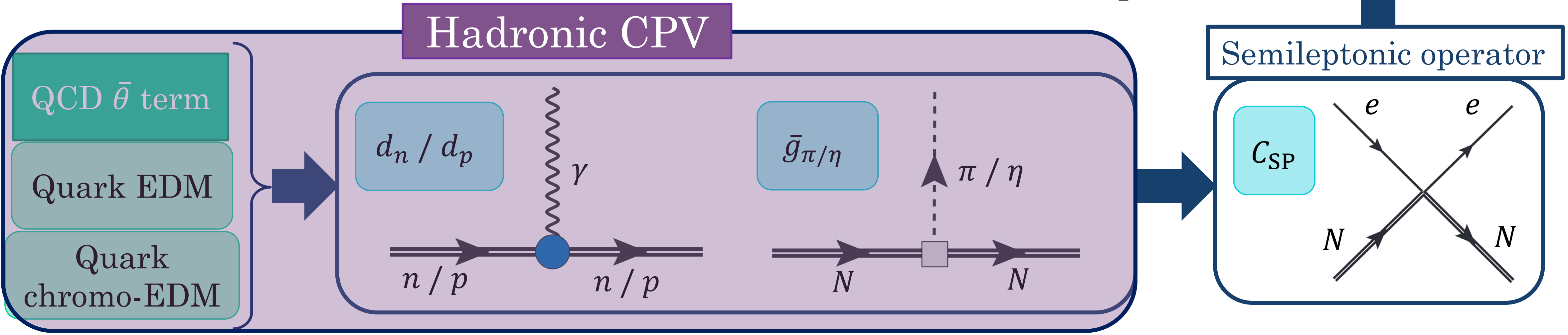

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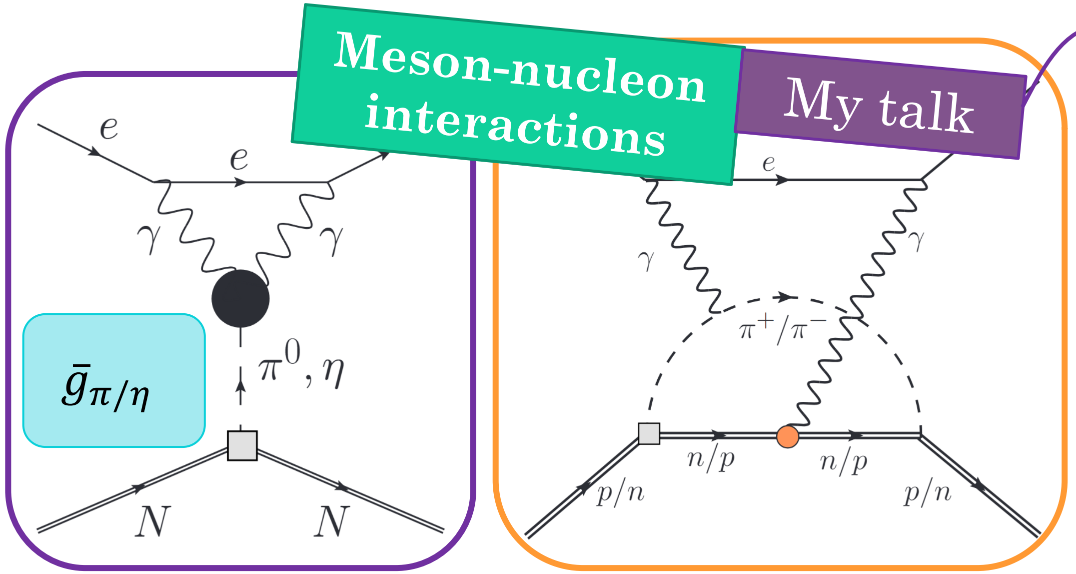
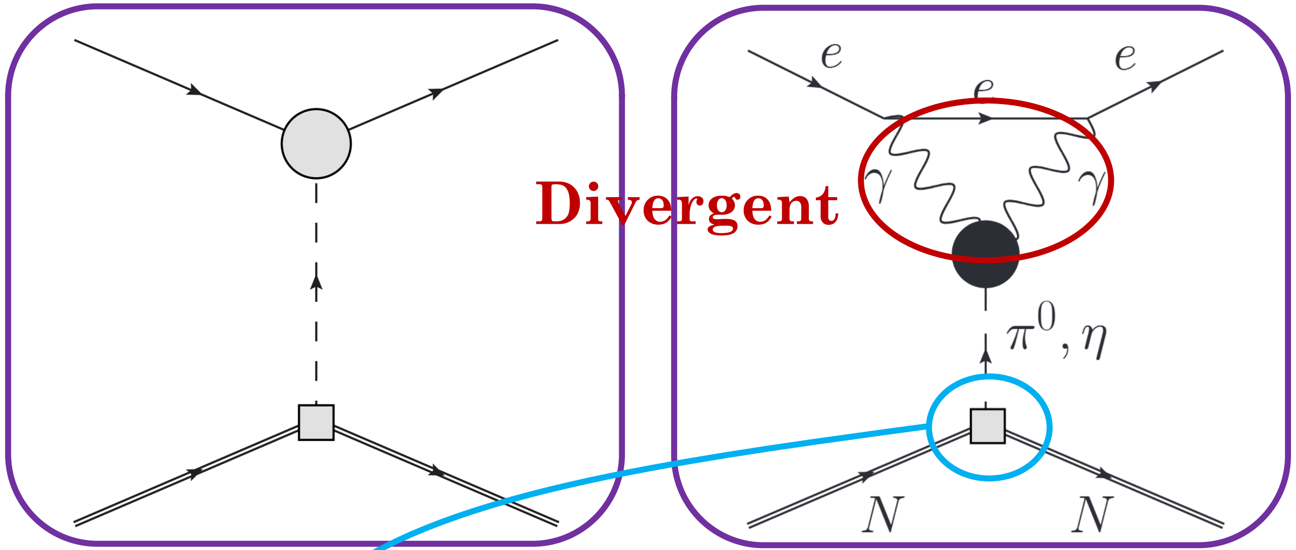


Organizational note:

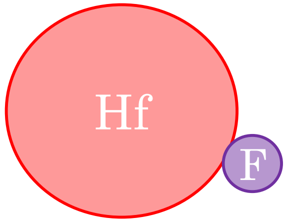
- In 2502.06406, focus on $\bar{\theta}$. Why?
  → $\bar{g}_{\pi/\eta}(\bar{\theta})$ values known more precisely than for q(C)EDM
- Results given in terms of $\bar{g}$
  → generalize in 2510.14933

Meson Exchange

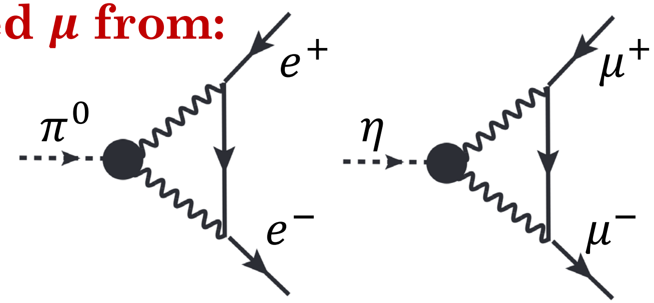


New aspects of our calculation:

- Counterterm diagram
- Eliminate μ-dependence
- Include $\bar{g}_1$ coupling



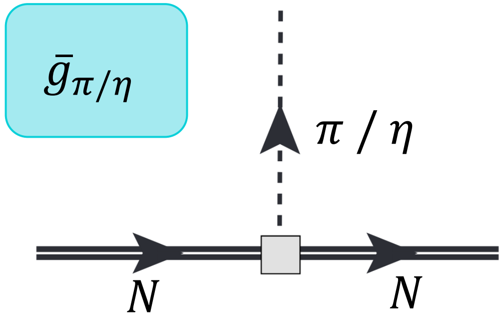
Determine finite counter-term at fixed μ from:



C_{SP} at nucleon level, or averaged:

- $C_{\text{SP}}^{N,ME} = \pm\alpha * \bar{g}_0 + \beta * \bar{g}_{\eta 0} + \gamma * \bar{g}_1$
- $C_{\text{SP}} = (\frac{Z}{A} C_{\text{SP}}^{p} + \frac{N}{A} C_{\text{SP}}^{n})$

Typically, Z/A ~ 0.4 and N/A ~ 0.6.



Can be $\bar{g}_0$ (π) or $\bar{g}_{\eta 0}$, but also $\bar{g}_1$ (π): for $\bar{\theta}$, expect

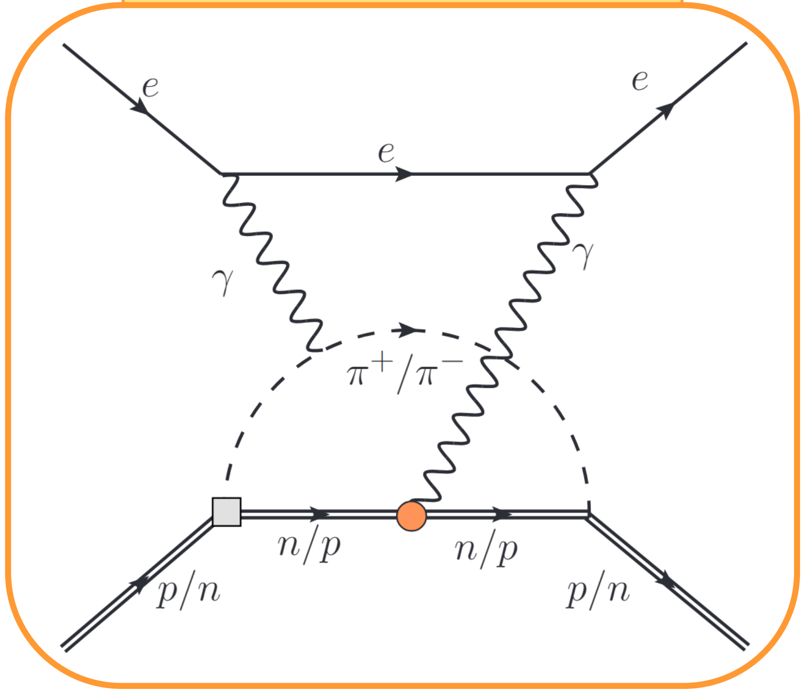
$\bar{g}_0 > \bar{g}_{\eta 0}$ & $\bar{g}_1$.

But: in the averaged C_{SP}, get

$\bar{g}_0 \sim \bar{g}_{\eta 0} \sim \bar{g}_1$!

Pion Loop

"Pion in flight"



Pospelov et al. factorize the upper γ and lower π loop:

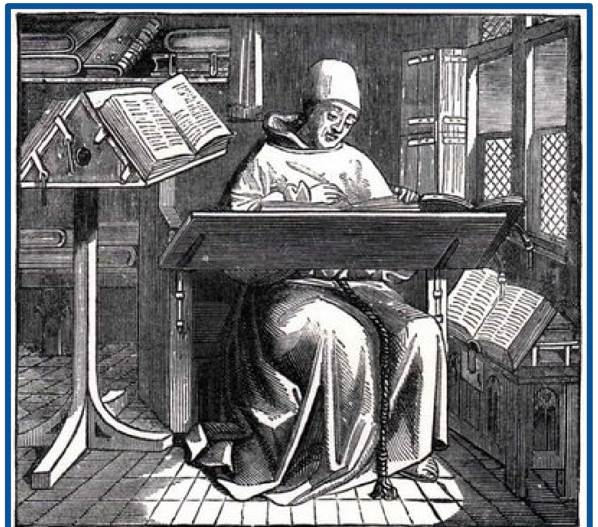
same **divergent** loop as before.

New aspects of our calculation:

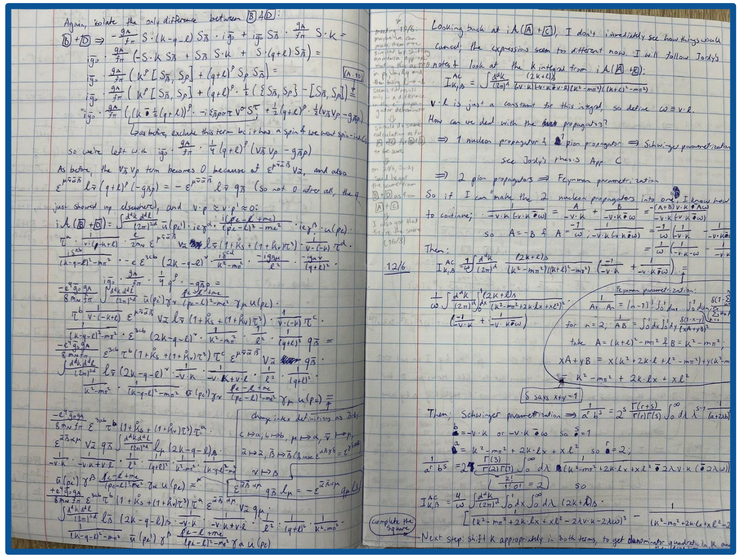
- Full two-loop calculation (scales mix)

Difficult…

- **Finite** result, without μ-dependence

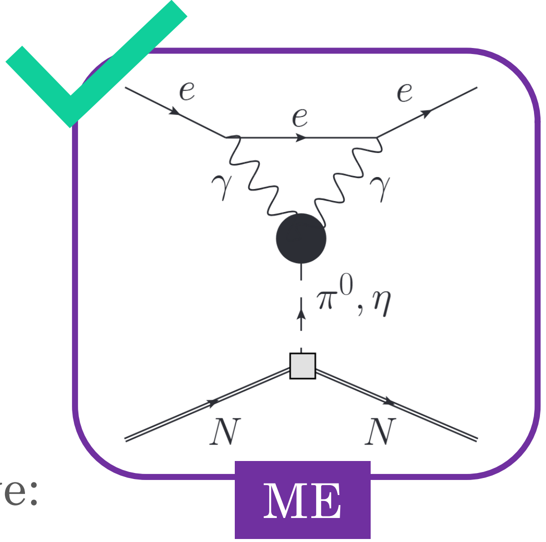


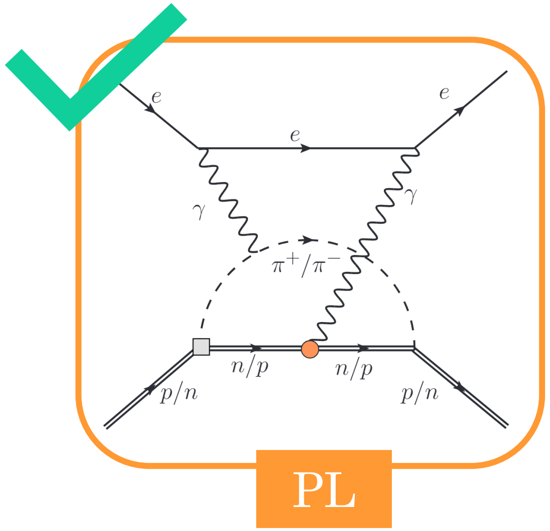
SCRIPTORIUM MONK AT WORK. (From *Lacroix*.)



De Vries et al. 1506.06247v2
Bsaisou et al. 1209.6306
T.S. Roussy et al. 2212.11841

Results





Values for $\bar{g}_{\pi/\eta}(\bar{\theta})$, Z/A = 0.4 and N/A = 0.6 give:

$$C_{\rm SP}^{\rm ME+PL}(\bar{\theta}) = (0.75[10]_{\bar{g}_0} - 0.72[22]_{\bar{g}_{0\eta}} + 0.74[33]_{\bar{g}_1} + 0.86[10]_{\rm PL}) \cdot 10^{-2}\bar{\theta}$$
$$= (0.78[42]_{\rm ME} + 0.86[10]_{\rm PL}) \cdot 10^{-2}\bar{\theta} = 1.63[45] \cdot 10^{-2}\bar{\theta}\,.$$

Pospelov et al.: $(0.1[\quad]_{ME} + 1.0[0.5]_{PL}) \cdot 10^{-2}\, \bar{\theta} \sim 1.1 \cdot 10^{-2}\, \bar{\theta}$

More generally, in terms of $\bar{g}_{\pi/\eta}$:

→ NLO contributions become LO in average!

$$C_{\rm SP}^{\rm ME+PL} = \left(\bar{g}_0 \frac{Z-N}{Z+N} + \bar{g}_1\right) 2.18[14]_{\rm ME} + \bar{g}_{0\eta}\, 0.0615[27]_{\rm ME}$$
$$-\bar{g}_0 \left(\frac{Z}{Z+N} 0.391[24]_{\rm PL} + \frac{N}{Z+N} 0.571[36]_{\rm PL}\right)\,.$$

Experimental HfF^+ bound from JILA:

$$C_{\rm SP} = (-1.4 \pm 2.2_{\rm stat} \pm 0.7_{\rm syst}) \cdot 10^{-10}$$

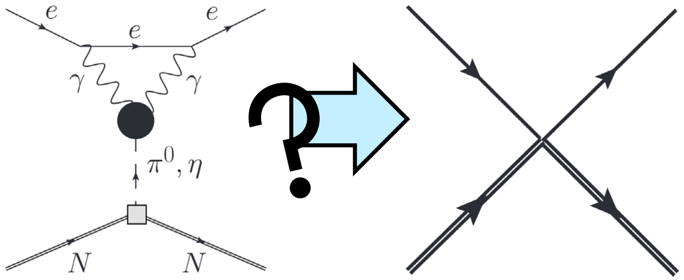
Bounds:
$|\bar{\theta}|_{\rm HfF^+} < 1.5 \cdot 10^{-8}$
(90% CL)

($|{\rm qCEDM}|_{\rm HfF^+} < \ldots$)

CAREFUL!

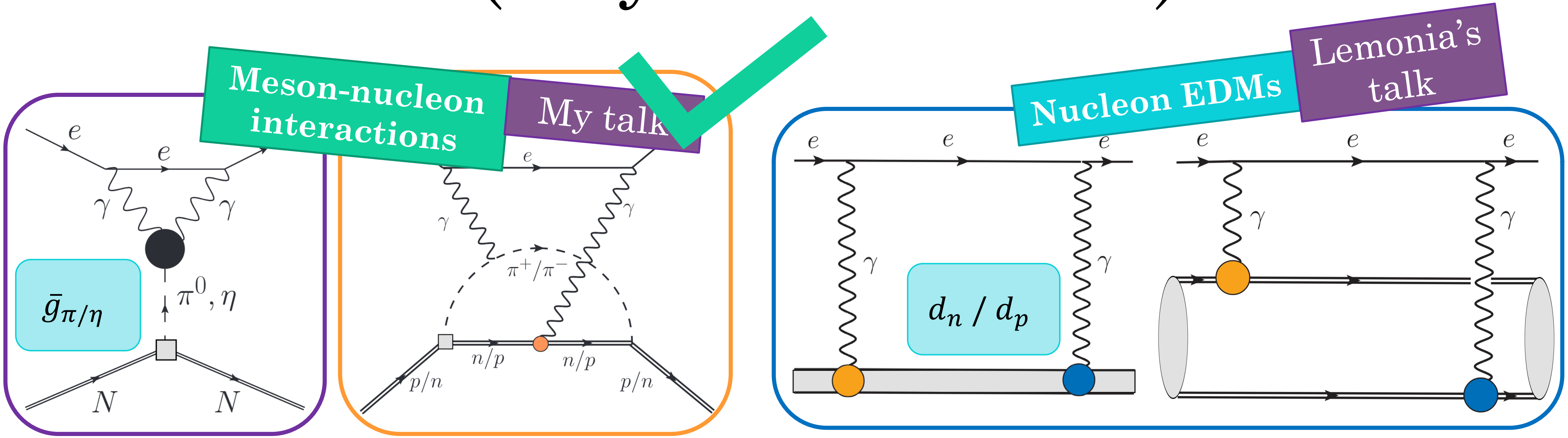
Outlook (long term)

Momentum dependence



- ME amplitude depends on momentum transfer q: $\frac{q^2}{m_e^2} \to 0$?
- Longer-range CP-odd e-N potential

Outlook (very short term ☺)



Thank you for listening!
Any questions?