Nucleon EDM & Decay from the Lattice

Eigo Shintani(RIKEN-BNL)

for the RBC-UKQCD collaborations

Topics

- Introduction
- Neutron and proton EDM
- Proton decay matrix elements
- Summary and future work

Introduction

Search for NP from lattice QCD

- Precise bound of undetected observables
  - Direct constraint on BSM

    EDM (nucleon (quark), electron, …), Proton(neutron) decay, NNbar oscillation, LFV, dark matter search, …
  - Intensity frontier physics
  - Hadronic correction should be significant

    Need to take account of nucleon structure, and low energy physics of QCD
  - Require the model independent method for strong interaction

Lattice QCD plays a key role !

Lattice fermion

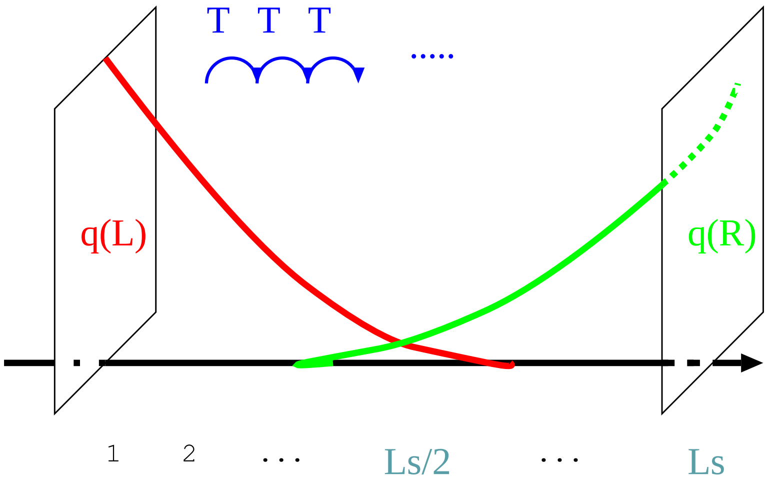
- There are several kinds of fermion definition on the lattice

  Due to Nielsen-Ninomiya no-go theorem
- Require "realistic" fermion for the precise calculation
  - Wilson-clover (and staggered fermions) may not be appropriate (due to sys. error maybe…)
  - Domain-wall fermion (and also overlap fermion) we use here
- Domain-Wall fermion (DWF)
  - L, R fermion are localized on boundaries

    ⇒ Chiral symmetry (if $L_s \to \infty$).
  - Good chiral symmetry

    Chiral symmetry breaking is suppressed as $am_{res} \sim \exp(-L_s)$.

  [Blum Soni, (97), CP-PACS(99), RBC(00), RBC/UKQCD. (05 --)]



Our strategy

- Non-perturbative determination of QCD contribution to nucleon (neutron and proton) EDM & decay from lattice
- Domain-wall fermion
  - High precision, but highly computational cost

    spend more than 1 year using powerful supercomputer
  - New development of algorithm to carry out efficiently
- All-mode-averaging (AMA) algorithm Blum, Izubichi, ES, 1208.4349
  - more than 5 times faster !
  - various applications to other observables

    (nucleon form factor)
  - possible to perform high precision measurement

Nucleon EDM from the lattice

Nucleon EDM in the SM and BSM

- Sensitive to P, CP violation
- Upper limit from experiment: $< 2.9 \times 10^{-26}$ e·cm
- Contribution from weak boson: CKM phase

Very tiny, which is 3-loop : $d_N^{\rm KM} \simeq 10^{-30}$ -- 10^{-32} e·cm

Khriplovich and Zhitnitsky, PLB109, 490 (1982); Czarnecki, Krause, PRL78, 4339 (1997)

- Contribution from QCD: θ term

Unnaturally small (strong CP problem): $\bar\theta < 10^{-9\pm1}$

Crewther, et al. (1979), Ellis, Gaillard (1979)

- Contribution from BSM: dim-5,6 operator

$$\mathcal{O}_{\rm qEDM} = d_q \bar q(\sigma \cdot F)\gamma_5 q,\ \mathcal{O}_{\rm cEDM} = d_q^c \bar q(\sigma \cdot G)\gamma_5 q,\ \mathcal{O}_{\rm Weinberg} = d^G G G \tilde G$$

$$\begin{aligned} d_N &= d_N^{\rm QCD}\bar\theta + d_N(d_q, d_q^c) + d_N(d^G) \\ &\sim 10^{-17}[\mathrm{e}\cdot\mathrm{cm}]\bar\theta + (1.4\text{--}0.47)d_d - (0.12\text{--}0.35)d_u + O(10^{-2})d_q^c \\ &\sim O(10^{-25}\text{--}10^{-27})\,\mathrm{e}\cdot\mathrm{cm} \end{aligned}$$

Hisano, Shimizu (04), Ellis, Lee, Pilaftsis (08),
Hisano, Lee, Nagata, Shimizu (12)

Nucleon EDM from lattice QCD

- Non-perturbative determination of QCD effect
  - L_θ

    From lattice QCD we obtain d_N in $d_N^{\mathrm{QCD}} = \bar{\theta} d_N$

    θ parameter can be estimated by $d_N^{exp}/d_N = \theta$ (if there is no BSM)
  - L_{qEDM} , L_{cEDM}

    From lattice QCD we obtain C_{qEDM} , C_{cEDM}

$$d_N^{\mathrm{BSM}} = \sum_q \left[d_q^{\mathrm{qEDM}} C^q_{\mathrm{qEDM}} + d_q^{\mathrm{cEDM}} C^q_{\mathrm{cEDM}} \right]$$

d^{qEDM} , d^{cEDM} depend on BSM parameters.

Result of lattice QCD is an important input value for BSM search

Methods

- Spectrum

$m_{\uparrow\,\text{spin}} - m_{\downarrow\,\text{spin}} = 2d_N\theta E$

$$R_3 = \frac{\langle N(t)\bar{N}(0)\rangle^{\text{up}}_{\theta,E}}{\langle N(t)\bar{N}(0)\rangle^{\text{down}}_{\theta,E}} \simeq 1 + d_N E\theta t$$

E: External electric field

Aoki and Gocksch, PRL63, 1125 (1989); ES, et al., (CP-PACS) PRD75, 034507 (2007); ES et al.,PRD78, 014503 (2008)

- CPV Form factor

$$\langle n(P_1)|J^{\text{EM}}_\mu|n(P_2)\rangle_\theta = \bar{u}^\theta_N \Big[\underbrace{\frac{F^\theta_3(Q^2)}{2m_N}\gamma_5\sigma_{\mu\nu}Q_\nu}_{\text{P,T-odd}} + \underbrace{F_1\gamma_\mu + \frac{F_2}{2m_N}\sigma_{\mu\nu}Q_\nu}_{\text{P,T-even}} + \cdots \Big] u^\theta_N$$

$$d_N = \lim_{Q^2\to 0} F_3(Q^2)/2m_N$$

ES, et al., (CP-PACS), PRD72, 014504 (2005); Berruto, et al. (RBC) PRD73, 05409 (2006).

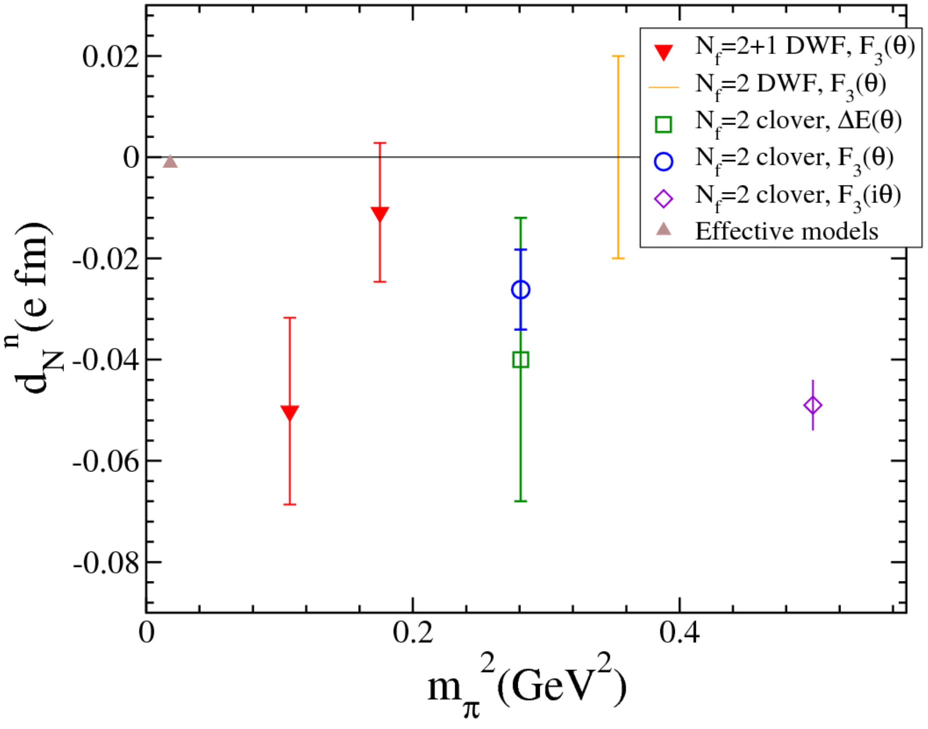
- Imaginary θ

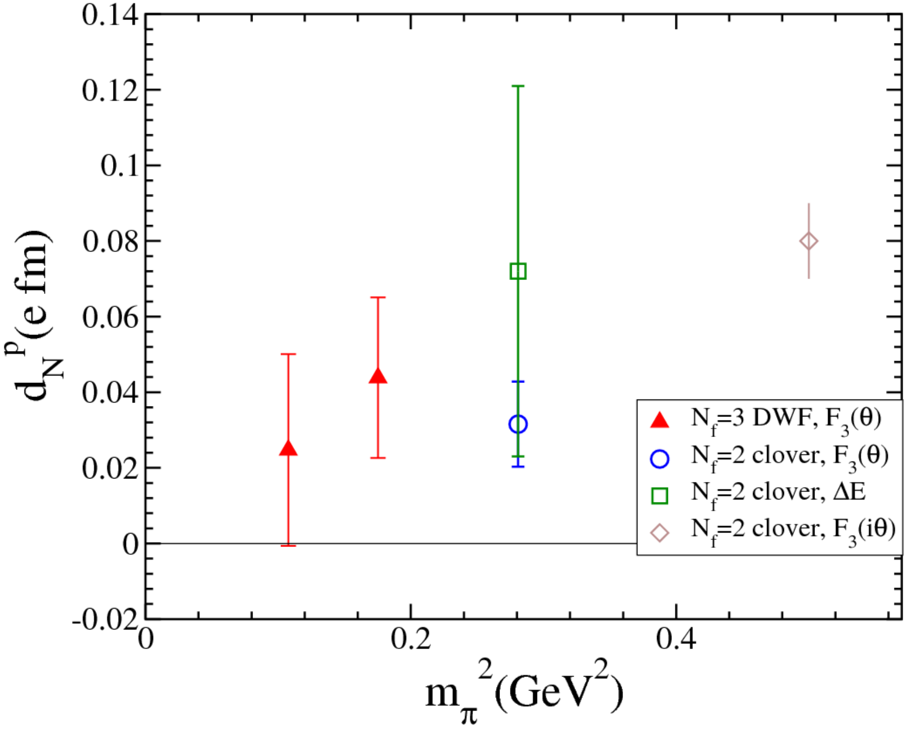
New generation of imaginary θ action: $\langle O e^{i\theta Q}\rangle \to \langle O e^{-\theta^I Q}\rangle$

T. Izubuchi, Lattice 2007

Recent results

- DWF in Nf=2+1 (RBC/UKQCD) m_π = 300--400 MeV
  - AMA is very helpful, cost is reduced to 1/5 or less.
  - Statistical error is more than 40%, and also we need to estimate systematic error (finite size effect).





Nucleon decay from the lattice

Effective operator

- Dimension-6 BV operator

$$\mathcal{L}_{\rm GUT} = \mathcal{L}_{\rm SM} + \sum_i C_i(\mu) O_i(\mu)/\Lambda^2_{\rm GUT} + \mathcal{O}((O(\mu)/\Lambda^2_{GUT})^2)$$

$$O_i(\mu) = (qq)_\Gamma (ql)_{\Gamma'}$$

"i" labels chirality (Γ) and flavor (q,l)

C_i depends on type of GUTs model

- Matrix element

Lattice QCD provides each decay channels of W_0 from matrix element;

$$\langle \pi^0 | (ud)_\Gamma u_{\Gamma'} | p \rangle = P_{\Gamma'} \left[W_0^\Gamma - \frac{i\not{q}}{m_p} W_1^\Gamma \right] u_p$$

Aoki et al. (JLQCD), PRD62, 014506 (2000); Aoki et al.(RBC), PRD75, 014507 (2007)

which is extracted from 3-pt function.

W_0 : determine from QCD matrix element (model independent)

- Decay rate

$$\Gamma_{p\to\pi^0 e^+} = \frac{m_p}{32\pi^2}\left[1 - \left(\frac{m_e}{m_p}\right)^2\right]^2 \left| \sum_i C_i W_0^i (p \to \pi^0) \right|^2$$

Precision of W_0 is significant, since the decay rate is affected by twice of that.

How to obtain W_0 from lattice QCD

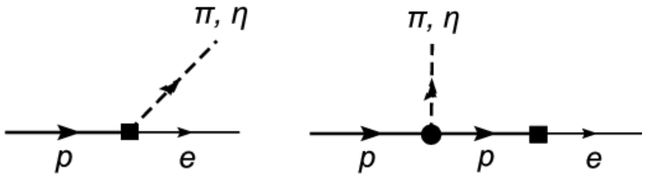
- The “indirect” method
  - Measurements of low-energy constant via tree level chiral perturbation theory.

$$W_0^{LR}(p \to \pi^0) \simeq \alpha(1+D+F)/\sqrt{2}f_0,$$

where D and F is given by experiment, and α is given by 2-pt function:

$$\langle 0|\big((ud)_R u_L\big)|p\rangle = \alpha P_L u_p$$

Claudson, et al., NPB195 (1982) 297



S. Aoki et al. (JLQCD), PRD62, 014506 (2000), Y. Aoki et al.(RBC), PRD75, 014507 (2007), Y. Aoki et al. (RBC-UKQCD), PRD78, 054505 (2008)

Easy calculation, BUT it has systematic error due to being based on ChPT.

- The “direct” method
  - Measurement of matrix element extracted from 3-pt function.
  - Rather expensive, while there is no uncertainty depending on models.
  - Provides each channels of decay mode.

S Aoki et al. (JLQCD), PRD62, 014506 (2000), Y. Aoki et al.(RBC), PRD75, 014507 (2007)

Low energy constant (indirect)

- Works with DWFs
  - Quenched QCD (direct/indirect)

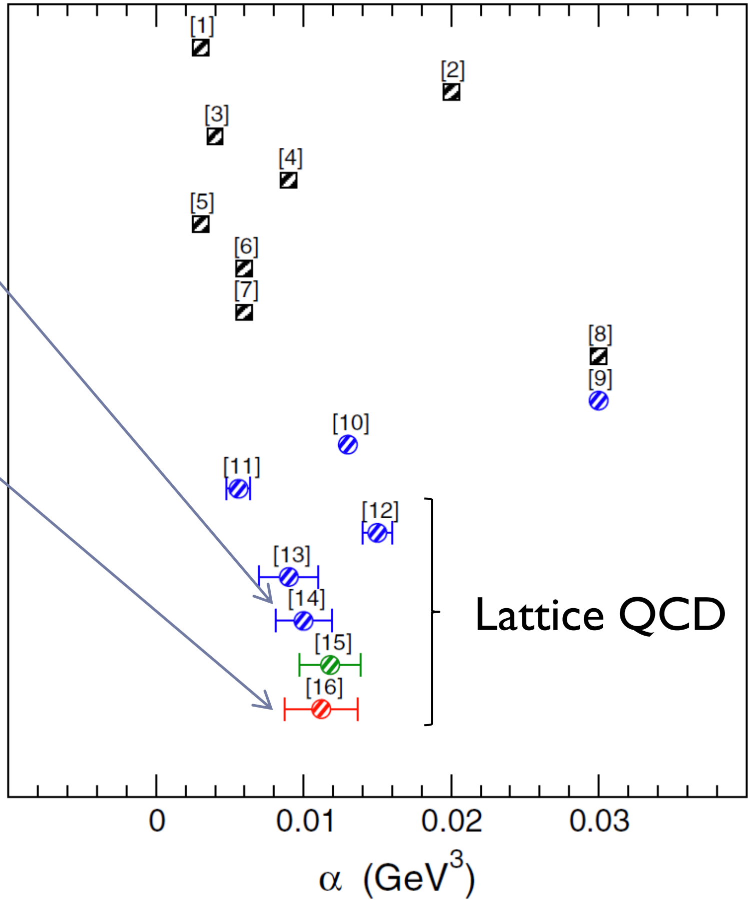
    Y. Aoki, C. Dawson, J. Noaki, and A. Soni, Phys. Rev. D75, 014507 (2007)

  - Nf=2+1 (indirect)

    Y. Aoki et al. (RBC-UKQCD), Phys. Rev. D78, 054505 (2008)

- Large model dependence
- Need to subtract ChPT ambiguity

  ⇒ direct calculation



W_0 (direct)

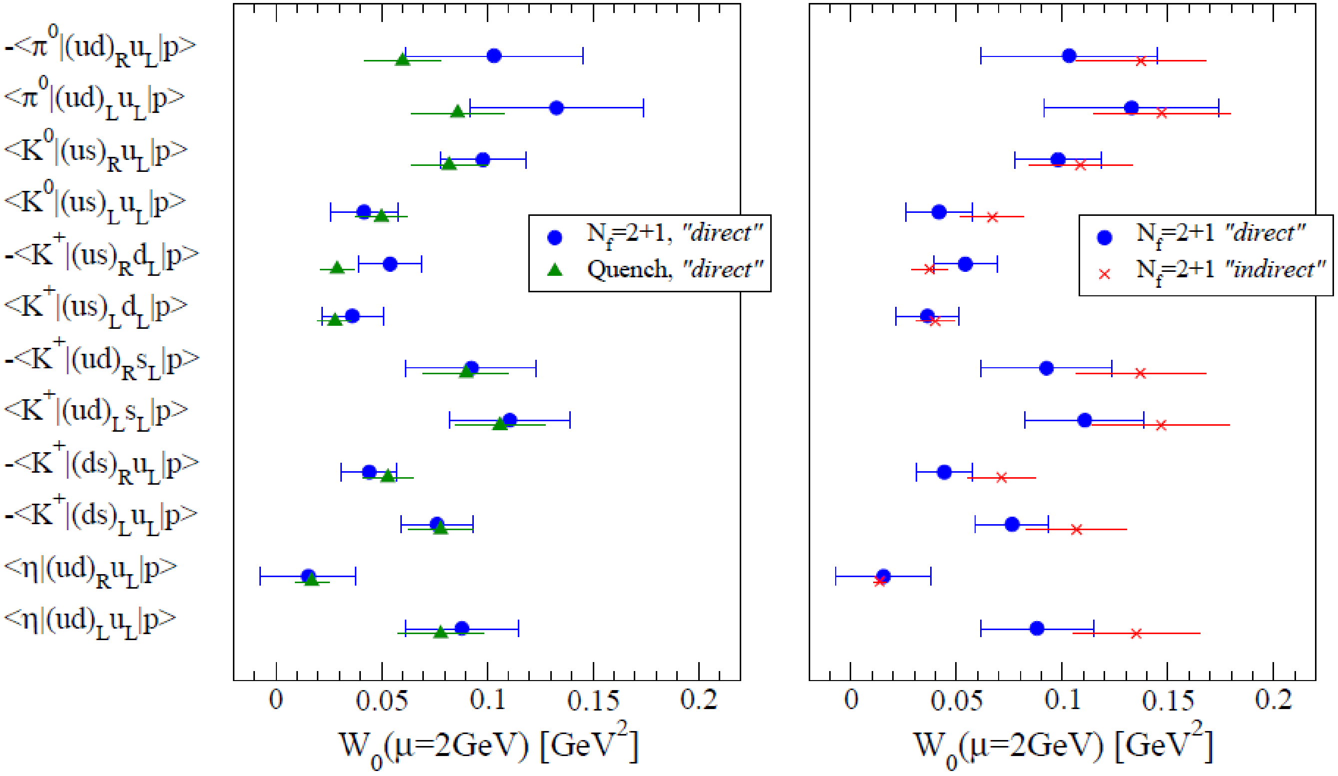
Aoki, ES, Soni, arXiv:1304.7424

- DWFs in Nf=2+1 (direct)

  $24^3 \times 64$ lattice in RBC/UKQCD collaboration,
  Chiral extrapolation with m=0.005, 0.01, 0.02, 0.03 (m_π = 0.3 -- 0.8 GeV)

- Physical kinematics
- Estimate all systematic errors
- Uncertainty is still large.

(stat + sys error):
  30--40% for p→π
  20--40% for p→K



Summary and future work

- Lattice study of nucleon EDM & decay
- Precise estimate of non-perturbative contribution
- Need to reduce the statistical + systematic error
  - Nucelon EDM : > 40% stat. error and large sys. error expected
  - Nucleon decay : p→π channel : 30--40% total error

    p→K channel: 20--40% total error
- AMA algorithm is very helpful. Blum, Izubichi, ES, 1208.4349
- Larger lattice size (~5 fm^3) at physical point will be available soon. We expect *10--20%* error level.

Thank you

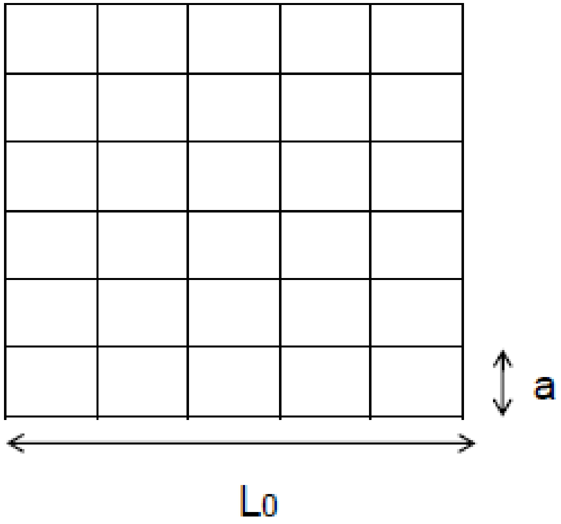
Backup

Lattice QCD

In lattice regularization, the path integral of $\langle O \rangle$ is computed by Monte-Carlo integral:

$$\langle O \rangle = Z^{-1} \int D\Psi \, O(\Psi) e^{-S(\Psi)} \simeq \frac{1}{N} \sum_i O(\Psi_i)$$

- Exact QCD calculation (enough large number of sampling N)
- Gauge invariant
- Translational invariant
- Ultraviolet cut-off *a* (lattice spacing)
  Infrared cut-off $V=L_0^D$ (lattice volume)
- Taking continuum limit, and infinite volume



Lattice QCD

- Hadron spectrum in Nf=2+1 QCD
  - Good agreement with various lattice action and fermion with experimental results !

Kronfeld, 1209.3468