Concluding remarks

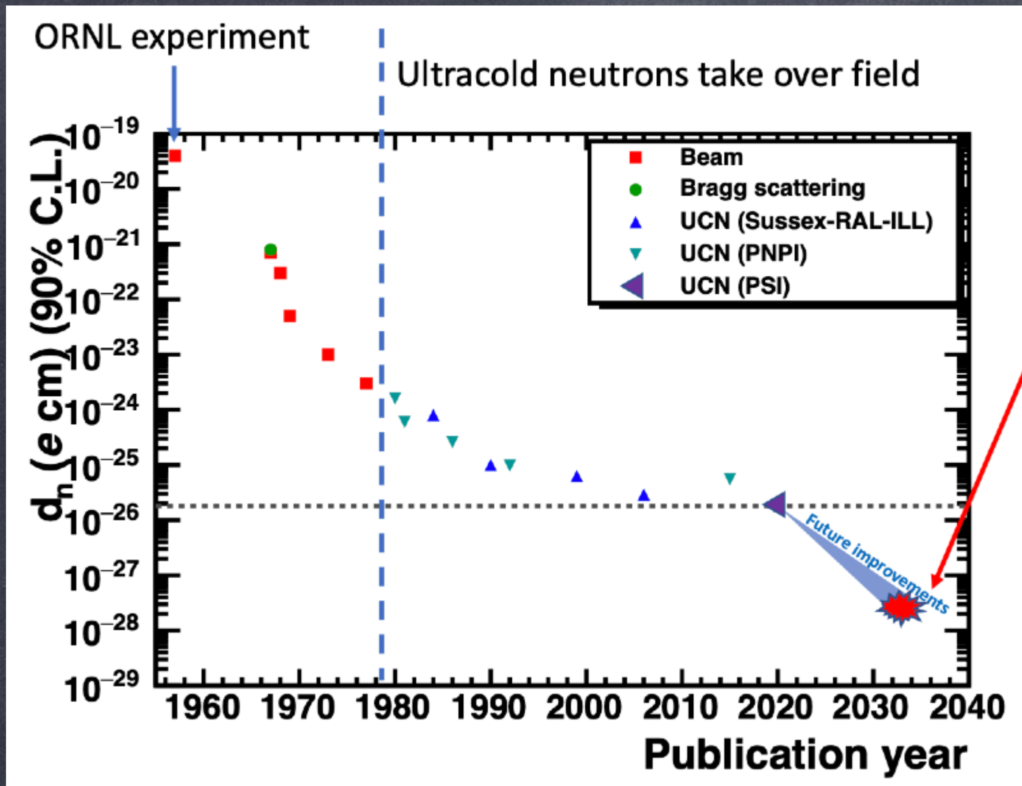
Andreas Athenodorou
Maria Paola Lombardo
Andrea Shindler

Neutron Electric Dipole Moment: from theory to experiment

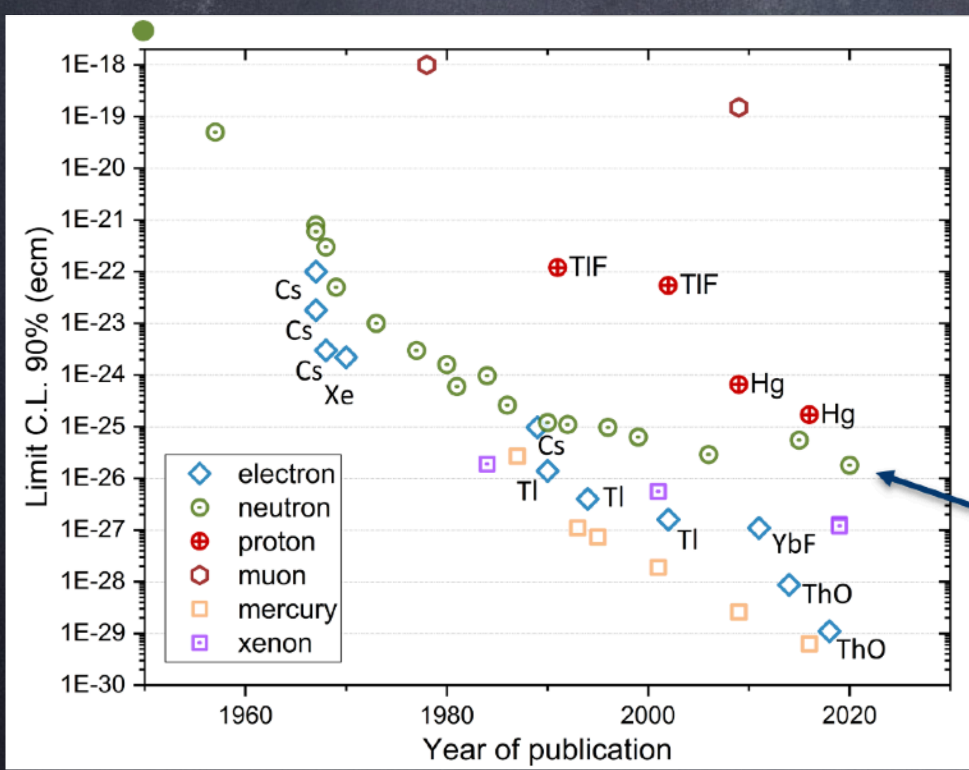
ECT* - Trento

August 1-5, 2022

Experiments



Experiment	Location	UCN source	Features
n2EDM	PSI	Spallation, SD_2	Ramsey method, double cell, ^{199}Hg comagnetometer
PanEDM	ILL	Reactor, LHe	Ramsey method, double cell, ^{199}Hg comagnetometer
LANL nEDM	LANL	Spallation, SD_2	Ramsey method, double cell, ^{199}Hg comagnetometer
Tucan	TRIUMF	Spallation, LHe	Ramsey method, double cell, ^{129}Xe comagnetometer
nEDM@SNS	ORNL	In-situ production in LHe	Cryogenic, double cell, ^{3}He comagnetometer, ^{3}He as the spin analyzer



Smith, Purcell, Ramsey
$d_n < 5 \times 10^{-20}$ e cm
PR 108 (1957) 120

~ 60 years

PSI
$d_n < 1.8 \times 10^{-26}$ e cm (90% C.L.)
Abel C. et al. PRL124 (2020) 081803

Leung: The nEDM @ Spallation Neutron Source experiment: our novel approach and other physics reach

Schmidt-Wellenburg: The most stringent limit on the nEDM and future improvements at PSI

Experiments

Piegsa: BeamEDM – A beam experiment to search for the neutron electric dipole moment

$$\boldsymbol{\sigma(d_n) \approx 5 \times 10^{-26}}\ \textbf{e cm per day}$$

- **Performed proof-of-principle experiments at PSI and ILL**
- **Future competitive full-scale experiment intended for ESS**

- Axion-like particles couple with gluons to induce an oscillating nEDM signal [Abel et al., Phys. Rev. X 7, 041034 (2017)]:

$$\omega_n(t) = |\gamma_n|B_0 \pm \frac{2d_n|E|}{\hbar} + \frac{2|E|\alpha_{\mathrm{ax}}}{\hbar}\cos(\omega_{\mathrm{ax}}t + \phi_{\mathrm{ax}})$$

Amplitude of oscillation (units: e.cm)

phase (free parameter in analysis)

$\omega \approx m_a c^2/\hbar$, Axion-field coherently oscillates:

Degenkolb: Updates on the PanEDM experiment and future outlook

SuperSUN	**Phase I**
Saturated source density [cm^{-3}]	330
Diluted density [cm^{-3}]	63
Density in cells [cm^{-3}]	3.9
PanEDM Sensitivity [1σ, e cm]	
Per run	5.5×10^{-25}
Per day	3.8×10^{-26}
Per 100 days	3.8×10^{-27}

|E| ≈ 2 MV/m

T ≈ 250 s

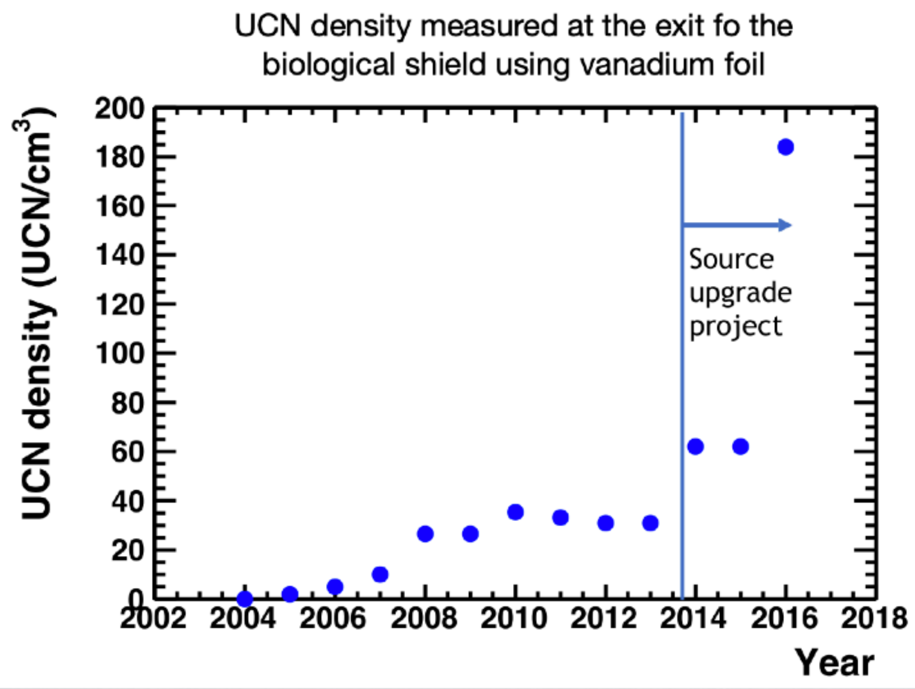
α ≈ 0.85

Transfer losses including dilution: 97-99% (for filling)

1. PanEDM is moving forward
2. Comagnetometry is very hard
3. Statistics can be improved! (systematics not yet clear)

Experiments

Ito: The LANL nEDM Experiment



Parameters	Values
E(kV/cm)	12.0
N(per cell)	39,100
T_{free} (s)	180
T_{duty} (s)	300
α	0.8
σ/day/cell (10^{-26} e-cm)	5.7
σ/day (10^{-26} e-cm) (for double cell)	4.0
σ/year (10^{-27} e-cm) (for double cell)	2.1
90% C.L./year (10^{-27} e-cm) (for double cell)	3.4

$$\delta d_n = \frac{\hbar}{2\alpha E T_{\rm free}\sqrt{N}}$$

*** "year" = 365 live days. In practice, it will take 5 calendar years to achieve this with 50% data taking efficiency**

- MSR was delivered in January 2022. It meets performance requirements. More detailed characterization is necessary.
- nEDM apparatus is being assembled.
- We plan to start an engineering run this summer.
  - We will start with confirming UCN transport and storage.

Theory review

Ramsey-Musolf: EDMs and Baryogenesis

- *Provide a context for drawing implications of EDM measurements for the cosmic baryon asymmetry*
- *Explain how electroweak baryogenesis works*
- *Review recent theoretical developments in EWBG and corresponding phenomenological implications*

- *Electroweak baryogenesis remains a theoretically attractive, phenomenologically viable, and experimentally testable scenario*
- *Collider & gravitational wave searches probe the "pre-conditions" for successful EWBG*
- *EDMs remain the most powerful probe of the necessary CPV for EWBG*
- *Considerable challenges remain at the "theory frontier" to achieve the most robust confrontation of EWBG with experiment*

Covi: Cosmological implications of the Neutron Electric Dipole Moment

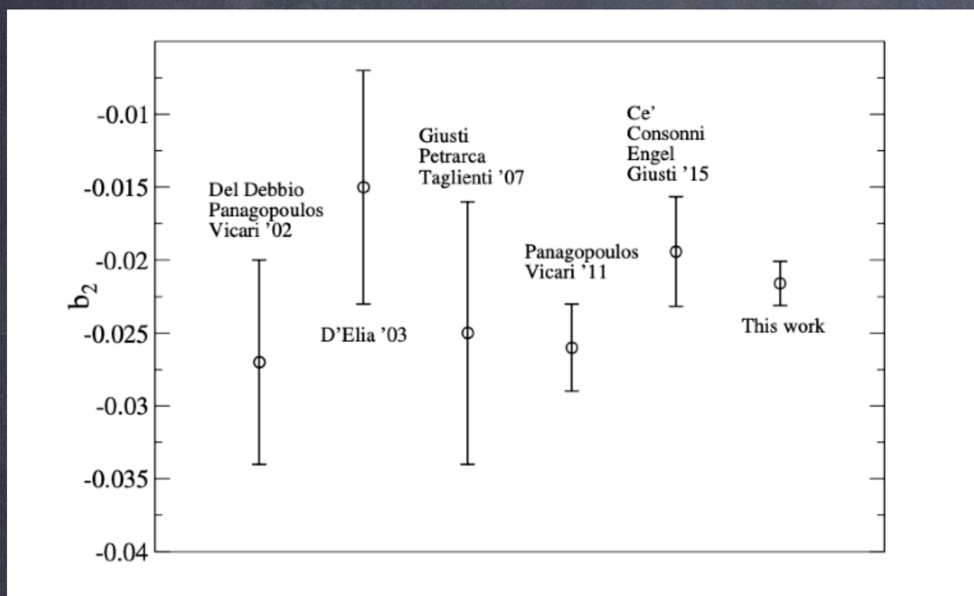
Cosmological implications of nEDM

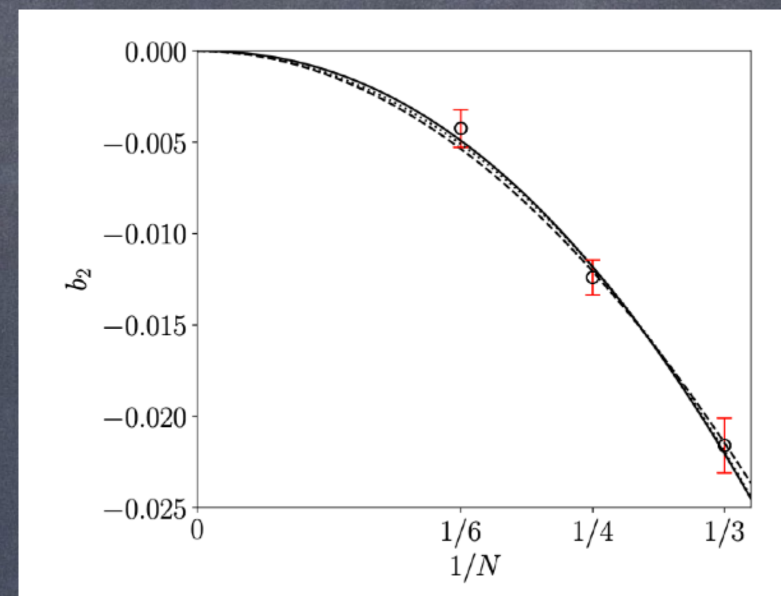
New model where PQ is an accidental symmetry of a new gauged U(1) symmetry

The axion can be DM if there are many exotic quarks, otherwise the RH neutrino can be a FIMP

Theory review

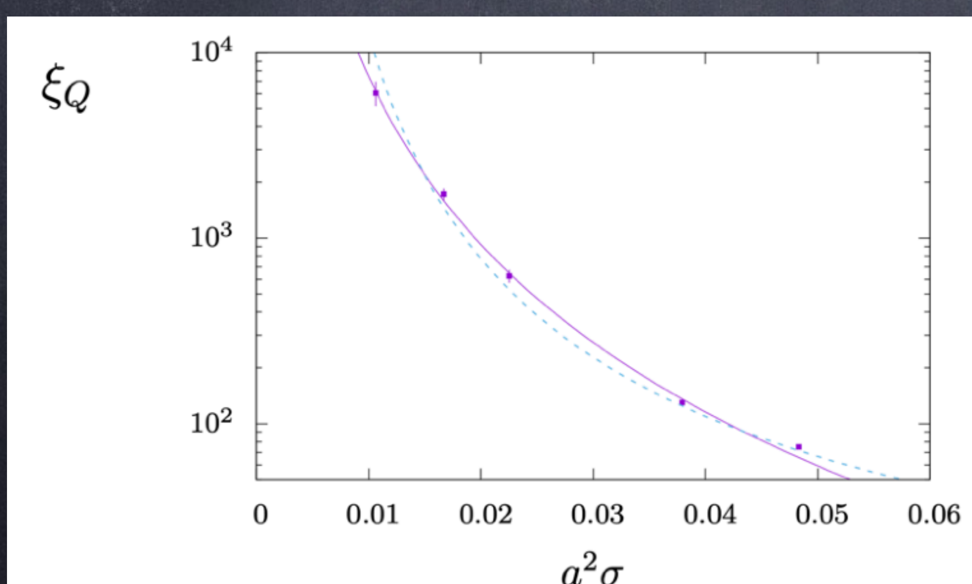
D'Elia: Theta Dependence of QCD and QCD-like Theories





$$b_2 = -0.193(10)/N_c^2$$

Piegsa: BeamEDM – A beam experiment to search for the neutron electric dipole moment



- introduce a suitable defect (M. Hasenbusch 1706.04443, C. Bonanno et al 2205.06190) : computationally expensive

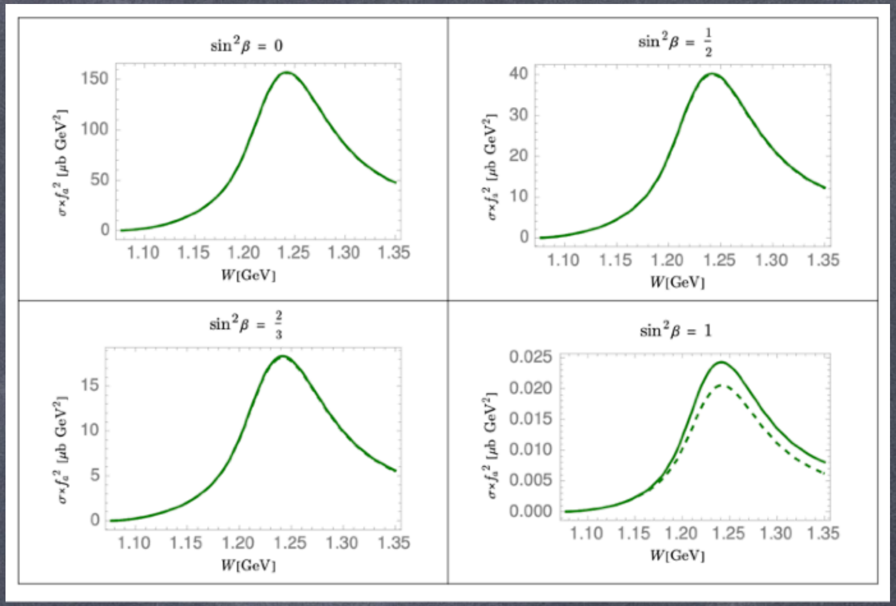
- Problem: given a lattice field $\{U_l\}_0$, how to calculate its physical density $Q(x)$?

$\Longrightarrow$ Some extra methods: 'repetition', blocking, smearing

Theory review

Meißner: Aspects of strong CP violation

- Calculated the θ-dependence of hadron masses and couplings
- Decreasing neutron lifetime for increasing θ, dramatic for $\theta \gtrsim 2.0$
- Deuteron stronger bound, dineutron & diproton bound for $\theta \gtrsim 0.2$ & $\theta \gtrsim 0.7$
- Binding energies of ^{3}H, ^{3}He and ^{4}He also increase
- BBN: ^{4}He mass fraction drops off for $\theta \gtrsim 1.0$
- Stellar evolution: still hydrogen burning, reaction rates of 3α process affected
  $\hookrightarrow$ lack of ^{16}O for $\theta \gtrsim 0.1$
- Constraints on θ from nucleosynthesis, as long as $\theta \lesssim 0.1$, the Universe is not much altered
  $\hookrightarrow$ anthropic principle not at work to explain the tiny θ



$$\sigma(aN \to \pi N) \approx \frac{F_\pi^2}{f_a^2}\sigma(\pi N \to \pi N)$$

Pion axioproduction $10^{-1} - 10^{-5}$ suppressed

CP-violation strong interactions

Tamarit: Cluster decomposition, the index theorem, and the strong CP problem

Garbrecht: Fermion correlations and absence of CP violation in the strong interactions

$$\mathcal{L}_{\rm pion} = \frac{1}{4} f_\pi^2 {\rm Tr} D_\mu U D^\mu U^\dagger + (a f_\pi^3 {\rm Tr} MU + |b| e^{-i\xi} f_\pi^4 {\rm det} U + {\rm h.c.})$$

$$|d_n| \propto (\xi + \alpha_u + \alpha_d + \alpha_s)$$

It is generally thought that $\xi = \theta$ [Baluni, Crewther et al]

$\xi = -\sum_i \alpha_i$ Alternative option → CP conservation

$$d_n \propto (\xi + \sum_i \alpha_i) = 0$$

Only real computation that we know of is `t Hooft's, using dilute instanton gas and yielding $\xi = \theta$ (→ CP violation)

$$\frac{1}{VT}\int d^4x \, \langle \bar\psi_i P_L \psi_i \rangle = \lim_{N\to\infty} \lim_{VT\to\infty} \frac{\sum_{\Delta n=-N}^{N} \frac{1}{VT}\int d^4x \, \langle \bar\psi_i P_L \psi_i \rangle_{\Delta n}}{\sum_{\Delta m=-N}^{N} Z_{\Delta m}} = 2 \mathfrak{m}_i \, \partial_{\mathfrak{m}_i \mathfrak{m}_i^*} \beta(\mathfrak{m}_k \mathfrak{m}_k^*),$$

-2 -2

Topological classification only enforced in infinite volume, which fixes ordering

$VT \to \infty$ **before** $\sum_{\Delta n}$	$\sum_{\Delta n}$ **before** $VT \to \infty$
$\mathcal{L} \to \mathcal{L} - \bar\psi(x)\Gamma e^{i\alpha\gamma^5}\psi(x)$	$\mathcal{L} \to \mathcal{L} + \bar\psi(x)\Gamma e^{-i\theta\gamma^5}\psi(x)$
Alignment with $\bar\psi m \exp(i\alpha\gamma^5)\psi$	Misaligned with $\bar\psi m \exp(i\alpha\gamma^5)\psi$
No CP-violating observables	CP-violating observables

- In order to resolve the ambiguity, we must match effective ${\rm det}U$ term in the chiral Lagrangian with results for correlators in QCD, paying special attention to complex phases

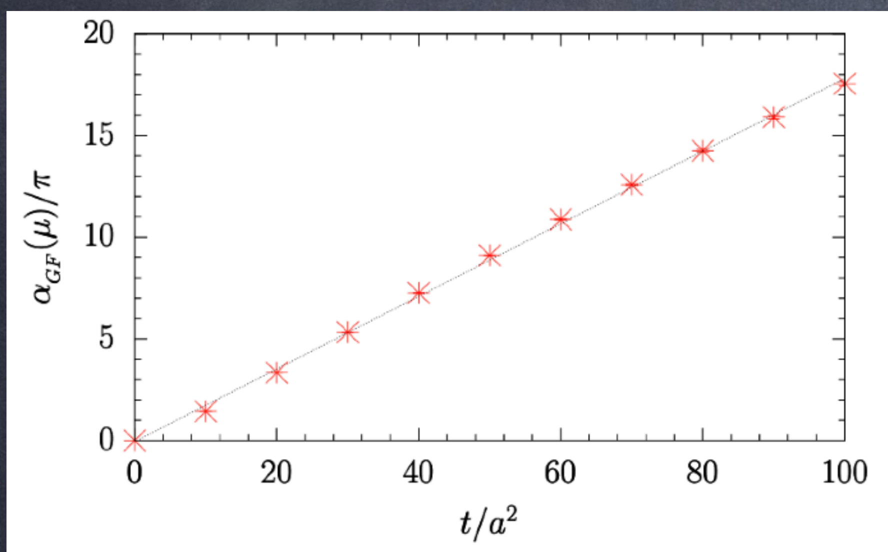
- Next we proceed to calculate the phase of QCD correlators starting from the path integral and using clustering and the index theorem.

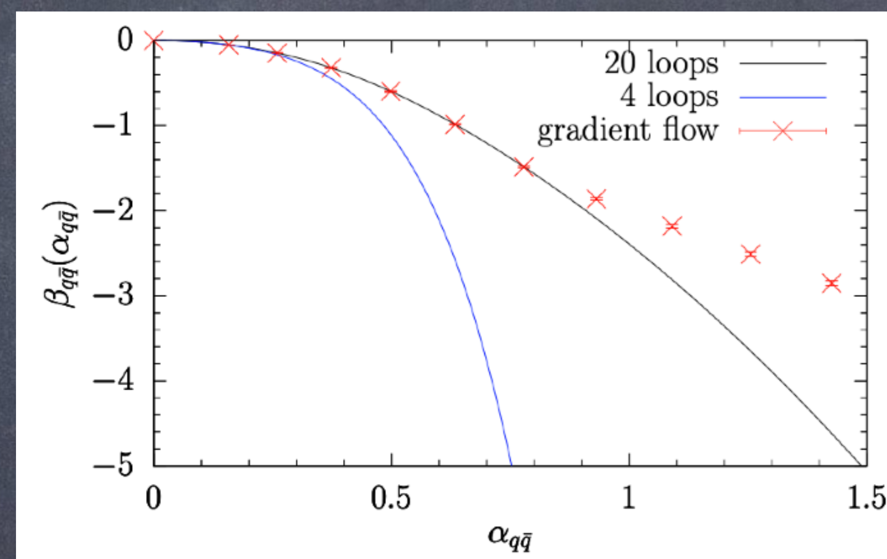
However: The order of limits is not a choice but dictated by the fact that boundary conditions for the topological sectors are imposed at infinity.

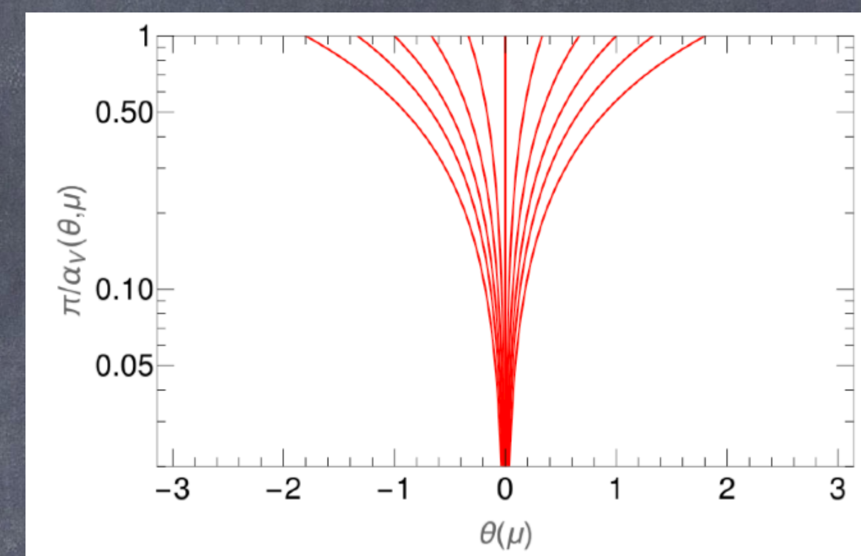
CP-violation strong interactions

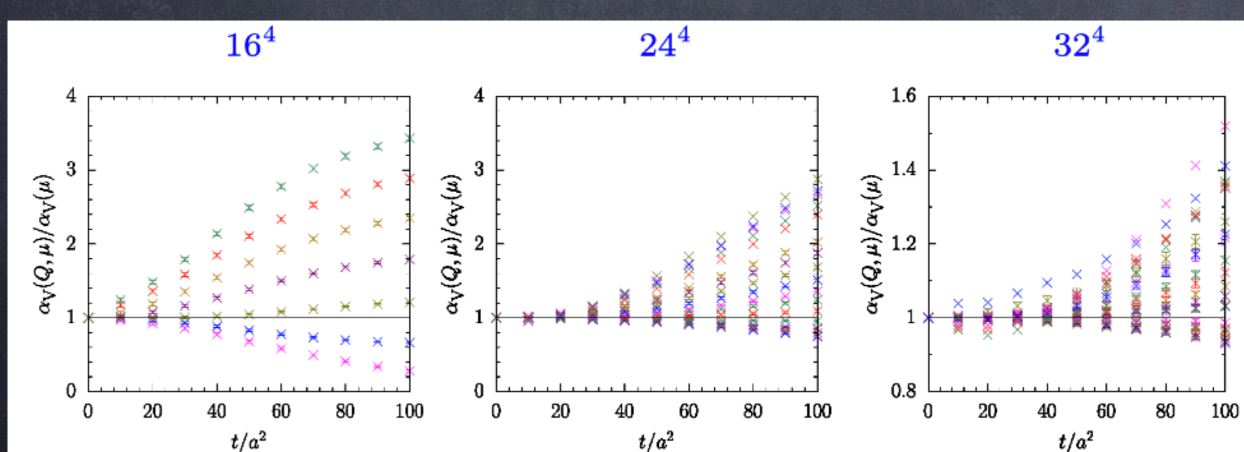
Schierholz: Neutron electric dipole moment from QCD?

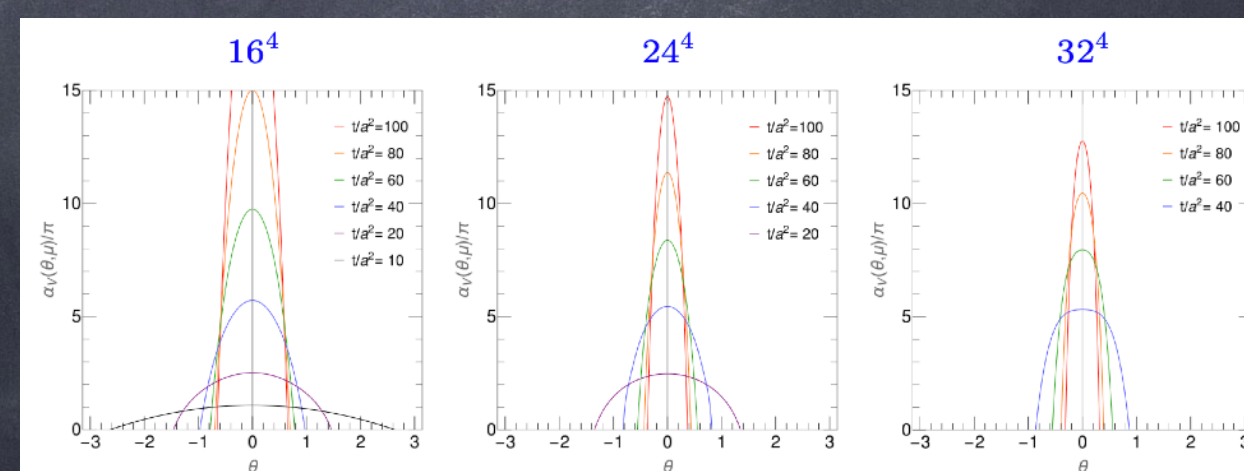
- In this talk I will investigate the long-distance properties of the theory in the presence of the θ term, S_θ, and show that CP is naturally conserved in the confining phase





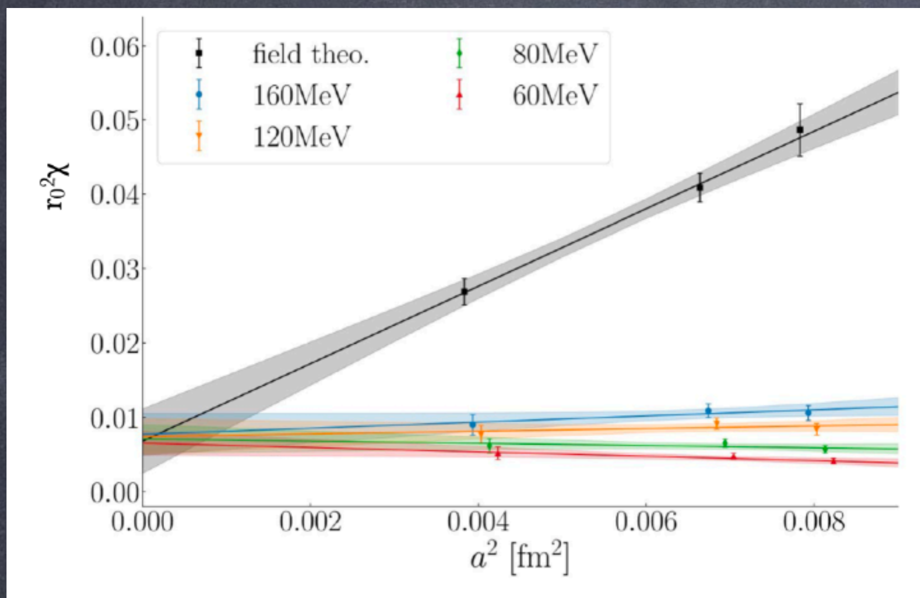


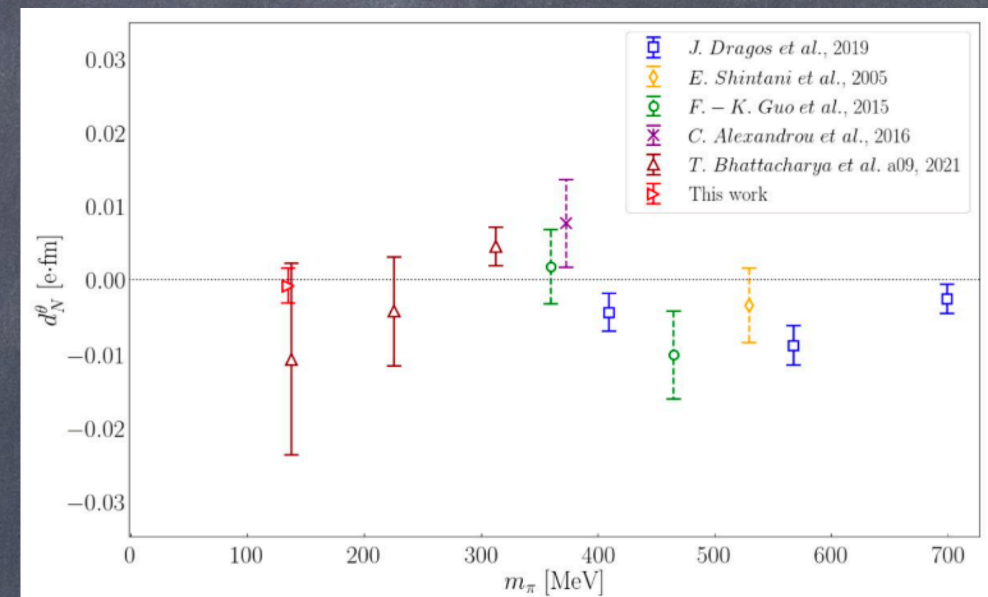




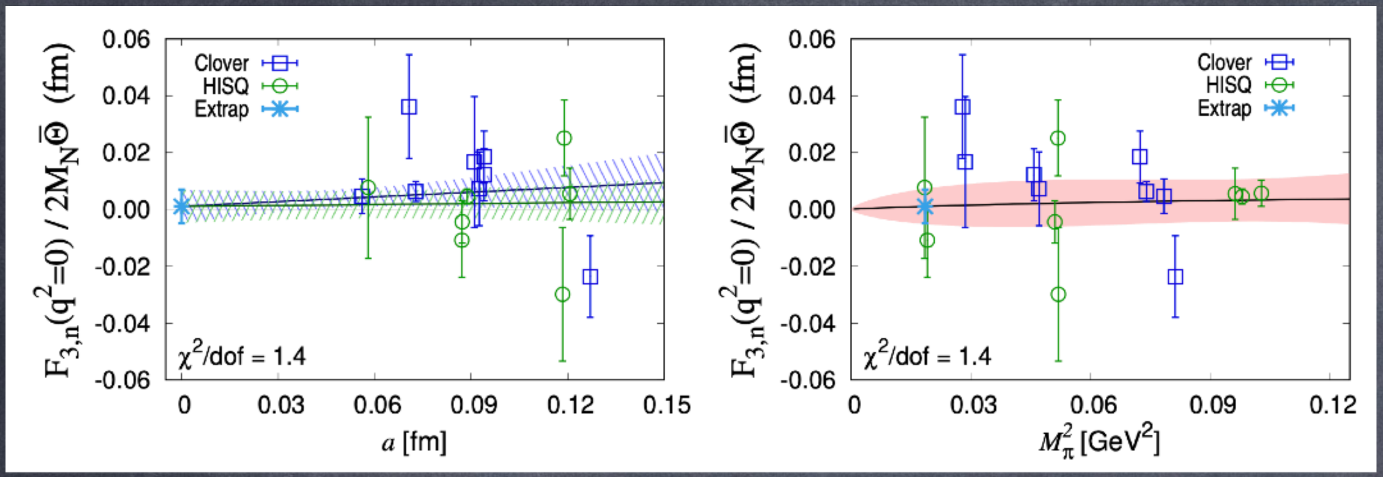
Lattice QCD results

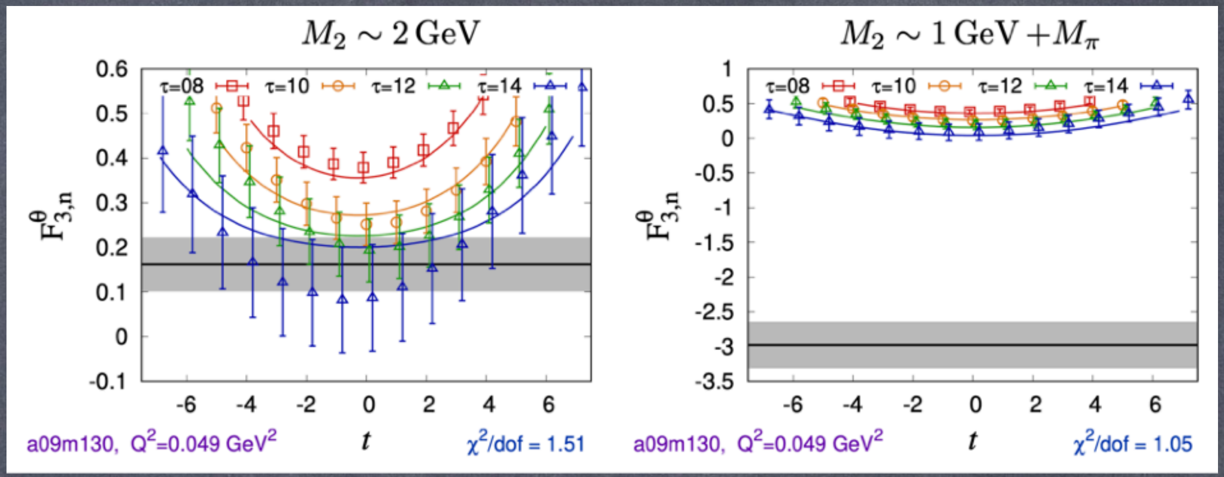
Alexandrou: Neutron electric dipole moment using lattice QCD



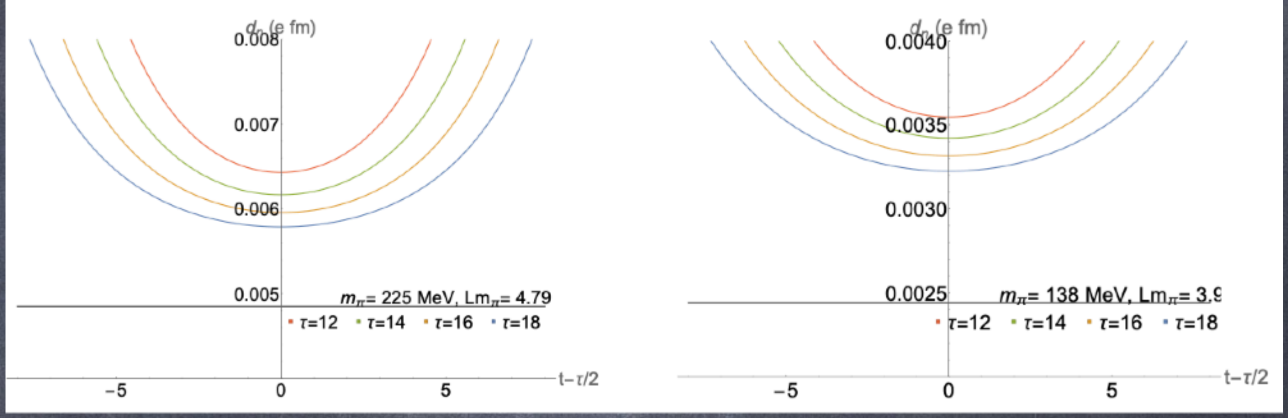


Lattice QCD results

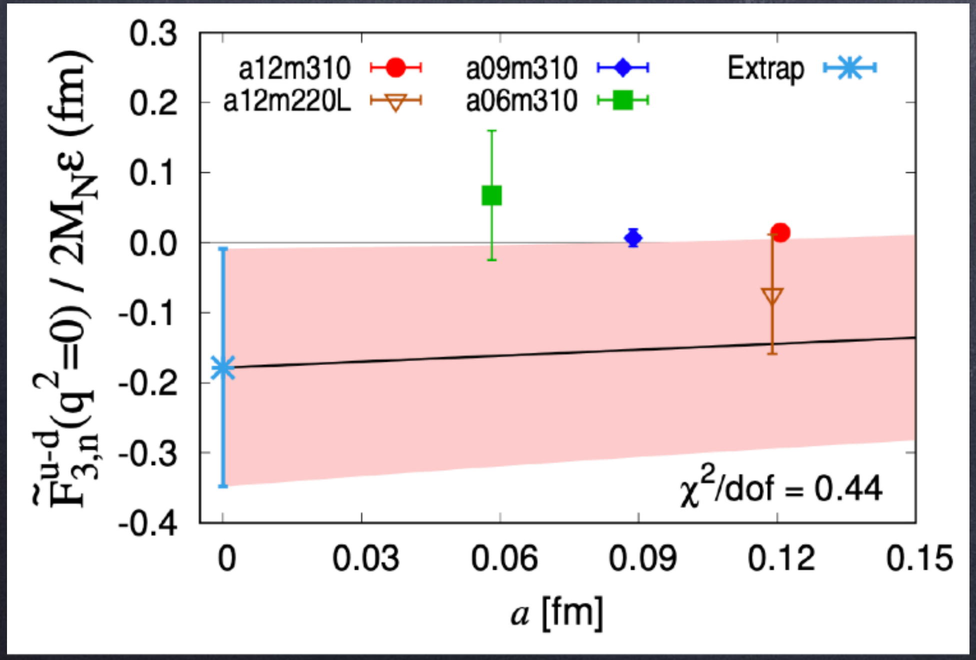


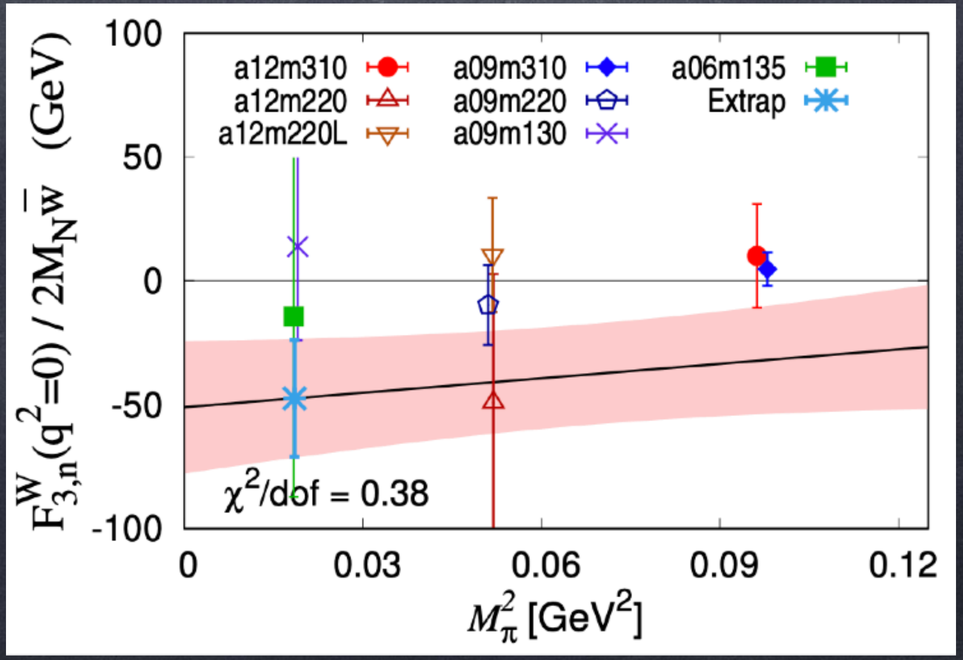


Yoon: Calculation of neutron EDMs on the lattice



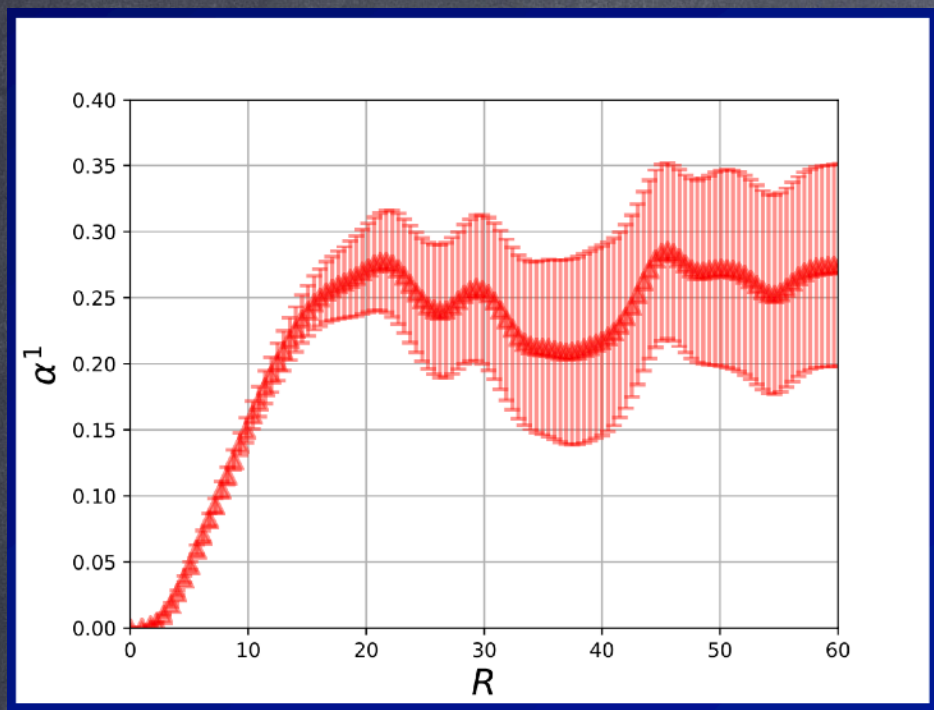
- $g_T^u = 0.784(28)(10)$, $g_T^d = -0.204(11)(10)$, $g_T^s = -0.0027(16)$ [PNDME 18B]

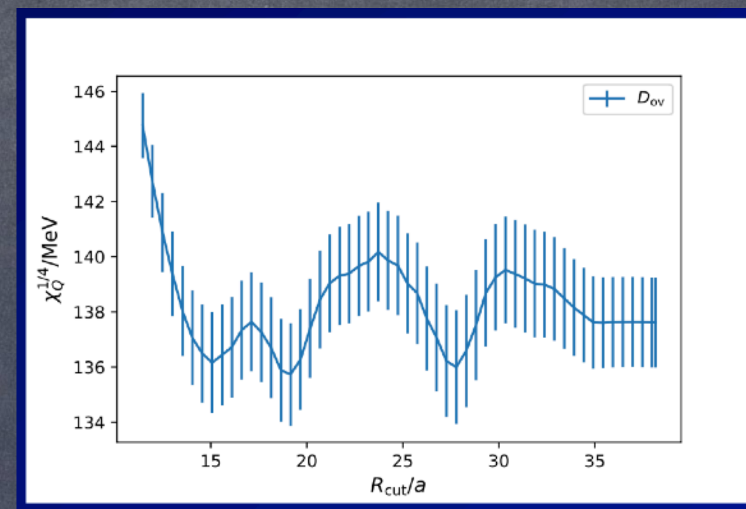


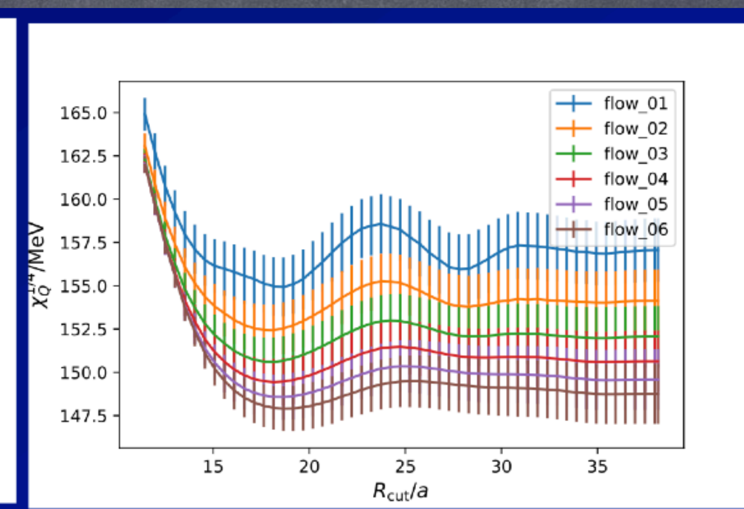


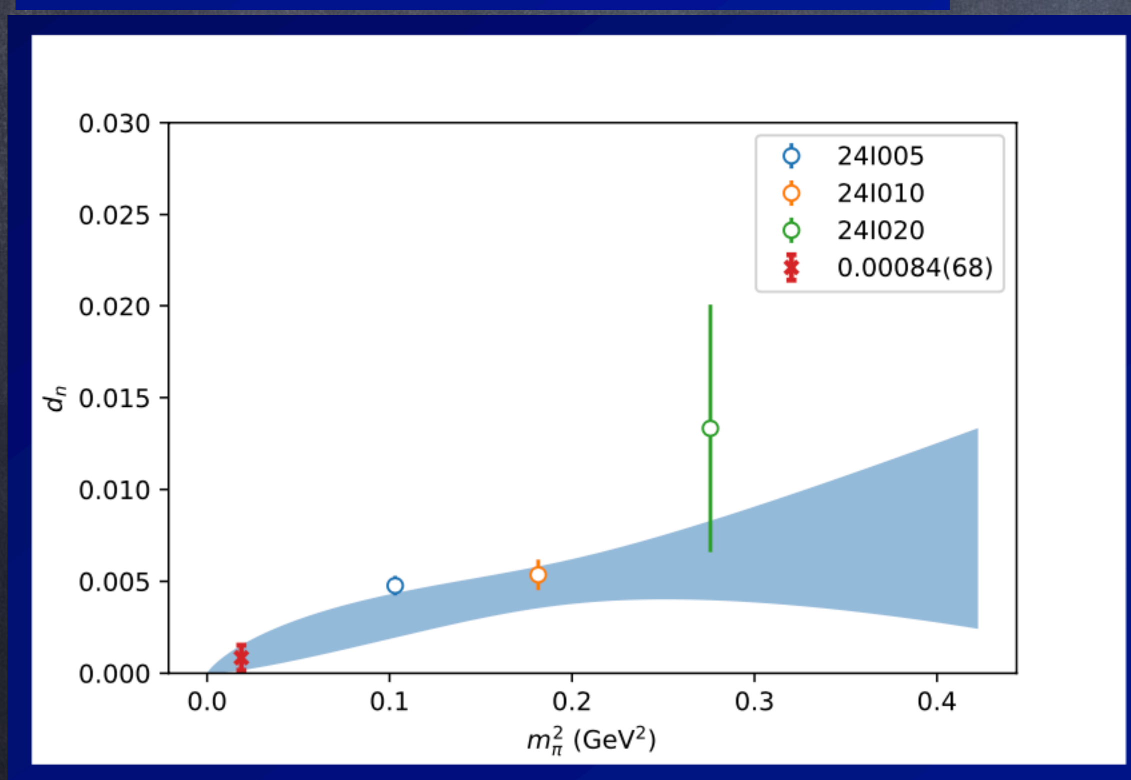
Lattice QCD results

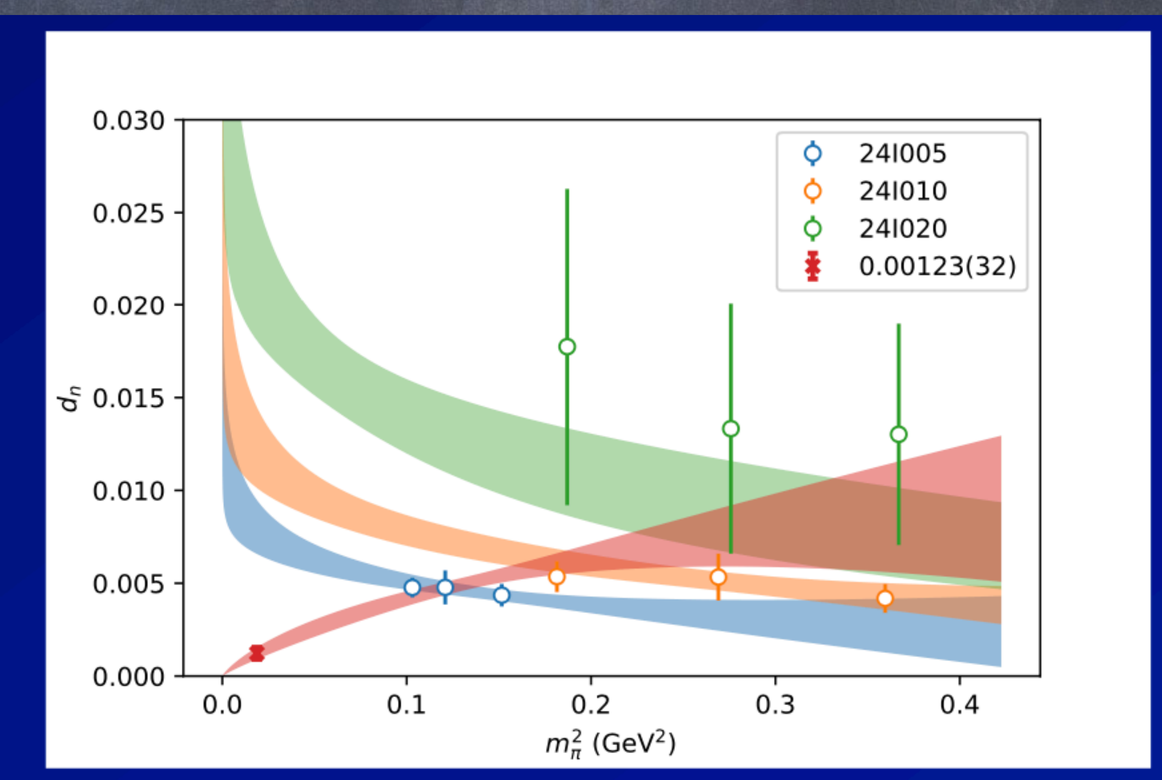
Liu: Neutron Electric Dipole Moment from the Theta Term with Overlap Fermions







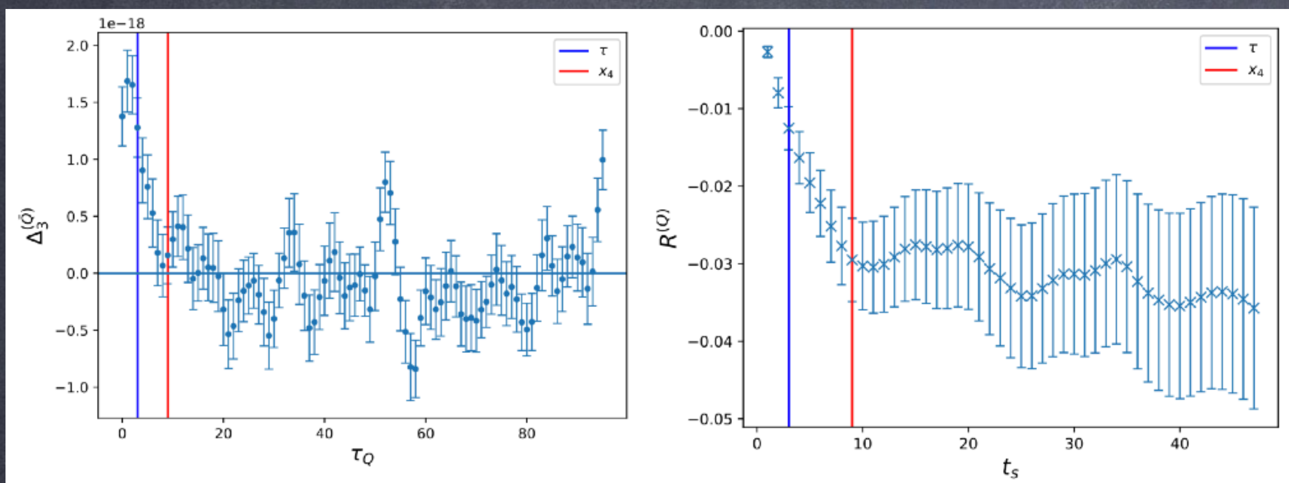


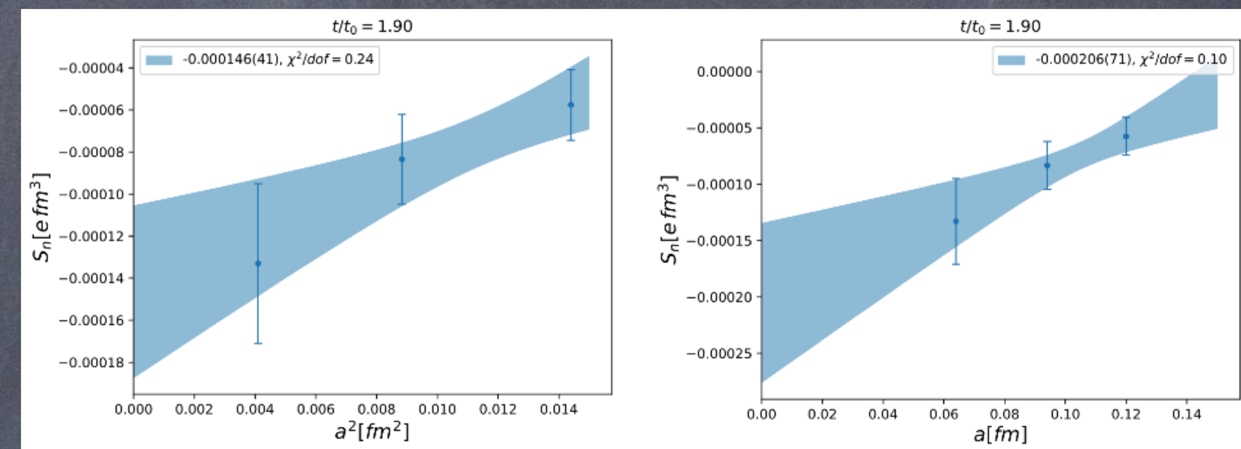


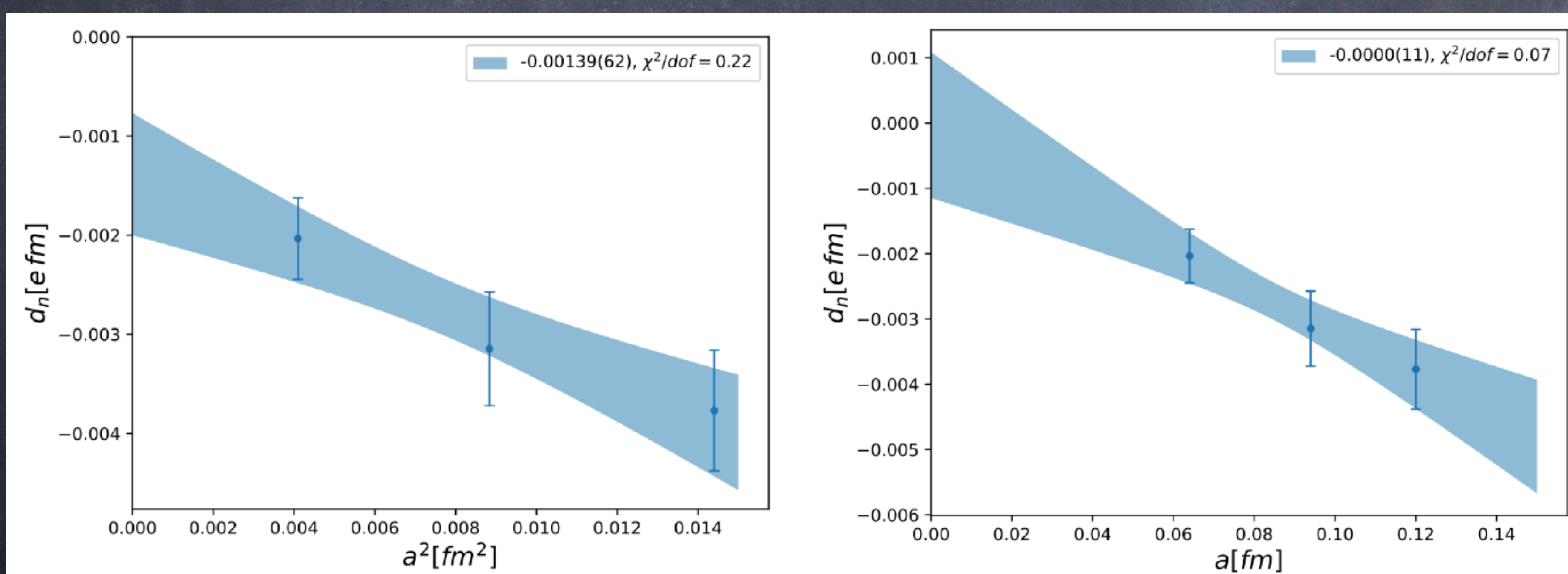
$d_n = 0.00123(32)\ \theta\ e \cdot fm$

Lattice QCD results

Kim: QCD Theta term contribution to nEDM with Stabilized Wilson Fermion on the lattice



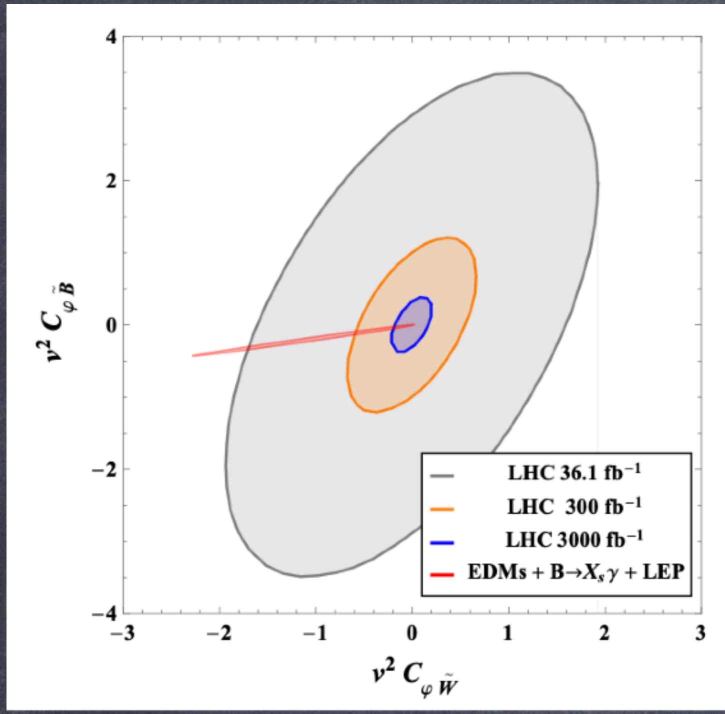


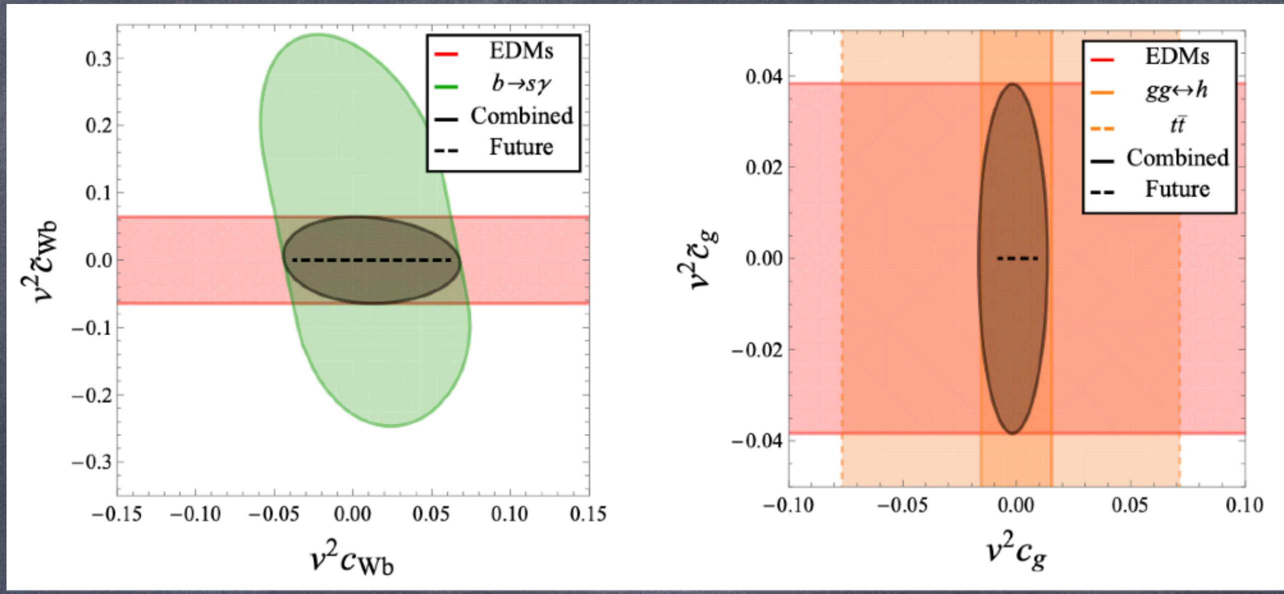


$$S_n = -1.7(3) \times 10^{-4} \bar{\theta} e fm^3$$

Physics BSM with EDM

Mereghetti: Disentangling physics beyond the Standard Model with EDMs

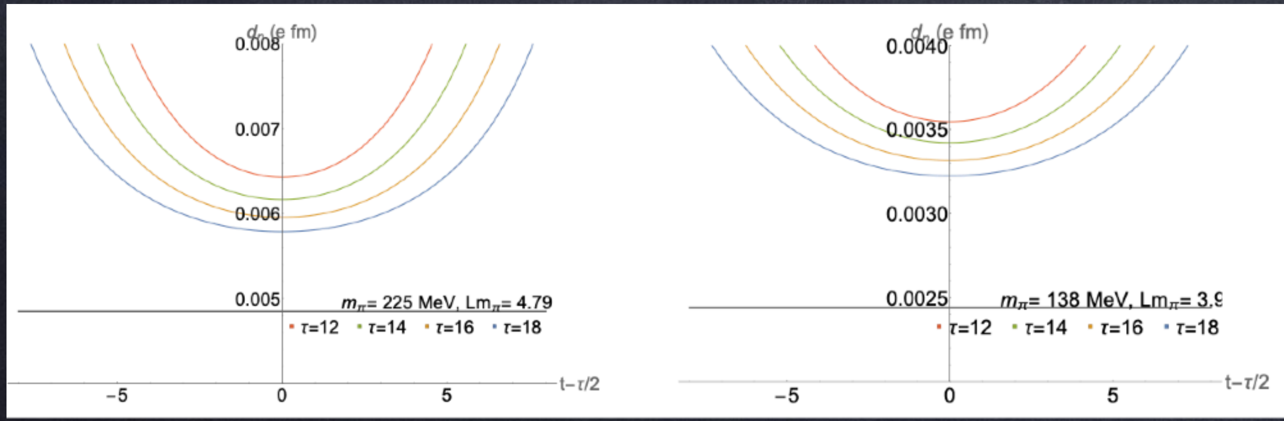




- $\tilde{c}_{Wb}$ and $\tilde{c}_g$ don't generate large eEDM
- $\tilde{c}_{Wb}$ constrained by nEDM and CP asymmetry in $B \to s\gamma$
- bound on gluonic dipole $\tilde{c}_g$ dominated by nEDM

  via qCEDM and gCEDM
- hadronic uncertainties weaken bounds by factors of 10 /100

  similar constraints on real and imaginary part



- large ESC at physical pion mass

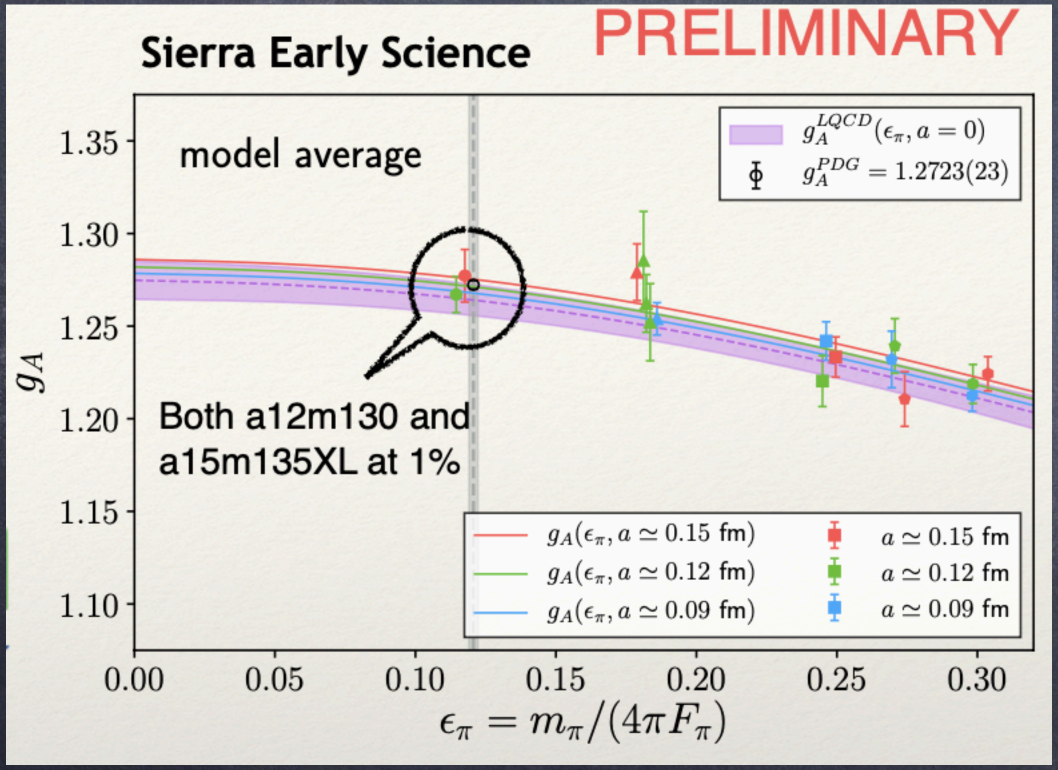
  factor of ~ 1.4 for lattice used in `arXiv:2101.07230`
- still important at $m_\pi \sim 220$ MeV
- FV correction between 5% and 10%

CP-odd pion-nucleon couplings

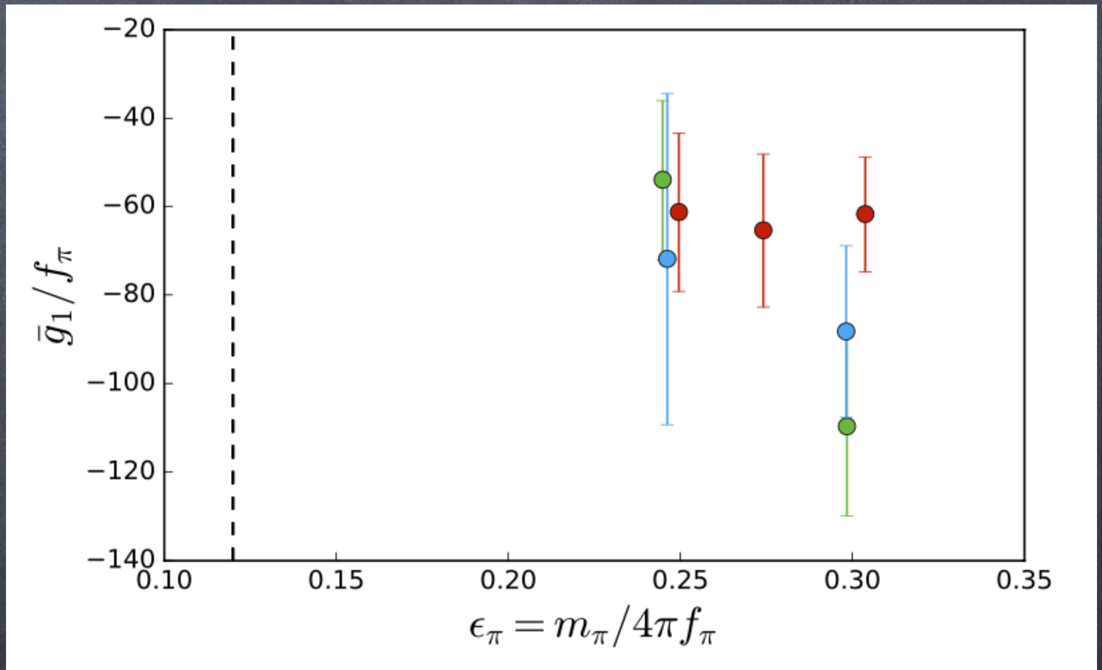
Walker-Loud: Estimating CP-violating nucleon matrix elements from CP-conserving ones

- The strategy should be to perform simultaneous calculations and extrapolations of the nucleon mass splitting combined with EDMs

- Solution: do simultaneous extrapolation of M_N and g_A - this is in the works for us



$g_A = 1.2711(125) \rightarrow 1.2641(93)$ [0.74%]

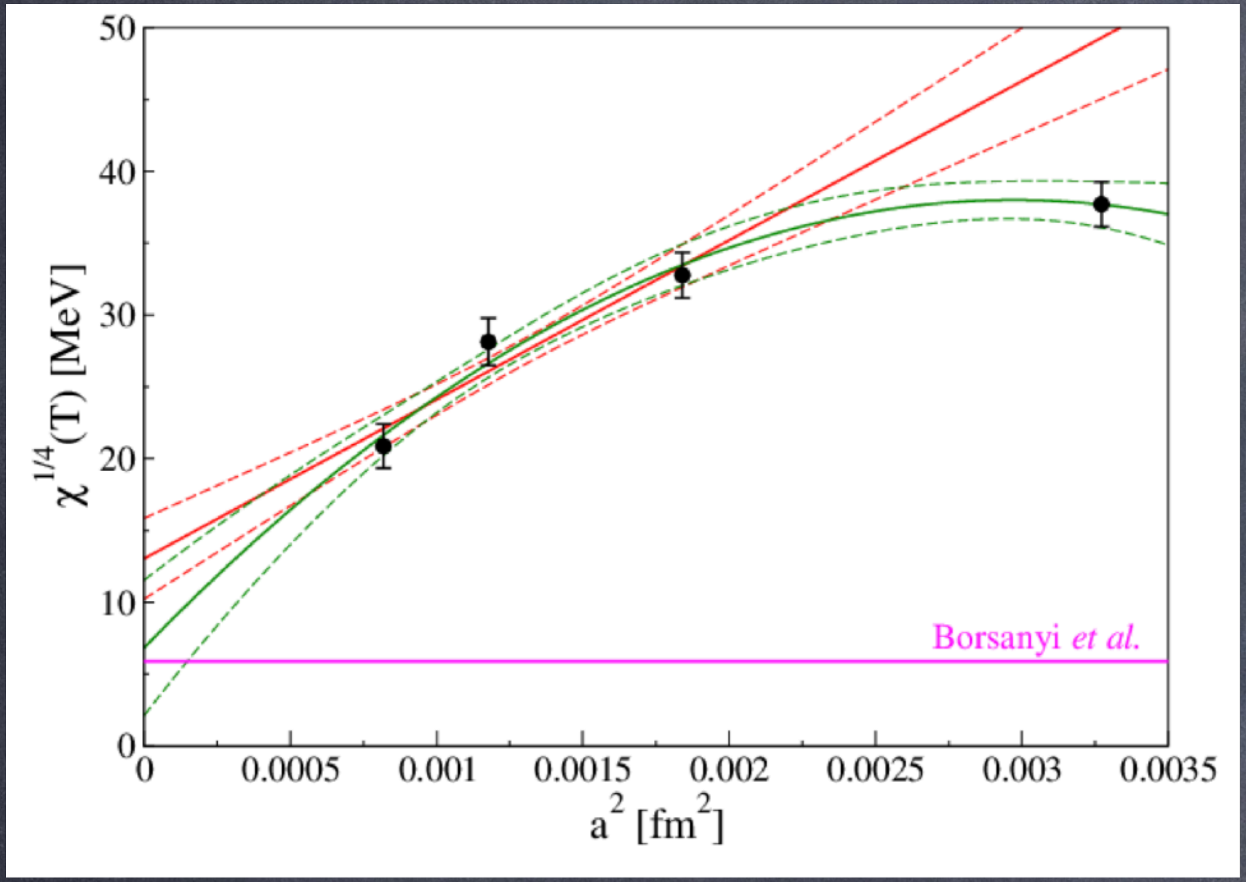


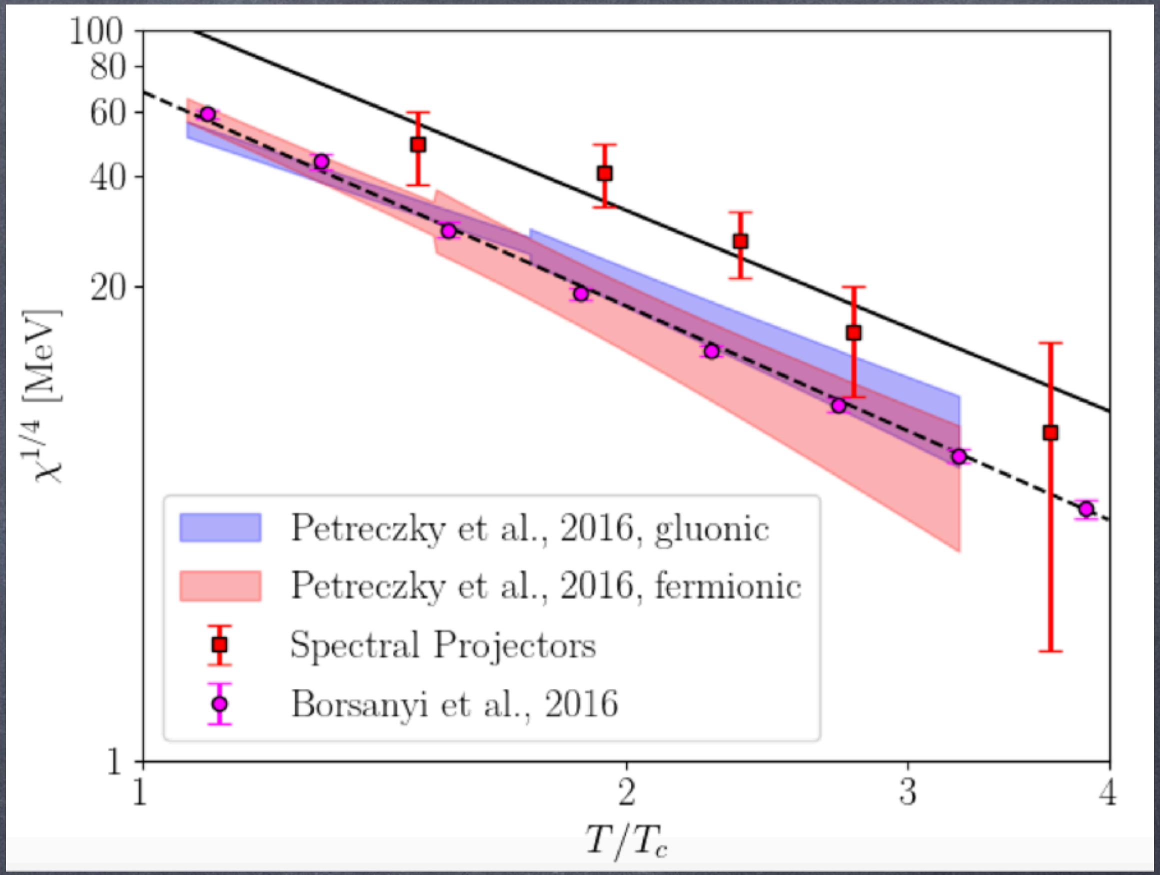
r-subtracted matrix element

$$-\frac{2}{f_\pi}\left(\langle p|\bar{q}\sigma_{\mu\nu}G_{\mu\nu}q|p\rangle_{latt} - r\langle p|\bar{q}q|p\rangle\right)$$

Axion and QCD topology

Bonanno: The Peccei-Quinn axion and QCD topology





Thanks!!

Personal conclusion

- nEDM experiments will improve by factors 10 (5 years) to 100 (10 years)
- New techniques (SNS+Beam EDM)
- CP-violation on strong interactions —> need to clarify
- nEDM is still crucial to understand EWBG + constraints on CPV SMEFT + Cosmological implications
- Relevant for axion physics (DM)
- Lattice QCD: new results for theta-term + first results for qCEDM & gCEDM - CP-odd couplings