Neutron and proton EDM in $N_f = 2+1$ domain-wall fermion

Eigo Shintani (RIKEN-BNL)

T. Blum and T Izubuchi and A. Soni for RBC/UKQCD collaboration

Outline

- Motivation of lattice calculation of EDM in θ term
- Strategy and method
- (Preliminary) results
- Summary and future work

Motivation

- CP violation (CPV) in QCD and BSM
  - EDM is sensitive to CPV in BSM
    - SM contribution is extremely small, 10^{-33} e・cm
  - Strong CP problem
  - There are many experimental plans of EDM

    pEDM experiment @ BNL,
    nEDM experiment @ ORNL, ILL, FRM-2, FNAL, PSI/KEK/TRIUMF, …
    Charged particle (d, p)EDM @ COSY
    Lepton EDM @ J-PARC, FNAL

    aim to 10^{-29} e・cm (present nEDM limit : $|d_N^{\rm exp}| < 2.9 \times 10^{-26}\,{\rm e}\cdot{\rm cm}$)
  - BSM (like SUSY) predicts ~10^{-27} e・cm
  - Large uncertainty is hadron effect in low-energy scale.
  - Lattice QCD provides important information of BSM prediction.

Nucleon EDM in lattice QCD

- θ term contribution
  - Renormalizable
  - Feasible study toward the BSM (quark EDM and chromo EDM) calculation

    Bhattacharya et al, Lattice 2012, Lattice 2013
  - Nice check of uncertainties in quark model, BChPT
- Some difficulties
  - Statistical noise
    - *Gauge background* (topological charge, sea quark) which are intrinsically noisy.
    - *Disconnected diagram* (flavor singlet) should include (In SU(3) limit this is vanishing. Study including disc. diagram is future work).
  - Systematic study
    - Finite volume effect may be significant. (e.g. BChPT discussion)

      O'Connell, Savage, PLB633, 319(2006), Guo, Meissner, 1210.5887
    - Chiral behavior(d_N~O(m)) is also important check.

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  - Error reduction techniques
    - All-mode-averaging (AMA)
    - Efficient way to reduce the statistical error of correlator

Blum, Izubuchi, ES, arXiv:1208.4349 [hep-lat], ES (lattice 2012)

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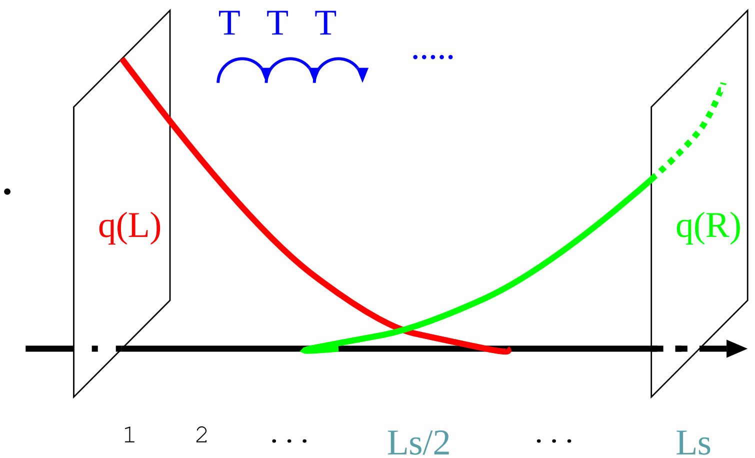
  - EDM form factor
    - Extraction from matrix element including CPV of θ angle
    - Extrapolation into physical kinematics, $-q^2 = 0$ and $m = m_{phy}$

Domain-wall fermion

- Chiral symmetry
  - L, R fermion is localized on boundaries
    ⇒ Chiral symmetry is realized (if $L_s \to \infty$).
  - Remaining good chiral symmetry
    $m_{res} \sim \exp(-L_s)$
  - Reasonable computational cost
- RBC/UKQCD collaboration
  - Generation of $N_f = 2+1$ configurations.
  - Various lattice size, lattice cut-off, quark mass are available.
  - Many studies of Keon physics, nucleon physics, finite temperature , …



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

Error reduction techniques

Blum, Izubuchi, ES, 1208.4349,
ES (lattice 2012),
Chulwoo, plenary on Fri

- Covariant approximation averaging (CAA)
  - For original correlator O, (unbiased) improved estimator is defined as

$$\mathcal{O}^{(\mathrm{imp})} = \mathcal{O}^{(\mathrm{rest})} + \frac{1}{N_G}\sum_{g\in G}\mathcal{O}^{(\mathrm{appx}),g}, \quad \mathcal{O}^{(\mathrm{rest})} = \mathcal{O} - \mathcal{O}^{(\mathrm{appx})}$$

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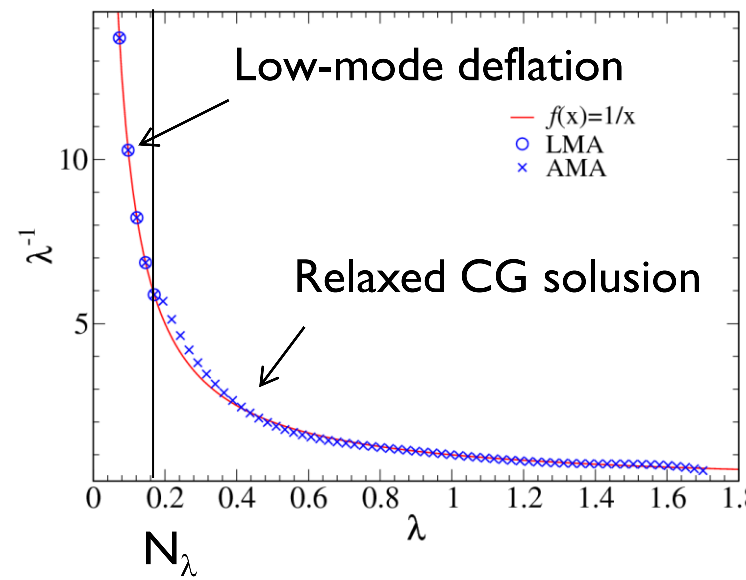
$$\mathcal{O}^{(\mathrm{appx})} = \mathcal{O}[S_l],\ S_l = \sum_{\lambda=1}^{N_\lambda} v_\lambda v_\lambda^\dagger \frac{1}{\lambda} + P_n(\lambda)|_{|\lambda|>N_\lambda}$$



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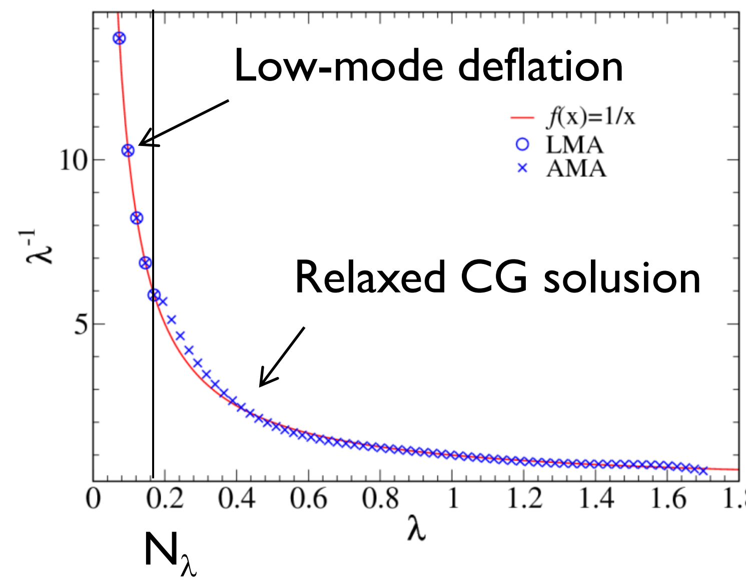
  - $P_n(\lambda)$ is polynomial approximation of $1/\lambda$
    - Low mode part : # of eigen mode
    - Mid-high mode : degree of poly.



EDM Form factor

ES, et al., Phys. Rev. D72, 014504 (2005),
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- EM Matrix element

$$\langle n(P_1)|J_\mu^{\rm EM}|n(P_2)\rangle_\theta = \bar{u}_N^\theta \Big[\underbrace{\frac{F_3^\theta(Q^2)}{2m_N}\gamma_5\sigma_{\mu\nu}Q_\nu}_{\text{P,T-odd}} + \underbrace{F_1\gamma_\mu + \frac{F_2}{2m_N}\sigma_{\mu\nu}Q_\nu}_{\text{P,T-even}} + \cdots \Big] u_N^\theta$$

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$$\sum_s u_N^\theta(s)\bar{u}_N^\theta(s) = \frac{ip\cdot\gamma + m_N e^{i\alpha_N^\theta\gamma_5}}{2E_N}$$

CPV phase α_N in nucleon propagator

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$$\langle 0|\eta_N(t_1)J_\mu^{\rm EM}(t)Q\bar{\eta}_N(t_0)|0\rangle$$

Computation

$$= \frac{\alpha_N}{2}\gamma_5\left[F_1\gamma_\mu + F_2\frac{q_\nu\sigma_{\mu\nu}}{2m_N}\right]\frac{ip\cdot\gamma + m_N}{2E_N} + \frac{1+\gamma_4}{2}\left[F_1\gamma_\mu + F_2\frac{q_\nu\sigma_{\mu\nu}}{2m_N}\right]\frac{\alpha_N}{2}\gamma_5$$

Subtraction

$$+\frac{1+\gamma_4}{2}\left[F_3\frac{q_\nu\gamma_5\sigma_{\mu\nu}}{2m_N} + F_A(iq^2\gamma_\mu\gamma_5 - 2m_N q_\mu\gamma_5)\right]\frac{ip\cdot\gamma + m_N}{2E_N}$$

Extraction

EDM Form factor

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Extraction

- Subtraction of CP-odd phase, α_N, in n propagator and CP-even part $F_{1,2}$

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

Parameters

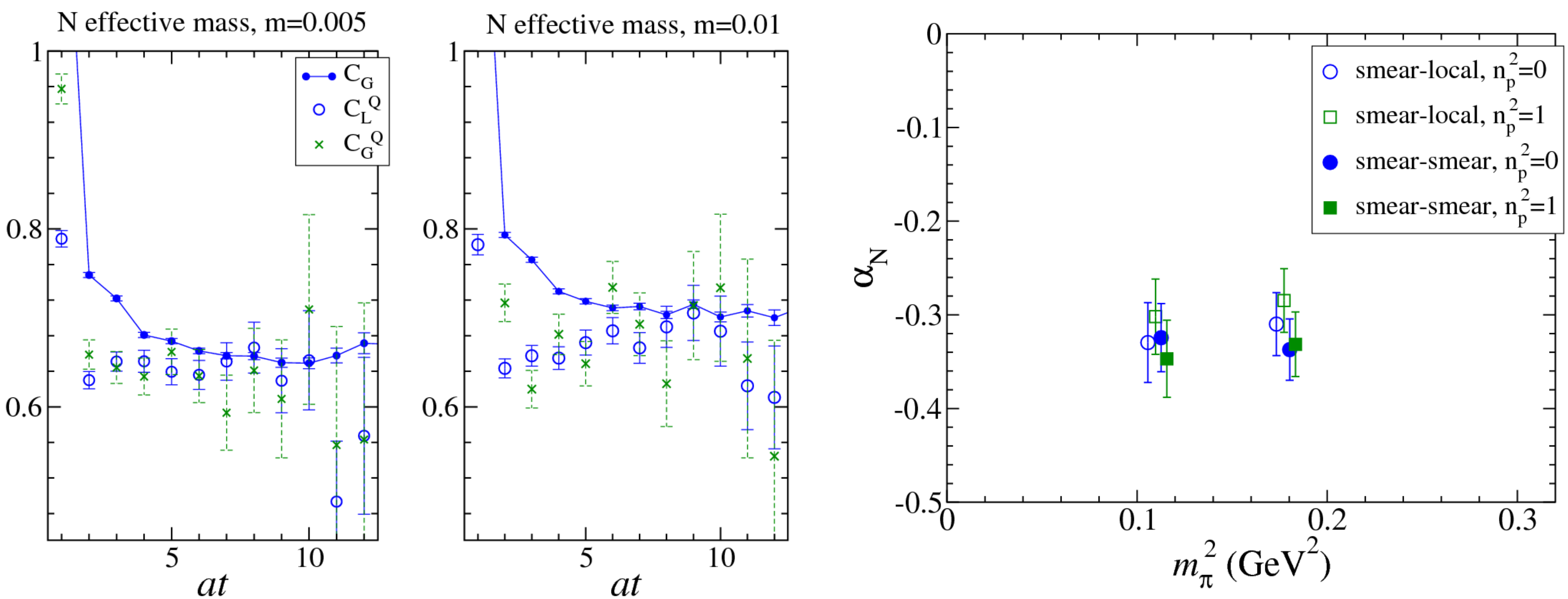
- DWF
  - $24^3 \times 64$ lattice, a^{-1} = 1.73 GeV (~3 fm^3 lattice)
  - L_s = 16 and am_{res} = 0.003
  - m = 0.005, 0.01 corresponding to m_π = 0.33, 0.42 GeV
  - Two temporal separation of N sink and source in 3 pt. function
    t_{sep} = 12 (t_{source} = 0, t_{sink} = 12), t_{sep} = 8 (t_{source} = 0, t_{sink} = 8)
  - # configs = 751 (m=0.005), 700 (m=0.01) [t_{sep} = 12]
    # configs = 180 (m=0.005) [t_{sep} = 8]
- AMA
  - # of low-mode : N_λ = 400 (m=0.005), 180 (m=0.01)
  - Stopping condition, $|r| < 0.003$
  - N_G = 32 (2 separation for spatial, 4 separation for temporal direction of source localtion) → effectively $O(10^4)$ statistics

α_N

- Projection with γ_5 for 2 pt with Q charge, global fitting with

$$\mathrm{tr}\left[\gamma_5\langle N(t)\bar{N}(0)Q\rangle\right] = Z_N \frac{2m_N}{E_N}\alpha_N e^{-E_N t} + O(e^{-E_{N^*}})$$

- By using AMA, this factor is determined within15 % error.
- It does not depend on smearing and momentum, but mass dependence is not so clear.



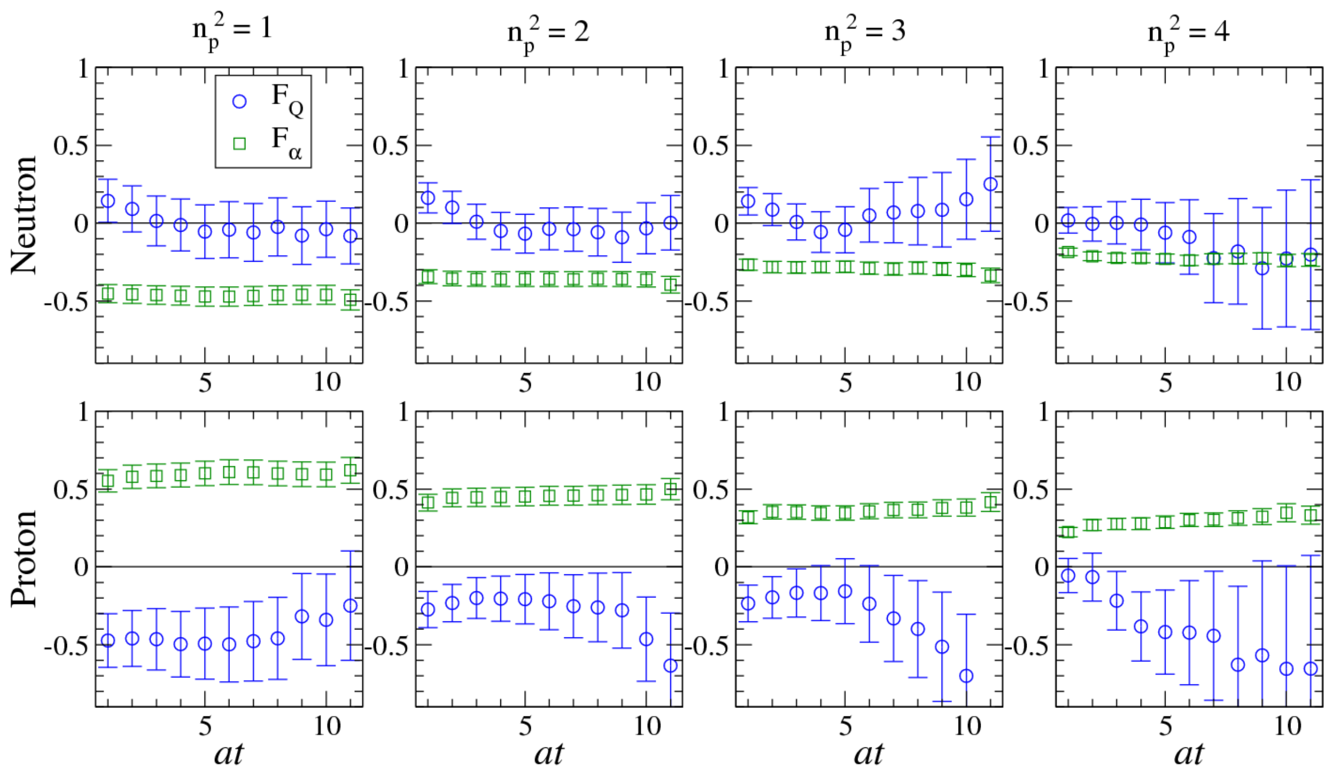
3. (Preliminary) Results

Subtraction term and 3pt function

- Splitting EDM form factor into two parts:

$$F_3 = F_Q + F_\alpha,\ F_Q = C(m_N)\langle N J_t^{\mathrm{EM}} \bar{N} Q\rangle,\ F_\alpha = F(\alpha_N, F_{1,2})$$

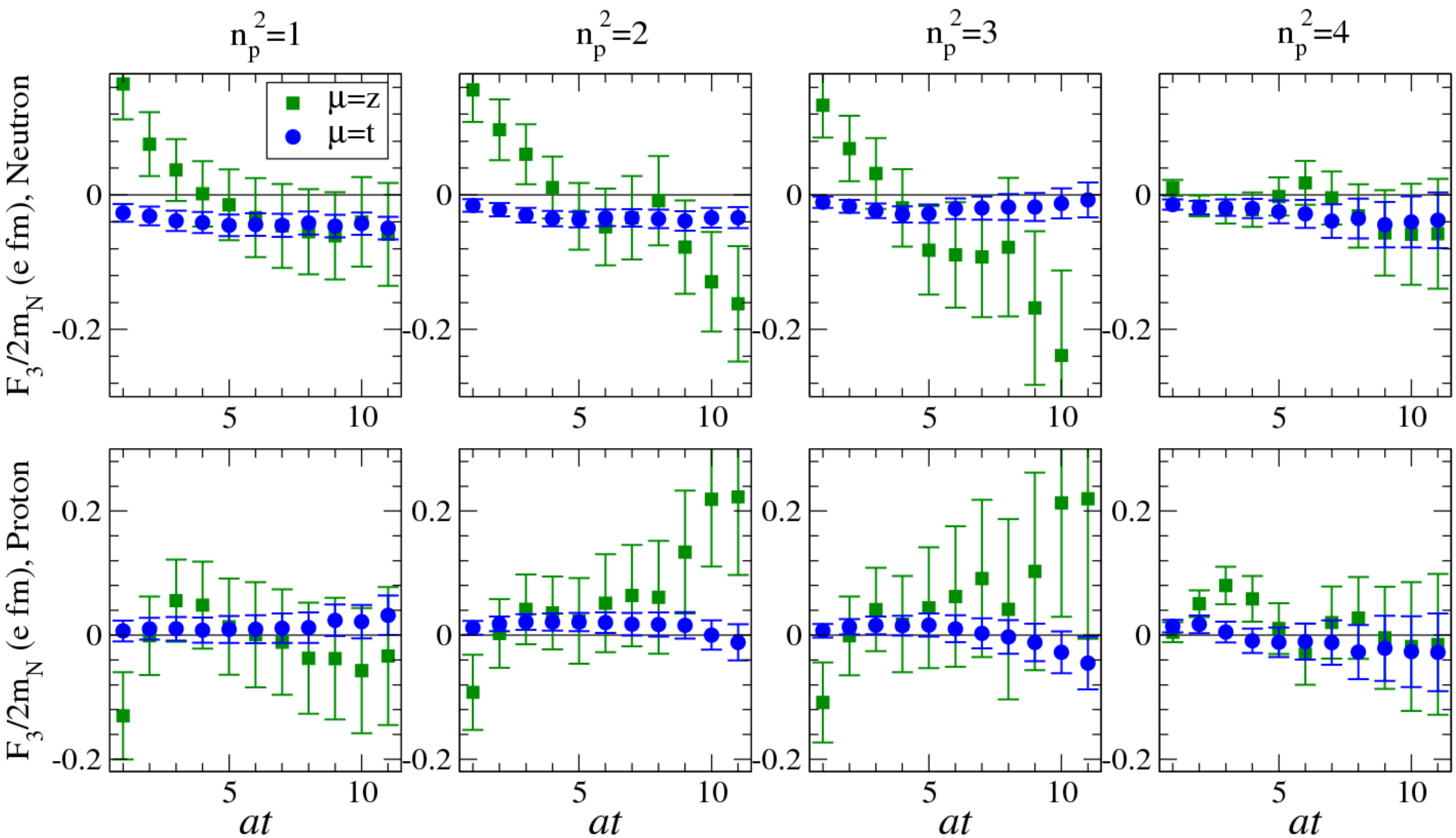
- F_α is good precision, and fluctuation of F_Q is large.



3. (Preliminary) Results

Comparison with μ = t, z

- EDM form factor is given from two directions of EM current
- Two signals are consistent, and data in t direction is much stable.

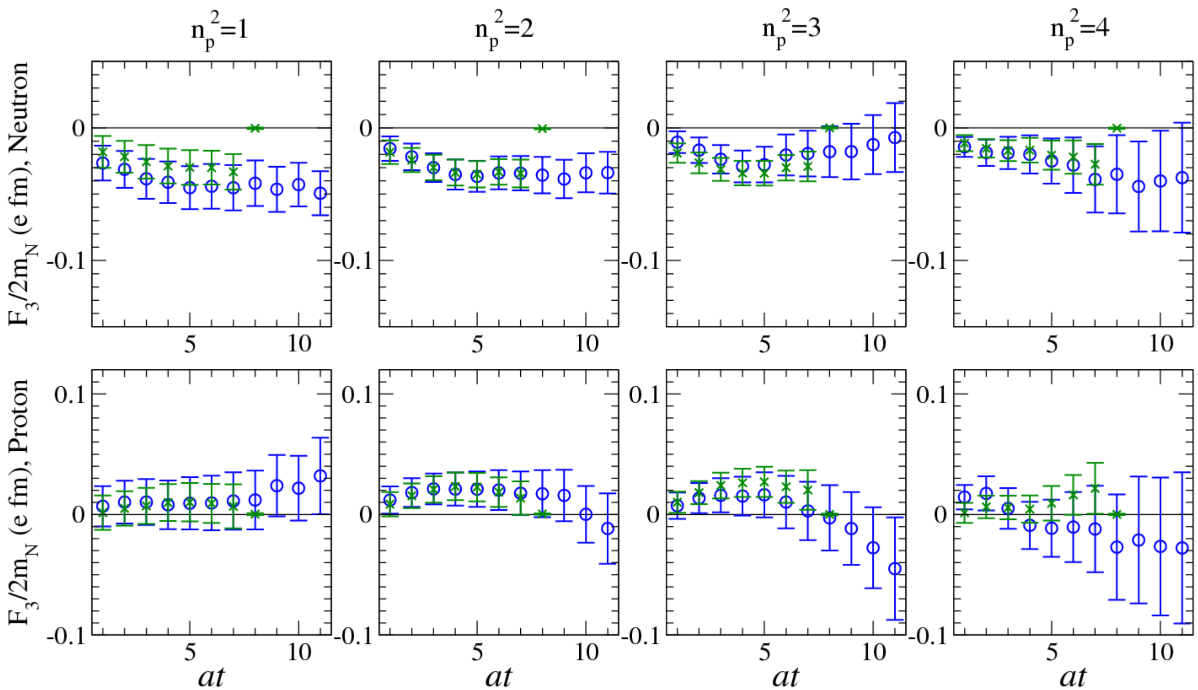


Comparison with different t_{sep}

- The sink and source separation in 3pt function enables us to control the statistical noise and excited state contamination
  - Short: statistical fluctuation < excited state contamination
  - Long: statistical fluctuation > excited state contamination
- Comparison

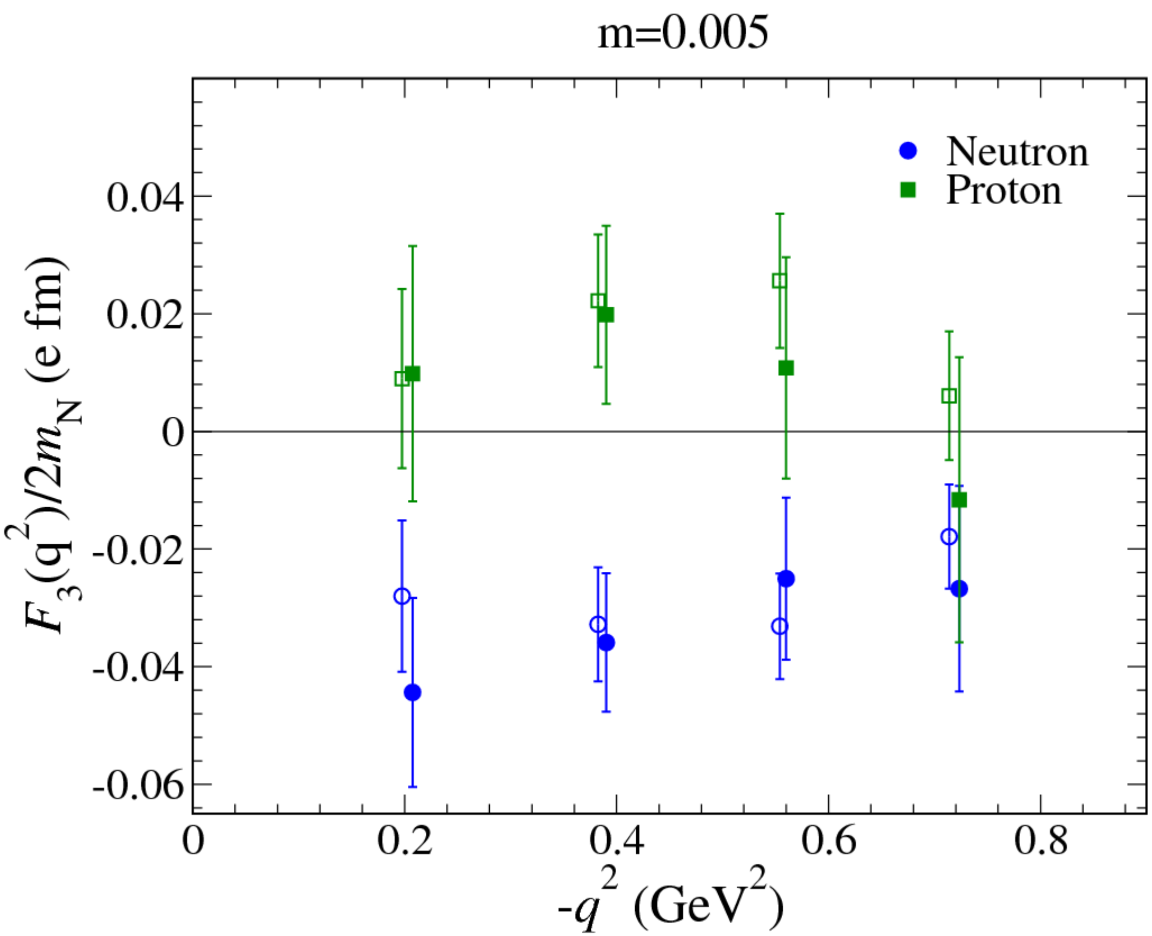
t_{sep} = 12 (blue),
[N_{conf} = 751]
t_{sep} = 8 (green)
[N_{conf} = 180]

- Good consistency between them.
- Precision in t_{sep}=8 is much better.



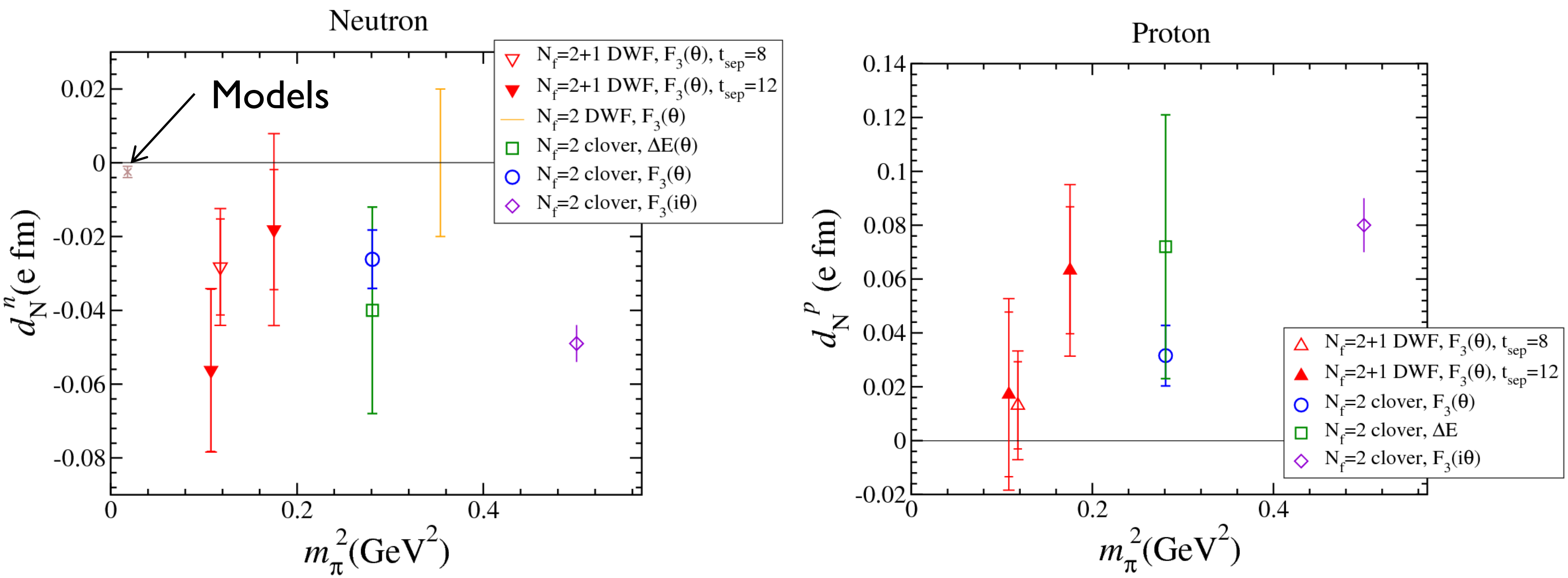
$-q^2 = 0$ extrapolation

- Fitting data of EDM form factor at each momenta.
- Open(t_{sep} = 8), filled (t_{sep} = 12)
- Fitting function
  3 point linear :
  $-q^2 < 0.55$ GeV^2
  2 point linear:
  $-q^2 < 0.4$ GeV^2
- Estimate of systematic error of extrapolation



Mass dependence

- Comparison with full QCD results
  - DWF results are in the lightest quark mass.
  - Statistical error is dominant rather than systematic one.
  - Central value is 10 times larger than models.



Statistical error

- Comparison between AMA error reduction and number of configurations.
- Number of configurations : reduce stat. error and relating to Q distribution

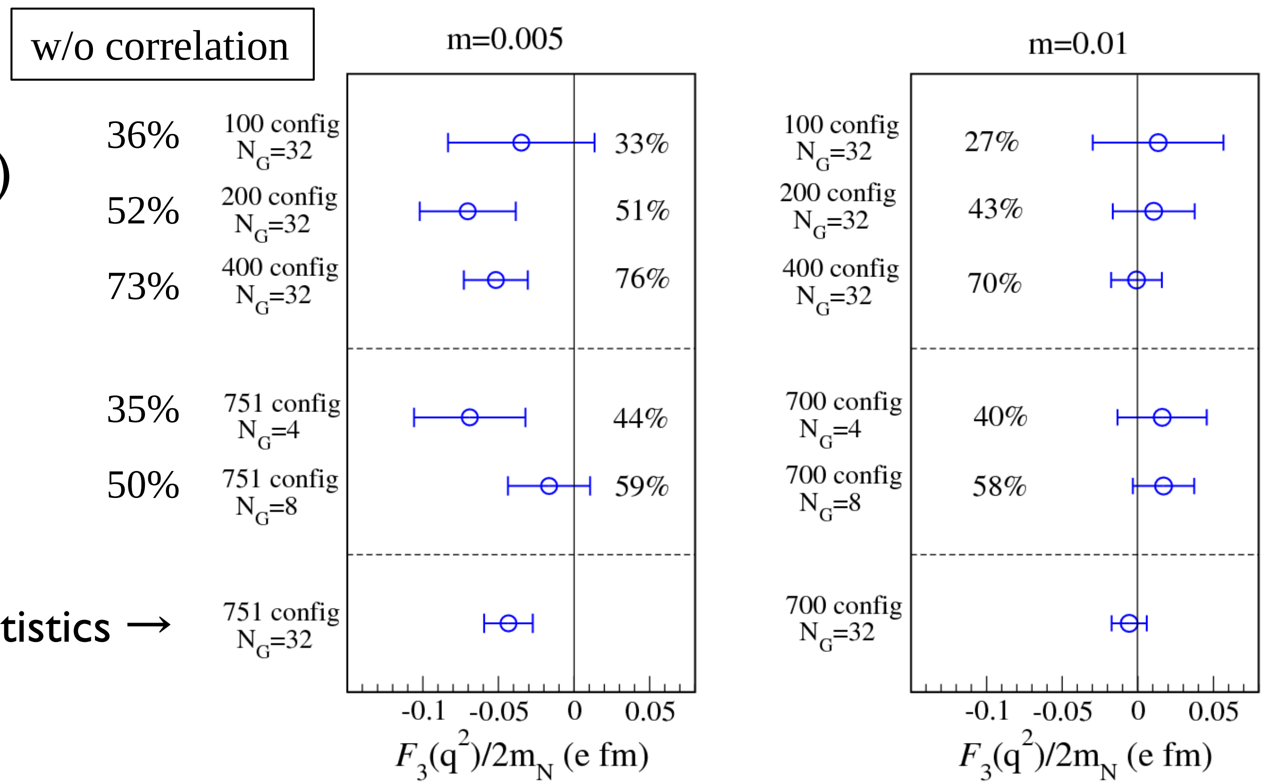
  AMA error reduction : reduce stat. error
- ?? % :

  Error rate

  = Error(full)/Error(N)
- AMA works well
- Reduction rate when

  increase of confgs.

  is slightly better.



Full statistics →

Summary and future plan

- Nucleon EDM in N_f = 2+1 DWF in θ vacuum
  - Signal of EDM within 40% statistical error using AMA techniques.
  - 3-pt function is still noisy.
  - Short t_{sep} allows us to reduce the statistical error without large excited state contamination effect.

Summary and future plan

- Nucleon EDM in N_f = 2+1 DWF in θ vacuum
  - Signal of EDM within 40% statistical error using AMA techniques.
  - 3-pt function is still noisy.
  - Short t_{sep} allows us to reduce the statistical error without large excited state contamination effect.
- (Near) physical point of DWF configurations
  - Ensembles near physical points and large volume are available.
  - AMA with Möbius-DWF approximation is helpful.
  - Remove chiral extrapolation → less than 10% precision

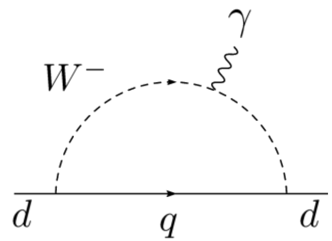
Lattice size	Physical size	*a*	L_s	Gauge action	Pion mass
$32^3 \times 64$	4.6 fm^3	0.135 fm	32	DSDR	171 -- 241 MeV
$48^3 \times 96$	5.5 fm^3	0.115 fm	16	Iwasaki	135 MeV

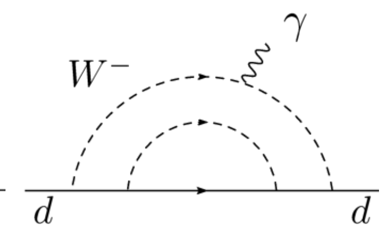
Thank you for your attention !

Backup

Nucleon EDM in the SM

- CKM phase in EDM
  - No CPV phase in 1-loop ($|V_{dq}|^2$: no phase) and 2-loop diagram (unitarity).



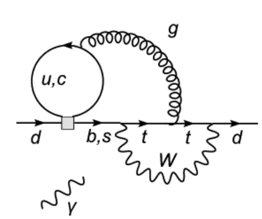


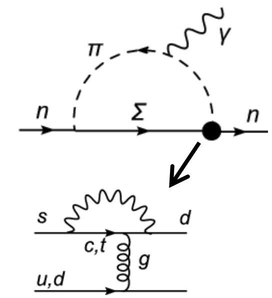
  - Three-loop order(short) or pion loop correction (long)

$$d_N^{\mathrm{KM\,short}} \sim -10^{-34}\,\mathrm{e\cdot cm}, \quad d_N^{\mathrm{KM\,long}} \sim 10^{-30}\text{–}10^{-32}\,\mathrm{e\cdot cm}$$

$$\Rightarrow d_N^{\mathrm{KM}} = d_N^{\mathrm{KM\,short}} + d_N^{\mathrm{KM\,long}} \simeq 10^{-30}\text{–}10^{-32}\,\mathrm{e\cdot cm}$$

6-order magnitude below the experimental upper limit.





- θ term in the QCD Lagrangian

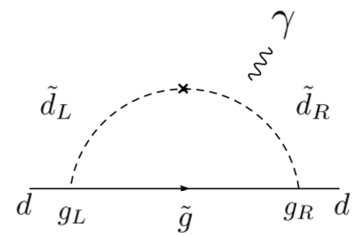
Renormalizable and CP-violating from in topological charge density.

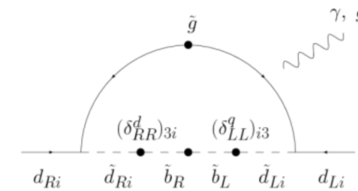
$$\mathcal{L}_\theta = \bar{\theta}\frac{1}{64\pi^2}G\widetilde{G}, \quad \bar{\theta} = \theta + \arg\det M, \quad \arg\det M \sim \eta\frac{m_u m_d m_s}{m_u m_d + m_d m_s + m_s m_u}$$

  - θ term has been estimated as $\bar{\theta} < 10^{-9\pm1}$ Crewther, et al. (1979), Ellis, Gaillard (1979)
  - Unnatural cancellation (strong CP problem)

Nucleon EDM in the BSM

- Possible higher dimension operators
  - In supersymmery (SUSY) model there is CPV phase from 1-loop ($\mathrm{Im}(g_L\, g_R^*)\neq 0$)





  - CPV effective Hamiltonian with higher dimension than θ term

$$H_{C\!\!\!/P} = \sum_k C_k(\mu)\,\mathcal{O}_k$$

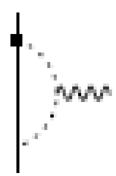
$$\mathcal{O}_{\rm qEDM} = d_q \bar{q}(\sigma\cdot F)\gamma_5 q$$: Quark-photon (5-dim)

$$\mathcal{O}_{\rm cEDM} = d_q^c \bar{q}(\sigma\cdot G)\gamma_5 q$$: Quark-gluon (5-dim)

$$\mathcal{O}_{\rm Weinberg} = d^G GG\widetilde{G}$$: Pure gluonic (6-dim)

  - Contribution to nEDM in low energy model

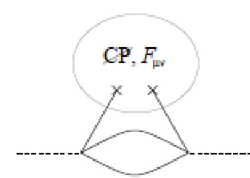
BChPT:



…

Mereghetti, Vries, Hockings, Maekawa, Kolck, Timmermans, ...

QCD sum rule:



…

Pospelov, Ritz, Hisano, Shimizu, Nagata, Lee, Yang, …

$$d_N = d_N^{\rm QCD}\bar{\theta} + d_N(d_q, d_q^c) + d_N(d^G)$$

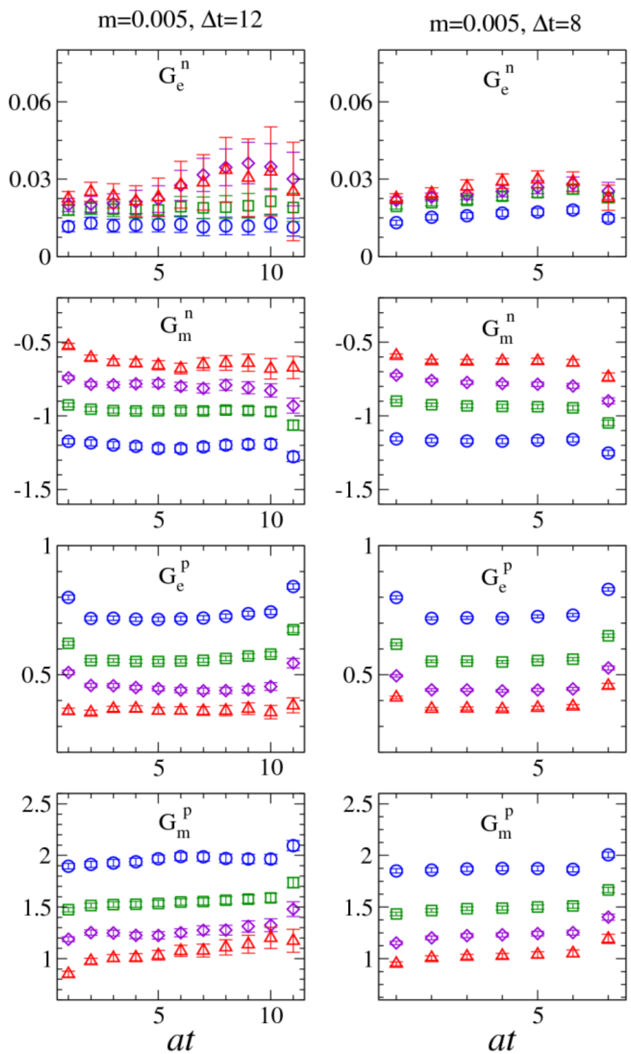
$$\sim 10^{-17}[\mathrm{e\cdot cm}]\bar{\theta} + (1.4\text{–}0.47)d_d - (0.12\text{–}0.35)d_u + O(10^{-2})d_q^c \sim O(10^{-25}\text{–}10^{-27})\,\mathrm{e\cdot cm}$$

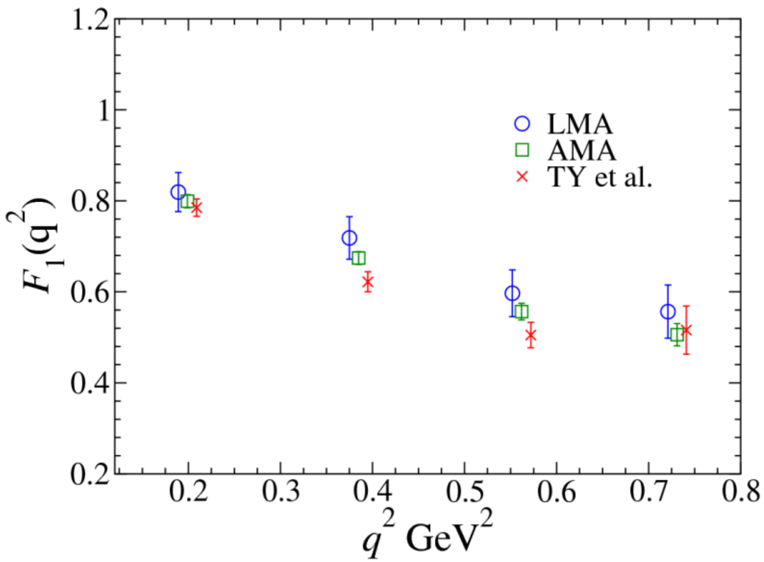
Hisano, Shimizu (04), Ellis, Lee, Pilaftsis (08), Hisano, Lee, Nagata, Shimizu (12)

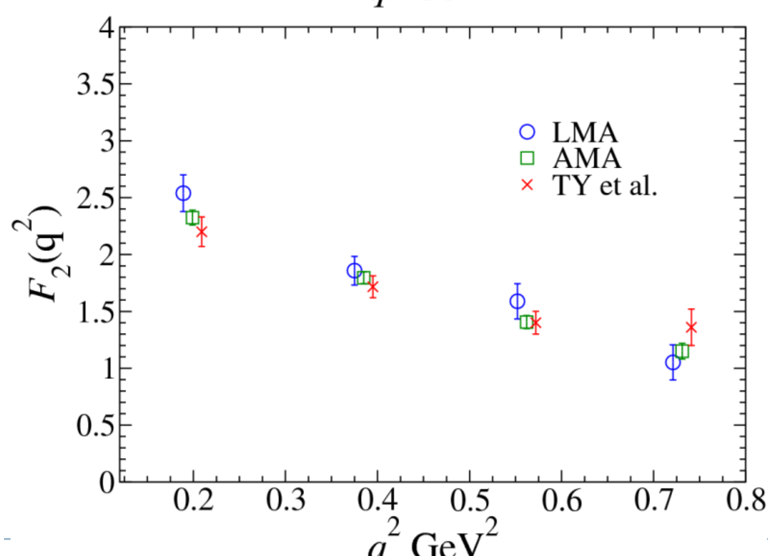
Lattice methods on EDM

- Spectrum method
  1. S. Aoki and A. Gocksch, Phys. Rev. Lett. 63, 1125 (1989).
  2. S. Aoki, A. Gocksch, A. V. Manohar, S. R. Sharpe, Phys. Rev. Lett. 65, 1092 (1990), in which they discussed about the possible lattice artifact in ref.1 results
  3. ES, et al., for CP-PACS collaboration, Phys. Rev. D75, 034507 (2007)
  4. ES, S. Aoki, Y. Kuramashi, Phys. Rev. D78, 014503 (2008)
- Form factor
  1. ES, et al., for CP-PACS collaboration, Phys. Rev. D72, 014504 (2005).
  2. Berruto, et al. for RBC collaboration, Phys. Rev. D73, 05409 (2006).
  3. ES et al., Lattice 2008.
- Imaginary θ
  1. T. Izubuchi, Lattice 2007.
  2. Horsley et al., arXiv:0808.1428 [hep-lat]

EM form factor

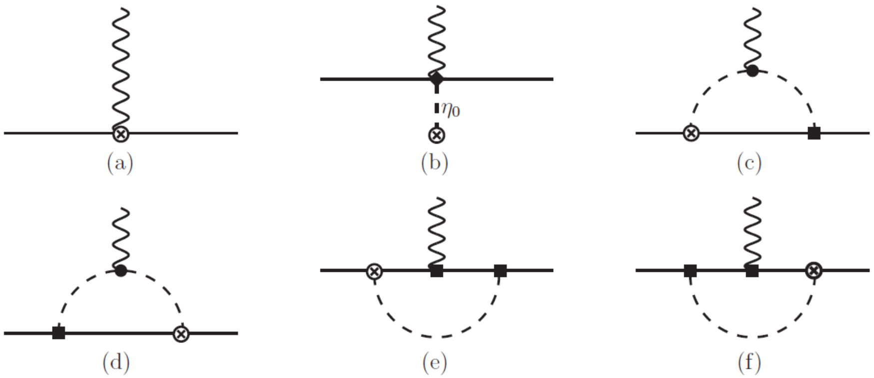






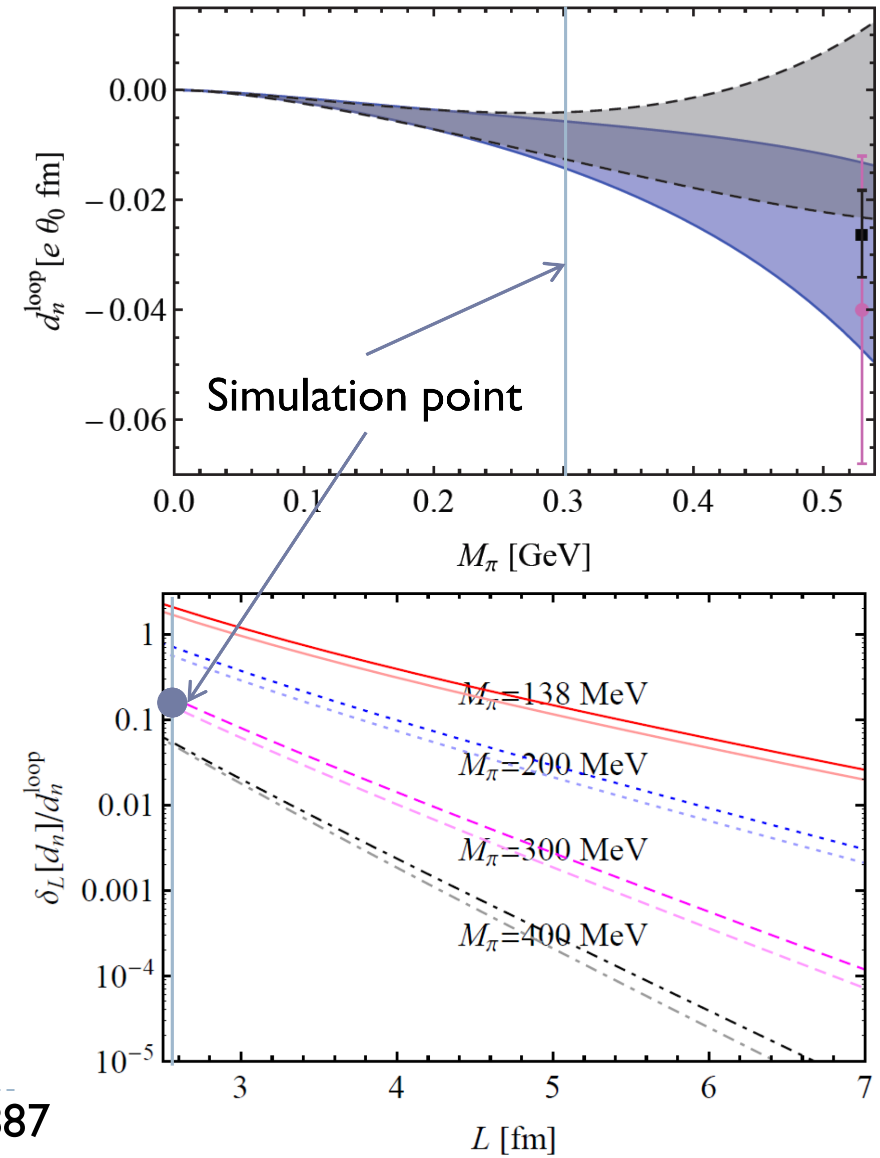
Volume effect ?

- BChPT analysis



$\otimes$ CP violating coupling

In LO, NLO BChPT analysis, there may be more than 20% finite size effect.



Guo, Meissner, 1210.5887