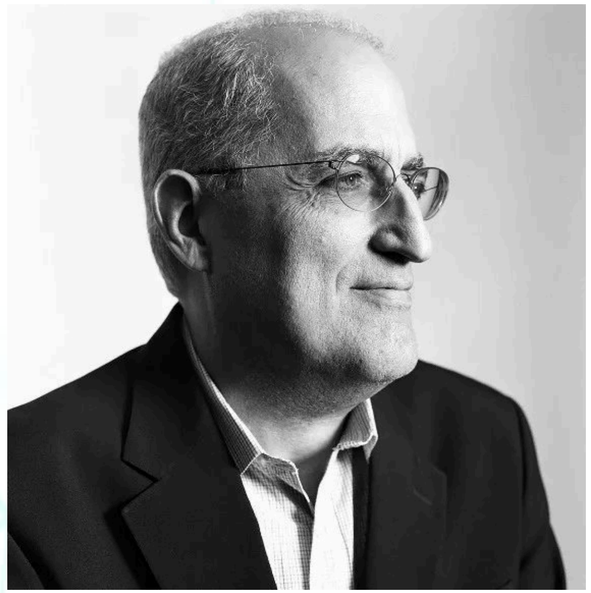
Theta Induced Nucleon EDM from Overlap Fermions

梁剑（华南师范大学 量子物质研究院）

xQCD Collaboration

04/28/2023 @ 彭桓武理论物理创新研究中心与中国高等科学技术中心(CCAST)联合项目“强子质量的非微扰起源”第十天 暨基金委格点QCD重大项目课题二“强子结构及其重整化的格点量子色动力学研究”启动会

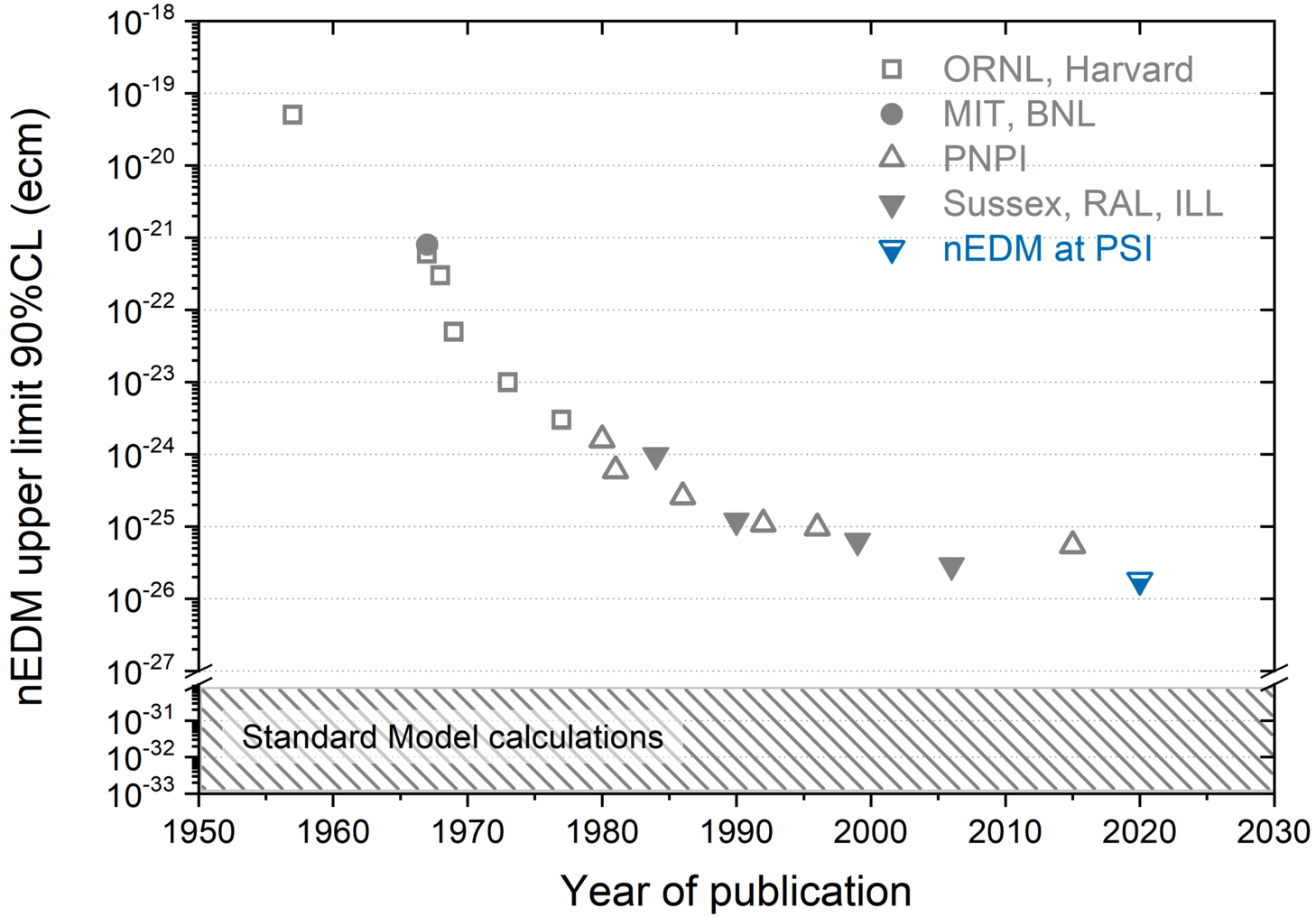
arXiv:2301.04331

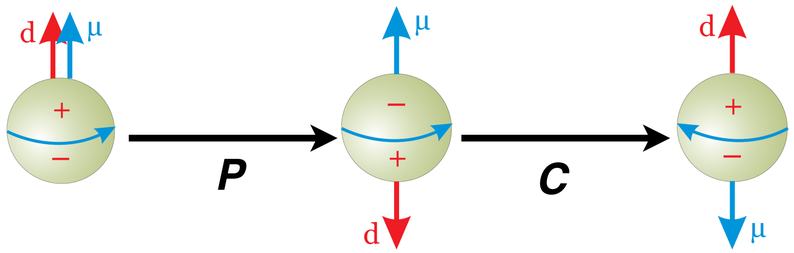


“It is also important to look for electron or neutron electric dipole moments, which may give a new physical signal, and under the energy scales we have already observed”

— Edward Witten: Where is the New Physics Lurking? (cern courier 2022)

Nucleon EDM and CP-Violation





Nucleon EDM (NEDM) is a sensitive probe of CP violation (CPV).

The contribution to the NEDM from the weak CP-violating phase is 5 orders of magnitude smaller than the current experimental limit.

Strong CPV ($G_{\mu\nu}\tilde{G}_{\mu\nu}$) and/or BSM physics?

Nucleon EDM from Lattice QCD

			m_π [MeV]	m_N [GeV]	F_2	α	$\tilde{F}_3$	F_3
PRD93:074503 (2016)	[10]	n	373	1.216(4)	$-1.50(16)^{a}$	$-0.217(18)$	$-0.555(74)$	0.094(74)
PRD72:014504 (2005)	[5]	n	530	1.334(8)	$-0.560(40)$	$-0.247(17)^{b}$	$-0.325(68)$	$-0.048(68)$
		p	530	1.334(8)	0.399(37)	$-0.247(17)^{b}$	0.284(81)	0.087(81)
PRD73:054509 (2006)	[6]	n	690	1.575(9)	$-1.715(46)$	$-0.070(20)$	$-1.39(1.52)$	$-1.15(1.52)$
		n	605	1.470(9)	$-1.698(68)$	$-0.160(20)$	0.60(2.98)	1.14(2.98)
PRL115:062001 (2015)	[8]	n	465	1.246(7)	$-1.491(22)^{c}$	$-0.079(27)^{d}$	$-0.375(48)$	$-0.130(76)^{d}$
		n	360	1.138(13)	$-1.473(37)^{c}$	$-0.092(14)^{d}$	$-0.248(29)$	$0.020(58)^{d}$

Watershed: *Abramczyk et al., PRD96:014501 (**2017**)* $F_3 = \tilde{F}_3 + 2\alpha^1 F_2$

		Neutron $\overline{\Theta}$ e · fm	Proton $\overline{\Theta}$ e · fm
This Work		$d_n = -0.003(7)(20)$	$d_p = 0.024(10)(30)$
This Work with $N\pi$		$d_n = -0.028(18)(54)$	$d_p = 0.068(25)(120)$
PRD103:054501 (2021) ETMC [66]		$\lvert d_n \rvert = 0.0009(24)$	–
PRC103:015202 (2021) Dragos et al. [44]		$d_n = -0.00152(71)$	$d_p = 0.0011(10)$
arXiv:1901.05455 Syritsyn et al. [67]		$d_n \approx 0.001$	–

T. Bhattacharya et al., PRD103:114507 (2021)

Chiral Symmetry on the Lattice

$$D_{\text{ov}} = \frac{1}{a}[1 + \gamma_5 \text{sgn}(H)] \qquad \text{sgn}(H) = \frac{H}{\sqrt{H^2}} \qquad H(\rho) = \gamma_5 D_w(\rho) = \gamma_5 [D_w(m=0) - \rho]$$

Ginsparg-Wilson relation: $\{\gamma_5, D\} = aD\gamma_5 D$

Massless overlap Dirac operator: $\rho D_{\text{ov}}(\rho)$

Massive overlap Dirac operator: $D_{\text{ov}}(\rho, m) = \rho D_{\text{ov}}(\rho) + m\left(1 - \frac{D_{\text{ov}}(\rho)}{2}\right)$

Effective propagator: $D^{-1} = \frac{1 - \frac{1}{2}D_{\text{ov}}(\rho)}{D_{\text{ov}}(\rho, m)} = \frac{1}{\frac{\rho D_{\text{ov}}(\rho)}{1 - \frac{1}{2}D_{\text{ov}}(\rho)} + m} \equiv \frac{1}{D_c + m}$

D_c is **continuum-like**.

$\{\gamma_5, D_c\} = 0$

NEDM from Overlap Fermions

1. **Well defined chiral limit at finite lattice spacing**
2. Improved algorithms & High statistics
3. CDER
4. Topological charge defined from the overlap operator

3 ensembles with lattice spacing ~0.11 fm

label	$m_{\pi,s}$ (MeV)	$m_{\pi,v}$ (MeV)	N_{cfg}
24I005	339	282 321 348 389	805
24I010	432	426 519 600	508
24I020	560	432 525 606	552

Y. Aoki et al. PRD83:074508 (2011)

The anomalous Ward identity holds for overlap fermions, and it guarantees that $d_n \to 0$ when $m_q \to 0$ even at finite lattice spacings.

P. Hasenfratz, et. al., NPB643:280 (2002)
***J. Liang** et. al., PRD98:074505 (2018)*
D. Guadagnoli, et. al., JHEP 0304, 019 (2003)

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Y. Aoki et al. PRD83:074508 (2011)

Multiple coherent grid sources + inversion with deflation + Stochastic Sandwich method + LMS

Y.-B. Yang et al., PRD93():034503 (2016)

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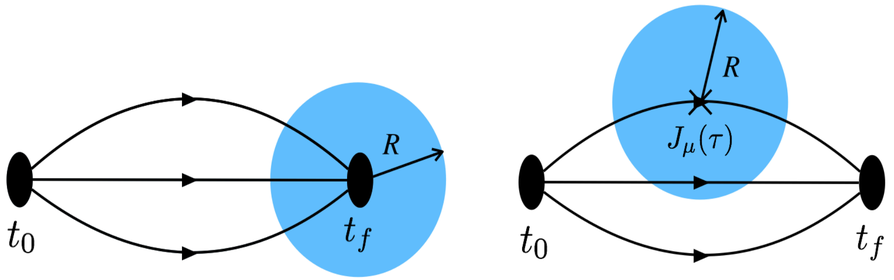
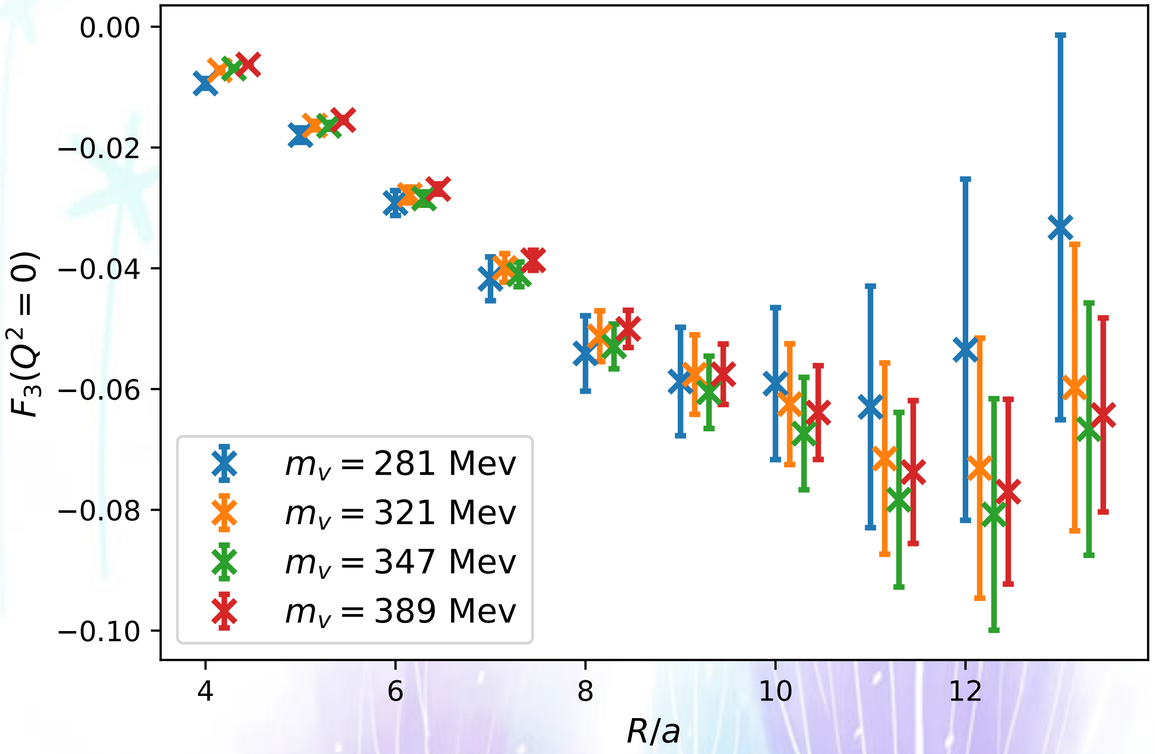
The cluster decomposition error reduction

*Liu, **Liang** and Yang, PRD97:034507 (2018)*

$$Q \to \sum_x q(x)$$





NEDM from Overlap Fermions

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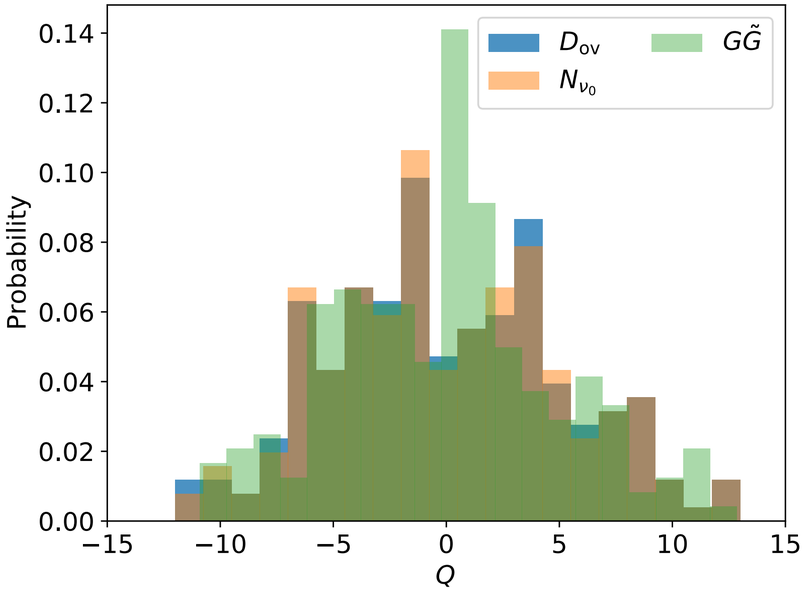
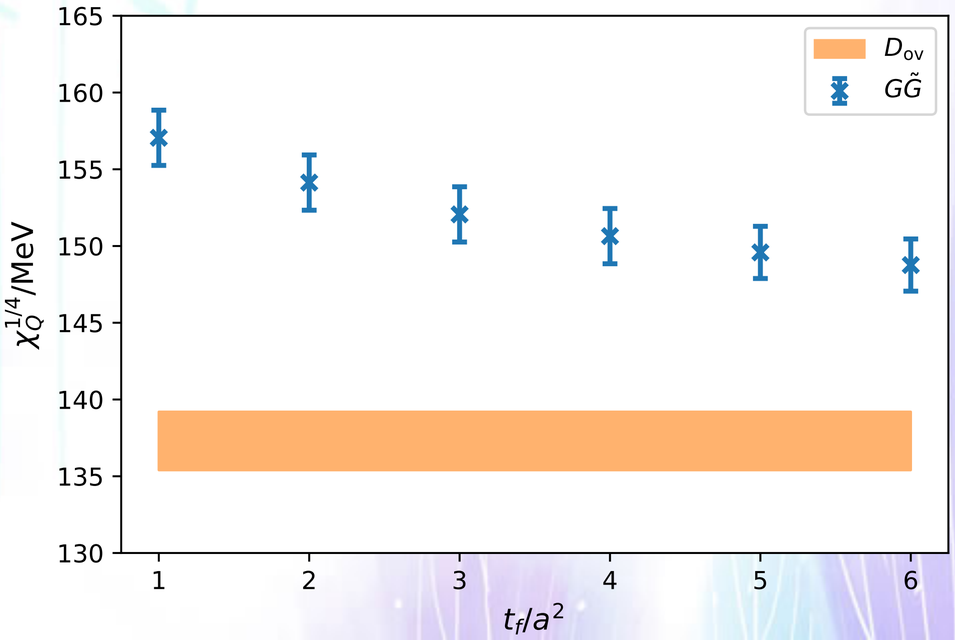
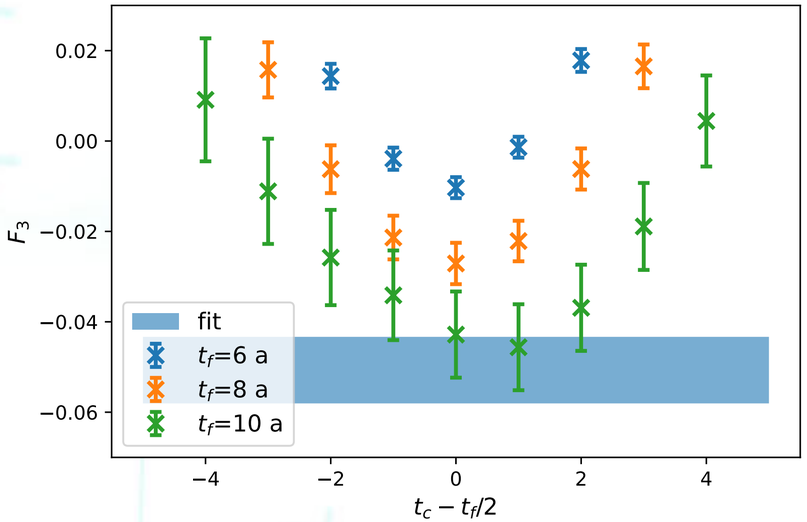
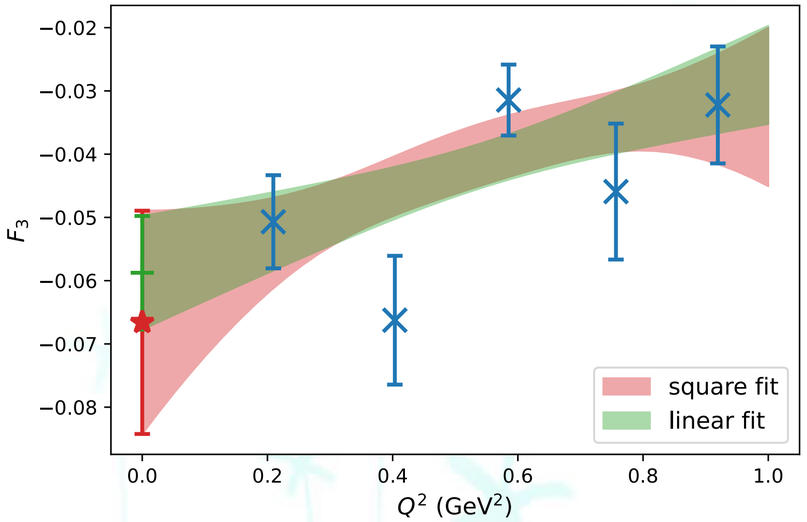
$$q(x) = \frac{1}{2}\mathrm{Tr}[\gamma_5 D_{\mathrm{ov}}]$$

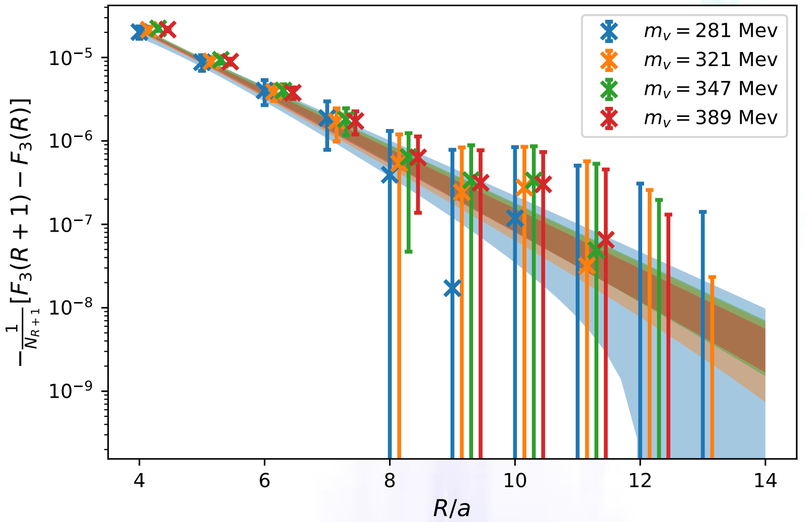




Systematic Uncertainties







The total systematic uncertainty is found to be 22%, which comes from the two-state fits (18%), the momentum extrapolation (4%), the CDER technique (12%) and the chiral extrapolation (3%).

“Partially Quenched” Chiral Extrapolation and Results

$$d_n^{(PQ)} = \frac{e\,\bar{\theta}\,m_{\rm sea}}{4\pi^2 f^2}\left[\,F_\pi\,\log\left(\frac{m_\pi^2}{\mu^2}\right) + F_J\,\log\left(\frac{m_J^2}{\mu^2}\right)\right] + \bar{\theta}\,\frac{e}{\Lambda_\chi^2}\left[\frac{m_{\rm sea}}{2}\,c(\mu) + d\,(m_{\rm sea}-m_{\rm val}) + f q_{jl}\,(m_{\rm sea}-m_{\rm val})\right]$$

D.O’Connell and M. J. Savage, PLB633:319 (2006)

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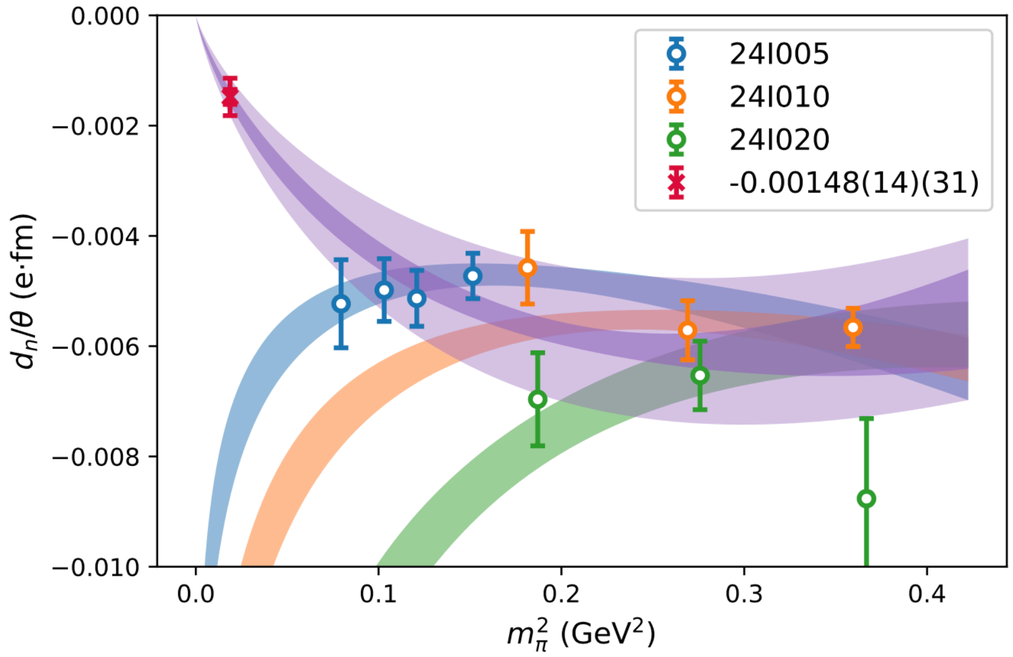

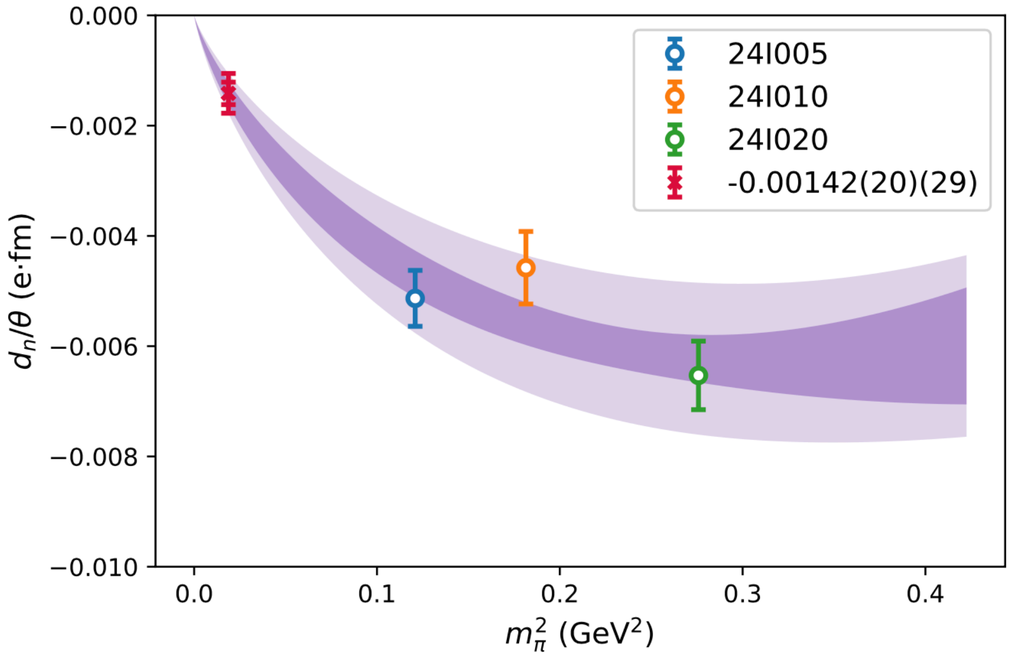

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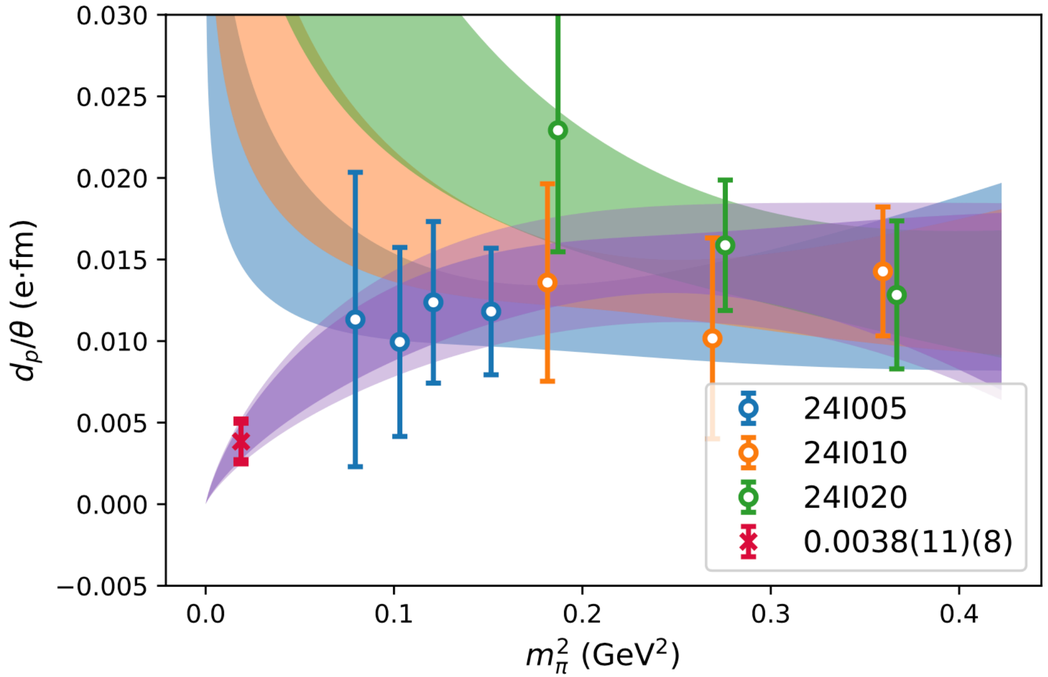

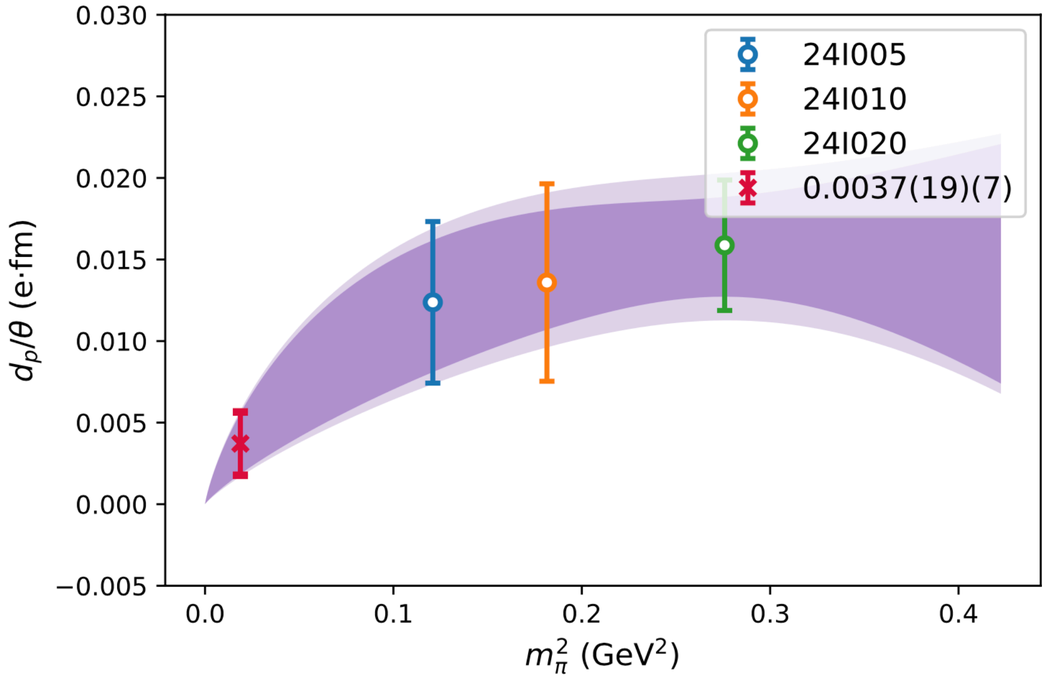

Summary and Outlook

- **Using overlap fermions, we are having very clear signal for nucleon EDM.**

- **Study with lighter pion masses and more lattice spacings is on going.**

Thank you

CP-violating Operators

- **theta term** $iG_{\mu\nu}\tilde{G}_{\mu\nu}$ dim-4
- quark EDM $i\bar{\psi}[\tilde{F}_{\mu\nu}\sigma^{\mu\nu}]\psi$ dim-5
- quark Chromo-EDM $i\bar{\psi}[\tilde{G}_{\mu\nu}\sigma^{\mu\nu}]\psi$ dim-5
- glue Chromo-EDM (Weinberg term) $f^{abc}\tilde{G}^{a\ \nu}_{\mu}G^{a\ \rho}_{\nu}G^{a\ \mu}_{\rho}$ dim-6
- 4-quark operators? $\bar{\psi}\gamma_5\psi\bar{\psi}\psi$ dim-6

Problematic due to renormalization and mixing