Neutron Electric Dipole Moments

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Standard model of particle physics with neutrino mass

- Explains all laboratory experiments.
- Is in violent contradiction with cosmology.

The universe:

- Can't be big, empty and homogeneous ("inflation")
- Can't have much matter ("baryogenesis")
- Can't clump into clusters of galaxies ("dark matter")
- Can't be accelerating ("dark energy")

Observed baryon asymmetry: $n_B/n_\gamma = 6.1^{+0.3}_{-0.2} \times 10^{-10}$.

WMAP + COBE 2003

Without CP violation, freezeout ratio: $n_B/n_\gamma \approx 10^{-20}$.

Kolb and Turner, *Front. Phys.* **69** (1990) 1.

Either asymmetric initial conditions or baryogenesis!
Sufficiently asymmetric initial conditions kills inflation.

Sakharov Conditions

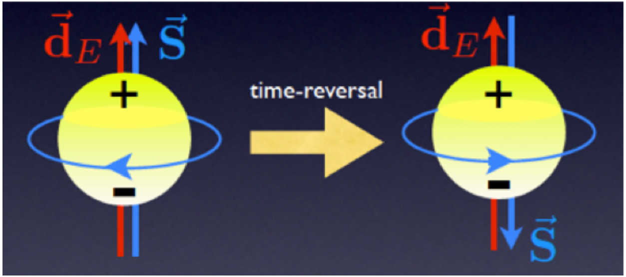
Sakharov, *Pisma Zh. Eksp. Teor. Fiz.* **5** (1967) 32.

- Baryon Number violation
- C and CP ($\Rightarrow$ T) violation
- Out of equilibrium evolution

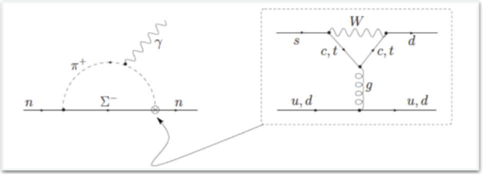
Sakharov conditions fullfilled in the standard model weak interactions.

- Baryon number anomaly (But $\mathrm{B}-\mathrm{L}$ conserved; could be Leptogenesis)
- CKM phase violates C and CP
- Higgs vev generation may go out-of-equilibrium.

Quantitatively insufficient, but BSM could have more CPV.

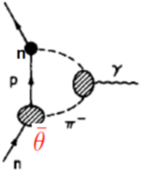


- Elementary particles are non-degenerate: spin is the only direction.
- Electric dipole moments violate P and T
- CPT implies they violate CP



CKM contribution small $d_n < 10^{-31}$e cm

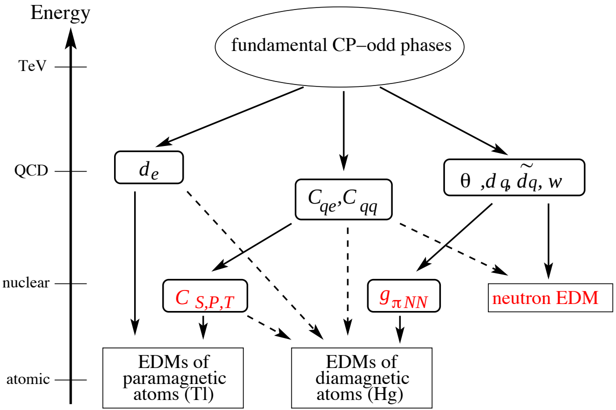
Seng, *PRC* **91** (2015) 025502.



$$d_n \sim \frac{m_*}{\Lambda^2_{\text{had}}} e\,\bar\theta \sim 10^{-17}\,\bar\theta\,\text{ecm} \rightarrow |\bar\theta| < 10^{-9}$$

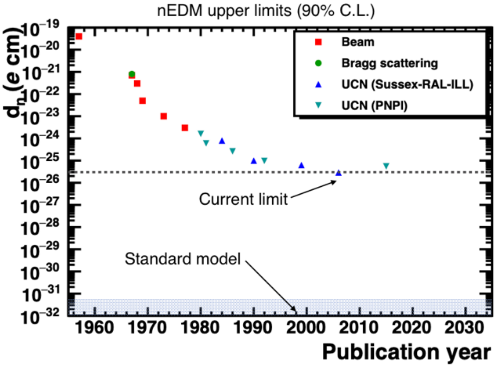
$$m_* = \frac{1}{\sum_i (1/m_i)} \simeq \frac{m_u m_d}{m_u + m_d}$$

Possibly large strong CPV. Assume suppressed



Pospelov and Ritz, *Ann. Phys.* **318** (2005) 119.

Experimental Status



	Current Limit	CKM prediction
e	10^{-29}	10^{-38}
μ	10^{-19}	10^{-35}
τ	10^{-16}	10^{-34}
n	10^{-26}	10^{-31}
p	10^{-23}	10^{-31}
^{199}Hg	10^{-29}	10^{-33}
^{129}Xe	10^{-27}	10^{-33}
^{225}Ra	10^{-23}	10^{-33}

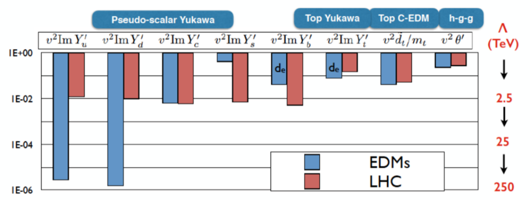
$$
\begin{aligned}
d_n &= -(0.20 \pm 0.01) d_u + (0.78 \pm 0.03) d_d + (0.0027 \pm 0.016) d_s \\
&\quad - (0.55 \pm 0.28) e\tilde{d}_u - (1.1 \pm 0.55) e\tilde{d}_d \pm (50 \pm 40)\ \mathrm{MeV}\, e d_W \\
\bar{g}_0 &= (5 \pm 10)(\tilde{d}_u + \tilde{d}_d)\mathrm{fm}^{-1} \\
\bar{g}_1 &= (20^{+40}_{-10})(\tilde{d}_u - \tilde{d}_d)\mathrm{fm}^{-1}
\end{aligned}
$$

Pospelov and Ritz, *Ann. Phys.* **318** (2005) 119.

Gupta *et al.*, *PRD* **88** (2018) 091501(R).

EDMs competitive or better than LHC for constraining CPV Higgs/top.
Will dominate if

- experiment at 5×10^{-27}e cm and
- light matrix elements at 25%
- strange and gluonic matrix elements at 50%



Pseudo-scalar Yukawas in units of SM Yukawa m_q/v

$$\mathcal{L} = \frac{m_q}{v} \, \tilde{\kappa}_q \, \bar{q} i \gamma_5 q \, h$$

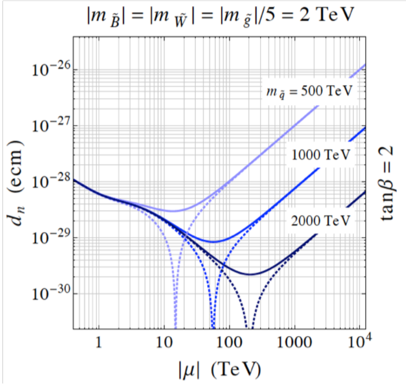
$\tilde{\kappa}_u$	$\tilde{\kappa}_d$	$\tilde{\kappa}_s$	$\tilde{\kappa}_c$	$\tilde{\kappa}_b$	$\tilde{\kappa}_t$
0.45	0.11	58	2.3	3.6	0.01

Cirigliano *et al.*, *PRD* **94** (2016) 016002

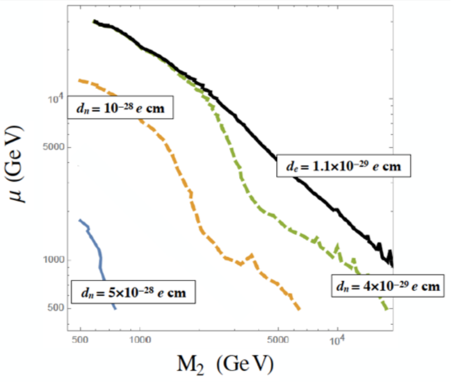
Chien *et al.*, *JHEP* **1602** (2016) 011

Brod *et al.*, *JHEP* **1311** (2013) 180

nEDM can constrain some SUSY models

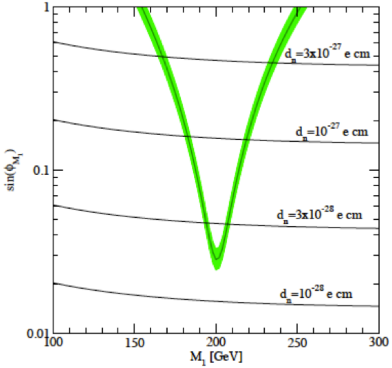


Altmannshofer *et al.*, *JHEP* **1311** (2013) 202



Gupta *et al.*, *PRD* **98** (2018) 091501(R)

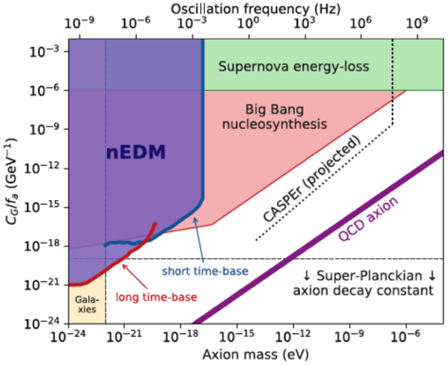
Especially constraining for some theories of Baryogenesis.



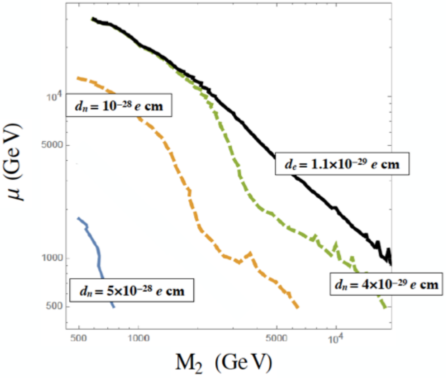
Li *et al.*, *PLB* **673** (2009) 95

Cirigliano *et al.*, *JHEP* **1001** (2010) 002

Other models



Abel *et al.*, *PRX* **7** (2017) 041034



Cirigliano *et al.*, *PLB* **767** (2017) 1

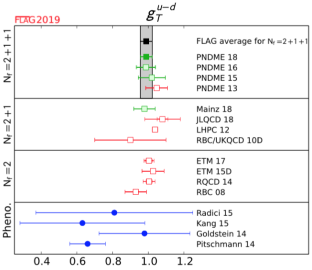
$$\mathcal{L} \supset d_q \bar{q} \sigma^{\mu\nu} \tilde{F}_{\mu\nu} q$$
$$\langle n | \bar{q} \sigma^{\mu\nu} q | n \rangle = g_T^q \bar{u}_n \sigma^{\mu\nu} u_n$$

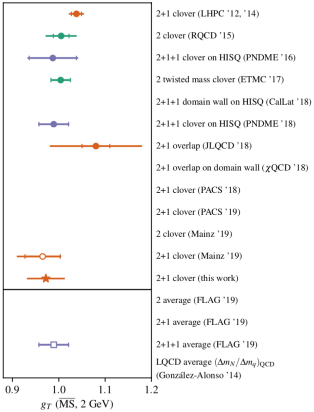
At leading order in electromagnetic interactions, the nEDM due to quark EDM is given by the tensor charge.

FLAG report:

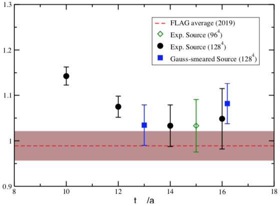
Collaboration	N_f	pub.	cont.	chiral	vol.	ren.	states	g_T^{u-d}
PNDME 18	2+1+1	A	★‡	★	★	★	★	0.989(32)(10)
PNDME 16	2+1+1	A	○‡	★	★	★	★	0.987(51)(20)
PNDME 15	2+1+1	A	○‡	★	★	★	★	1.020(76)
PNDME 13	2+1+1	A	■‡	■	★	★	★	1.047(61)
Mainz 18	2+1	C	★	○	★	★	★	0.979(60)
JLQCD 18	2+1	A	■	○	○	★	★	1.08(3)(3)(9)
LHPC 12	2+1	A	■‡	★	★	★	★	1.038(11)(12)
RBC/UKQCD 10D	2+1	A	■	■	○	★	■	0.9(2)
ETM 17	2	A	■	○	○	★	★	1.004(21)(2)(19)
ETM 15D	2	A	■	○	○	★	★	1.027(62)
RQCD 14	2	A	○	★	★	★	■	1.005(17)(29)
RBC 08	2	A	■	■	■	★	■	0.93(6)

‡ Not fully O(a) improved.

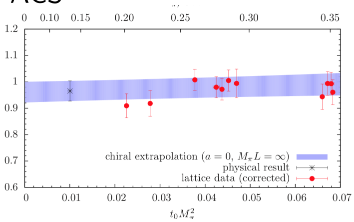




LHPC comparison



PACS

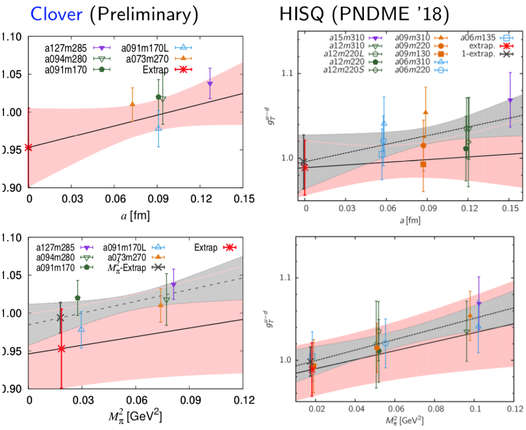


Mainz

$$g_T^{u-d} = 0.929(14)$$

$N_f = 2+1+1$, physical mass, $64^3 \times 128$

ETMC

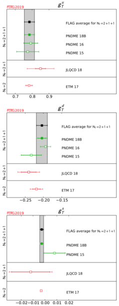


0.967(31) 0.989(32)

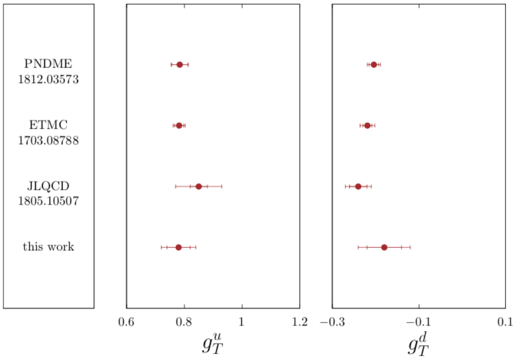
FLAG review:

Collaboration	N_f	pub.	cont.	chiral	vol.	ren.	states	g_T^u	g_T^d
PNDME 18B	2+1+1	P	★‡	★	★	★	★	0.784(28)(10)#	−0.204(11)(10)#
PNDME 16	2+1+1	A	○‡	★	★	★	★	0.792(42)#&	−0.194(14)#&
PNDME 15	2+1+1	A	○‡	★	★	★	★	0.774(66)#	−0.233(28)#
JLQCD 18	2+1	A	■	○	○	★	★	0.85(3)(2)(7)	−0.24(2)(0)(2)
ETM 17	2	A	■	○	○	★	★	0.782(16)(2)(13)	−0.219(10)(2)(13)
								g_T^s	
PNDME 18B	2+1+1	P	★‡	★	★	★	★	−0.0027(16)#	
PNDME 15	2+1+1	A	○‡	★	★	★	★	0.008(9)#	
JLQCD 18	2+1	A	■	○	○	★	★	−0.012(16)(8)	
ETM 17	2	A	■	○	○	★	★	−0.00319(69)(2)(22)	

$Z_T^{n.s.} = Z_T^s$ assumed. & Only 'connected'. ‡ Not fully O(a) improved.



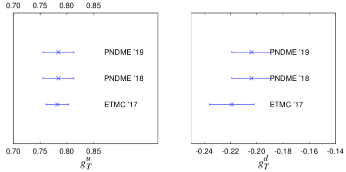
Flavor Diagonal



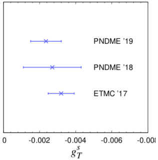
$$g_T^u = 0.78(4)(3) \qquad g_T^d = -0.18(4)(3)$$

Mainz

Preliminary



[PNDME, PRD98, 091501 (2018)]



PNDME

Consider a general mass term

$$m^s + m_5^s\gamma_5 + m^v\tau + m_5^v\tau$$

where τ are diagonal flavor matrices.
Unbroken non-singlet axial symmetry can be used to set all $m_5^v \equiv 0$. We will always choose to do that.
The singlet axial symmetry acts on the remaining $N_f + 1$ masses (m^s, m^v, and m_5^s) and Θ.
Can always eliminate Θ.
When all quark masses nonzero, can eliminate m_5^s instead.
Singular coordinates when some quark-masses zero: $(m_5^s)^{-1} \propto \Theta \sum m_q^{-1}$.

Method 1:

- Include constant electromagnetic field
- Measure energy difference between when spin aligned versus antialigned
- Take limit of zero electromagnetic field. (Difficult because quantized by box size)

Method 2:

- Calculate Vector Current Matrix Element at finite momentum:

$$\overline{u}_N \left[\gamma_\mu \, F_1(q^2) + i \frac{[\gamma_\mu, \gamma_\nu]}{2} q_\nu \, \frac{F_2(q^2)}{2m_N} + (2i\, m_N \gamma_5 q_\mu - \gamma_\mu \gamma_5 q^2) \, \frac{F_A(q^2)}{m_N^2} + \frac{[\gamma_\mu, \gamma_\nu]}{2} q_\nu \gamma_5 \, \frac{F_3(q^2)}{2m_N} \right] u_N$$

- Take zero momentum limit.
- Definition of CP violation for composite field N tricky.

With no parity in the theory, the propagator is

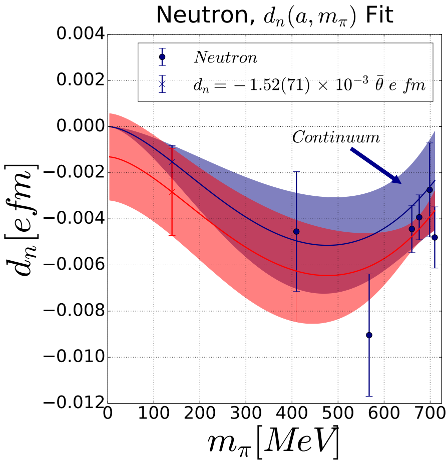
$$\sum \rho(\mu^2) Z_N(\mu^2) \frac{e^{-`\beta(\mu^2)\gamma_5'} \not{p} + e^{-i\alpha(\mu^2)\gamma_5} Z_m(\mu^2)\mu}{p^2 - (Z_m(\mu^2)\mu)^2} .$$

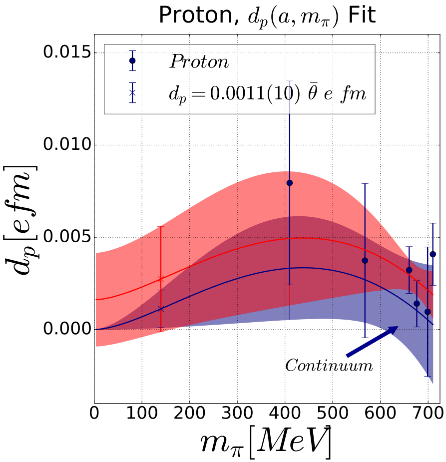
$\alpha(\mu^2) = 0$ when CP conserved, $\beta(\mu^2) = 0$ when PT is conserved.
Asymptotic state has non-standard Dirac equation and parity generator: a tranformation of γ-matrices needed to put in standard basis.
$\bar{u}_N \tilde{F}_{\mu\nu} \sigma^{\mu\nu} u_N$ may not break CP!

Abramczyk, *PRD* **96** (2017) 014501.

$N_{\rm st} = \exp\{(-\beta(m_N^2) + i\alpha(m_N^2))/2\} N$ is a more convenient operator. (Excited states still non-standard.)
Most previous calculations show no signal.

First full calculation





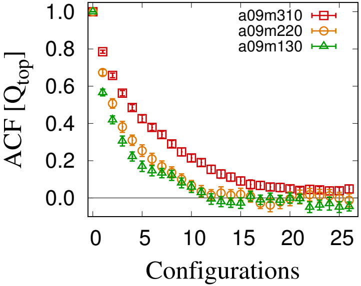
Dragos *et al.*, arXiv:1902.03254 [hep-lat]

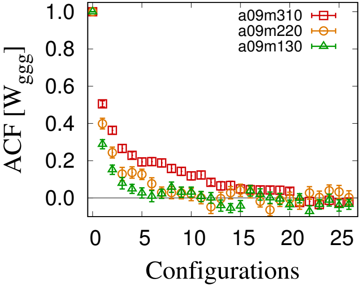
- Clover fermions on MILC HISQ lattices; $N_F = 2+1+1$

Ensemble	a (fm)	M_π (MeV)	$L^3 \times T$	$M_\pi L$	N_{conf}	N_{meas}
$a12m220L$	0.1189(09)	227.6(1.7)	$40^3 \times 64$	5.49	1000	128k
$a09m310$	0.0888(08)	313.0(2.8)	$32^3 \times 96$	4.51	2196	140k
$a09m220$	0.0872(07)	225.9(1.8)	$48^3 \times 96$	4.79	961	123k
$a09m130$	0.0871(06)	138.1(1.0)	$64^3 \times 96$	3.90	1289	165k

- Chroma QCD software suite
- Nucleon two- and three-point correlators
  - Truncated solver method (AMA) with 4HP + 128 or 64 LP per configuration
  - Current is renormalized by isovector vector charge g_V
- Topological charge and Weinberg's three-gluon operator
  - $\mathcal{O}(a^4)$-improved gluon field strength tensor
  - Gradient flow for cooling/renormalization

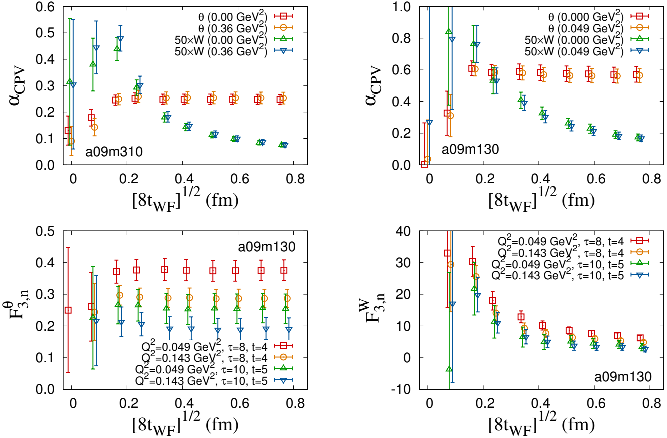
Autocorrelation





$(\sqrt{8t_{WF}} = 0.34 \text{ fm})$

Ensemble	a09m130	a09m220	a09m310	a12m220L
$\langle Q_{top} \rangle$	−0.30(31)	−0.30(27)	−0.01(13)	0.24(46)
$\langle W_{ggg} \rangle$	8(21)	−13(16)	−0.07(6.91)	−25(43)
F_3 anly. binsize	11	8	18	10

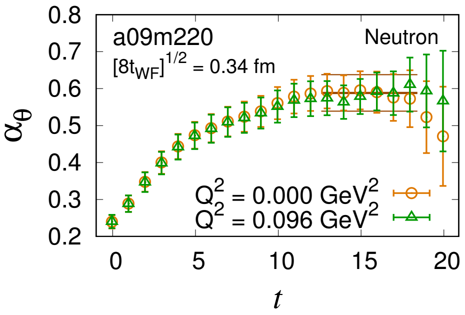


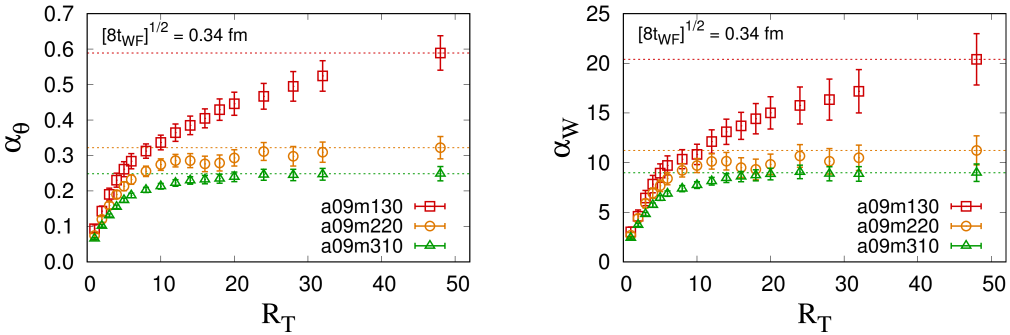
- Topological charge observables are saturating at $\sqrt{8t_{WF}} = 0.34$ fm

- CPV Phase α is extracted from γ_5-projected $C_{2\text{pt}}$

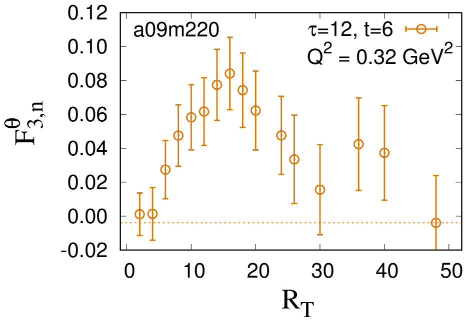
$$\frac{\text{Im}C^{P}_{2\text{pt}}(t)}{\text{Re}C_{2\text{pt}}(t)} \equiv \frac{\text{Im}\left[\gamma_5 \frac{1}{2}(1+\gamma_4)\langle N(t)\overline{N}(0)\rangle\right]}{\text{Re}\left[\frac{1}{2}(1+\gamma_4)\langle N(t)\overline{N}(0)\rangle\right]} = \frac{M_N \sin(2\alpha(t))}{E_N + M_N \cos(2\alpha(t))}$$

- Final α is obtained from plateau average over $\alpha(t \gg 1)$ where ESC is small

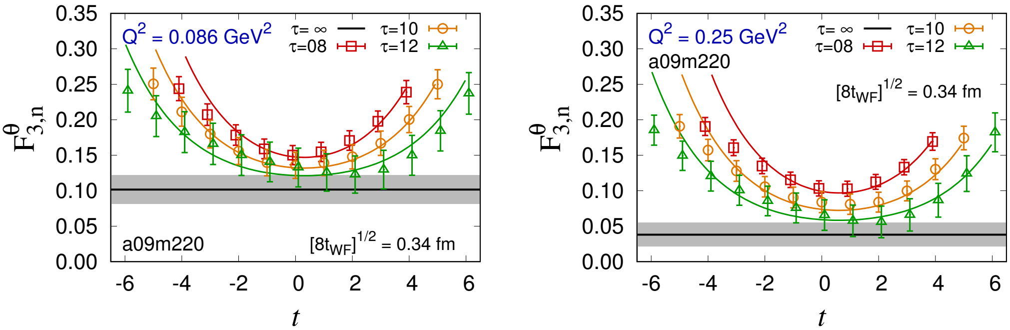




- Topological charge summed only within $|t_Q - t_{\rm src}| \leq R_T$
- CPV phase α forms plateau at $R_T \approx 25a$ for a09m310 and a09m220, but no saturation in a09m130; we use $R_T = \infty$ for α in this study
- Neutron F_3^N at small Q^2 is insensitive to α because of the $G_E^N(Q^2)$ suppression

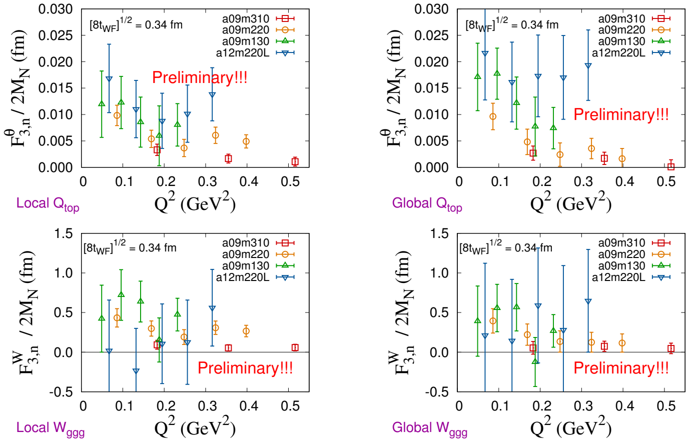


- Saturation depends on the distance from the current insertion t rather than $t_{\rm src}$
  $\longrightarrow$ Topological charge locally summed in $|t_Q - t| \le R_T$
- For most of the momenta, τ and t,
  $R_T/a =$ **14** (a09m310), **20** (a09m220), **36** (a09m130) and **12** (a12m220L)
  produce reasonable results



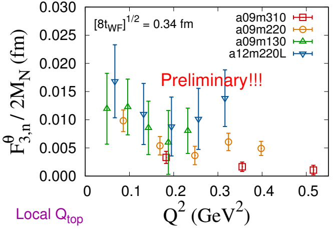
- **Two-state fit** to the F_3/g_V obtained at each τ and t

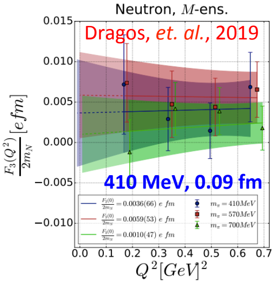
Results

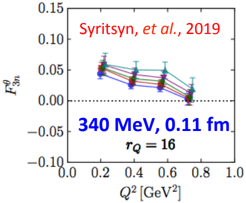


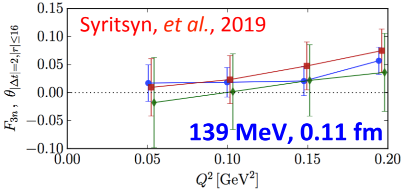
[8t_WF]^1/2 = 0.34 fm
a09m310
a09m220
a09m130
a12m220L
Preliminary!!!
F^θ_3,n / 2M_N (fm)
F^W_3,n / 2M_N (fm)
Q^2 (GeV^2)
Local Q_top
Global Q_top
Local W_ggg
Global W_ggg

This work


[8t_WF]^1/2 = 0.34 fm
a09m310
a09m220
a09m130
a12m220L
Preliminary!!!
F^θ_3,n / 2M_N (fm)
Q^2 (GeV^2)
Local Q_top


Neutron, M-ens.
Dragos, et. al., 2019
410 MeV, 0.09 fm
F_3(Q^2)/2m_N [e fm]
Q^2 [GeV]^2
F_3(0)/2m_N = 0.0036(66) e fm
F_3(0)/2m_N = 0.0059(53) e fm
F_3(0)/2m_N = 0.0010(47) e fm
m_π = 410MeV
m_π = 570MeV
m_π = 700MeV


Syritsyn, et al., 2019
340 MeV, 0.11 fm
r_Q = 16
F^θ_3n
Q^2 [GeV^2]

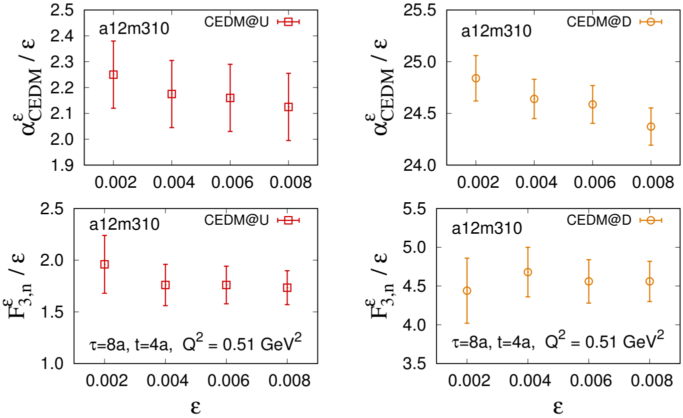

Syritsyn, et al., 2019
139 MeV, 0.11 fm
F_3n, θ_|Δt|=2,|r|≤16
Q^2 [GeV^2]

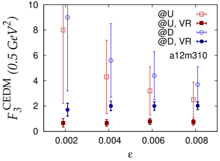
- Clover fermions on MILC HISQ lattices; $N_F = 2 + 1 + 1$

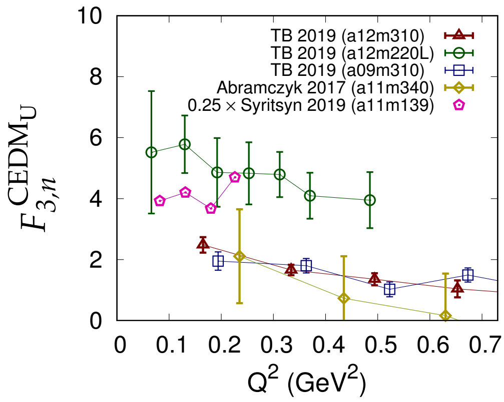
Ensemble	a (fm)	M_π (MeV)	$L^3 \times T$	$M_\pi L$	N_{conf}	N_{meas}
$a12m310$	0.1207(11)	310.2(2.8)	$32^3 \times 64$	4.55	1012	130k
$a12m220L$	0.1189(09)	227.6(1.7)	$40^3 \times 64$	5.49	475	61k
$a09m310$	0.0888(08)	313.0(2.8)	$32^3 \times 96$	4.51	447	57k

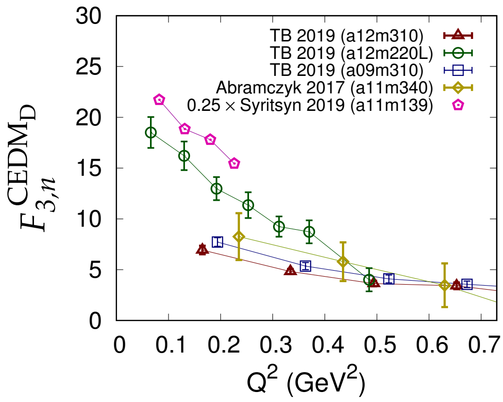
- Chroma QCD software suite
- Truncated solver method (AMA) with 4HP + 128LP per configuration
- Variance reduction using correlated zeros
- Results without renormalization
- Two CPV operators that mix under renormalization: $\frac{i}{2}\bar{q}(\sigma \cdot G)\gamma_5 q$ and $-i\bar{q}\gamma_5 q$

Linearity


a12m310
CEDM@U
CEDM@D
$\alpha^{\varepsilon}_{\text{CEDM}} / \varepsilon$
$F^{\varepsilon}_{3,n} / \varepsilon$
τ=8a, t=4a, Q^2 = 0.51 GeV^2
ε
2.5
2.4
2.3
2.2
2.1
2.0
1.9
25.5
25.0
24.5
24.0
1.5
1.0
5.5
5.0
4.5
4.0
3.5
0.002
0.004
0.006
0.008


@U
@U, VR
@D
@D, VR
a12m310
F_3^{CEDM} (0.5 GeV^2)
ε
0
2
4
6
8
10
0.002
0.004
0.006
0.008





- Syritsyn 2019 (a11m139) results are scaled by $\frac{1}{4}$ to make it fit within range
- No renormalization, no mixing, no continuum extrapolation!

- Quark edm contribution to nEDM has already had impact.
- Theta-term contribution is likely to be under control soon.
- CP-violating pion couplings are at the same level.
- Techniques for the gluon and quark chromo-EDM contributions are being developed.
- Four-quark operators need more study.