SPC Summary:
Nucleon Matrix Elements
for Beyond-SM Searches

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for the USQCD Scientific Program Committee

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Current **USQCD** proposals

- Nucleon Charges & Axial form factors
  1(EF/NP) : Clover-Wilson

- Nucleon Electric Dipole Moment (NP)
  3 proposals : Clover-Wilson, Domain Wall, DW+Overlap

- Gluon trace anomaly and energy-momentum form factors
  in the nucleon
 *1 (NP) : contribution to the proton mass*

Impact on Experimental programs

- Input to neutrino experiments DUNE / LBNE
  Axial form factors → neutrino cross-section

- Searches for BSM (HEP theory) in precision experiments (NP)
  Nucleon & Nuclear Electric dipole moments
  CPv πN couping
  Constraints on θ_{QCD} connected to PQ axions / DM
  Non-QCD sources of CPv may be connected to baryogenesis

- J/Ψ threshold photo-production at JLab, EIC
  Gluon EM tensor and contributions to the proton mass

# Precision Form factors & Nucleon "Charges"

Nucleon charges with unitary clover-imp. Wilson quarks (Continuation)
[NME collaboration (LANL/JLab/W&M); Rajan Gupta (PI), Sungwoo Park (talk), et al]
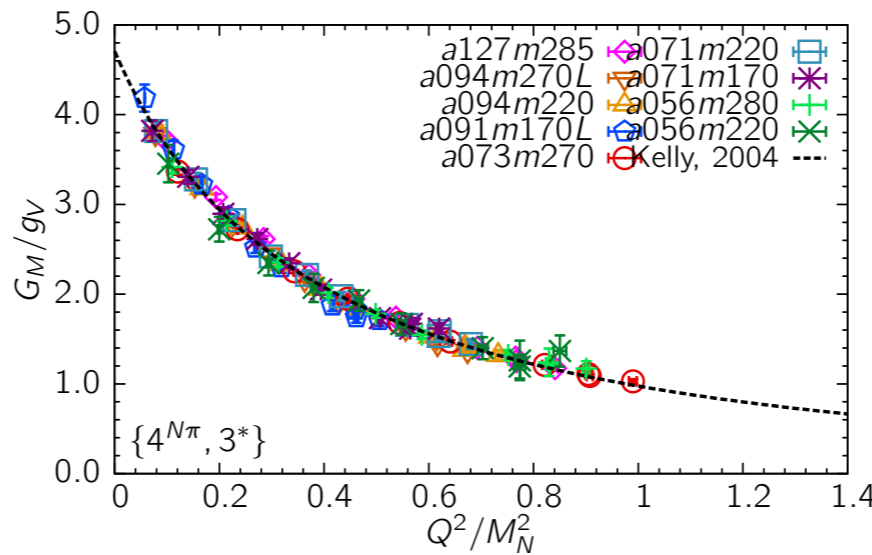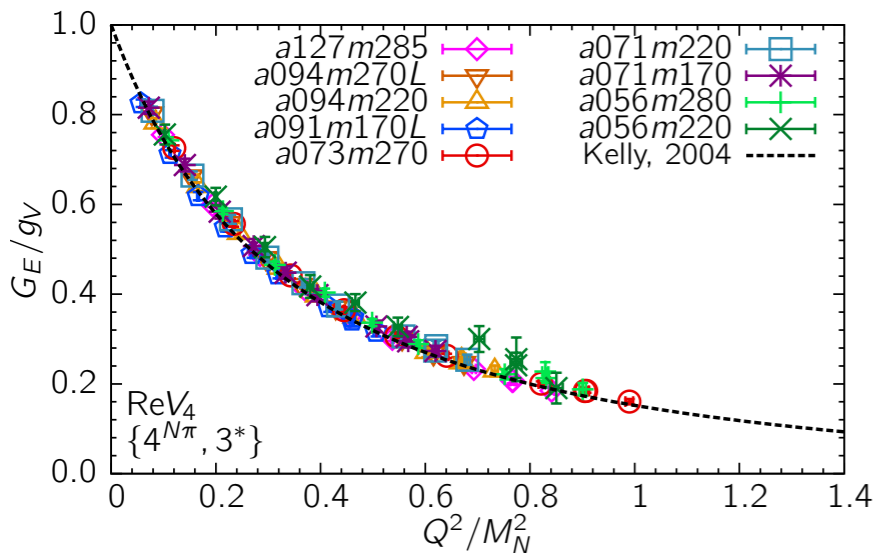
- electromagnetic structure & radii

- g_S, g_T : neutron β-decay sensitivity to beyond-SM physics

- g_T : Nucleon EDM from quark EDM

- helicity/transversity moments, quark momentum fraction

- disconnected contributions

[FLAG'21 Review]
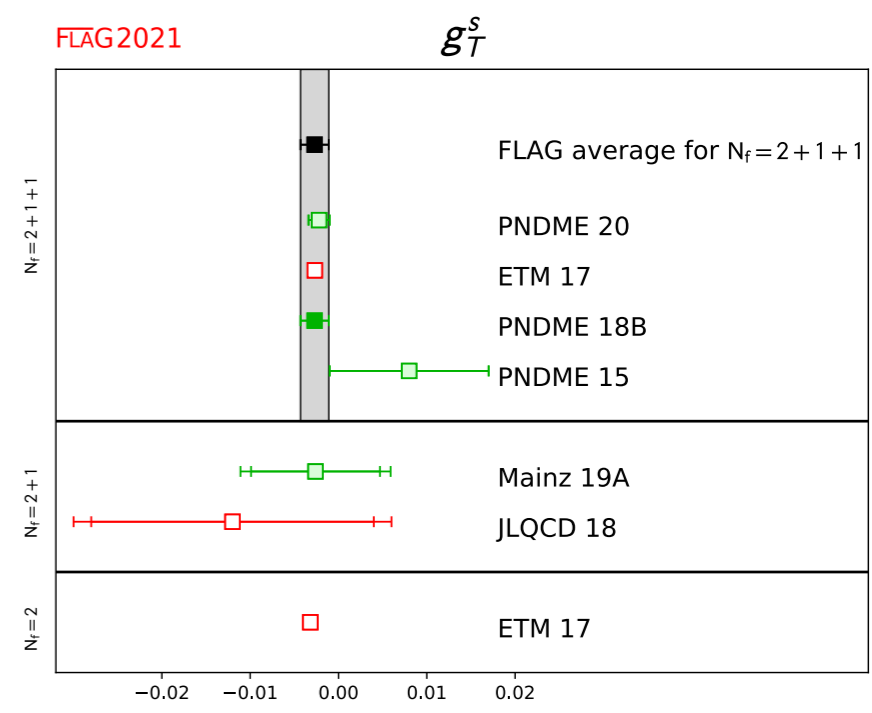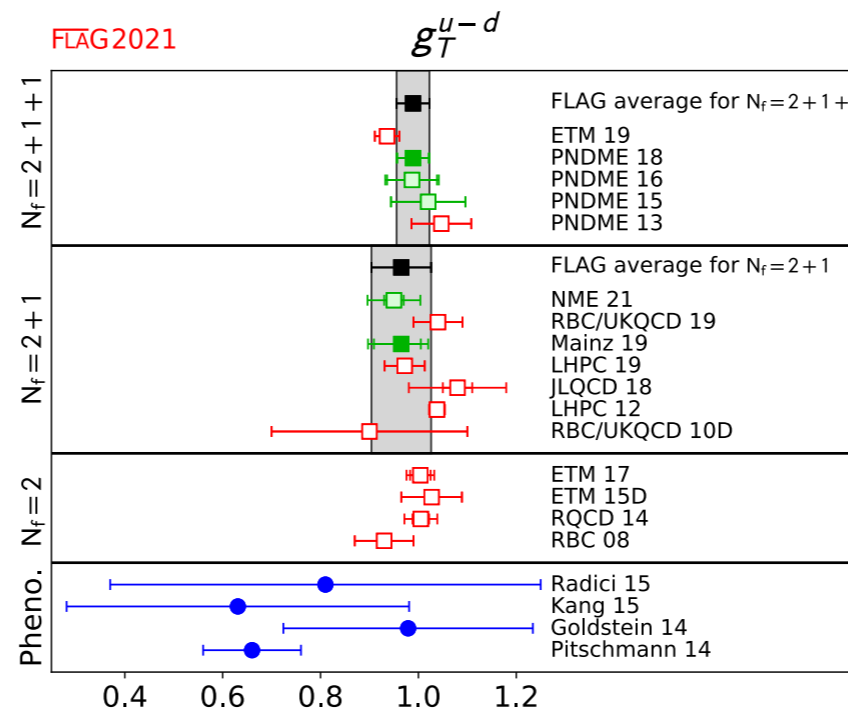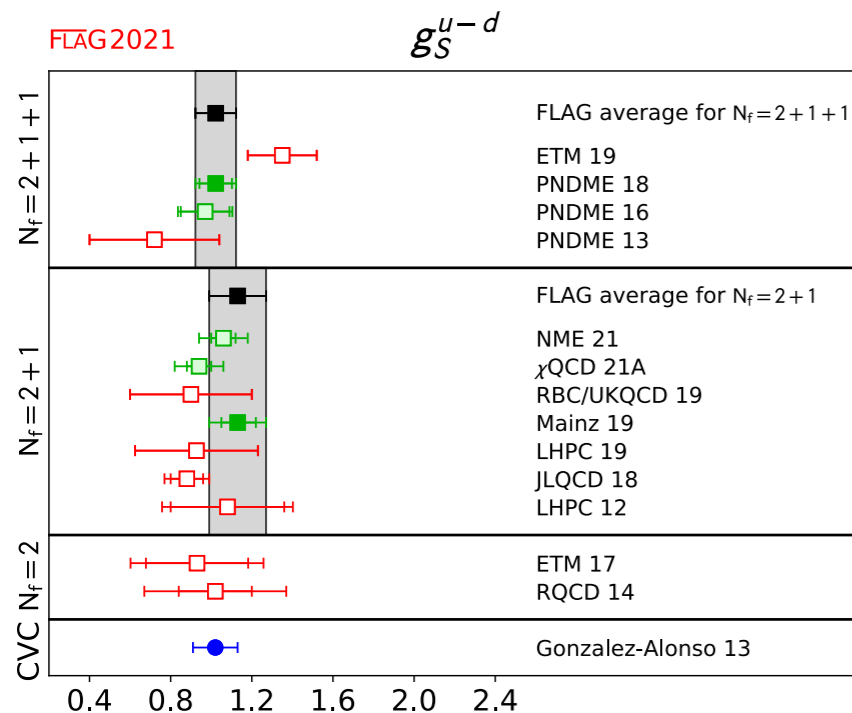
Vector, Axial & Pseudoscalar Form factors

$$\langle p(\boldsymbol{p})|\mathscr{A}_\mu^+|n(\boldsymbol{k})\rangle = \bar{u}_p(\boldsymbol{p})\left[\gamma_\mu\gamma^5 F_A(q^2) + \frac{q_\mu}{2M_N}\gamma^5 F_{\tilde{P}}(q^2)\right]u_n(\boldsymbol{k}),$$

$$\langle p(\boldsymbol{p})|\mathscr{P}_\mu^+|n(\boldsymbol{k})\rangle = \frac{2M_N}{m_u+m_d}\tilde{F}_P(q^2)\,\bar{u}_p(\boldsymbol{p})\gamma^5 u_n(\boldsymbol{k}),$$

$$\langle p(p)|\mathscr{V}_\mu|n(k)\rangle = \bar{u}_p(p)\left[\gamma_\mu F_1(q^2) + \frac{\sigma_{\mu\nu}q^\nu}{2M_N}F_2(q^2)\right]u_n(k)$$

2+1 Wilson-Clover quarks [R.Gupta (PI) ; Park et al 2103.05599]

- Axial form factor:
  quasi-elasticE neutrino scattering

- Pseudoscalar charge & form factor
  muon capture (MuCAP)
  explore low-Q^2 PCAC on a lattice
  role of $N\pi$ states

- Vector form factors:
  proton radius
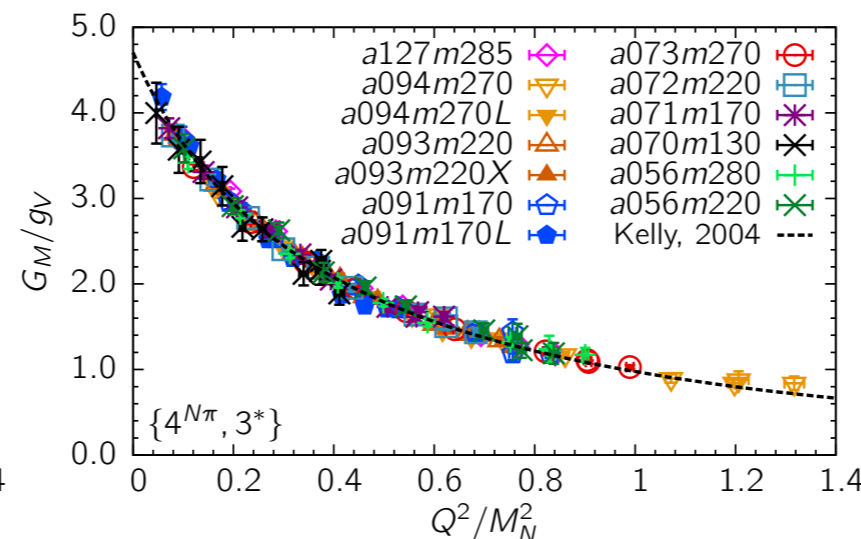 two-photon exchange
  input to GPD & PVES experiments
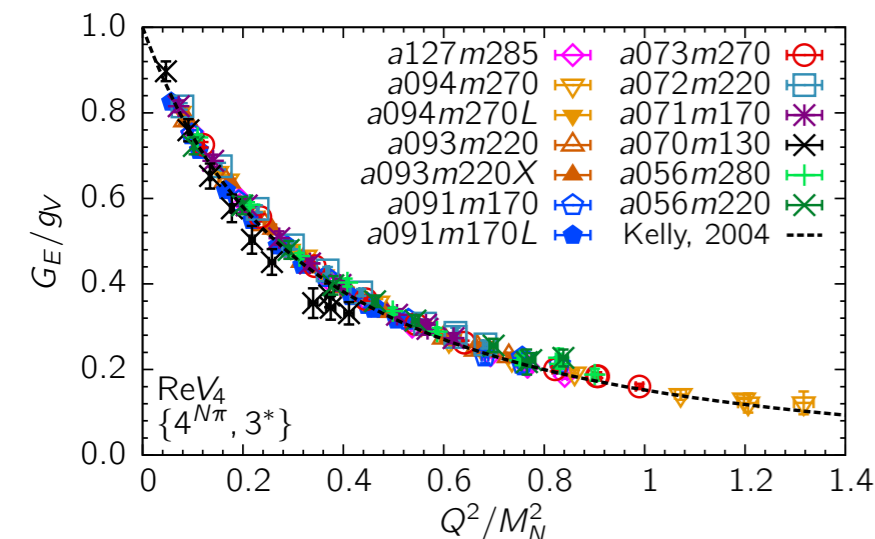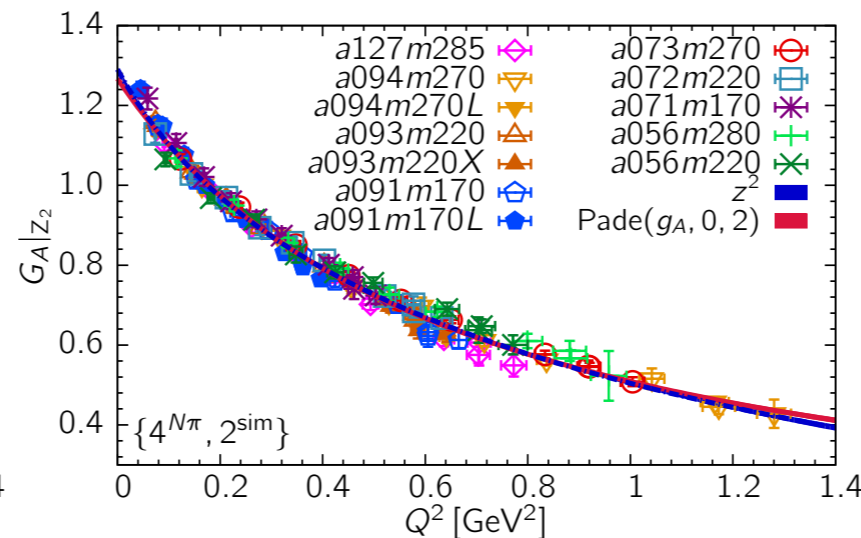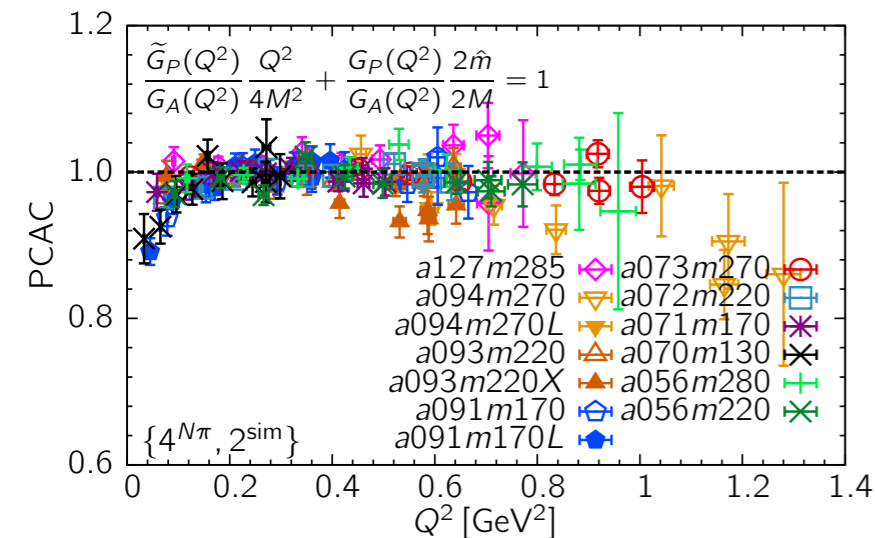 flavor structure : u/d/s contributions

Continuation:

Further analysis of 13 ensembles

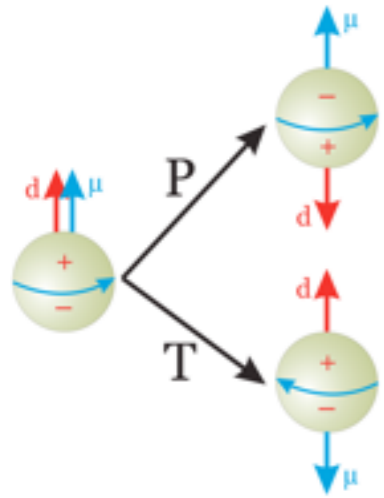- $m\pi$ = 280 ... 130 MeV

- a = 0.127 ... 0.056 fm

- $m\pi L$ = 3.7 ... 6.2

Disconnected contributions:
- chiral fits with $m\pi$ down to 170 MeV
- cont.limit with a down to 0.07 fm

Nucleon EDM

$$\mathcal{L}_{\text{int}} = eA_\mu^{\text{em}}\mathcal{V}^\mu \qquad [\sim \vec{B}\cdot\mu_N\vec{S}_N]$$

$$+ eA_\mu^{\text{em}}\mathcal{A}^\mu \qquad [\sim \vec{E}\cdot d_N\vec{S}_N]$$

may be induced by
- θ_{QCD} angle
- quark EDM (g_T)
- quark & gluon chromo-EDM
- higher-dim BSM interactions

The most sensitive probe of non-CKM CPv:

- Any signal >$10^{-5}\cdot$(current bound)→discovery
- θ_{QCD}-induced EDM : Strong-CP problem
- Prerequisite for Baryogenesis (non-θ_{QCD} EDM)

Lattice methods
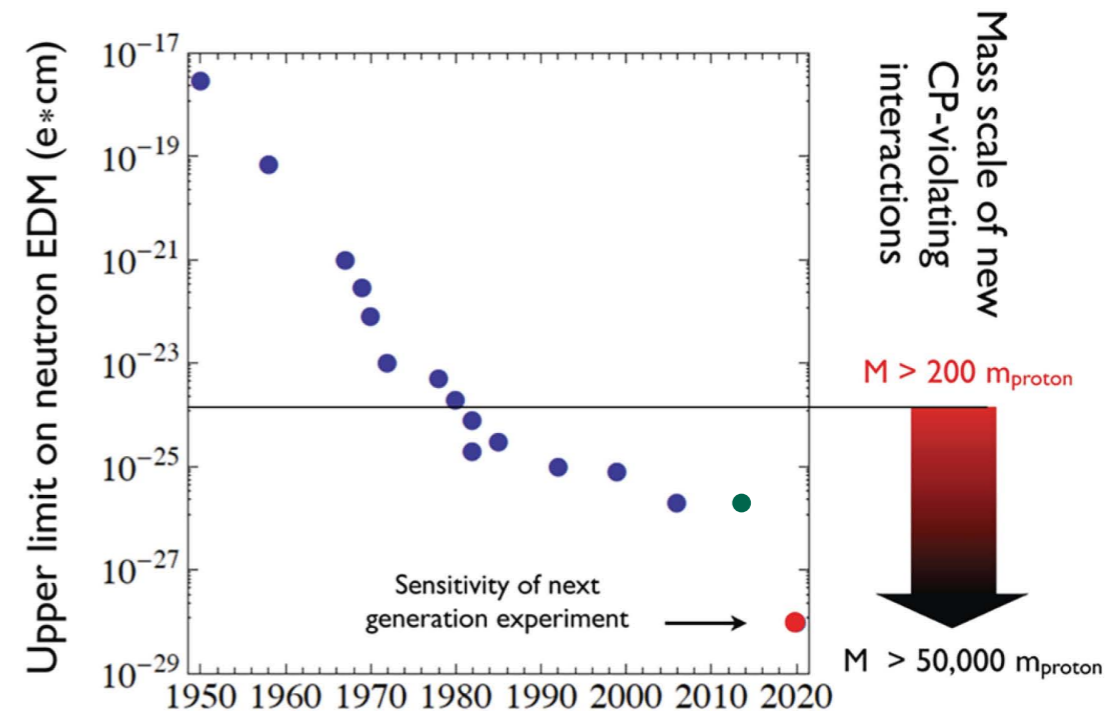
- (Imaginary) background electric field
$$\mathcal{H} = -\vec{d}_N\cdot\vec{E}$$

- CPv form factor $F_3(Q^2\to 0)$
$$\langle p+q|J^\mu|p\rangle_{\cancel{CP}} = \bar{u}_{p'}\left[F_1\gamma^\mu + (F_2 + iF_3\gamma_5)\frac{\sigma^{\mu\nu}q_\nu}{2m_N}\right]u_p$$

Dirac   Pauli (anomalous magnetic dipole)   Electric dipole

Mass scale of new CP-violating interactions

M > 200 m_{proton}

M > 50,000 m_{proton}

	10^{-28} e cm
CURRENT LIMIT	<300
Spallation Source @ORNL	**< 5**
Ultracold Neutrons @LANL	~30
PSI EDM	<50 (I), **<5 (II)**
ILL PNPI	<10
Munich FRMII	**< 5**
RCMP TRIUMF	<50 (I), **<5 (II)**
JPARC	**< 5**
Standard Model (CKM)	*< 0.001*

Nucleon EDM(1) : θ_{QCD}-Term
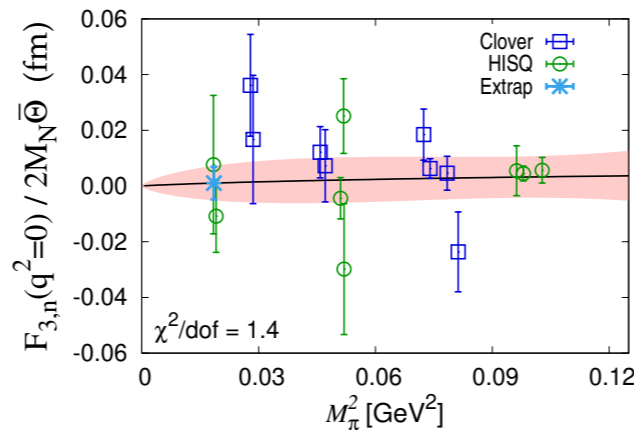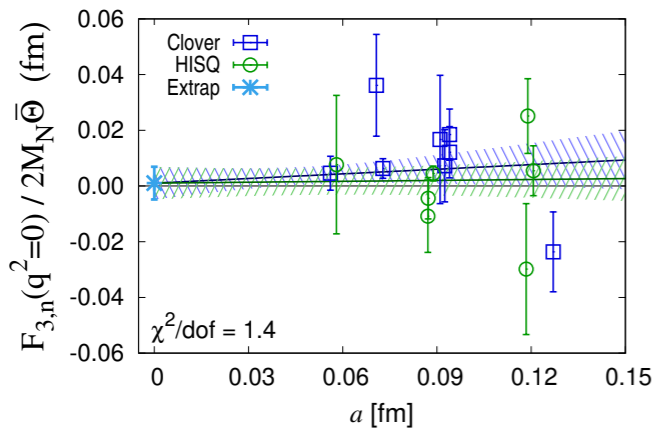
Challenges:

- effect of θ_{QCD} vanishes at $m_q \to \underline{m_q^{phys}}$
- noise in global $Q = \int F\tilde{F}$ grows with V_4
- dynamics depends on chiral symmetry
- $Q^2 \to 0$ extrapolation

Wilson-Clover quarks [T.Bhattacharya(PI),]

- gradient flow to determine top. charge density $\int F\tilde{F}$
- $\tilde{g}_P$: CPv πN coupling induced by θ_{QCD}
- NEXT: continue to improve stats., establish signal
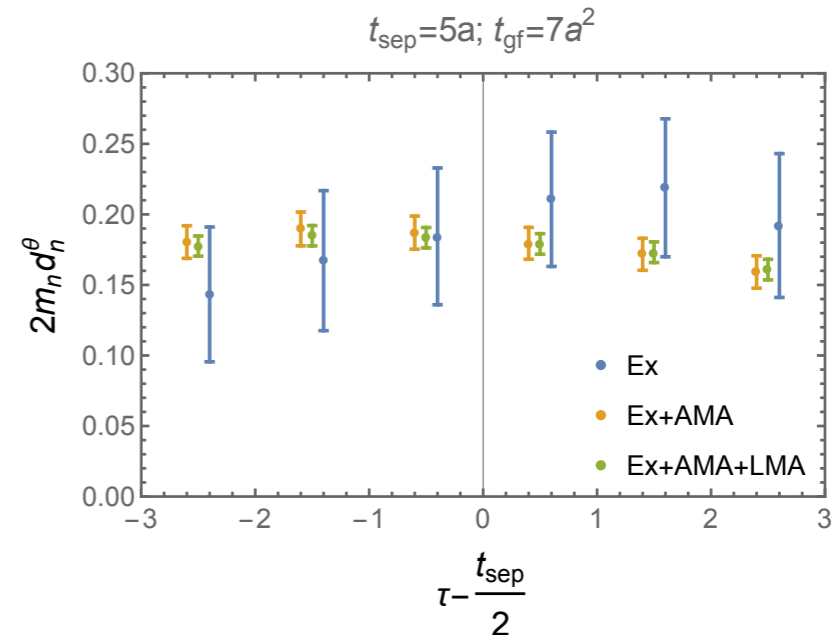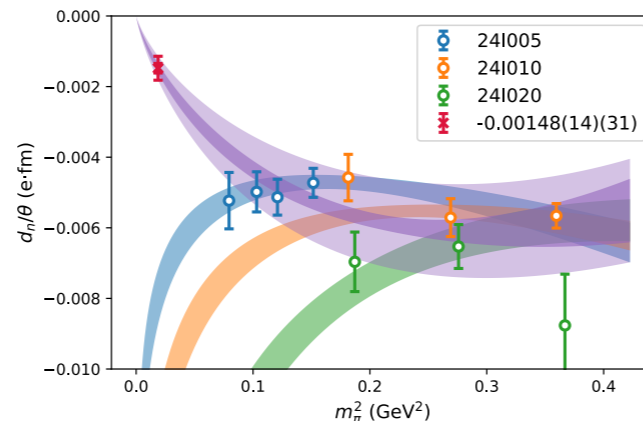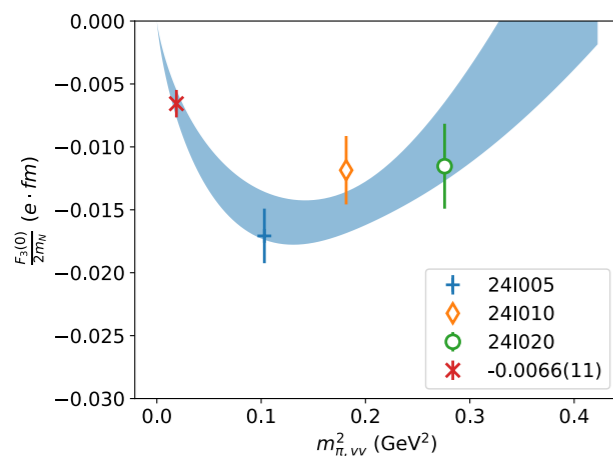
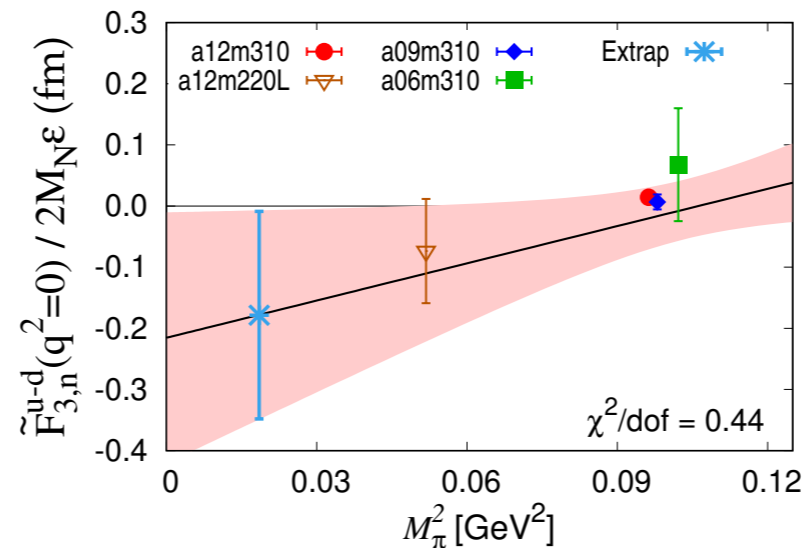$24^3 \times 64$, $m\pi \approx 420$ MeV, LMA vs LMA+AMA

DW quarks [T.Blum, S.Syritsyn(PI), F. He]

- background electric field (valence only)
- local (timeslice) sampling of top.charge
- exploit correlation of Q and Dslash 0-modes
- NEXT: proceed to physical point (24ID)

DW + Overlap quarks: [Jian Liang, K.-F.Liu(PI)]:

- partial-Vol$_{4D}$ sampling of Q (cluster decomp.)
- partial quenching : fit to valence m_q dependence
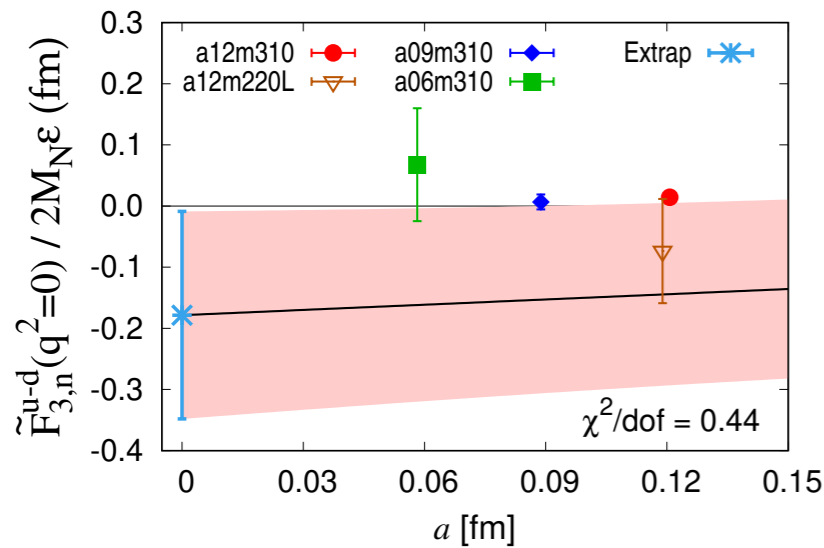- NEXT: continue on finer a = 0.081 fm

Nucleon EDM(2) : Quark & Gluon (Weinberg) cEDM

Nucleon EDM from Theta, quark & gluon(Weinberg) chromoEDM with clover fermions
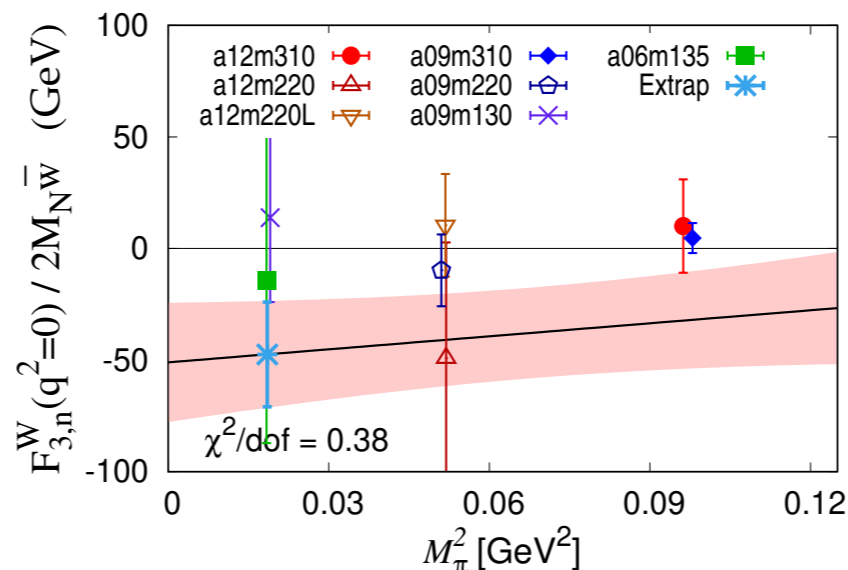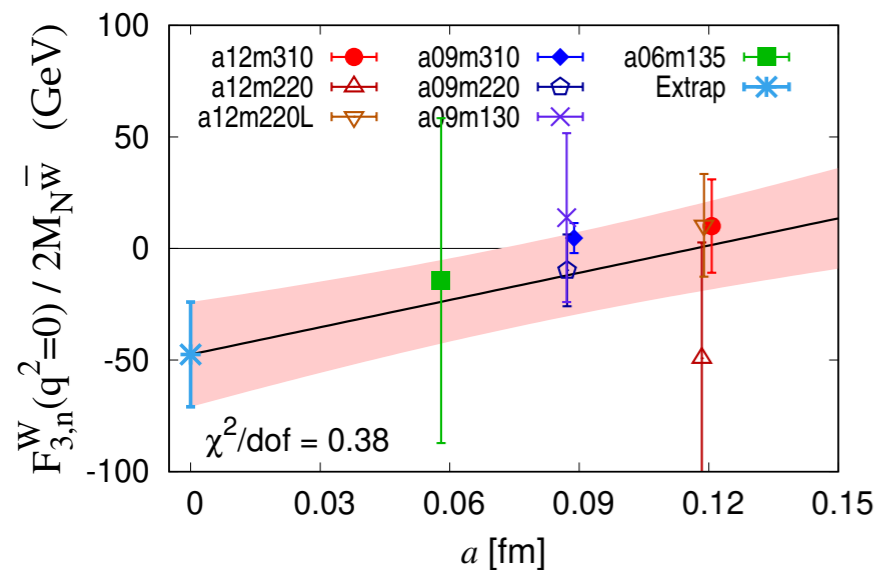[Tanmoy Bhattacharya (PI), et al]

- quark cEDM ($\bar{q}\,(\sigma\cdot G)\,\gamma_5 q$):

- Weinberg term ($\sim G\cdot G\cdot\tilde{G}$):

Wilson-Clover quarks [T.Bhattacharya, Lattice 2021; 2203.03746]

Challenges:

- renorm. & mixing
  with lower-dim operators
  (e.g. dim-4 $F\tilde{F}$ → θ_{QCD}-nEDM)

- quark cEDM (dim-5):
  disconnected quarks
  in vector current and cEDM

- Weinberg term (dim-6):
  gluon noise

- CONITNUATION :
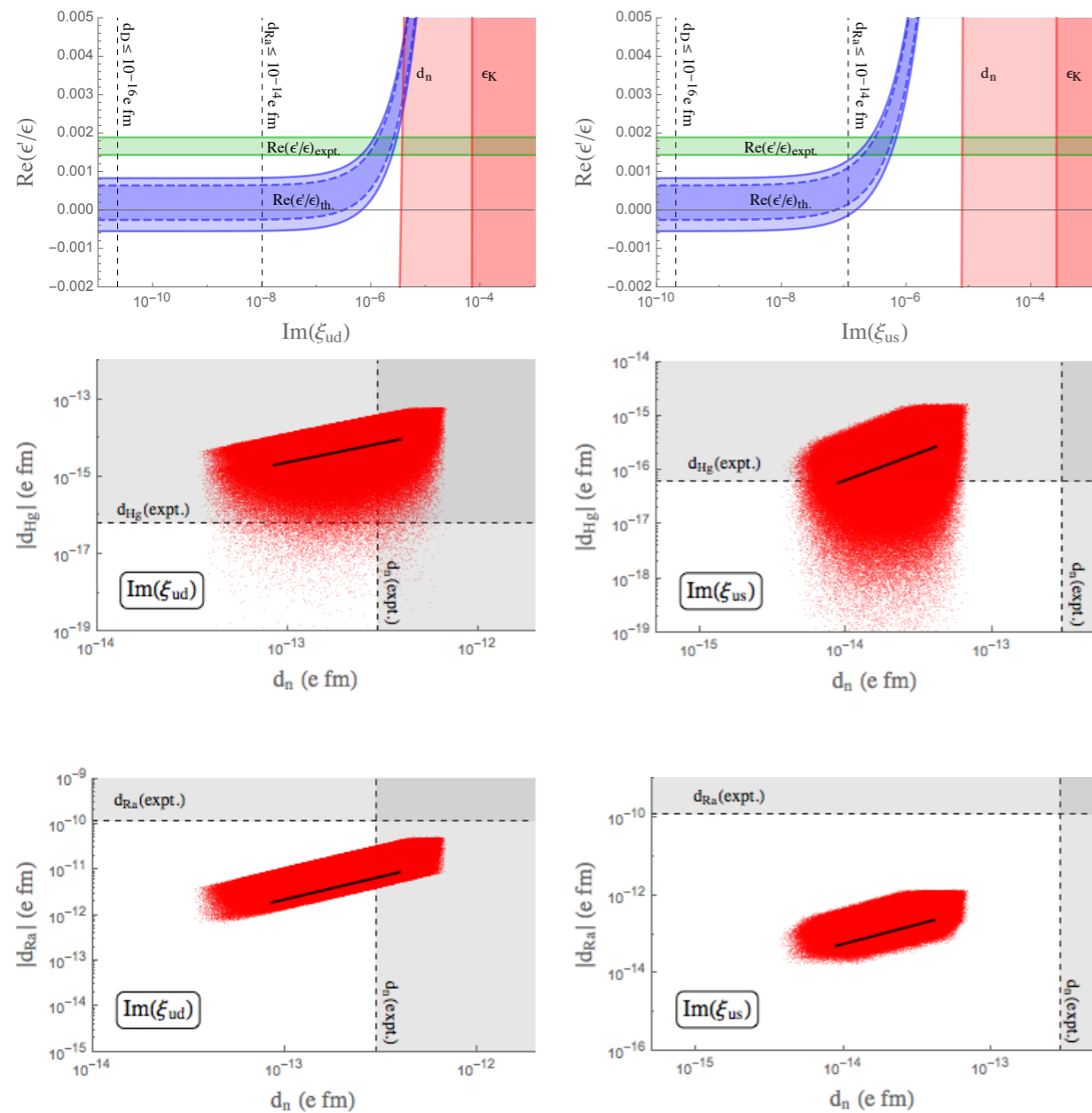 improve stats.for $m_\pi \approx 280$ MeV,
  a=0.073 ... 0.094 fm

Nucleon EDM from CPv 4-quark Operators

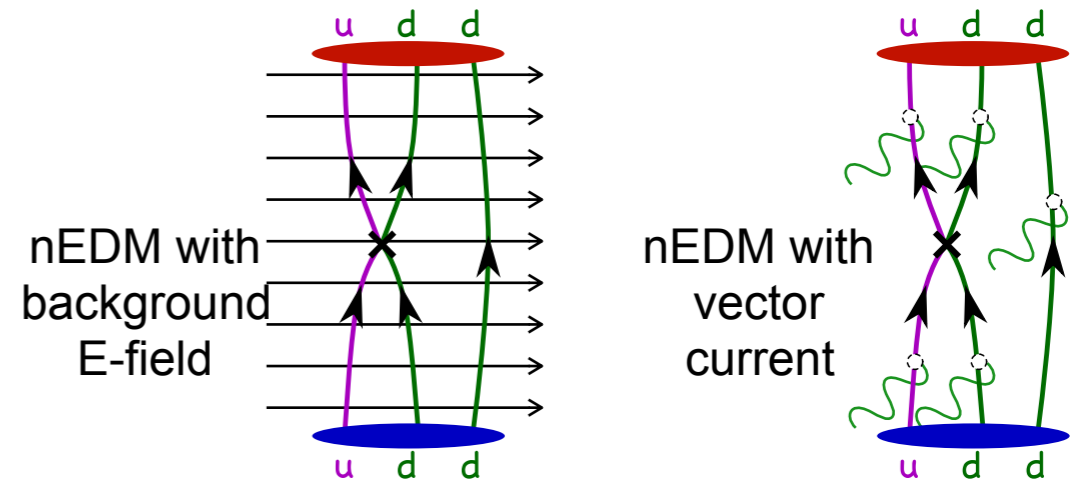CPv L-R interaction → CPv in K→ππ decays
nucleon/nuclear EDM

$$\mathcal{O}_{\varphi ud}^{(1)} = \frac{1}{3}(\bar{u}u)(\bar{d}\gamma_5 d) + (\bar{u}T^A u)(\bar{d}\gamma_5 T^A d) - [u \leftrightarrow d]$$

Also CPv from SUSY models

$$\mathcal{O}_{quqd}^{(1)} = (\bar{u}\gamma_5 u)(\bar{d}d) + (\bar{u}u)(\bar{d}\gamma_5 d)$$
$$- [(\bar{u}u)(\bar{d}d) \leftrightarrow (\bar{u}d)(\bar{d}u)]$$
$$\mathcal{O}_{quqd}^{(8)} = (\bar{u}\gamma_5 T^A u)(\bar{d}T^A d) + (\bar{u}T^A u)(\bar{d}\gamma_5 T^A d)$$
$$- [(\bar{u}u)(\bar{d}d) \leftrightarrow (\bar{u}d)(\bar{d}u)]$$

nEDM with background E-field

nEDM with vector current

[Cirigliano et al, 2017 (1612.03914)]

- constraints on Left-Right interaction from combined CPV in Kaons and nEDM
- nEDM from dim.analysis:
  large potential for impact from lattice QCD

nEDM contribution from 4q-CPV with Domain Wall quarks [Blum, Syritsyn(PI), F. He]
- uniform background electric field(*)
- A2A propagators of chiral-symmetric quarks

Gluon Trace Anomaly & Energy-Mom. FFs

Gluon contribution to the proton EM tensor using DW+Overlap [B.Wang(PI)]

$$\langle P'|(T^{\mu\nu}_{q,g})_R(\mu)|P\rangle/2M = \bar{u}(P')[T_{1_{q,g}}(q^2,\mu)\gamma^{(\mu}\bar{P}^{\nu)} + T_{2_{q,g}}(q^2,\mu)\frac{\bar{P}^{(\mu}i\sigma^{\nu)\alpha}q_\alpha}{2M}$$

$$+ D_{q,g}(q^2,\mu)\frac{q^\mu q^\nu - g^{\mu\nu}q^2}{M} + \bar{C}_{q,g}(q^2,\mu)Mg^{\mu\nu}]u(P)$$

- contribution to the hadron mass

$$M_H = \langle T^\mu_\mu \rangle_H = (1+\gamma_m)\langle H_m \rangle_H + \frac{\beta}{2g}\langle F^2 \rangle_H$$

- will be measured in *J/Ψ* threshold photo-production at JLab, EIC

- node in radial distribution of trace anomaly; driven by chiral condensate dynamics? [He, Sun, Yang, PRD'21]

- CONTINUATION: compute nucleon & pion trace anomaly dist. using DW+Overlap quarks up to Q² ~ 4 GeV² 24I (m$_\pi$=340MeV) 48I (m$_\pi$=140MeV)
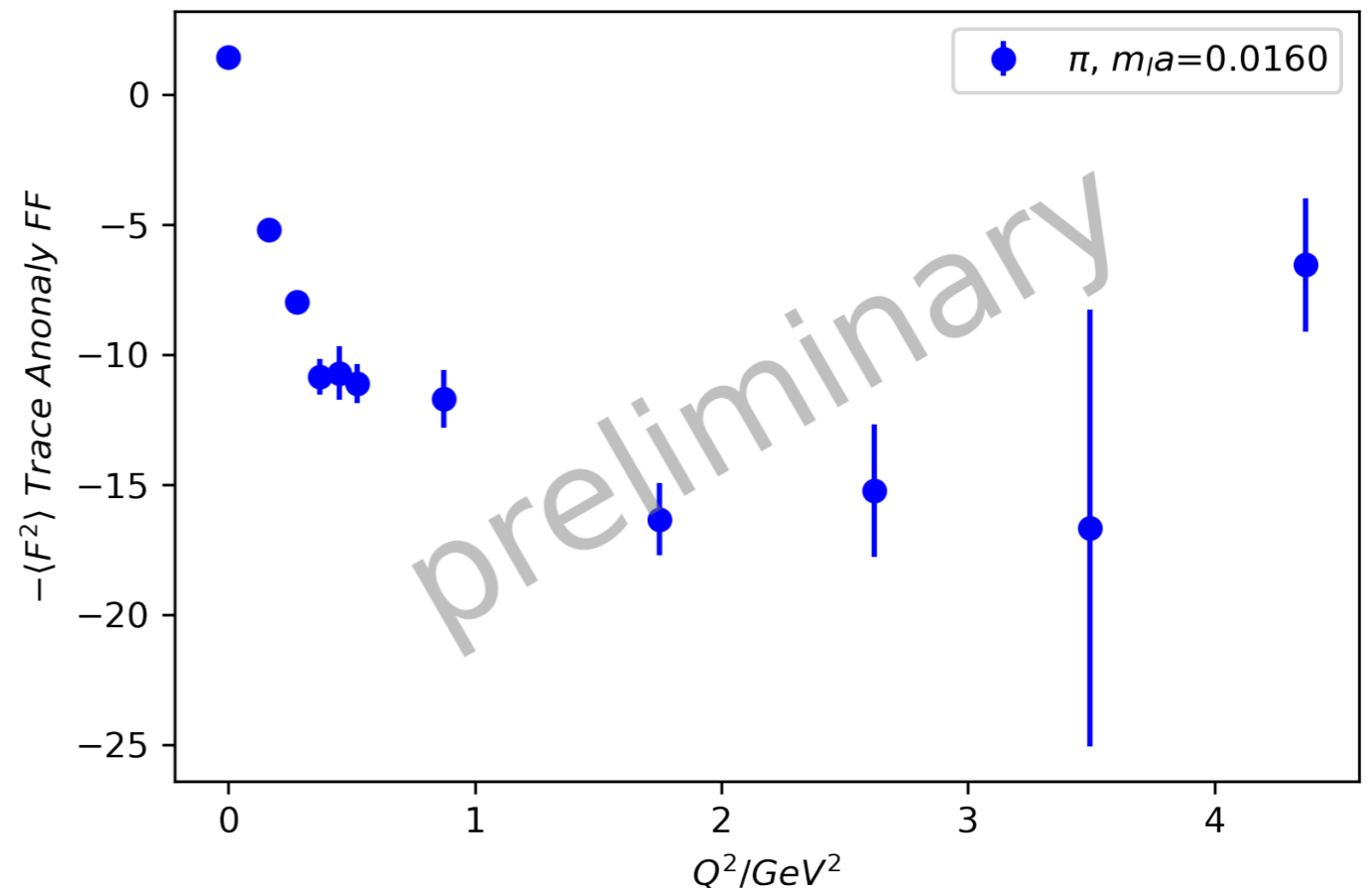
Presentations by PIs & Discussion

- *Nucleon EDM using Overlap fermions*

- *Nucleon EDM using Clover fermions*

  (PI: Tanmoy Bhattacharya)

- *Nucleon Matrix Elements using clover fermions*

  Sungwoo Park (Los Alamos National Laboratory)

- *QCD trace anomaly form factors of the nucleon energy-momentum tensor*

  Bigeng Wang (University of Kentucky) *[Partonic structure section]*

- *Discussion*