RESOLVING THE STRONG CP PROBLEM WITH THE EDM PORTFOLIO*

Jordy de Vries

University of Amsterdam & Nikhef

Based on recent work with Patrick Draper, Kaori Fuyuto, Jonathan Kozaczuk, Ben Lillard

And a lot of older work with the FZJ+Bonn crew (Andreas and Ulf and others)

* Title does not reflect contents of this talk

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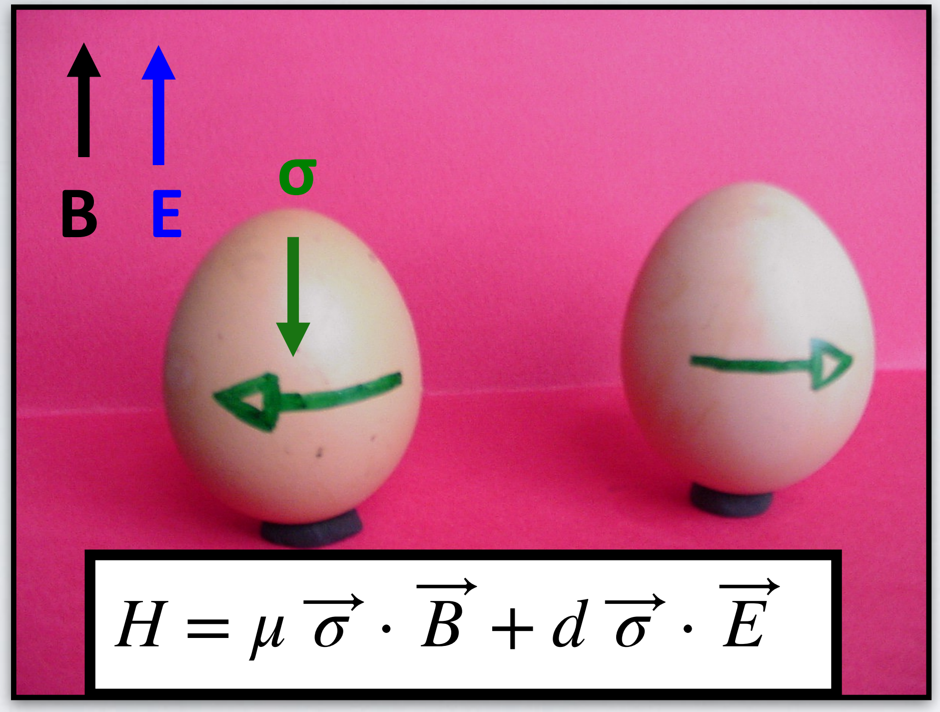
Electric dipole moments 101



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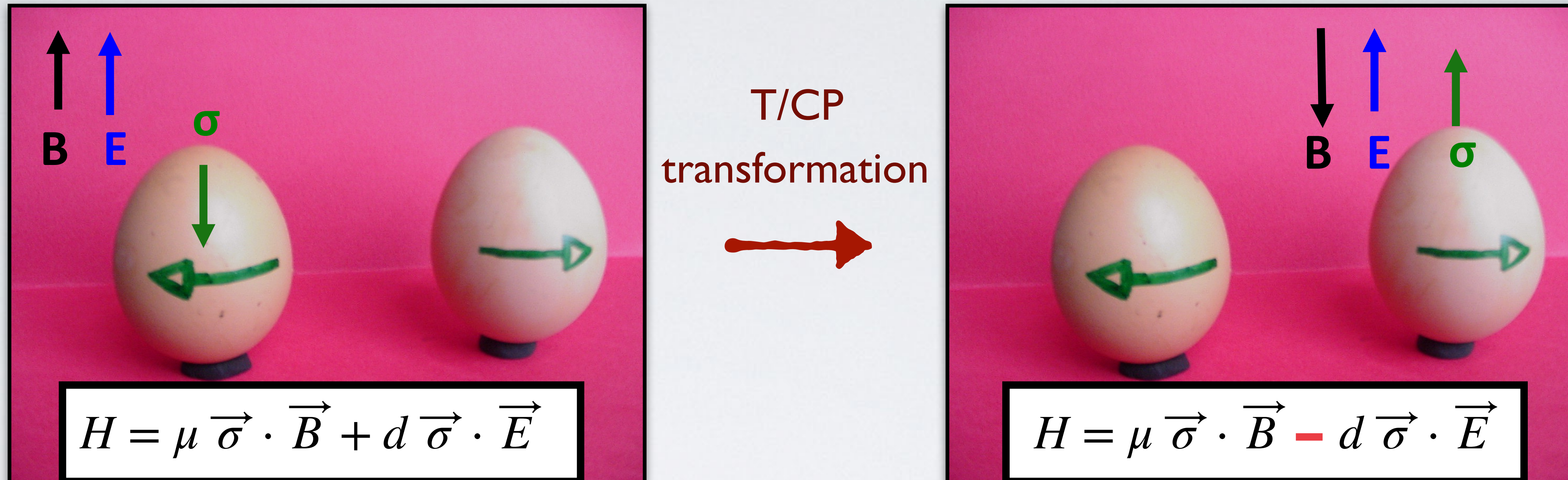

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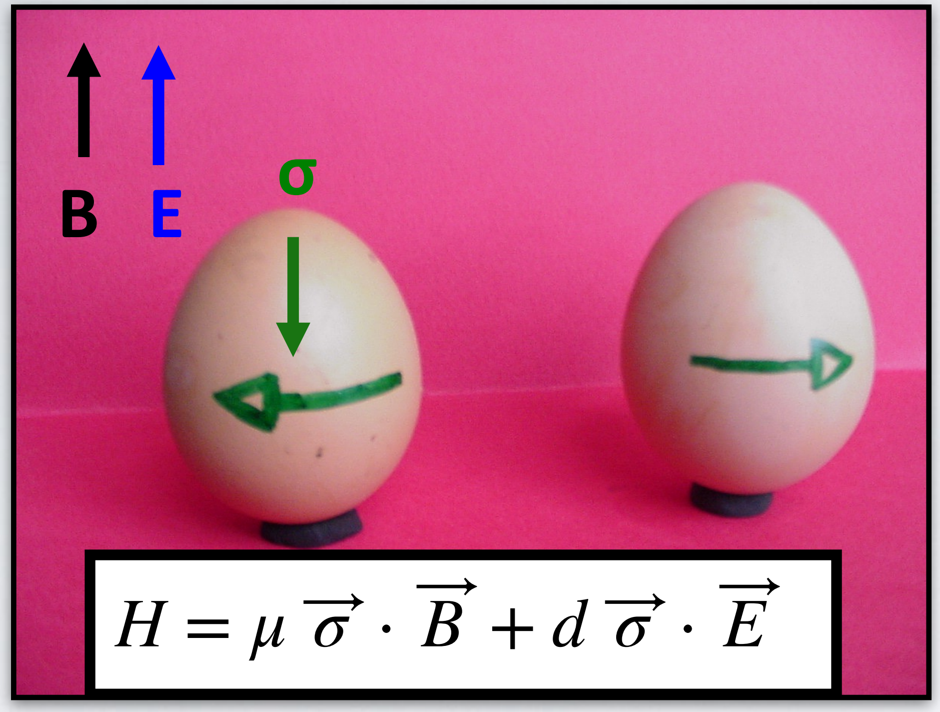
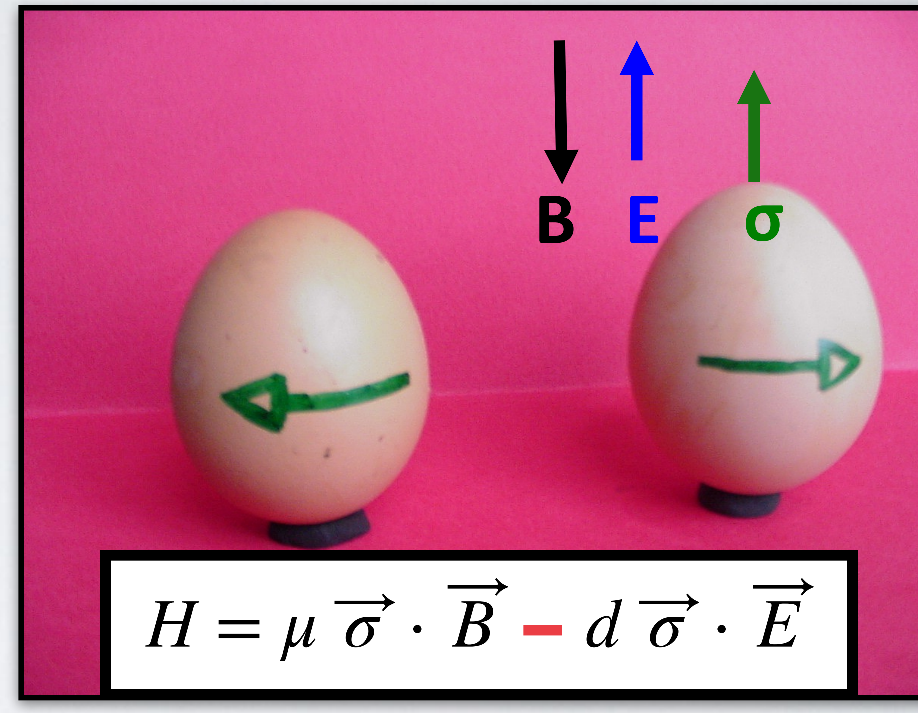
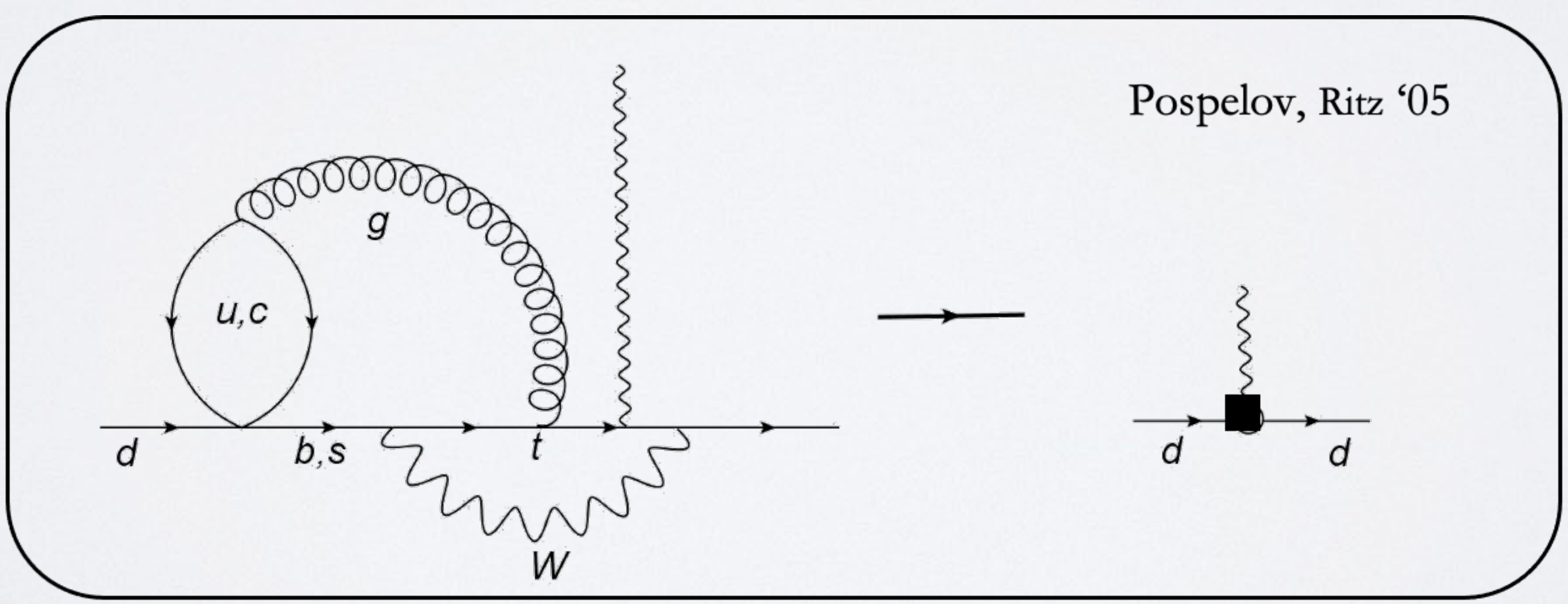


T/CP
transformation



- 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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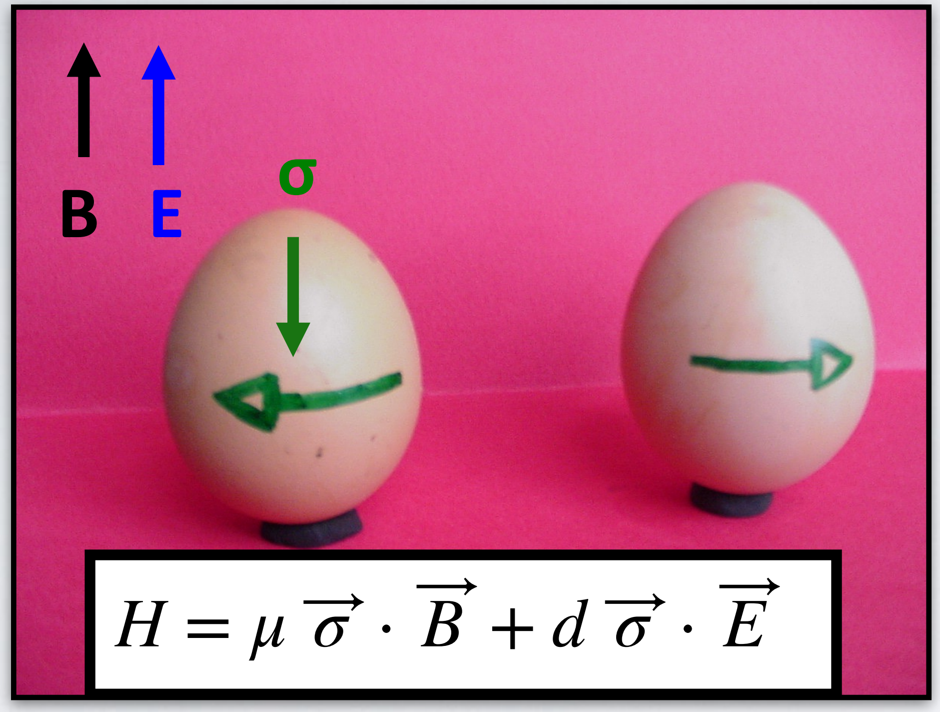

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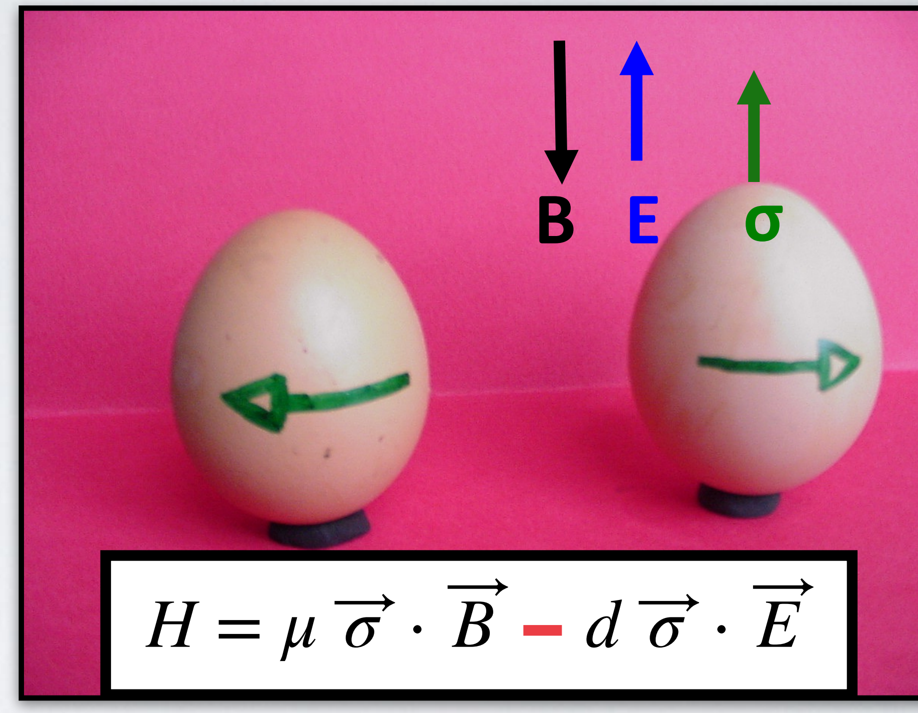

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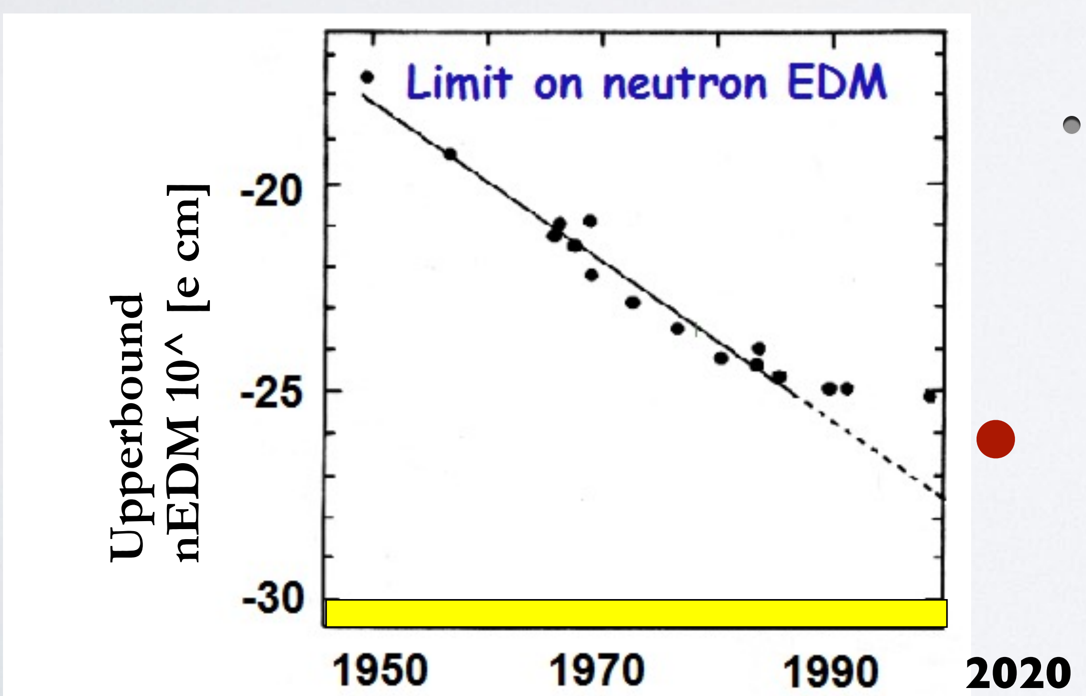
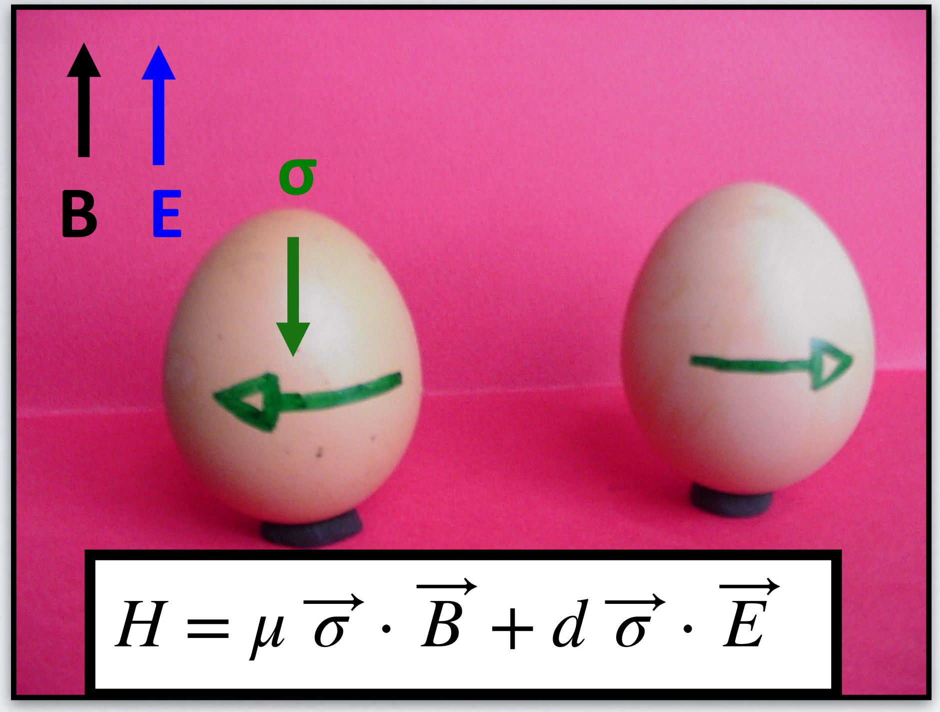


- SM prediction essentially out of reach

Electric dipole moments 101



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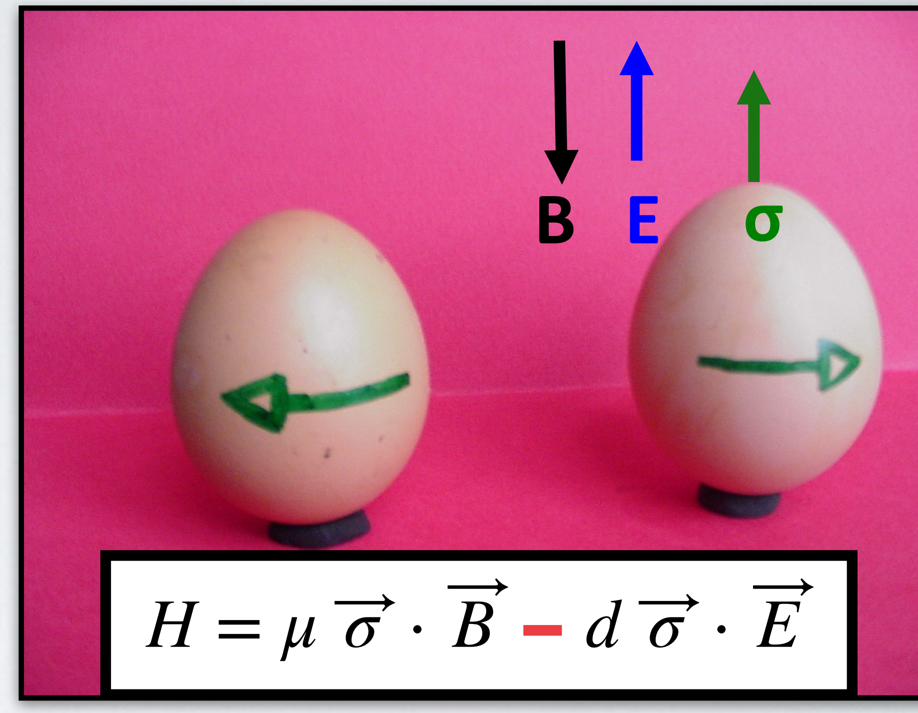

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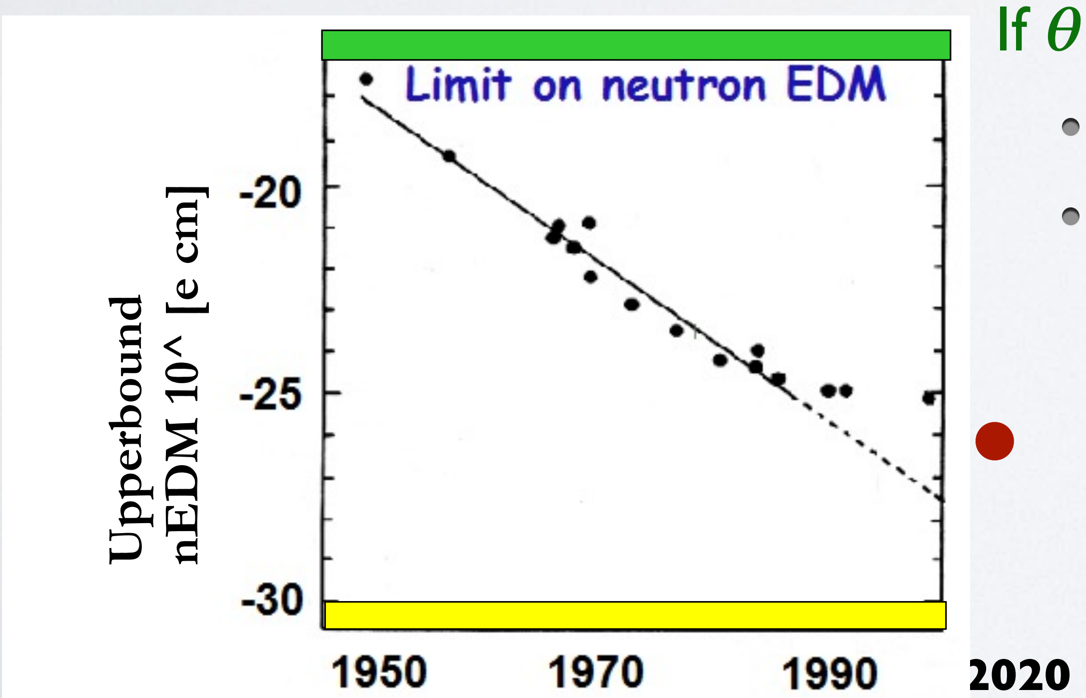


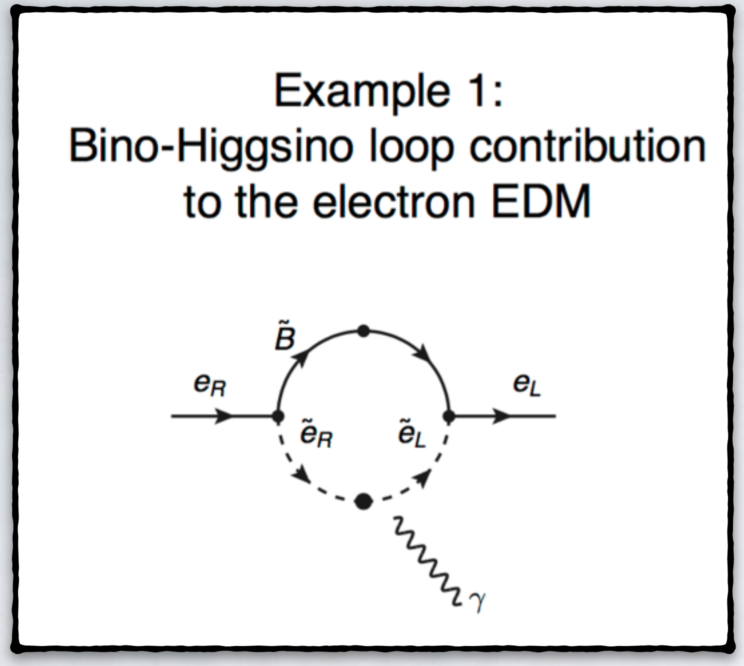
If θ ~ 1

- SM 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: $\boldsymbol{\theta}$ < 0.0000000001
- Sparked a lot of debate and theorizing

Electric dipole moments 101

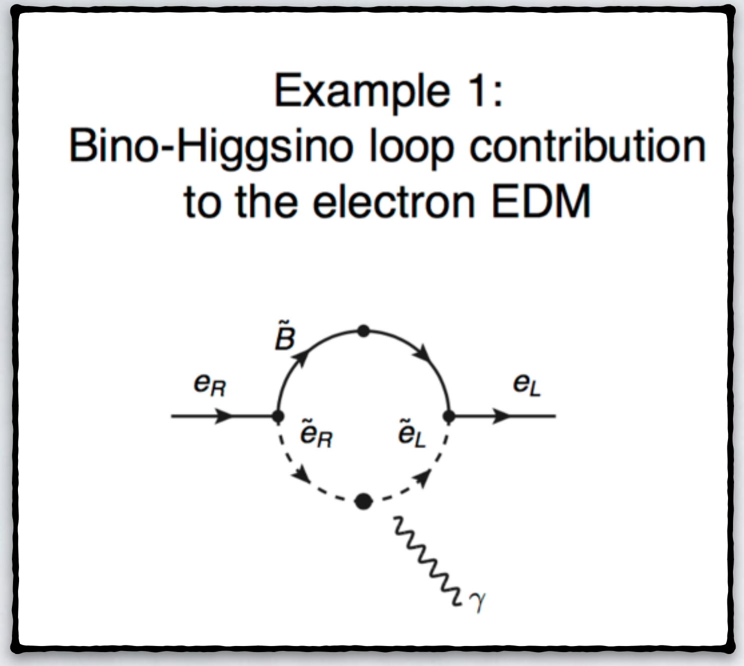


- Many BSM models: EDMs at zero-, one-, or two-loop

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

- If phase ~ O(1), then Λ > 30 TeV (n=1), or Λ > 2 TeV (n=2)

Electric dipole moments 101



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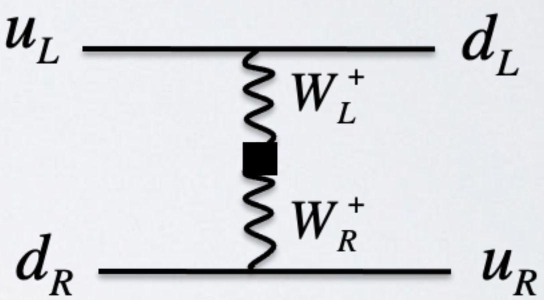
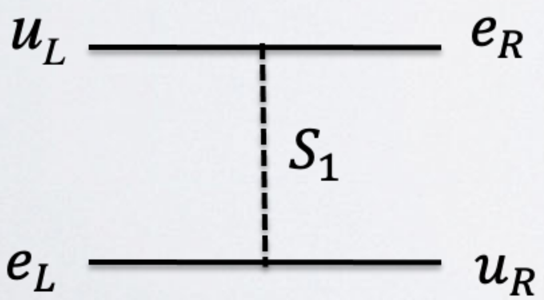
- Certain models EDMs are induced without loop suppression !
- For example, in left-right symmetric models:
- CP-odd four-quark operators induce hadronic EDMs

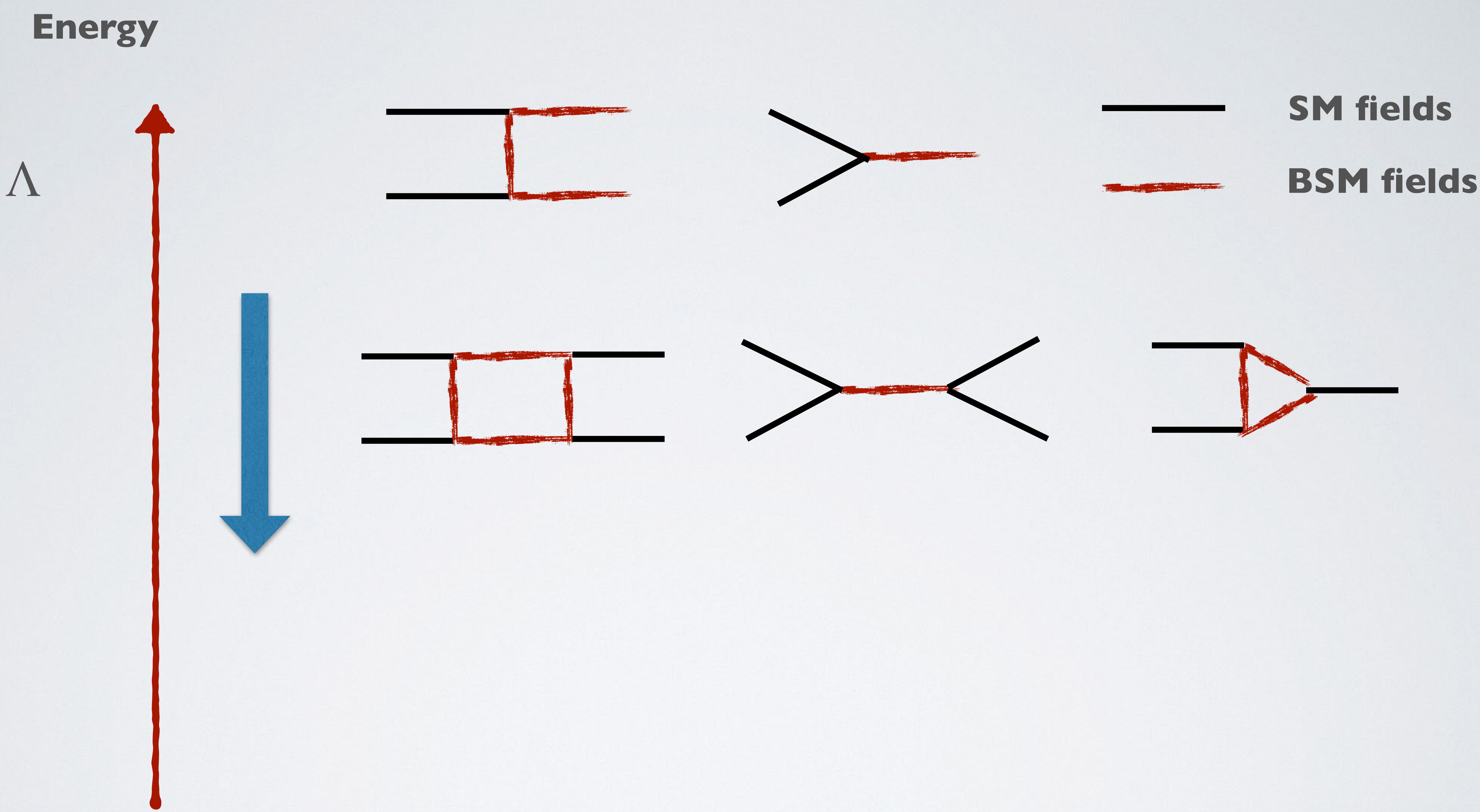




- Leptoquarks can induce CP-odd electron-quark interactions
- Induce atomic/molecular EDMs

- Tree-level CPV leads to Λ > 100-10000 TeV if phases are O(1)

EDMs are low-energy experiments



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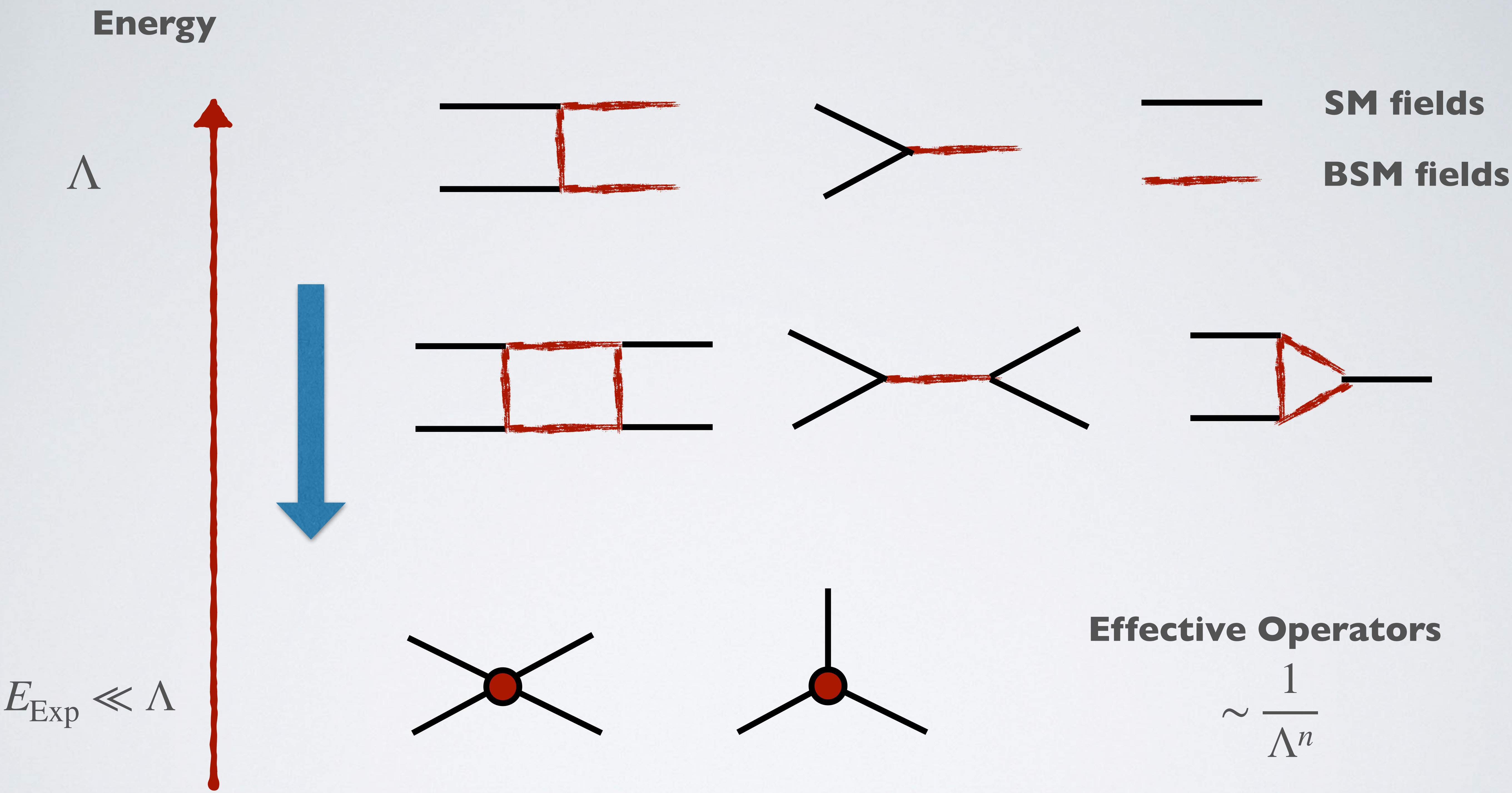


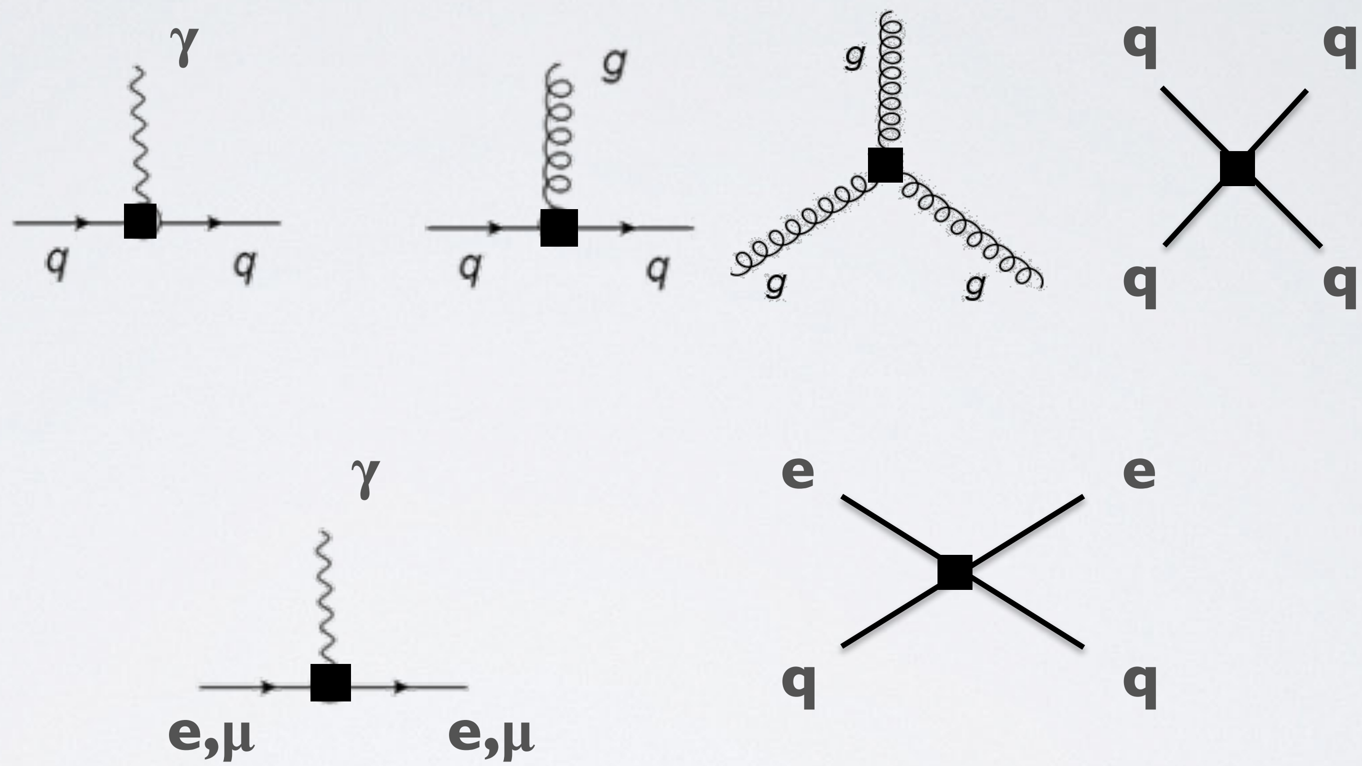
Effects of heavy BSM fields capture by local effective operators

For CP violation relevant operators start at dimension six

Strong CP violation

- 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**

CP violation in SM-EFT

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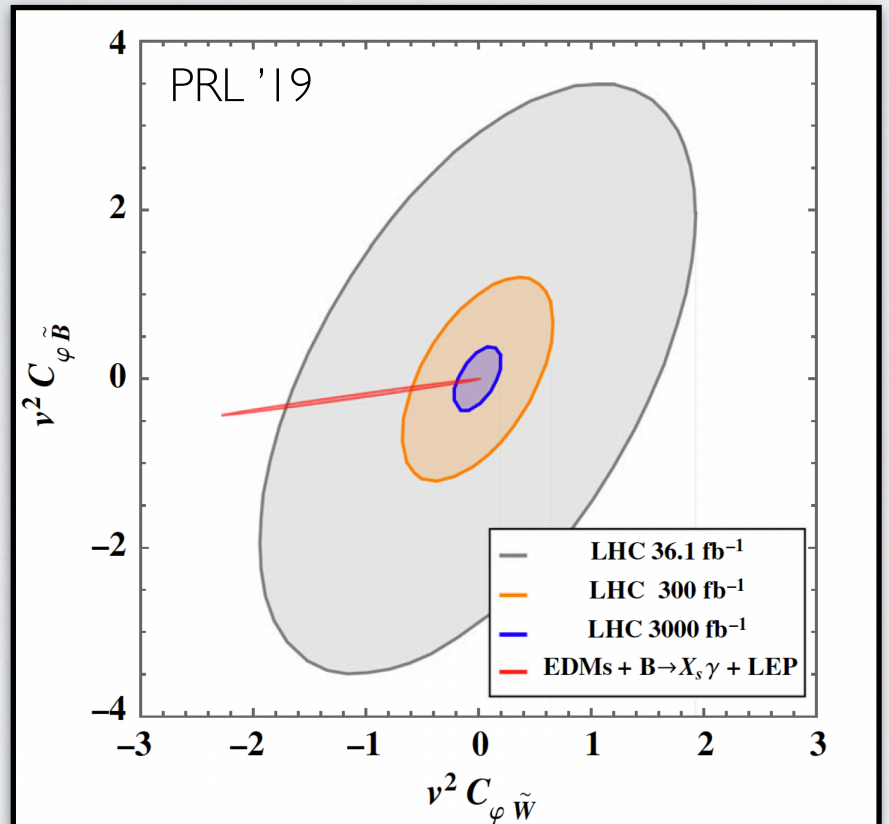
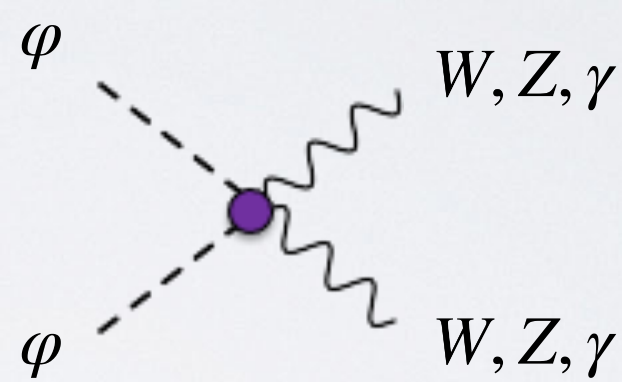




$$C_{\varphi X}\,\varphi^\dagger \varphi\, X \tilde{X}$$

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

- **Rich phenomenology of EDMs of leptons, hadrons, nuclei, atoms, molecules**

- Interesting complementarity with collider program. **Example: CP-violation in Higgs sector is best tested by combining LHC + flavor + EDMs.**
- **Direct impact for viability of electroweak baryogenesis**

Experimental searches

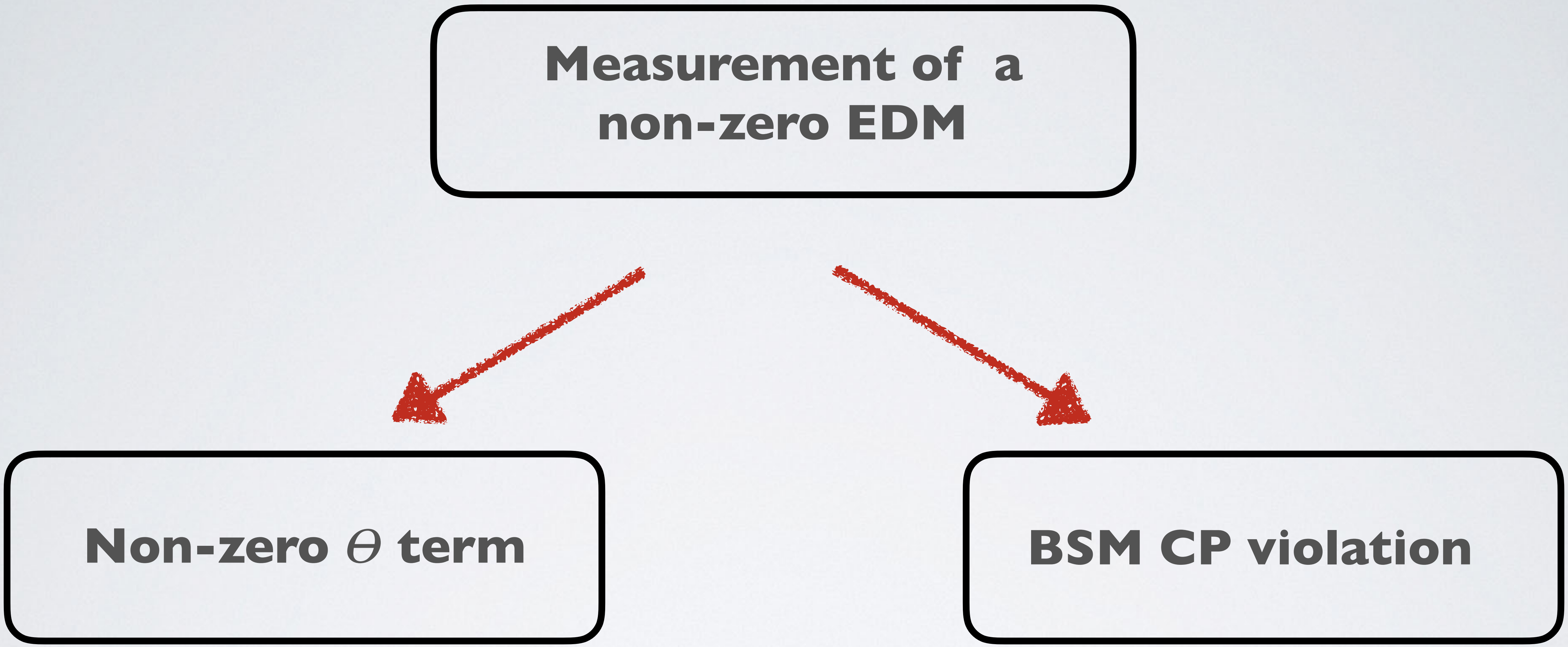
e

System	Group	Limit	C.L.	Value	Year
^{205}Tl	Berkeley	1.6×10^{-27}	90%	$6.9(7.4) \times 10^{-28}$	2002
YbF	Imperial	10.5×10^{-28}	90	$-2.4(5.7)(1.5) \times 10^{-28}$	2011
ThO	ACME	1.1×10^{-29}	90	$4.3(3.1)(2.6) \times 10^{-30}$	2018
HfF^+	Boulder	1.3×10^{-28}	90	$0.9(7.7)(1.7) \times 10^{-29}$	2017
n	PSI	1.8×10^{-26}	90	$0.0(1.1)(0.2) \times 10^{-26}$	2020
^{129}Xe	UMich	4.8×10^{-27}	95	$0.26(2.3)(0.7) \times 10^{-27}$	2019
^{199}Hg	UWash	7.4×10^{-30}	95	$-2.2(2.8)(1.5) \times 10^{-30}$	2016
^{225}Ra	Argonne	1.4×10^{-23}	95	$4(6.0)(0.2) \times 10^{-24}$	2016
muon	E821 BNL g−2	1.8×10^{-19}	95	$0.0(0.2)(0.9) \times 10^{-19}$	2009

+ planned experiments on other systems such as deuteron, Rn, BaF, ……

A lot of potential for progress !

A Luxury Problem



Dekens, JdV, Bernreuther, Hanhart, Meiβner, Nogga, Wirzba '14

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.

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

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

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

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

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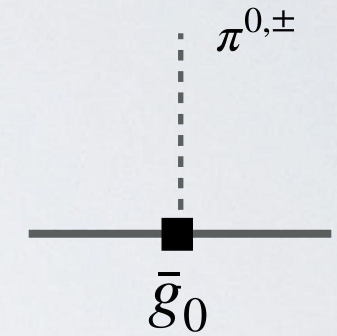
$$\mathscr{L}_{\chi+m} = \mathscr{L}_\chi - \frac{m_\pi^2}{2}\pi^2 - \delta m_N \bar{N}\tau^3 N \qquad + \bar{g}_0 \bar{N}\tau\cdot\pi N$$



Nucleon mass splitting (strong part, no EM)

CP-odd pion-nucleon

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SU$_A$(2) rotation

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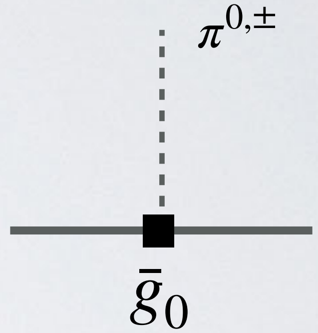

Nucleon mass splitting (strong part, no EM) ⟷ **CP-odd pion-nucleon**

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

δm_N from lattice-QCD

e.g. Borsanyi et al '14

Relation valid up to N^{2}LO corrections

JdV et al '15

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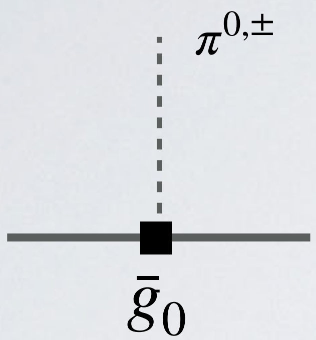
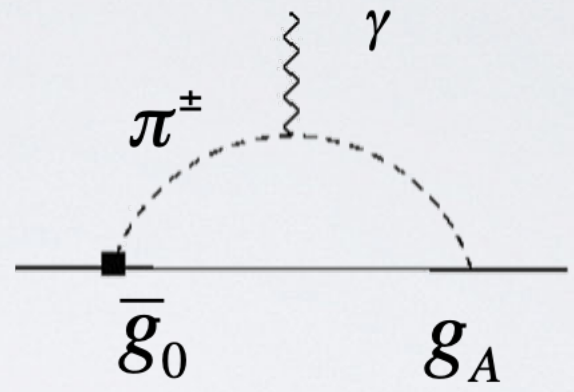


Neutron EDM
at 1 loop



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

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

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- The loop part gives $d_n \simeq -2.5 \cdot 10^{-16} e\,\mathrm{cm}$ → $\bar{\theta} < 10^{-10}$
- Lattice QCD is needed for a full calculation. But no consensus yet it seems.

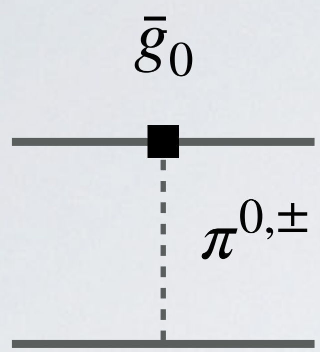
$d_n = -(1.5 \pm 0.8) \cdot 10^{-16} e\,\mathrm{cm}$ from Shindler et al '19

$d_n = -(3.9 \pm 1.1) \cdot 10^{-16} e\,\mathrm{cm}$ from Guo et al '15

Neither confirmed by recent calculations from LANL lattice group '21

Other probes of the theta term

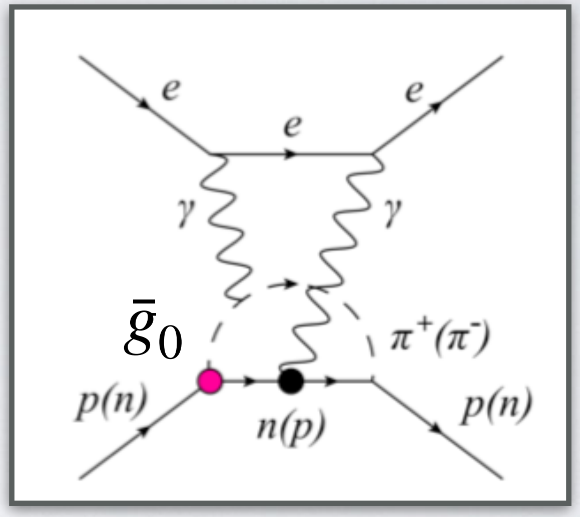
CP-odd nuclear force



Review: JdV/Meiβner '15

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

- Diamagnetic atoms (e.g. ^{199}Hg) gives stronger limits but large nuclear uncertainty $\bar{\theta} \sim < 10^{-11}$
- Storage ring experiments would be wonderful (deuteron)

- Polar molecules EDMs not competitive yet, **but experimental progress is rapid.** Might be the future ! Right now from ThO measurement $\bar{\theta} < 3 \cdot 10^{-8}$

Some musings

Is there really a problem ?

- Not really. **It is just a parameter**. No inconsistencies.
- **Could it have been larger?**
- Seems yes, nothing really changes in the universe if $\theta \sim$ **0.1** **No anthropic argument.**

Ubaldi '08, Inka Hammer '15,
Lee et al '20,

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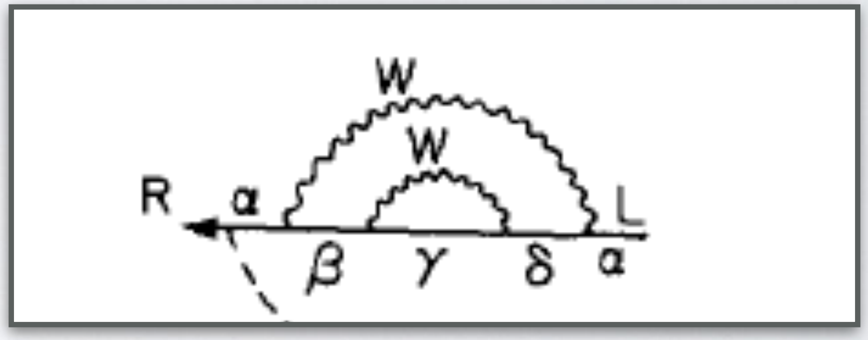
Is small theta radiatively stable?

- SM has a remarkable property: **theta is technically natural**
- **Ellis/Gaillard '79: tiny CKM contributions**

$$\Delta\bar{\theta} \sim 10^{-16}$$

- This property is lost in generic BSM extensions !



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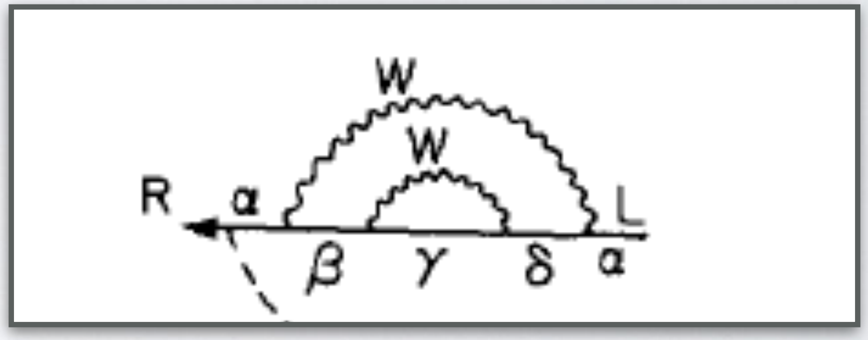


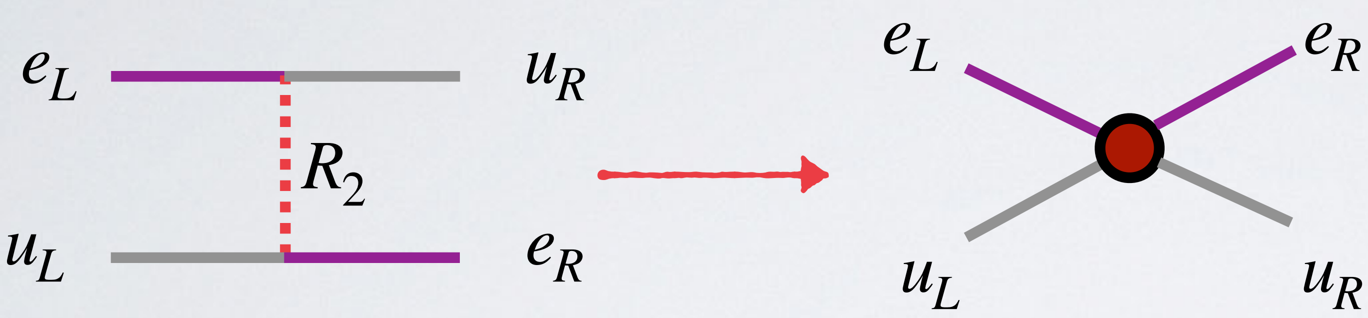
If we do think it is a problem, can we solve it ?

- **UV solutions:** P or CP is a symmetry of UV theory. Break at some scale to generate CKM phase —> Avoid generating a large theta term is not easy!
- **IR solution:** Use a Peccei-Quinn mechanism to dynamically set theta to zero. **AXIONS**
- **Ruled out solution:** massless up quark

The strong CP problem in BSM models

- **In general extension: theta is no longer protected**
- Simplest example: a scalar leptoquark model (so called S1 LQ for the experts)

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



$$\sim \frac{\mathrm{Im}(x_{LR}x_{RL}^*)}{m_{LQ}^2}$$

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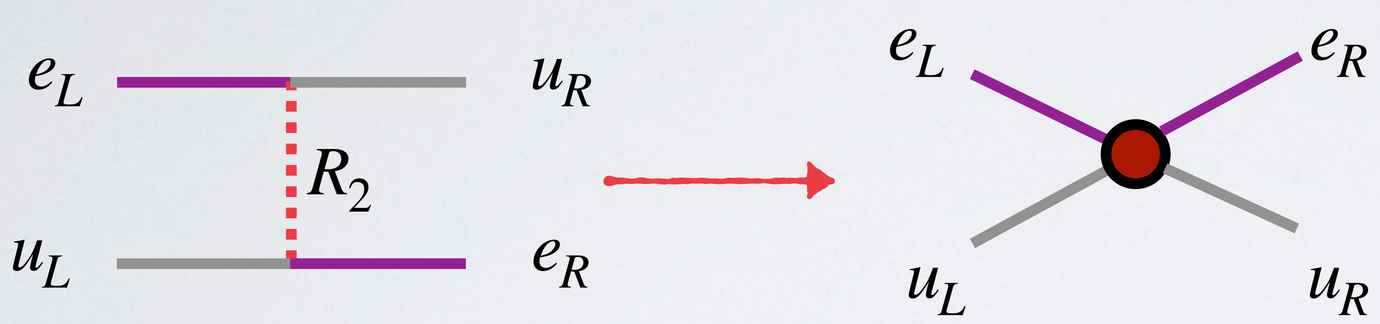
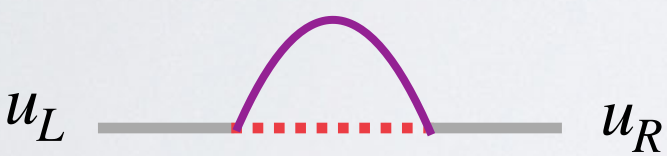


$$\sim \frac{\mathrm{Im}(x_{LR} x^*_{RL})}{m^2_{LQ}}$$

- But also a one-loop contribution to the theta term ! **No decoupling !**



$$\Delta\theta \sim \frac{1}{8\pi^2} \mathrm{Im}[y_u^{-1} x^*_{RL} y_e^\dagger x_{LR}] \sim 10^{-3} \mathrm{Im}[x_{LR} x^*_{RL}]$$

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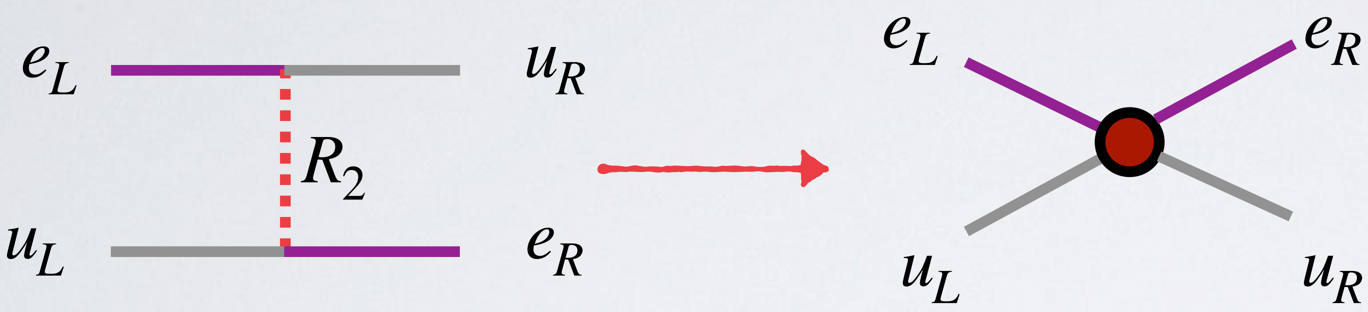

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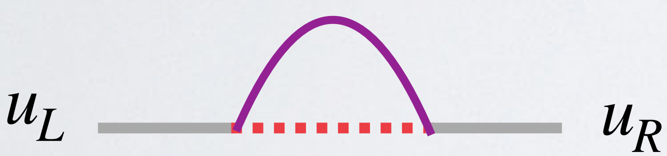

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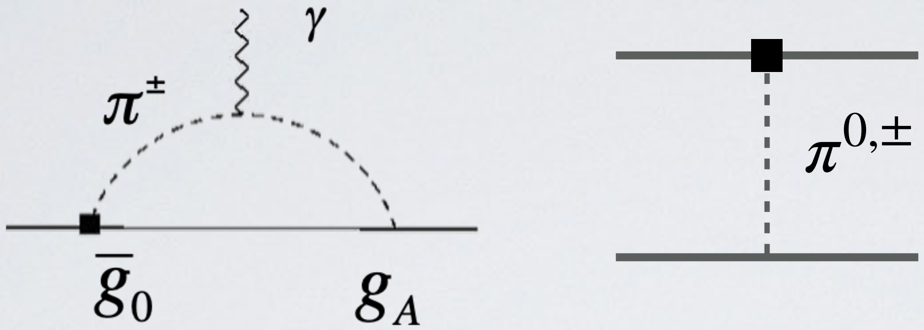
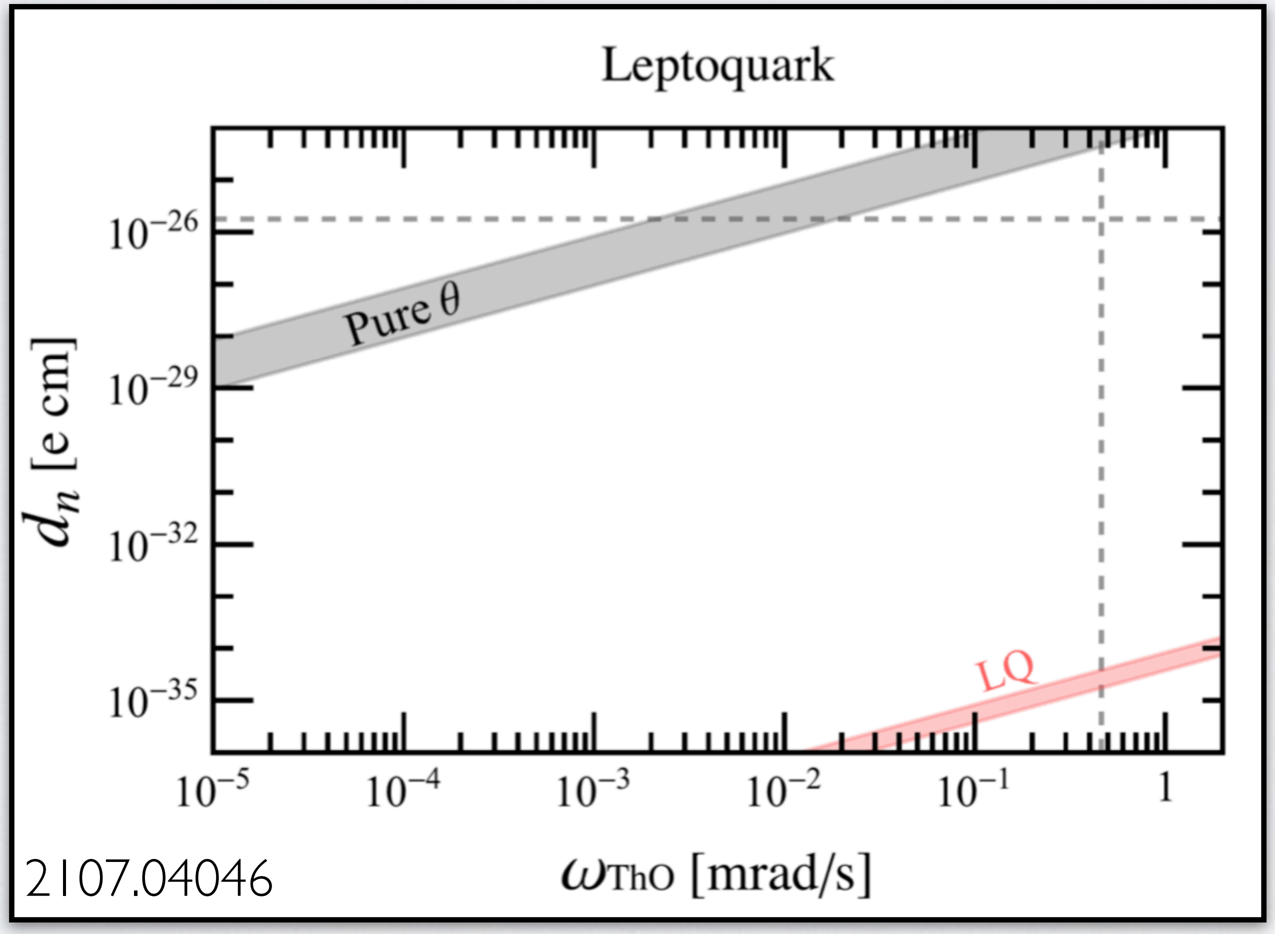
- UV `solution' : Set phase to $<10^{-7}$. Note that the dim-6 piece vanishes even quicker !
- **EDMs are now dominated by the 'remainder' of theta term**.

- Or Peccei-Quinn mechanism at low energies to effectively set $\theta_0 + \Delta\theta \to 0$
- But under a PQ: **Dimension-six term sticks around.**
- **EDMs dominated by dimension-six electron-quark interactions.**

- **UV solution:** Low-energy CPV dominated by theta. Neutron + Hg >> Paramagnetic EDMs



- **PQ mechanism:** Low-energy CPV dominated by dim-six electron-nucleon operators



Can we generalize this?

- This was just some stupid model. Is there a more thorough argument?
- Use divergence structure of dimension-six SM-EFT operators.

$$\delta\bar{\theta} = \delta\theta + \delta(\arg\det Y_u) + \delta(\arg\det Y_d)$$

- We study the mixing of EFT operators with theta term

Patrick Draper et al ‘ 18

$\mathcal{O}_{uH}$	$H^\dagger H \overline{Q_{Li}} \tilde{H} u_{Rj}$	$\mathcal{O}_{dH}$	$H^\dagger H \overline{Q_{Li}} H d_{Rj}$
$\mathcal{O}_{dG}$	$\overline{Q_{Li}} \sigma^{\mu\nu} T^a d_{Rj} H G^a_{\mu\nu}$	$\mathcal{O}_{dW}$	$\overline{Q_{Li}} \sigma^{\mu\nu} d_{Rj} \tau^a H W^a_{\mu\nu}$
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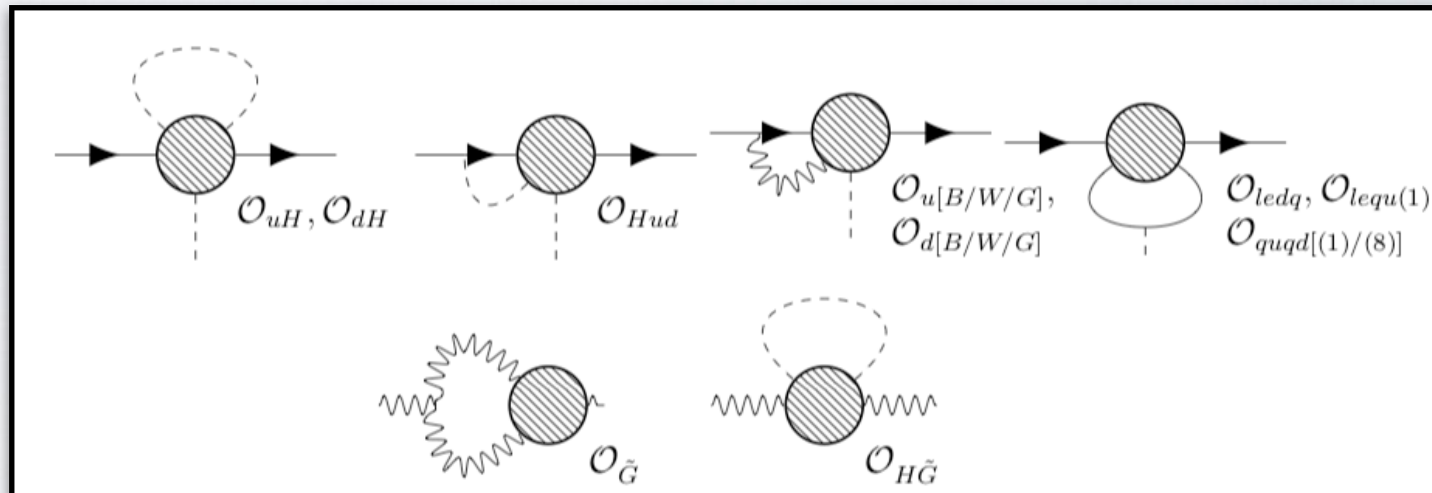

Can we generalize this?

- This was just some stupid model. Is there a more thorough argument?
- Use divergence structure of dimension-six SM-EFT operators.

$$\delta\bar{\theta} = \delta\theta + \delta(\arg\det Y_u) + \delta(\arg\det Y_d)$$

- We study the mixing of EFT operators with theta term

Patrick Draper et al ' 18

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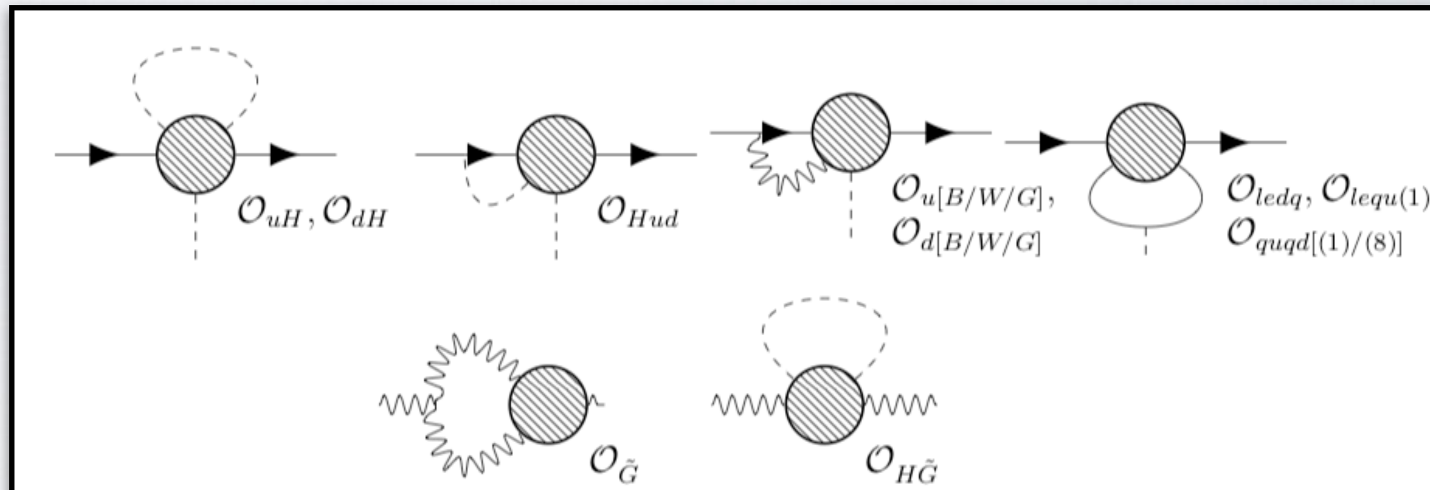

- Quadratic divergences (i.e. cut-off scheme) signal unsuppressed threshold corrections to theta
- Of course: cannot calculate threshold corrections within the EFT ! **Just a diagnostic tool**

$$
\begin{aligned}
16\pi^2\delta\bar{\theta} \sim\, & 16\pi^2\Big(\frac{2}{g_s^2}c_{H\tilde{G}} - \frac{9}{2g_s}c_{\tilde{G}}\Big) \\
& + \mathrm{Im\,Tr}[Y_d^{-1}(3c_{dH} + g'c_{dB} - 18gc_{dW} - 16g_s c_{dG})] \\
& + \mathrm{Im\,Tr}[Y_u^{-1}(3c_{uH} - 5g'c_{uB} - 18gc_{uW} - 16g_s c_{uG})] \\
& + \mathrm{Im\,Tr}[(Y_d^{-1}Y_u + Y_d^\dagger(Y_u^\dagger)^{-1})c_{Hud}] \\
& + \mathrm{Im}[2c^{mnij}_{lequ(1)}Y_e^{\dagger nm}(Y_u^{-1})^{ji} - 2c^{*mnij}_{ledq}Y_e^{mn}(Y_d^{-1})^{ij}] \\
& + \mathrm{Im}[(6c^{mnij}_{quqd(1)} + c^{inmj}_{quqd(1)} + \frac{4}{3}c^{inmj}_{quqd(8)})(Y_u^{\dagger nm}(Y_d^{-1})^{ji} + Y_d^{\dagger ji}(Y_u^{-1})^{nm})].
\end{aligned}
$$

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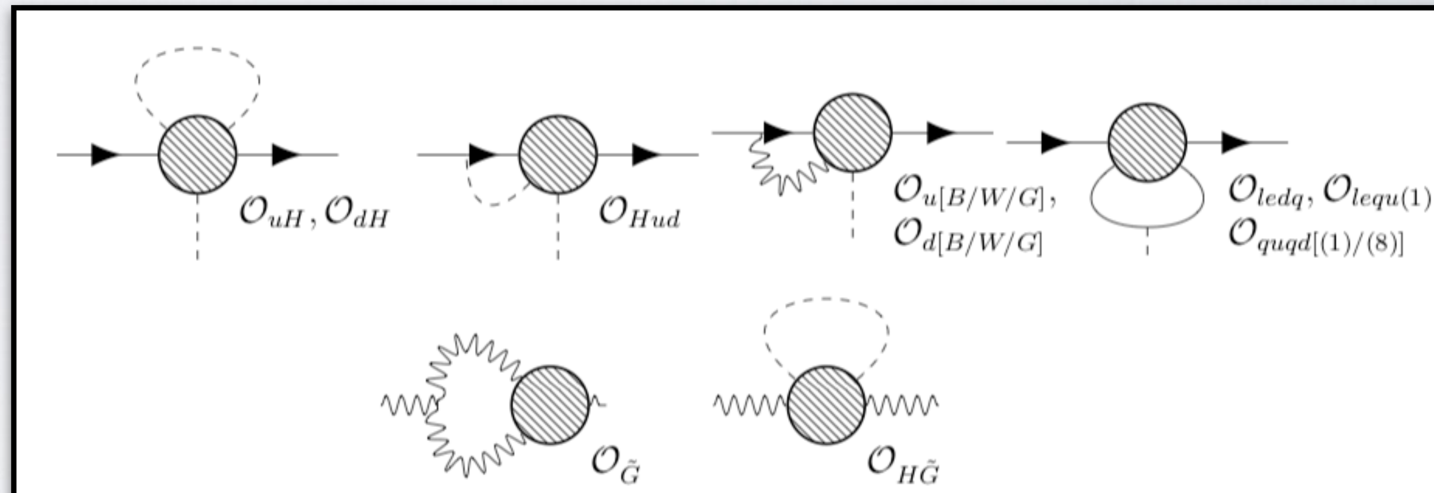


- Most dim-six operators relevant for EDMs, mix ‘quadratically’ with theta
- **If dim-6 dominate EDMs at low energy, then where is the dim-4 theta term?**

- **Should be resolved in the IR: a Peccei-Quin mechanism.**
- Deviations from the theta-term EDM pattern provide a hint for an IR solution (PQ mechanism)

Testing the EFT arguments

JdV et al '21

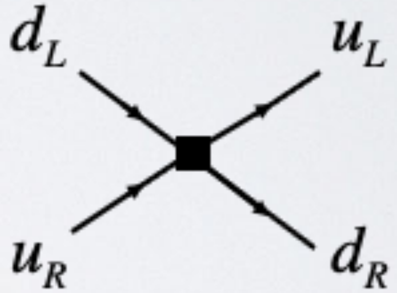
- Studied a broad class of models (SUSY, 2HDM, leptoquarks, left-right symmetry)
- In all cases, when a dimension-six operator appears: also large threshold correction to theta

    1. Suppress theta threshold at UV scale: all CPV gets suppressed and **theta dominates**
    2. Eliminate theta in IR by Peccei-Quinn: **Dimension-six CPV dominates.**

- Example: minimal left-right symmetric model.

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

- Dim-6 operator leads to CP-odd isospin-breaking four-quark operator



- **This has a very different EDM pattern** than theta!
- Can only be relevant if somehow $\Delta\bar{\theta}$ gets removed but not setting $\sin\alpha \to 0$

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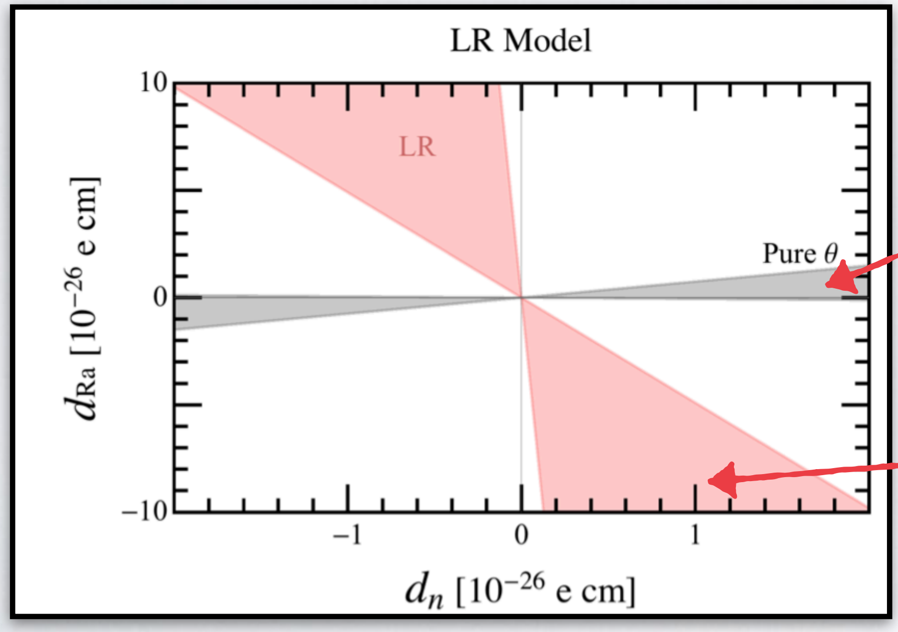

Left-right model with UV solution

Left-right model with Peccei-Quinn

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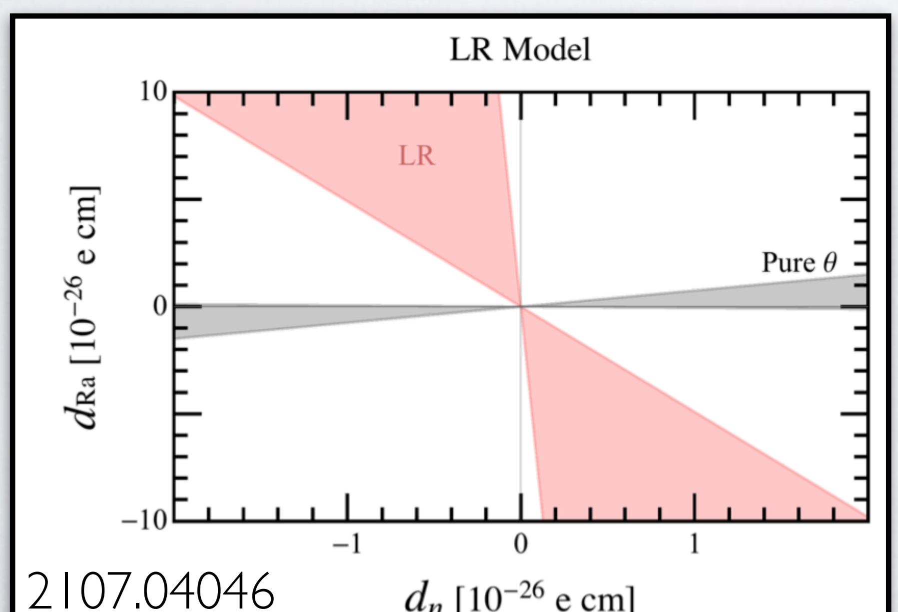

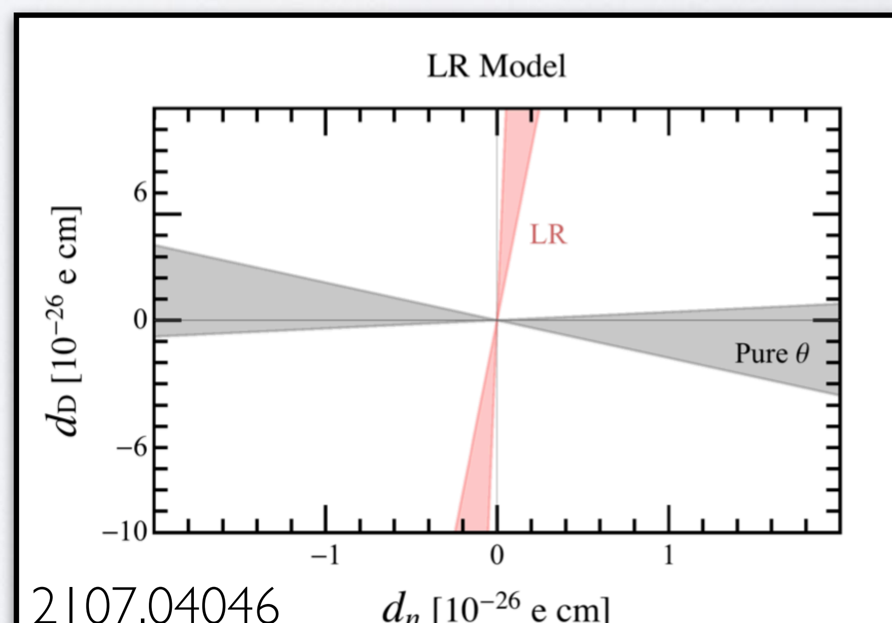

Conclusions/Summary

- EDMs are powerful ways to look for new CP violation
- 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)**

- Problem: there exists a dim-4 CPV term in SM (theta term)
- **Technically natural in SM, but not in generic BSM models**
- Reflected by mixing pattern of SM-EFT operators with theta
- Models that generate dim-6 operators also induce an unsuppressed theta

- Conclusion: pattern of EDMs that are inconsistent with theta term imply an IR mechanism of the strong CP problem → **Peccei-Quinn mechanism is only game in town.**
- So EDM measurements could hint towards a PQ mechanism without **seeing actual axions.**

- But naturalness arguments are dangerous…. So this would just be a hint, not a proof.

Work in progress/Outlook

- The combination of dimension-six CPV and Peccei-Quinn leads to CPV axion interactions.
- In addition, to the operators discussed by Thomas yesterday
- CPV axion couplings take the simple form

$$\mathcal{L}_{a,CPV} = g_s^e\, a\, \bar{e}e + g_s^N\, a\, \bar{N}N + g_s^\pi a \pi^2$$

- In progress: calculate these couplings in SMEFT + ChPT
- Compare EDM limits on SMEFT couplings to limits on axion couplings (fifth-force experiments)