INTERPRETING ELECTRIC DIPOLE MOMENTS (OF ATOMS AND MOLECULES)

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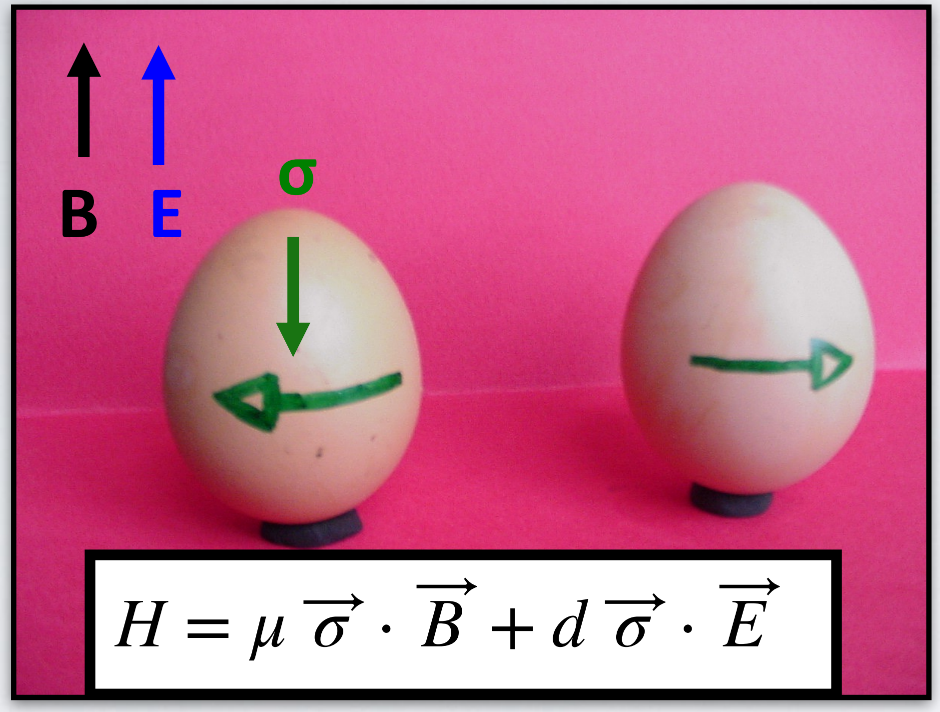
The plan of attack

1. **EDMs 101**

2. EDMs in the Standard Model revisited

3. BSM interpretations

Electric dipole moments 101



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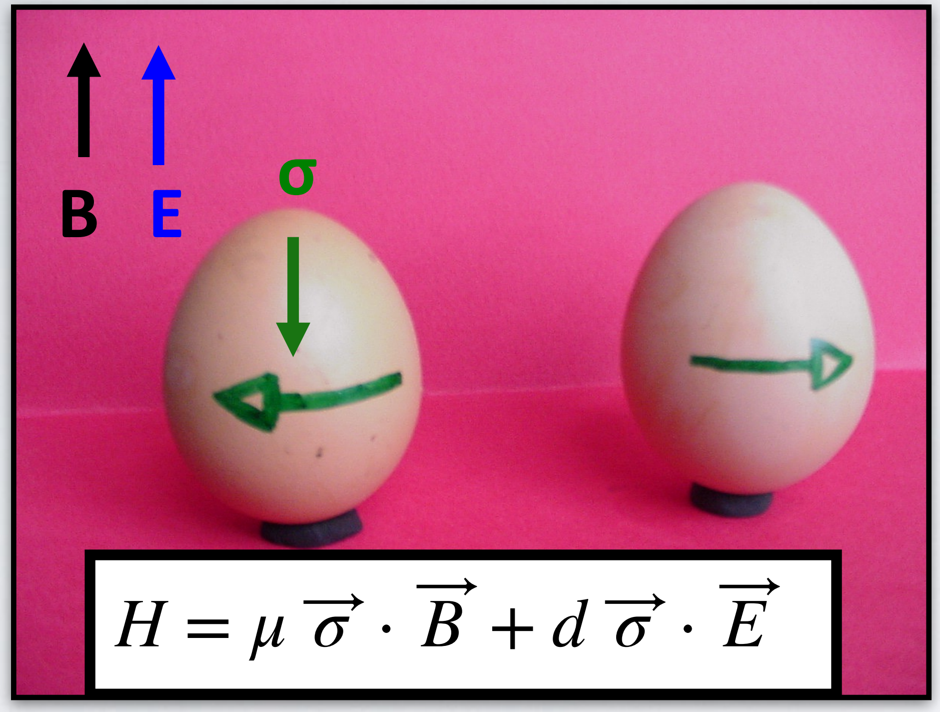
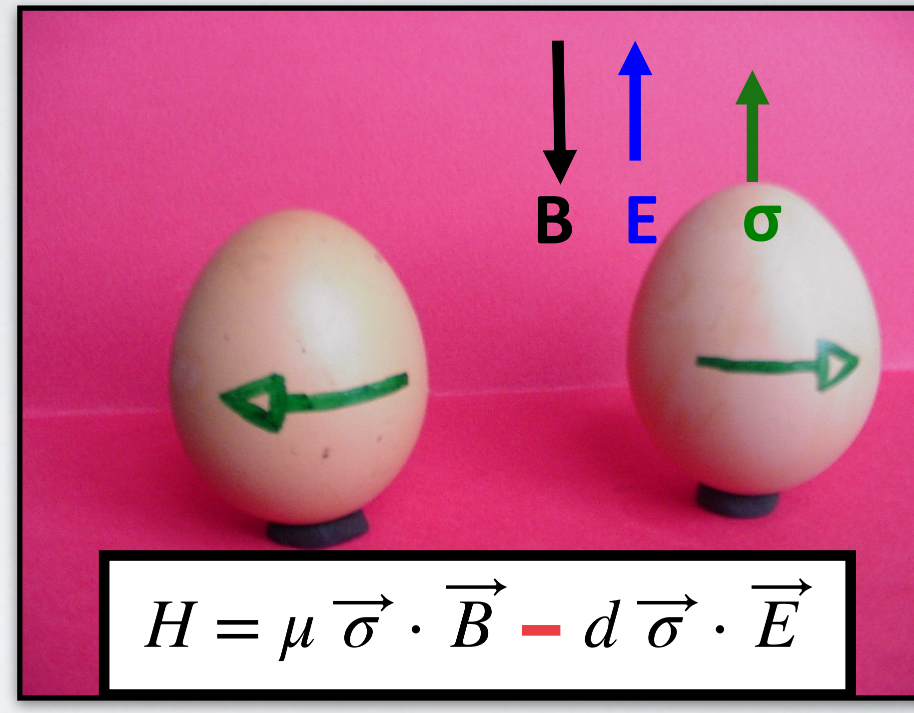


T/CP
transformation



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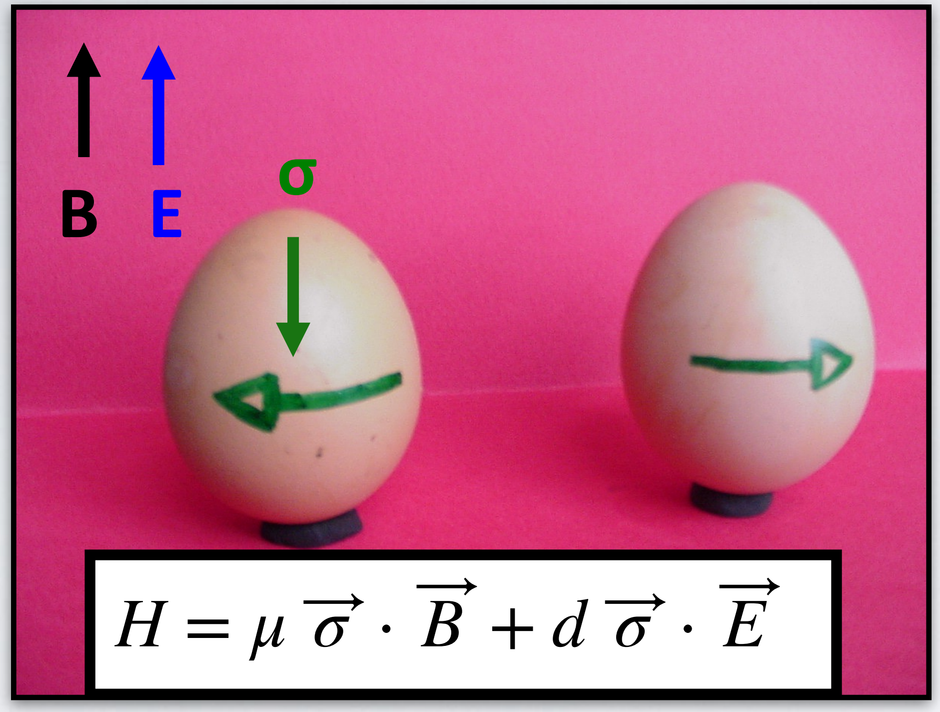

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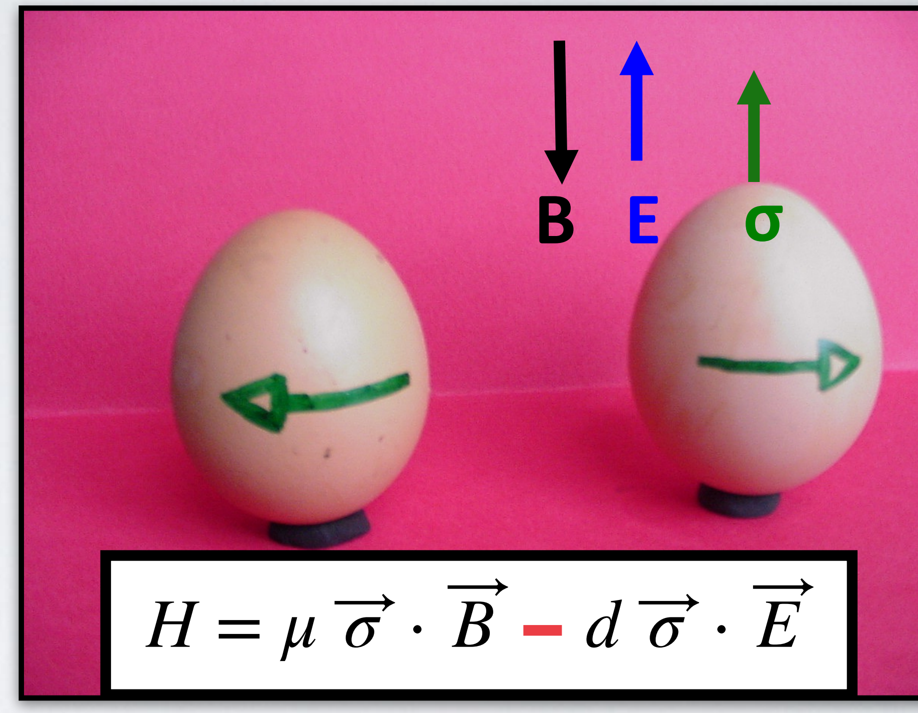
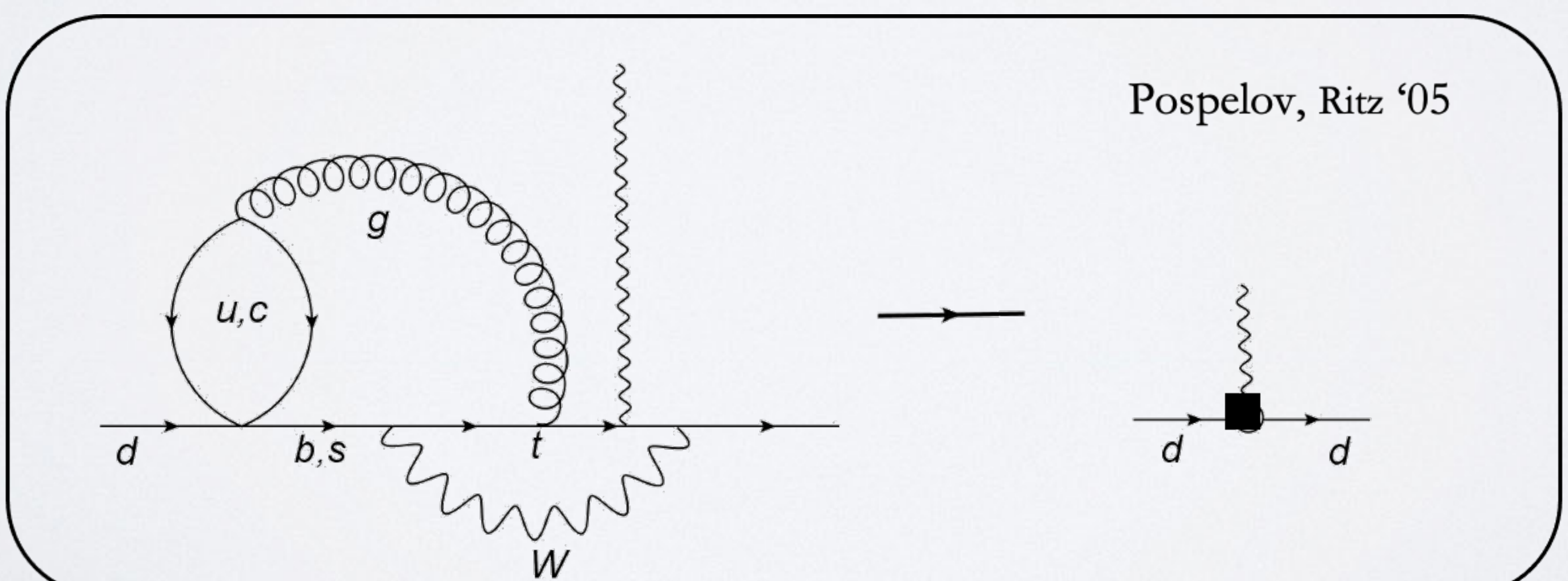


- EDMs from CKM phase only appear at high-loop level and are very suppressed !



Hoogeveen '90, Khriplovich, Zhitnitsky '82, Czarnecki, Krause '97, Uraltsev '13, Seng '14

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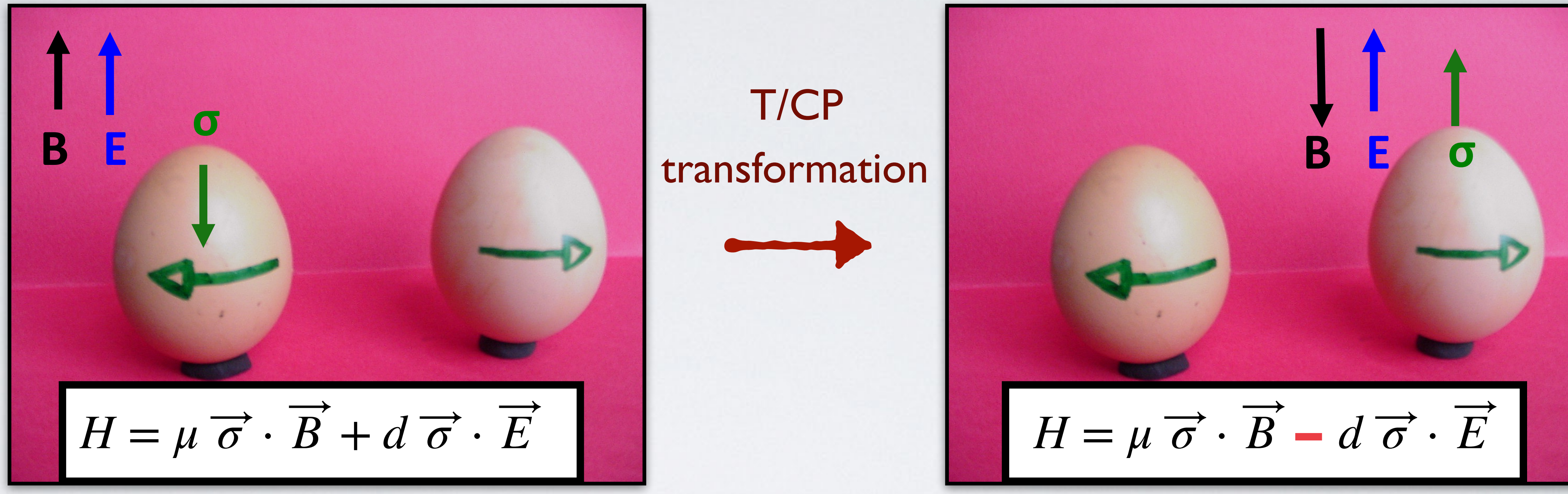
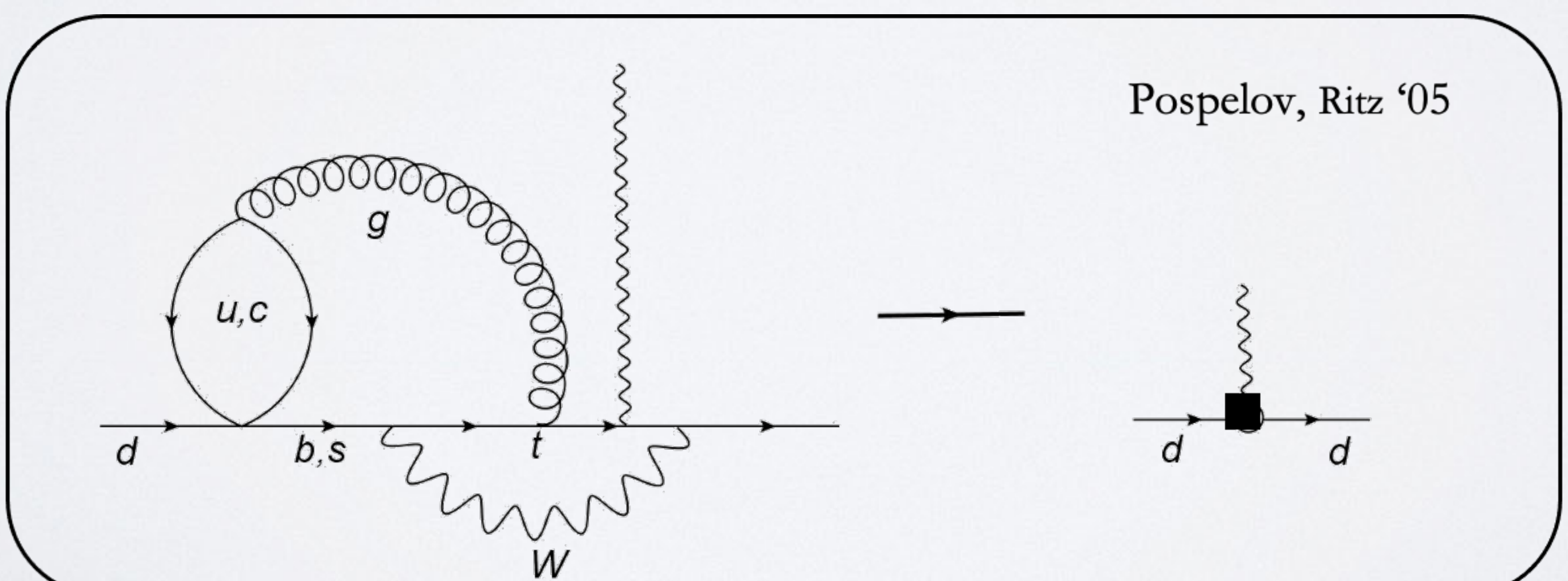


- EDMs from CKM phase only appear at high-loop level and are very suppressed !
- But maybe not as much as we thought… (later more)



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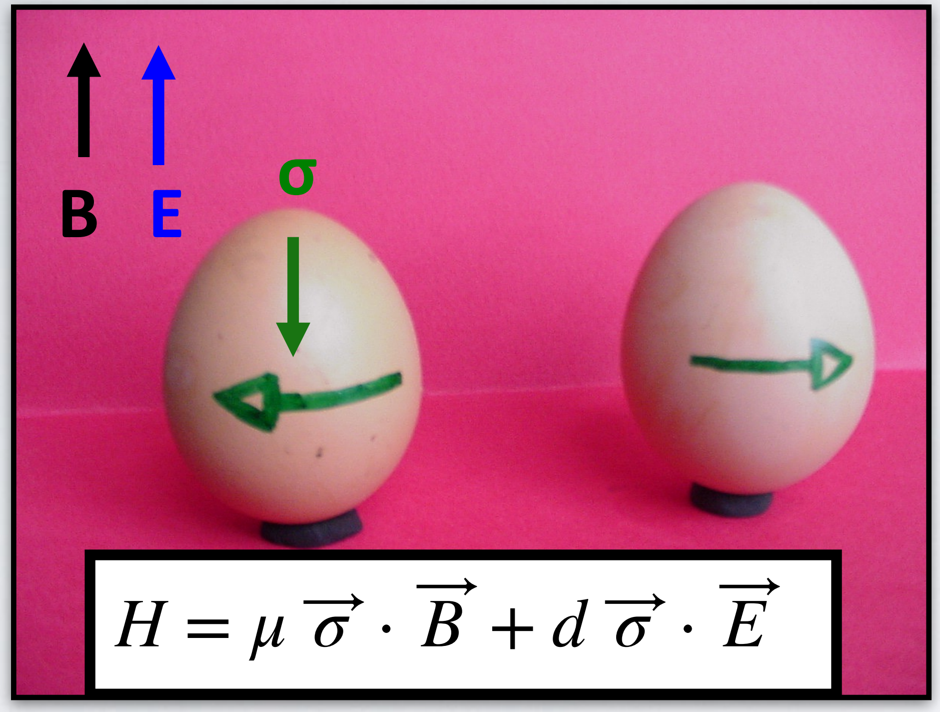

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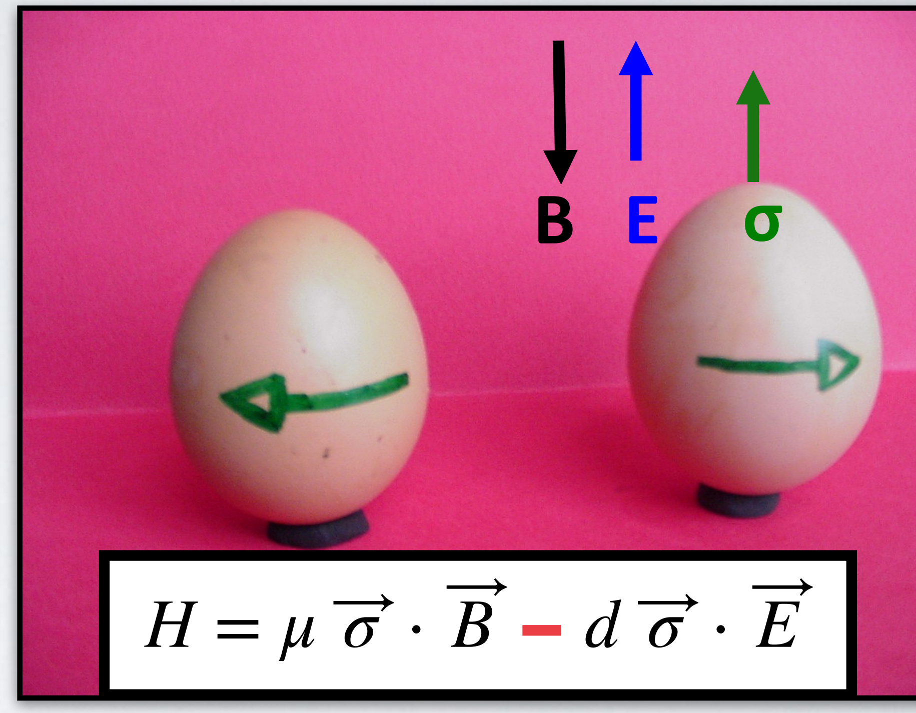

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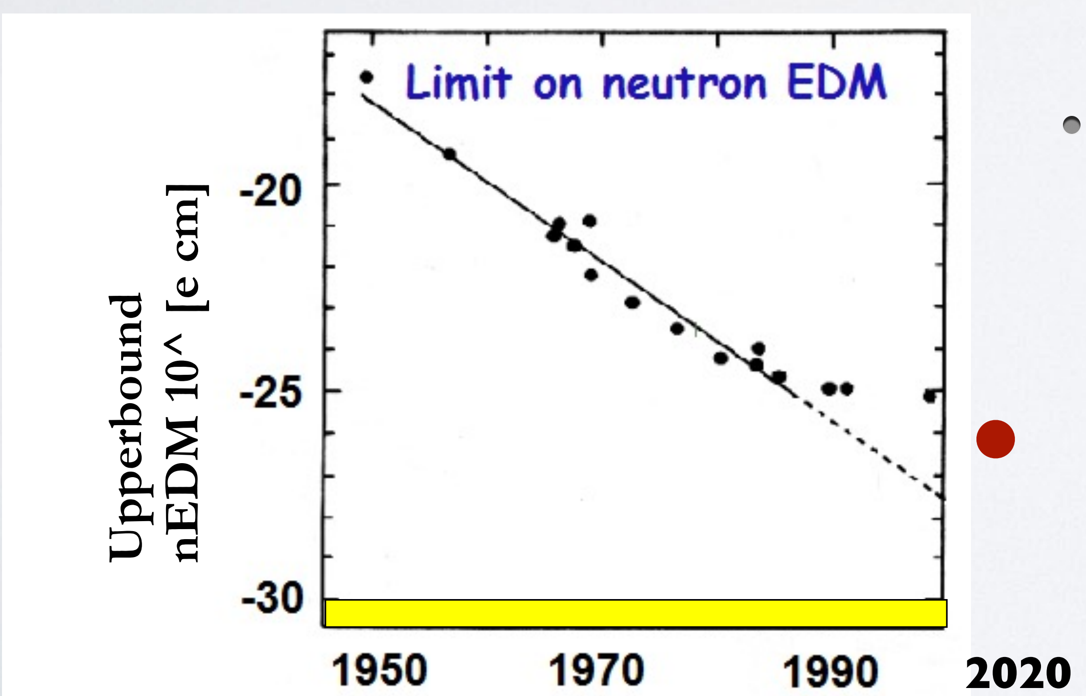
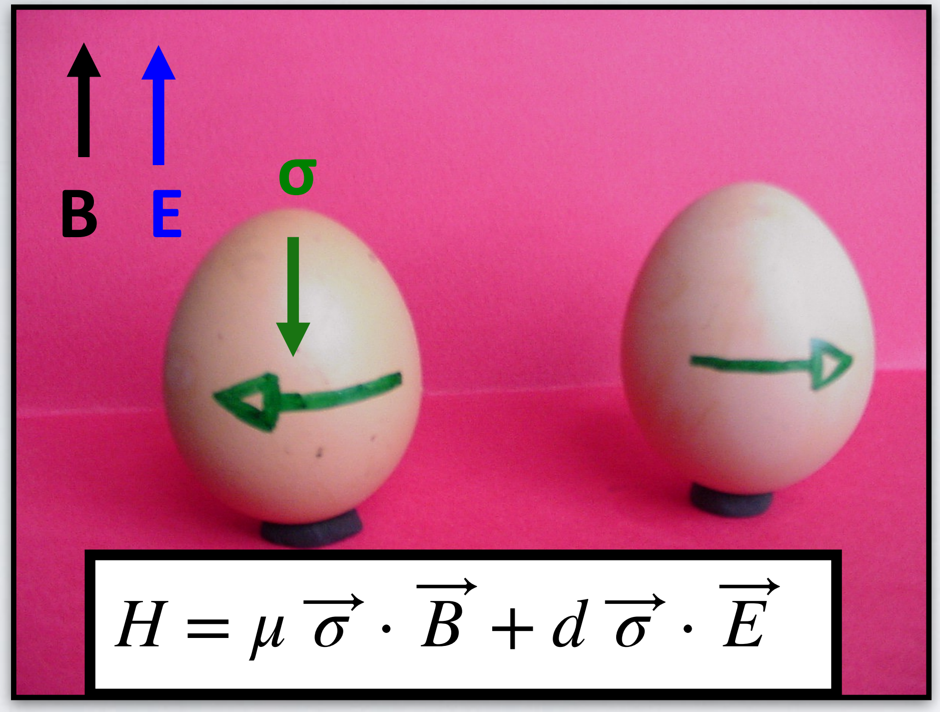


- CKM prediction essentially out of reach

Electric dipole moments 101



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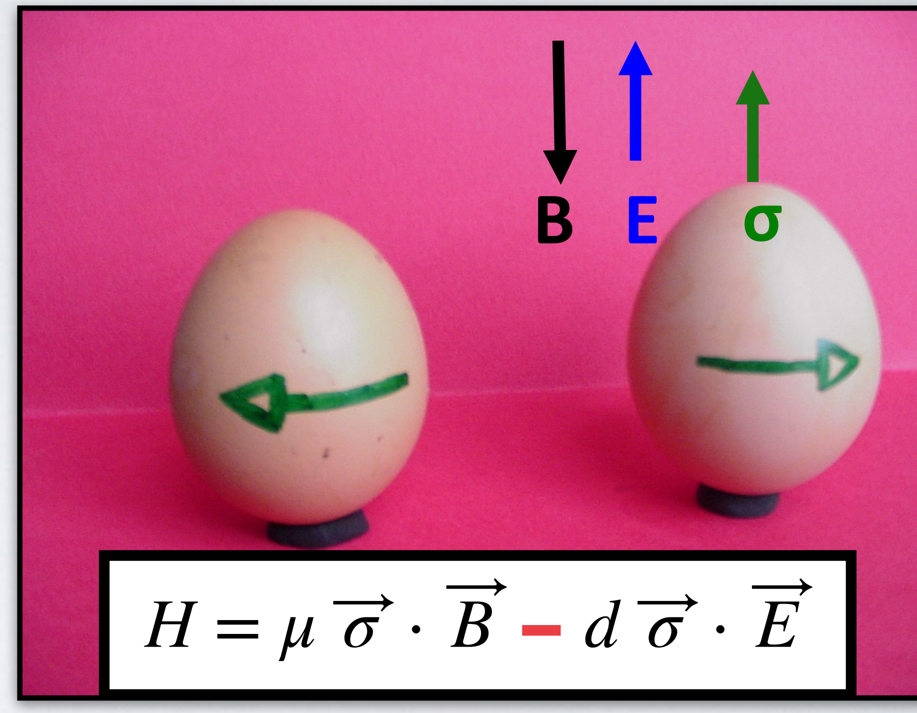

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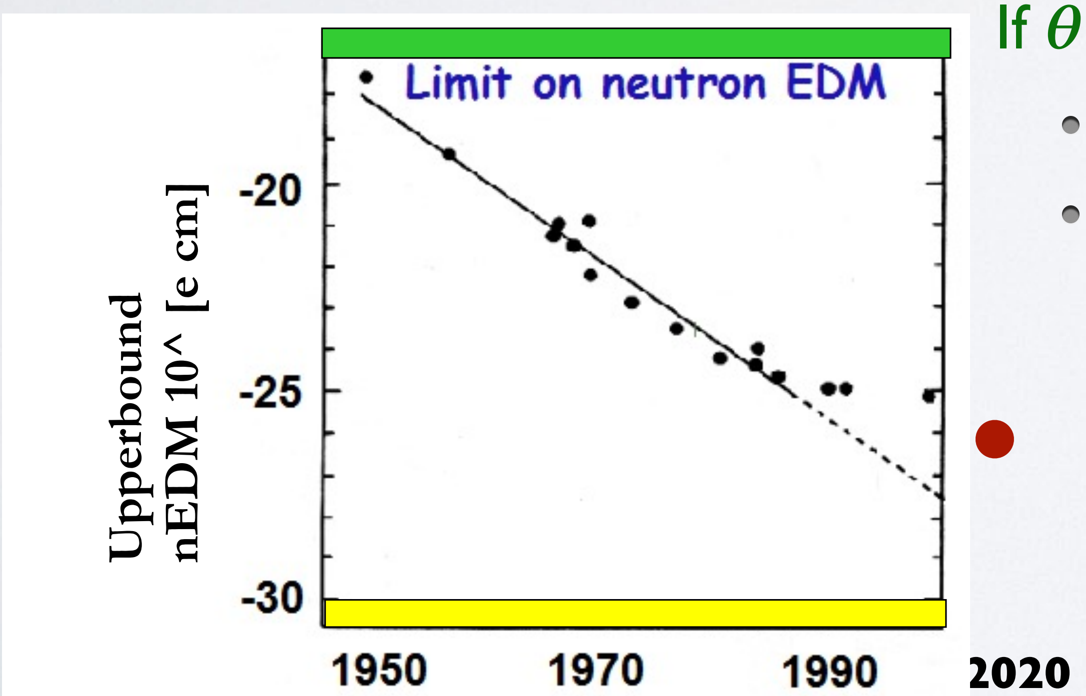


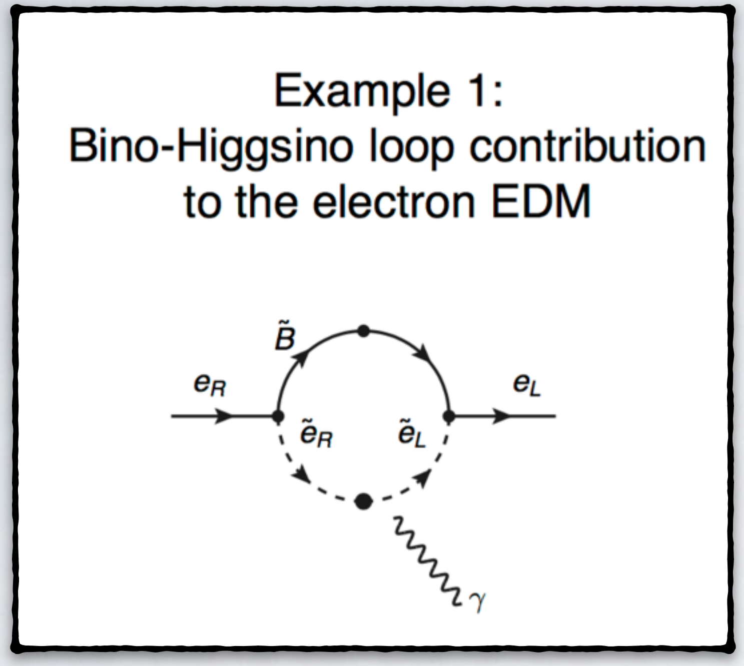
If θ ~ 1

- CKM prediction essentially out of reach
- EDMs can still arise from the QCD theta term

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

- Strong CP problem: θ < 0.0000000001
- Sparked a lot of debate and theorizing

Electric dipole moments 101



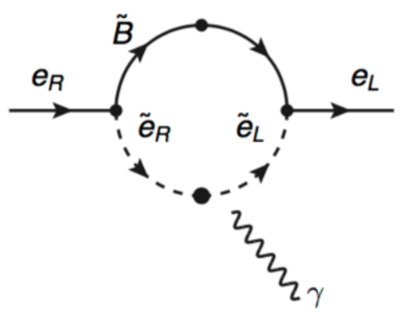
- In beyond-SM (BSM) models: EDMs at zero-, one-, or two-loop

$$d_f \quad \left(\frac{\alpha_{em}}{\pi}\right)^n \frac{m_e}{\Lambda^2} \sin\phi_{CPV}$$

- If phase ~ O(1), then Λ > 30 TeV (n=1), or Λ > 2 TeV (n=2)
- Very competitive with LHC or other probes of BSM physics

Electric dipole moments 101

Example 1:
Bino-Higgsino loop contribution
to the electron EDM



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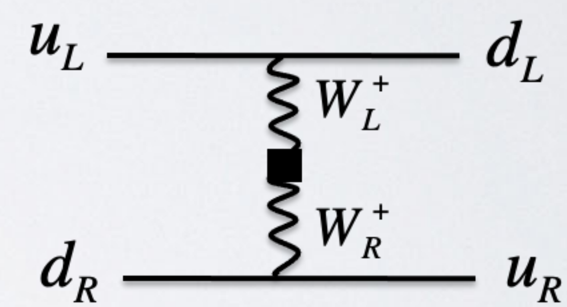
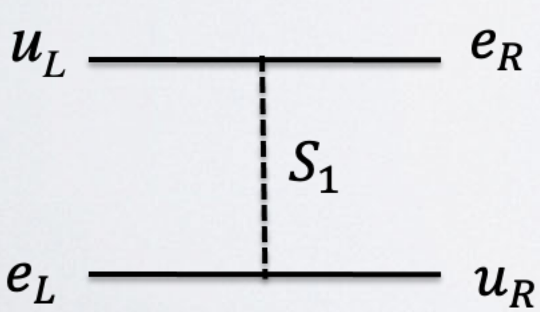
- Certain models EDMs are induced without loop suppression !
- For example, in left-right symmetric models:
- CP-odd four-quark operators induce hadronic EDMs





- Leptoquarks can induce CP-odd electron-quark interactions
- Induce atomic/molecular EDMs

- Tree-level CPV leads to Λ > 100-10000 TeV if phases are O(1) and no small Yukawa's

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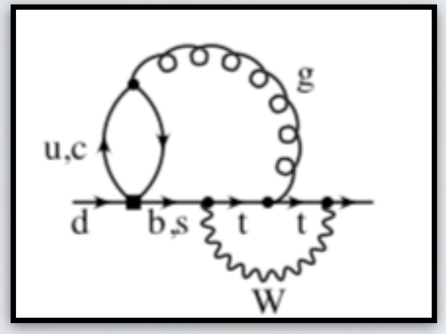
Electric dipole moments from CKM

- Czarnecki and Krause ('97) computed three-loop contributions to quark EDMs



$$d_d = -0.7 \times 10^{-34}\ e\ \mathrm{cm}$$
$$d_u = -0.15 \times 10^{-34}\ e\ \mathrm{cm}$$

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

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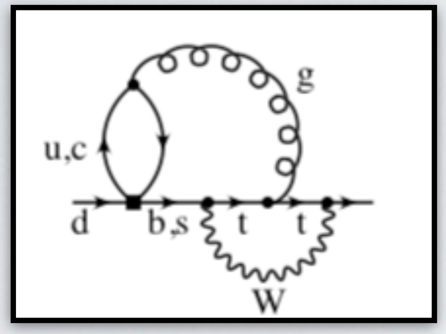

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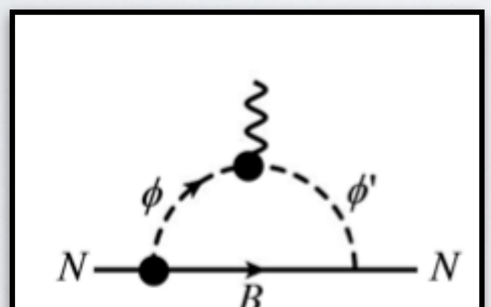
- Larger effects from CP-odd four-quark operators with strangeness. Then use a Kaon loop.



Khriplovich-Zhitnitsky ('82), recent update Seng (2014)

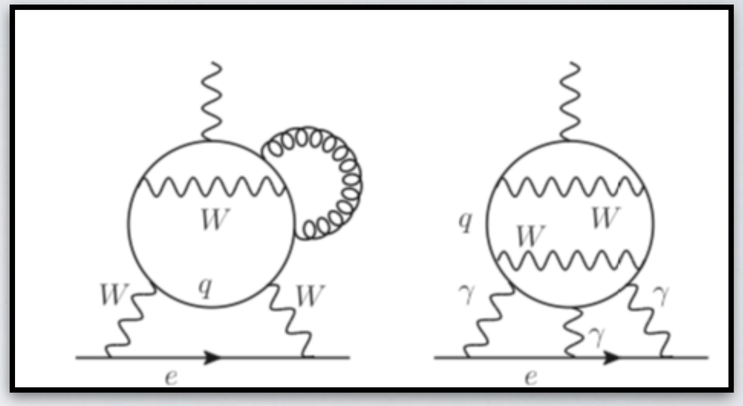
$$d_n \sim 10^{-32} e\,\mathrm{cm}$$

With order-of-magnitude uncertainty

Uncertain but stable and small. Very far away from experiments

Not so much papers about nuclear forces but Donoghue/Holstein/Ramsey-Musolf '87 argue no enhancement over nucleon EDMs. Maybe good to revisit.

Electric dipole moments from CKM



- What about the electron EDM ? Appears at 4 loops.

$$d_e \sim 10^{-44} e\,\mathrm{cm}$$

See e.g. Pospelov/Ritz '13

- 15 orders below current experimental reach ! $d_e^{exp} < 1.1 \cdot 10^{-29}\, e\,\mathrm{cm}$ ACME '18

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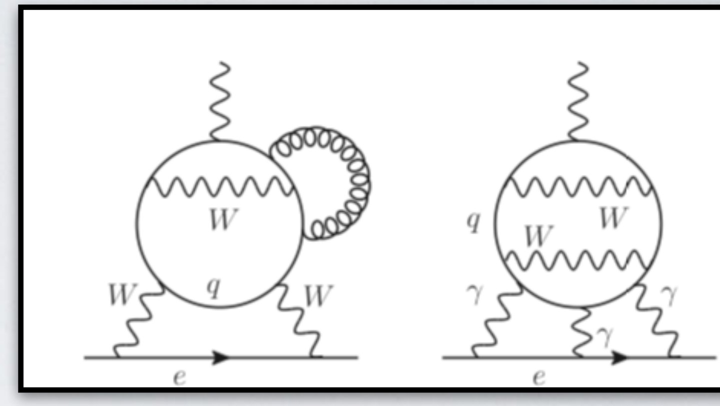

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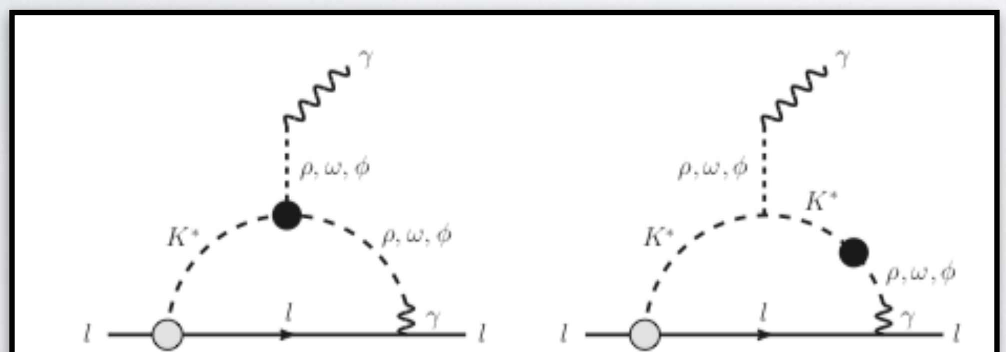
- Again long-distance hadronic effects can be significantly larger.



Yamanaka/Yamaguchi PRL '20

$$d_e^{(\mathrm{SM})} = 5.8 \times 10^{-40} e\,\mathrm{cm},$$
$$d_\mu^{(\mathrm{SM})} = 1.4 \times 10^{-38} e\,\mathrm{cm},$$
$$d_\tau^{(\mathrm{SM})} = -7.3 \times 10^{-38} e\,\mathrm{cm}.$$

Still minuscule !

Electric dipole moments from CKM

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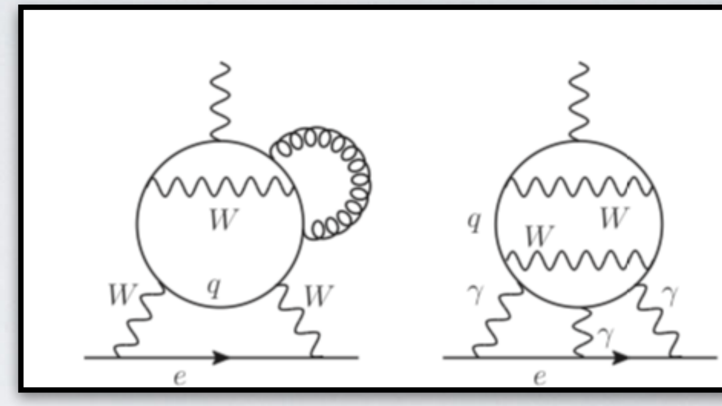

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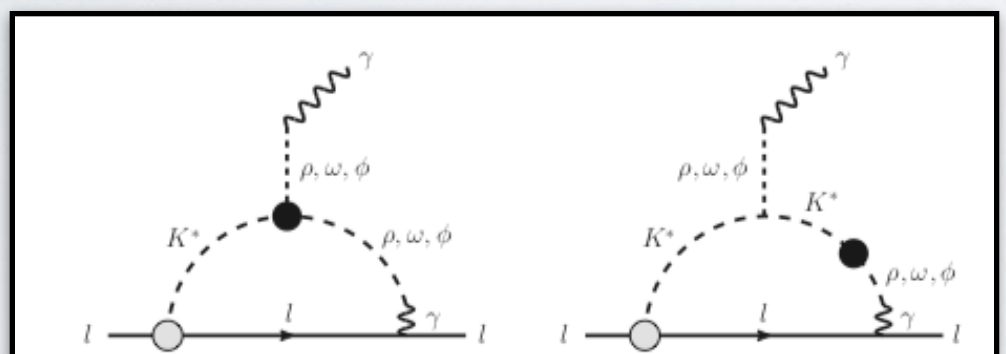

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Still minuscule !

- But we are comparing apples with pears! Experiments do not use isolated electrons !

- In paramagnetic systems we must include CP-odd forces between electrons and nucleus

Electric dipole moments from CKM

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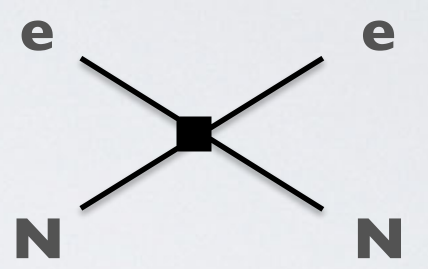
$$\mathscr{L}_{eN} = \bar{C}_S\, G_F\, \bar{N}N\, \bar{e} i\gamma^5 e$$



- Induces a second contribution to the energy shift $\omega_X \sim (d_e + r_X \bar{C}_S)$
- To compare it is useful to write

$$\bar{d}_e(\mathrm{ThO}) = d_e + \bar{C}_S \cdot 2.1 \cdot 10^{-9}\, e\,\mathrm{cm} \qquad \bar{d}_e(\mathrm{ThO}) < 1.1 \cdot 10^{-29}\, e\,\mathrm{cm}$$

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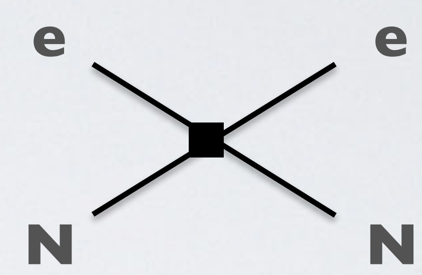

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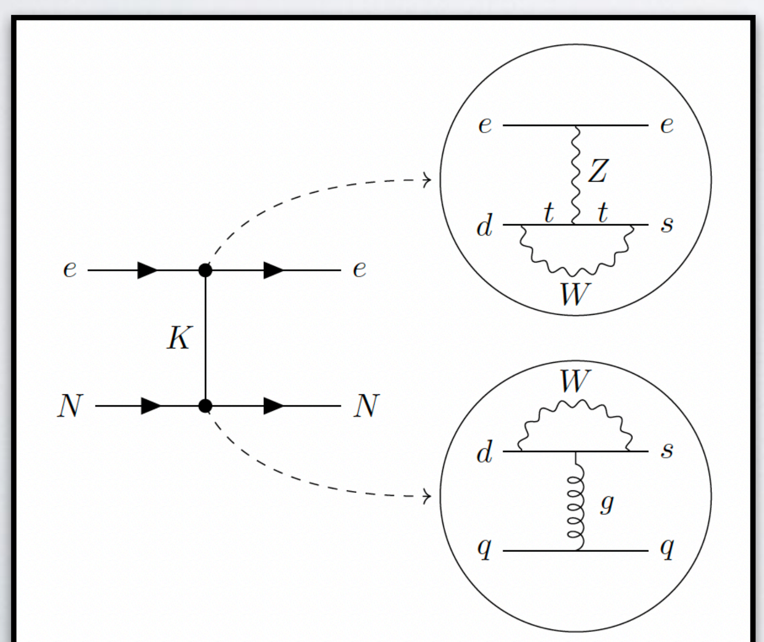

- Ema et al '22 found new large contributions to these forces through Kaon exchange mechanism

$$\bar{d}_e(\text{ThO}, CKM) \simeq 1.0 \cdot 10^{-35}\, e\,\text{cm}$$

- "only" 6 orders below current limit ! The field gained 2 orders since 2002…. Perhaps possible ?

Electric dipole moments from theta term

- Second source of CP violation is the QCD theta term

$$\mathscr{L} = \bar{q}\left(i\gamma^\mu D_\mu - M_q\right) q \;+\; \theta \frac{g_s^2}{32\pi^2}\epsilon^{\alpha\beta\mu\nu}G_{\alpha\beta}G_{\mu\nu} \qquad q = (u\, d)^T$$

- Remove gluonic theta term with a axial U(1) transformation in favor of complex quark mass

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

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

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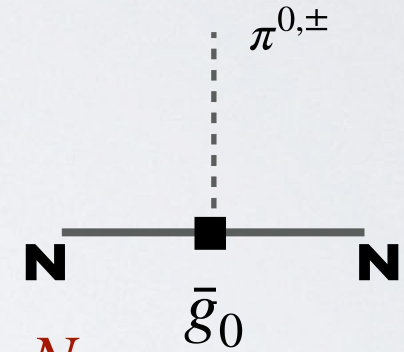
Chiral perturbation theory



$$\mathscr{L}_{\chi+m} = \mathscr{L}_\chi - \frac{m_\pi^2}{2}\pi^2 - \delta m_N \bar{N}\tau^3 N \qquad +\bar{g}_0\bar{N}\tau\cdot\pi N$$

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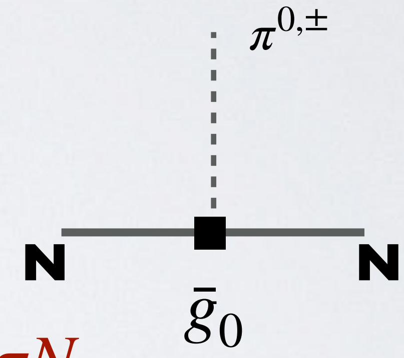
Chiral perturbation theory $\downarrow$ $\downarrow$ $\downarrow$



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nucleon mass splitting (strong part, no EM) $\longleftrightarrow$ **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

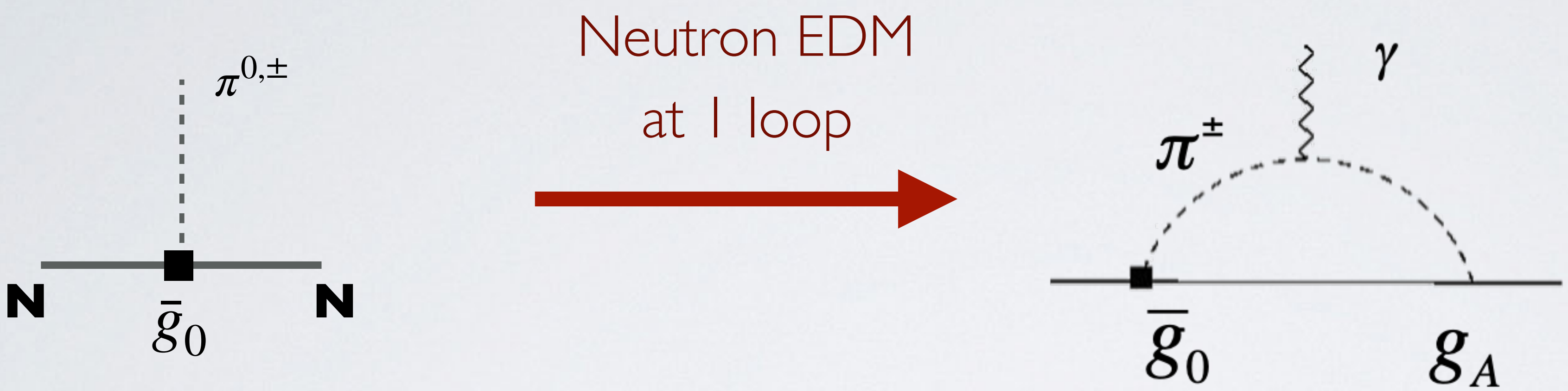
e.g. Borsanyi et al '14

Relation valid up to N^{2}LO corrections

JdV et al '15

Quantifying the strong CP problem

- **Problem:** Calculate EDMs in terms of the theta angle
- First calculation Crewther et al ’79, essentially leading-order Chiral perturbation theory.



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

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

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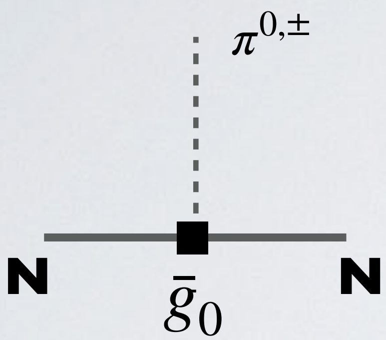
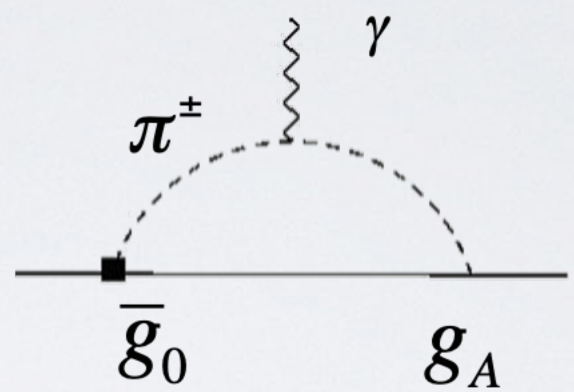


Neutron EDM
at 1 loop



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$d_n^{\mathrm{exp}} < 1.8 \cdot 10^{-26}\, e\,\mathrm{cm}$ PSI ‘20

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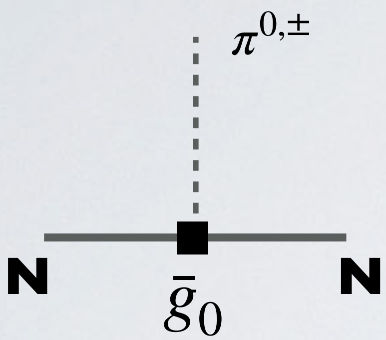

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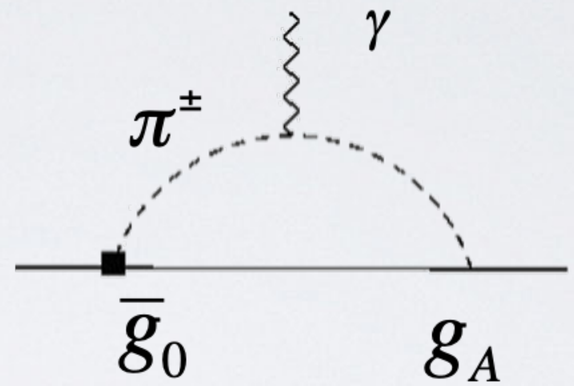

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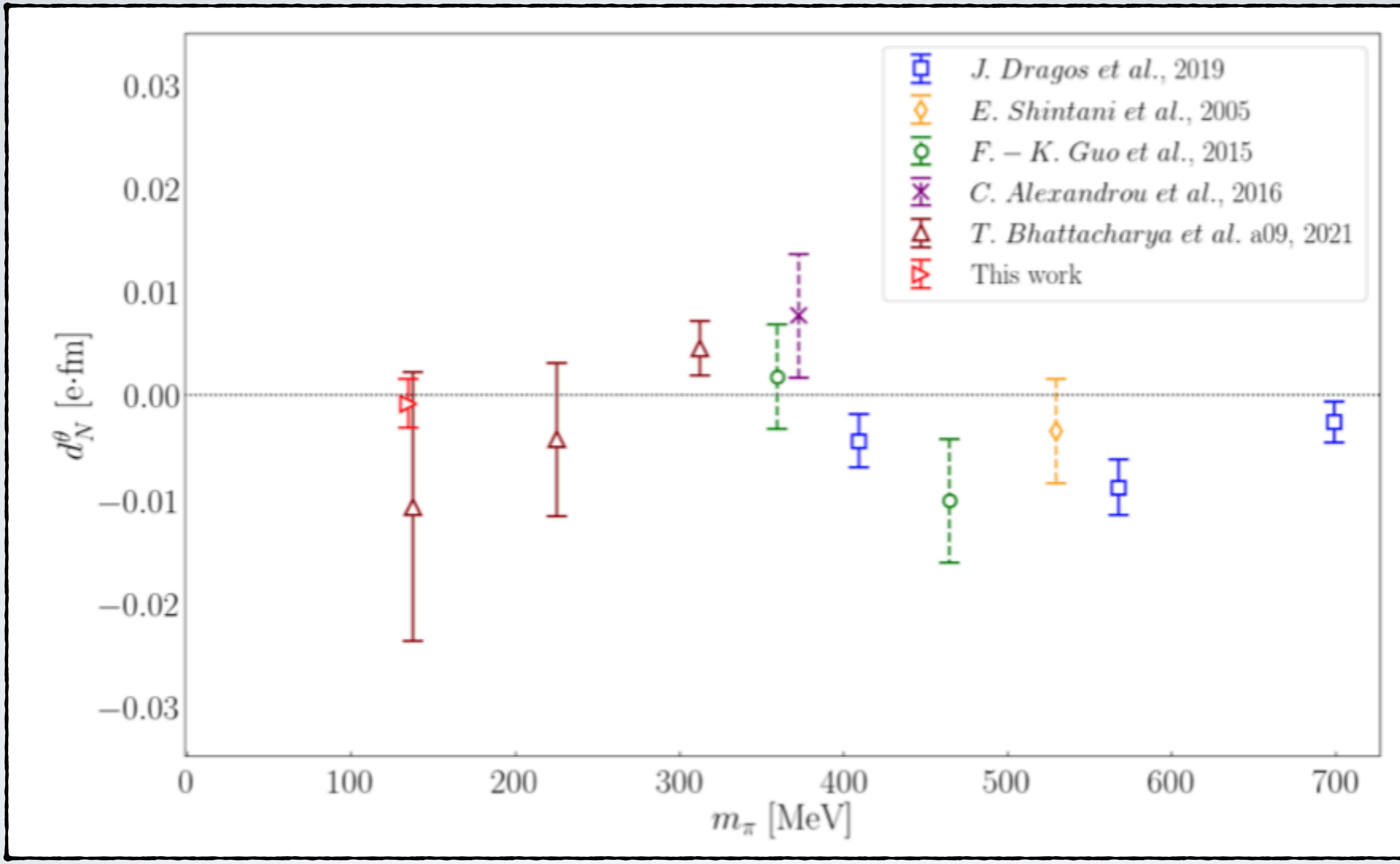
- Lattice QCD is needed for a full calculation. But no consensus yet it seems.

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

Not confirmed by recent calculations from LANL and Cyprus lattice group '21

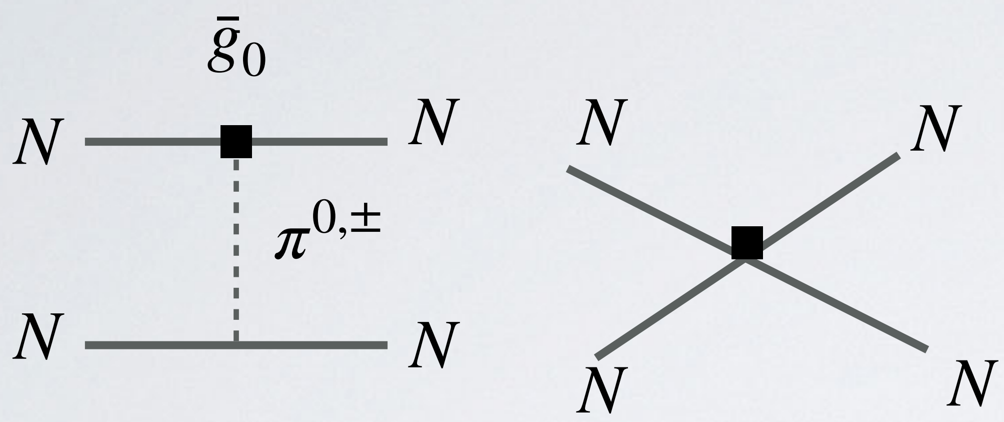
Quantifying the strong CP problem



Alexandrou et al, Arxiv: 2112.03989

Other probes of the theta term

CP-odd nuclear force



Review: JdV et al '21

Induces EDMs of nuclei and diamagnetic atoms (closed electron shells)

- Diamagnetic atoms (e.g. ^{199}Hg) gives stronger limits but large nuclear uncertainty $\bar{\theta} \sim < 10^{-10}$

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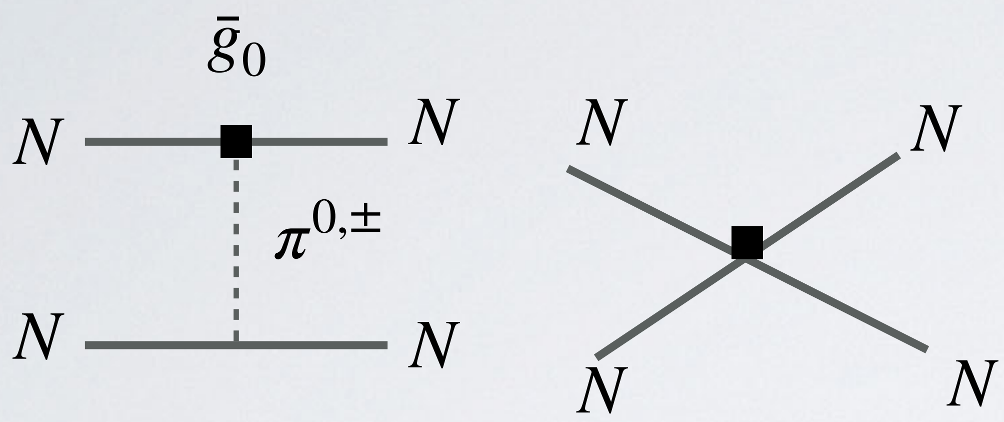

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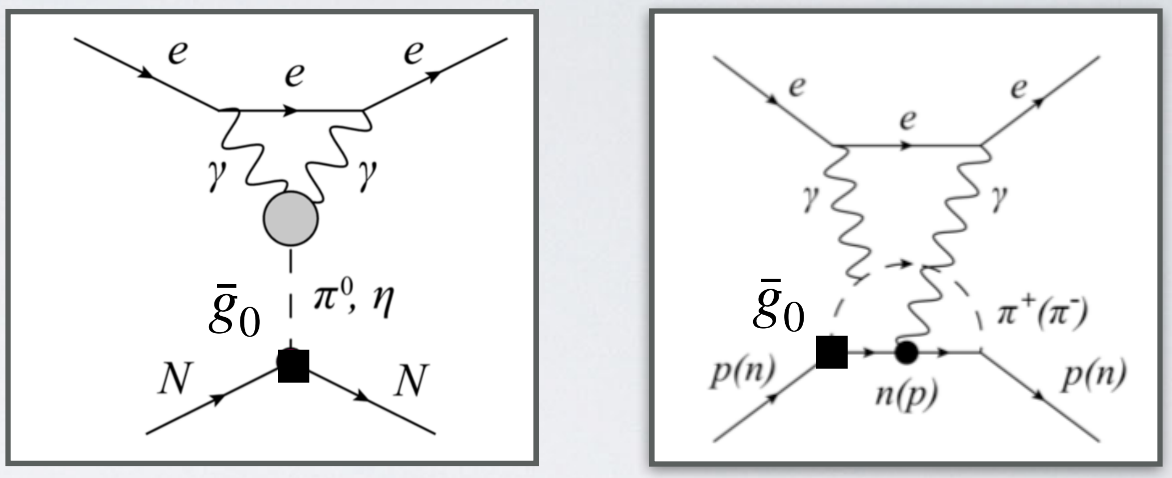
CP-odd nucleon-electron interactions



Flambaum, Pospelov, Ritz, Stadnik '19

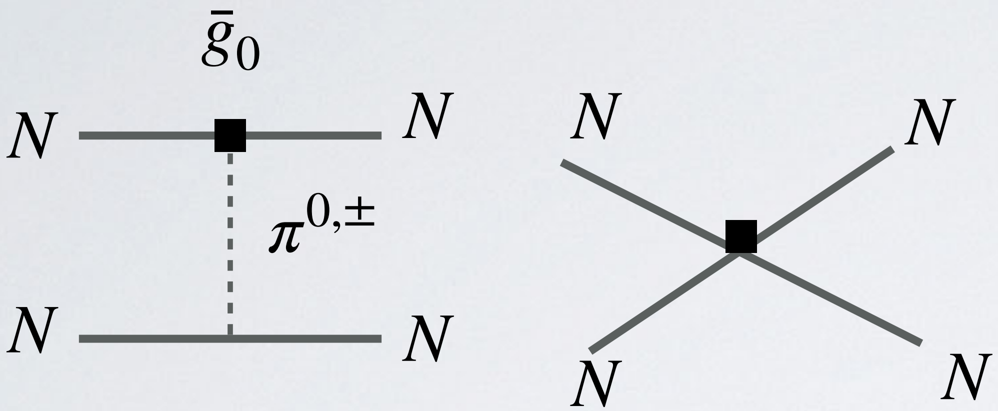
Induces EDMs of nuclei and diamagnetic atoms (closed electron shells)

Induces EDMs of paramagnetic atoms and molecules

- Diamagnetic atoms (e.g. ^{199}Hg) gives stronger limits but large nuclear uncertainty $\bar{\theta} \sim < 10^{-10}$
- Polar molecules EDMs not competitive yet, **but will be with 2 more orders!** Right now from ThO measurement $\bar{\theta} < 3 \cdot 10^{-8}$

Other probes of the theta term

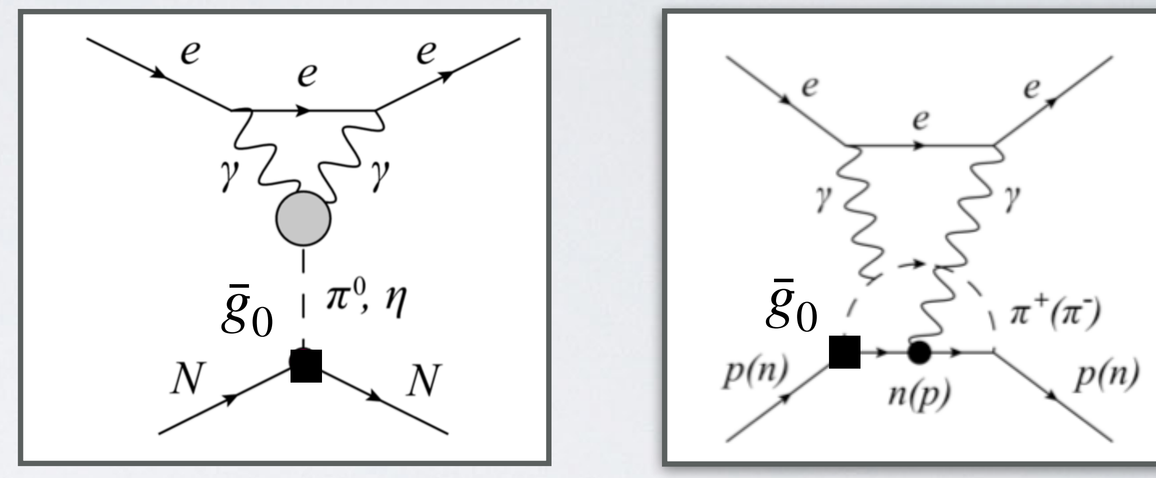
CP-odd nuclear force



Review: JdV et al '21

Induces EDMs of nuclei and diamagnetic atoms (closed electron shells)

CP-odd nucleon-electron interactions



Flambaum, Pospelov, Ritz, Stadnik '19

Induces EDMs of paramagnetic atoms and molecules

$\boxed{\text{Distinction between paramagnetic and diamagnetic systems is starting to lose its meaning}}$

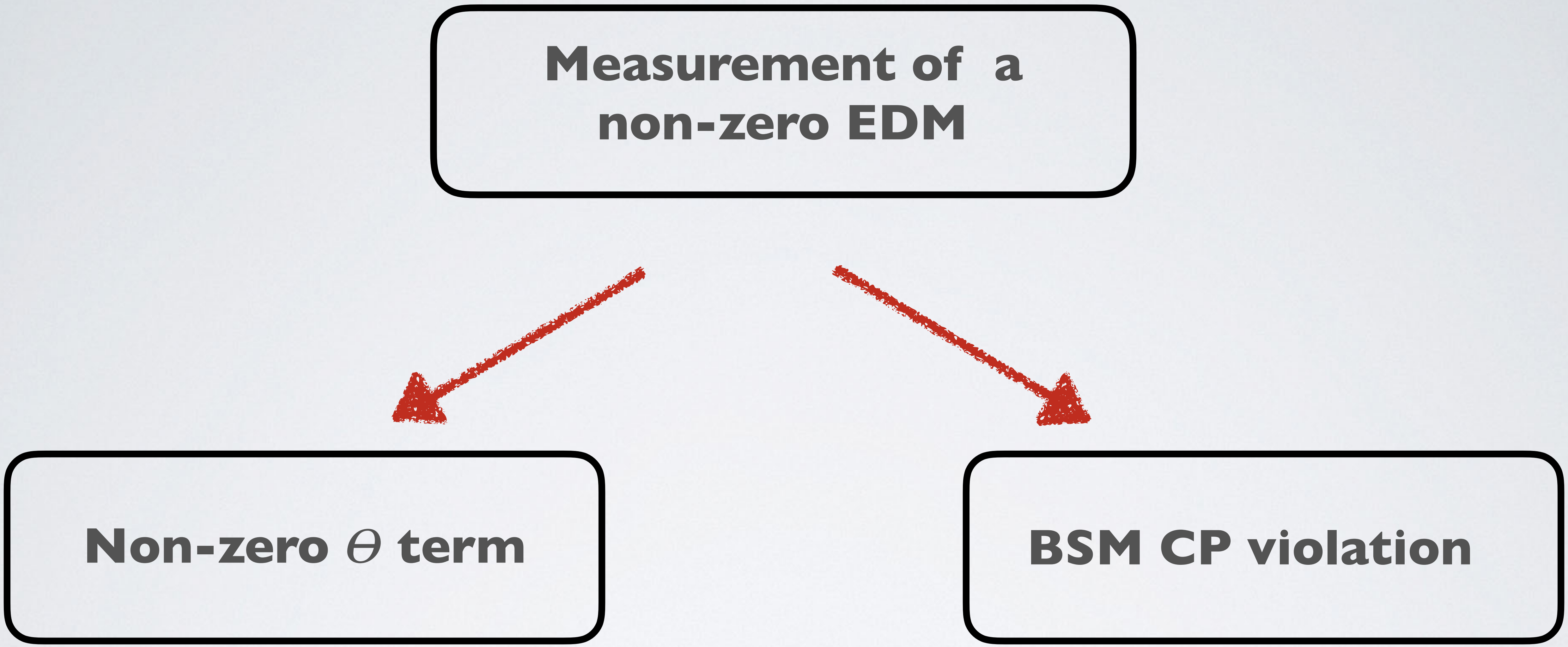
The plan of attack

1. EDMs 101

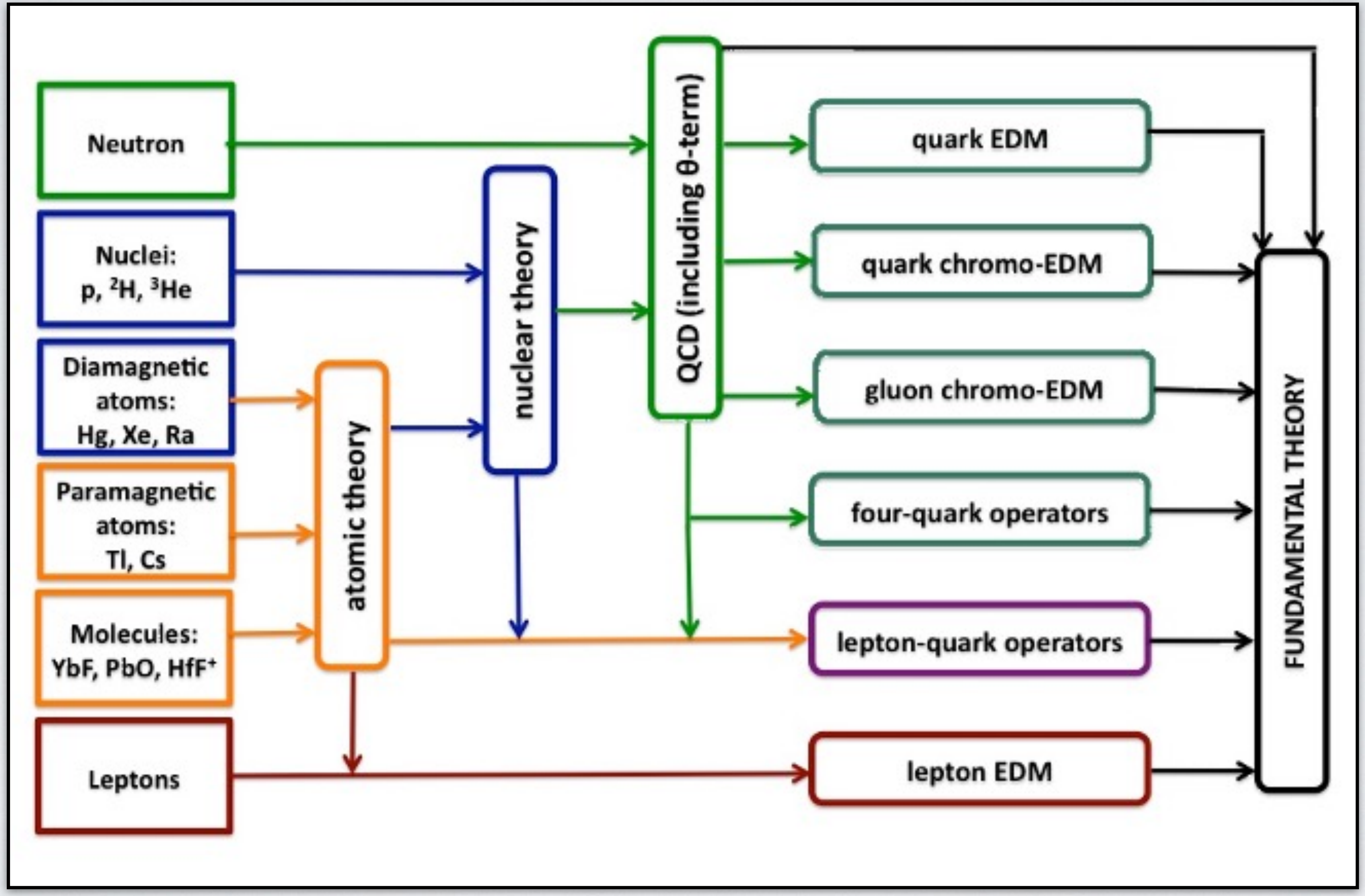
2. EDMs in the Standard Model revisited

3. **BSM interpretations**

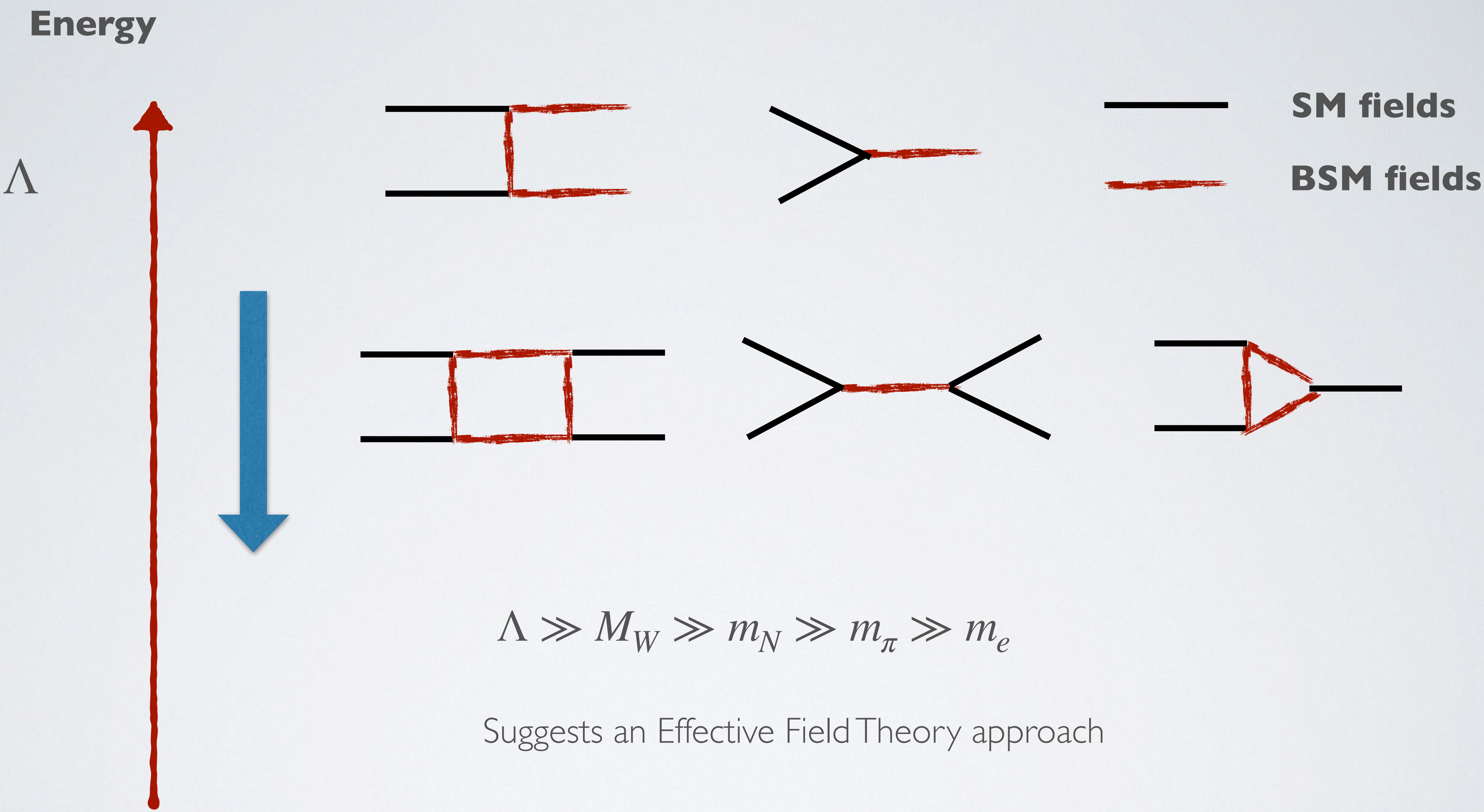
A Luxury Problem



The metro map



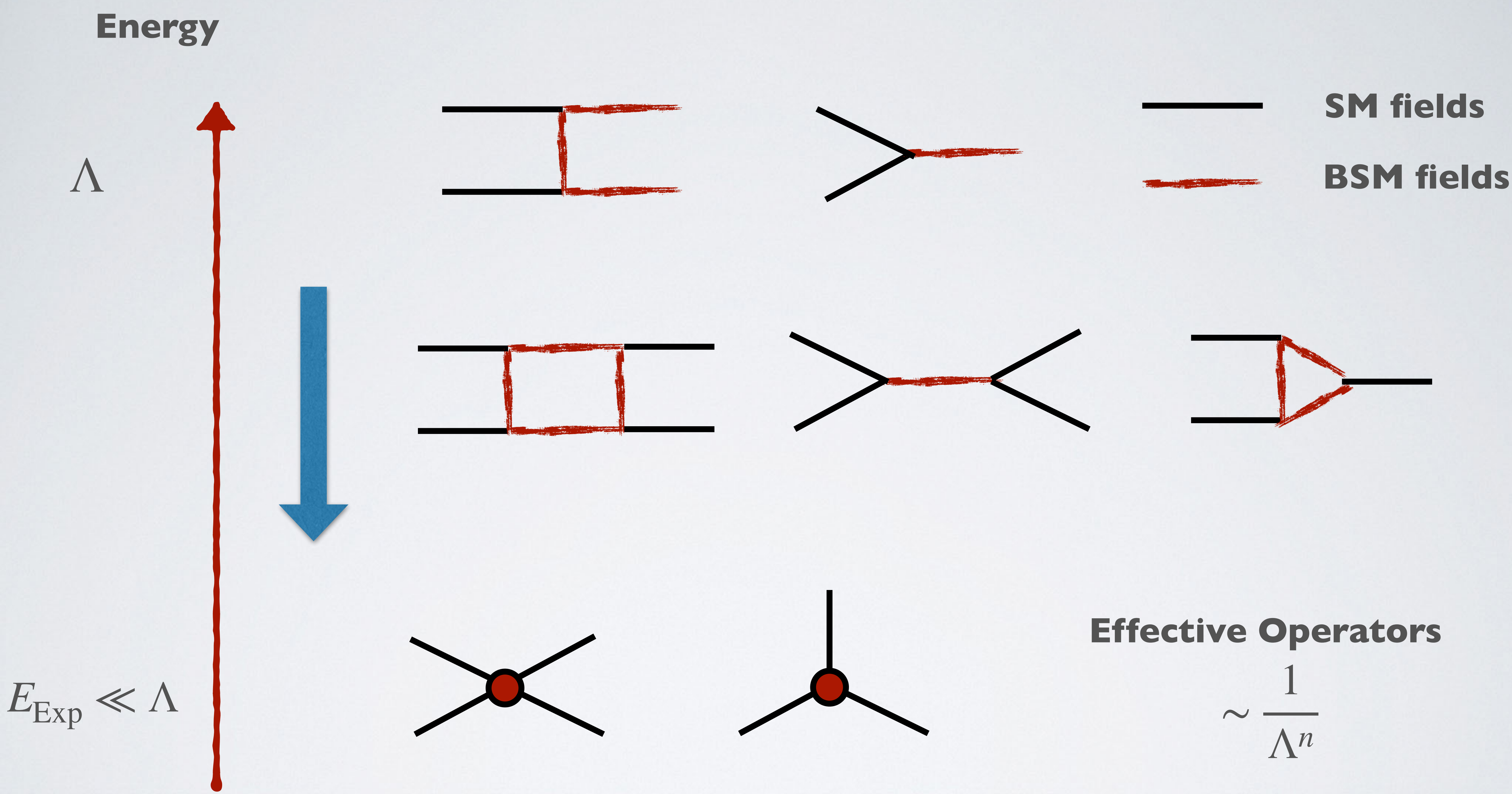
EDMs are low-energy experiments



$$\Lambda \gg M_W \gg m_N \gg m_\pi \gg m_e$$

Suggests an Effective Field Theory approach

EDMs are low-energy experiments



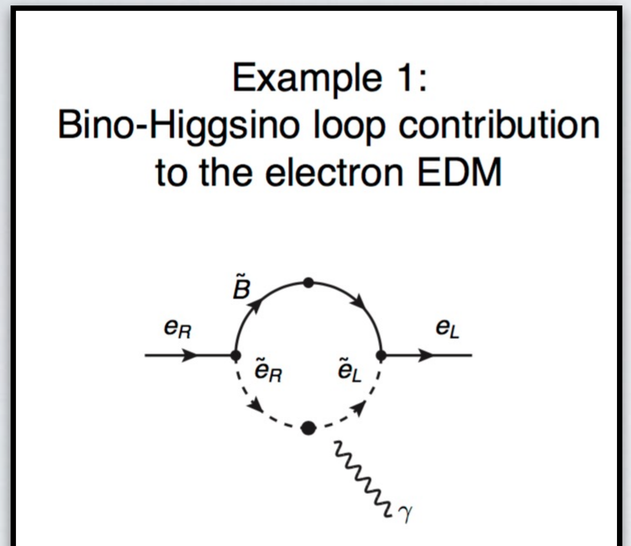
Effects of heavy BSM fields capture by local effective operators

Can do low-energy physics without knowing what is out there

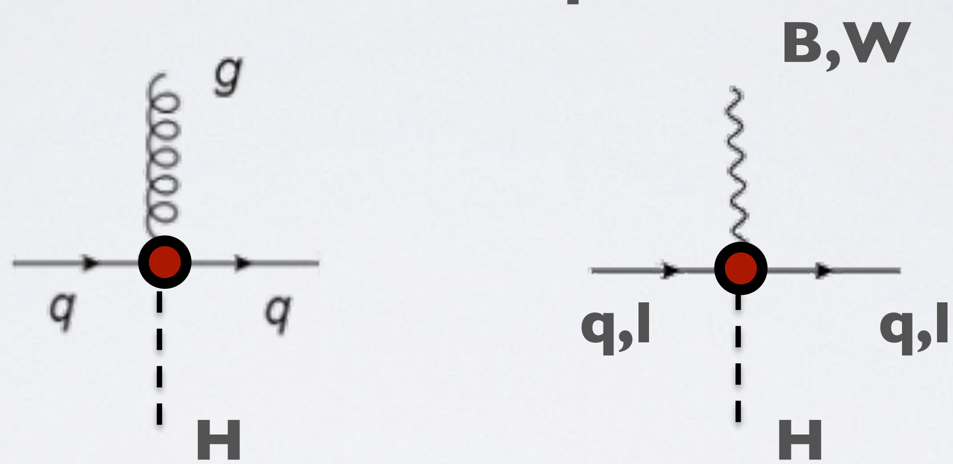
CP violation in SM-EFT

- Large number of **CP-odd** and **flavor-diagonal** dim-6 operators (unlike Standard Model)

- Many BSM models induce new CP violation

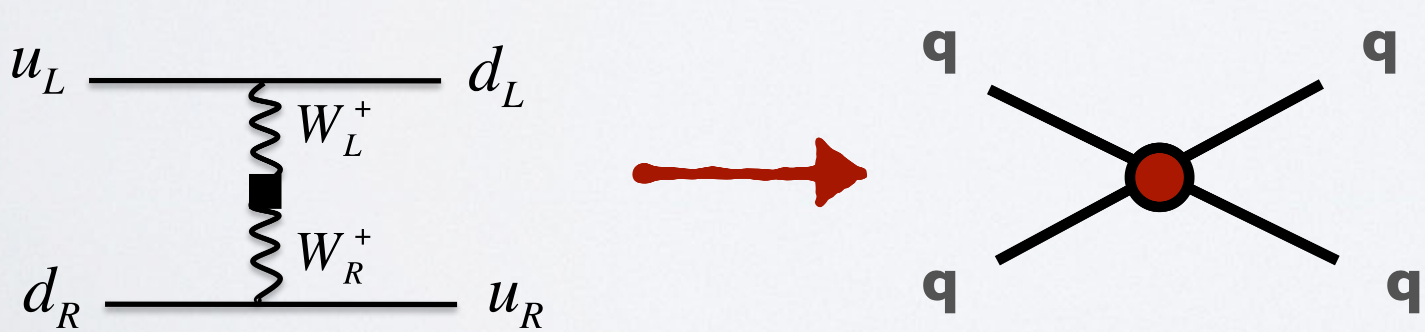


CP-odd dipoles



$$\sim \frac{1}{\Lambda^2}\frac{\alpha_{em}}{\pi}\sin\phi_{CP}$$

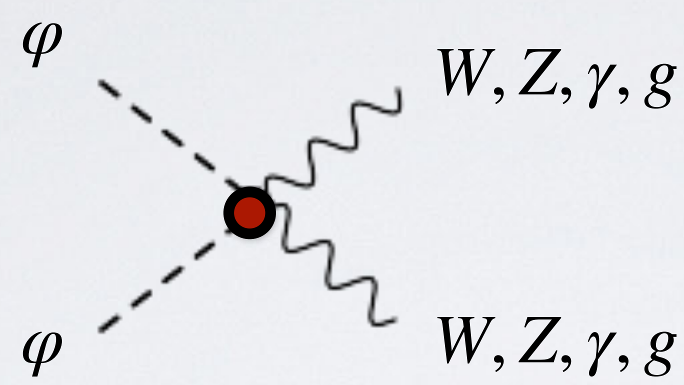
left-right symmetric models



$$\sim \frac{1}{\Lambda^2}\sin\phi_{CP}$$

Interplay with LHC

- Study how low-energy atomic/molecular EDMs probe interactions with Higgs
- Example CP-violating Higgs-gauge couplings (4 exist B, W, WB, G)



$$C_{\varphi X}\, \varphi^\dagger \varphi\, X\tilde{X}$$

$$X = W, Z, \gamma, g$$

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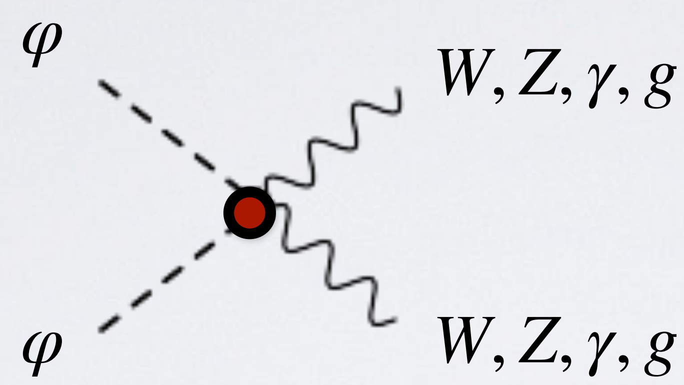

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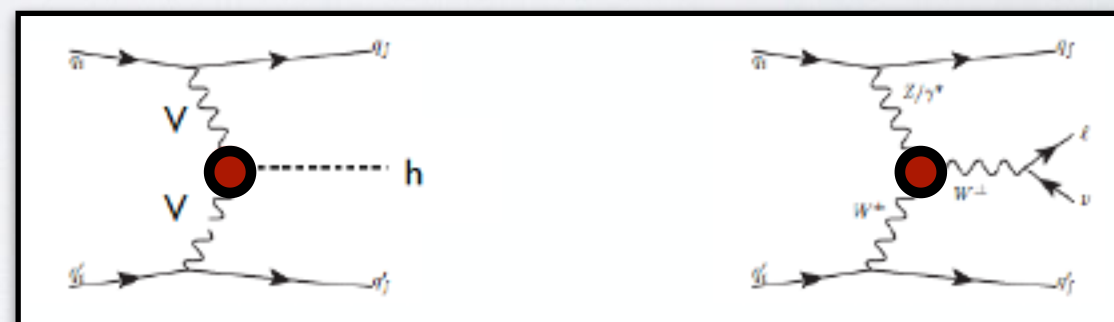
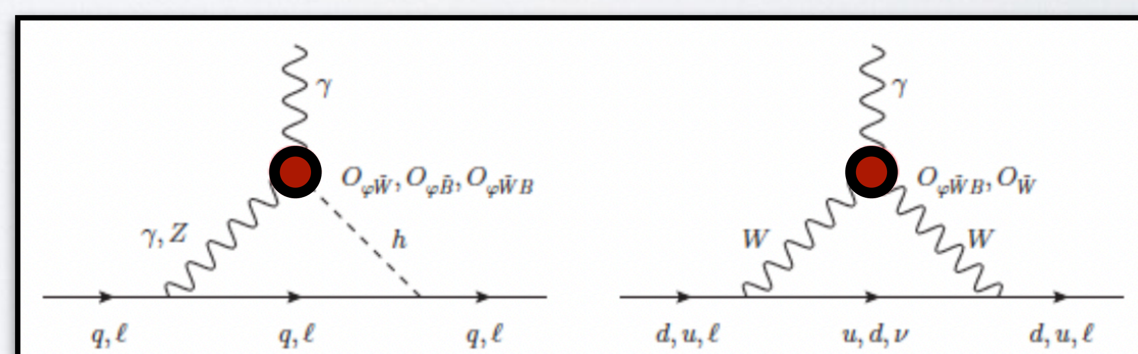
- Searched for at LHC in angular distributions



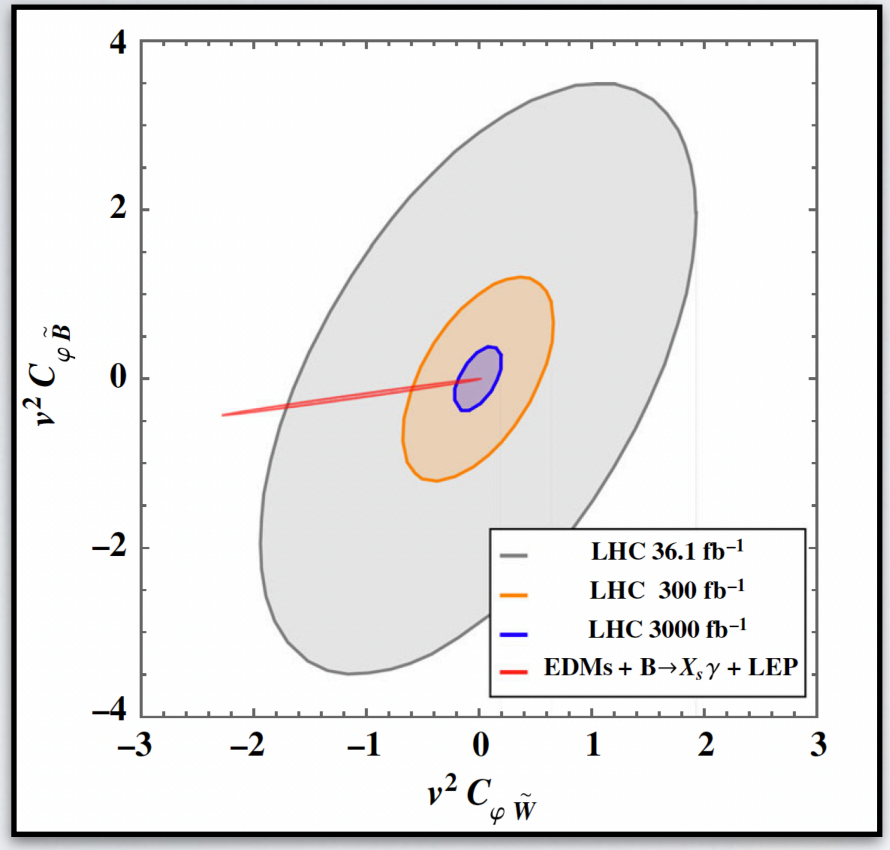
- Electric Dipole Moments induced at one loop

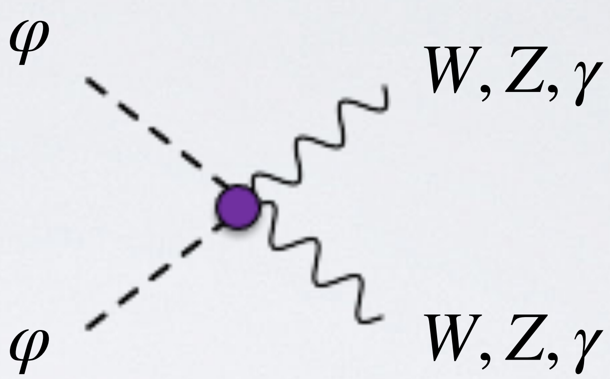


- EDMs give strong limits but leave ‘free’ directions

CP violation in SM-EFT

Cirigliano, JdV, Crivellin, Dekens, Hoferichter, Mereghetti, PRL '19





$$C_{\varphi X}\, \varphi^\dagger \varphi\, X\tilde{X}$$

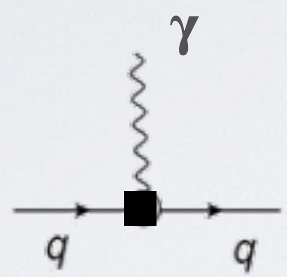
$$X = W, Z, \gamma$$

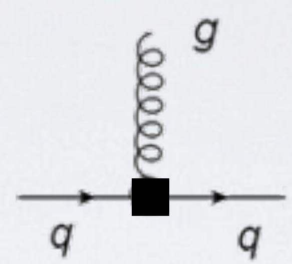
- **CP-violation in Higgs sector is best tested by combining LHC + flavor + EDMs**
- **Direct impact for viability of electroweak baryogenesis**

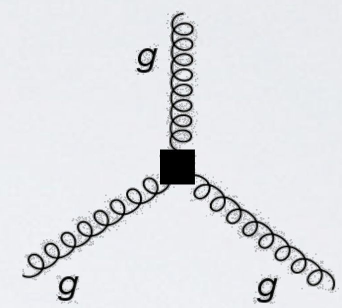
From SM-EFT to low energies

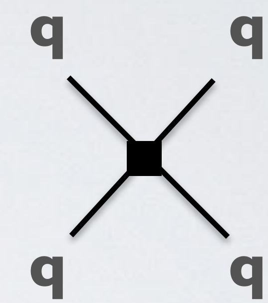
- Large number of **CP-odd** and **flavor-diagonal** dim-6 operators (unlike Standard Model)
- At energies around a few GeV: handful of operators left

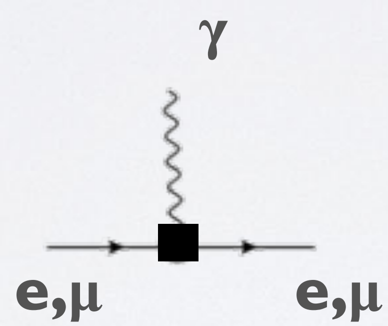
$$\mathscr{L}_\theta \sim \bar{\theta}\epsilon^{\mu\nu\alpha\beta}G^a_{\mu\nu}G^a_{\alpha\beta}$$

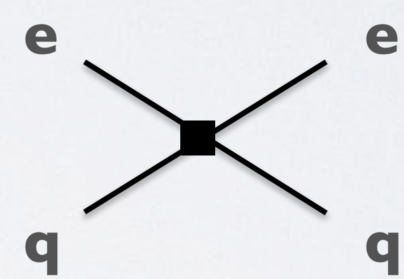








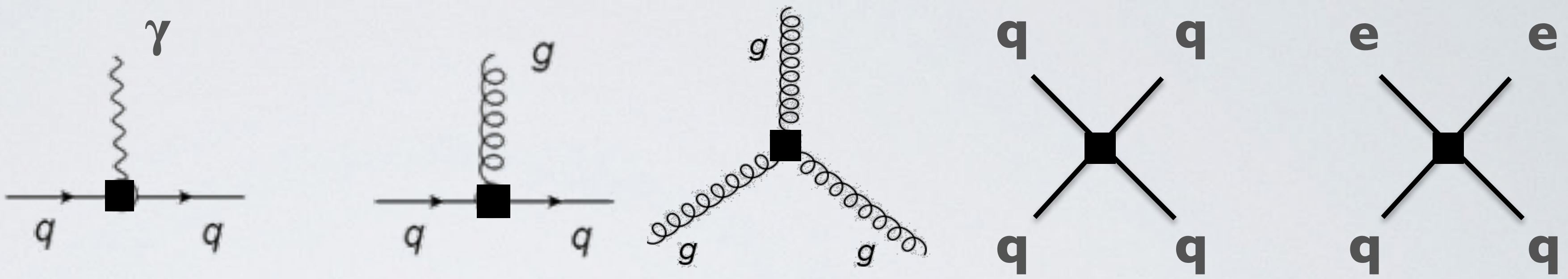




- Induce electric dipole moments of leptons, hadrons, nuclei, atoms, molecules

From SM-EFT to low energies

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



- They all break CP symmetry……
- But have different isospin and chiral symmetry properties → pattern of EDMs

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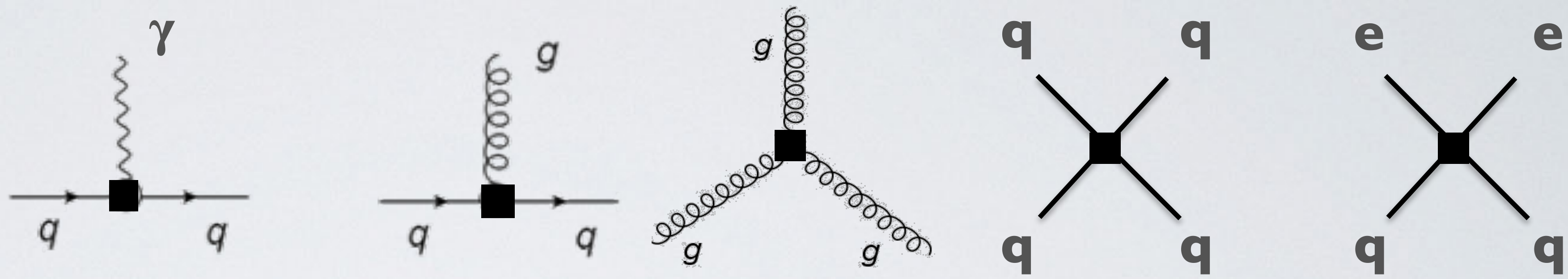
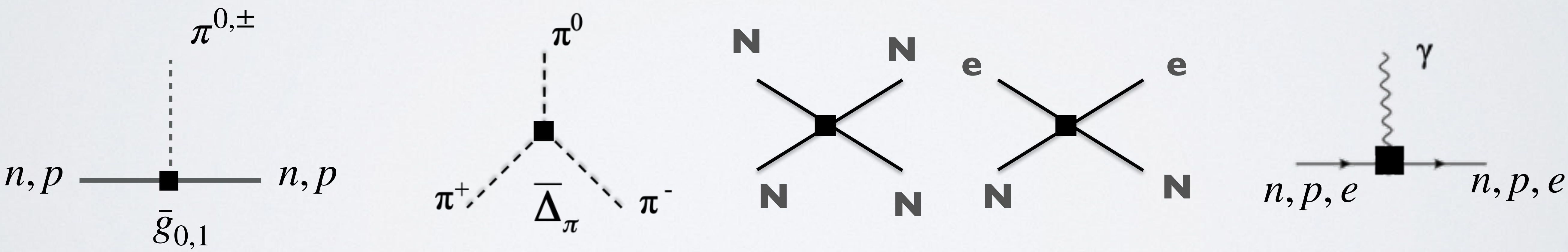


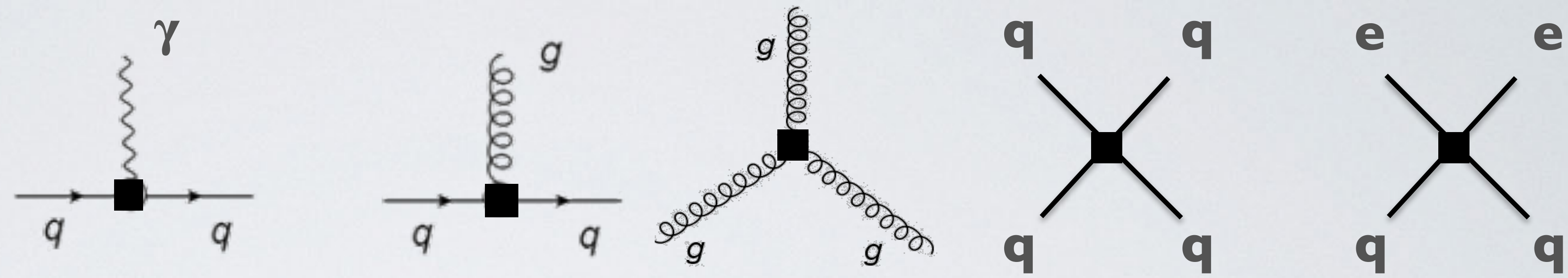
- They all break CP symmetry……
- But have different isospin and chiral symmetry properties → pattern of EDMs
- Use Chiral EFT to match quark-gluon operators to CP-odd hadronic couplings JdV et al '12



- For all sources of CPV: only a handful of hadronic interactions. A few more for magnetic quadrupole moments (pion-nucleon-photon)

Patterns of EDMs

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



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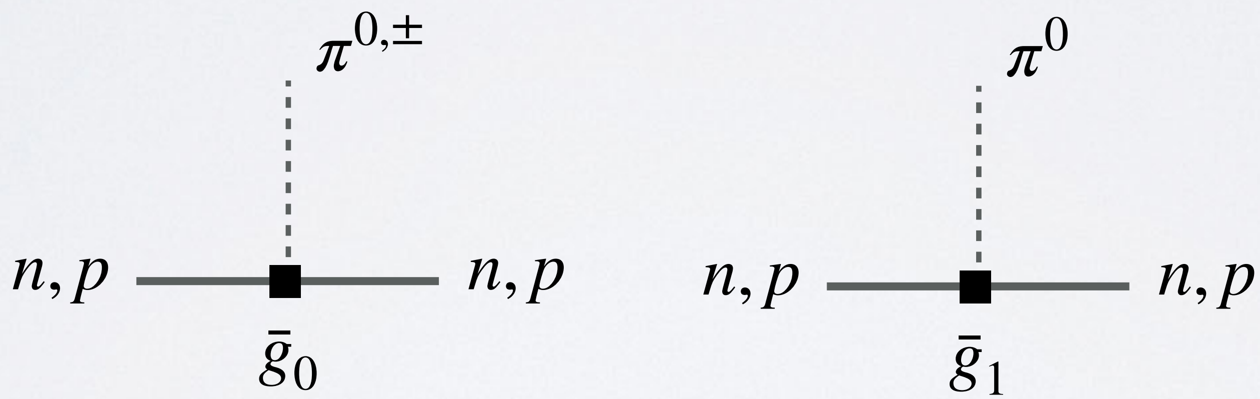
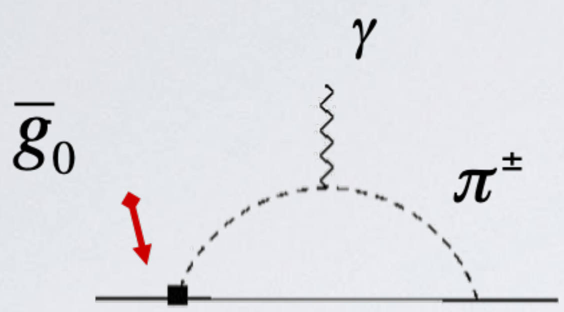


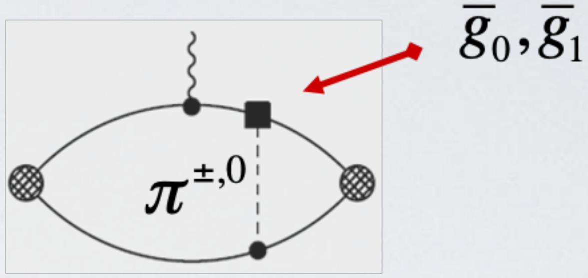
- Ratios vary

	Theta term	Quark CEDMs	FQLR	Quark EDM and Weinberg
$\frac{\bar{g}_1}{\bar{g}_0}$	–0.2	≈ 1	+50	Both couplings are suppressed !

JdV et al '12

Computing nuclear CP-odd moments





Khriplovich/Korkin '00
JdV, Mereghetti, Timmermans, van Kolck
PRL '11

- Nuclear CP violation can be larger than nucleon CP violation ! No loop suppression !
- Easiest example: the **deuteron EDM**

See talk by Mereghetti

$$d_D = 0.9(d_n + d_p) + \left[(0.18 \pm 0.02)\,\bar{g}_1 + (0.0028 \pm 0.0003)\,\bar{g}_0\right] e\ fm$$

`	Theta term	Quark CEDMs	Four-quark operator	Quark EDM and Weinberg
$\left\lvert \frac{d_D - d_n - d_p}{d_n} \right\rvert$	0.5 ± 0.2	5 ± 3	20 ± 10	$\cong 0$

- Ratio of deuteron-to-neutron EDM would tell a lot about the source !
- But deuteron EDM in storage ring is very far away !

Computing atomic CP-odd moments

- Similar computation needed for diamagnetic atoms. For instance Hg

$$
\begin{aligned}
d_{\mathrm{Hg}} &= -(2.1 \pm 0.5) \cdot 10^{-4} \left[(1.9 \pm 0.1) d_n + (0.20 \pm 0.06) d_p + \left(0.13^{+0.5}_{-0.07}\, \bar{g}_0 + 0.25^{+0.89}_{-0.63}\, \bar{g}_1 \right) e\,\mathrm{fm} \right] \\
&\quad + (0.012 \pm 0.012) d_e - \left[(0.028 \pm 0.006) C_S - \frac{1}{3}(3.6 \pm 0.4) \left(C_T + \frac{Z\alpha}{5 m_N R} C_P \right) \right] \cdot 10^{-20}\, e\,\mathrm{cm}
\end{aligned}
$$

See talk by Dobaczewski

- A lot of contributions! **And large uncertainties for nuclear part.**
- Not all operators not included! No short-range nuclear forces. But they can be relevant ! Shain et al '20
- Additional QCD uncertainty from expressing hadronic couplings in terms of SMEFT operators

Need Lattice !

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- Not all operators not included! No short-range nuclear forces. But they can be relevant ! Shain et al '20
- Additional QCD uncertainty from expressing hadronic couplings in terms of SMEFT operators

Need Lattice !

- To unravel these terms we need measurements on different systems !
- And need more theory input (both lattice and nuclear)
- Radium looks a bit better regarding the nuclear uncertainties

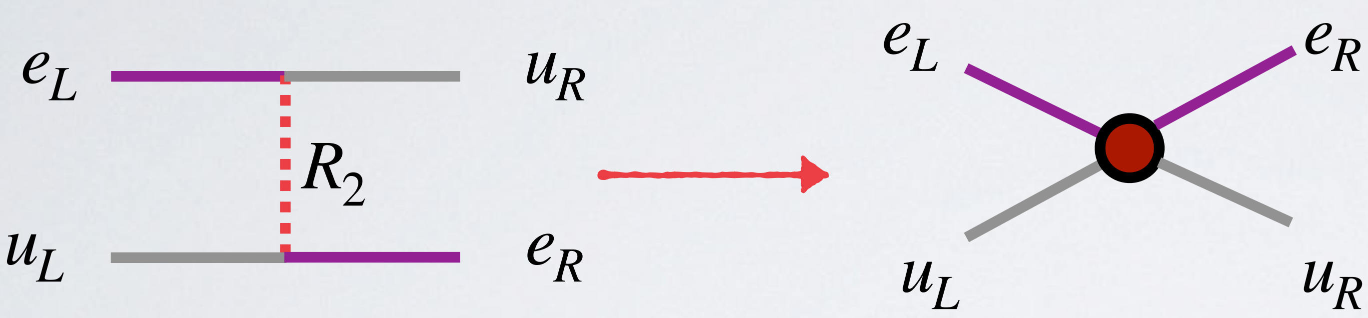
Dobaczewski et al PRL '18

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

Some examples to illustrate unraveling

- Simplest example: a scalar leptoquark model (so called S₁ LQ for the experts)

$$\mathscr{L} = R_2 \left(x_{RL} \bar{u}_R e_L + x_{LR} \bar{u}_L e_R \right) + \mathrm{h.c.}$$



$$\sim \frac{\mathrm{Im}(x^{eu}_{LR} x^{eu}_{RL})}{m^2_{LQ}}$$

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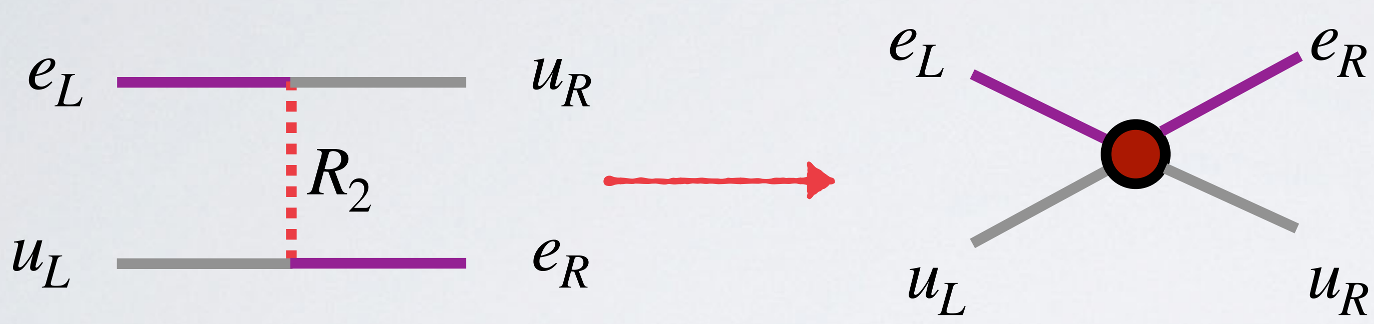

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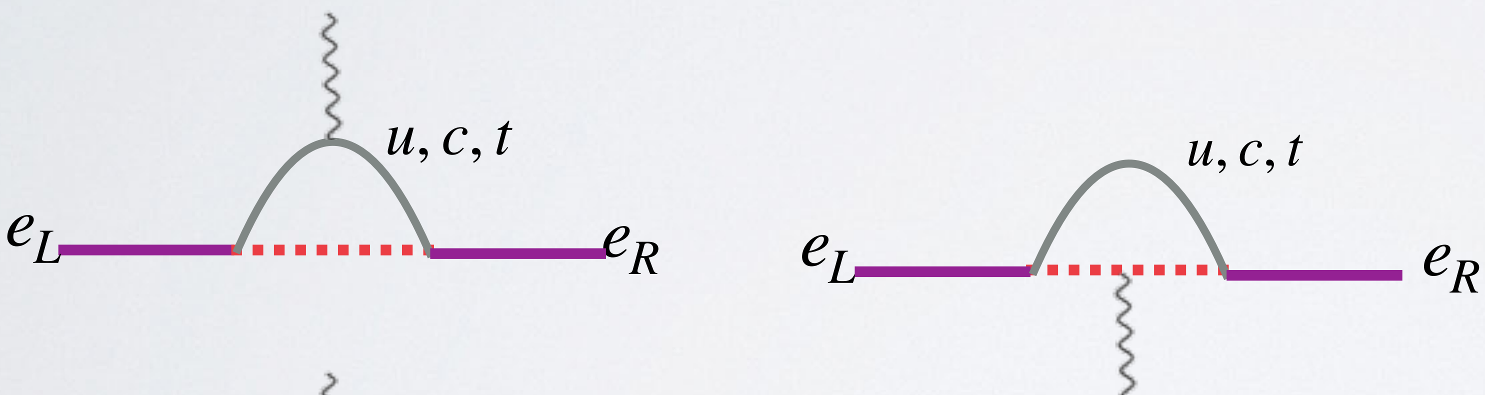
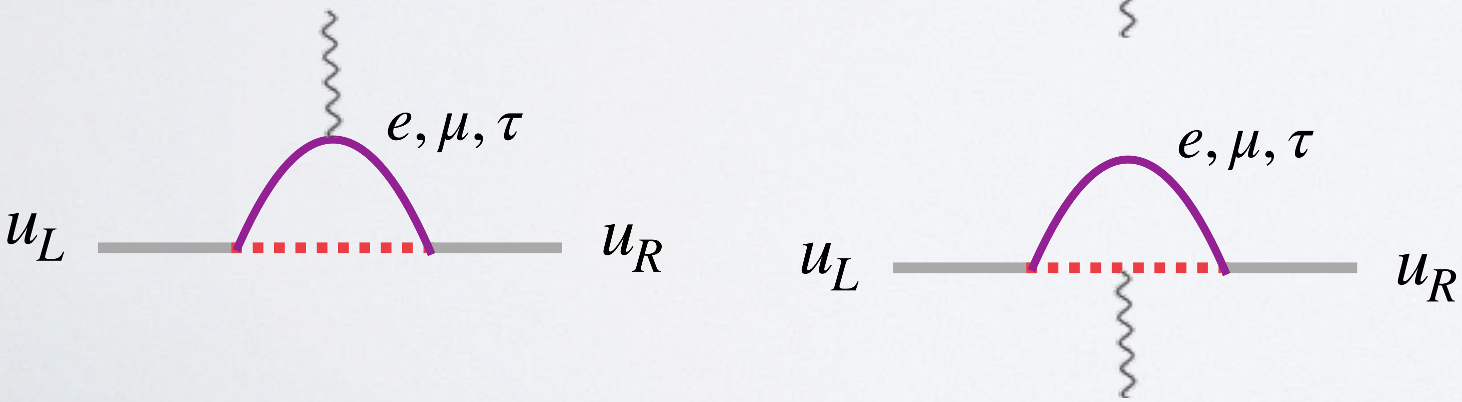


$$\sim \frac{\alpha}{4\pi} \frac{m_Q}{m_e} \frac{\mathrm{Im}(x^{eQ}_{LR} x^{eQ}_{RL})}{m^2_{LQ}}$$



$$\sim \frac{\alpha}{4\pi} \frac{m_L}{m_u} \frac{\mathrm{Im}(x^{uL}_{LR} x^{uL}_{RL})}{m^2_{LQ}}$$

- Tree-level wins for electron-up couplings, electron EDM wins for top-electron couplings.

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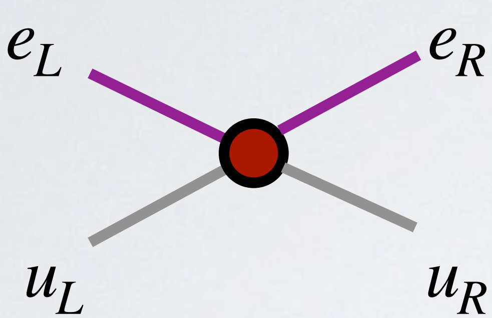

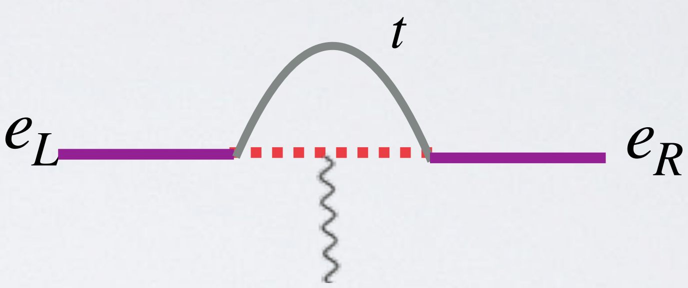

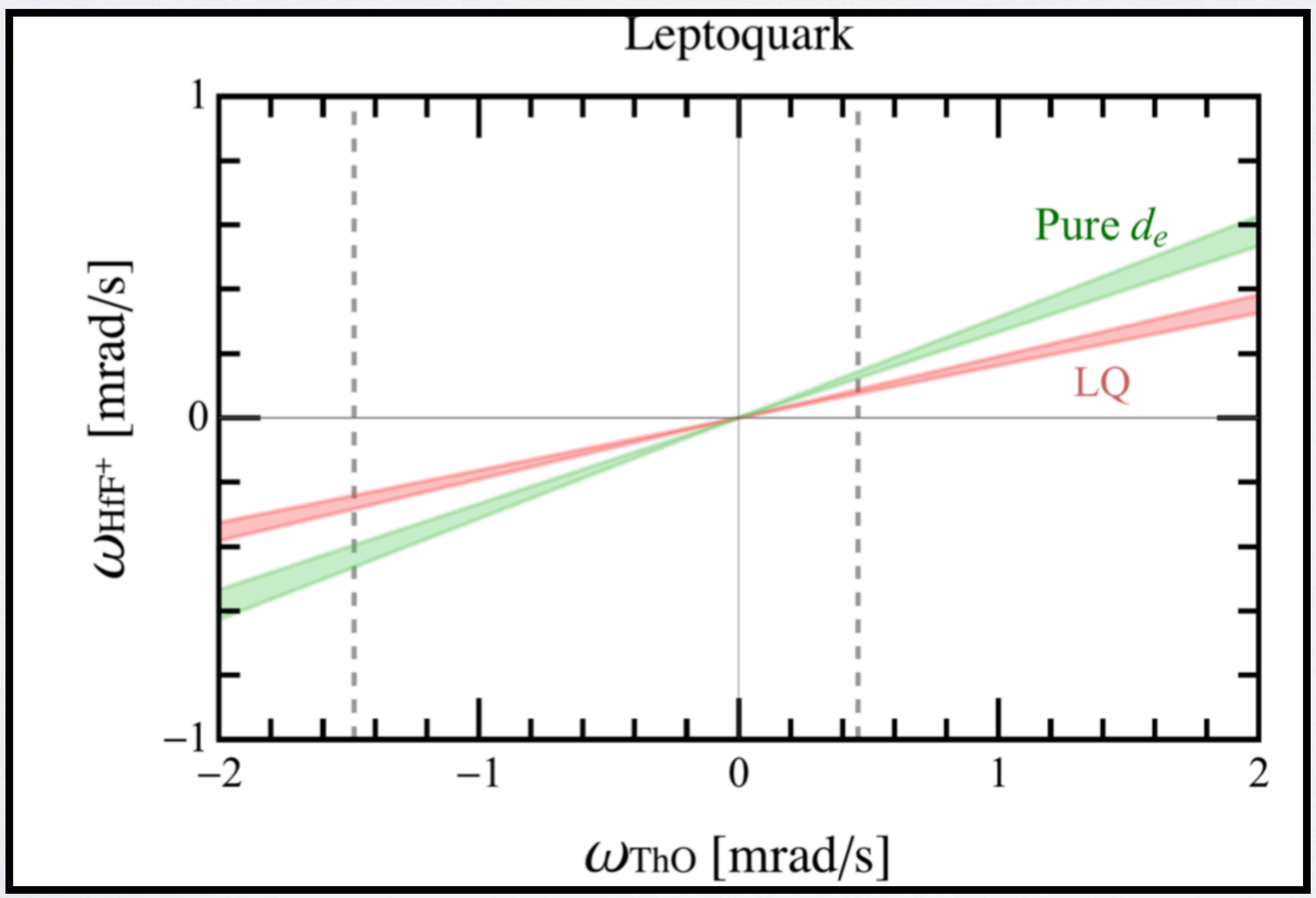

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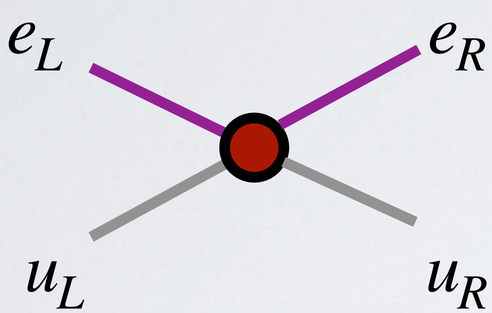
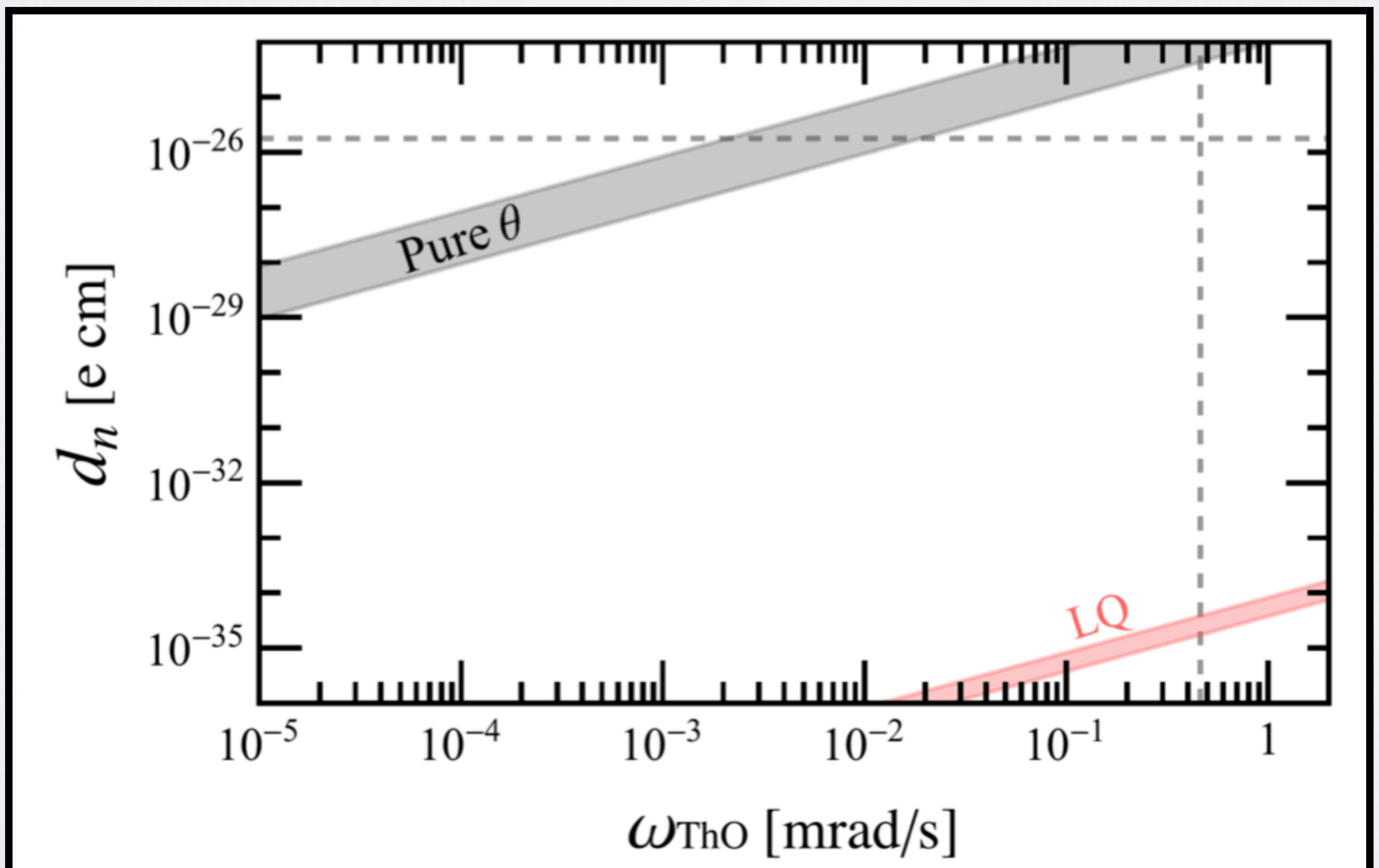


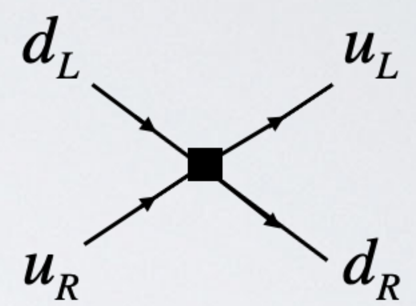
$$\theta \frac{g_s^2}{32\pi^2}\epsilon^{\alpha\beta\mu\nu}G_{\alpha\beta}G_{\mu\nu}$$

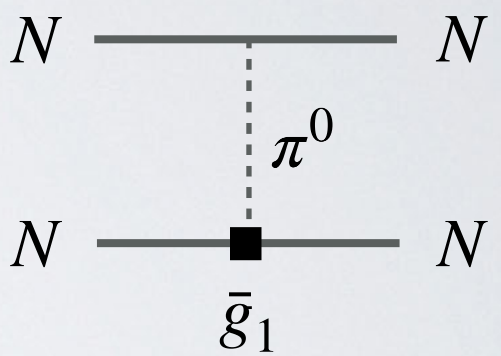


Some examples to illustrate unraveling

- Second example: the minimal left-right-symmetric model
- Mixing between left- and right-handed W bosons leads to unique dim-6 operators

$$\mathscr{L}_{6,CPV} \sim \frac{\sin\alpha}{m_{W_R}^2}\left[(\varphi^\dagger D_\mu \varphi)\bar{u}_R\gamma^\mu d_R - \mathrm{h.c.}\right]$$





- Isospin-violating four-quark operators leads to large isovector nuclear force

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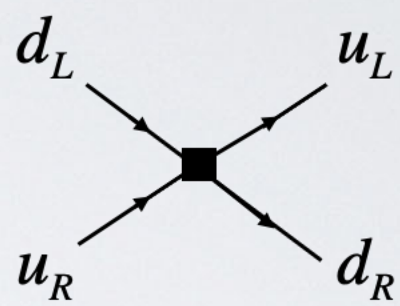

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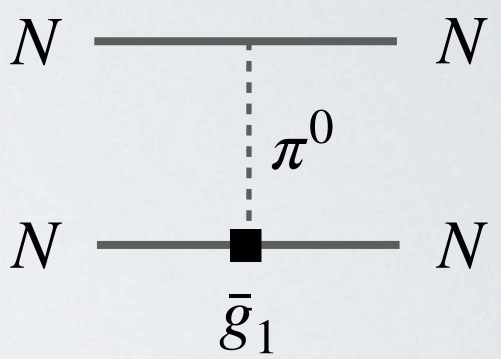

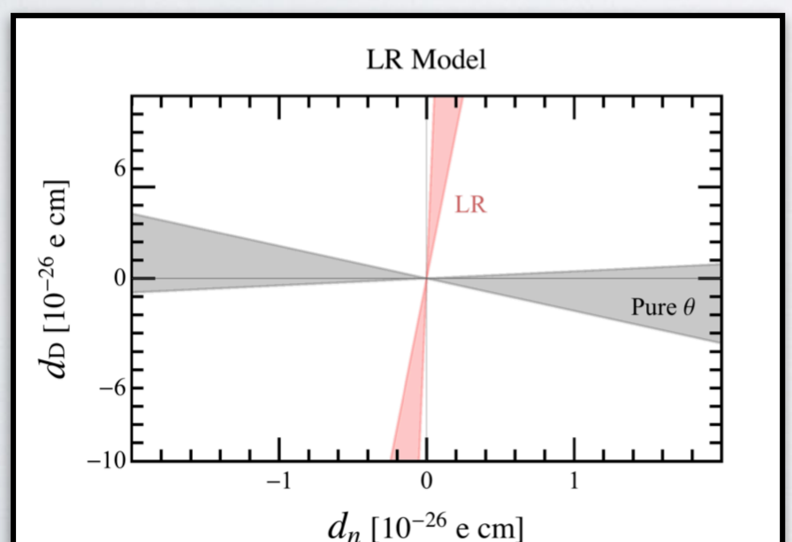

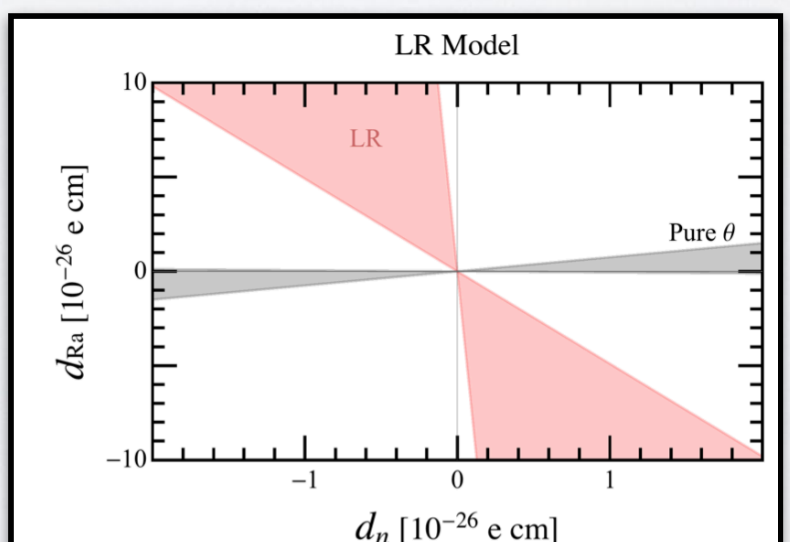

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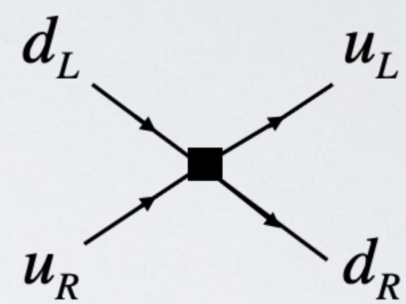
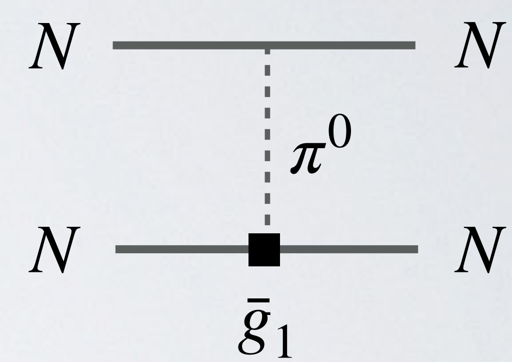
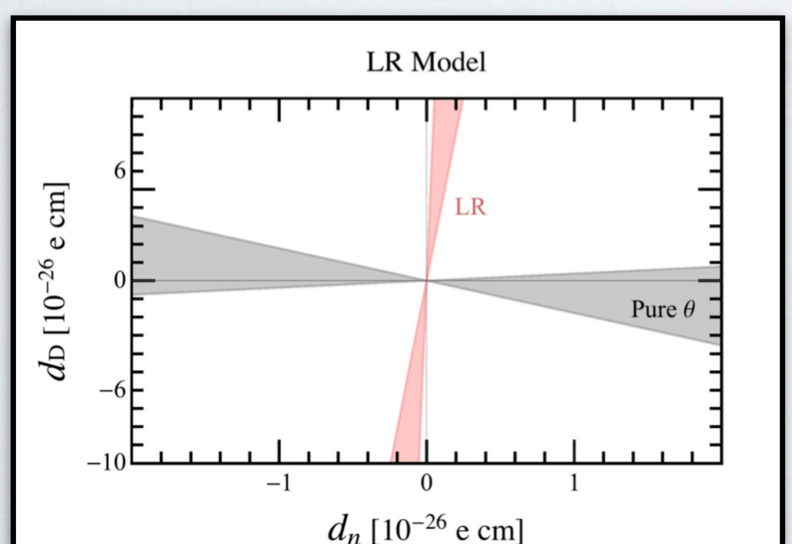
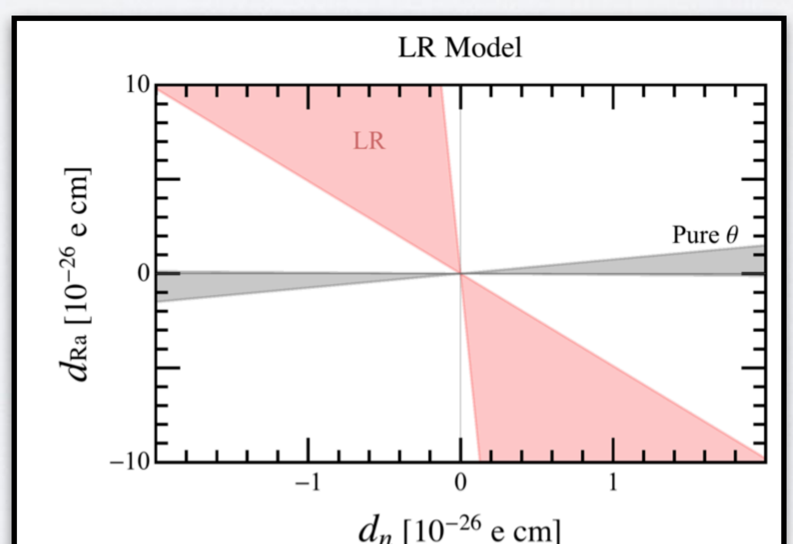
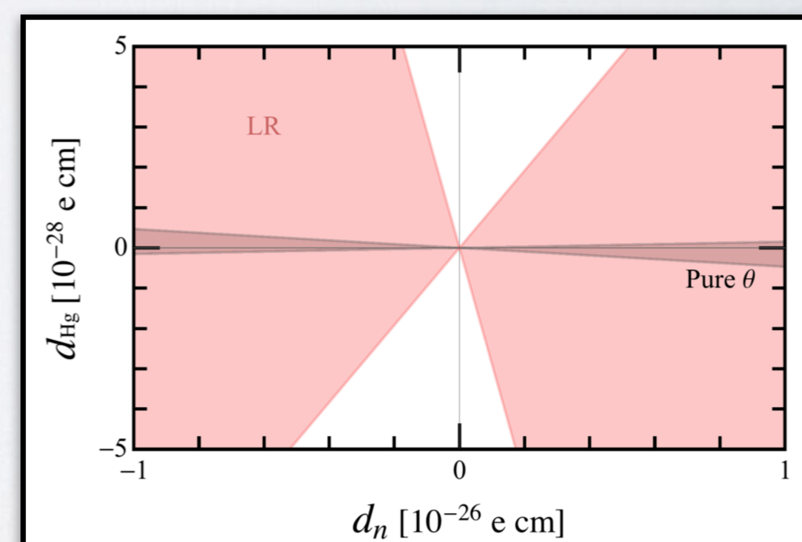




- Isospin-violating four-quark operators leads to large isovector nuclear force

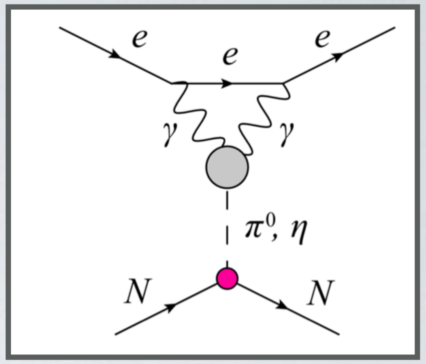






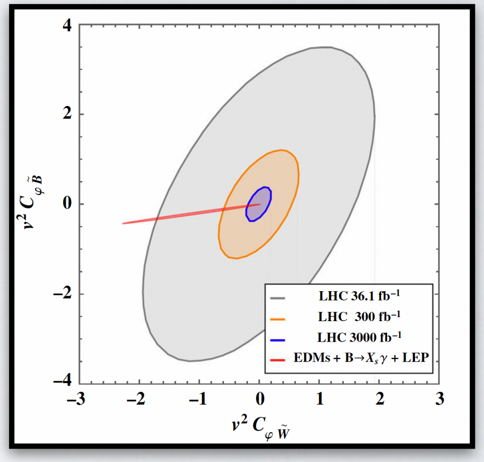
- Unraveling is limited by theoretical understanding of matrix elements (hadronic + nuclear)

Conclusions/Summary



- EDMs are powerful ways to look for new CP violation
- EFTs are extremely useful to bridge the scales

- Sensitive to dimension-six sources up to thousands of TeV (depending on operator)
- Last decade, a lot of theory improvements to calculate EDMs (EFT, lattice)



- EDMs from CKM still far away, but not as far as initially thought !
- Paramagnetic systems are becoming 'diamagnetic' as well

- Theoretical framework in place to connect high-scale sources of CPV to EDMs
- Clear and direct connection to LHC program
- Still need more effort to understand matrix elements (in particular hadronic and nuclear)