Neutron EDM in Four Generation Standard Model

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arXiv: 1107.3642

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Grenoble, France

Outline

- Brief Introduction
  - CPV, nEDM, Experiments, SM4, $\cdots$
- Strategy of nEDM4
  - QCD sum rule
  - W-W-g loop contribution
  - W-W-Z loop contribution
- Conclusion

Introduction

- Baryon Asymmetry of the Universe (BAU)
  Sakharov conditions
  - Baryon number violation
  - CP-violation
  - Interaction out of thermal equilibrium
- CPV in SM cannot explain BAU
- SM4 has large CPV phase, perhaps enough for BAU

  – M. Kohda, EPS-HEP 2011 Poster
- nEDM violates P and CP
- What is the nEDM value in SM4 (nEDM4)?

Long quest of nEDM (I)

- Single quark contribution
  - two weak loop order qEDM vanish

    E.P. Shabalin, 1978

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  - two weak loop + one gluonic loop

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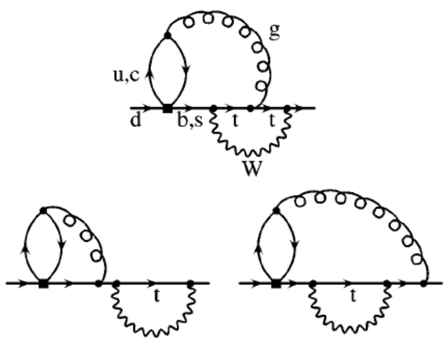
    A.Czarnecki and B. Krause, 1997



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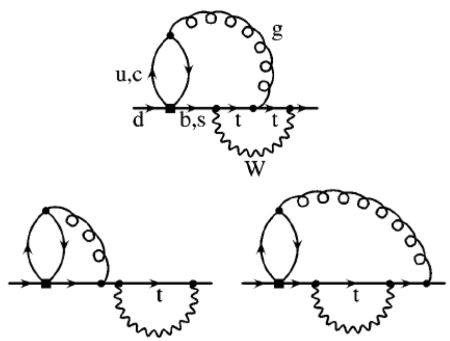

$$d_n \sim 10^{-34} e\,\mathrm{cm}$$

- LD enhancement: $\sim 10^{-32} e\,\mathrm{cm}$

  I.B. Khriplovich and A.R. Zhitnisky, 1982;

  M.B. Gavela, A. Le Yaouanc, L. Oliver, O. Pene, J.C. Raynal, T.N. Pham, 1982

Long quest of nEDM (II)

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)

First experiment

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 $D=(-0.1\pm2.4)\times10^{-20}$ 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 5×10^{-20} cm.

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PRL **97,** 131801 (2006) PHYSICAL REVIEW LETTERS week ending 29 SEPTEMBER 2006

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(Received 9 February 2006; revised manuscript received 29 March 2006; published 27 September 2006)

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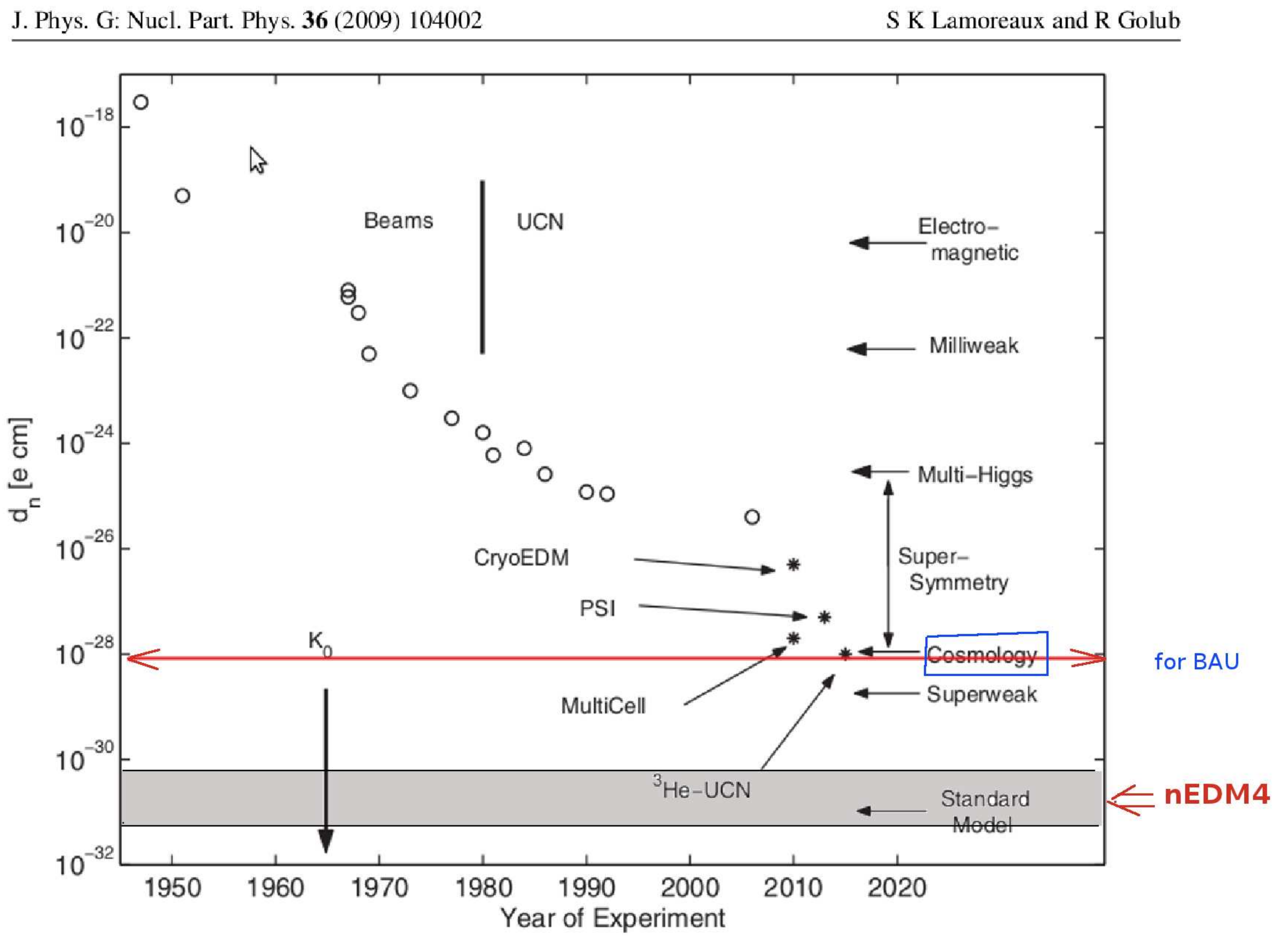
For next decade

CryoEDM/Grenoble, PSI, SNS, J-PARC, TRIUMF $\Longrightarrow 10^{-28} e\,\text{cm}$

Long qeust of nEDM (III)



nEDM approach

- P-odd, CP-odd operators (dim ≤ 5)

$$\mathcal{L}_{CP} = -\bar{\theta}\frac{\alpha_s}{8\pi}G\tilde{G} - \frac{d_q}{2}\bar{q}\sigma^{\mu\nu}i\gamma_5 qF_{\mu\nu} - \frac{\tilde{d}_q}{2}\bar{q}i\gamma_5 t^a qG^a_{\mu\nu}$$

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- QCD sum rule

M. Pospelov & A. Ritz , PRD'01

$$\begin{aligned} d_n &= (0.4 \pm 0.2)\left[\chi m_*(4e_d - e_u)\left(\bar{\theta} - \frac{1}{2}m_0^2\frac{\tilde{d}_s}{m_s}\right)\right. \\ &+\frac{1}{2}\chi m_0^2(\tilde{d}_d - \tilde{d}_u)\frac{4e_d m_d + e_u m_u}{m_u + m_d} \\ &\left.+\frac{1}{8}(4\tilde{d}_d\alpha_d^+ - \tilde{d}_u\alpha_u^+) + (4d_d - d_u)\right] \end{aligned}$$

LD parameters: χ, α^+

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LD parameters: χ, α^+

  - If PQ invoked, $\bar{\theta}$ removed, sCEDM cancelled
  - If PQ absent, sCEDM large for SM4

Flavor structure of qEDM4

Three loop calculation needs analysis of flavor structure.
Take $c = u \equiv \mathrm{u}$, $d = s = b \equiv \mathrm{d}$,

$$i \sum_{j,k,l} \mathrm{Im}(V^*_{fj} V_{kj} V^*_{kl} V_{fl}) fjklf$$

f, j, k, l - flavor indices and Green function

- $f = u$, qEDM vanishes
- $f = d, s$, qEDM prop. to

$$\mathrm{Im}(V^*_{tf} V_{tb'} V^*_{t'b'} V_{t'f}) \simeq -\mathrm{Im}(V^*_{tf} V_{tb} V^*_{t'b} V_{t'f}) \equiv \mathcal{J}_f$$

$$\begin{bmatrix} 0.974 & 0.225 & 0.0036e^{-i60^\circ} & 0.015e^{i64^\circ} \\ -0.226 & 0.972 & 0.041 & 0.060e^{i72^\circ} \\ 0.008e^{-i22^\circ} & -0.043e^{-i7^\circ} & 0.994 & 0.099e^{-i1^\circ} \\ -0.003e^{-i18^\circ} & -0.06e^{-i75^\circ} & -0.1 & 0.993 \end{bmatrix}$$

W.-S.Hou & C.-Y. Ma, PRD'10

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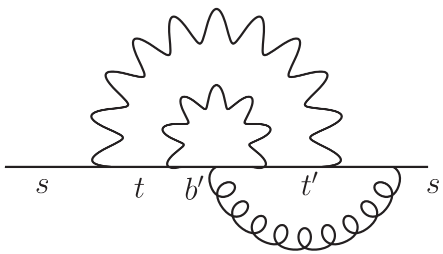
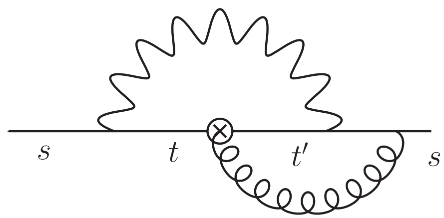
$\mathcal{J}_s \gg \mathcal{J}_d$ why strange CEDM !

W-W-g loop contribution

External field method
Large N limit



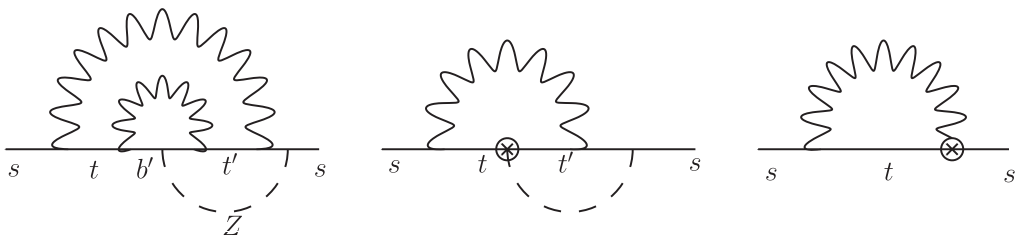


C. Hamzaoui & M.E. Pospelov, PLB'95

$$\tilde{d}_s^{(g)} = -\mathcal{J}_s m_s \frac{G_F}{\sqrt{2}} \frac{\alpha_s \alpha_W}{(4\pi)^4} \frac{5N_c}{6} \frac{m_t^2}{M_W^2} \frac{1}{2!} \ln^2\left(\frac{m_{t'}^2}{m_t^2}\right)$$

W-W-Z loop contribution

Effective Lagrangian approach



C. Hamzaoui & M.E. Pospelov, PRD’96

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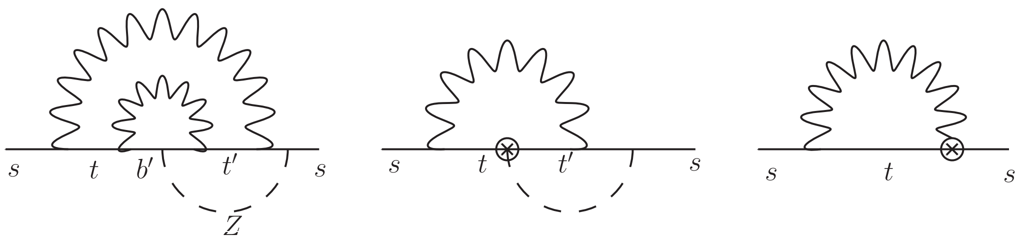

large momentum in loop

$\Rightarrow$ Goldstone coupling

C. Hamzaoui & M.E. Pospelov, PRD'96

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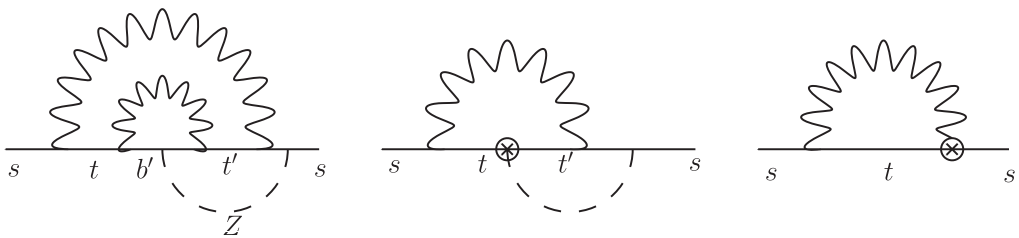

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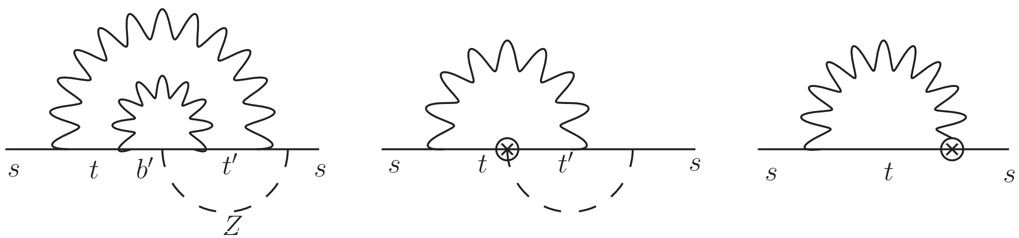

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- Z loop contribution in SM is small

W-W-Z loop contribution

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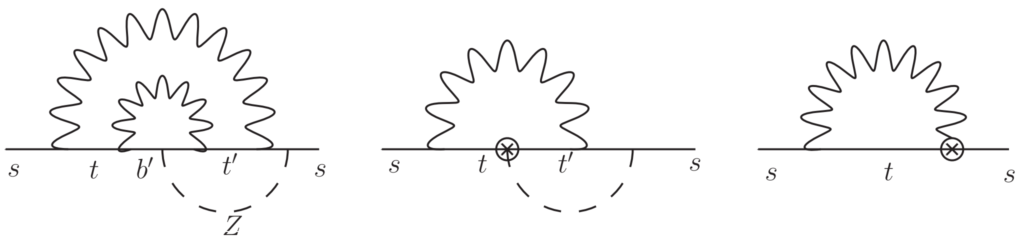

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- Z loop contribution in SM is small
- Z loop dominates gluonic loop

Numerical estimate

- The value of CKM factor

$$\mathcal{J}_s = \mathrm{Im}(V_{ts}^* V_{tb} V_{t'b}^* V_{t's}) \simeq 2.4 \times 10^{-4},$$
$$\mathcal{J}_d = \mathrm{Im}(V_{td}^* V_{tb} V_{t'b}^* V_{t'd}) \simeq 1.7 \times 10^{-7}.$$

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Measure $V_{t'b}^* V_{t's}$ by $B_s \to J/\psi\,\phi$ and $\mathcal{B}(B_s \to \mu^+\mu^-)$

Hou, Kohda and Xu, 1107.2343

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$$\tilde{d}_s^{(4)} \simeq -0.8 \times 10^{-29}\,\mathrm{cm}$$

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- nEDM4

$$\boxed{d_n^{(4)} = (2.2 \pm 1.1) \times 10^{-31} e\,\mathrm{cm}}$$

no PQ

Discussion

- if PQ operative, then

$$d_n^{\rm PQ} = (0.4 \pm 0.2)\left[1.6e(2\tilde{d}_d + \tilde{d}_u) + (4d_d - d_u)\right]$$

depends only on naive constituents of neutron, with $d_u = 0,\ \tilde{d}_u = 0$

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- Numerical estimate

$$\tilde{d}_d^{(4)} \simeq -3 \times 10^{-34}\mathrm{cm}, \quad d_d^{(4)} \simeq -4 \times 10^{-34} e\,\mathrm{cm}$$

$$\boxed{d_n^{(4)\mathrm{PQ}} = (1 \pm 0.5) \times 10^{-33} e\,\mathrm{cm}}$$

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- $d_d^{(4)}$ is stronger than in SM
- LD effect may have order of magnitude enhancement

Conclusion

- nEDM4 is stronger than nEDM3
  - without PQ: $d_n^{(4)} \sim 10^{-31} e\,\mathrm{cm}$
  - with PQ: $d_n^{(4)} \sim 10^{-33} e\,\mathrm{cm}$
- Hadronic uncertainty is large;
  LD effect might bring another order of magnitude enhancement
- nEDM4 is still below $10^{-28} e\,\mathrm{cm}$,
  Seems out of reach of next round of experiments in coming decade.

Thanks

Backup - flavor structure

- $f = u$

$$
\begin{aligned}
& i \sum_{j,k,l} \mathrm{Im}(V_{uj}^* V_{kj} V_{kl}^* V_{ul})\, u j k\, l u \\
= \; & \frac{i}{2} \sum_{k} \mathrm{Im}(V_{ub'}^* V_{kb'} V_{kb'}^* V_{ub'})\, u(\mathsf{d} k\, b' - b' k\, \mathsf{d}) u = 0
\end{aligned}
$$

- $f = d, s$

$$
\begin{aligned}
& i \sum_{j,k,l} \mathrm{Im}\,(V_{uj}^* V_{kj} V_{kl}^* V_{ul})\, f j k\, l f \\
= \; & i \;\; \mathrm{Im}(V_{tf}^* V_{tb} V_{t'b}^* V_{t'f})\, f \Big[t\, (\mathsf{d} - b')\, t' - t' (\mathsf{d} - b')\, t \\
& \quad + t' (\mathsf{d} - b')\, \mathsf{u} - \mathsf{u}(\mathsf{d} - b')\, t' \\
& \quad + \mathsf{u}(\mathsf{d} - b')\, t - t\, (\mathsf{d} - b')\, \mathsf{u} \Big] f
\end{aligned}
$$