Standard Model Nucleon EDM Revisited

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Outline

1. Brief review of the current situation
2. Long distance contribution to nucleon EDMs
3. Short distance contribution to nucleon EDMs
4. Conclusion

1. Brief review of the current situation

Why intrinsic EDMs are interesting?

- It breaks P and T- (and therefore CP-) symmetry!

$$H_{EDM} = -d_E \vec{E} \cdot \frac{\vec{J}}{|J|}$$

Andrei Sakharov

I need:

- Baryon number violation
- C and $\boxed{\text{CP-violation}}$
- Interaction out of thermal equilibrium

Current upper bounds on intrinsic EDMs

Particle	Upper bound on EDM (e cm)
Electron	8.7E-29
Mercury	3.1E-29
Proton	7.9E-25
Neutron	2.9E-26

- So far no definitive BSM signal has been observed.
- The CP-phase of the CKM matrix remains the only source for intrinsic EDMs.
- Question: *How far is the CKM-induced nucleon EDM below the current experimental bound?*

Existing studies on SM nucleon EDMs

- Barton and White (1969): first proposal of chiral enhancement
- Shabalin (1980): quark EDM starts at three-loops
- Gavela et.al. (1984, 1985): pole diagram contribution
- Khriplovich and Zhitnitsky (1982): possibility of long-range contribution to the SM neutron EDM
- He et.al. (1991): chiral-loop calculation using relativistic meson theory: 10^{-33} -10^{-31} ecm
- Czarnecki and Krause (1997): detailed calculation of the valence-quark contribution: 10^{-34} ecm
- Mannel and Uraltsev (2012): charm quark contribution

Shortcomings of the older calculations include:

- Poorly-determined weak interaction constants (we can do much better now!)
- Inconsistent application of an EFT (a self-consistent theory is now developed)

Our aim is to improve from older results in these two directions.

2. Long distance contribution to nucleon EDMs

CYS, arXiv:1411.1476 [hep-ph] (to be appeared in PRC)

Brief overview of HBchPT

- Chiral Perturbation Theory (ChPT) is an EFT of QCD at low energy.

$$\mathcal{L} = \mathcal{L}^{(0)} + \sum_n \frac{1}{\Lambda_\chi^n} \mathcal{L}^{(n)}$$

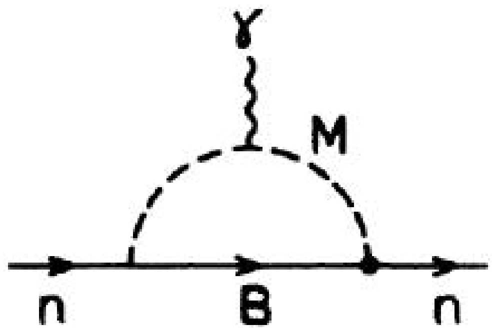
3 fundamental ingredients of any EFT:

Ingredient	ChPT
DOFs	Hadrons
Symmetry	Chiral Symmetry
Power Counting	p/ Λ_χ

- Straightforward inclusion of baryons breaks power counting because baryons are heavy!

EOM: $$\gamma . p u(p) = M_N u(p)$$

Loop integrals:



$$\int \frac{d^4 k}{(2\pi)^4} \frac{k^{2m}}{(k^2 - M_N{}^2)^n} \sim M_N^{2m+4-2n},$$

$$\frac{M_N}{\Lambda_\chi} \sim 1 \quad \text{is not small!}$$

- The way out: rescale the baryon field

$$p_\mu = m_N v_\mu + k_\mu,$$

$$B_v(x) = e^{i m_N v\cdot x}\frac{1+\not{v}}{2}B(x)$$

- The baryon field is split into “heavy” and “light” component. The former is integrated out.
- The Lagrangian is expanded in powers of $(1/M_N)$.
- Reduction of the Dirac structure:

$$1 \rightarrow 1$$

$$\gamma_5 \rightarrow 0$$

$$\gamma^\mu \rightarrow v^\mu$$

$$\gamma^\mu\gamma_5 \rightarrow 2S^\mu$$

$$\sigma^{\mu\nu} \rightarrow 2\varepsilon^{\mu\nu\rho\sigma}v_\rho S_\sigma$$

$$\sigma^{\mu\nu}\gamma_5 \rightarrow 2i(v^\mu S^\nu - v^\nu S^\mu)$$

Meaning: a 2-component spinor only couples to 1 and τ^i

The Relevant Lagrangian: Strong and EM

Degrees of Freedom :

1) The Pseudoscalar Meson Octet Φ

2) The $(1/2)^{+}$ Baryon Octet B

3) The $(1/2)^{-}$ Baryon Octet R

Covariant derivatives
Including EM interaction

Strong and EM Lagrangian involving U and B:

Meson Mass

B-Φ Interaction

$$\mathcal{L} = \frac{F_\pi^2}{4}\mathrm{Tr}[\mathcal{D}_\mu U \mathcal{D}^\mu U^\dagger] + \frac{F_\pi^2}{4}\mathrm{Tr}[\chi_+] + \mathrm{Tr}[\bar{B} iv \cdot \mathcal{D} B] + 2D\mathrm{Tr}[\bar{B} S^\mu \{\mathcal{A}_\mu, B\}] + 2F\mathrm{Tr}[\bar{B} S^\mu [\mathcal{A}_\mu, B]]$$
$$+ \frac{b_D}{2B_0}\mathrm{Tr}[\bar{B}\{\chi_+, B\}] + \frac{b_F}{2B_0}\mathrm{Tr}[\bar{B}[\chi_+, B]] + \frac{b_0}{2B_0}\mathrm{Tr}[\bar{B}B]\mathrm{Tr}[\chi_+] \qquad (7)$$

(Residual) B Mass Splitting

Strong and EM Lagrangian involving R:

(Residual) R Mass Splitting

$$
\begin{aligned}
\mathcal{L}_{\mathcal{R}} = {} & \mathrm{Tr}[\bar{\mathcal{R}} i v \cdot \mathcal{D} \mathcal{R}] - \bar{\delta}_{\mathcal{R}} \mathrm{Tr}[\bar{\mathcal{R}} \mathcal{R}] + \frac{\tilde{b}_D}{2B_0} \mathrm{Tr}[\bar{\mathcal{R}} \{\chi_+, \mathcal{R}\}] + \frac{\tilde{b}_F}{2B_0} \mathrm{Tr}[\bar{\mathcal{R}} [\chi_+, \mathcal{R}]] + \frac{\tilde{b}_0}{2B_0} \mathrm{Tr}[\bar{\mathcal{R}} \mathcal{R}] \mathrm{Tr}[\chi_+] \\
& - 2r_D (\mathrm{Tr}[\bar{\mathcal{R}} (v_\mu S_\nu - v_\nu S_\mu) \{f_+^{\mu\nu}, B\}] + \mathrm{Tr}[\bar{B} (v_\mu S_\nu - v_\nu S_\mu) \{f_+^{\mu\nu}, R\}]) \\
& - 2r_F (\mathrm{Tr}[\bar{\mathcal{R}} (v_\mu S_\nu - v_\nu S_\mu) [f_+^{\mu\nu}, B]] + \mathrm{Tr}[\bar{B} (v_\mu S_\nu - v_\nu S_\mu) [f_+^{\mu\nu}, \mathcal{R}]]). \qquad (9)
\end{aligned}
$$

BR-transition via EM interaction

The Relevant Lagrangian: Weak Δ S=1

Pure Mesonic:

$$\mathcal{L}_8 = g_8 e^{i\varphi}\mathrm{Tr}[\lambda_+ D_\mu U D^\mu U^\dagger] + h.c \qquad (\lambda_+ = \lambda_6 + i\lambda_7)$$

Ground State Baryon Octet:

$$\mathcal{L}_w^{(s)} = h_D e^{i\varphi_D}\mathrm{Tr}[\bar{B}\{\xi^\dagger\lambda_+\xi, B\}] + h_F e^{i\varphi_F}\mathrm{Tr}[\bar{B}[\xi^\dagger\lambda_+\xi, B]] + h.c.$$

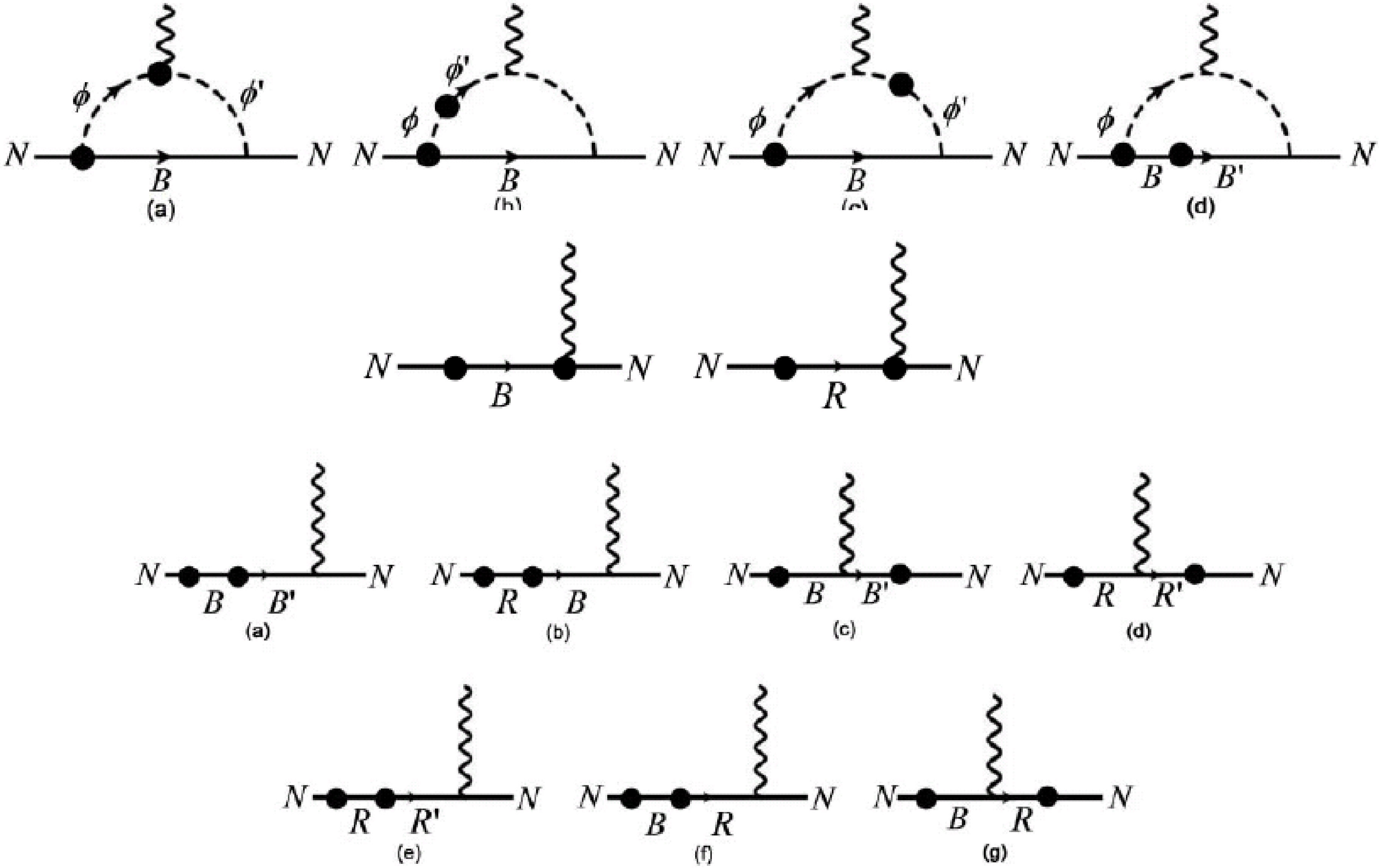
B-R Transition:

$$\mathcal{L}_w^{B\mathcal{R}} = i w_D e^{i\tilde{\varphi}_D}\mathrm{Tr}[\bar{\mathcal{R}}\{h_+, B\}] + i w_F e^{i\tilde{\varphi}_F}\mathrm{Tr}[\bar{\mathcal{R}}[h_+, B]] + h.c$$

Determination of LECs:

- K decay
- S and P-wave amptlidues of non-leptonic hyperon decays
- Theoretical Estimation based on short-distance Δ S=1 operators

Relevant Loop and Pole Diagrams



Major Sources of Uncertainty

Source of Uncertainty	Way to deal with it
Undetermined relative signs of LECs	Exhaust all possibilities and give a range
Higher order terms in the HB-expansion	$(m_K / m_N) \sim 1/2$. Assign a 100% error.

With these we obtain:

$$\boxed{d_N^{\text{long-distance}} \approx (1-6)\times 10^{-32}\, e\,\text{cm}}$$

3. Short distance contribution to nucleon EDMs

In Collaboration with Mario Pitschmann

- Motivation: the loop-integrals in the long-range contribution are UV-divergent. Counter-terms $d^0_{n,p}$ are required. They represent incalculable short-distance physics.
- Counter-terms are induced by effective CP-violating four-quark operators:

$$\mathscr{H}_{\rm eff} = \frac{G_{\rm F}}{\sqrt{2}} V_{\rm ud} V_{\rm us}^* \sum_i C_i(\mu) Q_i(\mu) ,$$

$$C_i(\mu) = z_i(\mu) + \tau y_i(\mu) , \qquad \tau = -V_{\rm td} V_{\rm ts}^* / V_{\rm ud} V_{\rm us}^*$$

Buchalla, Buras and Harlander, Nucl.Phys.,B337,313

- **A conservative naïve dimensional analysis (NDA) gives:**

$$d^0_{n,p} \sim \frac{1}{16\pi^2}\frac{G_F^2}{2}|V_{ud}V_{us}^*|^2\ \mathrm{Im}(C_2C_6^*)\Lambda_\chi^3$$
$$\approx 4\times 10^{-32}\, e\,\mathrm{cm}$$

loop factor

this combination gives the largest imaginary part

certain energy scale to make the dimension correct

It could be as large as the long-distance contribution!
A (model-dependent) detailed study is therefore very much desired.

- Our starting point:

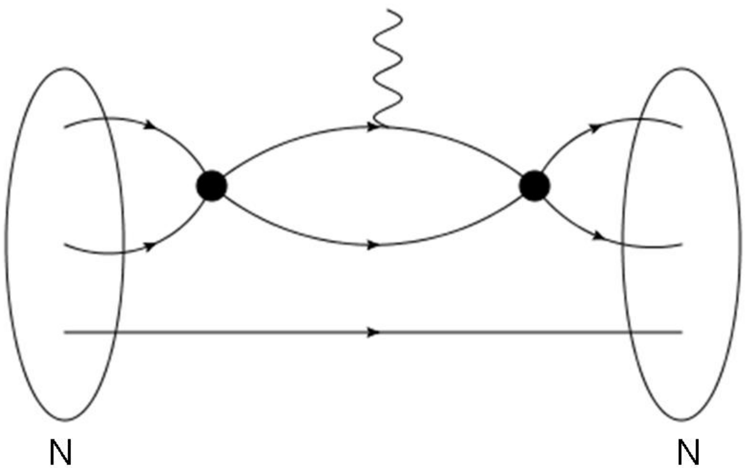
$$\boxed{\begin{aligned} d_N^0 = eG_F^2 J \sum_{i<j} (z_i y_j - y_i z_j) \int d^3x_1 d^4x_2 d^4x_3 (x_3)_3 \times \\ \mathrm{Im} \left\langle N\uparrow \middle| \hat{j}^0_{em}(\vec{x}_1) \hat{Q}_i(x_2) \hat{Q}_j^+(x_3) \middle| N\uparrow \right\rangle \end{aligned}}$$

Here $\left| N\uparrow \right\rangle$ is the nucleon state

normalized non-relativistically $(\langle \mathrm{N} | N \rangle = 1)$

Jarlskog invariant J=2.96x10^{-5}

- **MIT bag model** is used in our first trial and only ground-state quarks are retained. The only diagram at leading order is:



Others are suppressed by an extra loop or α_s (i.e. extra quark-gluon interaction) or both. Though α_s is not very small, neglecting it will not cause order-of-magnitude changes.

Preliminary Result : $\hat{Q}_2 \times \hat{Q}_6$

MODEL INPUT

Electroweak: $y_2 = -0.044, \; y_6 = -0.080$

$z_2 = 1.31, \quad z_6 = -0.011$

Strong: $m_u = m_d = 0, \; m_s = 0.279\,\text{GeV}$

$R = 5\,\text{GeV}^{-1}$

Preliminary Result: $\boxed{|d_n^0| = |d_p^0| = 7.5 \times 10^{-34}\, e\,\text{cm}}$

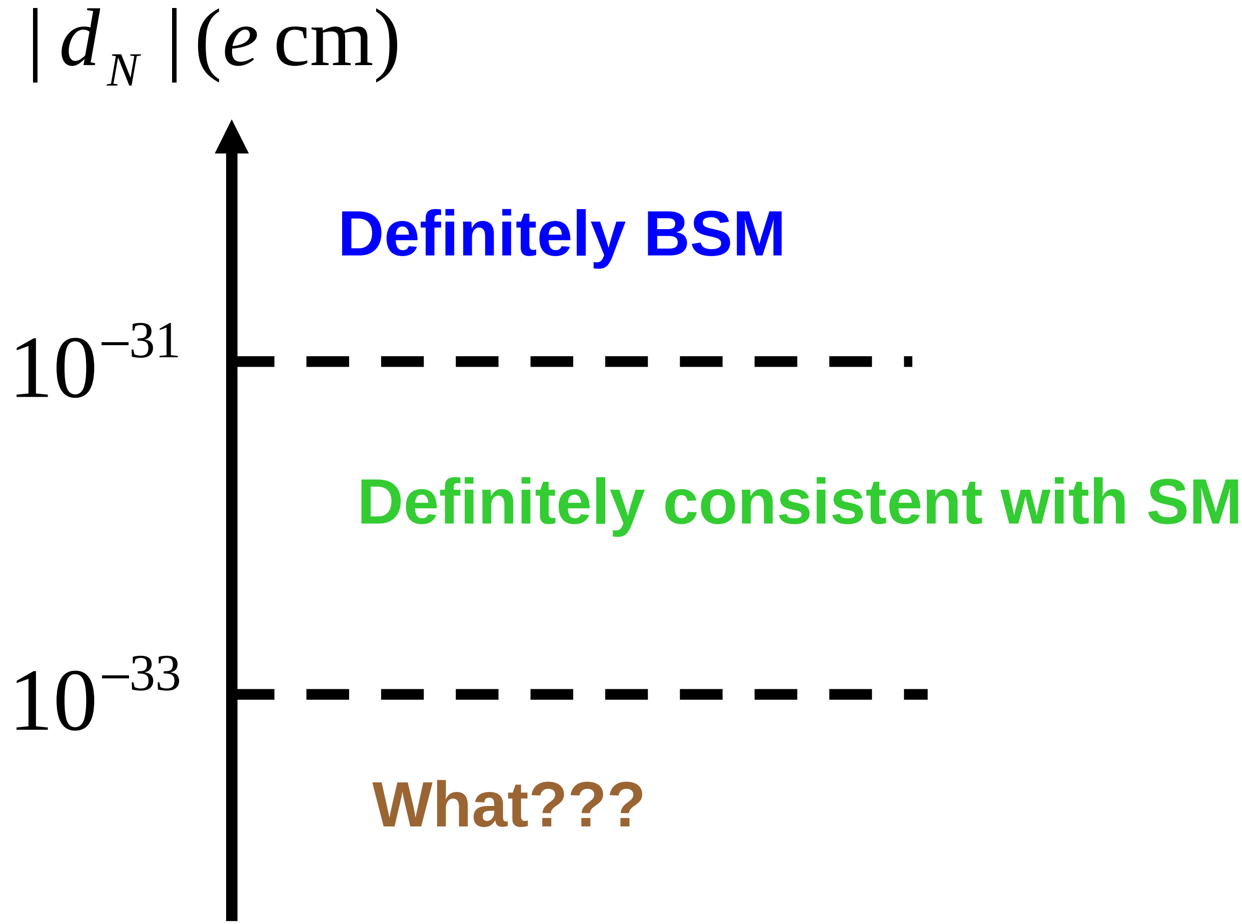
Reason for the suppression :

the effective mass scale of the model is

$R^{-1} \sim \Lambda_{QCD}$ instead of Λ_χ.

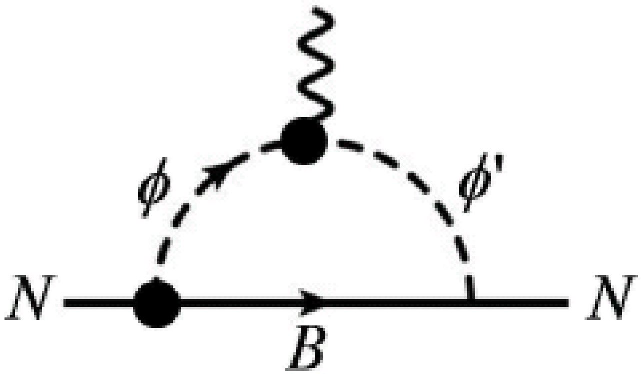
$(\Lambda_{QCD} / \Lambda_\chi)^3 \sim 10^{-2}$

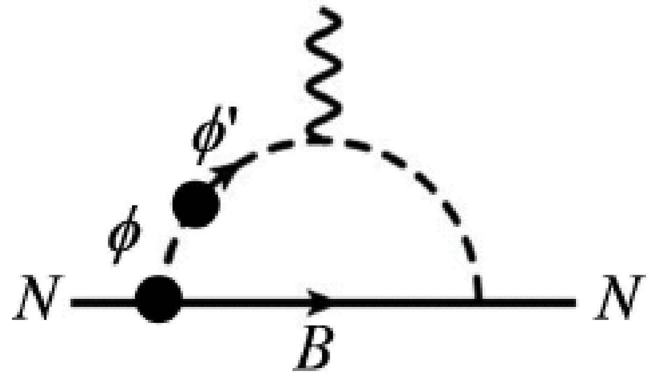
So, what do we understand so far?



4. Conclusion

1. We reanalyzed the long distance contribution to nucleon EDMs within an EFT framework that respects power counting.
2. The incalculable short distance counter-terms are studied using MIT bag model.
3. Nucleon EDMs below 10^{-31} ecm is consistent with the SM prediction.





Finally, it is…..

Commercial Time

and

THANKS FOR LISTENING!