Nucleon Electric Dipole Moments from Lattice QCD

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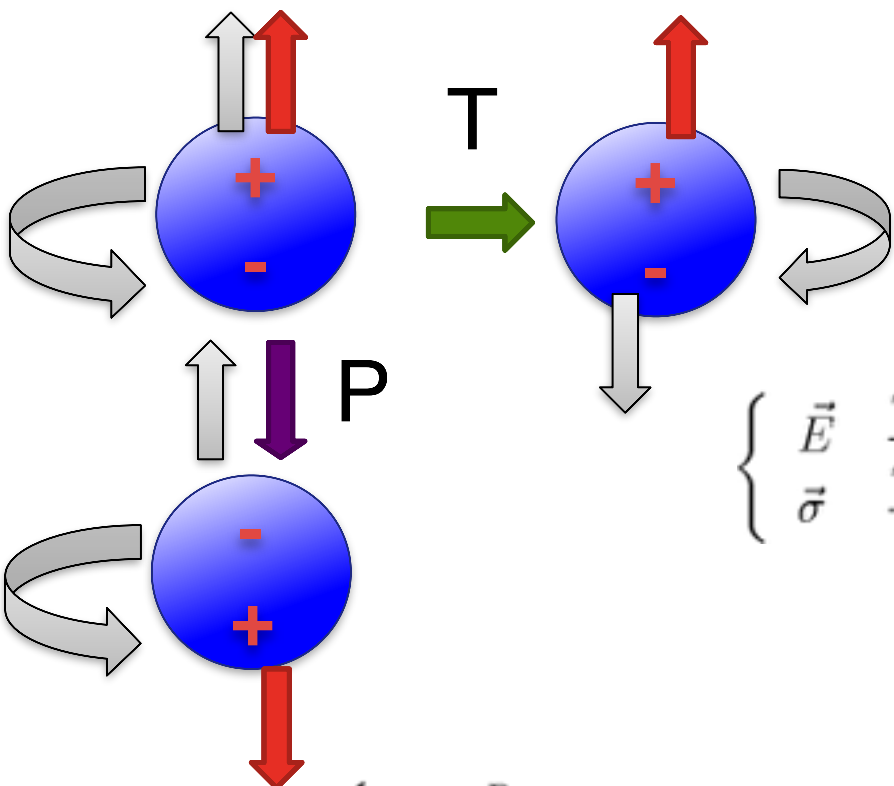
outline

- Introduction (EDM)
- Lattice Study
  - old formula v.s. new formula (on lattice)

  numerical check using chromo-EDM
- Implication to the θ-EDM
- quark EDM
- Summary

Introduction

- Electric Dipole Moment d
  Energy shift of a spin particle in an electric field
- Non-zero EDM : P&T (CP through CPT) violation



$$H_{\mathrm{EDM}} = -d \langle \vec{\sigma} \rangle \cdot \vec{E}$$

$$\begin{cases} \vec{E} \xrightarrow{\mathrm{T}} \vec{E} \\ \vec{\sigma} \xrightarrow{\mathrm{T}} -\vec{\sigma} \end{cases}$$

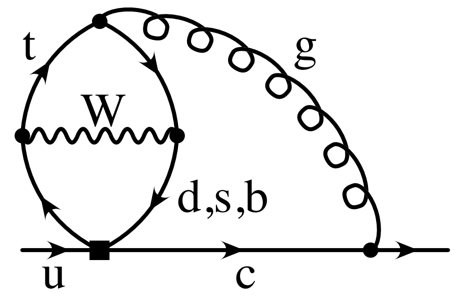
→ ***H_{EDM}* is CP-odd !**

$$\begin{cases} \vec{E} \xrightarrow{\mathrm{P}} -\vec{E} \\ \vec{\sigma} \xrightarrow{\mathrm{P}} \vec{\sigma} \end{cases}$$

→ ***H_{EDM}* is P-odd**

▪ Origin of EDM: CP-violating (CP-odd) interactions

CKM: CP violating interaction in SM
But, electron and quark EDM's are zero at 1 and 2 loop level.
at least three loops to get non-zero EDM's.
EDM's are very small in the standard model.

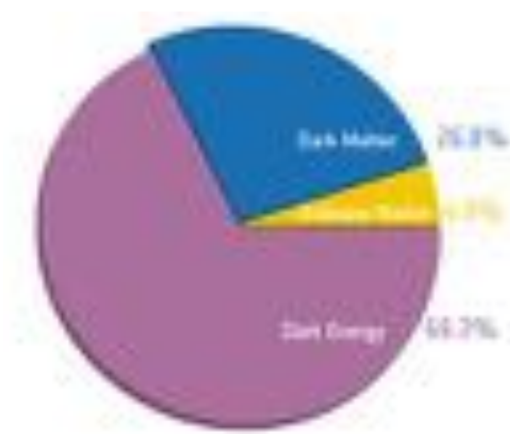


SM contribution (3-loop diagram)
Ref: [A. Czarnecki and B. Krause '97]

nucleon EDM from CKM : ~ 10^{-32} [e cm]

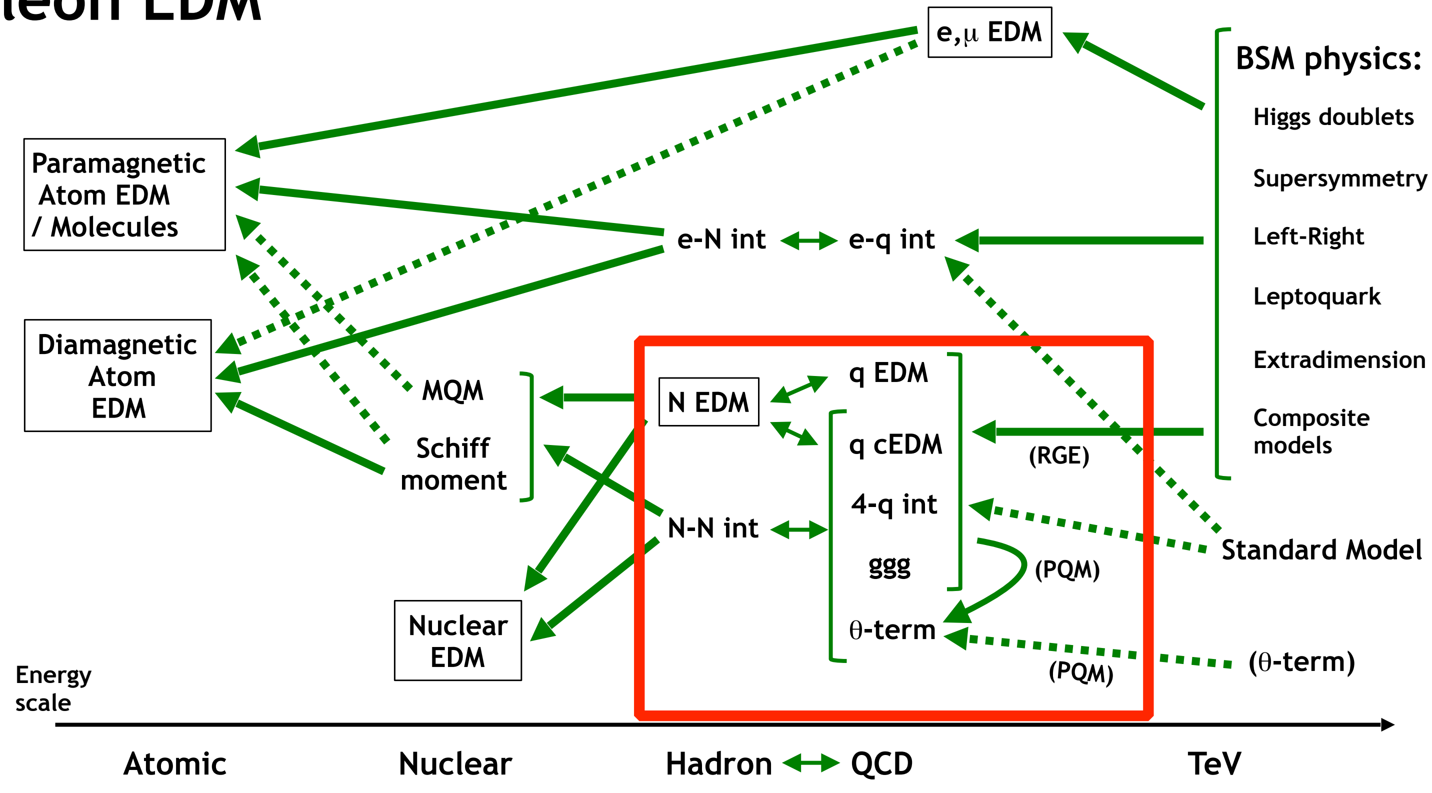
CP violation (CPV) in SM is not sufficient to reproduce matter/antimatter asymmetry. Large CPV beyond SM is required. (Sakharov's three conditions)

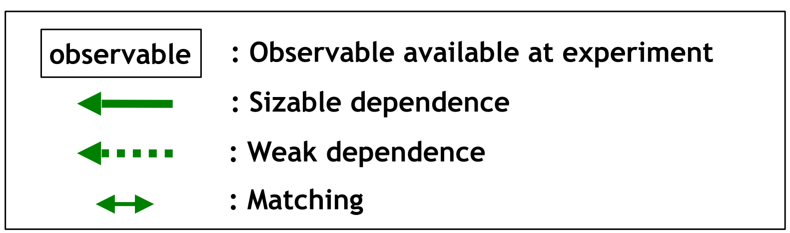
photon: matter		
	SM prediction	10^{20} : 1
	Observation	10^{10} : 1



•http://www.esa.int/ESA

•Nucleon EDM





Important bottleneck of the EDM calculation!

[N. Yamanaka, et al. Eur. Phys. J. A53 (2017) 54, Ginges and Flambaum Phys. Rep. 397, 63, 2004]

Role of (lattice) QCD : connect quark/gluon-level (effective) operators to hadron/nuclei matrix elements and interactions (Form factor, dn)

Non-perturbative determination is important → Lattice QCD calculation!

•Nucleon EDM Experiments

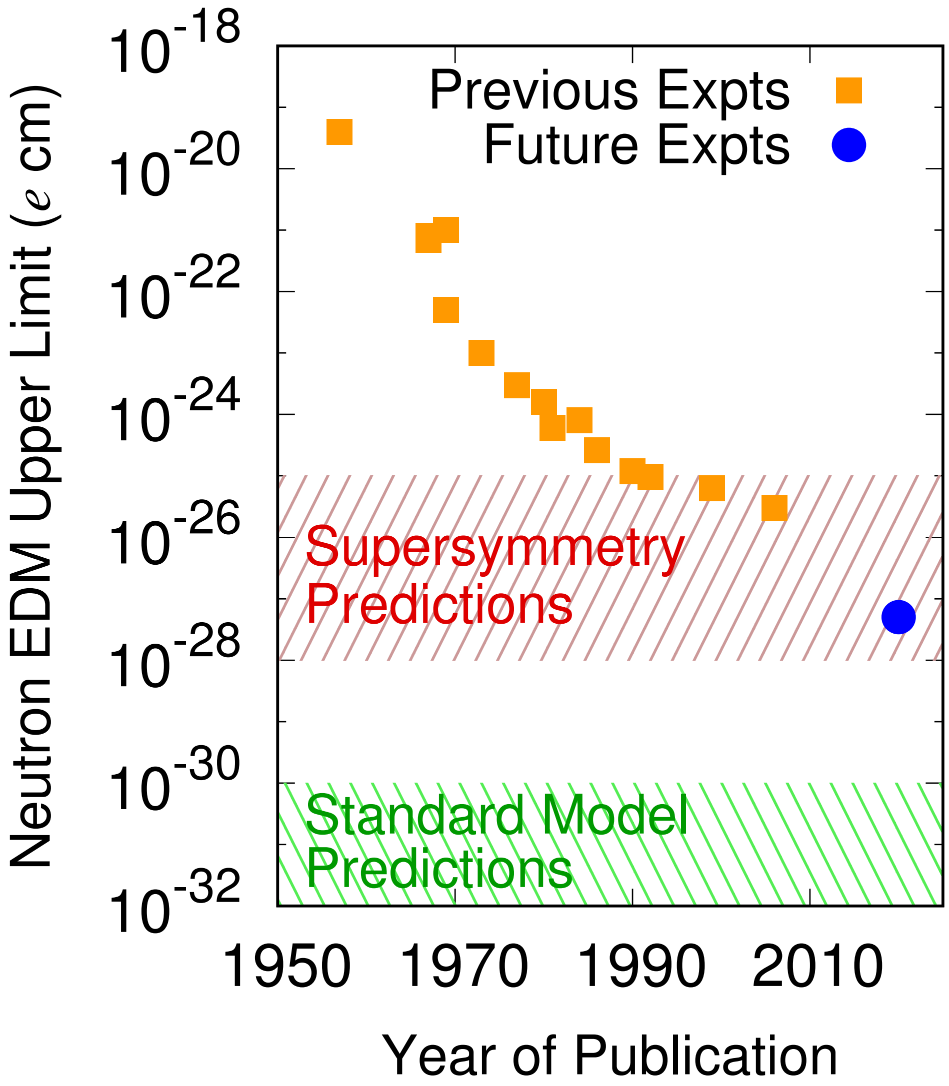
Current nEDM limits:

^{199}Hg spin precession (UW) [Graner et al, 2016]
Ultracold Neutrons in a trap (ILL) [Baker 2006]

$$|d_{Hg}| < 7.4 \times 10^{-30}\ \mathrm{e \cdot cm}$$
$$|d_n| < 2.6 \times 10^{-26}\ \mathrm{e \cdot cm}$$

SM nucleon EDMs expectation is

much smaller than the current bound.



[B. Yoon, talk at Lattice 2017]

- Several experimental projects are on going.

nucleon, charged hadrons, lepton,
PSI EDM, Munich FRMII, SNS nEDM, RCNP/TRIUMF, J-PARC

•Effective CPV operators

$$\mathcal{L}_{eff}^{\not{CP}} = \frac{g_s^2}{32\pi^2}\bar{\theta} G_{\mu\nu}\tilde{G}^{\mu\nu}$$ dim=4, θ_{QCD}

$$- \frac{i}{2}\sum_{i=u,d,s} \tilde{d}_i \bar{\psi}_i G \cdot \sigma\gamma_5 \psi_i$$ dim=5, chromo EDM

$$- \frac{i}{2}\sum_{i=e,u,d,s} d_i \bar{\psi}_i F \cdot \sigma\gamma_5 \psi_i$$ dim=5, e, quark EDM

$$+ \omega f^{abc} G_{\mu\nu,a} G^{\mu\beta,b} G^{\nu,c}_{\beta}$$ dim=6, Weinberg three gluon

$$+ \sum C_i^{(4q)} \mathcal{O}_i^{(4q)}$$ dim=6, Four-quark operators

$\bar{\theta} \leq \mathcal{O}(10^{-10})$: Strong CP problem
Dim=5 operators suppressed by m_q/Λ^2 -> effectively dim=6,
quark EDM … the most accurate lattice data for EDM (~10% for u,d)
Others are not well determined. cEDM, Weinberg ops just started.

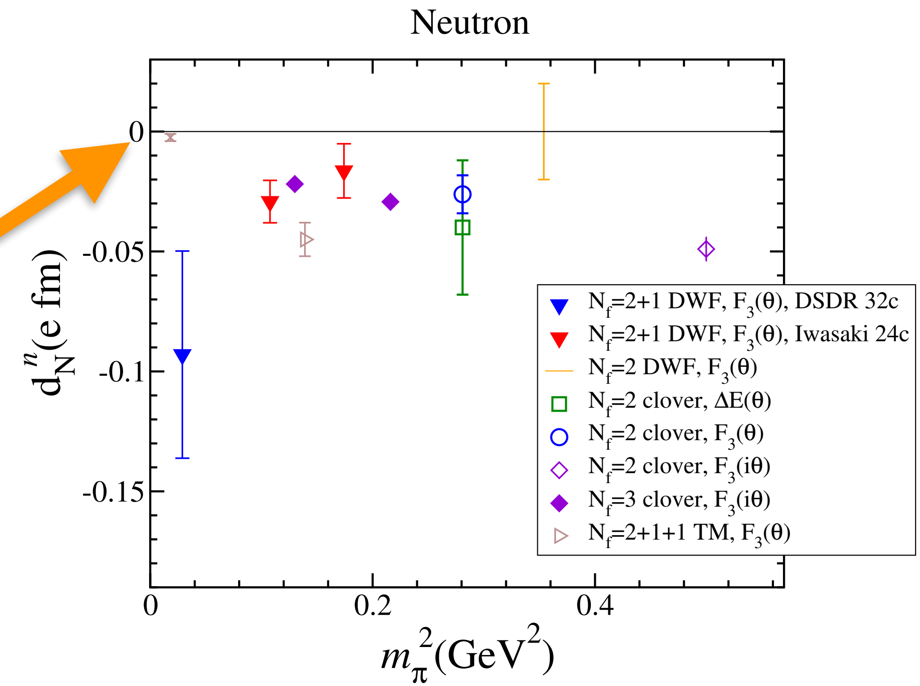
θ_{QCD} induced Nucleon EDMs

Phenomenological estimates

method	value
ChPT/NDA	~ 0.002 e fm
QCD sum rules [1,2]	0.0025 ± 0.0013 e fm
QCD sum rules [3]	$0.0004^{+0.0003}_{-0.0002}$ e fm

[1] M. Pospelov, A. Ritz, Nuclear Phys. B 573 (2000) 177,
[2] M. Pospelov, A. Ritz, Phys. Rev. Lett. 83 (1999) 2526,
[3] J. Hisano, J.Y. Lee, N. Nagata, Y. Shimizu, Phys. Rev. D 85 (2012) 114044.

Lattice calculations



[E. Shintani, T. Blum, T. Izubuchi, A. Soni, PRD93, 094503(2015)]

Phenomenology: |dn| ~ θ_{QCD} 10^{-3} e fm -> |θ_{QCD}| < 10^{-10}
Lattice : |dn| ~ θ_{QCD} 10^-2 e fm -> severer constraint on |θ_{QCD}|

Problem: a spurious mixing between EDM and magnetic moments in all previous lattice computations of nucleon form factor.

Parity mixing problem
on
the CP-violating nucleon form factors

Michael Abramczyk, HO, et al,
Lattice calculation of electric dipole moments and form factors of the nucleon
Phys.Rev. D96 (2017) no.1, 014501

Definition of nucleon form factors

Nucleon form factor in C, P-symmetric world (CP-even)

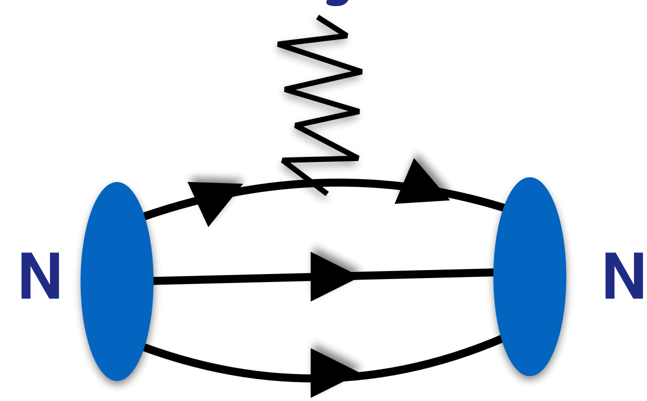
$$\langle p', \sigma' | J^\mu | p, \sigma \rangle = \bar{u}_{p',\sigma'} \left[F_1(Q^2)\gamma^\mu + F_2(Q^2) \frac{i\sigma^{\mu\nu} q_\nu}{2m_N} \right] u_{p,\sigma}$$

$$(q = p' - p, \quad Q^2 = -q^2)$$

u_p : spinor wave function for the nucleon ground state |p,σ>

$$(\not{p} - m_N) u_p = 0$$

J : electromagnetic current



Definition of nucleon form factors

Nucleon form factor in CP-broken world

$$\langle p', \sigma' | J^\mu | p, \sigma \rangle = \bar{u}_{p',\sigma'} \left[F_1(Q^2)\gamma^\mu + F_2(Q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2m_N} - F_3(Q^2)\frac{\gamma_5\sigma^{\mu\nu}q_\nu}{2m_N} \right] u_{p,\sigma}$$

P, T even

P, T odd

Refs. [many textbooks, e.g. Itzykson, Zuber, “Quantum Field Theory“]

- CP-odd form factor F3 is introduced.
- the same spinor up (F1, F2 are same as CP-even case.)
- Non-zero F3 is a signature of the CP violation (F3= 0 -> CP-even)
- permanent EDM:

$$d_n = \lim_{Q^2 \to 0} \frac{F_3(Q^2)}{2m_N}$$

All previous lattice studies (prior to 2017) use a different spin structure for the form factors. (Refs. original works [S. Aoki, et al., 2005]) revisit of the nucleon CP-odd (EDM) form

Nucleon 2 point function in CP-even world

$N = u[u^T C\gamma_5 d]$ Lattice nucleon operator for sink and source

$\langle 0|N|p,\sigma\rangle_{CP-even} = Z u_{p,\sigma}$ Nucleon ground state in CP-even vacuum

up is a solution spinor of the free Dirac equation: $(\not{p} - m_N)u_p = 0$

$$
\begin{aligned}
C_{2pt}(\vec{p};t)_{CP-even} &= \langle N(\vec{p};t)|\bar{N}(\vec{p};0)\rangle_{CP-even} \\
&= \langle N(\vec{p},t)\left[\sum_{k,\sigma}\frac{|k,\sigma\rangle\langle k,\sigma|}{2E_k}\right]\bar{N}(\vec{p};0)\rangle_{CP-even} + (\text{excited states}) \\
&\underset{t\to\infty}{\longrightarrow} |Z|^2\frac{e^{-E_p t}}{2E_p}\Big(\sum_\sigma u_{p,\sigma}\bar{u}_{p,\sigma}\Big) \\
&= |Z|^2 e^{-E_p t}\frac{m_N - i\not{p}}{2E_p}
\end{aligned}
$$

Completeness condition for free Dirac spinor

(From now on excited states are omitted.)

Nucleon 2 point function in CP-broken world

$$\langle 0|N|p,\sigma\rangle_{\not{CP}} = Z\tilde{u}_{p,\sigma}$$ Nucleon ground state in CP-broken vacuum

$\tilde{u}_p$ is a solution spinor of the free Dirac equation: $(\not{p} - m_N e^{-2i\alpha\gamma_5})\tilde{u}_p = 0$

Asymptotic state is modified: (CP-violating) γ5 mass is allowed in general.

$$\begin{aligned} C_{2pt}(\vec{p};t)_{\not{CP}} &= \langle N(\vec{p};t)|\bar{N}(\vec{p};0)\rangle_{\not{CP}} \\ &= |Z|^2 \frac{e^{-E_p t}}{2E_p}\left(\sum_\sigma \tilde{u}_{p,\sigma}\bar{\tilde{u}}_{p,\sigma}\right) \\ &= |Z|^2 e^{-E_p t}\frac{m_N e^{2i\alpha\gamma_5} - i\not{p}}{2E_p} \end{aligned}$$

Completeness condition for free Dirac spinor

$\tilde{u}_p = e^{i\alpha\gamma_5}u_p$ is a solution to the above Dirac equation.

$$\sum_\sigma \tilde{u}_{p,\sigma}\bar{\tilde{u}}_{p,\sigma} = e^{i\alpha\gamma_5}\left(\sum_\sigma u_{p,\sigma}\bar{u}_{p,\sigma}\right)e^{i\alpha\gamma_5} = m_N e^{2i\alpha\gamma_5} - i\not{p}$$

[Completeness condition for free Dirac spinor with γ5 mass]

Calculation of 3 point function in CP-broken world

$$C_{3pt}(\vec{p'},t;\vec{p},\tau)_{\not{CP}} = \sum_{\vec{y},\vec{z}} e^{-i\vec{p'}\cdot\vec{y}+i\vec{p}\cdot\vec{z}} \langle N(\vec{y},t) J^\mu(\vec{z},\tau) \bar{N}(0)\rangle_{\not{CP}}$$

$$= |Z|^2 \frac{e^{-E_{p'}(t-\tau)-E_p(\tau)}}{4E_{p'}E_p} \sum_{\sigma,\sigma'} \underbrace{\langle N(p')|p',\sigma\rangle_{\not{CP}}}_{①} \underbrace{\langle p',\sigma|J^\mu|p,\sigma'\rangle_{\not{CP}}}_{②} \underbrace{\langle p,\sigma'|N(p)\rangle_{\not{CP}}}_{③}$$

① & ③: $\langle 0|N|p,\sigma\rangle_{\not{CP}} = Z\tilde{u}_{p,\sigma}$

②: $\langle p',\sigma'|J^\mu|p,\sigma\rangle_{\not{CP}} = \bar{\tilde{u}}_{p',\sigma'} \left[\tilde{F}_1(Q^2)\gamma^\mu + \tilde{F}_2(Q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2m_N} - \tilde{F}_3(Q^2)\frac{\gamma_5\sigma^{\mu\nu}q_\nu}{2m_N} \right] \tilde{u}_{p,\sigma}$

Refs: original works since 2005

"All" previous (prior 2017) lattice studies:

$\tilde{F}_1, \tilde{F}_2, \tilde{F}_3$: defined in the rotated spinor basis $(\tilde{u})$

Two form factors are different!

$$\begin{cases} F_2(Q^2) \neq \tilde{F}_2(Q^2) \\ F_3(Q^2) \neq \tilde{F}_3(Q^2) \end{cases}$$

(u) $(\tilde{u})$

Relation between two spinor basis

$$\bar{\tilde{u}}_{p',\sigma'} \left[\tilde{F}_1 \gamma^\mu + (\tilde{F}_2 + i\tilde{F}_3\gamma_5) \frac{i\sigma^{\mu\nu} q_\nu}{2m_N} \right] \tilde{u}_{p,\sigma} = \bar{u}_{p',\sigma'} \left[\tilde{F}_1 \gamma^\mu + e^{2i\alpha\gamma_5} (\tilde{F}_2 + i\tilde{F}_3\gamma_5) \frac{i\sigma^{\mu\nu} q_\nu}{2m_N} \right] u_{p,\sigma}$$

[conventional "lattice" parametrization since 2005]

$$\equiv \bar{u}_{p',\sigma'} \left[F_1 \gamma^\mu + (F_2 + iF_3\gamma_5) \frac{i\sigma^{\mu\nu} q_\nu}{2m_N} \right] u_{p,\sigma}$$

[textbook]

A simple relations between $\{F_1, F_2, F_3\}$ and $\{\tilde{F}_1, \tilde{F}_2, \tilde{F}_3\}$

$$(F_2 + iF_3\gamma_5) = e^{2i\alpha\gamma_5}(\tilde{F}_2 + i\tilde{F}_3\gamma_5), \Leftrightarrow \begin{cases} \tilde{F}_2 = \cos(2\alpha)F_2 + \sin(2\alpha)F_3 \\ \tilde{F}_3 = -\sin(2\alpha)F_2 + \cos(2\alpha)F_3 \end{cases}$$

$$\Rightarrow \quad [F_2]_{\mathrm{correct}} = \tilde{F}_2 + \mathcal{O}(\alpha^2)$$

$$[F_3]_{\mathrm{correct}} = \tilde{F}_3 + 2\alpha F_2$$

There is a spurious contribution of order (α F2) to the previous lattice results.
In other words, CP violation effects come from both tilde{F3} and α, not only tilde{F3}.

This mixing angle α has to be calculated, and rotated away to get "net" CP-violation effect.

Similar issues in the ChPT (perturbative) calculations? (α may appear in the mass correction.)

Numerical check using the chromo EDM operator

Form factor method

vs

Energy shift method

Computational resources : ACCC HOKUSAI greatwave, Fermilab, JLab [USQCD project]

How to calculate CP-odd interaction on a lattice

Linearization of CP-odd interaction (e.g. : θ-EDM)

$$e^{-S_{QCD}-i\theta Q} = e^{-S_{QCD}}\left[1 - i\theta Q + \mathcal{O}(\theta^2)\right]$$

$$\langle \mathcal{O} \rangle_{\not{CP}} = \langle \mathcal{O} \rangle_{CP-even} - i\theta \langle Q \cdot \mathcal{O} \rangle_{CP-even} + \mathcal{O}(\theta^2)$$

(CP-even) **(CP-odd)**

Q: topological charge, θ << 1

Original (CP-even) gauge configurations can be used. No sign problem.

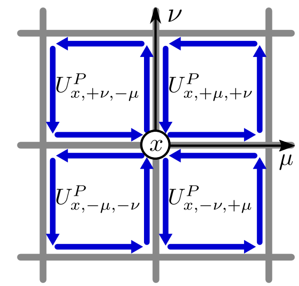
c.f. Dynamical simulation including CP-odd interactions

$$\langle \mathcal{O} \rangle_\theta \sim \int \mathcal{D}U(\mathcal{O}) e^{-S_{QCD}-\theta_{imag}Q}$$ **[R. Horsley et al. (2008); H. K. Guo, et al., 2015)]**

Non-perturbative treatment of CP-odd interactions.
Analytic continuation to imaginary θ.
Need additional simulation.
Check linearity of θ (ensemble generation for various imaginary θ)

•Chromo EDM operator

$$\mathcal{L}_{cEDM} = \sum_{q=u,d} \frac{\delta_q}{2} \bar{q}[G_{\mu\nu}\sigma^{\mu\nu}\gamma_5]q$$



✱Dimention 5 CP violating operator, mixing with dim-3 pseudo scalar operator.

✱Beyond standard model origin

✱Chiral symmetry is important.
The clover term in Wilson-type action = Chromo-magnetic dipole moment (chromo-MDM).

$$\mathcal{L}_{clover} = a\bar{q}\left[G_{\mu\nu}\sigma^{\mu\nu}\right]q$$

In presence of CPv, additional operator mixing of chromo-MDM appears.

➡We use chirally symmetric domain wall fermion
(gauge ensemble by RBC-UKQCD

1. Form factor method

Mixing parameter induced by cEDM

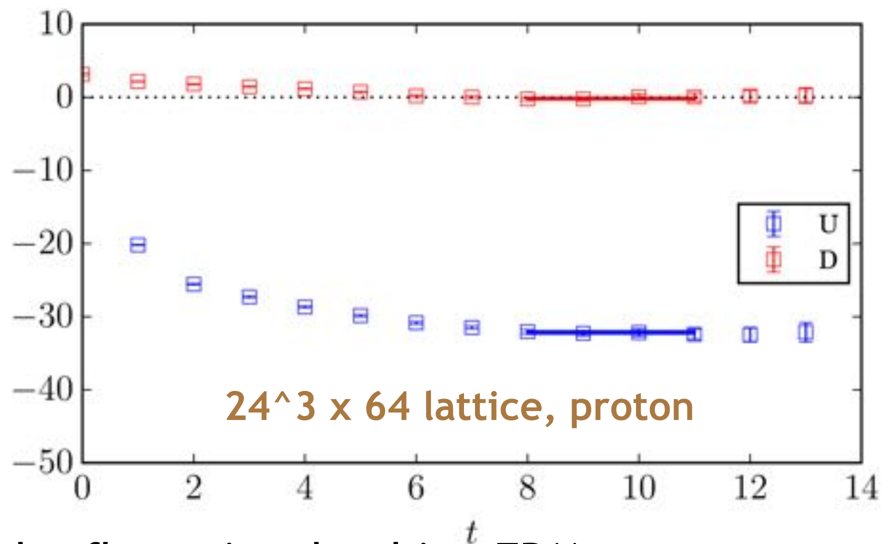
$$C_{2pt}^{CP-odd}(t) = \langle N(t)\bar{N}(0)\sum_x \mathcal{O}_{cEDM}(x)\rangle$$

$$C_{2pt}(\vec{p};t)_{\not{CP}} = |Z|^2 e^{-E_p t}\frac{m_N e^{2i\alpha\gamma_5} - i\not{p}}{2E_p}$$

$$= |Z|^2 \frac{e^{-E_p t}}{2E_p}\left[(m_N - i\not{p}) + 2i\alpha m_N \gamma_5\right] + \mathcal{O}(\alpha^2)$$

(CP-even) (CP-odd)

$$\alpha^{eff}(t) = -\frac{\mathrm{Tr}\left[T^+\gamma_5 C_{2pt}^{CP-odd}(t)\right]}{\mathrm{Tr}\left[T^+ C_{2pt}(t)\right]}$$



Mixing angle α depend strongly on the flavor involved in cEDM.

For proton, its strength for U-cEDM is large, no signal for D-cEDM.

For nucleon, no signal for U-cEDM.

Result of F3 form factor (L=24)

$$C_{3pt}^{CP-odd}(T,t) = \langle N(T) J^{\mu}(t) \bar{N}(0) \sum_{x} [\mathcal{O}_{cEDM}(x)] \rangle$$

a standard plateau method:

$$R(T,t) = \frac{C_{3pt}^{CP-odd}(T,t)}{c_{2pt}(t)} \sqrt{\frac{c'_{2pt}(T) c'_{2pt}(t) c_{2pt}(T-t)}{c_{2pt}(T) c_{2pt}(t) c'_{2pt}(T-t)}}$$

"correct" F3 :

$$(1+\tau) F_3(Q^2) = \frac{m_N}{q_z R} \mathrm{Tr}\left[T_{S_z}^{+} \cdot R(T,t)^{\mu=4} \right] - \alpha G_E(Q^2)$$

R: kinetic factor

projection operator : $T_{S_z}^{+} = \left[\frac{1+\gamma^4}{2} (-i\gamma^1\gamma^2) \right]$

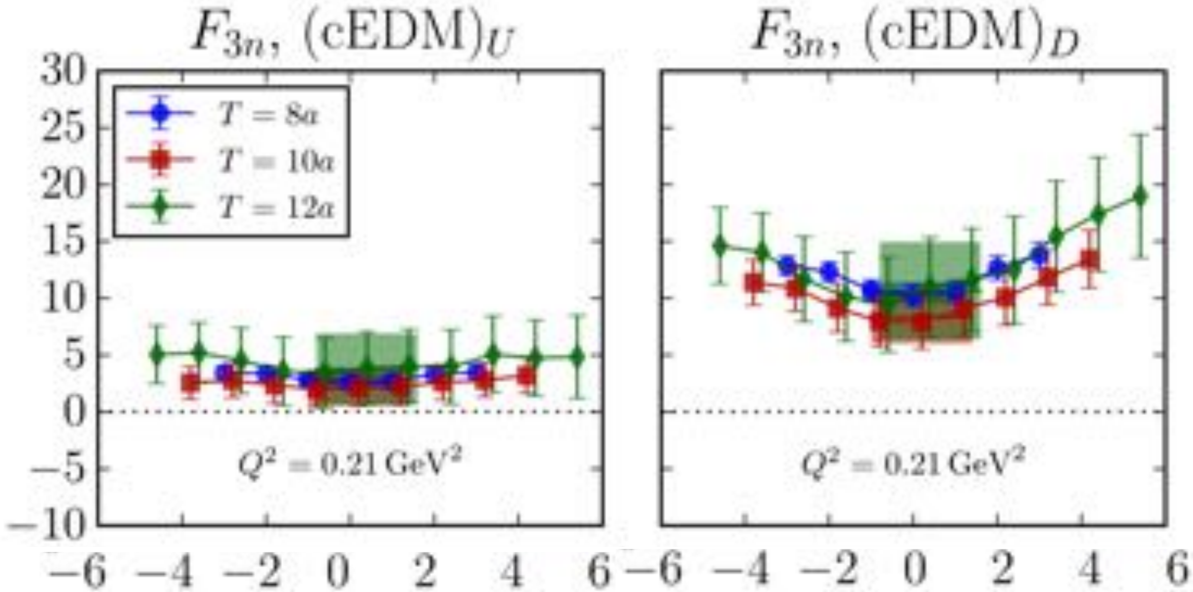
GE: Sachs electric form factor $G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2), \quad \tau = \frac{Q^2}{4m_N^2}$

Recall the 3 pt functions:

$$C_{3pt}(\vec{p}', t; \vec{p}, \tau)_{\not{CP}} = \sum_{\vec{y},\vec{z}} e^{-i\vec{p}'\cdot\vec{y} + i\vec{p}\cdot\vec{z}} \langle N(\vec{y}, t) J^{\mu}(\vec{z}, \tau) \bar{N}(0) \rangle_{\not{CP}}$$

$$= |Z|^2 \frac{e^{-E_{p'}(t-\tau) - E_p(\tau)}}{4E_{p'}E_p} \sum_{\sigma,\sigma'} \langle N(p') | p', \sigma \rangle_{\not{CP}} \langle p', \sigma | J^{\mu} | p, \sigma' \rangle_{\not{CP}} \langle p, \sigma' | N(p) \rangle_{\not{CP}}$$

Result

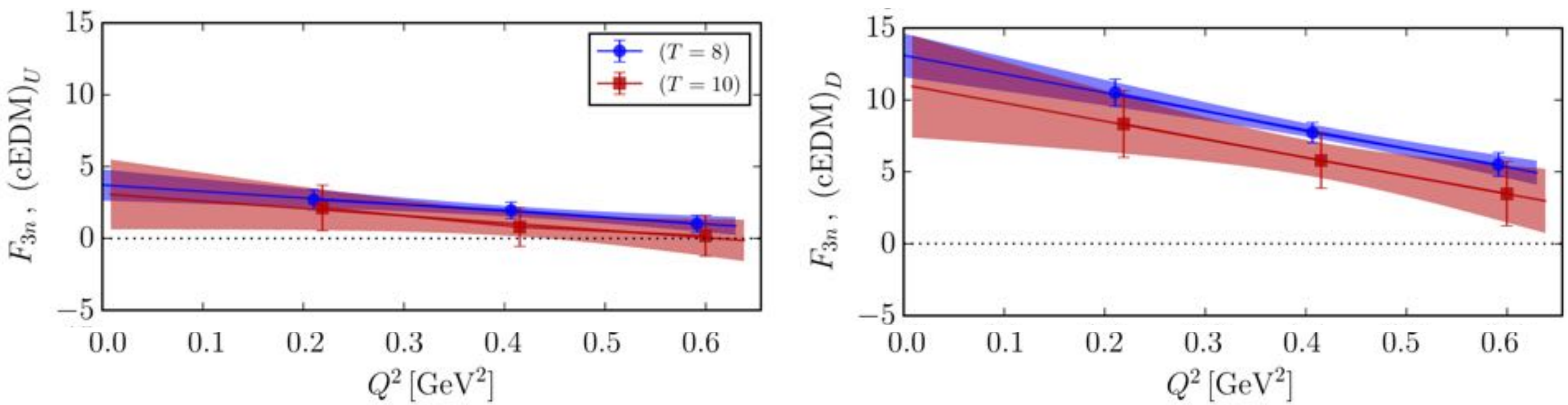


t-T/2

Neutron, u-cEDM

Neutron, d-cEDM

$m_\pi = 340[\mathrm{MeV}]$



Linear Q^2 fit to nucleon F3 form factor

2. Energy shift method

Lattice QCD with background constant electric field

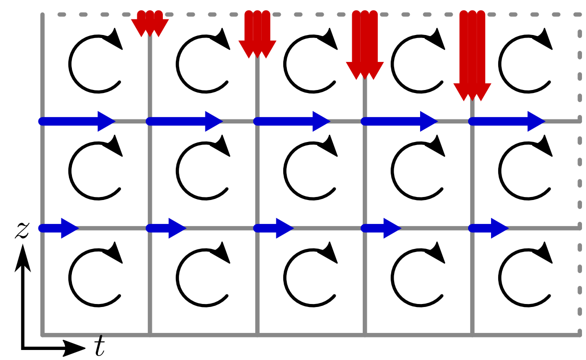
- Uniform electric field preserving translational invariance and periodic boundary conditions on a lattice (Euclidean imaginary electric field)
- used for the nucleon polarizability [W. Detmold, Tiburzi, and Walker-Loud, (2009)]
- First applied to the CP-violation effects.
- No sign problem: Analytic continuation of CP-odd interaction

$$U_\mu \to e^{iQ_q A_\mu} U_\mu$$

$$A_t(z,t) = \mathcal{E}_n z$$

$$A_z(z,t) = -\mathcal{E}_n L_z t \delta_{z=L_z-1}$$

Charge quantization due to finite volume.



strength of E field $\mathcal{E}_n = n\frac{6\pi}{L_z L_t}, \quad (n = \pm 1, \pm 2, \cdots)$

charge quanta $Q_q \mathcal{E}_n L_z L_t = 2\pi m, \quad (m : \text{integer})$

$(Q_u = 2/3, \quad Q_d = -1/3)$

24^3x 64 lattice minimal value of E (|n|=1) $\mathcal{E}_0 = \frac{6\pi}{L_z L_t} \sim 0.037 \text{ GeV}^2$

$\sim 186 \text{ MV/fm}$

Nucleon 2 point function with a constant Ez-field

$$C_{2pt}^{\not{CP}}(\vec{p}=0,t,\mathcal{E}) = |Z|^2 e^{i\alpha\gamma_5}\left(\frac{1+\gamma_4}{2}\right)\left[\frac{1+\Sigma_z}{2}e^{-(m+\delta E)t} + \frac{1-\Sigma_z}{2}e^{-(m-\delta E)t}\right]e^{i\alpha\gamma_5} + \mathcal{O}((\kappa,\mathcal{E})^2)$$

$$\sim |Z|^2 e^{-mt}\left[\frac{1+\gamma_4}{2} + i\alpha\gamma_5 - \Sigma_z \delta E t\right]$$

(t >> 1) **(CP-even)** **(CP-odd)**

spin dependent interaction energy

Energy shift : $\delta E = -\frac{\zeta}{2m}(i\mathcal{E})$

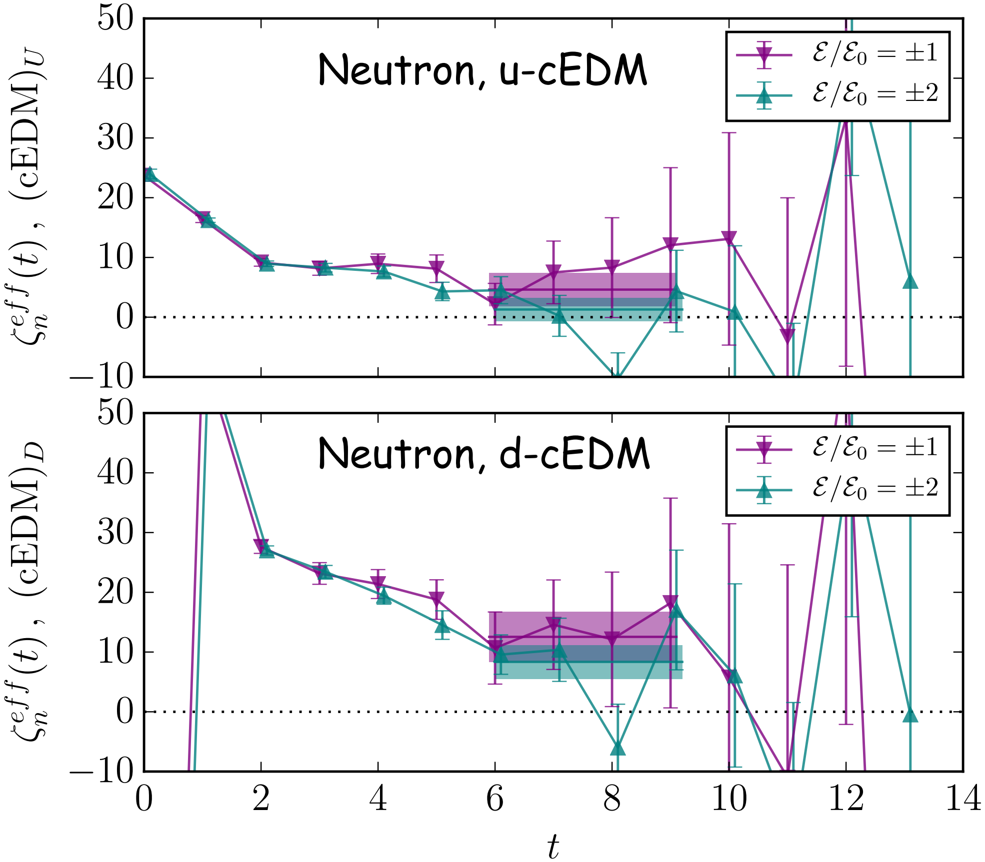
"Effective" energy shift (extraction of the term proportion to linear-time)

$$\zeta^{eff} = 2mF_3^{eff}(0) = -\frac{2m}{\mathcal{E}_z}[R_z(t+1) - R_z(t)],$$

$$R_z(t) = \frac{\mathrm{Tr}[T^+_{S_z} C_{2pt}^{CP-odd}(t,\mathcal{E})]}{\mathrm{Tr}[T^+ C_{2pt}(t,\mathcal{E})]}$$

$$C_{2pt}^{CP-odd}(t,\mathcal{E}) = \langle N(t)N(0)\sum_x [\mathcal{O}_{cEDM}(x)]\rangle_{\mathcal{E}\neq 0}$$

Effective energy shift for Neutron (L=24)



$m_\pi = 340[\mathrm{MeV}]$

Only neutron is considered. (Analysis of charged particle propagators is more complicated.)

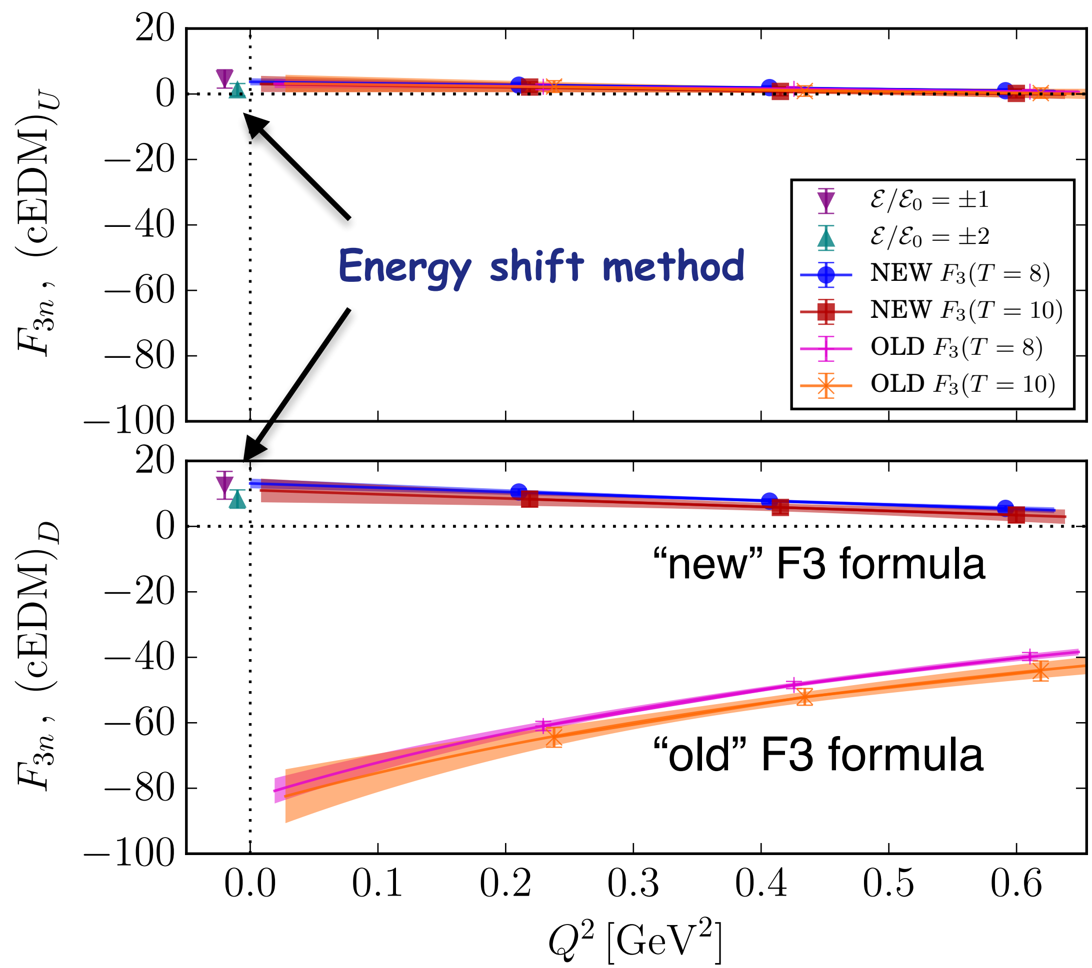
Non-zero signal for spectator d-cEDM.

Effective energy plateau around t = 6~10.

Results for |Ez|=1, |Ez|=2 are consistent. -> Higher order effects of E-field can be neglected.

New formula vs. Old formula

$m_\pi = 340[\text{MeV}]$



Neutron, u-cEDM

F2 mixing effect is tiny.

$\alpha_u \sim 0$

Neutron, d-cEDM

large spurious mixing.

$\alpha_d \sim 30$

u-cEDM: New and Old formula results give similar value consistent with energy shift method.

d-cEDM: "new" formula result is consistent with the energy shift method.

"old" F3 has a sizable mixing due to large α (cEDM mixing α ~ 30) [c.f. α for topological charge]

Implication of new formula for the theta induced EDM

Dim=4 : QCD theta term

$$\mathcal{L}_{eff}^{\not{CP}} = \frac{g_s^2}{32\pi^2}\bar{\theta} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Reanalysis of “lattice” θ induced EDM

Correction is simple: $$[F_3]_{\rm correct} = \tilde{F}_3 + 2\alpha F_2$$

Correction made by ourselves

		m_π [MeV]	m_N [GeV]	F_2	α	$\tilde{F}_3$	F_3
Ref[1]	n	373	1.216(4)	−1.50(16)	−0.217(18)	−0.555(74)	0.094(74)
Ref[2]	n	530	1.334(8)	−0.560(40)	−0.247(17)	−0.325(68)	−0.048(68)
	p	530	1.334(8)	0.399(37)	−0.247(17)	0.284(81)	0.087(81)
Ref[3]	n	690	1.575(9)	−1.715(46)	−0.070(20)	−1.39(1.52)	−1.15(1.52)
	n	605	1.470(9)	−1.698(68)	−0.160(20)	0.60(2.98)	1.14(2.98)
Ref[4]	n	465	1.246(7)	−1.491(22)	−0.079(27)	−0.375(48)	−0.130(76)
	n	360	1.138(13)	−1.473(37)	−0.092(14)	−0.248(29)	0.020(58)

Ref[1] : C. Alexandrou et al., Phys. Rev. D93, 074503 (2016),
Ref[2] : E. Shintani et al., Phys.Rev. D72, 014504 (2005).
Ref[3] : F. Berruto, T. Blum, K. Orginos, and A. Soni, Phys.Rev. D73, 054509 (2006)
Ref[4] : F. K. Guo et al., Phys. Rev. Lett. 115, 062001 (2015).

After removing spurious contributions, no signal of EDM.

The lattice results are consistent with phenomenological estimates.

Dim=5 : qEDM

$$-\frac{i}{2}\sum_{i=e,u,d,s} d_i\bar{\psi}_i F\cdot\sigma\gamma_5\psi_i$$

quark EDM operator

$$\langle N| \frac{\delta(\bar{\psi}\sigma \cdot \tilde{F}\psi)}{\delta A_\mu} |N\rangle \propto \epsilon_{k\lambda\mu\nu} q_k \langle N|\bar{\psi}\sigma_{\lambda\nu}\psi)|N\rangle$$

$$\langle N|\bar{\psi}\sigma_{\lambda\nu}\psi|N\rangle = g_T \bar{u}_N \sigma_{\lambda\nu} u_N$$ (nucleon tensor charge)

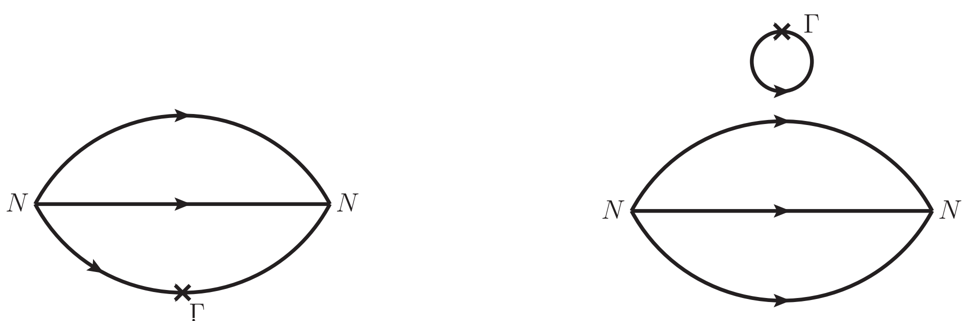
⇨ $$\frac{F_3}{2m_N} \equiv d_N \propto g_T \qquad d_N = d_u g_T^u + d_d g_T^d + d_s g_T^s$$

- Dimension 5 CP violating operator
- No need for CP-odd form factor

→ No spurious mixing problem in quark EDM

- dq ~ mq in most models, $m_s/m_d \sim 20$

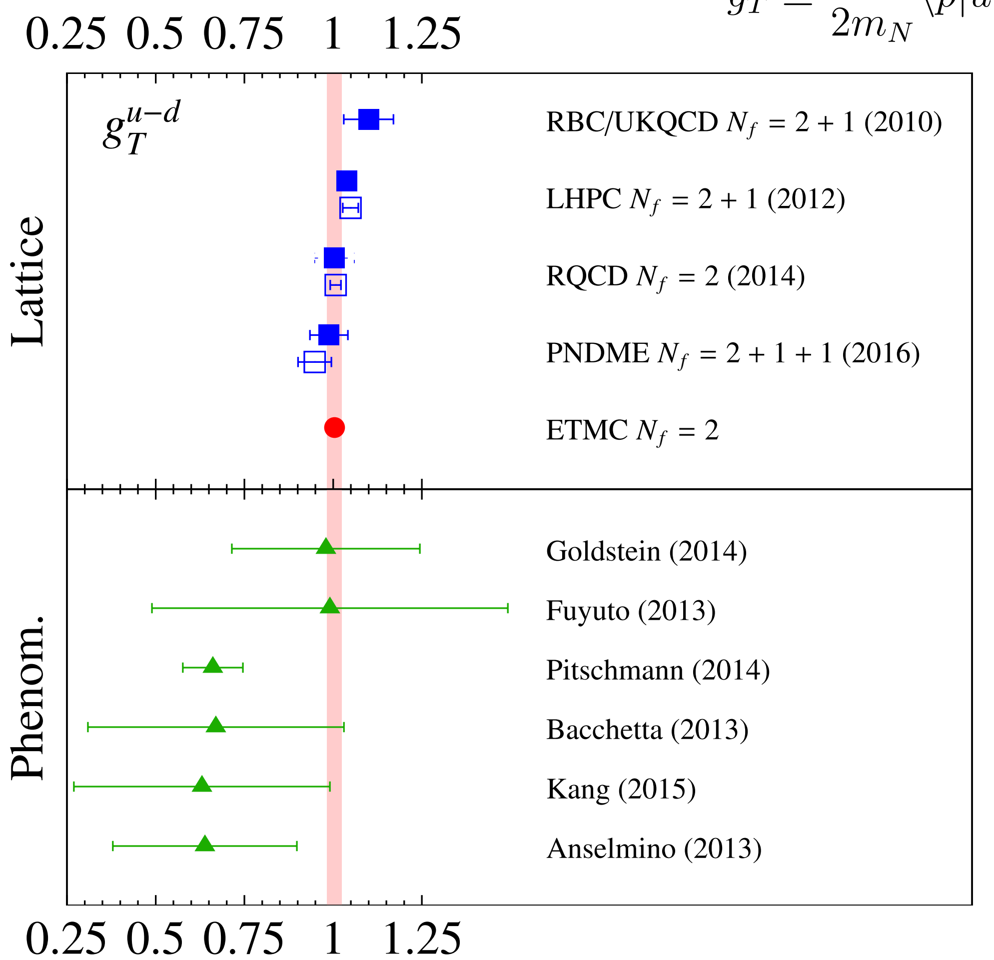
→ strange quark contribution (disconnected diagram) is important.



Strange contribution : purely disconnected diagrams (noisy)

Recent results: the isovector tensor charge

$$g_T \equiv \frac{1}{2m_N}\langle p|\bar{u}i\sigma_{03}\gamma_5 u - \bar{d}i\sigma_{03}\gamma_5 d|p\rangle = \delta u - \delta d,$$

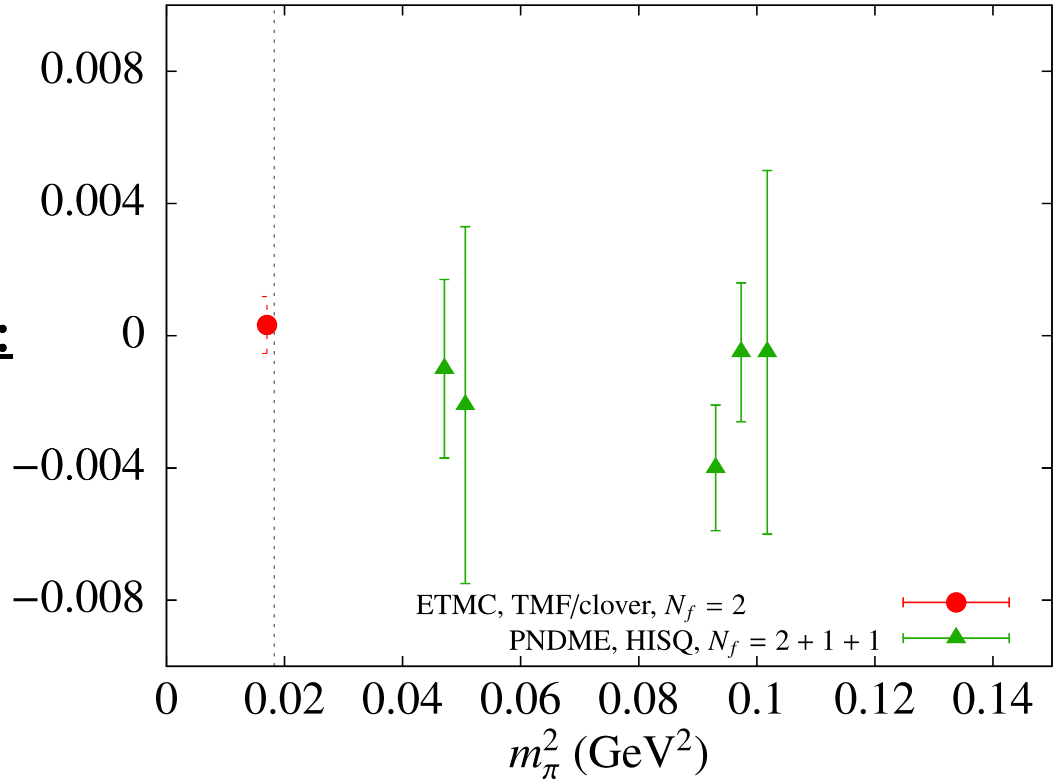


Ref. [C. Alexandrou, et al., PRD 95, 114514(2017)]

All lattice results are very accurate and show consistency among them.
The lattice error is much smaller than phenomenological estimates.
lattice : important input for nEDM

Recent results: the strange quark tensor charge

δs:



Ref. [C. Alexandrou, et al., PRD 95, 114514(2017)]

The disconnected part of the tensor charges is consistent with zero.
Need more precision. $\delta_s = -0.002(3)$ [C. Alexandrou, et al., PRD 95, 114514(2017)]

Current status of lattice EDMs

* θ-EDM

Many lattice results: after correcting spurious mixing, results consistent with zero.

* chromo-EDM

Exploratory studies started.
Nonzero signals for bare operators. Need to calculate operator mixing and renormalization -> position space renormalization.
(c.f. RI-MOM: Bhattacharya, et al., “15)

* quark-EDM

u,d quark: 10% error,   s-quark: need better precision

* Weinberg operator

Just started.

* 4 quark operators

Not explored yet.

Summary

Precision study of Nucleon structure is important.

EDM

- Beyond the Standard model physics searches using nuclei are competitive and complementary to the energy frontier new physics searches.

Lattice computation of EDM

- Reanalysis of the lattice method to compute the (CP-odd) nucleon form factors.
  - There exists a spurious mixing between MDM and EDM form factors on lattice.
- Lattice numerical confirmation of “new” form factor formula
  - proposal to calculate EDM on a lattice using energy shift, that is not affected the mixing problem.
  - cEDM operator is used to check the consistency between “new” form factor method and the energy shift method.
- All the previous lattice θ-EDM results using the form factor method must to be corrected.
  - Resulting EDM form factor |F3| are reduced, become one σ signal or less.
  - High precision computation is more important.

- Various nucleon EDM computations on lattice are ongoing.