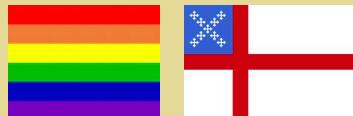


# *Electric Dipole Moments I*



M.J. Ramsey-Musolf

*Wisconsin-Madison*



## NPAC

Theoretical Nuclear, Particle, Astrophysics & Cosmology

<http://www.physics.wisc.edu/groups/particle-theory/>

TUM Excellence Cluster, May 2013

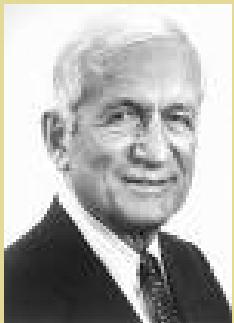
# Goals

- *Set framework for interpreting EDM searches in terms of BSM CPV*
- *Delineate physics at multiple scales that enters the EDM search interpretation*
- *Identify open problems*
- *Provide a few examples*
- *Set stage for rest of workshop*

## References

- *EDM review: J. Engel, M. R-M, U. van Kolck, arXiv:1303.2371 (to appear in PPNP)*
- *Baryogenesis review: D. Morrissey, M. R-M, arXiv:1206.2942, NJP 14 (2012) 125003*

# EDMs: History



PHYSICAL REVIEW

VOLUME 108, NUMBER 1

OCTOBER 1, 1957

## Experimental Limit to the Electric Dipole Moment of the Neutron

J. H. SMITH,\* E. M. PURCELL, AND N. F. RAMSEY

*Oak Ridge National Laboratory, Oak Ridge, Tennessee, and Harvard University, Cambridge, Massachusetts*

(Received May 17, 1957)

An experimental measurement of the electric dipole moment of the neutron by a neutron-beam magnetic resonance method is described. The result of the experiment is that the electric dipole moment of the neutron equals the charge of the electron multiplied by a distance  $D = (-0.1 \pm 2.4) \times 10^{-29}$  cm. Consequently, if an electric dipole moment of the neutron exists and is associated with the spin angular momentum, its magnitude almost certainly corresponds to a value of  $D$  less than  $5 \times 10^{-30}$  cm.

### I. INTRODUCTION

SEVERAL years ago Purcell and Ramsey<sup>1</sup> pointed out that the usual parity arguments for the non-existence of electric dipole moments for nuclei and elementary particles, although appealing from the point of view of symmetry, were not necessarily valid. In particular they pointed out that the validity of the parity assumption must rest on experimental evidence and that the experimental evidence was not as conclusive as then generally supposed in the case of nuclei and elementary particles, even though there was abundant evidence for the assumption in the case of electromagnetic forces. Analysis of the experimental

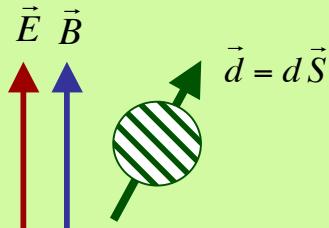
existence of electric dipole moments of particles. The effects of the first two of these have been observed by Wu, Ambler, Hayward, Hoppes, and Hudson,<sup>7</sup> and by Garwin, Lederman, and Weinrich.<sup>8</sup> Since electric moments are primarily determined by the strong forces, Lee and Yang<sup>9</sup> showed that the effect of mixed parity should produce an electric dipole moment even smaller than the upper limit set by the experiment described in the present paper. In their most recent theories, Lee and Yang<sup>9</sup> no longer anticipate the existence of an electric dipole moment for the neutron, and arguments involving time-reversal invariance<sup>9,10</sup> can be advanced against its existence. These arguments, however, like the original ones of parity, can be questioned.

Although the negative results of the experiment described here are fully consistent with the current theories, a brief description of the experiment and its results seems appropriate at the present time since the experiment provides the most sensitive experimental upper limit to an electric dipole moment of any elementary particle or nucleus and since the original parity arguments against the existence of such electric dipole moments are now known to be invalid.

# *EDMs: New CPV?*

In units of e cm, selected EDM limits are:

| Particle          | EDM limit              | System                                  | SM Prediction | New Physics |
|-------------------|------------------------|---|---------------|-------------|
| e                 | $10.5 \times 10^{-28}$ | YbF                                     | $10^{-38}$    | $10^{-27}$  |
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| n                 | $2.9 \times 10^{-26}$  | UCN                                     | $10^{-31}$    | $10^{-26}$  |
| $^{199}\text{Hg}$ | $3.1 \times 10^{-29}$  | atom cell                               | $10^{-33}$    | $10^{-28}$  |



$$\nu_{EDM} = -\frac{d\vec{S} \cdot \vec{E}}{h}$$

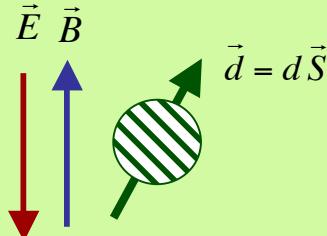
T-odd, CP-odd  
by CPT  
theorem

# EDMs: New CPV?

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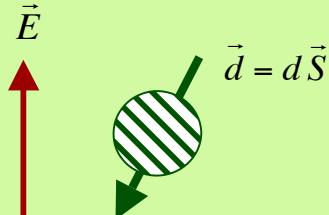
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C-Y Liu



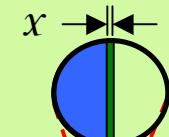
$$v_{EDM} = -\frac{d \vec{S} \cdot (-\vec{E})}{h}$$

P-odd



$$v_{EDM} = -\frac{d(-\vec{S}) \cdot \vec{E}}{h}$$

T-odd, CP-odd  
by CPT theorem

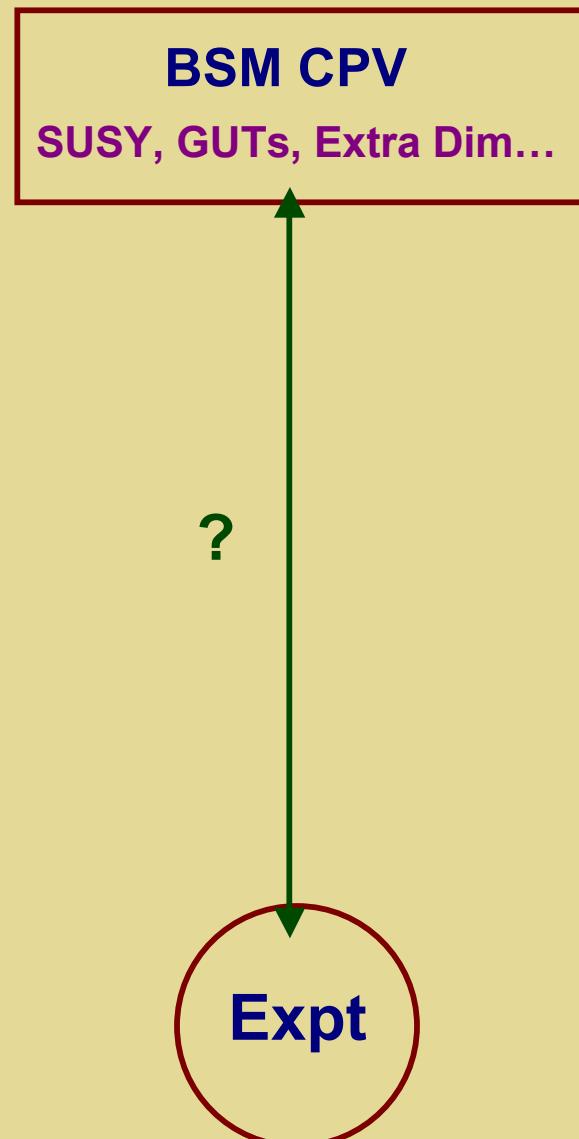


$d_n: x < 0.5 \text{ mm}$

# *Outline*

1. *EDM Interpretation: Multiple Scales*
2. *Expt vs the Standard Model*
3. *Effective Operators: Classification*
4. *Origin of Wilson Coefficients: Examples*
5. *Low Scale Observables*
6. *Running & Matching*
7. *Implications & Open Problems*

## ***EDM Interpretation & Multiple Scales***



## *EDM Interpretation & Multiple Scales*

**Baryon Asymmetry**

Early universe CPV

**BSM CPV**

SUSY, GUTs, Extra Dim...

**Collider Searches**

Particle spectrum; also  
scalars for baryon asym

?

**Expt**

## *EDM Interpretation & Multiple Scales*

**Baryon Asymmetry**

Early universe CPV

*EW Baryogenesis  
Quantum transport  
theory*

**BSM CPV**

SUSY, GUTs, Extra Dim...

**Collider Searches**

Particle spectrum; also  
scalars for baryon asym

*LHC phenomenology  
B Physics  
Dark Matter*

?

**Expt**

## *EDM Interpretation & Multiple Scales*

**Baryon Asymmetry**

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SUSY, GUTs, Extra Dim...

**Collider Searches**

Particle spectrum; also  
scalars for baryon asym

?

**QCD Matrix Elements**

$d_n, \bar{g}_{\pi NN}, \dots$

**Nuclear & atomic MEs**

Schiff moment, other P- &  
T-odd moments, e-nucleus  
CPV

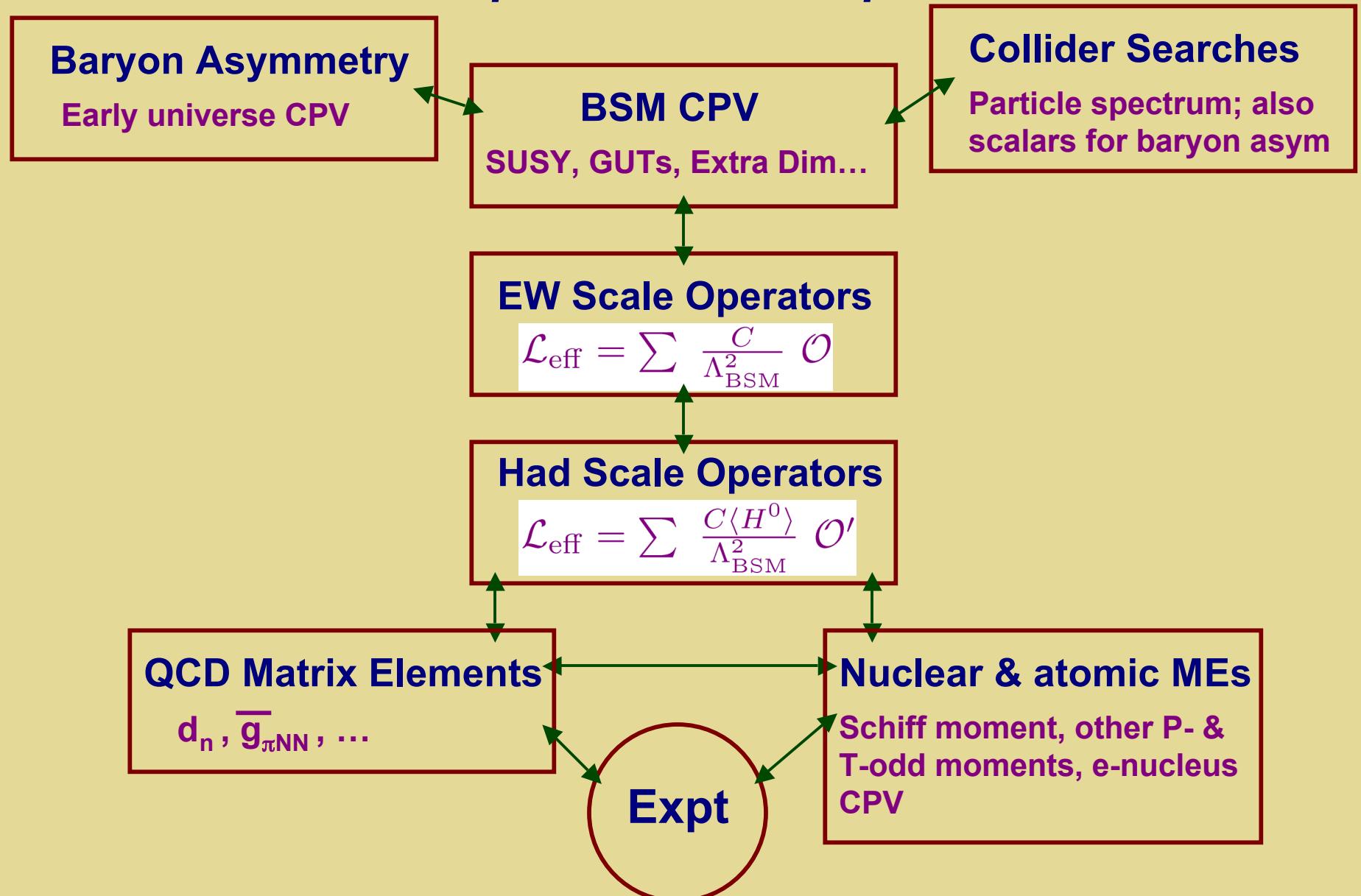
**Expt**

## *Effective Operators*

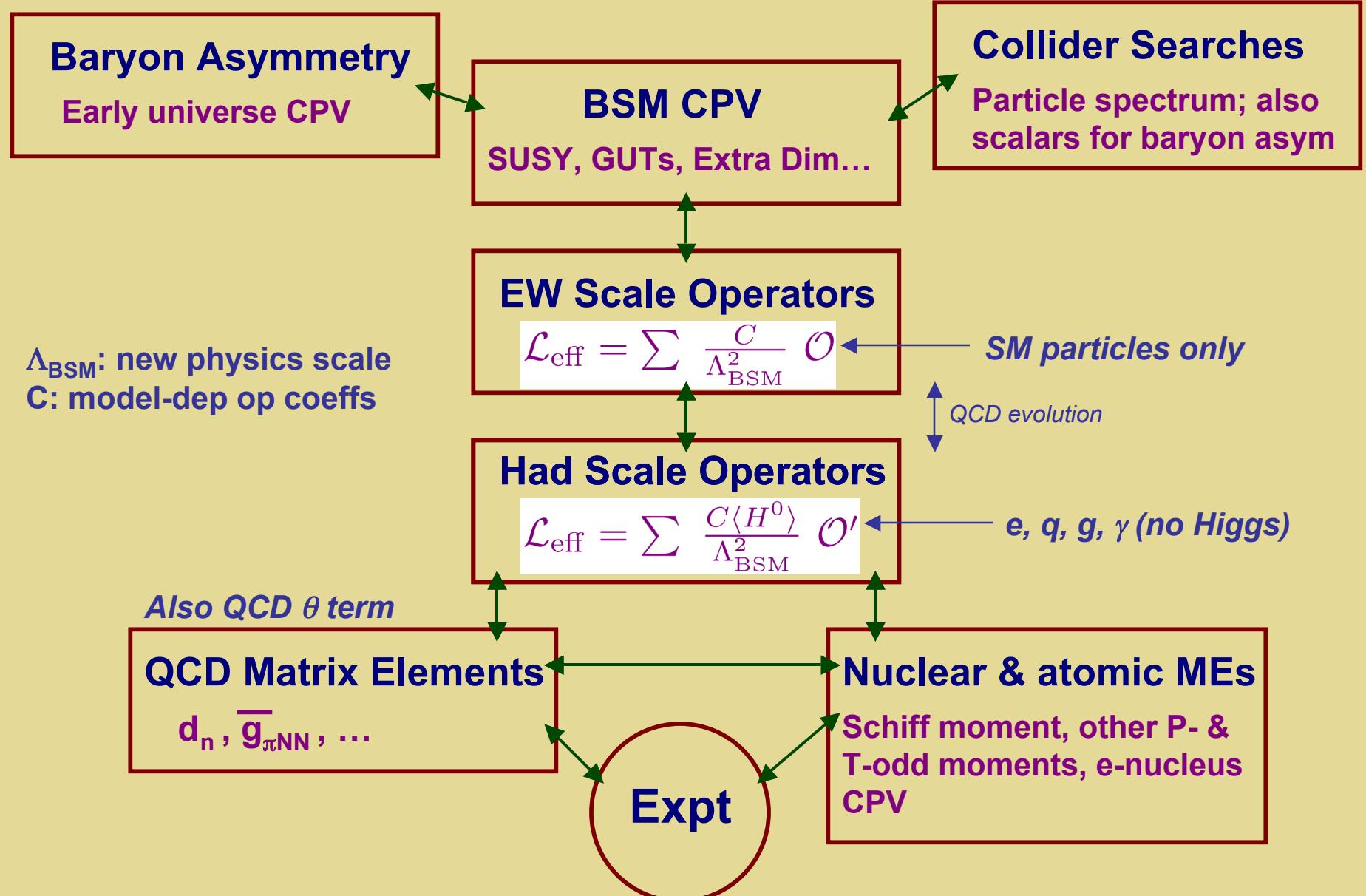
$$\mathcal{L}_{\text{CPV}} = \mathcal{L}_{\text{CKM}} + \mathcal{L}_{\bar{\theta}} + \mathcal{L}_{\text{BSM}}^{\text{eff}}$$

$$\mathcal{L}_{\text{BSM}}^{\text{eff}} = \frac{1}{\Lambda^2} \sum_i \alpha_i^{(n)} O_i^{(6)} \quad + \dots$$

# *EDM Interpretation & Multiple Scales*



# EDM Interpretation & Multiple Scales



# *EDMs: Exp't vs Standard Model*

In units of e cm, selected EDM limits are:

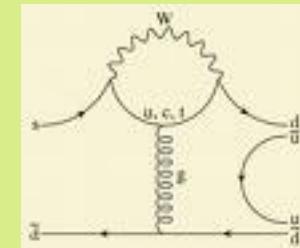
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$$\mathcal{L}_{\text{CPV}} = \mathcal{L}_{\text{CKM}} + \mathcal{L}_{\bar{\theta}} + \mathcal{L}_{\text{BSM}}^{\text{eff}}$$

# EDMs: Standard Model CKM

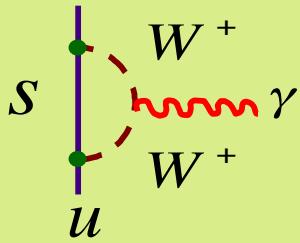
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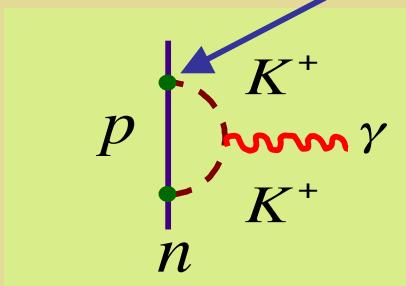


Penguin:  $\Delta S = 1$

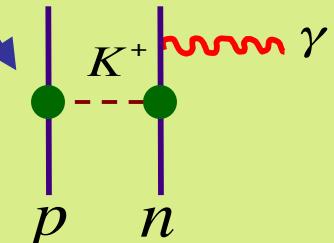
## CKM CPV



- 1 loop vanishes ( $\sim V_{us} V_{us}^*$ )
- 2 loop shown to vanish explicitly



- Khriplovich et al; McKellar...



- Donoghue, Holstein, RM; Khriplovich et al

# *EDMs: Exp't vs Standard Model*

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or  $\theta_{QCD}$

$$\mathcal{L}_{CPV} = \mathcal{L}_{CKM} + \mathcal{L}_{\bar{\theta}} + \mathcal{L}_{BSM}^{\text{eff}}$$

# EDMs: Standard Model $\theta$ -term

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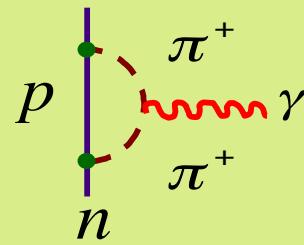
$d_n$  &  $d_A$  ( $^{199}\text{Hg}$ ):

$$\bar{\theta} < 10^{-10}$$

Peccei -Quinn Sym?

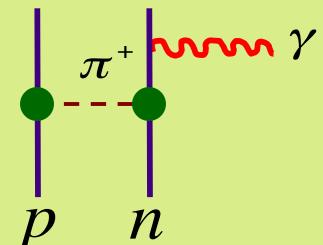
$$\mathcal{L}^\theta_{QCD}$$

$$\frac{\alpha_s \bar{\theta}}{4\pi} \text{Tr } \tilde{G}_{\mu\nu} G^{\mu\nu}$$



- vanishes for any  $m_q=0$
- “bar”: absorb quark field redefinition

- Crewther et al; van Kolck et al ; Herczeg



- Haxton & Henley; Engel;

# EDMs: Peccei-Quinn & Axions I

*θ-term*

$$\frac{\alpha_s \bar{\theta}}{4\pi} \text{Tr } \tilde{G}_{\mu\nu} G^{\mu\nu}$$

*Axion Field: GB of Spont Broken  $U(1)_{PQ}$*

$$\mathcal{L}_a = \frac{1}{2} \partial_\mu a \partial^\mu a + \frac{a(x)}{f_a} \frac{\alpha_s}{8\pi} G \tilde{G},$$

$$\bar{\theta} \rightarrow \bar{\theta} + \frac{a}{f_a}$$

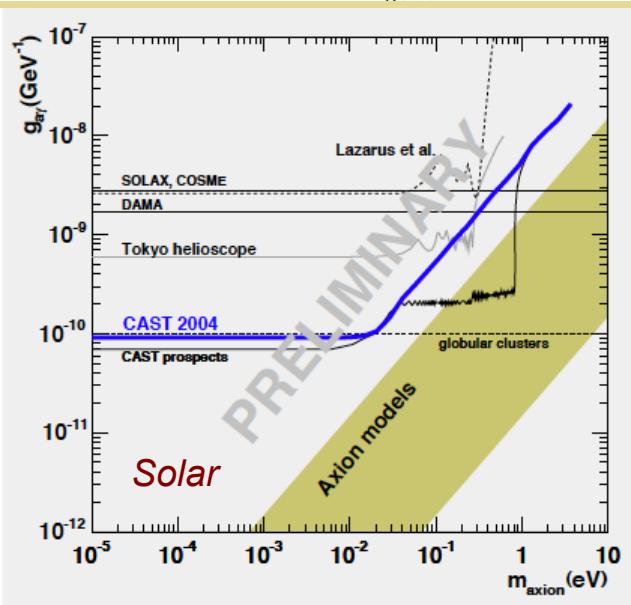
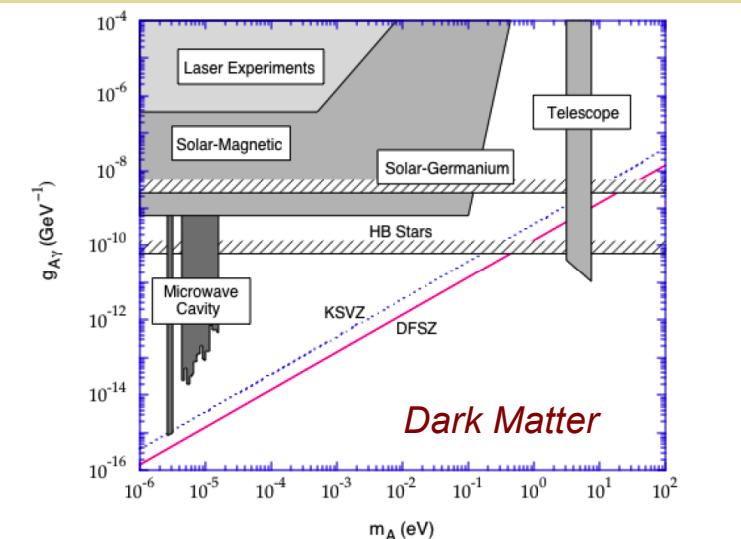
*Chiral Anomaly:*

$$a \rightarrow \langle a \rangle + \delta a$$

$$\bar{\theta} \rightarrow \boxed{\bar{\theta} + \frac{\langle a \rangle}{f_a}} + \frac{\delta a}{f_a}$$

*Axion*   
*Observed  $\theta \sim 0$*  

# EDMs: Peccei-Quinn & Axions II



$$\frac{\alpha_s \bar{\theta}}{4\pi} \text{Tr } \tilde{G}_{\mu\nu} G^{\mu\nu}$$

$$\bar{\theta} \rightarrow \bar{\theta} + \frac{a}{f_a}$$

*Axion*

$$\bar{\theta} \rightarrow \boxed{\bar{\theta} + \frac{\langle a \rangle}{f_a} + \frac{\delta a}{f_a}}$$

↓

*Observed  $\theta \sim 0$*

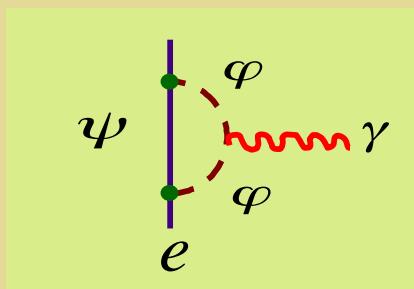
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- SM “background” well below new CPV expectations

## *Mass Scale Sensitivity*



$$\sin\phi_{CP} \sim 1 \rightarrow M > 5000 \text{ GeV}$$

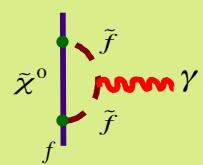
$$M < 500 \text{ GeV} \rightarrow \sin\phi_{CP} < 10^{-2}$$

# EDM Probes

| System            | Present 90 % C.L.<br>Limit ( $e \text{ fm}$ ) <sup>a</sup> | Sensitivity Goal <sup>b</sup>   | Group              | SM CKM ( $e \text{ fm}$ ) <sup>c</sup>                |
|-------------------|--|---------------------------------|--------------------|---|
| Cs                | $1.2 \times 10^{-10}$                                      |                                 | [167]              | $\sim 10^{-23}$                                       |
| Tl                | $9.5 \times 10^{-12}$                                      |                                 | [168]              | $\sim 10^{-22}$                                       |
| YbF <sup>d</sup>  | $10.5 \times 10^{-15}$                                     |                                 | [150]              | $\sim 10^{-19}$                                       |
| ThO <sup>d</sup>  | -  | $10^{-15} \rightarrow 10^{-17}$ |                    |   |
| <i>n</i>          | $2.7 \times 10^{-13}$                                      |                                 | [169]              | $1.6 \times 10^{-18} \rightarrow 1.4 \times 10^{-20}$ |
| <i>n</i>          |  | $(1 - 3) \times 10^{-14}$       | CryoEDM            |   |
| <i>n</i>          |  | $4 \times 10^{-15}$             | nEDM/SNS           |   |
| <i>n</i>          |  | $5 \times 10^{-14}$             | nEDM/PSI           |   |
| <i>n</i>          |  | $5 \times 10^{-15}$             | n2EDM/PSI          |   |
| <i>n</i>          |  | $2 \times 10^{-15}$             | nedm/FRM-II Munich |   |
| <i>n</i>          |  | $10^{-14} - 10^{-15}$           | TRIUMF             |   |
| <i>p</i>          |  | $10^{-16}$                      | srEDM              |   |
| <sup>199</sup> Hg | $2.6 \times 10^{-16}$                                      | $(2.6 - 5) \times 10^{-17}$     | [170]              | -   |
| <sup>225</sup> Ra |  | $(10 - 100) \times 10^{-15}$    | Argonne            | -   |
| <sup>225</sup> Rn |  | $1.3 \times 10^{-14}$           | TRIUMF             | -   |
| <sup>225</sup> Rn |  | $2 \times 10^{-15}$             | FRIB               | -   |
| <sup>129</sup> Xe | $5.5 \times 10^{-14}$                                      |                                 | [171]              | -   |

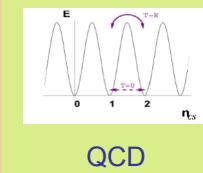
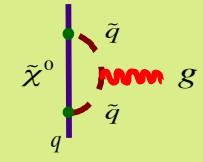
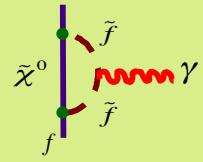
# *EDMs: Complementary Searches*

*Electron*



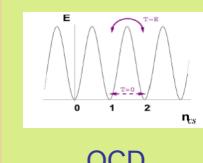
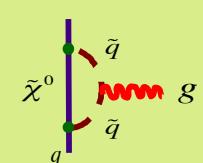
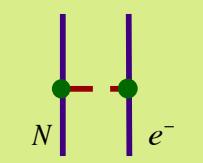
*Improvements  
of  $10^2$  to  $10^3$*

*Neutron*



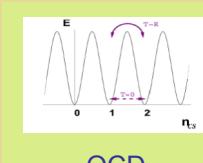
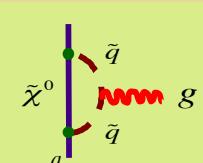
*QCD*

*Neutral  
Atoms*



*QCD*

*Deuteron*



*QCD*

## *Dimension Six Operators*

- *What are they ?*
- *Where do they come from ?*
- *How do they appear in hadronic,  
nuclear, and atomic systems ?*
- *How well can we match them onto  
physics of many-body and non-  
perturbative systems ?*
- *What are present & prospective  
experimental constraints ?*

## *Dimension Six Operators: I*

- *What are they ?*
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# Operator Classification

| Pure Gauge          |  | Gauge-Higgs                   |  | Gauge-Higgs-Fermion |  |
|---------------------|--|-------------------------------|--|---------------------|--|
| $Q_{\tilde{G}}$     | $f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$               | $Q_{\varphi \tilde{G}}$       | $\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$           | $Q_{uG}$            | $(\bar{Q} \sigma^{\mu\nu} T^A u) \tilde{\varphi} G_{\mu\nu}^A$ |
| $Q_{\widetilde{W}}$ | $\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | $Q_{\varphi \widetilde{W}}$   | $\varphi^\dagger \varphi \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$       | $Q_{dG}$            | $(\bar{Q} \sigma^{\mu\nu} T^A d) \varphi G_{\mu\nu}^A$         |
|                     |  | $Q_{\varphi \tilde{B}}$       | $\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$              | $Q_{fW}$            | $(\bar{F} \sigma^{\mu\nu} f) \tau^I \Phi W_{\mu\nu}^I$         |
|                     |  | $Q_{\varphi \widetilde{W} B}$ | $\varphi^\dagger \tau^I \varphi \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$ | $Q_{fB}$            | $(\bar{F} \sigma^{\mu\nu} f) \Phi B_{\mu\nu}$                  |

# Operator Classification

| Pure Gauge          |  | Gauge-Higgs                   |  | Gauge-Higgs-Fermion |  |
|---------------------|--|-------------------------------|--|---------------------|--|
| $Q_{\tilde{G}}$     | $f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$               | $Q_{\varphi \tilde{G}}$       | $\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$           | $Q_{uG}$            | $(\bar{Q} \sigma^{\mu\nu} T^A u) \tilde{\varphi} G_{\mu\nu}^A$ |
| $Q_{\widetilde{W}}$ | $\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | $Q_{\varphi \widetilde{W}}$   | $\varphi^\dagger \varphi \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$       | $Q_{dG}$            | $(\bar{Q} \sigma^{\mu\nu} T^A d) \varphi G_{\mu\nu}^A$         |
|                     |  | $Q_{\varphi \tilde{B}}$       | $\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$              | $Q_{fW}$            | $(\bar{F} \sigma^{\mu\nu} f) \tau^I \Phi W_{\mu\nu}^I$         |
|                     |  | $Q_{\varphi \widetilde{W} B}$ | $\varphi^\dagger \tau^I \varphi \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$ | $Q_{fB}$            | $(\bar{F} \sigma^{\mu\nu} f) \Phi B_{\mu\nu}$                  |

Weinberg 3 gluon

# Operator Classification

| Pure Gauge          |  | Gauge-Higgs                 |  | Gauge-Higgs-Fermion |  |
|---------------------|--|-----------------------------|--|---------------------|--|
| $Q_{\tilde{G}}$     | $f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$               | $Q_{\varphi \tilde{G}}$     | $\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$     | $Q_{uG}$            | $(\bar{Q} \sigma^{\mu\nu} T^A u) \tilde{\varphi} G_{\mu\nu}^A$ |
| $Q_{\widetilde{W}}$ | $\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | $Q_{\varphi \widetilde{W}}$ | $\varphi^\dagger \varphi \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{dG}$            | $(\bar{Q} \sigma^{\mu\nu} T^A d) \varphi G_{\mu\nu}^A$         |

$$\varphi^\dagger \varphi \rightarrow v^2$$

*θ-term renormalization*

# Operator Classification

| Pure Gauge          |  | Gauge-Higgs                   |  | Gauge-Higgs-Fermion |  |
|---------------------|--|-------------------------------|--|---------------------|--|
| $Q_{\tilde{G}}$     | $f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$               | $Q_{\varphi \tilde{G}}$       | $\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$           | $Q_{uG}$            | $(\bar{Q} \sigma^{\mu\nu} T^A u) \tilde{\varphi} G_{\mu\nu}^A$ |
| $Q_{\widetilde{W}}$ | $\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | $Q_{\varphi \widetilde{W}}$   | $\varphi^\dagger \varphi \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$       | $Q_{dG}$            | $(\bar{Q} \sigma^{\mu\nu} T^A d) \varphi G_{\mu\nu}^A$         |
|                     |  | $Q_{\varphi \tilde{B}}$       | $\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$              | $Q_{fW}$            | $(\bar{F} \sigma^{\mu\nu} f) \tau^I \Phi W_{\mu\nu}^I$         |
|                     |  | $Q_{\varphi \widetilde{W} B}$ | $\varphi^\dagger \tau^I \varphi \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$ | $Q_{fB}$            | $(\bar{F} \sigma^{\mu\nu} f) \Phi B_{\mu\nu}$                  |

Quark chromo-EDM

# Operator Classification

| Pure Gauge          |  | Gauge-Higgs                 |  | Gauge-Higgs-Fermion |  |
|---------------------|--|-----------------------------|--|---------------------|--|
| $Q_{\tilde{G}}$     | $f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$               | $Q_{\varphi \tilde{G}}$     | $\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$     | $Q_{uG}$            | $(\bar{Q} \sigma^{\mu\nu} T^A u) \tilde{\varphi} G_{\mu\nu}^A$ |
| $Q_{\widetilde{W}}$ | $\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | $Q_{\varphi \widetilde{W}}$ | $\varphi^\dagger \varphi \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{dG}$            | $(\bar{Q} \sigma^{\mu\nu} T^A d) \varphi G_{\mu\nu}^A$         |

Fermion EDM

# *Operator Classification*

| $(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$ |   |
|---|---|
| $Q_{ledq}$  | $(\bar{L}^j e)(\bar{d}Q^j)$   |
| $Q_{quqd}^{(1)}$                                  | $(\bar{Q}^j u)\epsilon_{jk}(\bar{Q}^k d)$                                 |
| $Q_{quqd}^{(8)}$                                  | $(\bar{Q}^j T^A u)\epsilon_{jk}(\bar{Q}^k T^A d)$                         |
| $Q_{lequ}^{(1)}$                                  | $(\bar{L}^j e)\epsilon_{jk}(\bar{Q}^k u)$                                 |
| $Q_{lequ}^{(3)}$                                  | $(\bar{L}^j \sigma_{\mu\nu} e)\epsilon_{jk}(\bar{Q}^k \sigma^{\mu\nu} u)$ |

# Operator Classification

| $(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$ |   |
|---|---|
| $Q_{ledq}$  | $(\bar{L}^j e)(\bar{d}Q^j)$   |
| $Q_{quqd}^{(1)}$                                  | $(\bar{Q}^j u)\epsilon_{jk}(\bar{Q}^k d)$                                 |
| $Q_{quqd}^{(8)}$                                  | $(\bar{Q}^j T^A u)\epsilon_{jk}(\bar{Q}^k T^A d)$                         |
| $Q_{lequ}^{(1)}$                                  | $(\bar{L}^j e)\epsilon_{jk}(\bar{Q}^k u)$                                 |
| $Q_{lequ}^{(3)}$                                  | $(\bar{L}^j \sigma_{\mu\nu} e)\epsilon_{jk}(\bar{Q}^k \sigma^{\mu\nu} u)$ |

Semileptonic: atomic &  
molecular EDMs

# *Operator Classification*

| $(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$ |   |
|---|---|
| $Q_{ledq}$  | $(\bar{L}^j e)(\bar{d}Q^j)$   |
| $Q_{quqd}^{(1)}$                                  | $(\bar{Q}^j u)\epsilon_{jk}(\bar{Q}^k d)$                                 |
| $Q_{quqd}^{(8)}$                                  | $(\bar{Q}^j T^A u)\epsilon_{jk}(\bar{Q}^k T^A d)$                         |
| $Q_{lequ}^{(1)}$                                  | $(\bar{L}^j e)\epsilon_{jk}(\bar{Q}^k u)$                                 |
| $Q_{lequ}^{(3)}$                                  | $(\bar{L}^j \sigma_{\mu\nu} e)\epsilon_{jk}(\bar{Q}^k \sigma^{\mu\nu} u)$ |

*Nonleptonic: hadronic  
EDMs & Schiff moment*

# Operator Classification

$$\begin{aligned}\mathcal{L}_{\text{CPV}}^{\text{eq}} = & i \frac{\text{Im}C_{\ell edq}}{2\Lambda^2} [\bar{e}\gamma_5 e \bar{d}d - \bar{e}e \bar{d}\gamma_5 d] - i \frac{\text{Im}C_{\ell equ}^{(1)}}{2\Lambda^2} [\bar{e}\gamma_5 e \bar{u}u + \bar{e}e \bar{u}\gamma_5 u] \\ & - \frac{\text{Im}C_{\ell equ}^{(3)}}{2\Lambda^2} \epsilon_{\mu\nu\alpha\beta} \bar{e}\sigma^{\mu\nu} e \bar{u}\sigma^{\alpha\beta} u\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{\text{CPV}}^{\text{qq}} = & i \frac{g_3^2 \text{Im}C_{quqd}^{(1)}}{2\Lambda^2} [\bar{u}\gamma_5 u \bar{d}d + \bar{u}u \bar{d}\gamma_5 d - \bar{d}\gamma_5 u \bar{u}d - \bar{d}u \bar{u}\gamma_5 d] \\ & + i \frac{g_3^2 \text{Im}C_{quqd}^{(8)}}{2\Lambda^2} [\bar{u}\gamma_5 T^A u \bar{d}T^A d + \bar{u}T^A u \bar{d}\gamma_5 T^A d - \bar{d}\gamma_5 T^A u \bar{u}T^A d - \bar{d}T^A u \bar{u}\gamma_5 T^A d]\end{aligned}$$

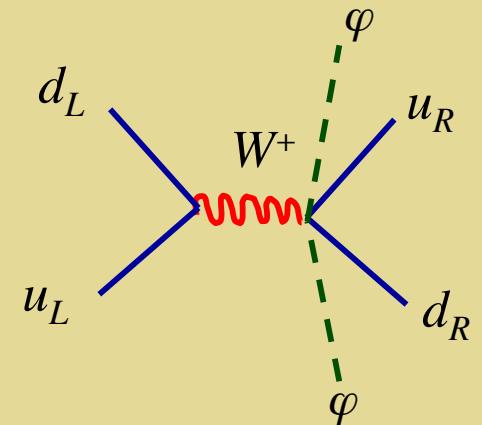
*Nonleptonic: hadronic  
EDMs & Schiff moment*

# *Operator Classification*

$$Q_{\varphi ud} = i\tilde{\varphi}^\dagger D_\mu \varphi \bar{u}_R \gamma^\mu d_R$$

# Operator Classification

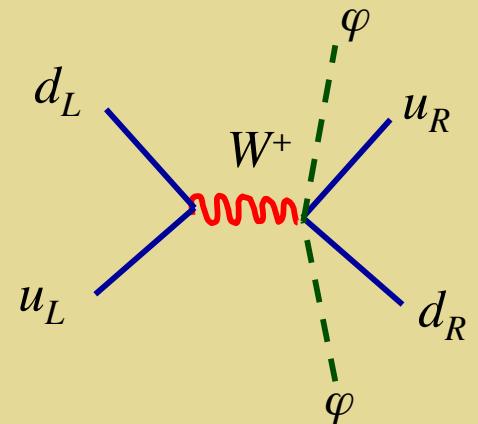
$$Q_{\varphi ud} = i\tilde{\varphi}^\dagger D_\mu \varphi \bar{u}_R \gamma^\mu d_R$$



# Operator Classification

$$Q_{\varphi ud} = i\tilde{\varphi}^\dagger D_\mu \varphi \bar{u}_R \gamma^\mu d_R$$

$\varphi \rightarrow v$



$$\mathcal{L}_{\text{LR, CPV}}^{\text{eff}} = -i \frac{\text{Im } C_{\varphi ud}}{\Lambda^2} [\bar{d}_L \gamma^\mu u_L \bar{u}_R \gamma_\mu d_R - \bar{u}_L \gamma^\mu d_L \bar{d}_R \gamma_\mu u_R]$$

Nonleptonic: hadronic EDMs & Schiff moment

# Wilson Coefficients: *EDM* & *CEDM*

$$\begin{aligned} & (\bar{Q}\sigma^{\mu\nu}T^A u)\tilde{\varphi} G_{\mu\nu}^A \\ & (\bar{Q}\sigma^{\mu\nu}T^A d)\varphi G_{\mu\nu}^A \\ & (\bar{F}\sigma^{\mu\nu} f)\tau^I \Phi W_{\mu\nu}^I \\ & (\bar{F}\sigma^{\mu\nu} f)\Phi B_{\mu\nu} \end{aligned}$$

$$\begin{aligned} \mathcal{L}^{\text{CEDM}} &= -i \sum_q \frac{g_3 \tilde{d}_q}{2} \bar{q} \sigma^{\mu\nu} T^A \gamma_5 q G_{\mu\nu}^A \\ \mathcal{L}^{\text{EDM}} &= -i \sum_f \frac{d_f}{2} \bar{f} \sigma^{\mu\nu} \gamma_5 f F_{\mu\nu} \end{aligned}$$

$$\alpha_{fV_k}^{(6)} \equiv g_k C_{fV_k}$$

$$\begin{aligned} \tilde{d}_q &= -\frac{\sqrt{2}}{v} \left(\frac{v}{\Lambda}\right)^2 \text{Im } C_{qG}, \\ d_f &= -\frac{\sqrt{2}e}{v} \left(\frac{v}{\Lambda}\right)^2 \text{Im } C_{f\gamma} \end{aligned}$$

$$\text{Im } C_{f\gamma} \equiv \text{Im } C_{fB} + 2I_3^f \text{Im } C_{fW}$$

# Wilson Coefficients: *EDM* & *CEDM*

$$\begin{aligned} & (\bar{Q}\sigma^{\mu\nu}T^A u)\tilde{\varphi} G_{\mu\nu}^A \\ & (\bar{Q}\sigma^{\mu\nu}T^A d)\varphi G_{\mu\nu}^A \\ & (\bar{F}\sigma^{\mu\nu}f)\tau^I\Phi W_{\mu\nu}^I \\ & (\bar{F}\sigma^{\mu\nu}f)\Phi B_{\mu\nu} \end{aligned}$$

$$\begin{aligned} \mathcal{L}^{\text{CEDM}} &= -i \sum_q \frac{g_3 \tilde{d}_q}{2} \bar{q} \sigma^{\mu\nu} T^A \gamma_5 q G_{\mu\nu}^A \\ \mathcal{L}^{\text{EDM}} &= -i \sum_f \frac{d_f}{2} \bar{f} \sigma^{\mu\nu} \gamma_5 f F_{\mu\nu} \end{aligned}$$

*Chirality  
flipping*

$$\begin{aligned} \text{Im } C_{qG} &\equiv Y_q \tilde{d}_q \rightarrow \tilde{d}_q = -\frac{2m_q}{v^2} \left(\frac{v}{\Lambda}\right)^2 \tilde{\delta}_q, \\ \text{Im } C_{f\gamma} &\equiv Y_f \delta_f \rightarrow d_f = -e \frac{2m_f}{v^2} \left(\frac{v}{\Lambda}\right)^2 \tilde{\delta}_f \end{aligned}$$

$\tilde{\delta}_f, \tilde{\delta}_q$  appropriate for comparison  
with other  $d=6$  Wilson coefficients

# *Wilson Coefficients: Summary*

|                     |                      |     |
|---------------------|----------------------|-----|
| $\delta_f$          | <i>fermion EDM</i>   | (3) |
| $\tilde{\delta}_q$  | <i>quark CEDM</i>    | (2) |
| $C_{\widetilde{G}}$ | <i>3 gluon</i>       | (1) |
| $C_{quqd}$          | <i>non-leptonic</i>  | (2) |
| $C_{lequ, ledq}$    | <i>semi-leptonic</i> | (3) |
| $C_{\varphi ud}$    | <i>induced 4f</i>    | (1) |

*12 total +  $\overline{\theta}$*

*light flavors only (e,u,d)*

## *Dimension Six Operators: II*

- *What are they ?*
- *Where do they come from ?*
- *How do they appear in hadronic, nuclear, and atomic systems ?*
- *How well can we match them onto physics of many-body and non-perturbative systems ?*
- *What are present & prospective experimental constraints ?*

## *BSM Origins*

|                     |                |                        |
|---------------------|----------------|------------------------|
| $\delta_f$          | MSSM, RS, LRSM | 1 & 2 loop             |
| $\tilde{\delta}_q$  | MSSM, RS, LRSM | 1 & 2 loop             |
| $C_{\widetilde{G}}$ | MSSM           | 2 loop                 |
| $C_{quqd}$          | (MSSM d=8)     |                        |
| $C_{lequ, ledq}$    | (MSSM d=8)     |                        |
| $C_{\varphi ud}$    | LRSM           | tree ( $\theta_{LR}$ ) |

11 total +  $\overline{\theta}$

*light flavors only (u,d)*

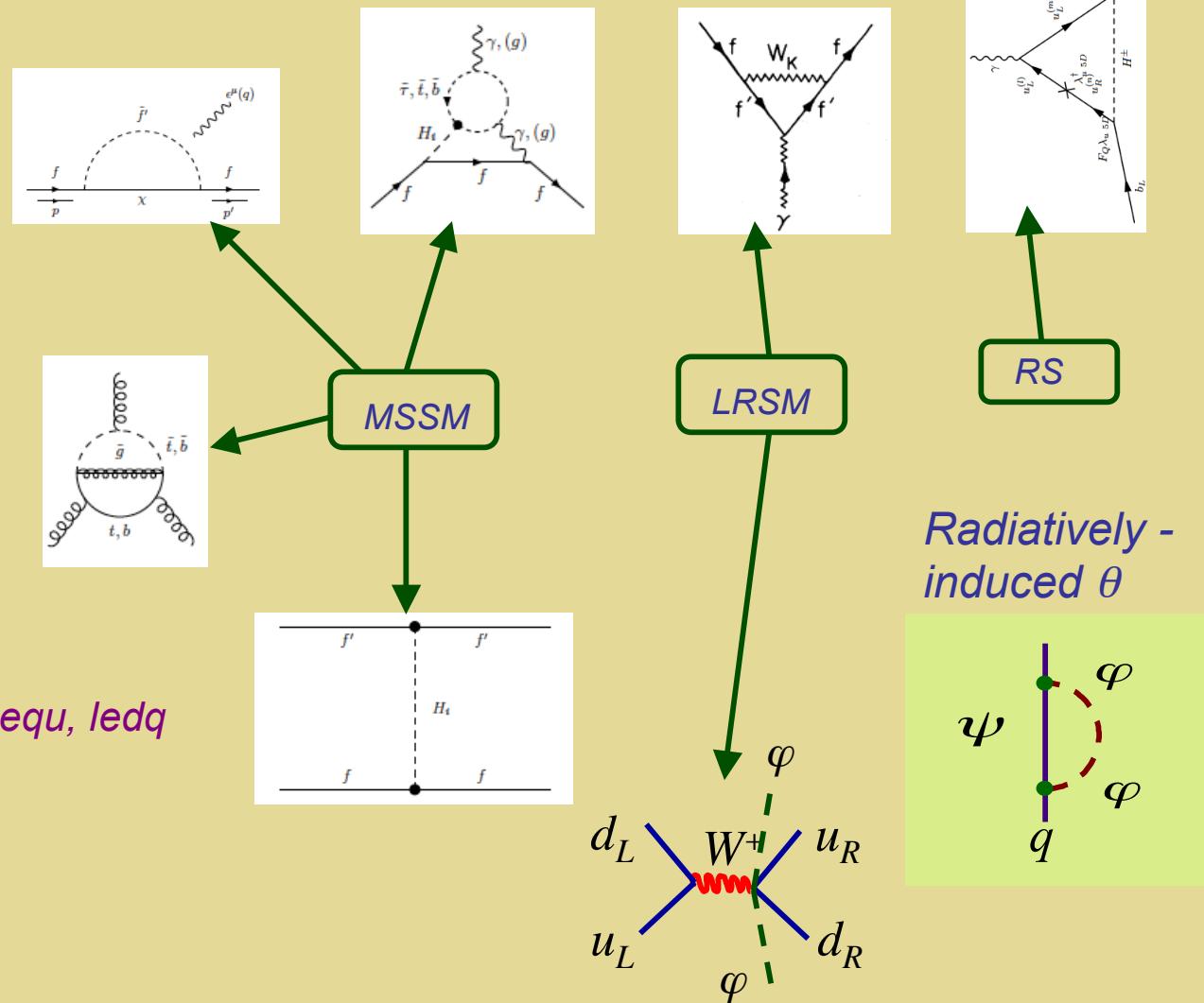
# BSM Origins

$\delta_f$

$C_G \sim$

$C_{quqd}; C_{lequ, ledq}$

$C_{\varphi ud}$



# *Effective Operators & $\theta_{ind}$*

$$\mathcal{L}_{\text{axion}} = \frac{1}{2} \partial^\mu a \partial_\mu a - V(a) - \frac{a(x)}{f_a} \frac{g_3^2 \bar{\theta}}{16\pi^2} \text{Tr} \left( G^{\mu\nu} \tilde{G}_{\mu\nu} \right)$$

$$V(a) = \chi(0) \mathcal{O}_{\text{CPV}} \left( \bar{\theta} - \frac{a}{f_a} \right) + \frac{1}{2} \chi(0) \left( \bar{\theta} + \frac{a}{f_a} \right)^2 + \dots ,$$

$$\chi(0) \mathcal{O}_{\text{CPV}} = -i \lim_{k \rightarrow 0} \int d^4x e^{ix \cdot k} \langle 0 | T\{ G \tilde{G}(x), \mathcal{O}_{\text{CPV}}(0) \} | 0 \rangle$$

*12 total +  $\overline{\theta}$*

$\overline{\theta} \rightarrow \theta_{ind} \propto \tilde{\delta}_q, C, \dots$

## *Dimension Six Operators: III*

- *What are they ?*
- *Where do they come from ?*
- *How do they appear in hadronic, nuclear, and atomic systems ?*
- *How well can we match them onto physics of many-body and non-perturbative systems ?*
- *What are present & prospective experimental constraints ?*

## *Low Scale Observables*

$$\begin{aligned}\mathcal{L}_{N\pi}^{\text{PVTV}} = & -2\bar{N} (\bar{d}_0 + \bar{d}_1 \tau_3) S_\mu N v_\nu F^{\mu\nu} \\ & + \bar{N} [\bar{g}_\pi^{(0)} \boldsymbol{\tau} \cdot \boldsymbol{\pi} + \bar{g}_\pi^{(1)} \pi^0 + \bar{g}_\pi^{(2)} (3\tau_3 \pi^0 - \boldsymbol{\tau} \cdot \boldsymbol{\pi})] N \\ & + \bar{C}_1 \bar{N} N \partial_\mu (\bar{N} S^\mu N) + \bar{C}_2 \bar{N} \boldsymbol{\tau} N \cdot \partial_\mu (\bar{N} S^\mu \boldsymbol{\tau} N) + \dots\end{aligned}$$

*Nonleptonic: hadronic EDMs, Schiff moment (atomic EDMs)*

## Low Scale Observables

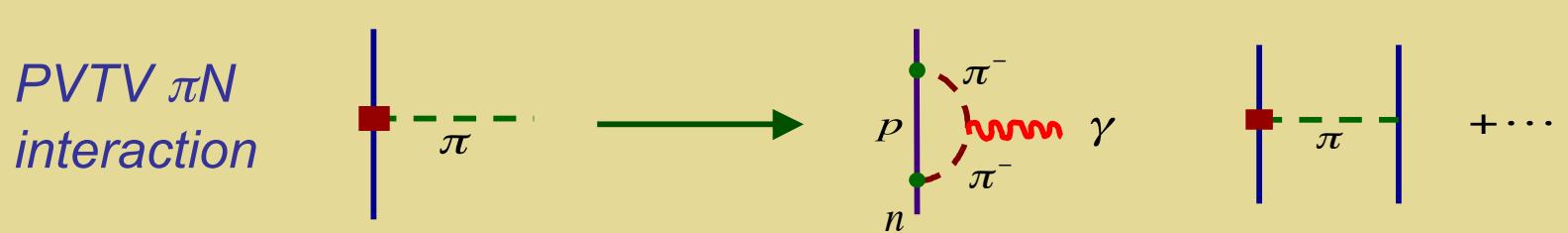
$$\begin{aligned}\mathcal{L}_{N\pi}^{\text{PVTV}} = & -[2\bar{N}(\bar{d}_0 + \bar{d}_1\tau_3)S_\mu N v_\nu F^{\mu\nu}] \\ & + \bar{N}[\bar{g}_\pi^{(0)}\boldsymbol{\tau} \cdot \boldsymbol{\pi} + \bar{g}_\pi^{(1)}\pi^0 + \bar{g}_\pi^{(2)}(3\tau_3\pi^0 - \boldsymbol{\tau} \cdot \boldsymbol{\pi})]N \\ & + \bar{C}_1\bar{N}N\partial_\mu(\bar{N}S^\mu N) + \bar{C}_2\bar{N}\boldsymbol{\tau}N \cdot \partial_\mu(\bar{N}S^\mu \boldsymbol{\tau}N) + \dots\end{aligned}$$

*Nucleon EDMs*

*Nonleptonic: hadronic EDMs, Schiff moment (atomic EDMs)*

## Low Scale Observables

$$\begin{aligned}
 \mathcal{L}_{N\pi}^{\text{PTV}} = & -2\bar{N} (\bar{d}_0 + \bar{d}_1 \tau_3) S_\mu N v_\nu F^{\mu\nu} \quad l = 0, 1, 2 \\
 & + \boxed{\bar{N} [\bar{g}_\pi^{(0)} \boldsymbol{\tau} \cdot \boldsymbol{\pi} + \bar{g}_\pi^{(1)} \pi^0 + \bar{g}_\pi^{(2)} (3\tau_3 \pi^0 - \boldsymbol{\tau} \cdot \boldsymbol{\pi})] N} \\
 & + \bar{C}_1 \bar{N} N \partial_\mu (\bar{N} S^\mu N) + \bar{C}_2 \bar{N} \boldsymbol{\tau} N \cdot \partial_\mu (\bar{N} S^\mu \boldsymbol{\tau} N) + \dots
 \end{aligned}$$



Nonleptonic: hadronic EDMs, Schiff moment (atomic EDMs)

## Low Scale Observables

$$\begin{aligned}\mathcal{L}_{N\pi}^{\text{PVTV}} = & -2\bar{N} (\bar{d}_0 + \bar{d}_1 \tau_3) S_\mu N v_\nu F^{\mu\nu} \\ & + \bar{N} [\bar{g}_\pi^{(0)} \boldsymbol{\tau} \cdot \boldsymbol{\pi} + \bar{g}_\pi^{(1)} \pi^0 + \bar{g}_\pi^{(2)} (3\tau_3 \pi^0 - \boldsymbol{\tau} \cdot \boldsymbol{\pi})] N \\ & + \boxed{\bar{C}_1 \bar{N} N \partial_\mu (\bar{N} S^\mu N) + \bar{C}_2 \bar{N} \boldsymbol{\tau} N \cdot \partial_\mu (\bar{N} S^\mu \boldsymbol{\tau} N) + \dots}\end{aligned}$$

PVTV 4N  
interaction

Nonleptonic: hadronic EDMs, Schiff moment (atomic EDMs)

# Low Scale Observables

## Nuclear Moments

|         | $P_T$ | $\not{P}_T$ | $P\cancel{T}$ | $\not{P}\cancel{T}$ |                       |
|---------|-------|-------------|---------------|---------------------|-----------------------|
| $C_J$   | E     | ✗           | ✗             | O                   | <i>EDM, Schiff...</i> |
| $T^M_J$ | O     | ✗           | ✗             | E                   | <i>MQM....</i>        |
| $T^E_J$ | ✗     | O           | E             | ✗                   | <i>Anapole...</i>     |

# Low Scale Observables

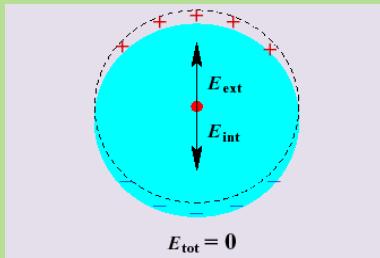
## Nuclear Moments

|         | $P_T$ | $\not{P}_T$ | $P\cancel{T}$ | $\not{P}\cancel{T}$ |                  |
|---------|-------|-------------|---------------|---------------------|------------------|
| $C_J$   | E     | ×           | ×             | O                   | $EDM, Schiff...$ |
| $T^M_J$ | O     | ×           | ×             | E                   | $MQM....$        |
| $T^E_J$ | ×     | O           | E             | ×                   | $Anapole...$     |

*Nuclear Enhancements*

# Nuclear Schiff Moment I

## Schiff Screening



Atomic effect from nuclear finite size:  
Schiff moment

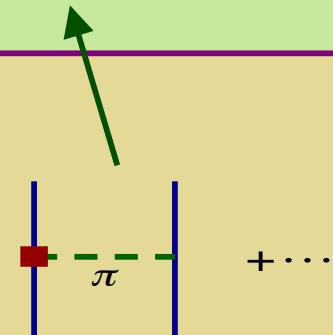
## Nuclear Schiff Moment

$$S \sim \int d^3x x^2 \vec{x} \rho(\vec{x})^{\text{CPV}}$$

Nuclear EDM: Screened in atoms

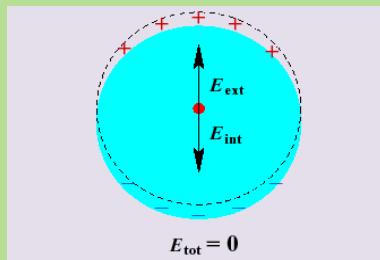
$$d_{\text{nuc}} \sim \int d^3x \vec{x} \rho(\vec{x})^{\text{CPV}}$$

EDMs of diamagnetic atoms ( $^{199}\text{Hg}$ )

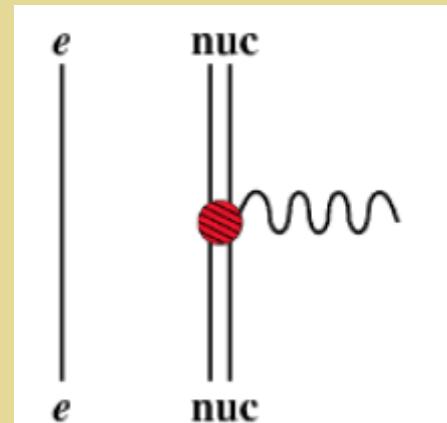


# Nuclear Schiff Moment II

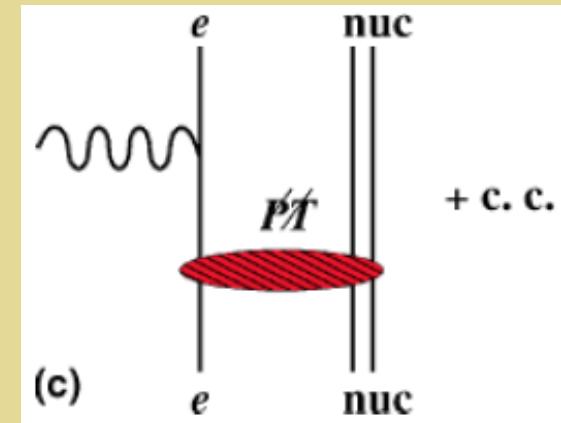
## Schiff Screening



Atomic effect from  
nuclear finite size:  
Schiff moment



Screened EDM

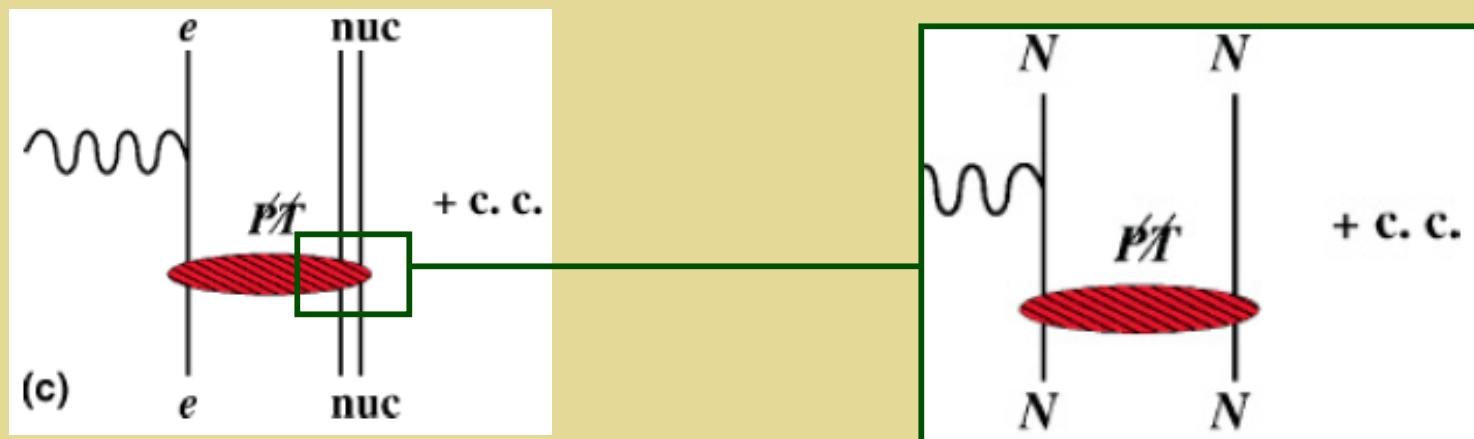


Schiff moment, MQM, ...

EDMs of diamagnetic atoms ( $^{199}\text{Hg}$ )

# Nuclear Schiff Moment III

## Nuclear Enhancements



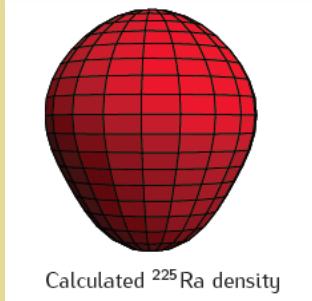
Schiff moment, MQM, ...

Nuclear polarization:  
mixing of opposite parity  
states by  $H^{TVPV} \sim 1 / \Delta E$

EDMs of diamagnetic atoms ( $^{199}\text{Hg}$ )

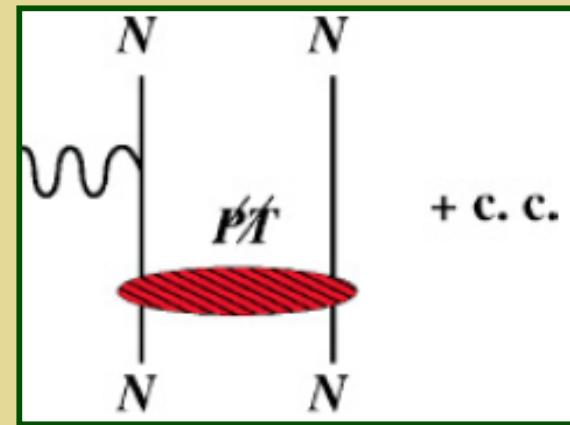
# Nuclear Schiff Moment IV

*Nuclear Enhancements:  
Octupole Deformation*



$$|\pm\rangle = \frac{1}{\sqrt{2}}(|\bullet\rangle \pm |\circlearrowleft\rangle)$$

*Opposite parity states  
mixed by  $H^{\text{TVPV}}$*



*Nuclear polarization:  
mixing of opposite parity  
states by  $H^{\text{TVPV}} \sim 1/\Delta E$*

*EDMs of diamagnetic atoms ( $^{199}\text{Hg}$ )*

*Thanks: J. Engel*

# Nuclear Matrix Elements

$$S = a_0 g \bar{g}_\pi^{(0)} + a_1 g \bar{g}_\pi^{(1)} + a_2 g \bar{g}_\pi^{(2)}$$

The coefficients  $a_i$  in  $^{199}\text{Hg}$  from a variety of nuclear-structure calculations.

| Ref.    | Method                         | $a_0$       | $a_1$         | $a_2$       |
|---------|--------------------------------|-------------|---------------|-------------|
| [130]   | Schematic                      | 0.087       | 0.087         | 0.174       |
| [41,42] | Phenomenological RPA           | 0.00004     | 0.055         | 0.009       |
| [39]    | Skyrme QRPA                    | 0.002–0.010 | 0.057–0.090   | 0.011–0.025 |
| [128]   | Odd-A Skyrme mean-field theory | 0.009–0.041 | −0.027–+0.005 | 0.009–0.024 |

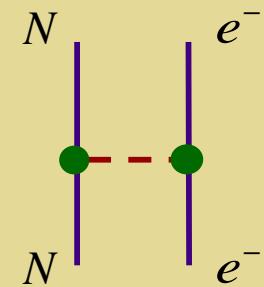
Best values and ranges for the coefficients  $a_i$  in three nuclei used in experiments.

| Nucl.             | Best value |            |        | Range          |                |               |
|-------------------|------------|------------|--------|----------------|----------------|---------------|
|                   | $a_0$      | $a_1$      | $a_2$  | $a_0$          | $a_1$          | $a_2$         |
| $^{199}\text{Hg}$ | 0.01       | $\pm 0.02$ | 0.02   | 0.005–0.05     | −0.03–(+0.09)  | 0.01–0.06     |
| $^{129}\text{Xe}$ | −0.008     | −0.006     | −0.009 | −0.005–(−0.05) | −0.003–(−0.05) | −0.005–(−0.1) |
| $^{225}\text{Ra}$ | −1.5       | 6.0        | −4.0   | −1–(−6)        | 4–24           | −3–(−15)      |

# Semileptonic CPV

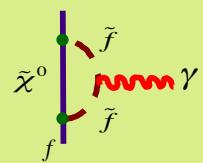
$$\begin{aligned}\mathcal{L}_{eN}^{\text{eff}} = & \frac{G_F}{\sqrt{2}} \left\{ \bar{e} i \gamma_5 e \bar{N} \left[ C_S^{(0)} + C_S^{(1)} \tau_3 \right] N \right. \\ & \left. + 8 \bar{e} \sigma_{\mu\nu} e v^\nu \bar{N} \left[ C_T^{(0)} + C_T^{(1)} \tau_3 \right] S^\mu N \right\} + \dots\end{aligned}$$

*EDMs of atoms &  
molecules (TI, YbF...)*



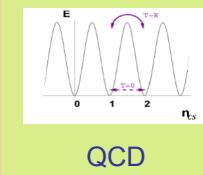
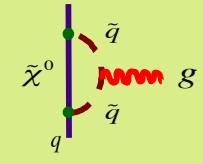
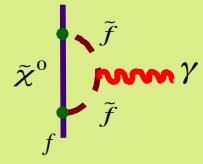
# ***EDMs: Complementary Searches***

*Electron*



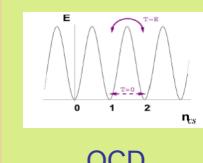
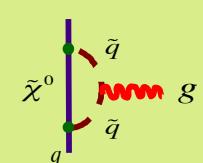
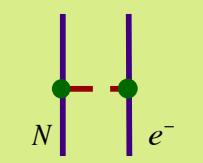
*Improvements  
of  $10^2$  to  $10^3$*

*Neutron*



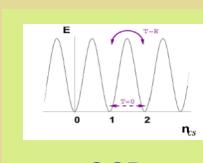
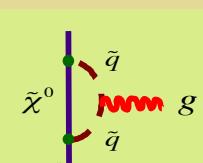
QCD

*Neutral  
Atoms*



QCD

*Deuteron*



QCD

## *Dimension Six Operators: IV*

- *What are they ?*
- *Where do they come from ?*
- *How do they appear in hadronic, nuclear, and atomic systems ?*
- *How well can we match them onto physics of many-body and non-perturbative systems ?*
- *What are present & prospective experimental constraints ?*

# Running & Matching

**Baryon Asymmetry**

Early universe CPV

**BSM CPV**

SUSY, GUTs, Extra Dim...

**Collider Searches**

Particle spectrum; also scalars for baryon asym

**EW Scale Operators**

$$\mathcal{L}_{\text{eff}} = \sum \frac{C}{\Lambda_{\text{BSM}}^2} \mathcal{O}$$

*SM particles only*

$\Lambda_{\text{BSM}}$ : new physics scale  
C: model-dep op coeffs

**Had Scale Operators**

$$\mathcal{L}_{\text{eff}} = \sum \frac{C \langle H^0 \rangle}{\Lambda_{\text{BSM}}^2} \mathcal{O}'$$

e, q, g,  $\gamma$  (*no Higgs*)

*QCD evolution*

*Also QCD  $\theta$  term*

**QCD Matrix Elements**

$$d_n, \bar{g}_{\pi NN}, \dots$$

**Nuclear & atomic MEs**

Schiff moment, other P- & T-odd moments, e-nucleus CPV

**Expt**

## *Running & Matching*

$$\text{Im } C_j(\Lambda_\chi) = K_{jk} \text{Im } C_k(\Lambda)$$

| Operator           | $K_Q$ | Reference |
|--------------------|-------|-----------|
| $Q_{qG}$           | 3.30  | [35]      |
| $Q_{qV}, V = B, W$ | 1.53  | [35]      |
| $Q_{\bar{G}}$      | 3.30  | [35, 36]  |
| $Q_{quqd}^{(1,8)}$ |       |           |

# *Running & Matching*      Hadronic

$$\begin{aligned}
 d_N &= \alpha_N \bar{\theta} + \left(\frac{v}{\Lambda}\right)^2 \sum_k \beta_N^{(k)} (\text{Im } C_k) \\
 \bar{g}_\pi^{(i)} &= \lambda_{(i)} \bar{\theta} + \left(\frac{v}{\Lambda}\right)^2 \sum_k \gamma_{(i)}^{(k)} (\text{Im } C_k)
 \end{aligned}$$

$$\begin{aligned}
 \left(\frac{v}{\Lambda}\right)^2 \left[ \beta_N^{qG} (\text{Im } C_{qG}) + \beta_N^{q\gamma} (\text{Im } C_{q\gamma}) \right] &= e \tilde{\rho}_N^q \tilde{d}_q + \rho_N^q d_q = \left(\frac{v}{\Lambda}\right)^2 \left[ e \tilde{\zeta}_N^q \tilde{\delta}_q + e \zeta_N^q \delta_q \right] \\
 \left(\frac{v}{\Lambda}\right)^2 \left[ \gamma_{(i)}^{qG} (\text{Im } C_{qG}) + \gamma_{(i)}^{q\gamma} (\text{Im } C_{q\gamma}) \right] &= \tilde{\omega}_{(i)}^q \tilde{d}_q + \omega_{(i)}^q d_q = \left(\frac{v}{\Lambda}\right)^2 \left[ \tilde{\eta}_{(i)}^q \tilde{\delta}_q + \eta_{(i)}^q \delta_q \right]
 \end{aligned}$$

*How well can we compute the  $\beta, \rho, \zeta, \dots$  ?*

# *Running & Matching*

*Nuclear*

$$S = a_0 g \bar{g}_\pi^{(0)} + a_1 g \bar{g}_\pi^{(1)} + a_2 g \bar{g}_\pi^{(2)}$$

*Nuclear many-body  
computations*

$$\bar{g}_\pi^{(i)} = \lambda_{(i)} \bar{\theta} + \left(\frac{v}{\Lambda}\right)^2 \sum_k \gamma_{(i)}^{(k)} (\text{Im } C_k)$$

*Non-perturbative hadronic  
computations*

# *Running & Matching*

*Atomic &  
Molecular*

$$\begin{aligned} d_A &= \rho_A^e d_e + \sum_{N=p,n} \rho_Z^N d_N + \kappa_S S \\ &+ \left(\frac{v}{\Lambda}\right)^2 \left\{ \left[ k_S^{(0)} g_S^{(0)} + k_P^{(1)} g_P^{(1)} \right] \text{Im}C_{eq}^{(-)} \right. \\ &+ \left[ k_S^{(1)} g_S^{(1)} + k_P^{(0)} g_P^{(0)} \right] \text{Im}C_{eq}^{(+)} \\ &\left. + \left[ k_T^{(0)} g_T^{(0)} + k_T^{(1)} g_T^{(1)} \right] \text{Im}C_{\ell equ}^{(3)} \right\} \end{aligned}$$

$$\rho_A^e d_e = e \zeta_A^e \left(\frac{v}{\Lambda}\right)^2 \delta_e$$

$$C_{eq}^{(\pm)} = C_{\ell edq} \pm C_{\ell equ}^{(1)}$$

# Running & Matching

Atomic &  
Molecular

$$\begin{aligned}
 d_A &= \rho_A^e d_e + \sum_{N=p,n} \rho_Z^N d_N + \kappa_S S \\
 &+ \left(\frac{v}{\Lambda}\right)^2 \left\{ \left[ k_S^{(0)} g_S^{(0)} + k_P^{(1)} g_P^{(1)} \right] \text{Im} C_{eq}^{(-)} \right. \\
 &+ \left[ k_S^{(1)} g_S^{(1)} + k_P^{(0)} g_P^{(0)} \right] \text{Im} C_{eq}^{(+)} \\
 &\left. + \left[ k_T^{(0)} g_T^{(0)} + k_T^{(1)} g_T^{(1)} \right] \text{Im} C_{\ell equ}^{(3)} \right\}
 \end{aligned}$$

$$S = a_0 g \bar{g}_\pi^{(0)} + a_1 g \bar{g}_\pi^{(1)} + a_2 g \bar{g}_\pi^{(2)}$$

$$\bar{g}_\pi^{(i)} = \lambda_{(i)} \bar{\theta} + \left(\frac{v}{\Lambda}\right)^2 \sum_k^n \gamma_{(i)}^{(k)} (\text{Im} C_k)$$

$$\rho_A^e d_e = e \zeta_A^e \left(\frac{v}{\Lambda}\right)^2 \delta_e$$

$$C_{eq}^{(\pm)} = C_{\ell edq} \pm C_{\ell equ}^{(1)}$$

# Running & Matching

Atomic &  
Molecular

$$\begin{aligned}
 d_A &= \rho_A^e d_e + \sum_{N=p,n} \rho_Z^N d_N + \kappa_S S \\
 &+ \left(\frac{v}{\Lambda}\right)^2 \left\{ \left[ k_S^{(0)} g_S^{(0)} + k_P^{(1)} g_P^{(1)} \right] \text{Im} C_{eq}^{(-)} \right. \\
 &+ \left[ k_S^{(1)} g_S^{(1)} + k_P^{(0)} g_P^{(0)} \right] \text{Im} C_{eq}^{(+)} \\
 &\left. + \left[ k_T^{(0)} g_T^{(0)} + k_T^{(1)} g_T^{(1)} \right] \text{Im} C_{\ell equ}^{(3)} \right\}
 \end{aligned}$$

$$S = a_0 g \bar{g}_\pi^{(0)} + a_1 g \bar{g}_\pi^{(1)} + a_2 g \bar{g}_\pi^{(2)}$$

$$\bar{g}_\pi^{(i)} = \lambda_{(i)} \bar{\theta} + \left(\frac{v}{\Lambda}\right)^2 \sum_k \gamma_{(i)}^{(k)} (\text{Im } C_k)$$

*Hadronic coefficients,  
including form factors  $g_\Gamma$*

$$\rho_A^e d_e = e \zeta_A^e \left(\frac{v}{\Lambda}\right)^2 \delta_e$$

$$C_{eq}^{(\pm)} = C_{\ell edq} \pm C_{\ell equ}^{(1)}$$

# Running & Matching

Atomic &  
Molecular

$$\begin{aligned}
 d_A &= \boxed{\rho_A^e} d_e + \sum_{N=p,n} \rho_Z^N d_N + \boxed{\kappa_S} S \\
 &+ \left(\frac{v}{\Lambda}\right)^2 \left\{ \boxed{k_S^{(0)}} g_S^{(0)} + \boxed{k_P^{(1)}} g_P^{(1)} \right] \text{Im} C_{eq}^{(-)} \\
 &+ \boxed{k_S^{(1)}} g_S^{(1)} + \boxed{k_P^{(0)}} g_P^{(0)} \right] \text{Im} C_{eq}^{(+)} \\
 &+ \boxed{k_T^{(0)}} g_T^{(0)} + \boxed{k_T^{(1)}} g_T^{(1)} \right] \text{Im} C_{\ell equ}^{(3)} \}
 \end{aligned}$$

$$S = a_0 g \bar{g}_\pi^{(0)} + a_1 g \bar{g}_\pi^{(1)} + a_2 g \bar{g}_\pi^{(2)}$$

$$\bar{g}_\pi^{(i)} = \lambda_{(i)} \bar{\theta} + \left(\frac{v}{\Lambda}\right)^2 \sum_k^n \gamma_{(i)}^{(k)} (\text{Im} C_k)$$

Atomic / molecular  
coefficients

$$\rho_A^e d_e = e \zeta_A^e \left(\frac{v}{\Lambda}\right)^2 \delta_e$$

$$C_{eq}^{(\pm)} = C_{\ell edq} \pm C_{\ell equ}^{(1)}$$

# Running & Matching

Atomic &  
Molecular

$$\begin{aligned}
 d_A &= \boxed{\rho_A^e} d_e + \sum_{N=p,n} \rho_Z^N d_N + \boxed{\kappa_S} S \\
 &+ \left(\frac{v}{\Lambda}\right)^2 \left\{ \boxed{k_S^{(0)}} g_S^{(0)} + \boxed{k_P^{(1)}} g_P^{(1)} \right] \text{Im} C_{eq}^{(-)} \\
 &+ \boxed{k_S^{(1)}} g_S^{(1)} + \boxed{k_P^{(0)}} g_P^{(0)} \right] \text{Im} C_{eq}^{(+)} \\
 &+ \boxed{k_T^{(0)}} g_T^{(0)} + \boxed{k_T^{(1)}} g_T^{(1)} \right] \text{Im} C_{lequ}^{(3)} \}
 \end{aligned}$$

$$S = a_0 g \bar{g}_\pi^{(0)} + a_1 g \bar{g}_\pi^{(1)} + a_2 g \bar{g}_\pi^{(2)}$$

$$\bar{g}_\pi^{(i)} = \lambda_{(i)} \bar{\theta} + \left(\frac{v}{\Lambda}\right)^2 \sum_k \gamma_{(i)}^{(k)} (\text{Im} C_k)$$

Atomic / molecular  
coefficients

Paramag\*:  $\delta_e, \text{Im } C_{eq}^{(-)} (k_s^0)$

Diamag\*\*:  $S, \text{Im } C_{lequ}^{(3)} (k_T)$

$$\rho_A^e d_e = e \zeta_A^e \left(\frac{v}{\Lambda}\right)^2 \delta_e$$

$$C_{eq}^{(\pm)} = C_{ledq} \pm C_{lequ}^{(1)}$$

\*  $Tl, Cs, YbF\dots$

\*\*  $Hg, Ra, Rn\dots$

# Matching: $\chi$ Sym & Other Methods

| CPV Parameter  | Coefficient     | Method            | Value                                       | Remarks                          |
|----------------|-----------------|-------------------|---|----------------------------------|
| $\bar{\theta}$ | $\alpha_n$      | ChPT              | $\sim 0.002 \text{ e fm}$                   |                                  |
| $\bar{\theta}$ | $\alpha_n$      | Lattice QCD[30]   | -0.040(28) e-fm                             | $m_\pi = 0.53 \text{ GeV}$       |
| $\bar{\theta}$ | $\alpha_p$      | Lattice QCD[30]   | 0.072(49) e-fm                              | $m_\pi = 0.53 \text{ GeV}$       |
| $\bar{\theta}$ | $\alpha_n$      | Lattice QCD[31]   | -0.049(5) e-fm                              | $m_\pi \approx 0.61 \text{ GeV}$ |
| $\bar{\theta}$ | $\alpha_p$      | Lattice QCD[31]   | 0.080(10) e-fm                              | $m_\pi \approx 0.61 \text{ GeV}$ |
| $\bar{\theta}$ | $\alpha_n$      | QCD Sum Rules[6]  | $(0.0025 \pm 0.0013) \text{ e-fm}$          | $\lambda$ from QCD SR            |
| $\bar{\theta}$ | $\alpha_n$      | QCD Sum Rules[35] | $(0.0004^{+0.0003}_{-0.0002}) \text{ e-fm}$ | $\lambda$ from lattice           |
| $\bar{\theta}$ | $\lambda_{(0)}$ | ChPT              | $\sim m_\pi^2/\Lambda_\chi F_\pi$           | See Eq. (3.62)                   |
|                |                 |                   | -0.05                                       | See Eq. (3.60)                   |
| $\bar{\theta}$ | $\lambda_{(1)}$ | ChPT              | $\sim m_\pi^4/\Lambda_\chi^3 F_\pi$         | See Eq. (3.63)                   |

$\theta$  term

# Matching: $\chi$ Sym & Other Methods

| CPV Parameter      | Coefficient          | Method    | Value  | Remarks           |
|--------------------|----------------------|-----------|--|-------------------|
| $\tilde{d}_q$      | $\tilde{\rho}_N$     | ChPT      | $\sim -0.7$                                  |                   |
| $\tilde{d}_q$      | $\tilde{\rho}_N^u$   | QCD SR[6] | $0.55 \pm 2.8$                               | PQ assumed        |
| $\tilde{d}_q$      | $\tilde{\rho}_N^d$   | QCD SR[6] | $1.1 \pm 0.55$                               | PQ assumed        |
| $\tilde{d}_u$      | $\tilde{\rho}_N$     | QM/NDA    | $\sim -0.09$                                 | includes $K_{qG}$ |
| $\tilde{d}_d$      | $\tilde{\rho}_N$     | QM/NDA    | $\sim 0.36$                                  | includes $K_{qG}$ |
| $\tilde{\delta}_q$ | $e\tilde{\zeta}_N$   | ChPT      | $\sim 5 \times 10^{-8} e \text{ fm}$         |                   |
| $\tilde{\delta}_u$ | $e\tilde{\zeta}_N^u$ | QCD SR[6] | $-(0.9 \pm 0.5) \times 10^{-8} e \text{ fm}$ | PQ assumed        |
| $\tilde{\delta}_d$ | $e\tilde{\zeta}_N^d$ | QCD SR[6] | $(-3.6 \pm 1.8) \times 10^{-8} e \text{ fm}$ | PQ assumed        |
| $\tilde{\delta}_u$ | $e\tilde{\zeta}_N^u$ | QM/NDA    | $\sim 0.15 \times 10^{-8} e \text{ fm}$      | includes $K_{qG}$ |
| $\tilde{\delta}_d$ | $e\tilde{\zeta}_N^d$ | QM/NDA    | $\sim -1.2 \times 10^{-8} e \text{ fm}$      | includes $K_{qG}$ |

CEDM

# Hadronic Matrix Elements

| Param                         | Coeff                  | Best value <sup>a</sup> | Range                         | Coeff                       | Best value <sup>b,c</sup> | Range <sup>b,c</sup>       |
|-------------------------------|------------------------|-------------------------|-------------------------------|-----------------------------|---------------------------|----------------------------|
| $\bar{\theta}$                | $\alpha_n$             | 0.002                   | (0.0005–0.004)                | $\lambda_{(0)}$             | 0.02                      | (0.005–0.04)               |
|                               | $\alpha_p$             | 0.002                   | (0.0005–0.004)                | $\lambda_{(1)}$             | $2 \times 10^{-4}$        | $(0.5 – 4) \times 10^{-4}$ |
| $\text{Im } C_{qG}$           | $\beta_n^{uG}$         | $4 \times 10^{-4}$      | $(1 – 10) \times 10^{-4}$     | $\gamma_{(0)}^G$            | -0.01                     | (-0.03)–0.03               |
|                               | $\beta_n^{dG}$         | $8 \times 10^{-4}$      | $(2 – 18) \times 10^{-4}$     | $\gamma_{(1)}^G$            | -0.02                     | (-0.07)–(-0.01)            |
| $\tilde{d}_q$                 | $e\tilde{\rho}_n^u$    | -0.35                   | $-(0.09 – 0.9)$               | $\tilde{\omega}_{(0)}$      | 8.8                       | (-25)–25                   |
|                               | $e\tilde{\rho}_n^d$    | -0.7                    | $-(0.2 – 1.8)$                | $\tilde{\omega}_{(1)}$      | 17.7                      | 9–62                       |
| $\tilde{\delta}_q$            | $e\tilde{\zeta}_n^u$   | $8.2 \times 10^{-9}$    | $(2 – 20) \times 10^{-9}$     | $\tilde{\eta}_{(0)}$        | $-2 \times 10^{-7}$       | $(-6 – 6) \times 10^{-7}$  |
|                               | $e\tilde{\zeta}_n^d$   | $16.3 \times 10^{-9}$   | $(4 – 40) \times 10^{-9}$     | $\tilde{\eta}_{(1)}$        | $-4 \times 10^{-7}$       | $-(2 – 14) \times 10^{-7}$ |
| $\text{Im } C_{q\gamma}$      | $\beta_n^{u\gamma}$    | $0.4 \times 10^{-3}$    | $(0.2 – 0.6) \times 10^{-3}$  | $\gamma_{(0)}^{+\gamma}$    | -                         | -                          |
|                               | $\beta_n^{d\gamma}$    | $-1.6 \times 10^{-3}$   | $-(0.8 – 2.4) \times 10^{-3}$ | $\gamma_{(1)}^{-\gamma}$    | -                         | -                          |
| $d_q$                         | $\rho_n^u$             | -0.35                   | $(-0.17)–0.52$                | $\omega_{(0)}$              | -                         | -                          |
|                               | $\rho_n^d$             | 1.4                     | 0.7–2.1                       | $\omega_{(1)}$              | -                         | -                          |
| $\delta_q$                    | $\zeta_n^u$            | $8.2 \times 10^{-9}$    | $(4 – 12) \times 10^{-9}$     | $\eta_{(0)}$                | -                         | -                          |
|                               | $\zeta_n^d$            | $-33 \times 10^{-9}$    | $-(16 – 50) \times 10^{-9}$   | $\eta_{(1)}$                | -                         | -                          |
| $C_{\tilde{G}}$               | $\beta_n^{\tilde{G}}$  | $2 \times 10^{-7}$      | $(0.2 – 40) \times 10^{-7}$   | $\gamma_{(i)}^{\tilde{G}}$  | $2 \times 10^{-6}$        | $(1 – 10) \times 10^{-6}$  |
| $\text{Im } C_{\varphi ud}$   | $\beta_n^{\varphi ud}$ | $3 \times 10^{-8}$      | $(1 – 10) \times 10^{-8}$     | $\gamma_{(1)}^{\varphi ud}$ | $1 \times 10^{-6}$        | $(5 – 150) \times 10^{-7}$ |
| $\text{Im } C_{quqd}^{(1,8)}$ | $\beta_n^{quqd}$       | $40 \times 10^{-7}$     | $(10 – 80) \times 10^{-7}$    | $\gamma_{(i)}^{quqd}$       | $2 \times 10^{-6}$        | $(1 – 10) \times 10^{-6}$  |
| $\text{Im } C_{eq}^{(-)}$     | $g_S^{(0)}$            | 12.7                    | 11–14.5                       |                             |                           |                            |
| $\text{Im } C_{eq}^{(+)}$     | $g_S^{(1)}$            | 0.9                     | 0.6–1.2                       |                             |                           |                            |

J. Engel, U. van Kolck, MRM 1303.2371

# Nuclear Matrix Elements

$$S = a_0 g \bar{g}_\pi^{(0)} + a_1 g \bar{g}_\pi^{(1)} + a_2 g \bar{g}_\pi^{(2)}$$

The coefficients  $a_i$  in  $^{199}\text{Hg}$  from a variety of nuclear-structure calculations.

| Ref.    | Method                         | $a_0$       | $a_1$         | $a_2$       |
|---------|--------------------------------|-------------|---------------|-------------|
| [130]   | Schematic                      | 0.087       | 0.087         | 0.174       |
| [41,42] | Phenomenological RPA           | 0.00004     | 0.055         | 0.009       |
| [39]    | Skyrme QRPA                    | 0.002–0.010 | 0.057–0.090   | 0.011–0.025 |
| [128]   | Odd-A Skyrme mean-field theory | 0.009–0.041 | −0.027–+0.005 | 0.009–0.024 |

Best values and ranges for the coefficients  $a_i$  in three nuclei used in experiments.

| Nucl.             | Best value |            |        | Range          |                |               |
|-------------------|------------|------------|--------|----------------|----------------|---------------|
|                   | $a_0$      | $a_1$      | $a_2$  | $a_0$          | $a_1$          | $a_2$         |
| $^{199}\text{Hg}$ | 0.01       | $\pm 0.02$ | 0.02   | 0.005–0.05     | −0.03–(+0.09)  | 0.01–0.06     |
| $^{129}\text{Xe}$ | −0.008     | −0.006     | −0.009 | −0.005–(−0.05) | −0.003–(−0.05) | −0.005–(−0.1) |
| $^{225}\text{Ra}$ | −1.5       | 6.0        | −4.0   | −1–(−6)        | 4–24           | −3–(−15)      |

## *Dimension Six Operators: V*

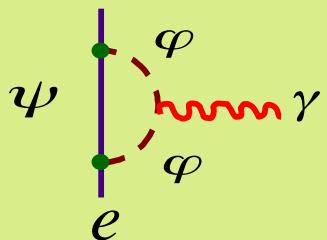
- *What are they ?*
- *Where do they come from ?*
- *How do they appear in hadronic, nuclear, and atomic systems ?*
- *How well can we match them onto physics of many-body and non-perturbative systems ?*
- *What are present & prospective experimental constraints ?*

# Generic Implications

In units of  $e\text{ cm}$ , selected EDM limits are:

| Particle          | EDM limit              | System                                  | SM Prediction | New Physics |
|-------------------|------------------------|---|---------------|-------------|
| $e$               | $10.5 \times 10^{-28}$ | YbF                                     | $10^{-38}$    | $10^{-27}$  |
| $\mu$             | $1.1 \times 10^{-19}$  | rest frame $E$                          | $10^{-35}$    | $10^{-22}$  |
| $\tau$            | $3.1 \times 10^{-16}$  | $e^+e^- \rightarrow \tau^+\tau^-\gamma$ | $10^{-34}$    | $10^{-20}$  |
| $p$               | $6.5 \times 10^{-23}$  | TlF molecule                            | $10^{-31}$    | $10^{-26}$  |
| $n$               | $2.9 \times 10^{-26}$  | UCN                                     | $10^{-31}$    | $10^{-26}$  |
| $^{199}\text{Hg}$ | $3.1 \times 10^{-29}$  | atom cell                               | $10^{-33}$    | $10^{-28}$  |

## Mass Scale & $\phi_{CP}$ Sensitivity



$$\sin\phi_{CP} \sim 1 \rightarrow M > 5000 \text{ GeV}$$

$$M < 500 \text{ GeV} \rightarrow \sin\phi_{CP} < 10^{-2}$$

# *Analysis Strategies*

- *Work within a given BSM scenario:  
constraints on  $\phi_{CPV}$ ,  $M, \dots$*
- *Model-independent analysis:  
constraints on Wilson coefficients*

# MSSM Global Analysis

$$W_{\text{MSSM}} = \mu \hat{H}_u \cdot \hat{H}_d + W_{\text{yukawa}}$$

$$\begin{aligned}\mathcal{L}_{\text{soft}} &= -\frac{1}{2}(M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B}) + c.c. \\ &\quad -(\tilde{\bar{u}} \mathbf{a_u} \tilde{Q} H_u - \tilde{\bar{d}} \mathbf{a_d} \tilde{Q} H_d - \tilde{\bar{e}} \mathbf{a_e} \tilde{L} H_d) + c.c. \\ &\quad -\tilde{Q}^\dagger \mathbf{m_Q^2} \tilde{Q} - \tilde{L}^\dagger \mathbf{m_L^2} \tilde{L} - \tilde{\bar{u}} \mathbf{m_{\bar{u}}^2} \tilde{\bar{u}}^\dagger - \tilde{\bar{d}} \mathbf{m_{\bar{d}}^2} \tilde{\bar{d}}^\dagger - \tilde{\bar{e}} \mathbf{m_{\bar{e}}^2} \tilde{\bar{e}}^\dagger - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d \\ &\quad -(b H_u H_d + c.c.)\end{aligned}$$

# MSSM Global Analysis

$$W_{\text{MSSM}} = \mu \hat{H}_u \cdot \hat{H}_d + W_{\text{yukawa}}$$

$$\begin{aligned} \mathcal{L}_{\text{soft}} = & -\frac{1}{2} (M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B}) + c.c. \\ & - (\tilde{u} \mathbf{a}_u \tilde{Q} H_u - \tilde{d} \mathbf{a}_d \tilde{Q} H_d - \tilde{e} \mathbf{a}_e \tilde{L} H_d) + c.c. \\ & - \tilde{Q}^\dagger \mathbf{m}_Q^2 \tilde{Q} - \tilde{L}^\dagger \mathbf{m}_L^2 \tilde{L} - \tilde{\bar{u}} \mathbf{m}_{\bar{u}}^2 \tilde{\bar{u}}^\dagger - \tilde{\bar{d}} \mathbf{m}_{\bar{d}}^2 \tilde{\bar{d}}^\dagger - \tilde{\bar{e}} \mathbf{m}_{\bar{e}}^2 \tilde{\bar{e}}^\dagger - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d \\ & - (b H_u H_d + c.c.) \end{aligned}$$

$$\phi_j = \arg(\mu M_j b^*)$$

$$\phi_A = \arg(A_f M_j)$$

*Li, Profumo, R-M '10*

- Dominant operators: *EDM, CEDM*
- No theory error (QCD SR)
- Includes full 2-loop (*Li, Profumo, R-M*)

# MSSM Global Analysis

$$W_{\text{MSSM}} = \mu \hat{H}_u \cdot \hat{H}_d + W_{\text{yukawa}}$$

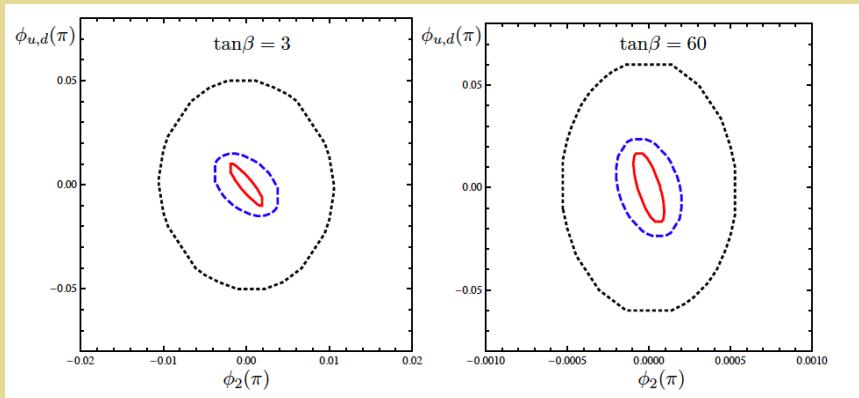
$$\begin{aligned} \mathcal{L}_{\text{soft}} = & -\frac{1}{2} (M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B}) + c.c. \\ & - (\tilde{u} \mathbf{a}_u \tilde{Q} H_u - \tilde{d} \mathbf{a}_d \tilde{Q} H_d - \tilde{e} \mathbf{a}_e \tilde{L} H_d) + c.c. \\ & - \tilde{Q}^\dagger \mathbf{m}_Q^2 \tilde{Q} - \tilde{L}^\dagger \mathbf{m}_L^2 \tilde{L} - \tilde{u} \mathbf{m}_{\bar{u}}^2 \tilde{\bar{u}}^\dagger - \tilde{d} \mathbf{m}_{\bar{d}}^2 \tilde{\bar{d}}^\dagger - \tilde{e} \mathbf{m}_{\bar{e}}^2 \tilde{\bar{e}}^\dagger - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d \\ & - (b H_u H_d + c.c.) \end{aligned}$$

$$\phi_j = \arg(\mu M_j b^*)$$

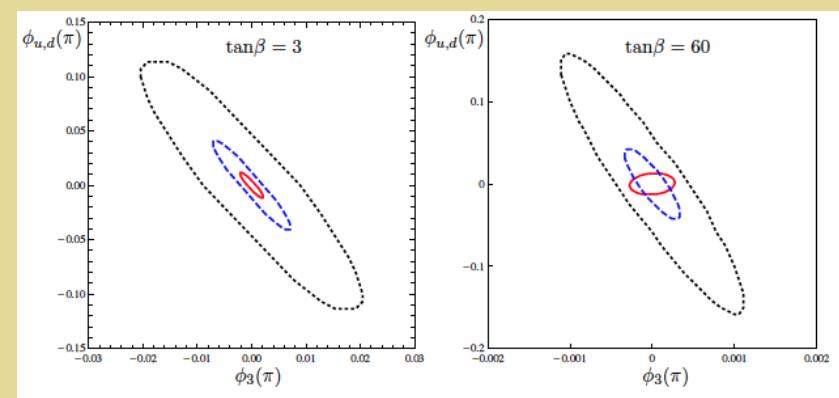
$$\phi_A = \arg(A_f M_j)$$

## Correlated Constraints

Li, Profumo, R-M '10



Present



Present: <sup>199</sup>Hg impact

# MSSM Global Analysis

$$W_{\text{MSSM}} = \mu \hat{H}_u \cdot \hat{H}_d + W_{\text{yukawa}}$$

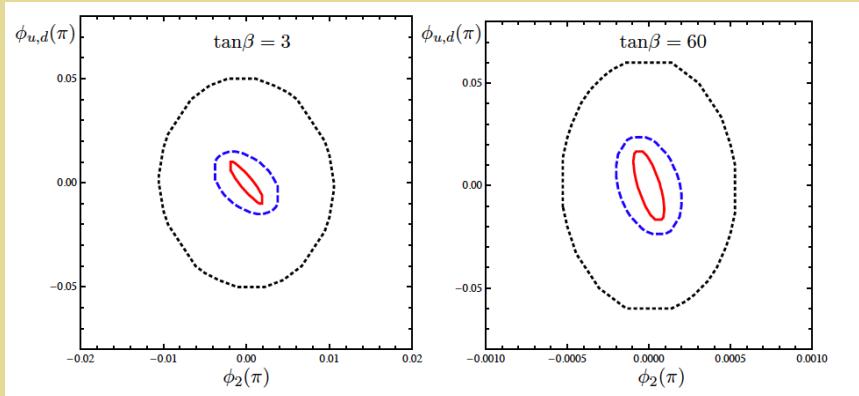
$$\begin{aligned} \mathcal{L}_{\text{soft}} = & -\frac{1}{2} (M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B}) + c.c. \\ & - (\tilde{u} \mathbf{a}_u \tilde{Q} H_u - \tilde{d} \mathbf{a}_d \tilde{Q} H_d - \tilde{e} \mathbf{a}_e \tilde{L} H_d) + c.c. \\ & - \tilde{Q}^\dagger \mathbf{m}_Q^2 \tilde{Q} - \tilde{L}^\dagger \mathbf{m}_L^2 \tilde{L} - \tilde{u} \mathbf{m}_{\bar{u}}^2 \tilde{\bar{u}}^\dagger - \tilde{d} \mathbf{m}_{\bar{d}}^2 \tilde{\bar{d}}^\dagger - \tilde{e} \mathbf{m}_{\bar{e}}^2 \tilde{\bar{e}}^\dagger - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d \\ & - (b H_u H_d + c.c.) \end{aligned}$$

$$\phi_j = \arg(\mu M_j b^*)$$

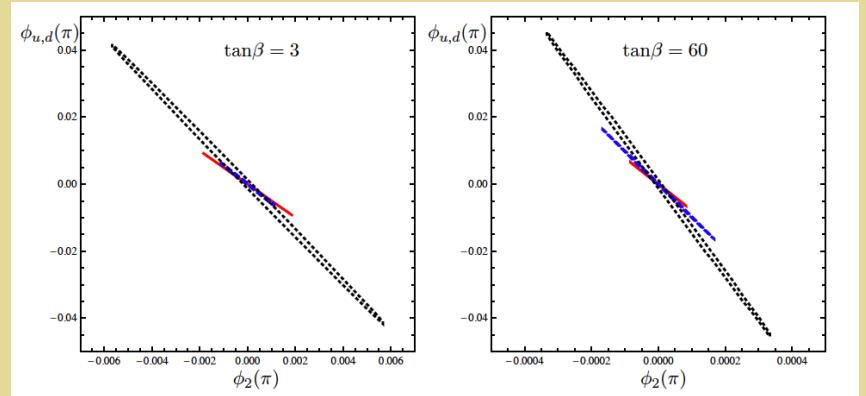
$$\phi_A = \arg(A_f M_j)$$

## Correlated Constraints

*Li, Profumo, R-M '10*



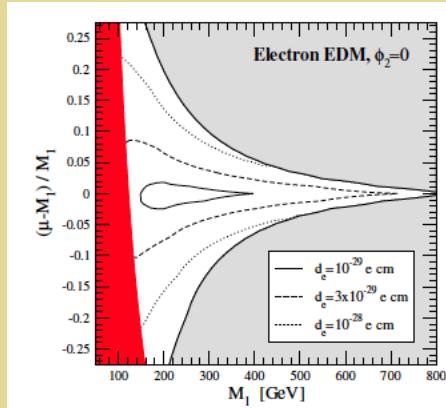
Present



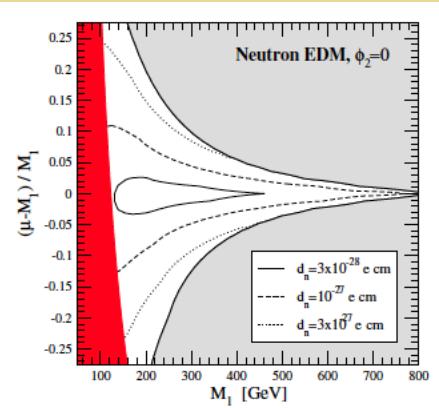
Future  $d_n$ :  $100 \times$   
present sensitivity

# Baryogenesis Implications

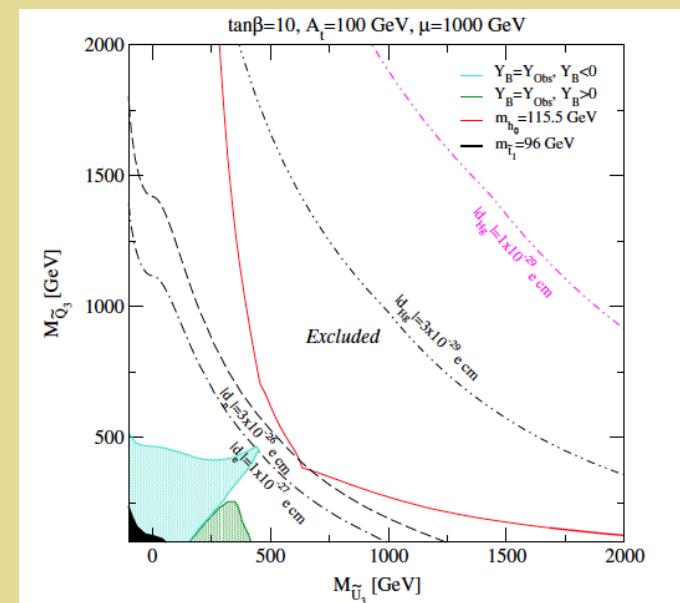
MSSM:  $\phi_1$  only



Gaugino sources



Sfermion (stop) sources



Cirigliano, Li, Profumo, R-M '10

Kocaczuk, Wainwright, Profumo,  
R-M '12

# AMO Global Analysis

Atomic &  
Molecular

$$\begin{aligned}
 d_A &= \boxed{\rho_A^e} d_e + \sum_{N=p,n} \rho_Z^N d_N + \boxed{\kappa_S} S \\
 &+ \left(\frac{v}{\Lambda}\right)^2 \left\{ \left[ \boxed{k_S^{(0)}} g_S^{(0)} + \boxed{k_P^{(1)}} g_P^{(1)} \right] \text{Im} C_{eq}^{(-)} \right. \\
 &+ \left[ \boxed{k_S^{(1)}} g_S^{(1)} + \boxed{k_P^{(0)}} g_P^{(0)} \right] \text{Im} C_{eq}^{(+)} \\
 &\left. + \left[ \boxed{k_T^{(0)}} g_T^{(0)} + \boxed{k_T^{(1)}} g_T^{(1)} \right] \text{Im} C_{lequ}^{(3)} \right\}
 \end{aligned}$$

$$S = a_0 g \bar{g}_\pi^{(0)} + a_1 g \bar{g}_\pi^{(1)} + a_2 g \bar{g}_\pi^{(2)}$$

$$\bar{g}_\pi^{(i)} = \lambda_{(i)} \bar{\theta} + \left(\frac{v}{\Lambda}\right)^2 \sum_k^n \gamma_{(i)}^{(k)} (\text{Im} C_k)$$

Atomic / molecular  
coefficients

Paramag\*:  $\delta_e, \text{Im } C_{eq}^{(-)} (k_s^0)$

Diamag\*\*:  $S, \text{Im } C_{lequ}^{(3)} (k_T)$

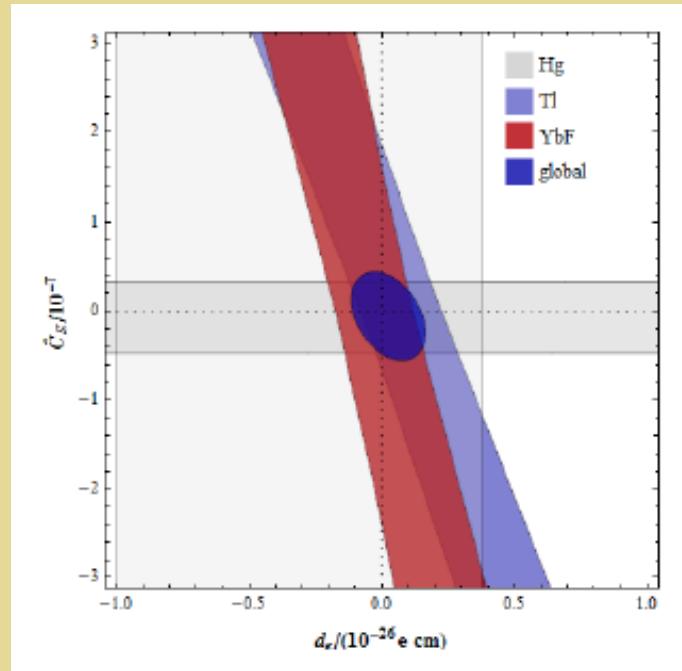
$$\rho_A^e d_e = e \zeta_A^e \left(\frac{v}{\Lambda}\right)^2 \delta_e$$

$$C_{eq}^{(\pm)} = C_{ledq} \pm C_{lequ}^{(1)}$$

\*  $Tl, Cs, YbF\dots$

\*\*  $Hg, Ra, Rn\dots$

# AMO Global Analysis



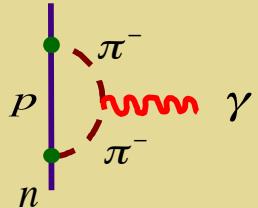
Jung '13

$$\frac{k_S^{(0)}}{e\zeta_A^e} \approx -37$$

- Dominant operators: e EDM,  $C_S^{(0)} \sim \text{Im } C_{eq}^{(-)}$
- Includes  $^{199}\text{Hg}$  w/  $C_S^{(0)}$  no Schiff moment !
- TI & YbF only:  $|d_e| < 0.89 \times 10^{-26} \text{ e cm}$

# Global Analysis: Hadronic

$$\begin{aligned}\mathcal{L}_{N\pi}^{\text{PVTV}} = & -2\bar{N} (\bar{d}_0 + \bar{d}_1 \tau_3) S_\mu N v_\nu F^{\mu\nu} \\ & + \bar{N} [\bar{g}_\pi^{(0)} \boldsymbol{\tau} \cdot \boldsymbol{\pi} + \bar{g}_\pi^{(1)} \pi^0 + \bar{g}_\pi^{(2)} (3\tau_3 \pi^0 - \boldsymbol{\tau} \cdot \boldsymbol{\pi})] N\end{aligned}$$

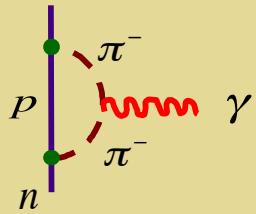


$$d_0 = \bar{d}_0 - \frac{eg_A}{16\pi F_\pi} \left\{ \bar{g}_\pi^{(0)} \left[ \frac{3m_\pi}{m_N} - \frac{4(\Delta m_N)_q}{m_\pi} \right] + \bar{g}_\pi^{(1)} \frac{m_\pi}{m_N} \right\}$$

$$d_1 = \bar{d}_1(\mu) + \delta \bar{d}_1(\mu) - \frac{eg_A}{(2\pi)^2 F_\pi} \left\{ \bar{g}_\pi^{(0)} \left[ \ln \frac{m_N^2}{m_\pi^2} + \frac{5\pi m_\pi}{4m_N} - \frac{\Delta m_\pi^2}{m_\pi^2} \right] - \bar{g}_\pi^{(1)} \frac{\pi m_\pi}{4m_N} \right\}$$

# Global Analysis: Hadronic

$$\begin{aligned}\mathcal{L}_{N\pi}^{\text{PVTV}} = & -2\bar{N} (\bar{d}_0 + \bar{d}_1 \tau_3) S_\mu N v_\nu F^{\mu\nu} \\ & + \bar{N} [\bar{g}_\pi^{(0)} \boldsymbol{\tau} \cdot \boldsymbol{\pi} + \bar{g}_\pi^{(1)} \pi^0 + \bar{g}_\pi^{(2)} (3\tau_3 \pi^0 - \boldsymbol{\tau} \cdot \boldsymbol{\pi})] N\end{aligned}$$



$$d_0 = \bar{d}_0 - \frac{eg_A}{16\pi F_\pi} \left\{ \bar{g}_\pi^{(0)} \left[ \frac{3m_\pi}{m_N} - \frac{4(\Delta m_N)_q}{m_\pi} \right] + \bar{g}_\pi^{(1)} \frac{m_\pi}{m_N} \right\}$$

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$\delta_q, \tilde{\delta}_q, \theta, \dots$

$\tilde{\delta}_q, \theta, \dots$

$C_{qud}, \tilde{\delta}_q, \dots$

Need multiple hadronic systems to disentangle

## *Open Problems*

- *How many complementary EDM searches needed*
- *What is robust theory error at hadronic, nuclear, and AMO levels ?*

## *Summary*

- *BSM CPV at d=6 provides a bridge between low-scale EDM physics (atomic, nuclear, hadronic) and high scale BSM physics and cosmology*
- *Challenging interpretation problem requiring refinements of non-perturbative and many-body computations*
- *Additional, complementary EDM searches needed to provide comprehensive probe of possible flavor diagonal CPV that may be living at the multi-TeV scale*