Nucleon structure study in domain wall fermion for physics beyond the standard model; chromo-electric dipole moment, proton decay operator, and (axial) vector form factor

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Our goal

Understand nucleon structure and probe BSM physics

(i) Nucleon vector and axial-vector form factors

(ii) Proton decay matrix element

(iii) Electric dipole moments induced by quark chromo-electric dipole moments

We measure nucleon matrix elements using 2+1 flavor of chirally-symmetric domain wall fermions.

For (i) form factor, and (ii) proton decay matrix elements,

we compute them at the physical point (m_π=140MeV) on $48^3 \times 96$ lattice (Lm_π=3.86).

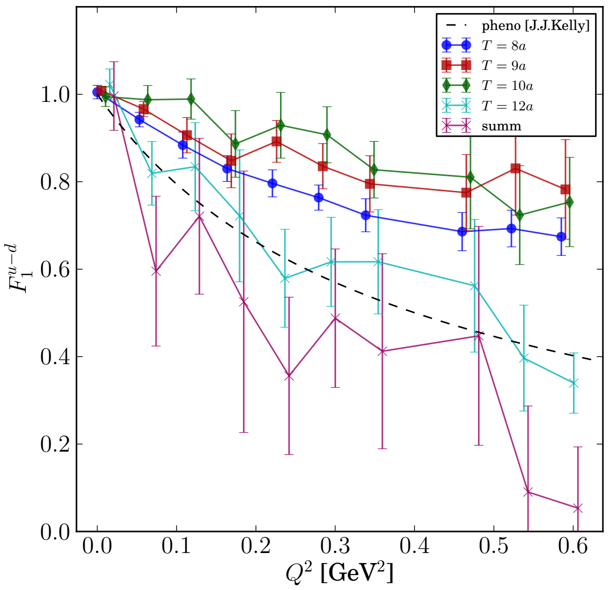
For (iii) we compute it on $32^3 \times 64$ lattice ($m_\pi \sim$ 170 MeV) and take a chiral extrapolation.

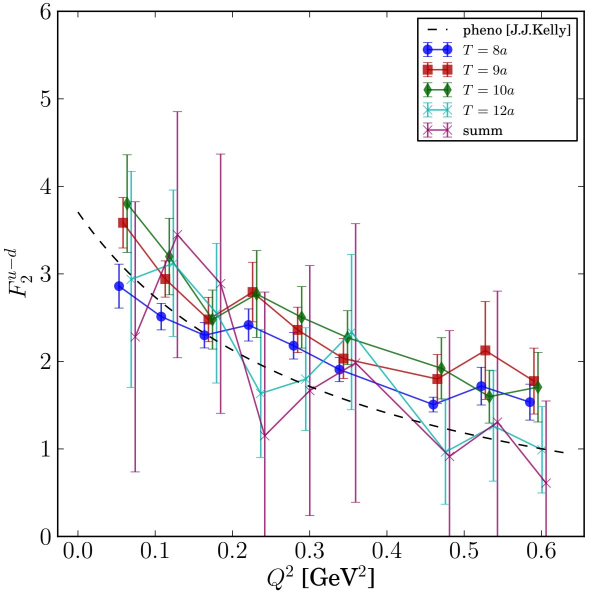
Gauge ensembles are generated by RBC/UKQCD collaborations.

Electromagnetic form factor of Nucleon

$$\langle N|V_\mu^{EM}|\bar{N}\rangle = F_1(q^2)\gamma_\mu + \frac{iF_2(q^2)}{2m_N}\frac{\sigma_{\mu\nu}}{2}q_\nu$$

2+1 Mobius DWF, Physical point, 48 x 96 (a=0.114 fm, Lmπ=3.86)





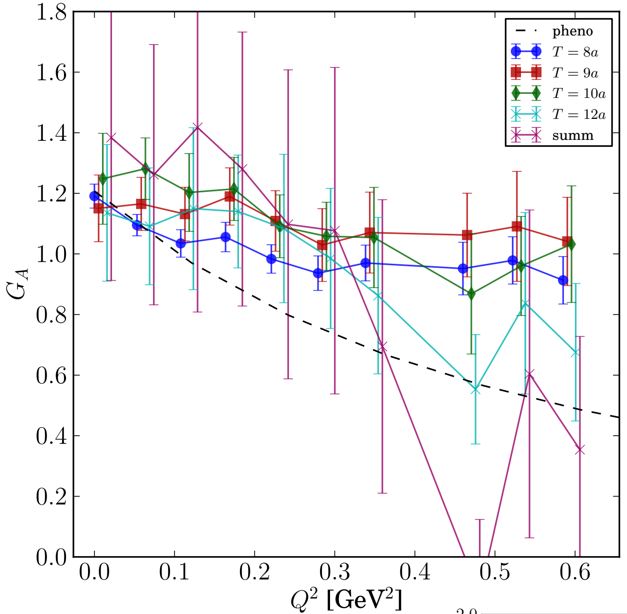
[Sergey, et al. 2015]

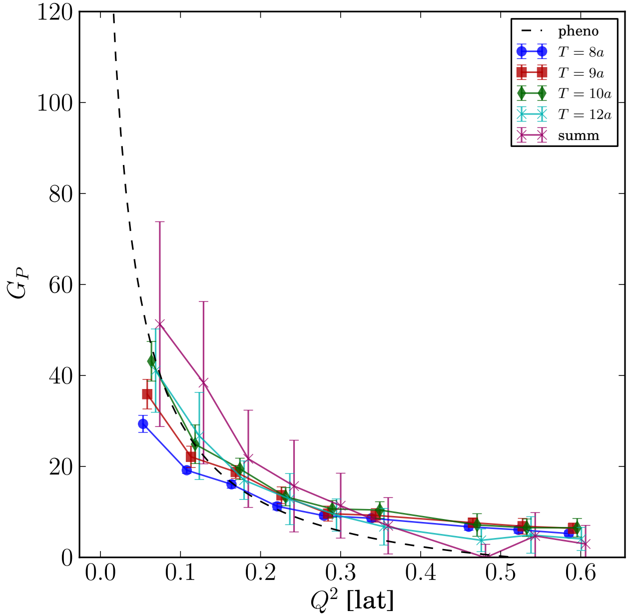
No disconnected diagram calculation, statistics is not good.

A large excited state contamination is observed.

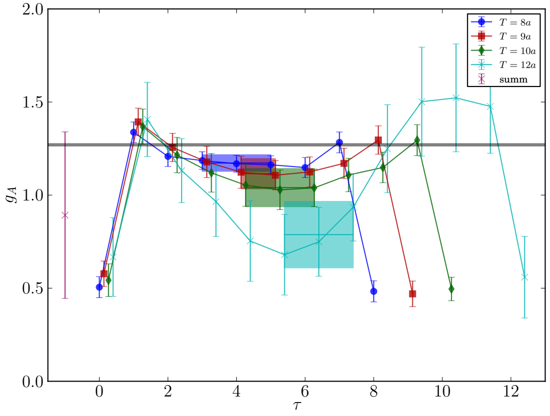
Axial form factor of Nucleon

$$\langle N|A_\mu^{EM}|\bar{N}\rangle = G_A(q^2)\gamma_\mu\gamma_5 + \frac{iG_P(q^2)}{2m_N}\gamma_5 q_\nu$$





$$g_A = G_A(0)$$



[Sergey, et al. 2015]

The axial charge radius is an important parameter for precision measurement of neutrino scattering off nucleons.

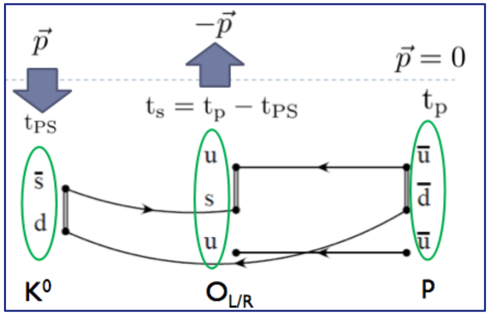
Statistical improvement for Nucleon form factor

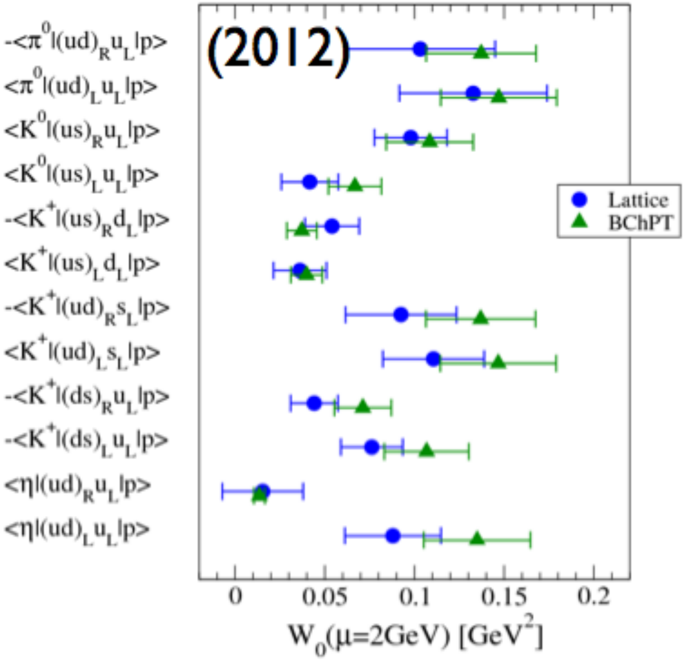
Increase # of Eigenvectors, in all-mode averaging AMA,
500 [Blum, et al. 2013] -> 2,000
# of measurement per configs. 32 -> 32 x 4 (coherent) = 128
# of configs 20 -> 100
(We use coherent sequential trick [LHP, K. Orginos, et al.])

Goal : 4% statistical error on gA and 10% axial charge radius at the physical point.
Having 3 different time separations between sink & source,
we will carry out a careful study of the excited state contamination.
Finite size correction should be sufficiently small compared to the target nucleon quantities ($m_\pi L = 3.86$).

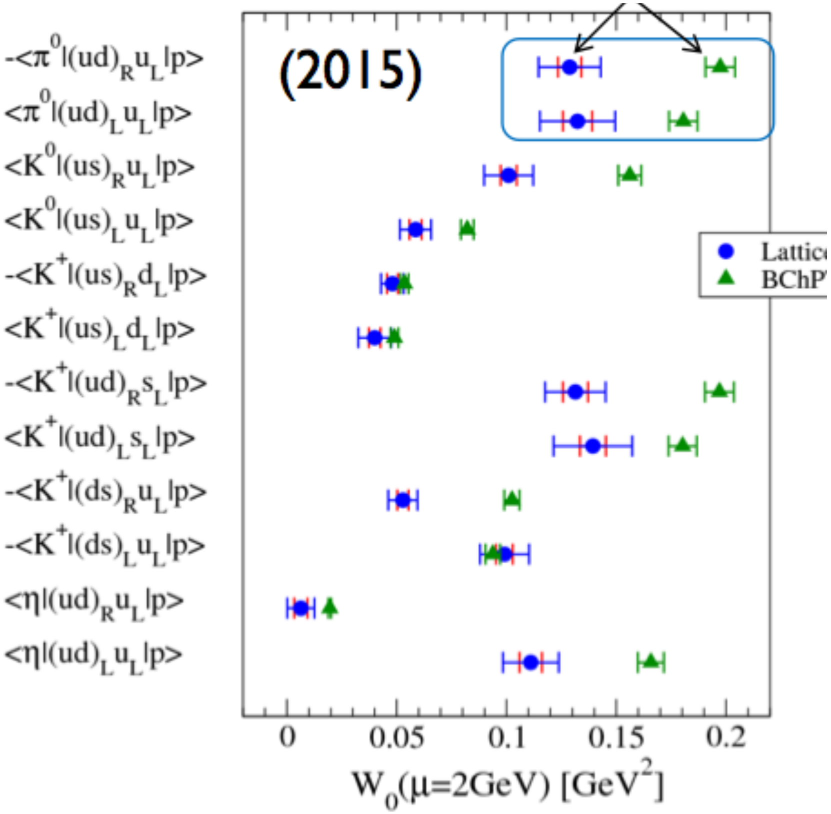
2.Proton decay matrix elements

[E. Shintani, et al.]





Update



Calculation done on Mπ >= 300 MeV, extrapolated linearly in quark mass and q^2 .
Calculation @ M_π=140 MeV is proposed. The chiral bag model's prediction of orders of magnitude suppression at a small quark mass [A. Martin and G. C. Stavenga, 2012]

3. Nucleon EDM matrix elements

We will calculate these nucleon matrix element for CP-odd operators

$$\mathcal{L} = d^{\mathrm{qEDM}}\bar{q}(\sigma\cdot F)\gamma_5 q + d^{\mathrm{cEDM}}\bar{q}(\sigma\cdot G)\gamma_5 q + \cdots$$

$$\mathcal{L} = \frac{\bar{\theta}}{64\pi^2}G\tilde{G}, \qquad \bar{\theta} = \theta + \arg\det \mathrm{M}$$

Our primary target : chromo EDM (cEDM) nucleon matrix element

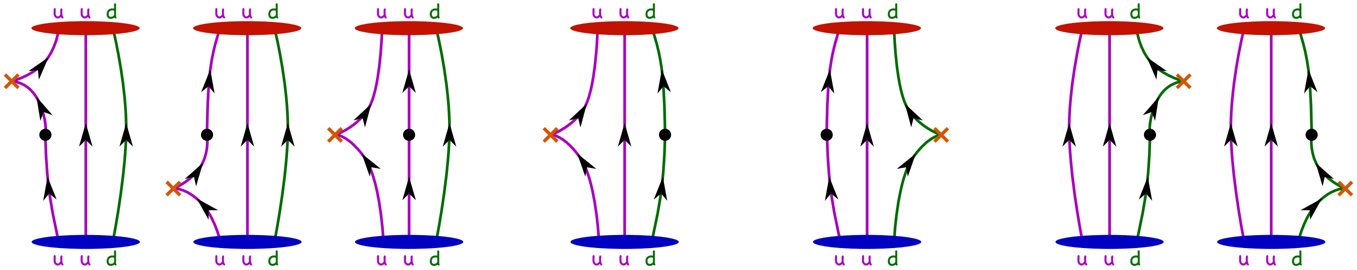
The cEDM is a low-energy effective interaction which is induced by BSM physics
The (c)EDM may be in the discovery reach of future EDM measurement experiments.

DWF : Chiral symmetry is very important
No mixing with mass-proportional chromo-magnetic dipole (clover) term
c.f. Wilson fermions

We will calculate 4-point function with cEDM operator and electromagnetic current (9 different types of diagrams)

$$C_{4pt}(T,t,0) = \langle N(T)|J_\mu^{EM}(t)\left(\int d^4x\bar{q}G_{\nu\rho}\sigma^{\nu\rho}\gamma_5 q\right)|N(0)\rangle$$

$$\langle u_N(p')|J^\mu|u_N(p)\rangle_{C\not{P}} = \gamma^\mu F_1(q^2) + \sigma^{\mu\nu}q_\nu\frac{F_2(q^2)}{2m_N} + i\gamma_5\frac{\sigma^{\mu\nu}q_\nu}{2m_N}F_3(q^2)$$



$\mathcal{B}_u(\sigma\tilde{G})\mathcal{C}_{(u)}$ $\mathcal{E}_u(\sigma\tilde{G})\mathcal{F}_{(u)}$ $\mathcal{G}_{u|J_u}(\sigma\tilde{G})\mathcal{F}_{(u)}$ $\mathcal{G}_{u|J_d}(\sigma\tilde{G})\mathcal{F}_{(u)}$ $\mathcal{G}_{d|J_u}(\sigma\tilde{G})\mathcal{F}_{(d)}$ $\mathcal{B}_d(\sigma\tilde{G})\mathcal{C}_{(d)}$ $\mathcal{E}_d(\sigma\tilde{G})\mathcal{F}_{(d)}$

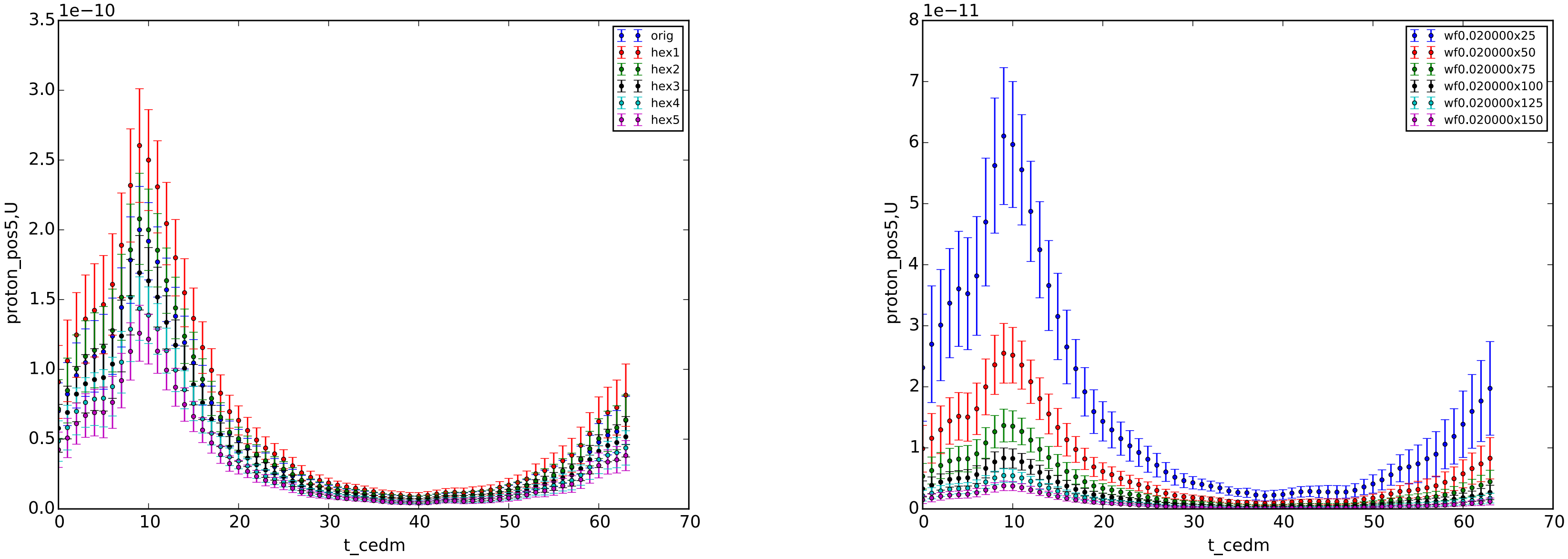
We use sequential-source for propagators for cEDM insertions (X)
and EM current (●).
For cEDM three- and four- point functions, we have cross-checked against background method with quark propagator

$$D^{-1} \to (D+\epsilon\mathcal{O})^{-1} \sim D^{-1} - \epsilon D^{-1}\mathcal{O}D^{-1}$$

Preliminary study : CP mixing angle (α) induced by cEDM operator

$$\sum_s u_N(p,s)\bar{u}_N(p,s) = E_N\gamma_0 - i\vec{p}\vec{\gamma} + m_N e^{i\alpha\gamma_5}$$

$$\mathrm{Tr}\frac{1+\gamma_t}{2}\gamma_5\left\langle N(T)\sum_x O_{\mathrm{cEDM}}(x)\bar{N}(0)\right\rangle \propto \alpha$$



Test of cEDM operator smearing.
cEDM operator insertion time (t_cedm) dependence of Nucleon 2pt function.
Left: HEX smearing, Right: Wilson flow smearing
t_source=0, t_sink=8

Preliminary study : CP mixing angle (α) induced by cEDM operator

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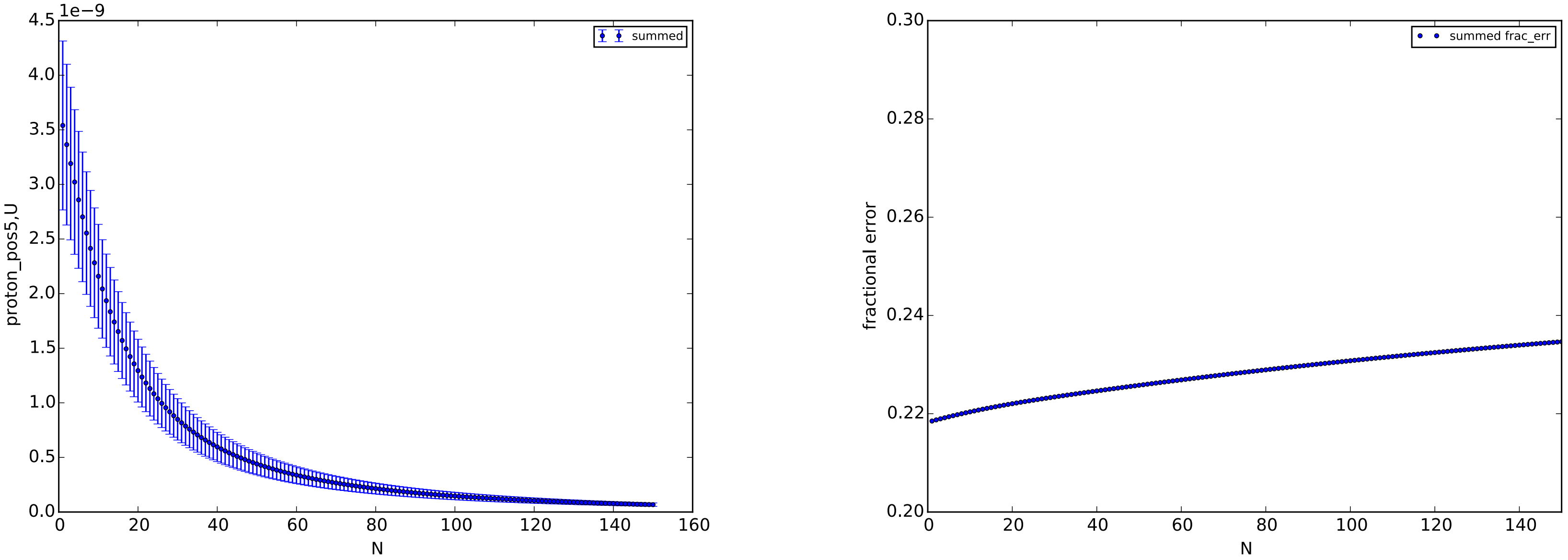


$$(t_{WF} = 0.02 \times N)$$

Wilson flow time dependence of total result and its error.

Ongoing calculation: current USQCD allocation,

2+1 DWF, 32x64, 170 MeV pion ensemble

Study of the renormalization scheme using Wilson flow is underway.

zMobius acceleration of chiral fermions

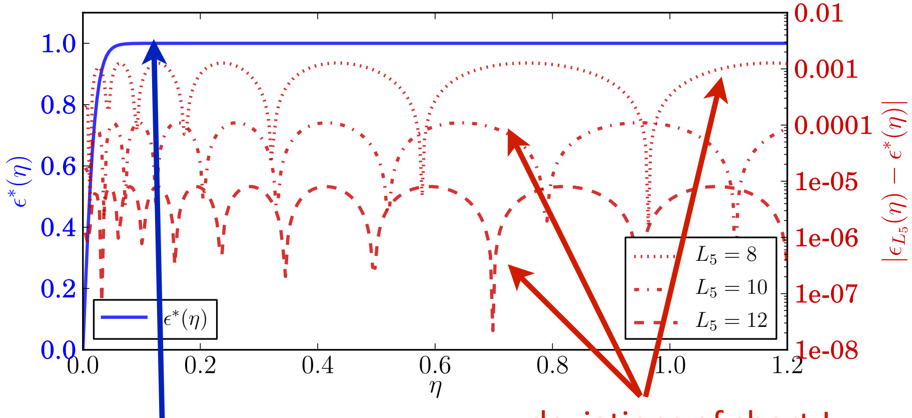
Effective 4d "overlap" operator

$$\bar{\Psi}_L\left(1+\gamma_5\,\mathrm{sign}_{L_5}\left[\mathcal{H}_W\right]\right)\Psi_L+\mathrm{h.c}$$

$$\mathrm{sign}_{L_5}(\mathcal{H}_W)\approx\frac{\prod_s(1+\alpha_s\mathcal{H}_W)-\prod_s(1-\alpha_s\mathcal{H}_W)}{\prod_s(1+\alpha_s\mathcal{H}_W)+\prod_s(1-\alpha_s\mathcal{H}_W)}$$

Mobius: Choose s-dependent α_s for MinMax polynomial
[R.Brower, H.Neff, K.Orginos (2006)]

zMobius: approximate sea operator with complex α_s and the shortest L_5=8...12 possible
[T. Blum, T.Izubuchi, S. Syritsyn, *in prep.*]



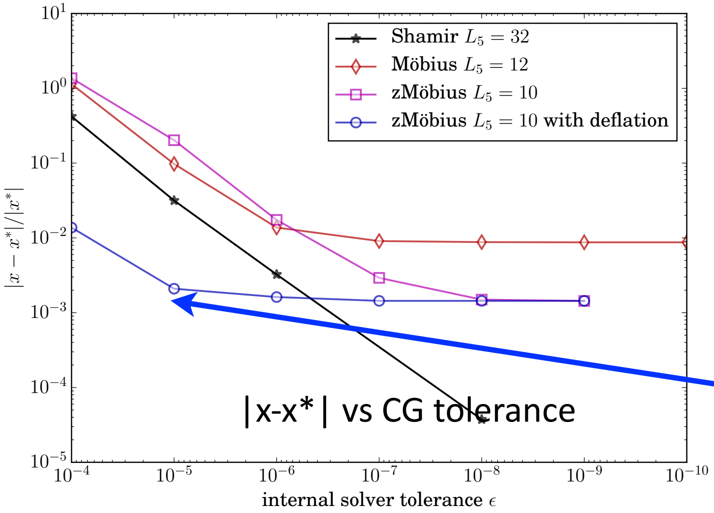
target "sign" function,
L_5=24 (sea quark Mobius)

deviations of short-L_5
(zMobius) from the target

- cheaper AMA approximation
- smaller eigenvectors for 5D deflation

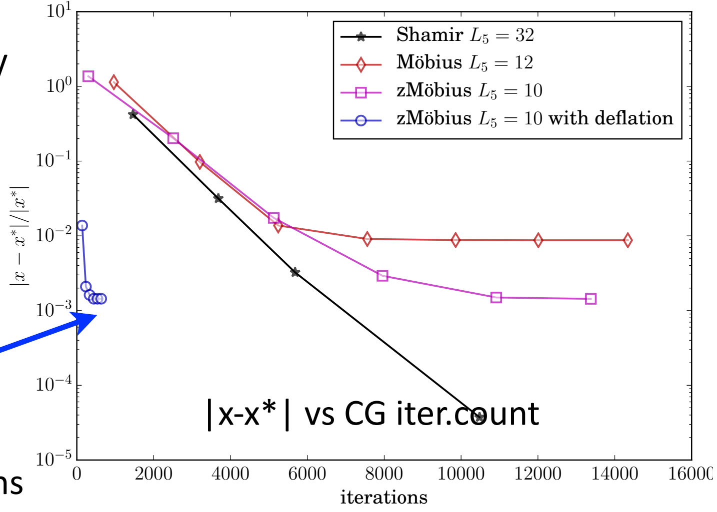
- acceleration of exact solve through iterative refinement ("zMADCG")

Comparison of short-L5 and exact (x*) propagators (4D part)



|x-x*| vs CG tolerance

32^3x64 170 MeV
lattice



|x-x*| vs CG iter.count

saturation at
~300 CG iterations
after deflation

Cost of One Solve
zMobius vs Overlap

- On Physical point ensemble, 48 cube DWF,
  - ~ 20 k CG iteration with Ls=24 DWF
  - Becomes ~220 CG iteration with Ls=10 zMobius, sloppy solve
  - This is roughly equivalent to
    <u>5.6 k Wilson-mult, or 2.8 k Wilson CG iteration</u>
  - One overlap ~ 600 Wilson polynomial to construct. Cost of sloppy zMobius solve is equivalent of
    5.6 / (2*0.6) = 4.7 outer CG of overlap.
    <u>If low-precision outer CG of overlap is 50, zMobius is more than 10 times faster.</u>
- We will consider low mode substitutions of ChiQCD to further reduce cost, thanks to SPC

Request: Summary table

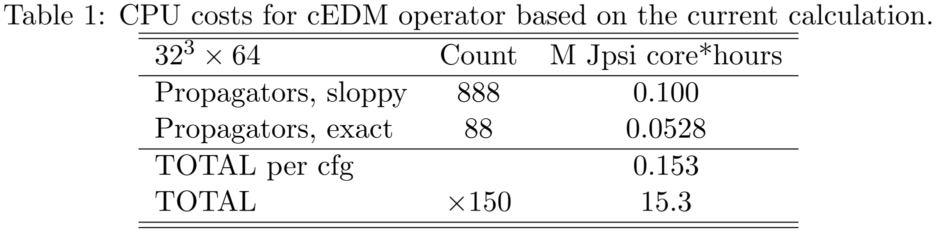


Table 1: CPU costs for cEDM operator based on the current calculation.

$32^3 \times 64$	Count	M Jpsi core*hours
Propagators, sloppy	888	0.100
Propagators, exact	88	0.0528
TOTAL per cfg		0.153
TOTAL	×150	15.3

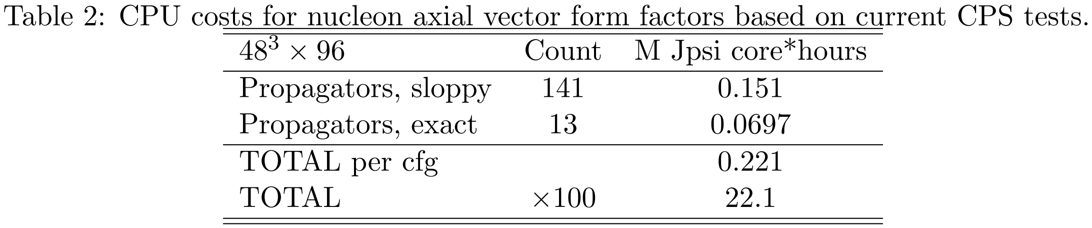


Table 2: CPU costs for nucleon axial vector form factors based on current CPS tests.

$48^3 \times 96$	Count	M Jpsi core*hours
Propagators, sloppy	141	0.151
Propagators, exact	13	0.0697
TOTAL per cfg		0.221
TOTAL	×100	22.1

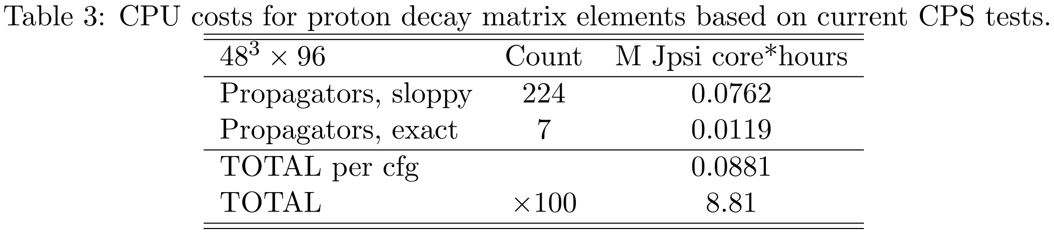


Table 3: CPU costs for proton decay matrix elements based on current CPS tests.

$48^3 \times 96$	Count	M Jpsi core*hours
Propagators, sloppy	224	0.0762
Propagators, exact	7	0.0119
TOTAL per cfg		0.0881
TOTAL	×100	8.81

Total computing: 46.21 M Jpsi core hours on Fermilab clusters

512 TB tape storage, equivalent to 1.84 M Jpsi core hours at Fermilab 64 TB disk storage, equivalent to 2.56 M Jpsi core hours at Fermilab

(50.61 M Jpsi core hours total computing and storage)

16 % of proton decay calculation will be removed due to overlapping

(See SPC questions and our answers)

Total request change: 50.61 -> 47.4 [M Jpsi core hours]

SPC questions

1) In your proposal you specify the statistical uncertainties you expect to obtain for gA and the Dirac radius. What are your expectations for the systematic errors?

Our central value for pilot calculation for gA on the physical point 48 cube ensemble turns out to be lower the experimental values. The plateau for gA indicates significant excited state contamination, while the value from the summation method is consistent with experiment but with a larger statistical error (50%).
About the charge radii, the statistics are not sufficient to analyze the form factor in particular with larger time separation. In both cases, additional statistics will be needed to reduce their uncertainties, which also enables us to carry out a careful analysis of excited state contamination and other systematics. Volume is one of the largest existing lattice (48^3 x 96), which corresponding to mπL = 3.86, which should be sufficient to suppress finite volume effects to below the target statistical error for the nucleon quantities. As for the discretization error, we have 64^3 already generated years ago, which we could use to remove the systematic error from discretization, which would be small for DWF, in following calculations in next years.

For proton decay matrix element, the calculation on the physical quark mass has a strong motivation due to the chiral bag model's prediction of orders of magnitude suppression at a small quark mass [5]. Thus, calculations at the physical quark mass would remove the claimed huge uncertainty due to chiral fit and extrapolations.

2) In your proposal you request resources to calculate EDMs, Nucleon form factors, and proton decay matrix elements. How much overlap is there in the computation of the three different quantities? How would the computational cost for this project change, if you were to perform the calculations sequentially?

16 % of proton decay calculation will be overlapping with nucleon form factor calculation. We like to emphasis that this overlap is besides the shared cost that already computed eigenvectors at Argonne g-2 calculation, which we will use to leverage both the proton decay and the form factor calculations.

3) Since you are planning to calculate gA for which there already exists an accurate measurement, have you considered performing a “blind analysis” to prevent any inadvertent bias? To blind your analysis, you could add an overall off-set factor to the correlation functions that would be kept unknown to the people doing the analysis until the systematic error analysis is finalized.

We would certainly consider the blind analysis. In fact, we have already been exercising the blind analysis in the V_us determination of tau-inclusive decay to remove possible human prejudices (Blum's proposal).

4) With the new resources at JLab being as yet unspecified, we would like to know if you are in a position to use them efficiently if they are a) cpu, b) GPU, c) KNL. If you are not, that is fine, but it will help in our allocation decisions to know this information from every proposal.

Our main measurement program is based on Qlua code, and we are ready to use CPU resources, at J-lab. For b) GPU, c) KNL, we prefer KNL due to the existing efficient code based on Grid of Peter Boyle. For deflation, we would prefer to have 96GB/node for KNL.

5) The SPC would like you to explore possibilities for coordinating or collaborating with the chiQCD collaboration which also has a hadron structure program on the same or similar lattices.

We have a concerns about the potential systematic error due to the partially quenched effect in chQCD's overlap, whose Dirac kernel may be significantly different from that of sea quark. We note that the 4D kernel inside the approximated sign function of sea quark action (Mobius parameter is set, b-c = 1) is different from that in overlap (Neuberger) (b-c=0), so the unitarity violation may not be removed simply by adjusting quark mass at the finite lattice spacing.

Thanks to SPC's suggestion we started productive conversations with Keh-Fei Liu. At this point, both of parties strongly feel having two independent strategies and calculations would be better and healthy especially considering about relatively premature states of nucleon matrix element calculations compared to meson calculations. It would be good to try further various explorations of methods as well as different quark discretizations (MDWF or Overlap). We do, however, think it would be very beneficial to learn from each other, especially about methods, to maximize the outcome of the precious USQCD resources.

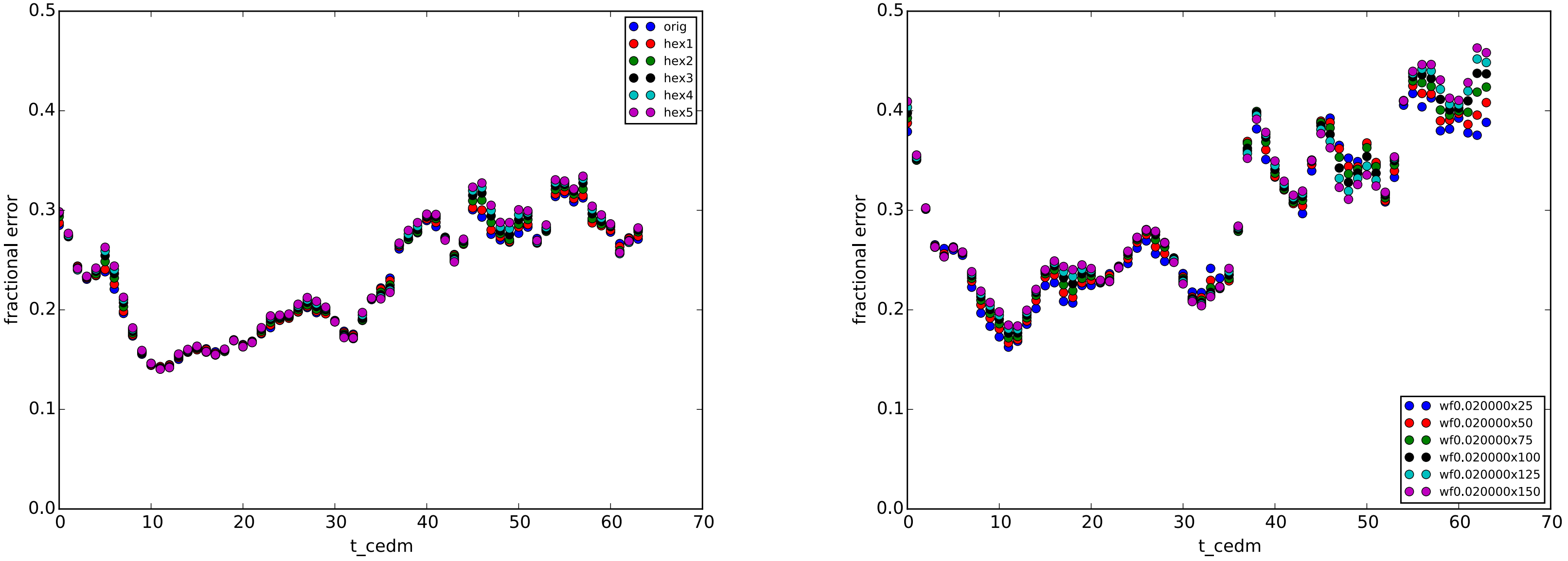
Thank you

Backup

Preliminary study : CP mixing angle (α) induced by cEDM operator

$$\sum_s u_N(p,s)\bar{u}_N(p,s) = E_N\gamma_0 - i\vec{p}\vec{\gamma} + m_N e^{i\alpha\gamma_5}$$

$$\mathrm{Tr}\frac{1+\gamma_t}{2}\gamma_5\left\langle N(T)\sum_x O_{\mathrm{cEDM}}(x)\bar{N}(0)\right\rangle \propto \alpha$$



cEDM operator insertion time (t_cedm) dependence of the error.

Left: HEX smearing, Right: Wilson flow smearing

t_source=0, s_sink=8