THE THEORY OF ELECTRIC DIPOLE MOMENTS: THE VIEW FROM BELOW

Jordy de Vries

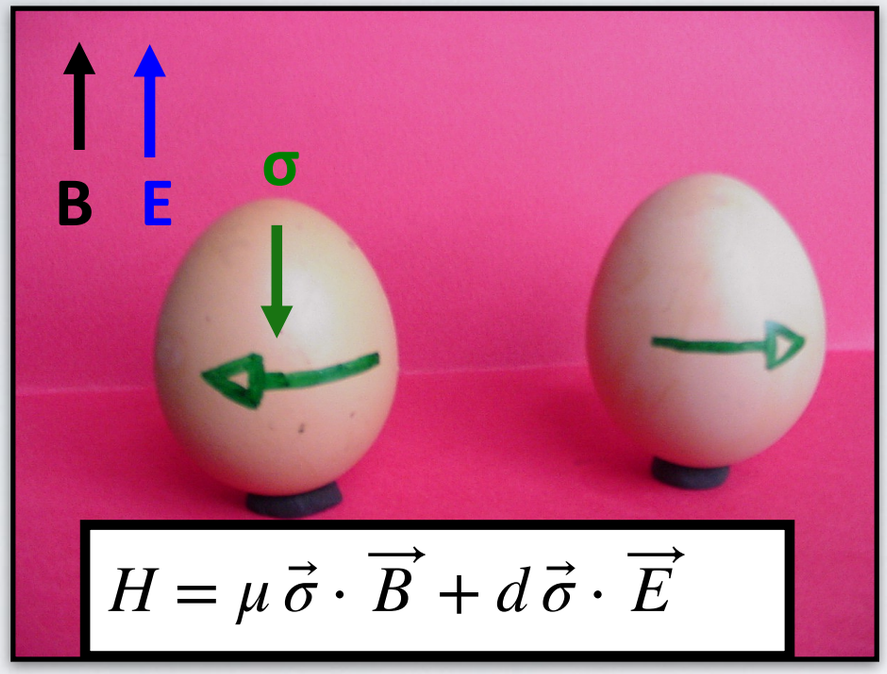
University of Amsterdam & Nikhef



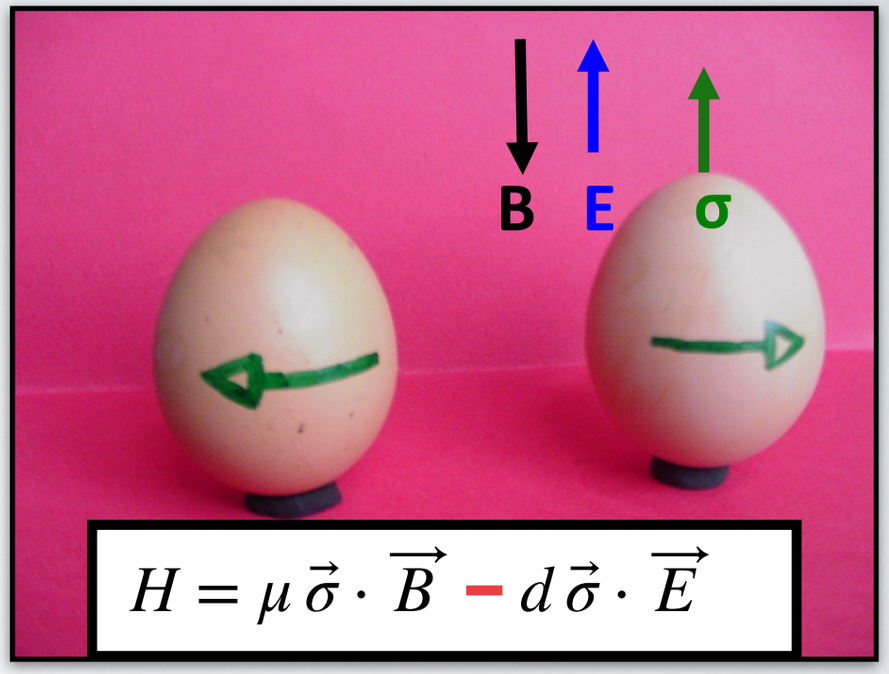
Funded by the European Union

European Research Council
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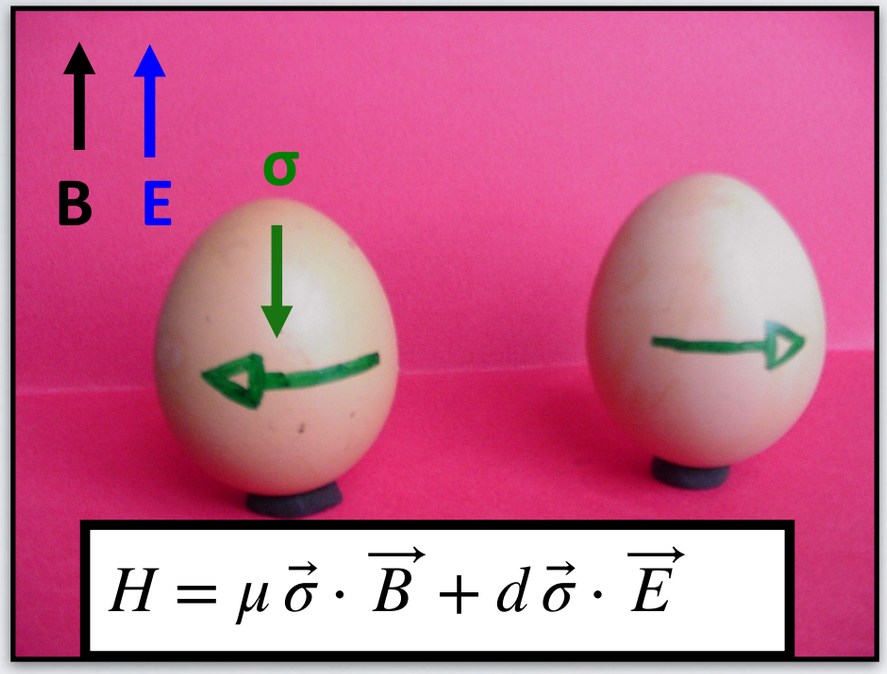
Electric dipole moments 101



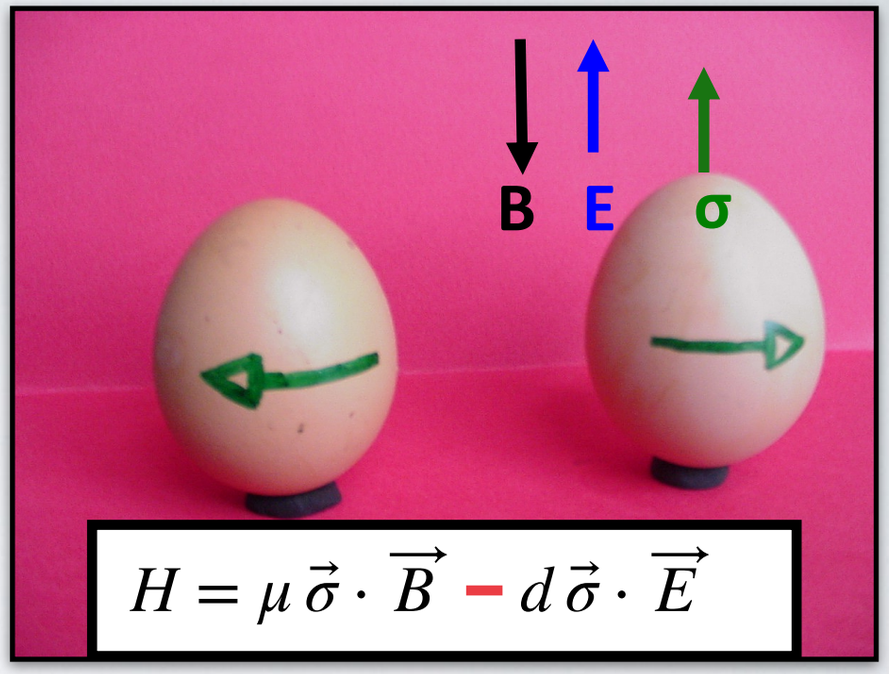
T/CP
transformation



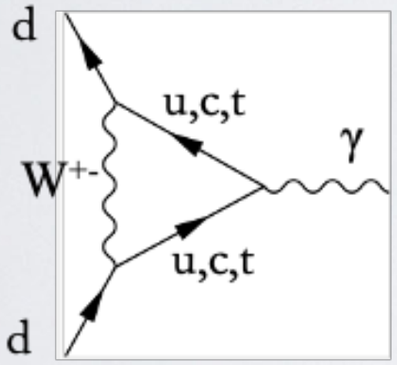
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T/CP transformation

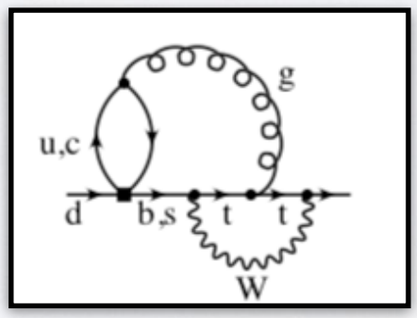


- EDMs can be induced by CP violation in the weak interaction (CKM phase) Czarnecki/Krause '97



Quark EDMs vanish at 1 and 2 loops

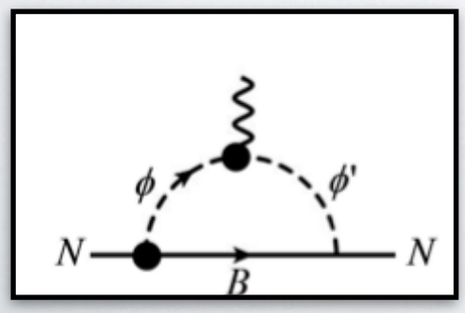
$$d_d \sim Im\left[V_{qd} V_{qd}^*\right] = 0$$



$$d_d \simeq m_d \frac{m_c^2 \alpha_s G_F^2}{108\pi^5} \mathcal{J}_{CP}$$

$$d_q \sim 10^{-34}\, e\,\mathrm{cm}$$

- Somewhat larger effects from long-distance mesonic loops

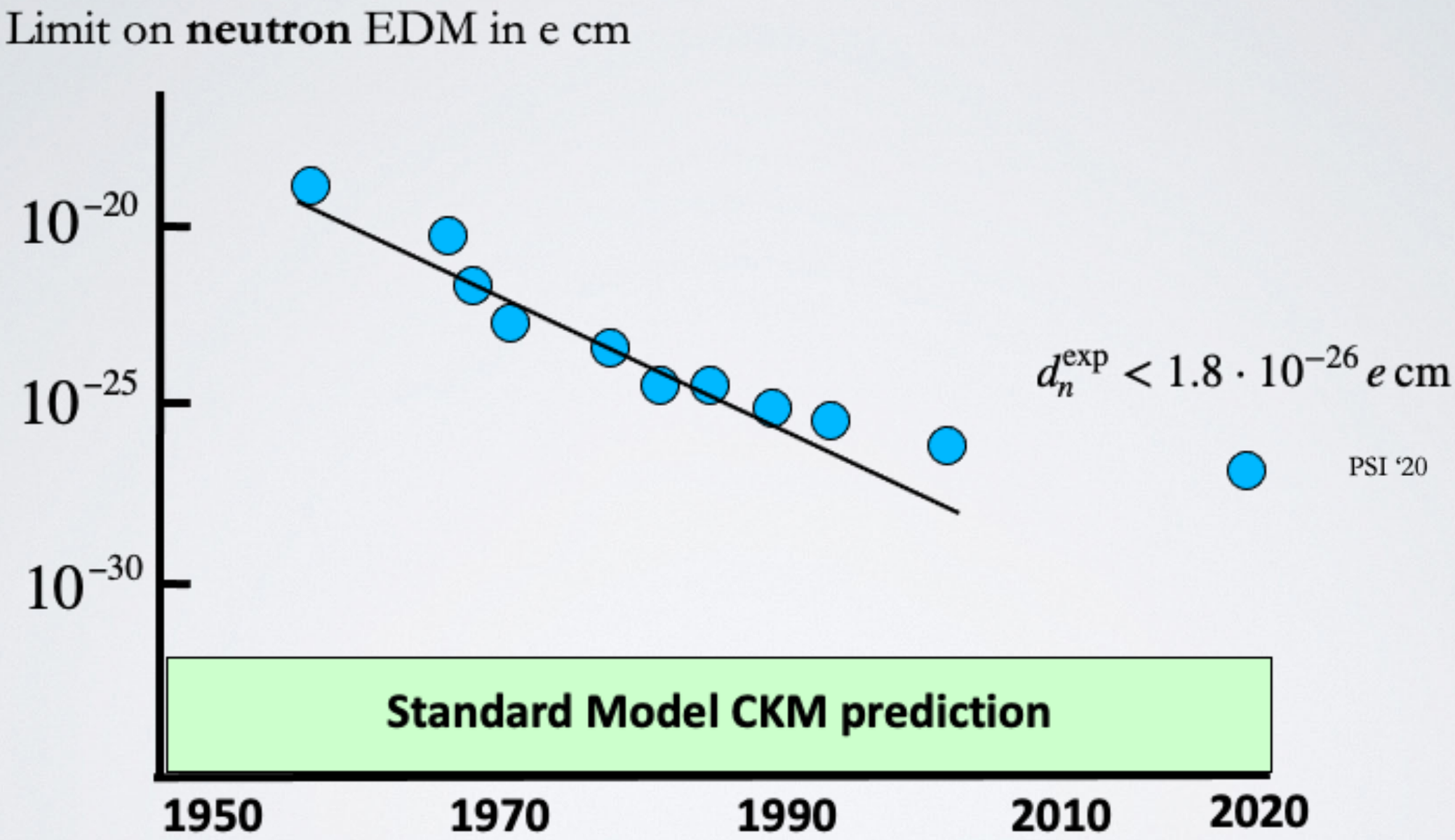


Khriplovich-Zhitnitsky ('82), Seng ('14)

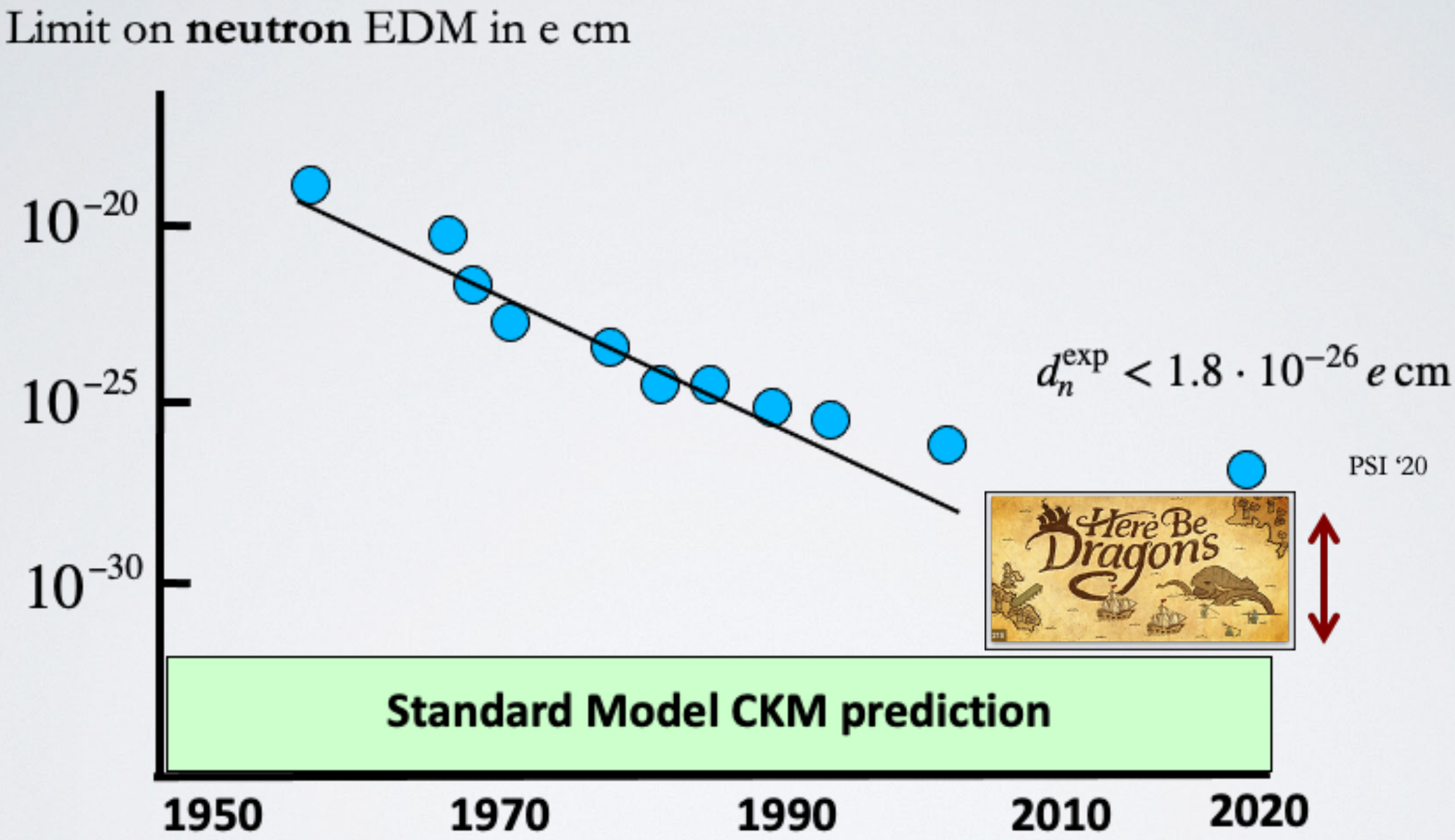
$$d_n \sim \left(10^{-31} - 10^{-32}\right) e\,\mathrm{cm}$$

With order-of-magnitude uncertainty

Electric dipole moments 101



Electric dipole moments 101



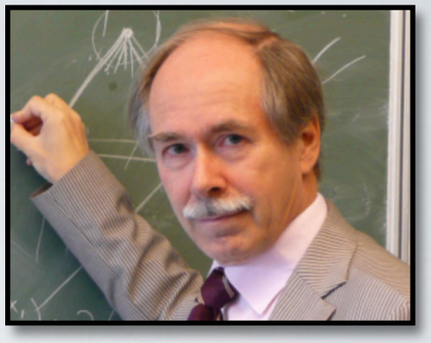
Strong dragons

- Gauge + Lorentz symmetries allow for a term

$$\varepsilon^{\alpha\beta\mu\nu} G_{\alpha\beta} G^{\mu\nu} = \partial_\mu \varepsilon^{\alpha\beta\mu\nu} (A_\nu F_{\alpha\beta} + A_\alpha A_\beta A_\nu)$$

- Total derivative and not relevant for QED but relevant for QCD (instantons)

- Standard Model parameter: theta-angle $\theta \varepsilon^{\mu\nu\alpha\beta} G_{\mu\nu} G_{\alpha\beta}$



't Hooft '76, '78

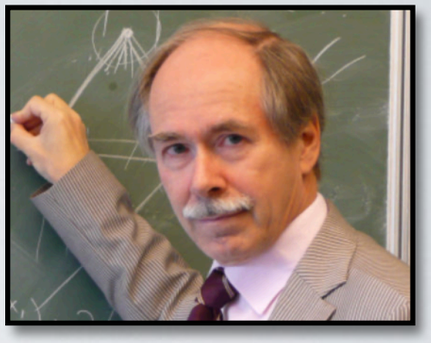
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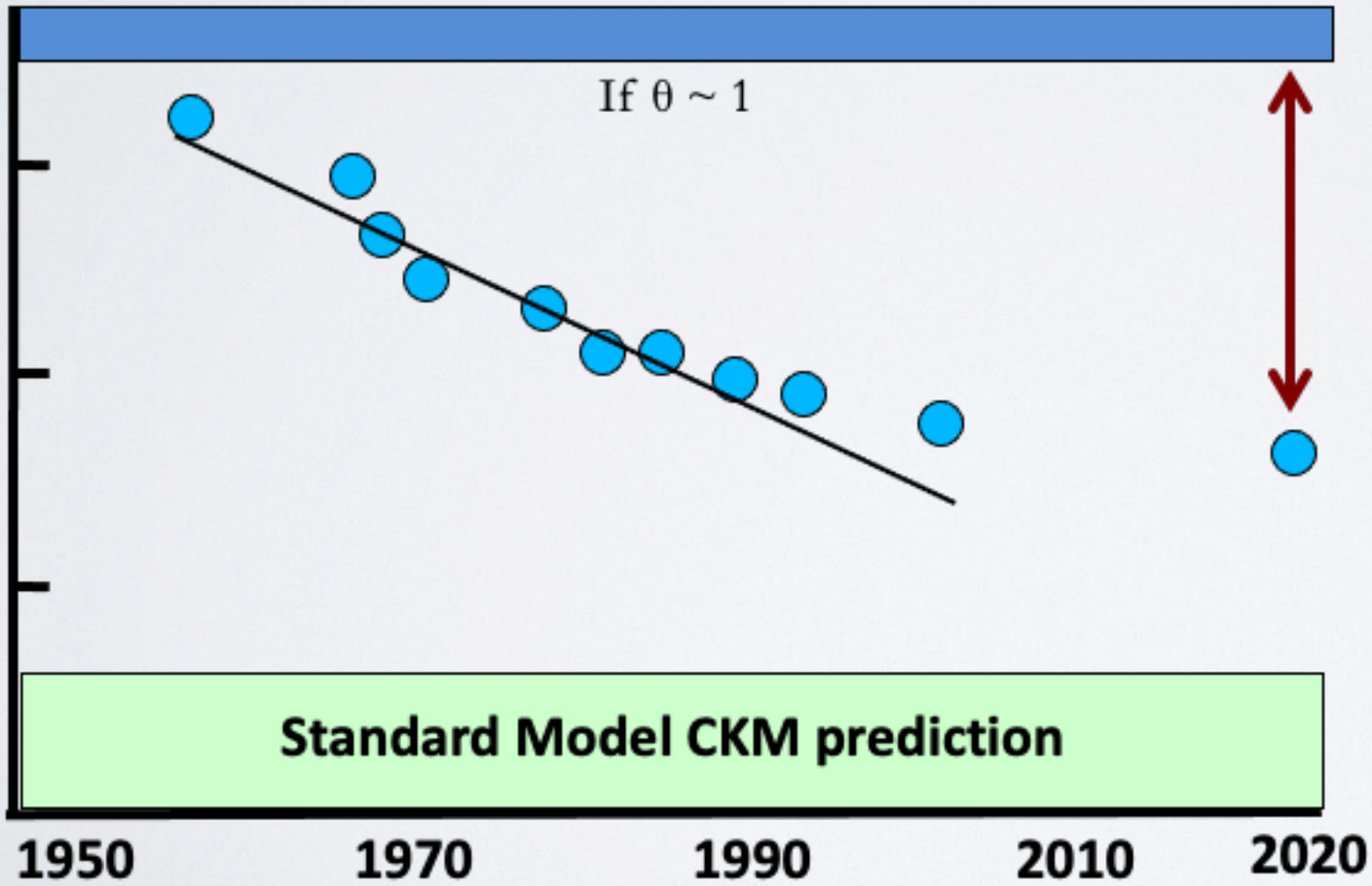
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This gap is 'the strong CP problem'

$\theta < 0.0000000001$

Driven by EDM experiments

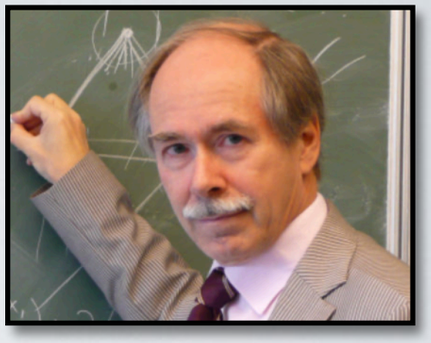
Main motivation for **axions**

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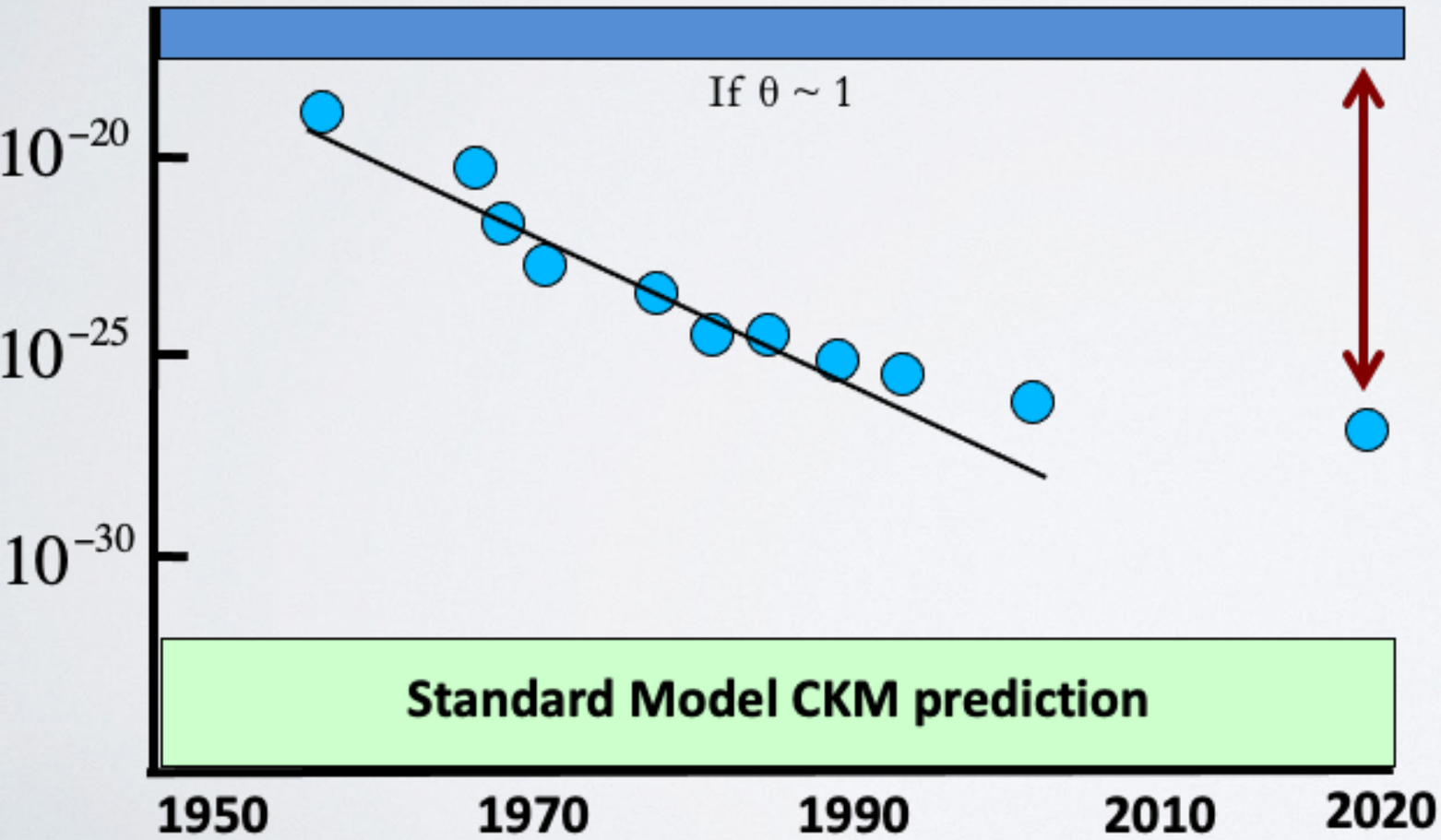
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See talk by Carlos tomorrow about recent concerns…



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Driven by EDM experiments

Main motivation for **axions**



Traditional Division of Labor

Two classes of EDM experiments

'Paramagnetic' EDMs

Systems with non-zero electron spin

'Diamagnetic' EDMs

Systems with non-zero nucleon/nuclear spin

Traditional Division of Labor

Two classes of EDM experiments

‘Paramagnetic’ EDMs

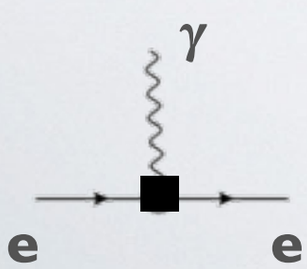
Systems with non-zero electron spin

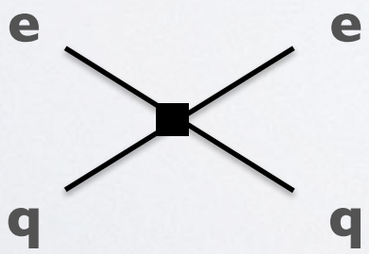
Free electron (no experiments)
Paramagnetic atoms (225TI …)
Polar molecules (YbF, ThO, HfF, BaF)

‘Diamagnetic’ EDMs

Systems with non-zero nucleon/nuclear spin

Interpreted in terms of **electron EDM**
and semi-leptonic four-fermion interactions





Traditional Division of Labor

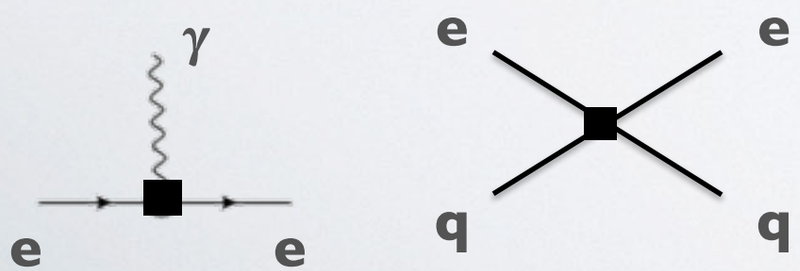
Two classes of EDM experiments

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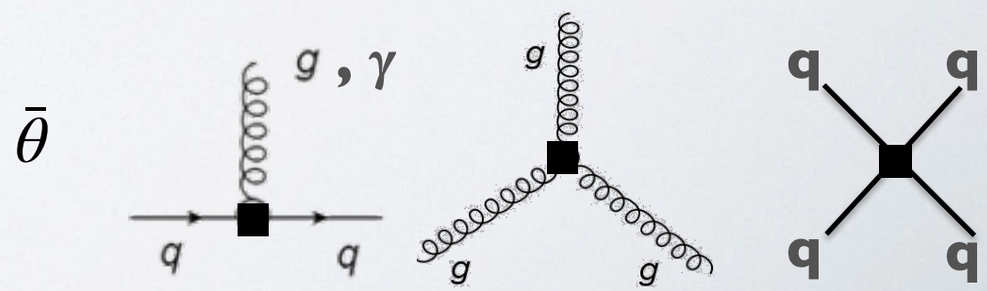


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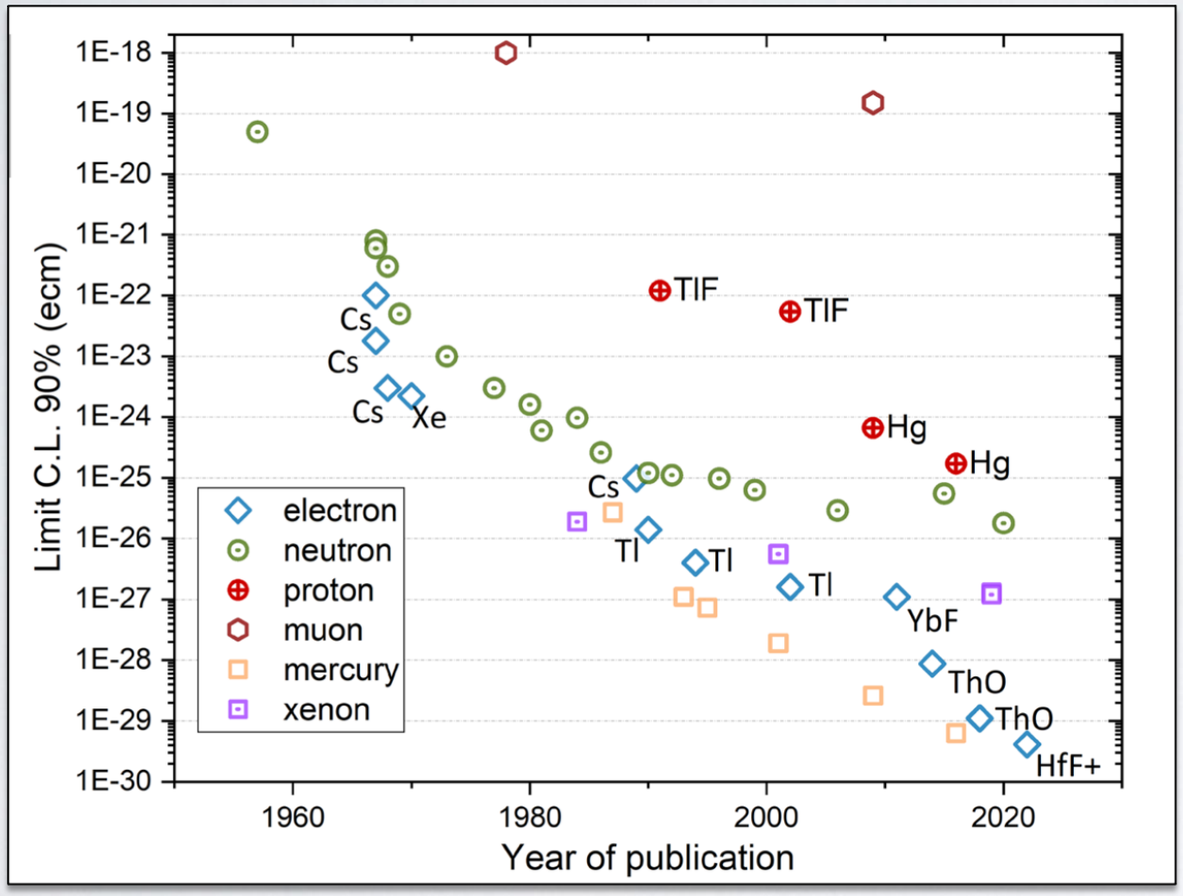
Free neutrons
Nuclear ions (storage rings, no experiments)
Diamagnetic atoms (128Xe, 199Hg, 225Ra)
Radioactive molecules (RaF, RaOH)

Interpreted in terms of **hadronic CP-violation** (Theta term, higher-dimensional operators)

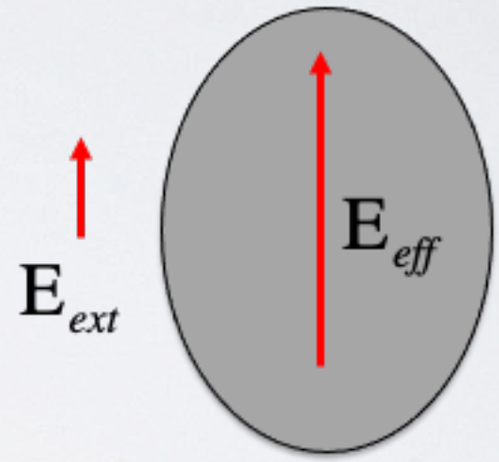


Molecular revolution

- **Last decade: huge progress on EDM measurements with molecules**
- Much less progress on neutron or diamagnetic systems (nuclear/hadronic CPV)



Polar molecules: huge EDM enhancement



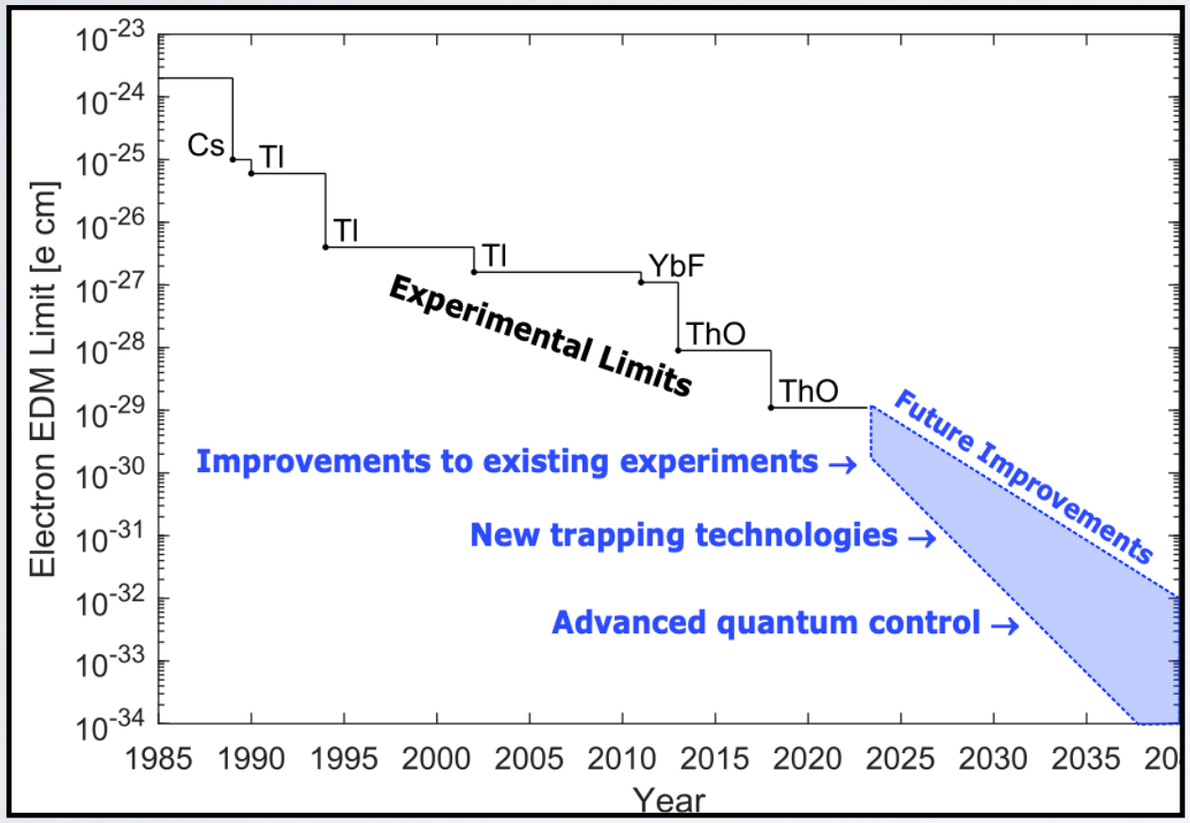
$$d_{ThO} \sim 10^6 \, d_e$$

$$d_e < 4.1 \cdot 10^{-30} \, e \, cm$$

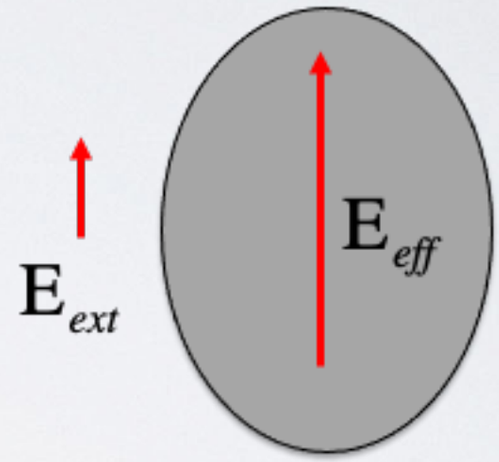
- Limit on eEDM is **10.000x stronger** than neutron EDM limit (**used to be 10-100x**)

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- Right now limit on eEDM is 10.000x stronger than neutron EDM limit (used to be 10-100x)
- **And the future is bright.** What does this imply for the field ?
- In view of time: take theta term as example but story similar for dimension-six operators with quarks/gluons (chromo-EDM, Weinberg, 4q)

Traditional limit on theta term

- **Traditional bounds from neutron EDM**
- First calculation Crewther et al '79, essentially leading-order chiral perturbation theory

$$\mathscr{L}_{QCD} = \mathscr{L}_{kin} - \bar{m}\bar{q}q - \varepsilon\bar{m}\bar{q}\tau^3 q \qquad +m_\star\bar{\theta}\bar{q}i\gamma^5 q$$

$$q = (u\ d)^T$$

$$m_\star = \frac{m_u m_d}{m_u + m_d}$$

$$\bar{m} = (m_u + m_d)/2$$

$$\varepsilon\bar{m} = (m_d - m_u)/2$$

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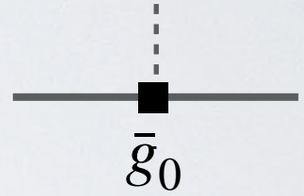
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Nucleon mass splitting (strong part, no EM)

CP-odd pion-nucleon coupling

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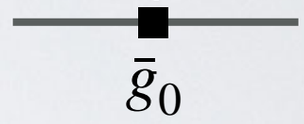
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Nucleon mass splitting (strong part, no EM) ⟷ **CP-odd pion-nucleon coupling**

$$\bar{g}_0 = -\frac{\delta m_N}{2f_\pi}\frac{1-\varepsilon^2}{2\varepsilon}\,\bar{\theta} \quad = (15.5 \pm 2.5)\cdot 10^{-3}\,\bar{\theta}$$

from lattice-QCD

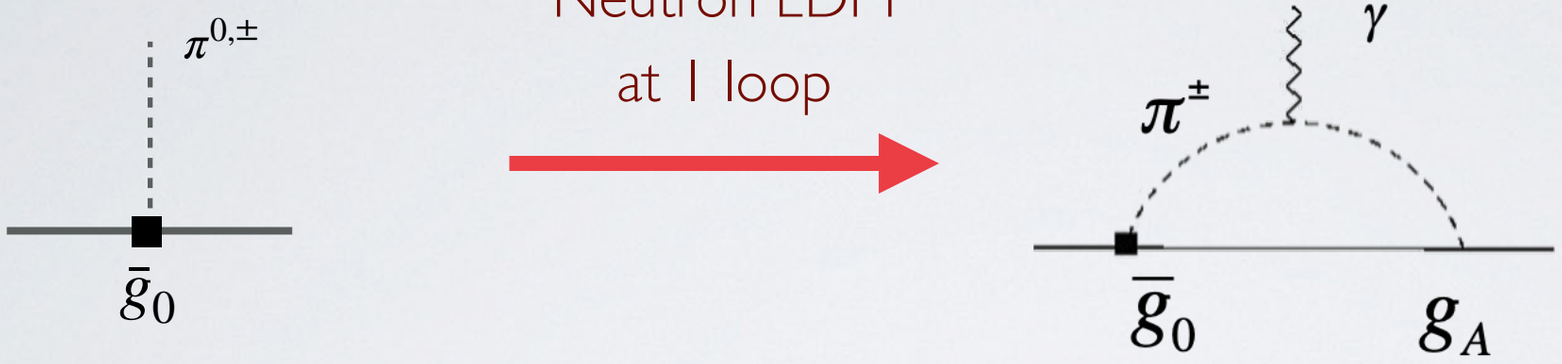
e.g. Borsanyi et al '14

Relation valid up to N^{2}LO corrections

JdV et al '15

Traditional limit on theta term

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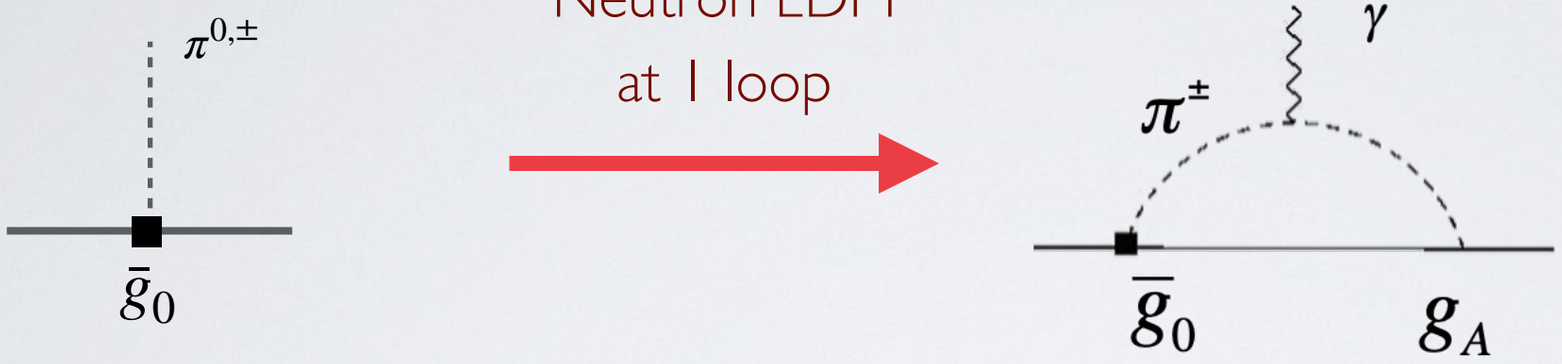
$$d_n = \bar{d}_n(\mu = m_N) - \frac{e g_A \bar{g}_0}{4\pi^2 F_\pi}\left(\ln\frac{m_\pi^2}{m_N^2} - \frac{\pi m_\pi}{2m_N}\right)$$

Note: loop is divergent. Short-distance piece not calculable with ChpT

- The loop part gives $d_n \simeq -2.5 \cdot 10^{-16} e\,\mathrm{cm}$ → $\bar{\theta} < 10^{-10}$

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- Lattice QCD for a full calculation. First non-zero calculations in recent years (still very uncertain)

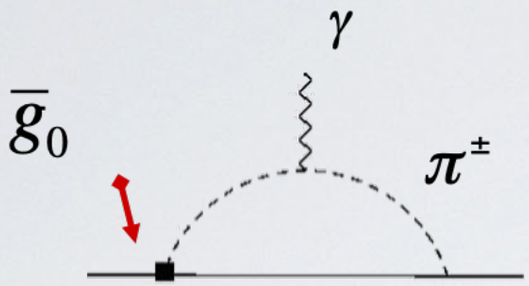
$$d_n = -(1.5 \pm 0.8) \cdot 10^{-16} e\,\mathrm{cm}$$ Shindler, JdV, et al '19

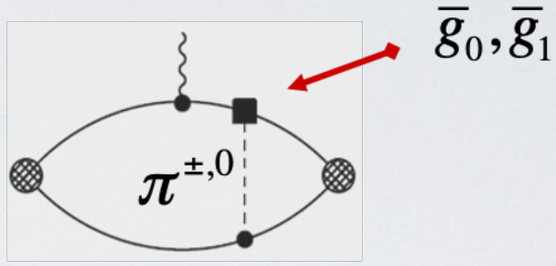
$$d_n = -(1.4 \pm 0.4) \cdot 10^{-16} e\,\mathrm{cm}$$ Liang et al '23

Seems sensible but large pion masses and results are not reproduced in '21 LANL lattice calculation. More work is needed.

Review Keh-Fei Liu '24

Nuclear EDMs





- Nuclear CP violation can be larger than nucleon CP violation ! No chiral loop suppression !
- EDMs of light nuclei can be calculated with chiral EFT methods

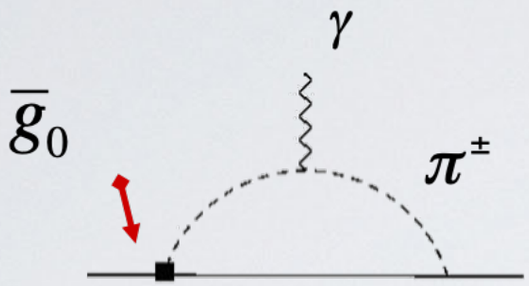
JdV et al '11, Bsaisou et al '15

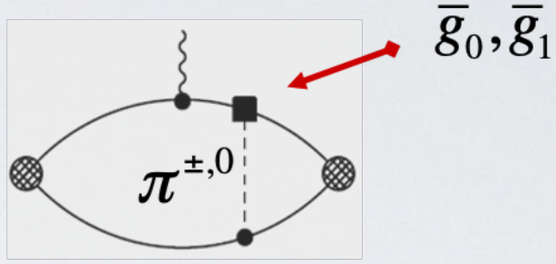
Froese, Navratil '21 extension up to 19F

- Example deuteron EDM:

$$d_D = (d_n + d_p) + \frac{e g_A \bar{g}_1 m_N}{12\pi m_\pi F_\pi} \frac{1 + \gamma/m_\pi}{(1 + 2\gamma/m_\pi)^2} \simeq d_n + d_p + (0.23\,\bar{g}_1)\, e\,\mathrm{fm}$$

Nuclear EDMs





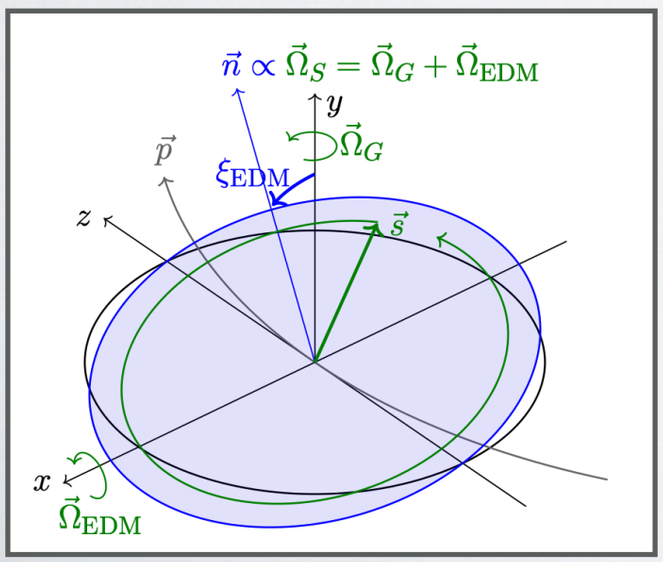
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- First limit: $d_D < 10^{-17}\, e\,\mathrm{cm}$ JEDI collaboration '26
- This gives a limit $\bar{\theta} < 10^{-2}$ JdV et al '11, Bsaisou et al '15
- Not competitive (*yet*?)

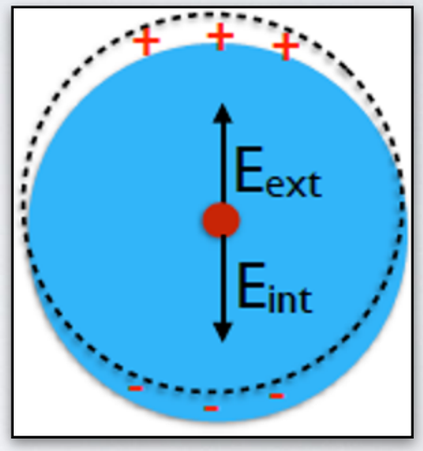
Diamagnetic atoms

- There is a very strong limit on the 199Hg atom $d_{199Hg} < 6 \cdot 10^{-30}\, e\,\mathrm{cm}$
- But we have to account for **Schiff screening**

Schiff Theorem: EDMs of charged constituents are screened in a neutral atom

Schiff' 63

- Theorem is exact for electrostatic forces, non-relativistic point particles

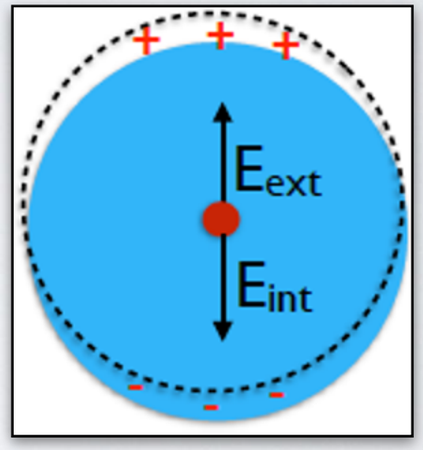


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- Theorem is exact for electrostatic forces, non-relativistic point particles
- For large diamagnetic systems: correction mainly from **nuclear finite size**
- Atomic EDM sensitive to nuclear dipole radius (**=Schiff moment**)

$$\frac{d_{atom}}{d_{nucleus}} \sim Z^2 \left(\frac{R_N}{R_A}\right)^2 \sim 10^{-4}$$

Schiff' 63

- Atomic screening is well understood but challenge is to compute the nuclear Schiff moment

Diamagnetic atoms

- Similar computation needed for diamagnetic atoms. For instance Hg

Engel et al' 13

$$d_{\rm Hg} = -(2.1 \pm 0.5) \cdot 10^{-4} \left[(1.9 \pm 0.1) d_n + (0.20 \pm 0.06) d_p + \left(0.13^{+0.5}_{-0.07}\, \bar{g}_0 + 0.25^{+0.89}_{-0.63}\, \bar{g}_1 \right) e\,\mathrm{fm} \right]$$

- **Large uncertainties for nuclear part.**

Speak, Auerbach '95
Sushkov, Flambaum '80

- Using **central values**: similar limits on theta as neutron EDM

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Sushkov, Flambaum '80

- Using **central values**: similar limits on theta as neutron EDM

- Systems exist that are more sensitive due to 'octopole deformation' (close-lying P-state)

$$d_{\rm Ra} = (-7.7 \pm 0.8) \cdot 10^{-4} \cdot [(-2.5 \pm 7.6)\ \bar{g}_0 + (63 \pm 38)\ \bar{g}_1]\, e\,\mathrm{fm}$$

Dobaczewski et al PRL '18

- But experiments with 225Ra are hard (radioactive) and not yet competitive

Bishof et al '16

- Push towards measurements with radium molecules such as RaOH (Nick Hutzler @ Calltech)

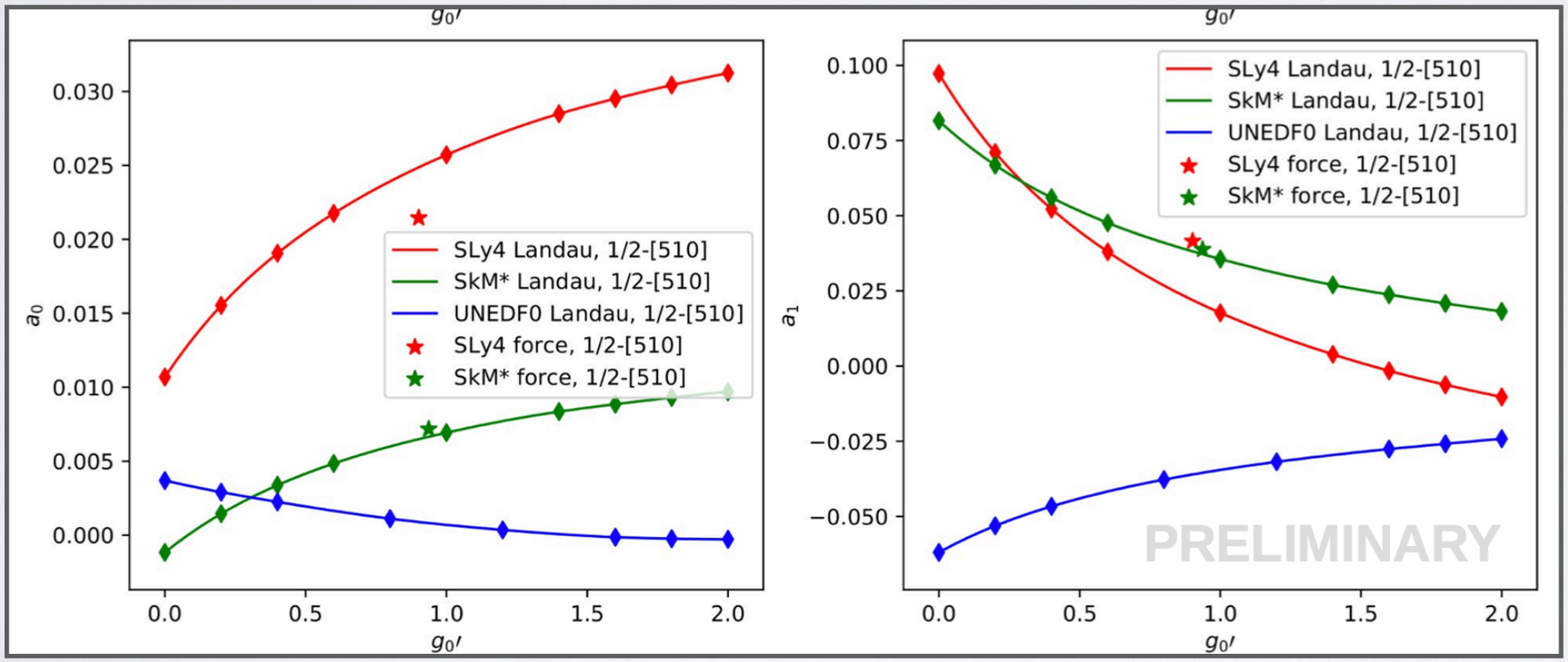
Diamagnetic atoms

- Similar computation needed for diamagnetic atoms. For instance Hg

Engel et al' 13

$$d_{\rm Hg} = -(2.1 \pm 0.5) \cdot 10^{-4} \left[(1.9 \pm 0.1) d_n + (0.20 \pm 0.06) d_p + \left(0.13^{+0.5}_{-0.07}\, \bar{g}_0 + 0.25^{+0.89}_{-0.63}\, \bar{g}_1 \right) e\,\mathrm{fm} \right]$$

- Not a lot of progress in recent years on better calculations —> very important



Talk by Markus Kortelainen at ECT* '24

- **Is this a nuclear many-body problem or a more conceptual problem ?**
  (I have some thoughts but no time now ;))

Theta limit from paramagnetic systems ?

- Seems not relevant. Theta can induce a small electron EDM at order α_{em}^2 Choi, Hoing '91

$$d_e \simeq 5 \cdot 10^{-27}\, \bar{\theta}\, e\,\mathrm{cm} \longrightarrow \bar{\theta} < 10^{-3}$$

- But we are not measuring bare electrons! **Look at electron-nucleus CP-odd interactions**



Flambaum, Pospelov, Ritz, Stadnik, '19

Mulder, Timmermans, JdV '25

Dekens, JdV, Gialidi, Menendez, Mulder, Romeo '25

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Flambaum, Pospelov, Ritz, Stadnik, '19

Mulder, Timmermans, JdV '25

Dekens, JdV, Gialidi, Menendez, Mulder, Romeo '25

- Easiest example: a short-distance electron-nucleon interactions $C_S\, \bar{N} N\, \bar{e} i\gamma^5 e$ $N = (p\ n)^T$
- Measurements with polar molecules aim to detect a level splitting induced by external E field

Measured in experiments ← $\omega_{HfF} = (r_e\, d_e + r_C\, C_S)$

Molecular matrix elements.

Computed with molecular many-body approaches

Meyer, Bohn '08

Dzuba, Flambaum '09

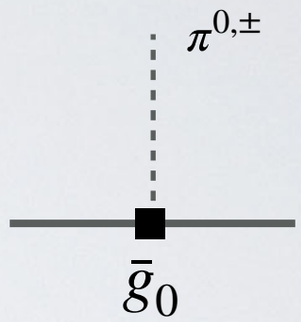
Fleig, Jung '18

Haase et al '21

Induce Cs from hadronic CP violation

- Easiest example: a short-distance electron-nucleon interactions $C_S\,\bar{N}N\,\bar{e}i\gamma^5 e \qquad N = (p\,n)^T$

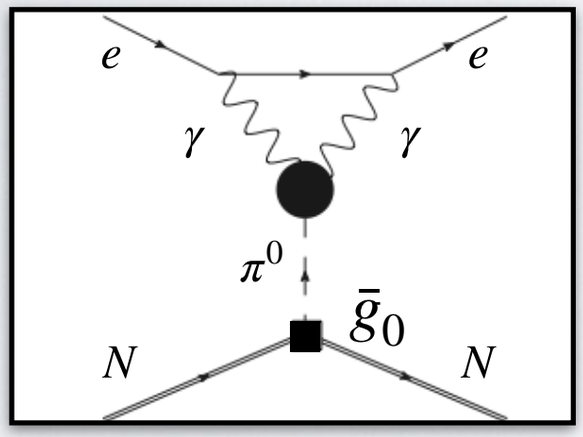
- How can we induce this from the QCD theta term?



Induce Cs from hadronic CP violation

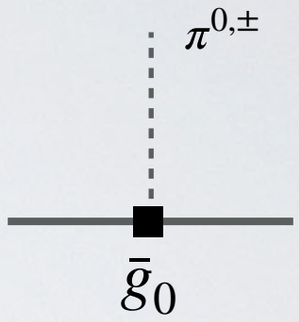
- Easiest example: a short-distance electron-nucleon interactions $C_S\,\bar{N}N\,\bar{e}i\gamma^5 e \qquad N=(p\,n)^T$

- How can we induce this from the QCD theta term?



Flambaum, Pospelov, Ritz, Stadnik, '19

Mulder, Timmermans, JdV '25



- Use the pion/eta anomaly $\dfrac{\alpha}{4\pi F_\pi}(F\tilde{F})\pi^0 \qquad F\tilde{F}\sim \vec{E}\cdot\vec{B}$

$$C_S(\mathrm{LO}) = \mp\frac{3\alpha^2 m_e}{4\pi^2 F_\pi m_\pi^2}\bar{g}_0\left(\log\frac{\mu^2}{m_e^2}+\chi_{\mathrm{short}}(\mu)\right)$$

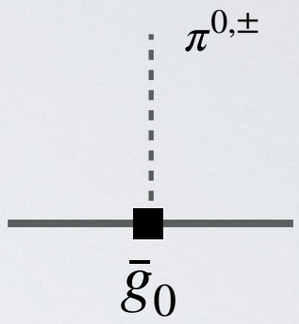
- Loop is again divergent. But renormalize from rare meson decay data

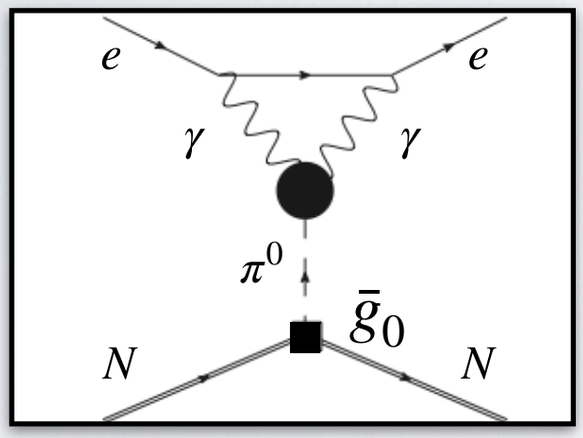
$\pi^0\to e^+e^-$ NA62, '24

Induce Cs from hadronic CP violation

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Flambaum, Pospelov, Ritz, Stadnik, '19

Mulder, Timmermans, JdV '25

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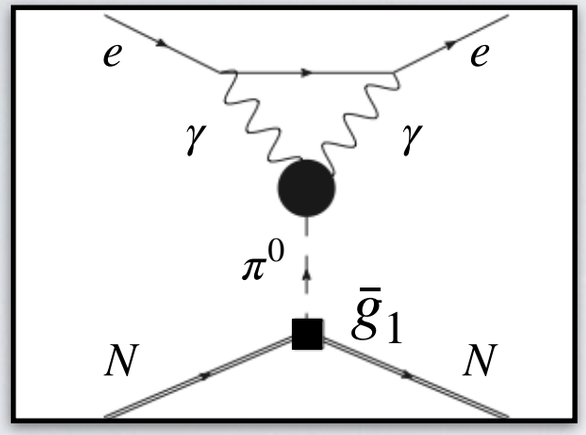
$$\pi^0\to e^+e^- \qquad \text{NA62, '24}$$

- Opposite sign from neutrons and protons. When summed over heavy nucleus:

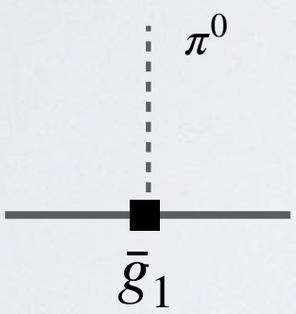
$$|(Z-N)/A|\simeq 0.2$$

Suppression….. We should include NLO.

Next-to-leading-order corrections

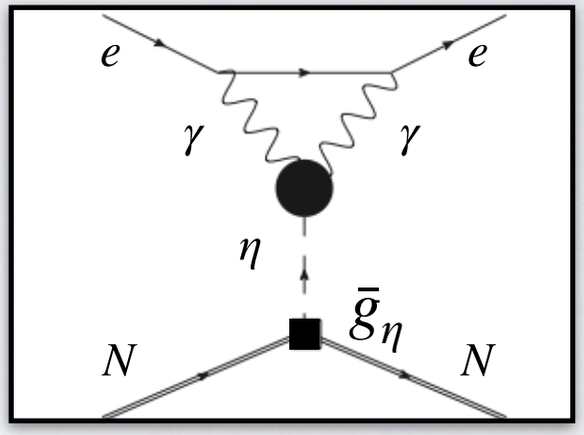


- Isospin-breaking correction

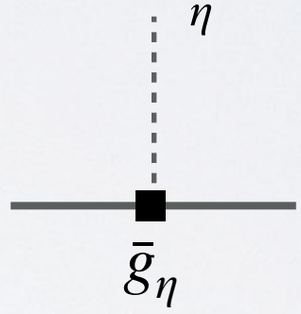


$+\bar{g}_1\,\pi^0\,\bar{N}N$

- Suppressed because theta conserves isospin
- Coherent in nucleus (Z+N) instead of (Z-N)



- Strangeness correction



$+\bar{g}_\eta\,\eta\,\bar{N}N$

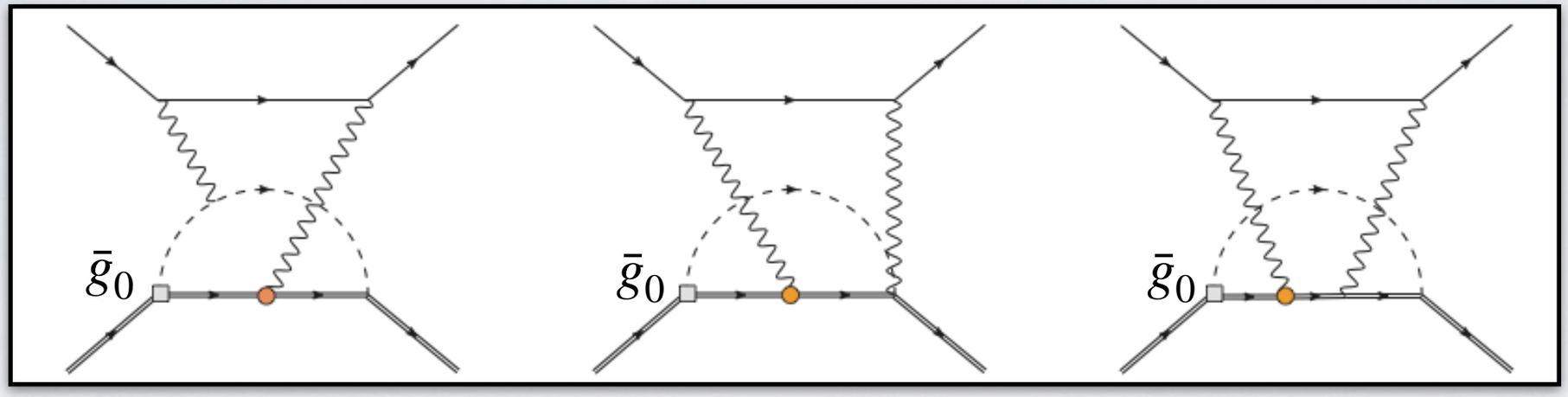
- Suppressed by m_π^2/m_η^2
- Coherent in nucleus

Next-to-leading-order corrections

- Two-loop pion-photon diagrams

Flambaum, Pospelov, Ritz, Stadnik, '19

Mulder, Timmermans, JdV '25



- Total **nucleus-averaged** contribution

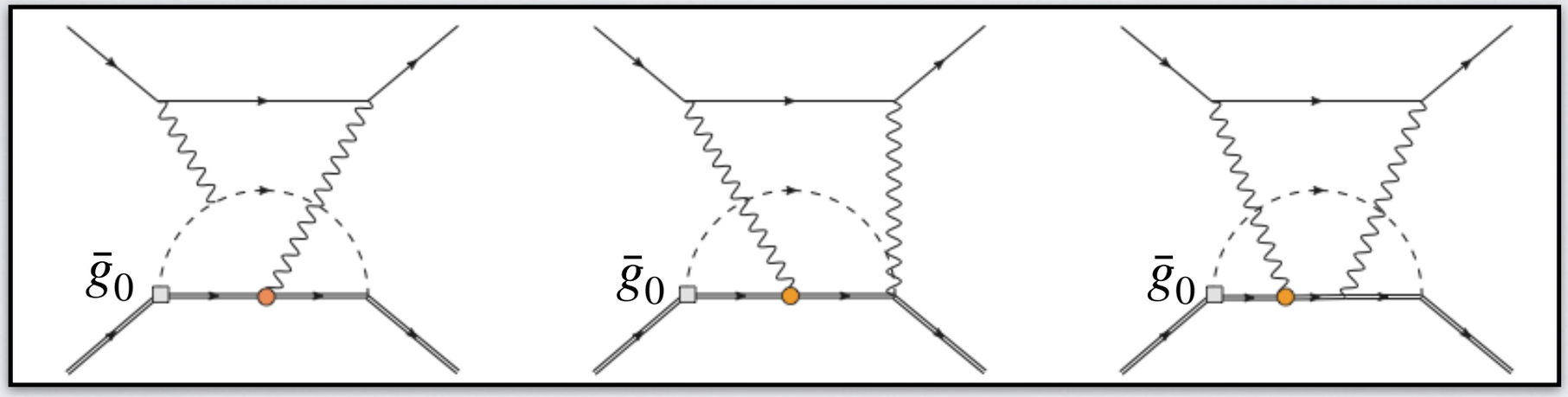
$$C_S(\bar{\theta}) = \underset{\bar{g}_0}{0.75[10]} - \underset{\bar{g}_\eta}{0.72[22]} + \underset{\bar{g}_1}{0.74[33]} + \underset{2-\text{loop}}{0.86[20]} \cdot 10^{-2}\,\bar{\theta} = (1.6 \pm 0.5) \cdot 10^{-2}\,\bar{\theta}$$

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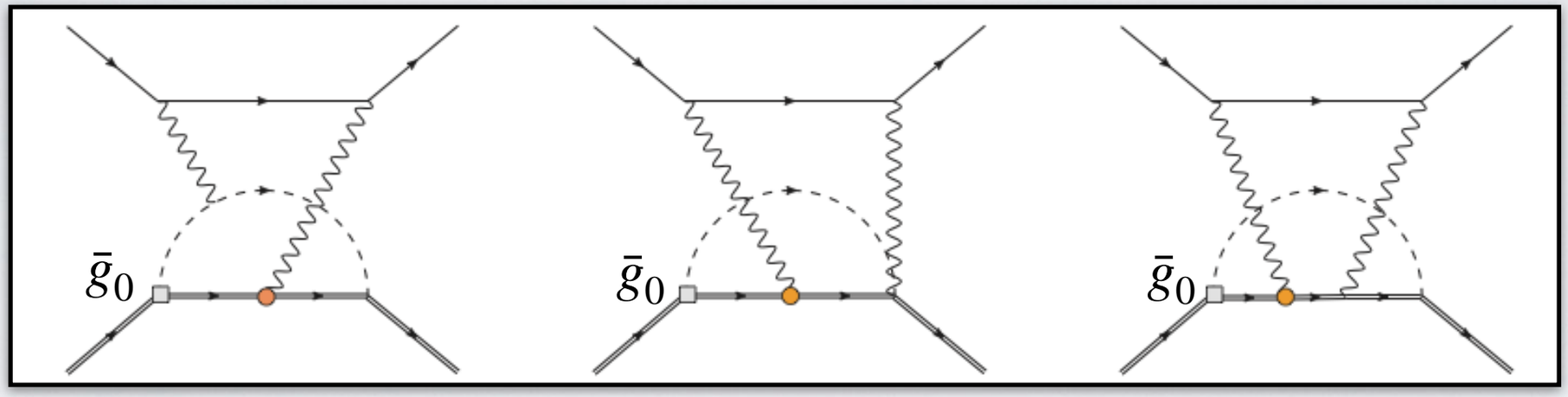
- **Strong CP problem from molecules** $|\bar{\theta}|_{HfF} < 1.5 \cdot 10^{-8}$
- **Limit is still 2 orders weaker than neutron EDM bound** $|\bar{\theta}|_n < 1.2 \cdot 10^{-10}$
- But this depends on lattice QCD….

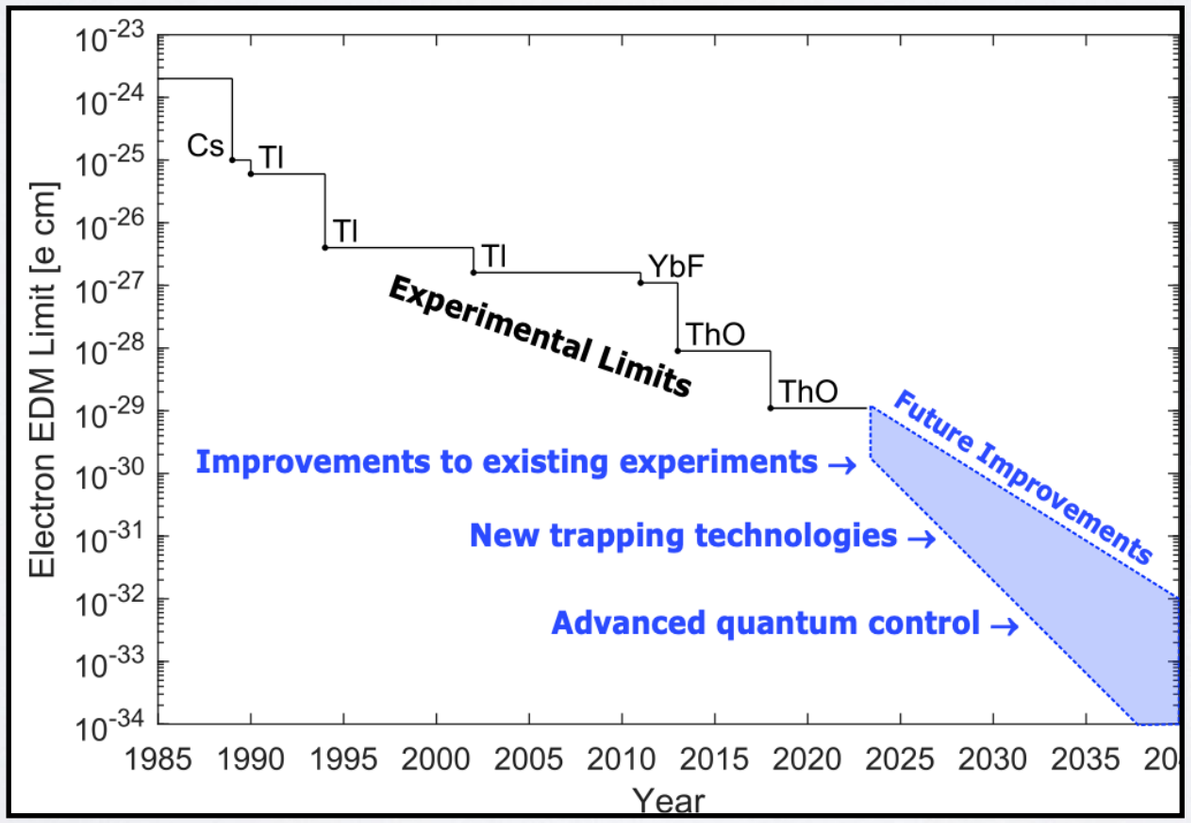
Next-to-leading-order corrections

- Two-loop pion-photon diagrams

Flambaum, Pospelov, Ritz, Stadnik, '19

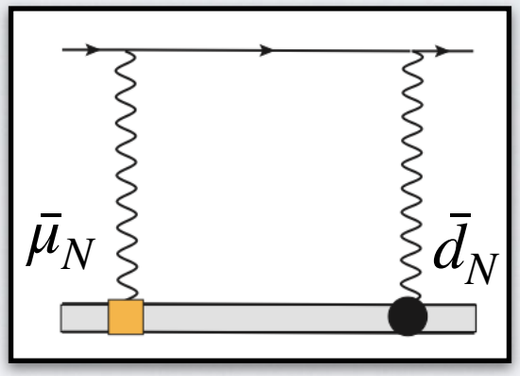
Mulder, Timmermans, JdV '25





What about nucleon EDMs ?

- Nucleon EDM ($\bar{d}_N$) induce **Cs** in combination with nucleon magnetic moments ($\bar{\mu}_N$)

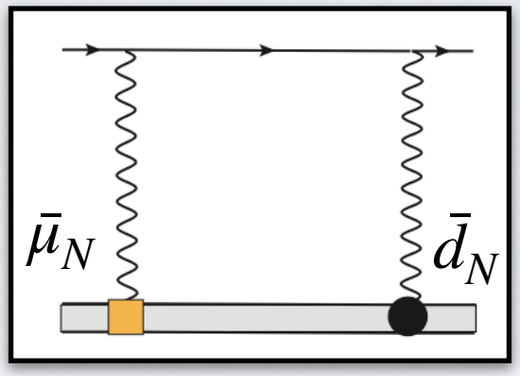


Dekens, JdV, Gialidi, Menendez, Mulder, Romeo PRL '26

- Loop-momentum is ***ultrasoft*** (no pion mass) and photons couple to entire nucleus
- Diagrams are sensitive to ***nuclear structure. Requires novel nuclear calculations***

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- Loop-momentum is ***ultrasoft*** (no pion mass) and photons couple to entire nucleus
- Diagrams are sensitive to ***nuclear structure. Requires novel nuclear calculations***
- **EFT** with ground-state nuclei, excited-state nuclei, electrons, and ultrasoft photons

$$\bar{C}_S = -\frac{4\alpha^2 m_e}{m_N}\sum_n \frac{A_n}{\Delta_n}\left(3\log\frac{m_e^2}{4\Delta_n{}^2} - 1\right)$$

$\Delta_n =$ Excitation energies (few MeV)

$A_n \sim \langle \Psi | d_N \vec{\sigma} | n \rangle \cdot \langle n | \mu_N \vec{\sigma} | \Psi \rangle$

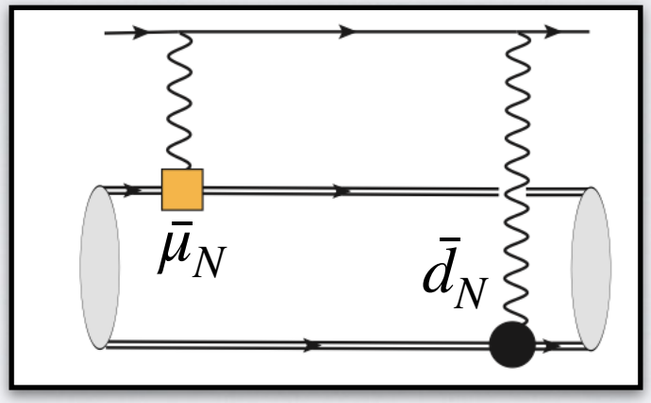
- Transitions and excitations computed with Nuclear Shell Model for **BaF** molecule

$$\bar{C}_S(\text{ultrasoft}) \sim 70\, d_p\, (e\,\text{fm})^{-1}$$

- Significant nuclear uncertainty ~ 40% because requires spectrum calculation

What about nucleon EDMs ?

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Flambaum, Pospelov, Ritz, Stadnik, '19

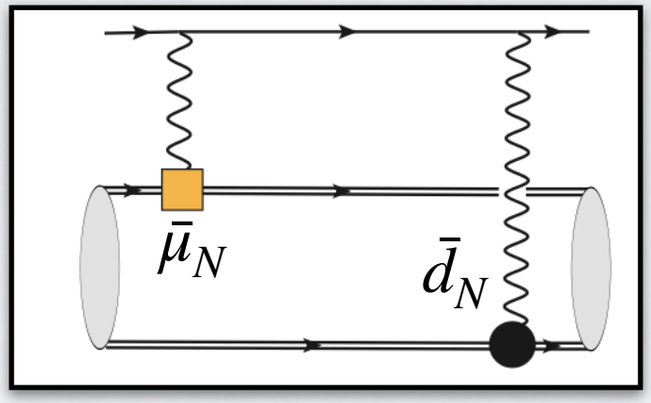
Dekens, JdV, Gialidi, Menendez, Mulder, Romeo PRL '26

- Two-nucleon contribution does sensitive to nuclear binding momentum **q** ~ 100 MeV
- Very similar to '***neutrinoless double beta decay (0vbb)***' nuclear matrix elements

$$\bar{C}_S(\text{potential}) = \langle \Psi \,|\, V_{2\gamma} \,|\, \Psi \rangle \qquad V_{2\gamma} = \frac{4e^4 m_e}{9 m_N} \sum_{i,j} \frac{\mu^{(i)} d^{(i)}}{\vec{q}^4} \vec{\sigma}^i \cdot \vec{\sigma}^j$$

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Flambaum, Pospelov, Ritz, Stadnik, '19

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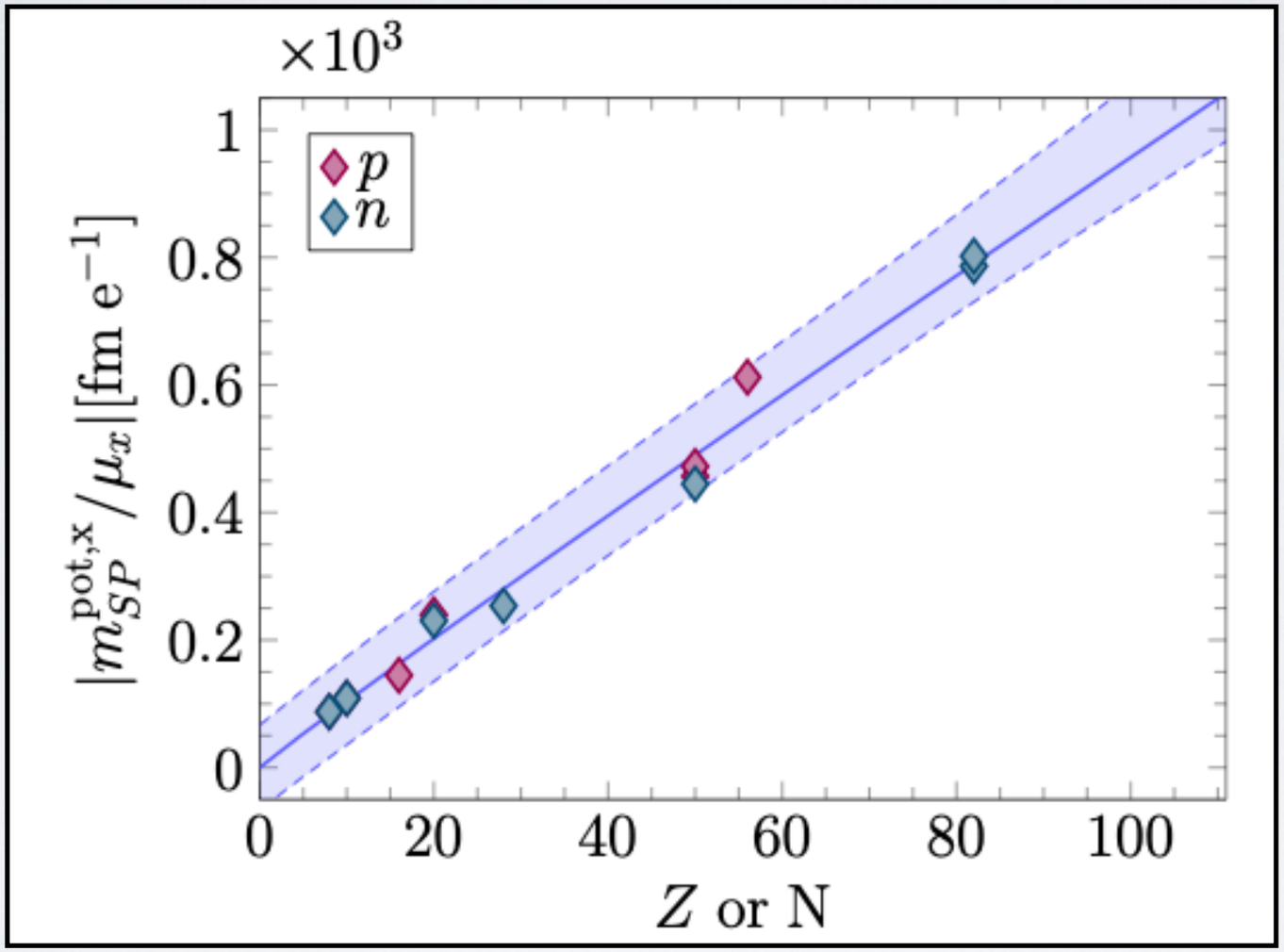
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- Shell Model codes for 0vbb modified for EDM purposes (Menendez + Romeo)

$$\bar{C}_S(\text{potential}) \sim \left(-430\, d_p + 390 d_n\right)\ (e\ \text{fm})^{-1}$$

- Larger than ultrasoft because nuclear matrix elements **scale with atomic number A**

What about nucleon EDMs ?



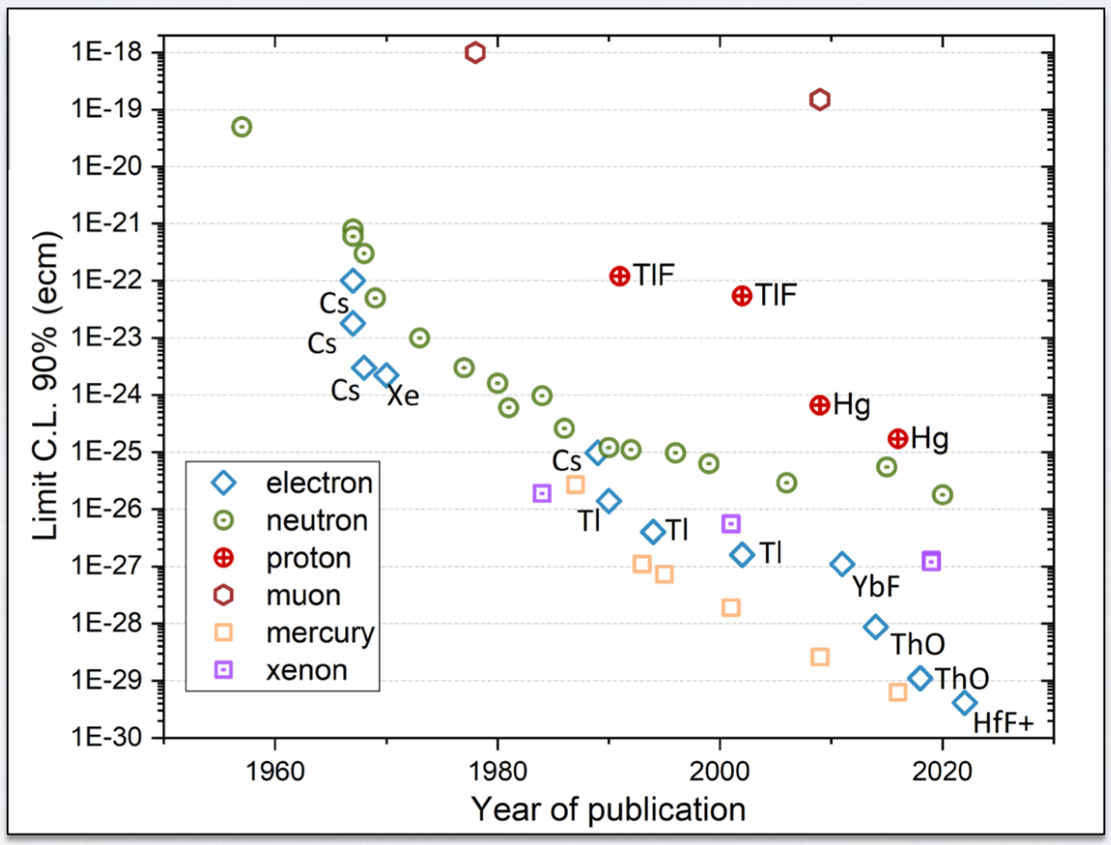
- **Linear scaling with A**

Limits on nucleon EDMs from molecules

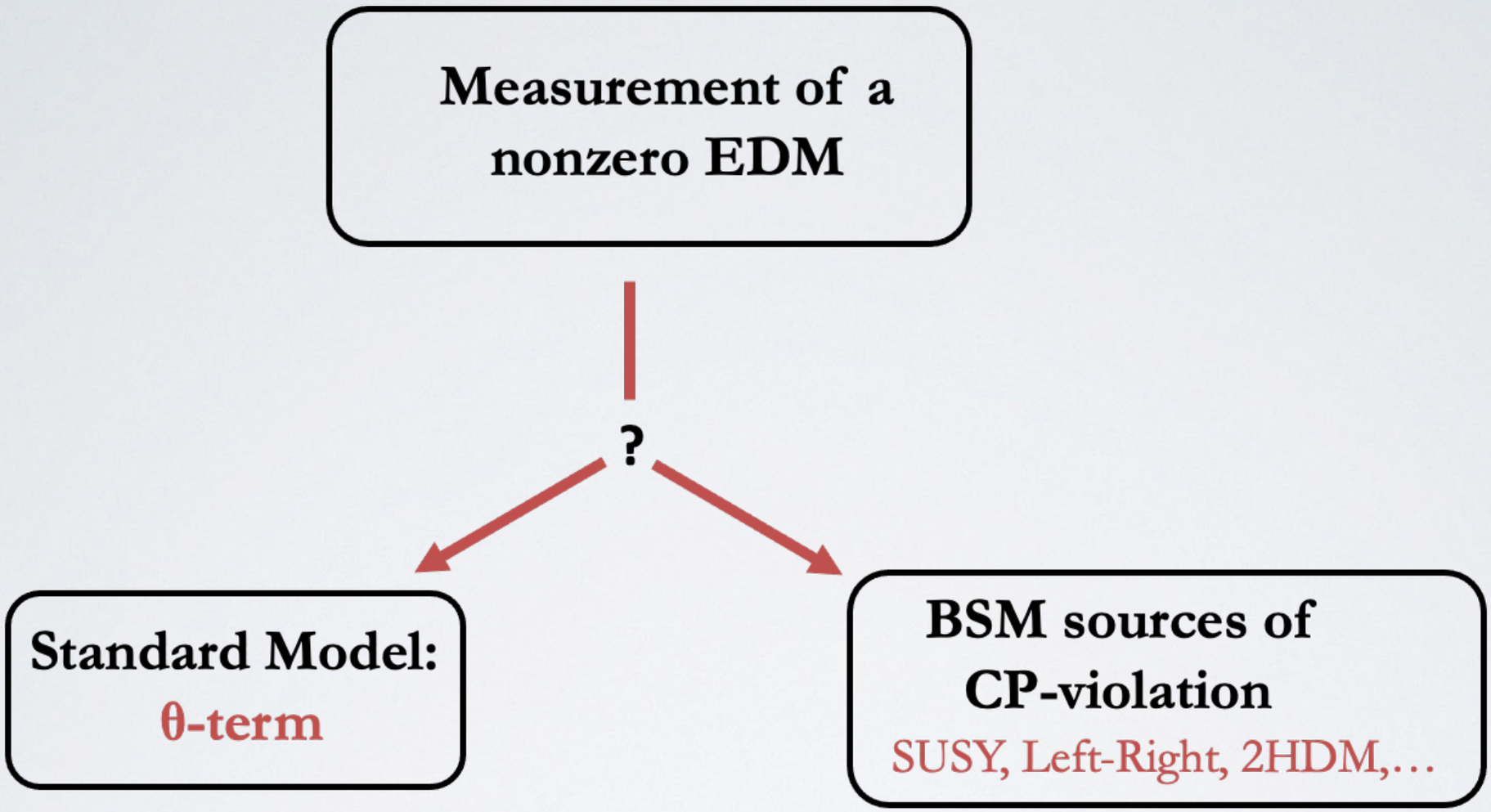
- We can now combine everything to read off limits on nucleon EDMs
- Best limits from ThO and HfF (require A-scaling argument)

$$|d_{n,p}|_{HfF} < 10^{-23}\, e\,\mathrm{cm}$$

- This is still 1000x weaker for neutron (direct) and 100x weaker for proton (from Hg)
- But…….



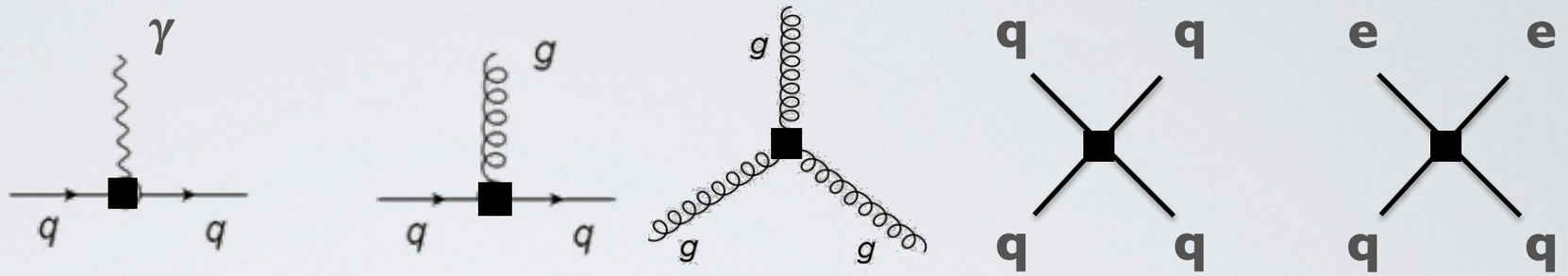
Pinpoint theta term at low energies



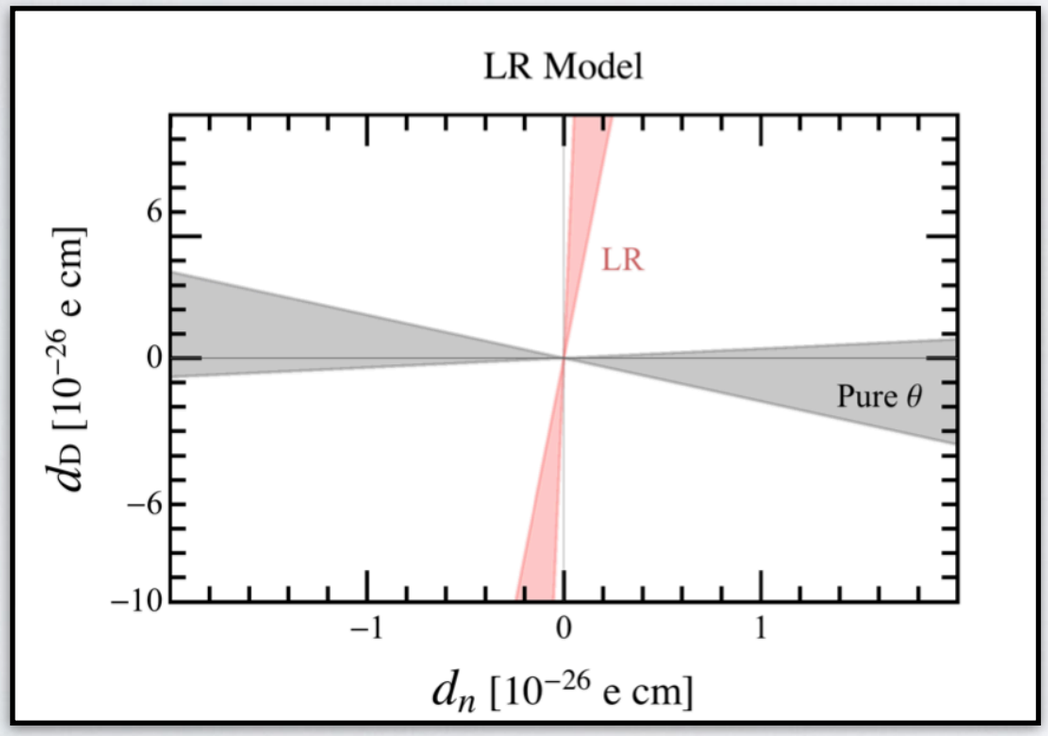
Theta term leads to unique pattern in nucleon-atomic-molecular EDMs

Pinpoint theta term at low energies

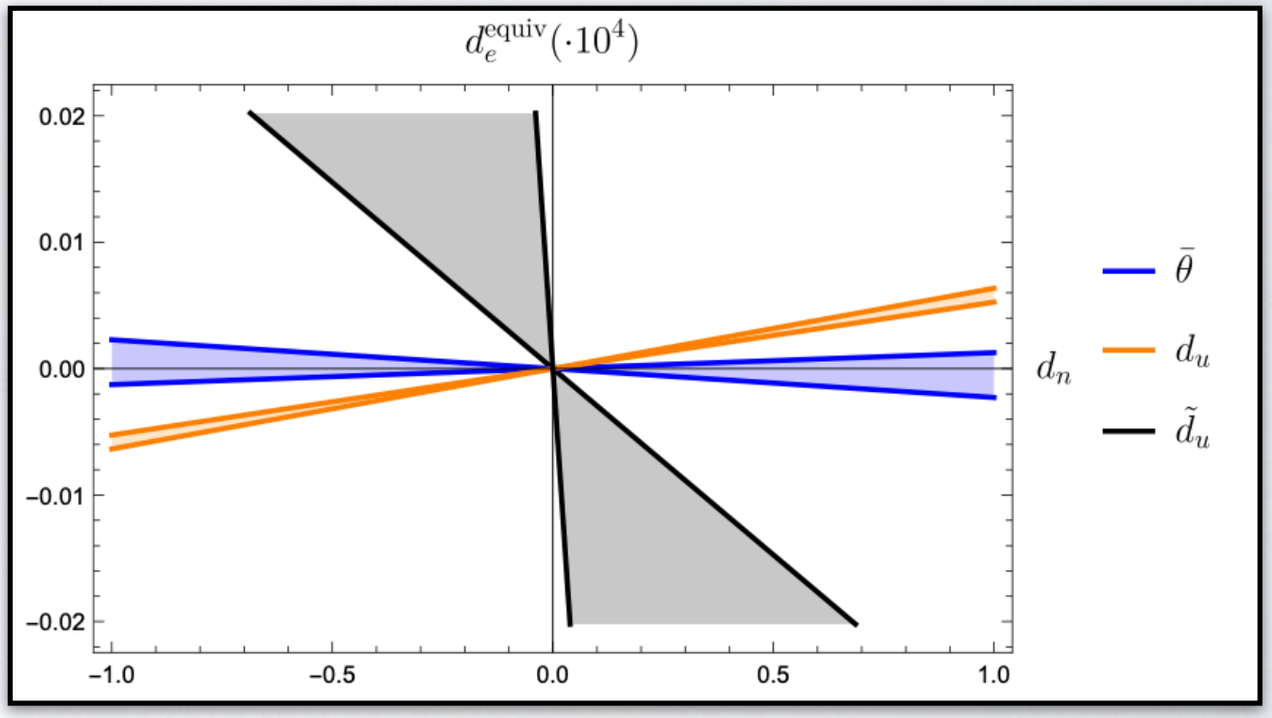
$$\mathscr{L}_\theta \sim \bar{\theta}\epsilon^{\mu\nu\alpha\beta}G^a_{\mu\nu}G^a_{\alpha\beta}$$



- Theta versus BSM parametrized by higher-dimensional sources of CP violation



Draper et al '21 Choi, Hui Im '26

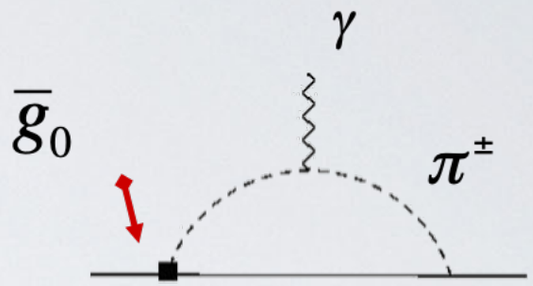


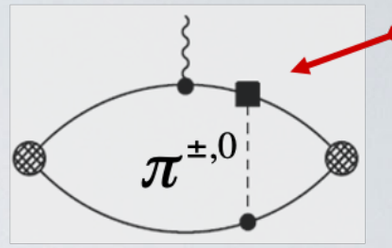
Dekens et al '26

- Ratio over nuclear-nucleon or molecular-nucleon EDMs can pinpoint theta term

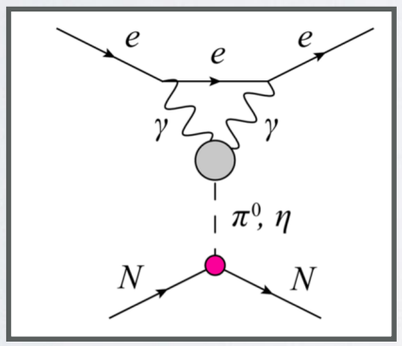
Conclusions/Summary

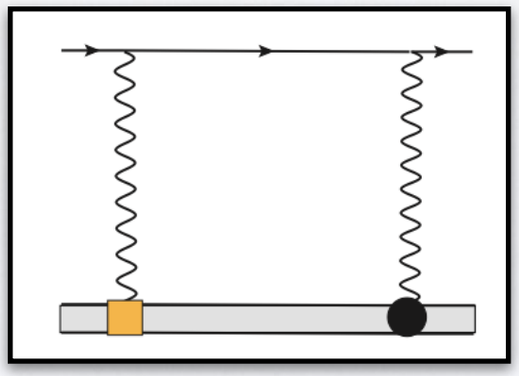
- EDMs are powerful ways to look for new CP violation
- Neutron EDM drives the strong CP problem
- Diamagnetic atoms powerful but **theory problematic**
- Light nuclei better under control (first deuteron EDM limit)



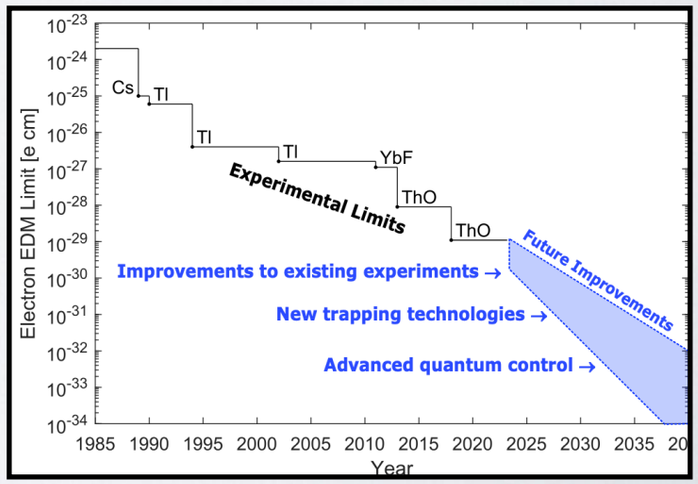


- **Paramagnetic systems are becoming 'diamagnetic' as well**
- Theory for molecular EDMs still in **infancy**! More work is needed on all aspects (particle, hadronic, nuclear, molecular !)





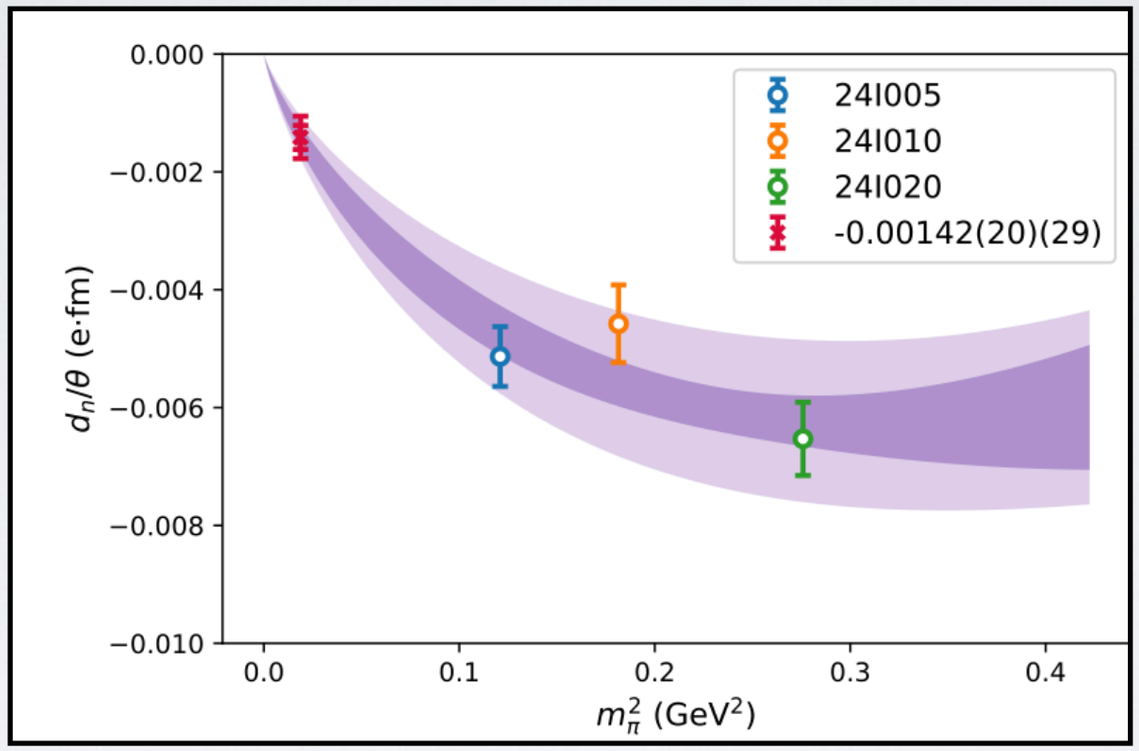
- **The experimental prospects are excellent !**



- *Polar molecules for axion Dark Matter detection ?*

BACKUP

LQCD still at large pion masses



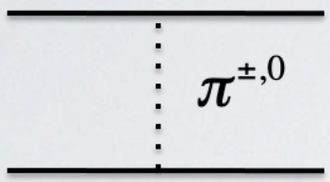
Review Keh-Fei Liu '24

Nuclear forces

See 2001.09050 for a review of CP-odd nuclear forces

CP-even

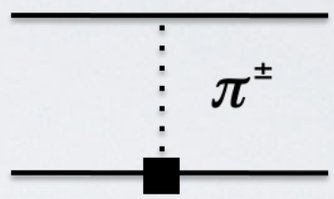
$$\frac{g_A}{2F_\pi}\,\bar{N}(\vec{\sigma}\cdot\vec{D}\pi^a)\tau^a N$$



$$\sim \frac{(g_A Q)^2}{Q^2} \sim Q^0$$

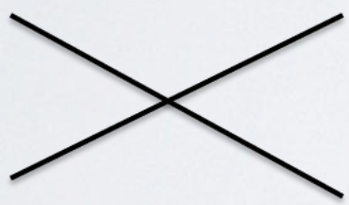
CP-odd

$$\bar{g}_0 \bar{N}(\vec{\tau}\cdot\vec{\pi})N$$



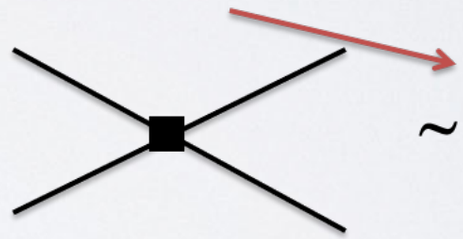
$$\sim \frac{(g_A Q)\bar{g}_0}{Q^2} \sim Q^{-1}$$

$$\bar{N}N\;\bar{N}N$$



$$\sim Q^0$$

$$(\bar{N}N)\,\partial^i(\bar{N}\sigma^i N)$$



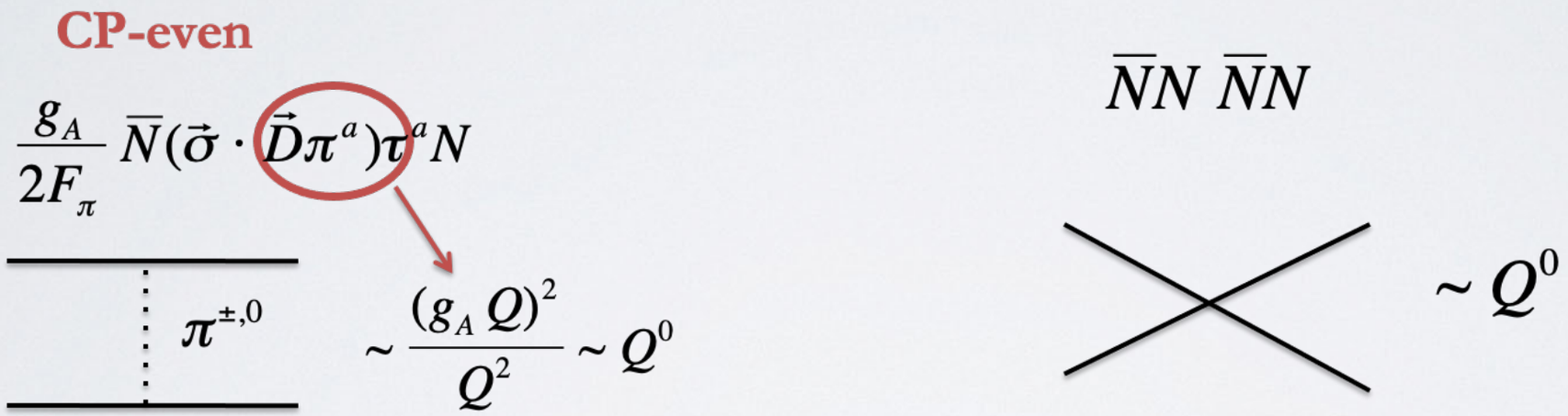
$$\sim Q^1$$

- In 'normal' nuclear forces, pions come with a derivative but contacts do not (S to S wave)
- CP-even forces are pion-exchange + contact terms (in S-waves)

- **Lore: CP-odd contact terms require a derivative —> higher order**

Do pure long-range CP-odd forces make sense?

- Revisited CP-odd forces with graduate student Sachin Shain
- Debate in chiral EFT nuclear physics literature about 'Weinberg counting'



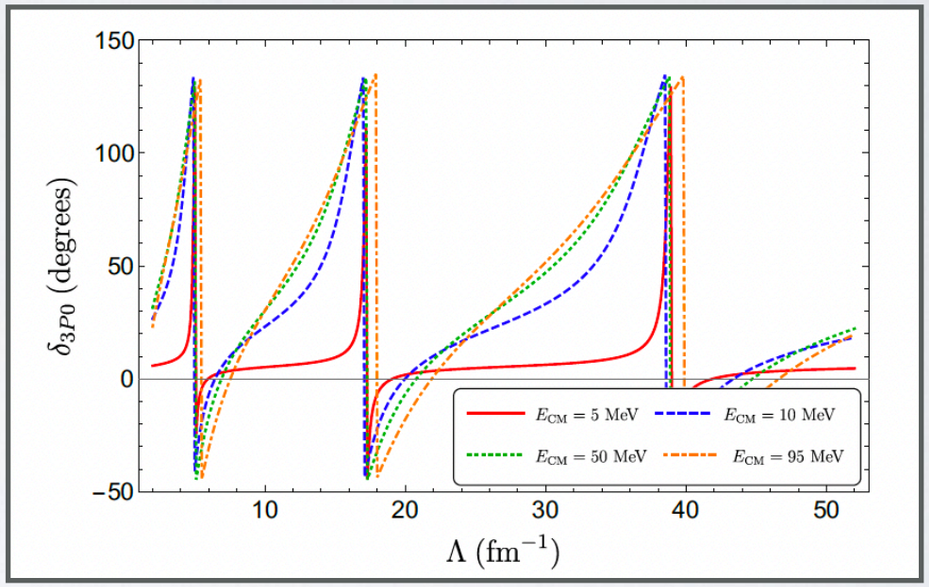
- Standard picture: LO force is pion-exchange + S-wave countqerterms
- **LO P-waves and higher from pion-exchange (naive dim analysis)**
- This lore was questioned by van Kolck, Timmermans, Nogga '05 —> showed that renormalization of nuclear forces require leading-order P-wave contact interactions
- *Similar story in neutrinoless double beta decay* Cirigliano et al' PRL '18, PRC '19

Revisit CP-odd nuclear forces a la Nogga/van Kolck/Timmermans

- Revisited CP-odd forces with graduate student Sachin Shain
- Nogga/van Kolck/Timmermans: need counter terms at LO in attractive P-waves 3P0 and 3P2

$$V_{\mathrm{str},\pi} = -\frac{1}{(2\pi)^3}\left(\frac{g_A}{2F_\pi}\right)^2 \vec{\tau}_1 \cdot \vec{\tau}_2 \frac{(\boldsymbol{\sigma}_1 \cdot \mathbf{q})(\boldsymbol{\sigma}_2 \cdot \mathbf{q})}{\mathbf{q}^2 + m_\pi^2},$$

Figures from dissertation Sachin Shain



- Regulator to solve LS equation

$$f_\Lambda(p, p') = e^{-(\mathbf{p}/\Lambda)^4} e^{-(\mathbf{p}'/\Lambda)^4},$$

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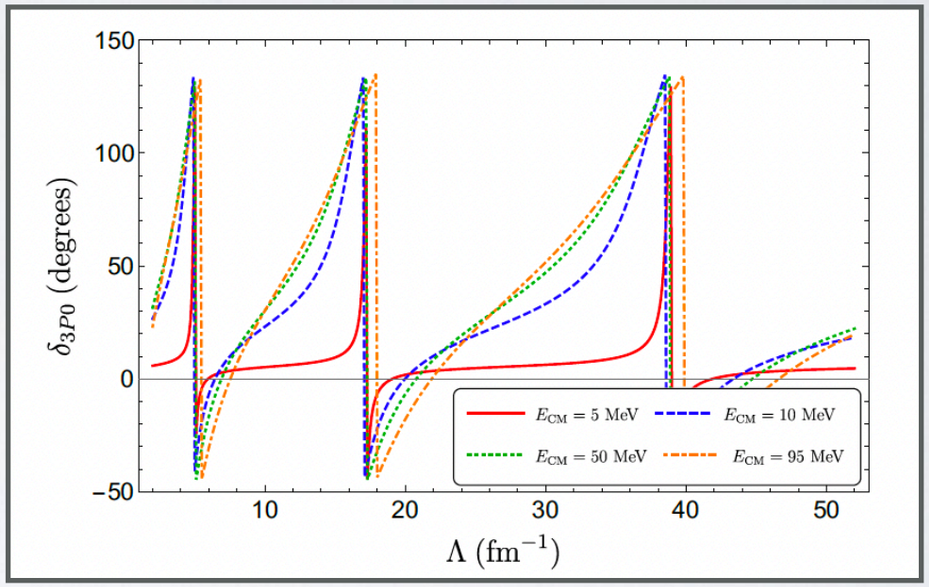
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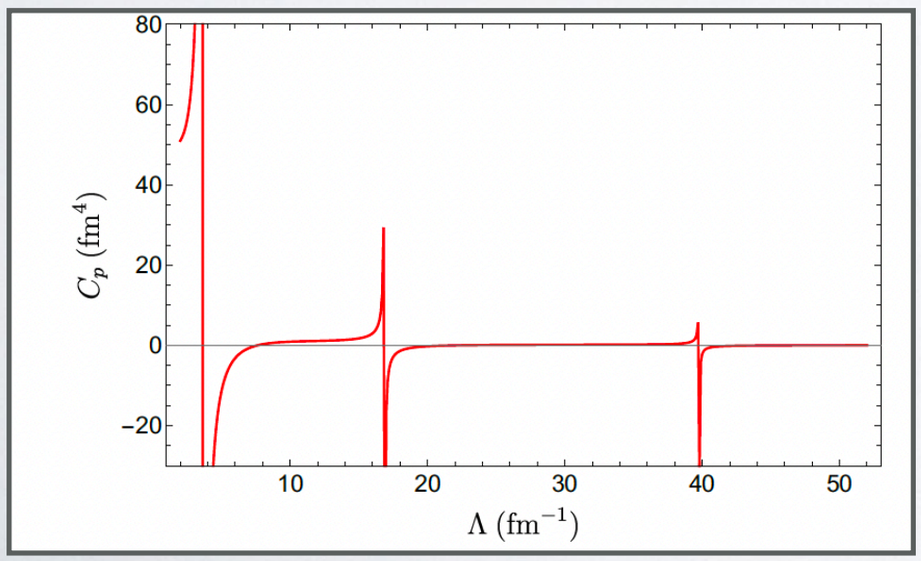
$$V_{\mathrm{str,sd}} = \frac{1}{(2\pi)^3}\left(C_S P_s + C_t P_t + \frac{1}{4} p p' C_P P_p\right)$$

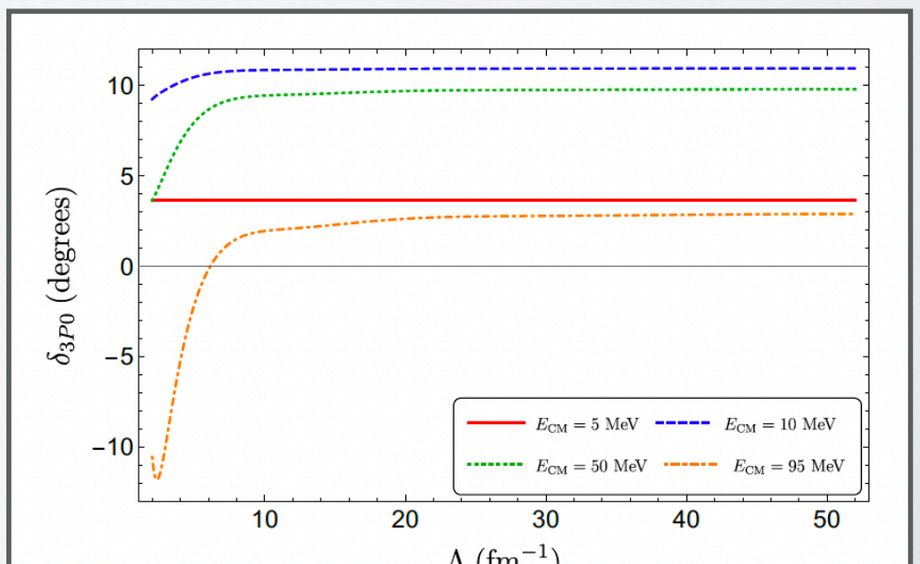
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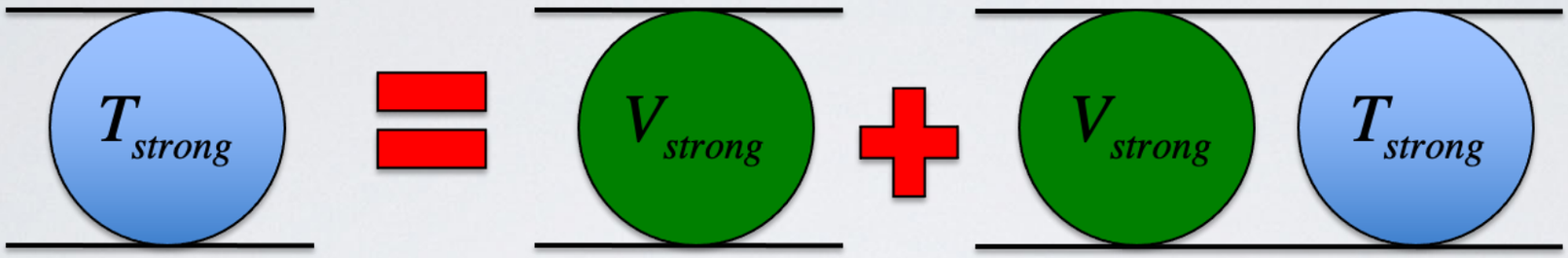






Adding CP violation

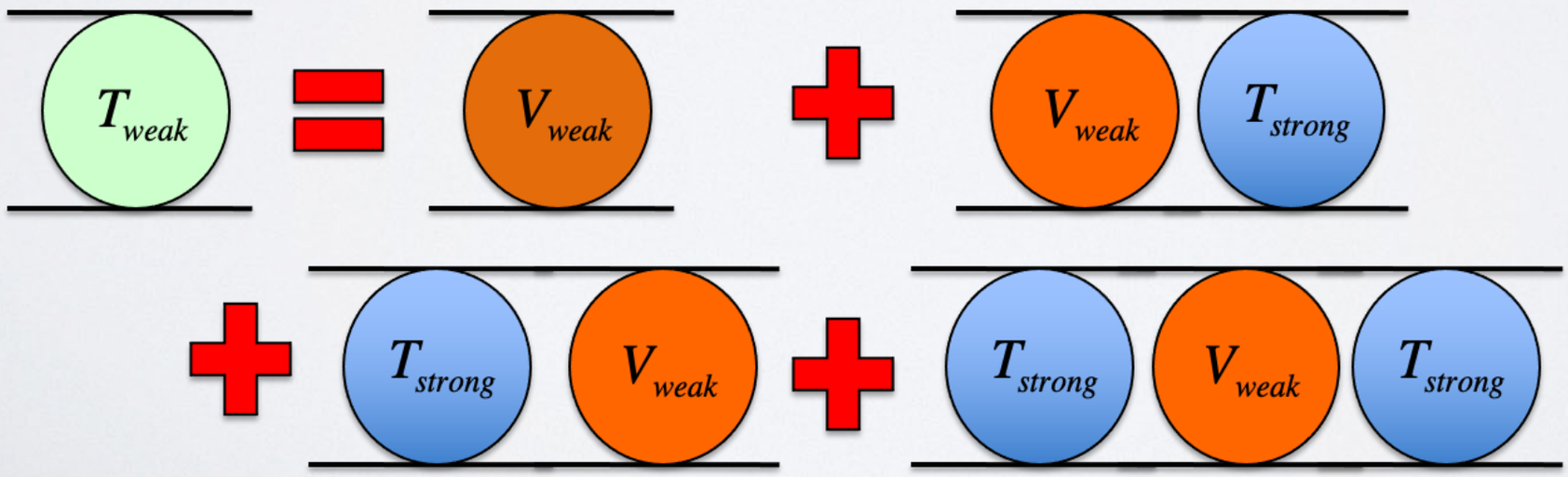
- Solved and renormalized strong scattering amplitude $T_{\text{strong}} = V_{\text{strong}} + V_{\text{strong}}\, G_0\, T_{\text{strong}}$



- Then solve in perturbation theory (CP violation is very very very weak)

$$T_{weak} = V_{weak} + V_{weak} G_0 T_{strong} + T_{strong} G_0 V_{weak} + T_{strong} G_0 V_{weak} G_0 T_{strong}$$

$$V_{\bar{g}_0} = -\frac{1}{(2\pi)^3} \frac{g_A \bar{g}_0}{2F_\pi} \vec{\tau}_1 \cdot \vec{\tau}_2 \frac{i(\boldsymbol{\sigma}_1 - \boldsymbol{\sigma}_2) \cdot \mathbf{q}}{\mathbf{q}^2 + m_\pi^2},$$

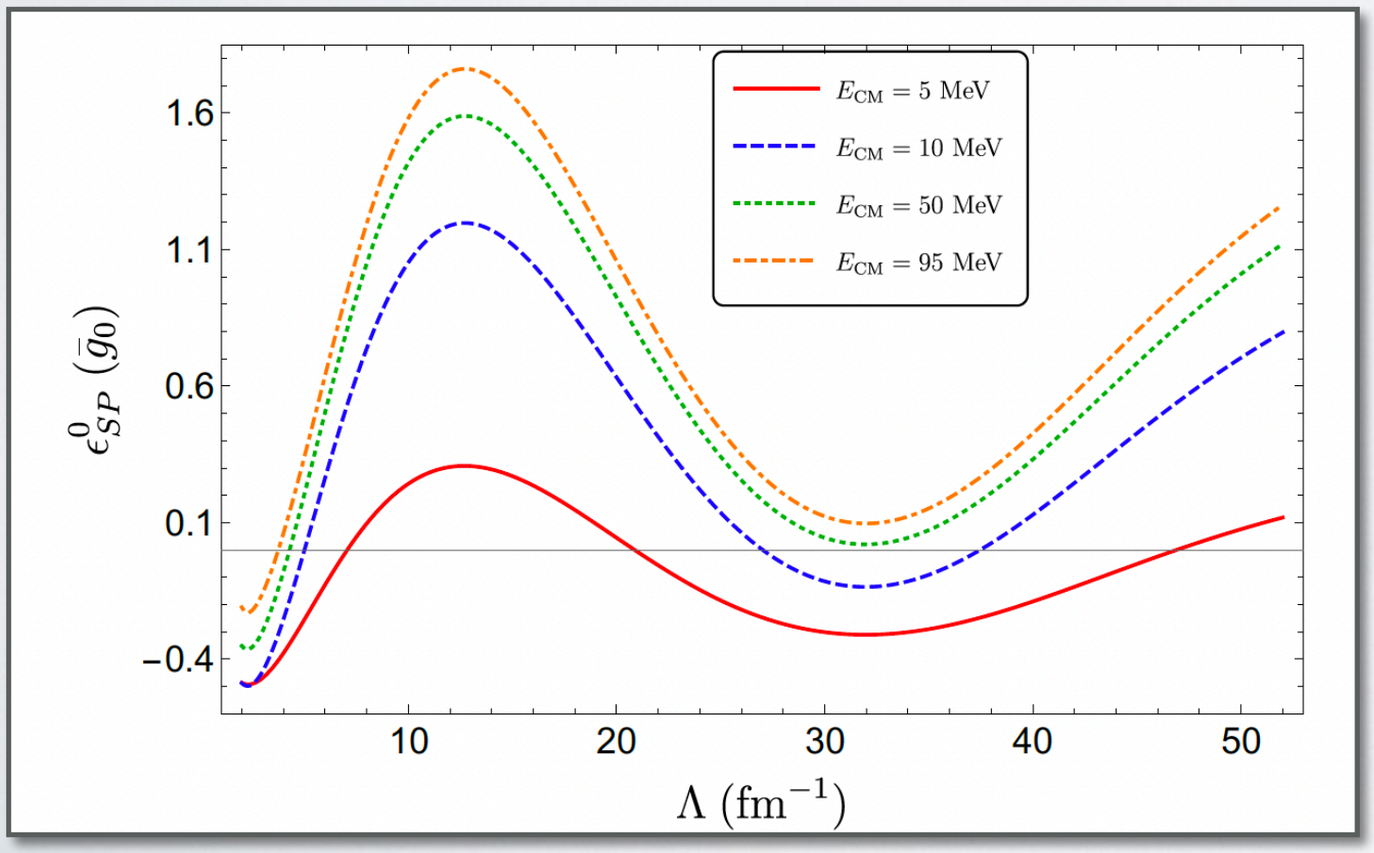


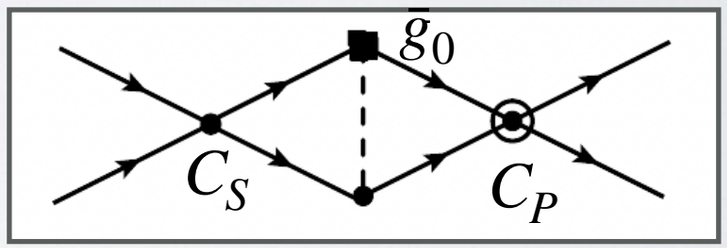
CP-odd phase shifts

- First consider j=0 states $^1S_0 \leftrightarrow {}^3P_0$
- CP-odd mixing angle in principle observable in spin rotations of polarized ultra cold neutrons on hydrogen target

$$S_{j=0} = \begin{pmatrix} e^{2i\delta_{1S_0}} & \epsilon^0_{\rm SP} e^{i[\delta_{1S_0}+\delta_{3P_0}]} \\ -\epsilon^0_{\rm SP} e^{i[\delta_{1S_0}+\delta_{3P_0}]} & e^{2i\delta_{3P_0}} \end{pmatrix}$$

- We compute the phase shifts in units of $\bar{g}_0$
- **Results are extremely cut-off dependent ! Driven by 3P0-3P0 counter term**





JdV, Gnech, Shain '20

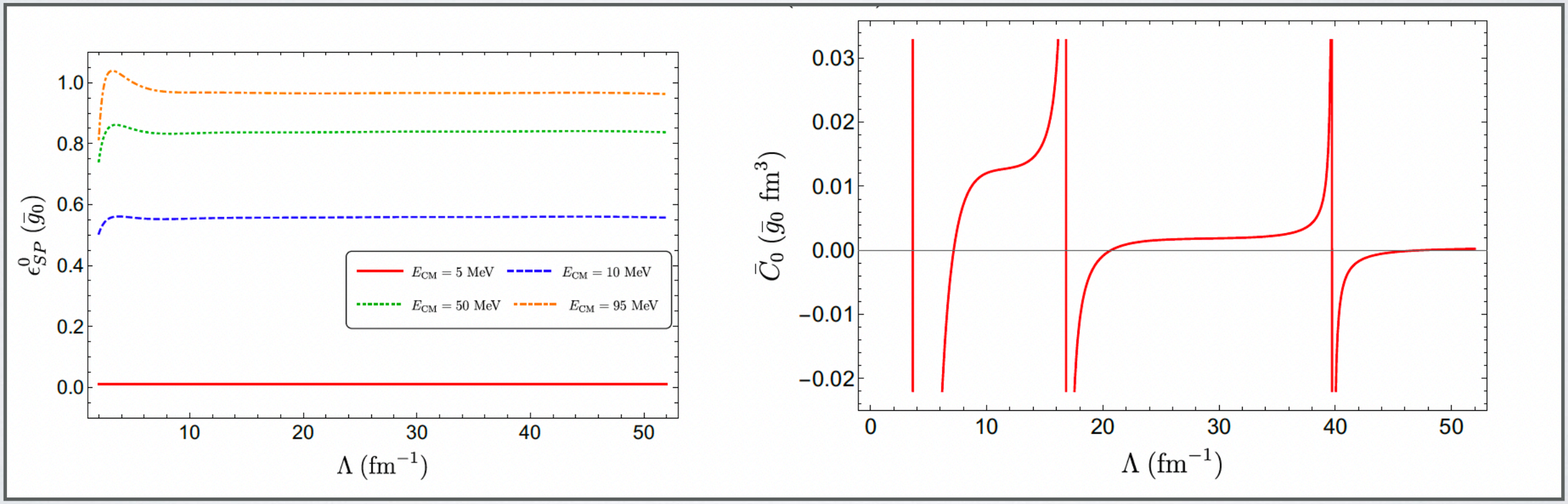
Lessons ?

- We probably need short-distance counter terms in certain CP-odd pion-induced transitions
- Let's add the 1S0-3P0 counter term

$$\mathcal{L}_{NN} = \bar{C}_0 \left[\bar{N}\boldsymbol{\sigma}N \cdot \boldsymbol{\nabla}(\bar{N}\,N) + \frac{1}{3}\bar{N}\vec{\tau}\boldsymbol{\sigma}N \cdot \boldsymbol{\nabla}(\bar{N}\vec{\tau}N) \right]$$

- And pretend we have some **fake measurement** of the mixing angle at some energy

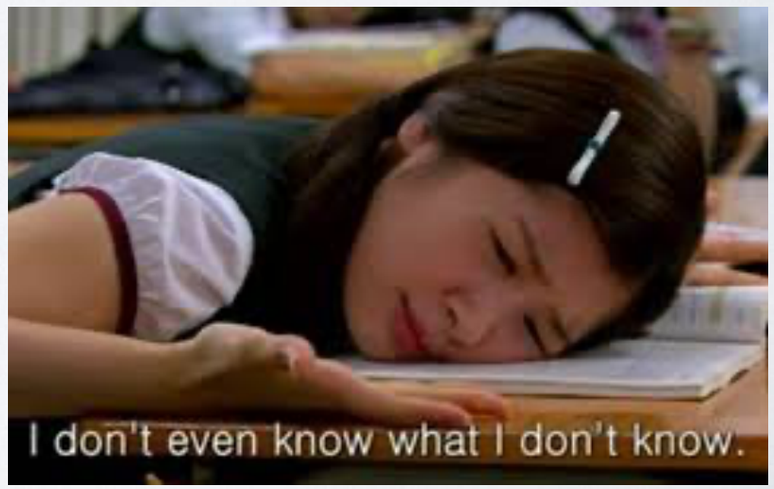
$$\epsilon_{SP}(5\,\mathrm{MeV}) = 0.01\,\bar{g}_0$$



- It works…. But of course the outcome depends on the fitting point (**no prediction !**)

So ?

- For a long time it has been thought that EDMs of nuclei and diamagnetic atoms can be computed from CP-odd pion exchange
- ***But if EDMs depend on 1S0 <-> 3P0 mixing this is probably not the case***
- The deuteron EDM is special (only intermediate 3P1 state) so calculation should be good
- *Not true for 3He or larger systems (unless there are selection rules)*
- Interesting to redo EDMs of light nuclei with modified power counting
- ***Can counter terms explain why Schiff moment computations are so hard ?***
- ***Can we fix the CP-odd counter term ?***



Obtaining the counter term for theta term

- For theta term might be a way out. Remember :

$$\mathscr{L}_{QCD} = \mathscr{L}_{kin} - \bar{m}\bar{q}q - \varepsilon\bar{m}\bar{q}\tau^3 q \quad \longleftrightarrow \quad +m_\star\bar{\theta}\bar{q}i\gamma^5 q$$

$$\mathcal{L}_{NN} = -\frac{iC_0}{8}\mathrm{Tr}[\chi_-]\left[\bar{N}\boldsymbol{\sigma}N\cdot\boldsymbol{\nabla}(\bar{N}N) + \frac{1}{3}\bar{N}\vec{\tau}\boldsymbol{\sigma}N\cdot\boldsymbol{\nabla}(\bar{N}\vec{\tau}N)\right]$$

$$\chi = u^\dagger\chi u^\dagger - u\chi^\dagger u$$

$$\chi = 2B(M_q + im_*\bar{\theta})$$

JdV, Gnech, Shain '20

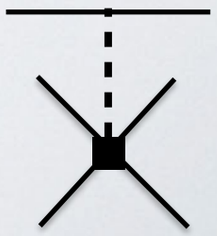
CP-odd counter term



CP-even isospin-breaking pion-nucleon-nucleon



- Task to do: fit to Charge-Symmetry-Breaking in measured $p + n \to d + \pi^0$ $d + d \to \alpha + \pi^0$
- Work done by van Kolck, Hanhart et al ' 00, '06 but with Weinberg power counting
- Also a new three-body force at N?LO ?



- ***In renormalized ChEFT the counter term appears at LO (can it be extracted ?)***