Contribution of Novel CP violating interactions to nEDM

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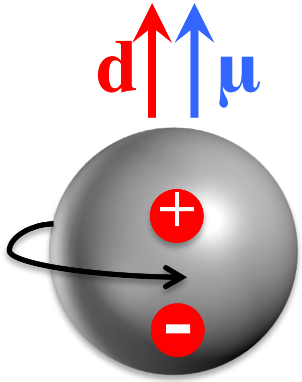

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Work done at LANL in collaboration with

- Tanmoy Bhattacharya
- Vincenzo Cirigliano
- Boram Yoon

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- NERSC
- OLCF
- USQCD
- LANL Institutional Computing

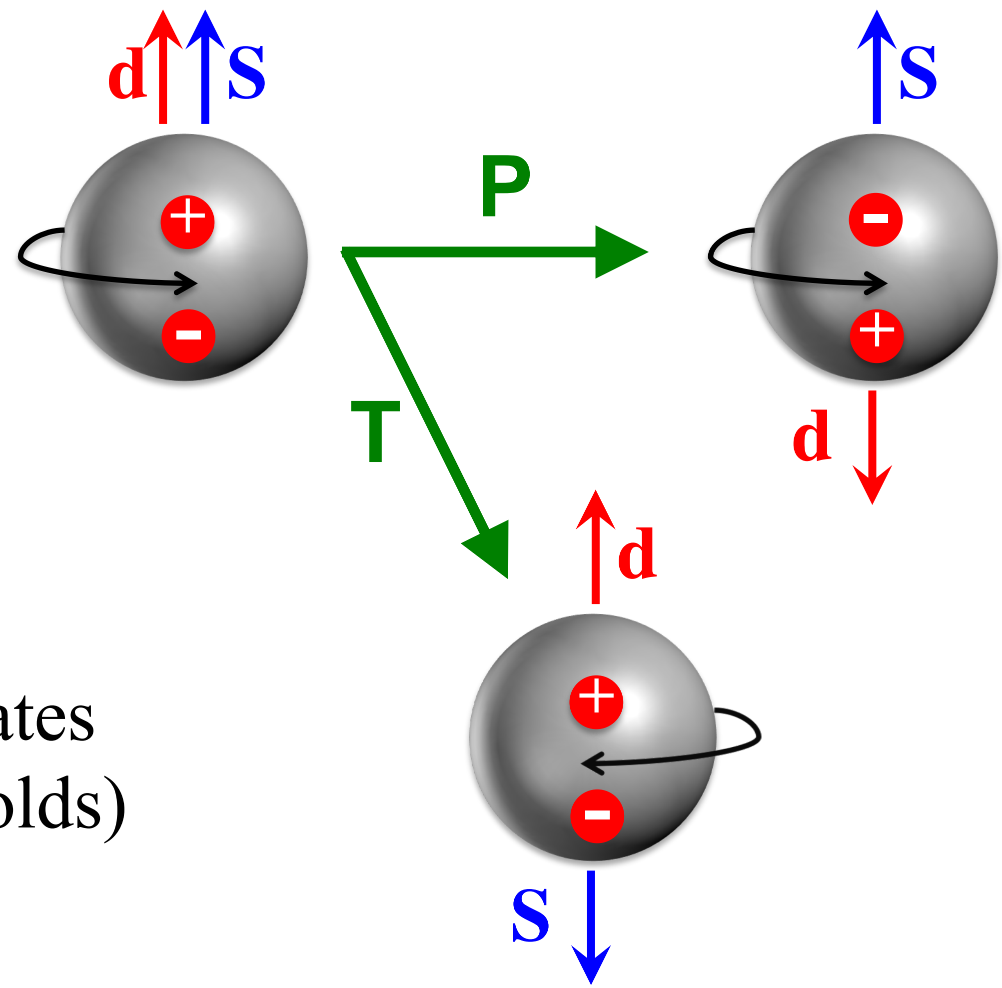
Neutron EDM and CP Violation

- Measures separation between centers of (+) and (-) charges

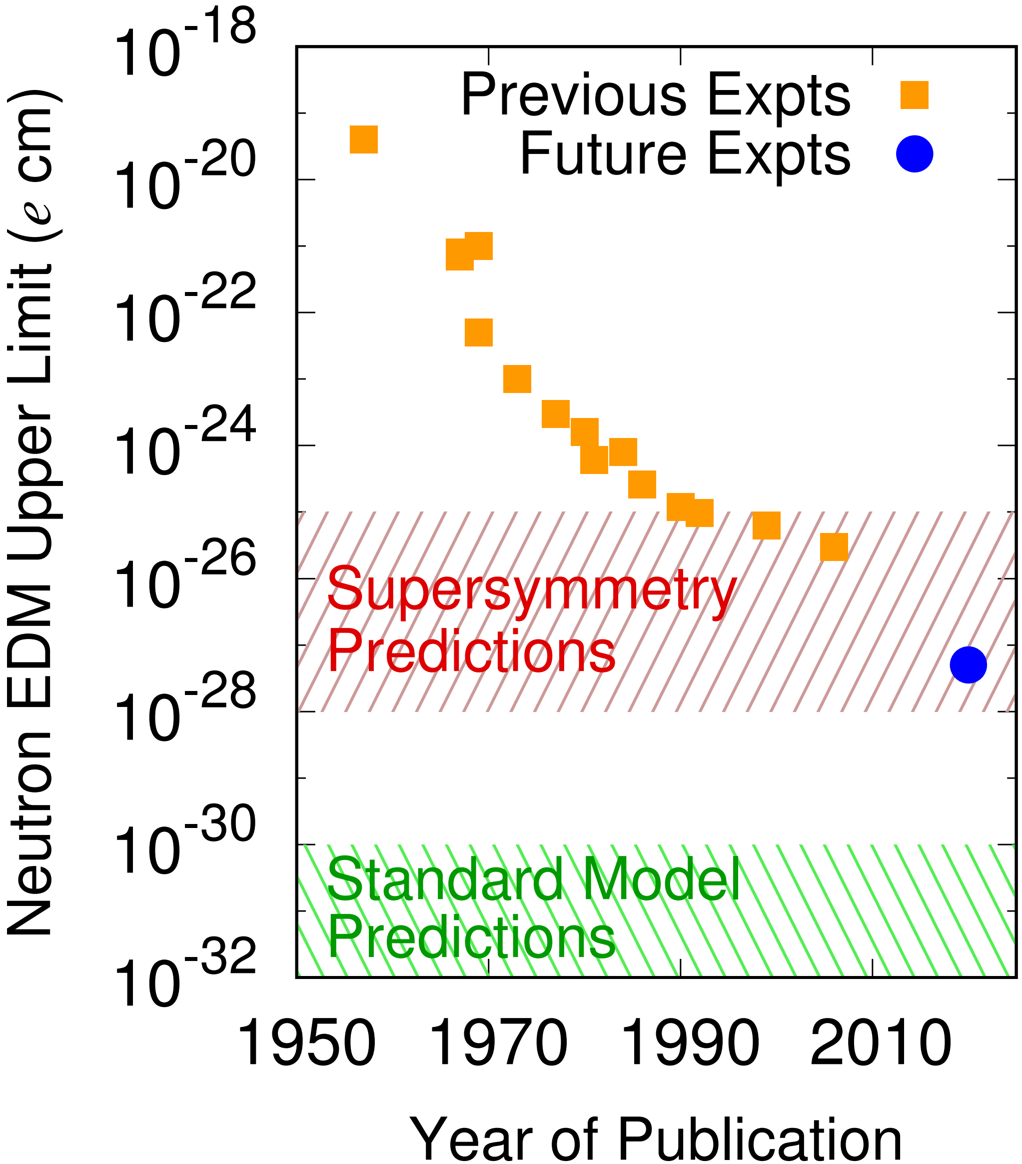
$$\delta H = d_N \hat{S} \cdot \vec{\mathcal{E}}$$

- Current bound:
  $|d_n| < 2.9 \times 10^{-26}\, e\cdot\text{cm}$

- Nonzero nEDM violates P and T (CP if CPT holds)



Neutron EDM Searches



- Predictions
  - Standard Model
    $|d_n| \sim 10^{-31}$ e·cm
  - Supersymmetry
    $|d_n| \sim 10^{-25} - 10^{-28}$ e·cm

- Experiments targeting 25–5 $\times 10^{-28}$ e·cm
  - PSI EDM
  - Munich FRMII
  - RCNP/TRIUMF
  - SNS nEDM
  - JPARC
  - LANL nEDM

Impacts

- New source of CP violation needed
  - CPV in SM is not sufficient to explain observed baryon asymmetry (Sakharov's conditions for weak-scale baryogenesis)
- Test of Supersymmetry and other BSM models
  - In many BSM theories, nEDM is predicted to be in the range 10^{-26}–10^{-28} $e\cdot$cm

Effective CPV Lagrangian at 1 GeV

$$\mathcal{L}_{\rm CPV}^{d\le 6} = -\frac{g_s^2}{32\pi^2}\bar{\theta} G\tilde{G}$$ dim=4 QCD θ-term

$$-\frac{i}{2}\sum_{q=u,d,s} d_q \bar{q}(\sigma\cdot F)\gamma_5 q$$ dim=5 Quark EDM (qEDM)

$$-\frac{i}{2}\sum_{q=u,d,s} \tilde{d}_q g_s \bar{q}(\sigma\cdot G)\gamma_5 q$$ dim=5 Quark Chromo EDM (CEDM)

$$+d_w \frac{g_s}{6} G\tilde{G}G$$ dim=6 Weinberg 3g operator

$$+\sum_i C_i^{(4q)} O_i^{(4q)}$$ dim=6 Four-quark operators

- $\bar{\theta} \le O(10^{-9} - 10^{-11})$: Strong CP problem
- effectively dim=5 suppressed by $d_q \approx v/\Lambda_{\rm BSM}{}^2$
- Dim=6 terms

Lattice QCD calculations of matrix elements can play an important role

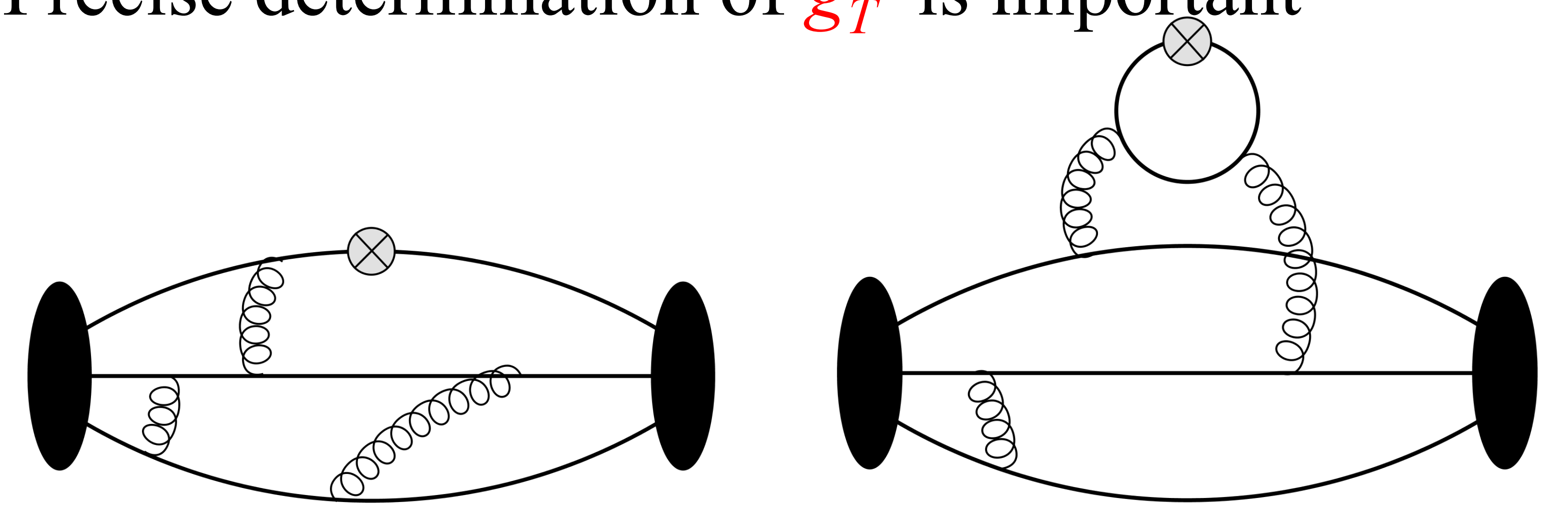
Quark EDM $-\frac{i}{2}\sum_{q=u,d,s} d_q \bar{q}(\sigma \cdot F)\gamma_5 q$

- nEDM from qEDMs given by the tensor charges g_T

$$\langle N|\bar{q}\sigma_{\mu\nu}q|N\rangle = g_T^q\, \bar{u}_N \sigma_{\mu\nu} u_N$$

$$d_N = d_u g_T^u + d_d g_T^d + d_s g_T^s + \cdots$$

- $d_q \propto m_q$ in many models; $m_u/m_d \approx 1/2$, $m_s/m_d \approx 20$
Precise determination of $g_T{}^s$ is important



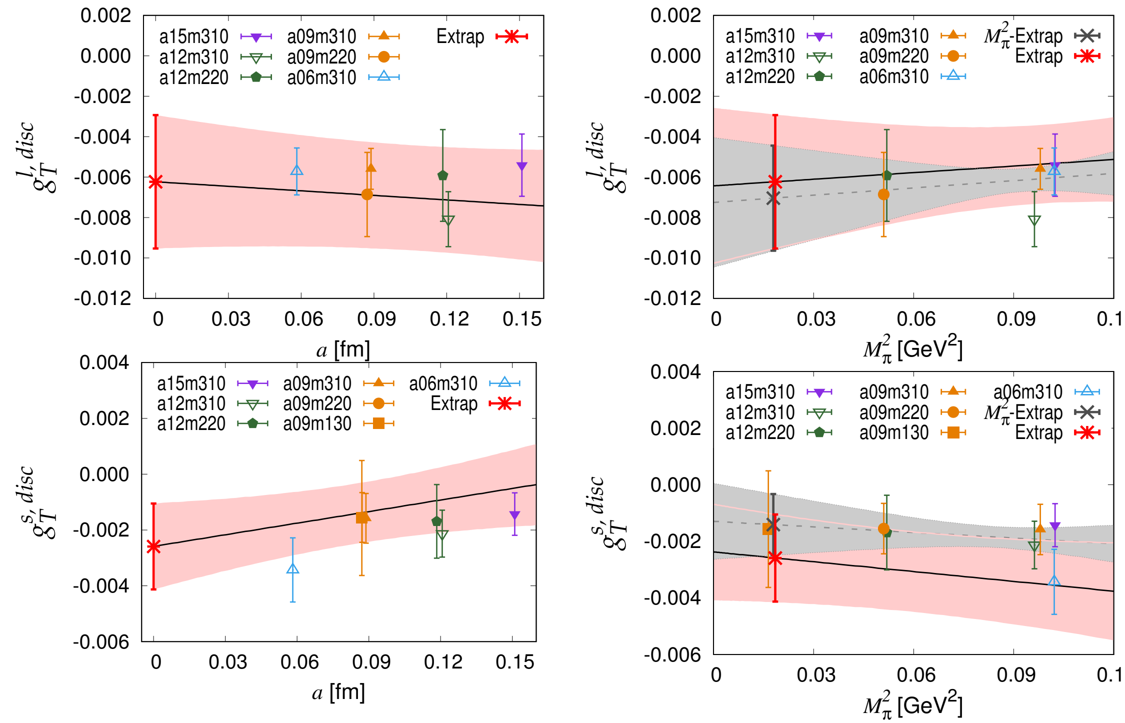
Contribution of quark EDM to neutron EDM

$$g_T^q = \langle n(0) | \bar{q} \sigma_{\mu\nu} q | n(0) \rangle$$

Disconnected

$$g_T^l = -0.0064(32)$$

$$g_T^s = -0.0027(16)$$



Connected + Disconnected for the proton

for neutron $u \leftrightarrow d$

$$g_T^u = 0.784(28); \quad g_T^d = -0.204(11); \quad g_T^s = -0.0027(16)$$

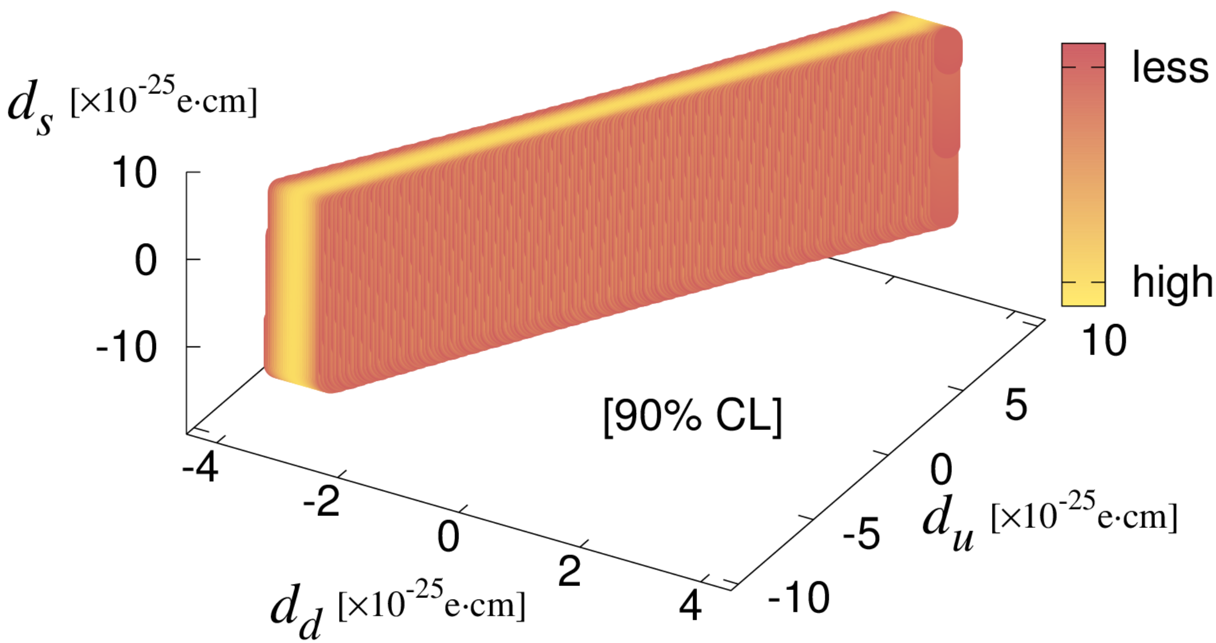
Gupta et al, PRD98 (2018) 091501

Contribution of quark EDM to neutron EDM

$$g_T^d = 0.784(28); \quad g_T^u = -0.204(11); \quad g_T^s = -0.0027(16)$$

Bound the couplings d_q^γ using relation between charges g_T^q and the neutron EDM d_n

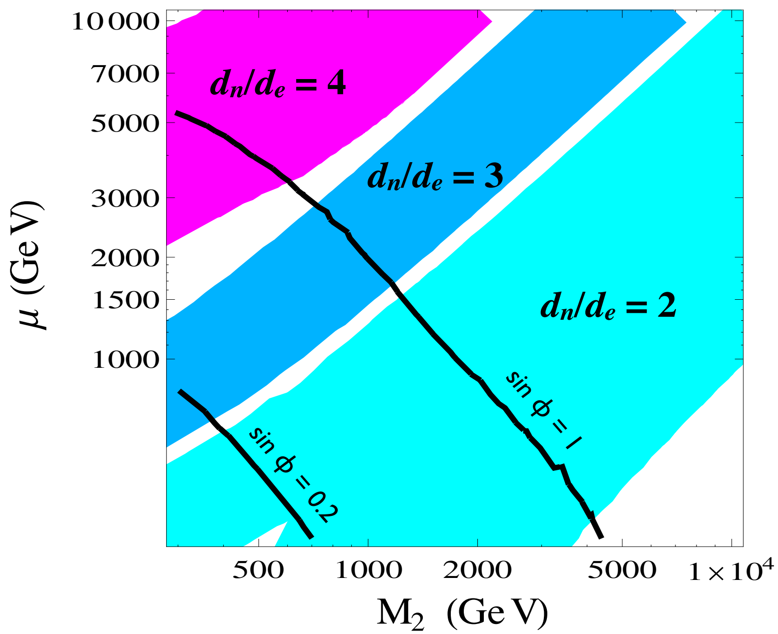
$$d_n = d_u^\gamma g_T^u + d_d^\gamma g_T^d + d_s^\gamma g_T^s + \cdots$$

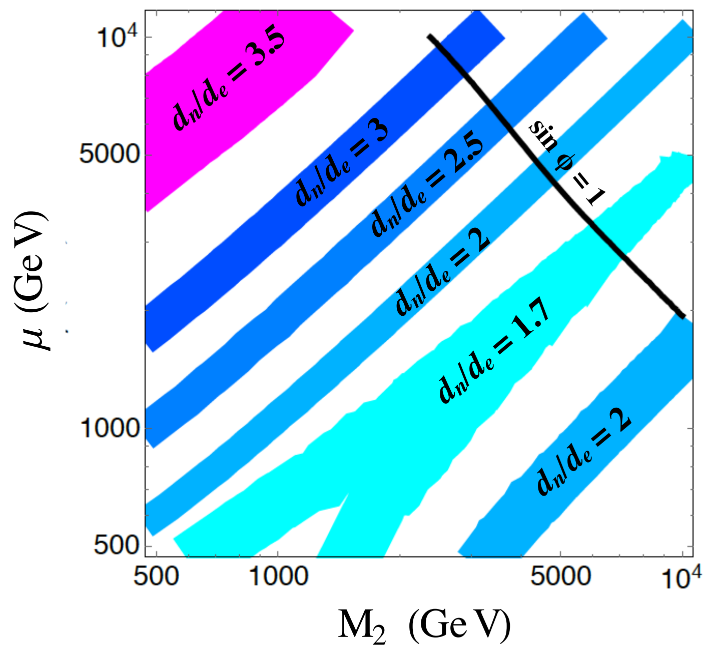


PhysRevLett.115.212002; PhysRevD.92.094511; PhysRevD.92.114026 ; PhysRevD.98 (2018) 091501

Constraint on d_n/d_e in Split SUSY

Following the work of Giudice and Romanino PLB 634 (2006) 307





$$g_T^d = 0.774(66)$$
$$g_T^u = -0.233(28)$$
$$g_T^s = -0.008(9)$$

Bhattacharya et al, PRL 115 (2015) 212002

$$g_T^d = 0.784(28)$$
$$g_T^u = -0.204(11)$$
$$g_T^s = -0.0027(16)$$

Gupta et al, PRD98 (2018) 091501

These are the only results so far on nEDM from lattice QCD

QCD θ-term

- Calculate d_N in presence of CP violating θ-term

$$S = S_{QCD} + S_\theta$$

$$S_\theta = -i\theta \int d^4x\, G\tilde{G} / 32\pi^2 = -i\theta\, Q_{\rm top}$$

- Lattice calculation strategies
  - Expansion in θ
  - External electric field method
  - Simulation with imaginary θ

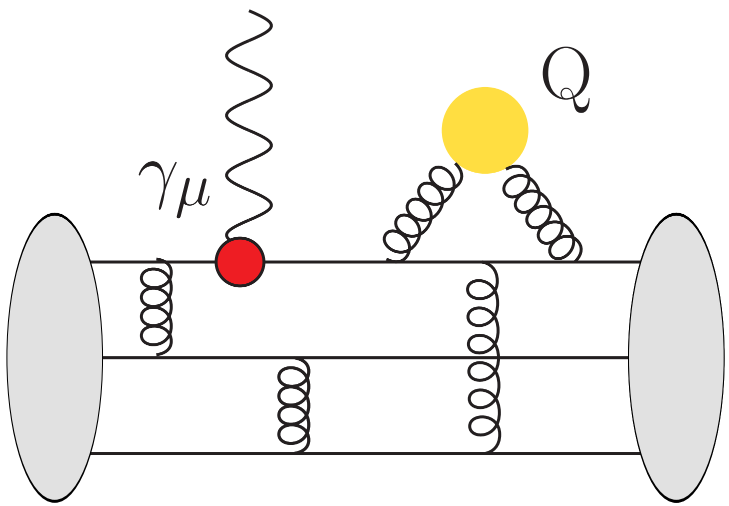
Expansion in θ

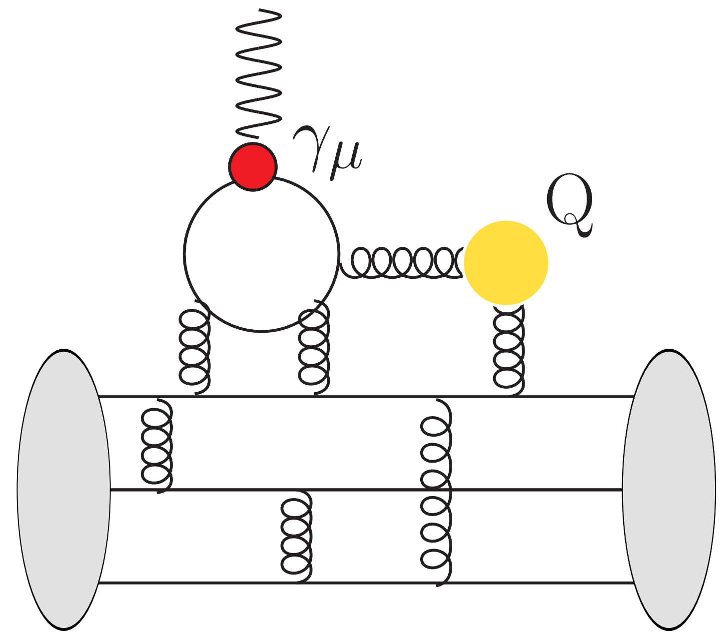
$$\langle \mathcal{O}(x) \rangle_\theta = \frac{1}{Z_\theta} \int d[U,q,\bar{q}]\, \mathcal{O}(x)\, e^{-S_{QCD} + i\theta Q_{\text{top}}}$$

$$= \langle \mathcal{O}(x) \rangle_{\theta=0} + i\theta \langle \mathcal{O}(x) Q_{\text{top}} \rangle_{\theta=0} + O\left(\theta^2\right)$$

- Measurements performed on regular (θ=0) lattices
- Nucleon interpolating operator $N = \varepsilon^{abc}\left(d^{Ta} C \gamma_5 u^b\right) d^c$
- $O(x) = \langle N(\tau) V_\mu N(0) \rangle$ nucleon 3-pt fn with the insertion of the vector current
- Calculate ground state matrix element → form factors
- d_n extracted from form-factor F_3 extrapolated to q^2=0

Correlation of $G\tilde{G}$ with nucleon 3-point function $\langle N\, J_\mu^{EM}\, N\rangle_{CPV}$





$\langle O(x) Q_{top}\rangle$: "reweight" the nucleon 3-point function *O(x)* by Q_{top}

F_3: The CP Violating Form Factor

Expand the nucleon matrix element in terms of form factors

$$\langle N|J_\mu^{EM}|N\rangle_{CPV} = e^{i\alpha(q^2)\gamma_5}\,\bar{u}\,[\gamma_\mu F_1(q^2) + \left(2im_N\gamma_5 q_\mu - \gamma_\mu\gamma_5 q^2\right)\frac{F_A(q^2)}{m_N^2}$$

$$+i\sigma_{\mu\nu}q_\nu\frac{F_2(q^2)}{2m_N} + \sigma_{\mu\nu}\mathrm{q}_\nu\gamma_5\frac{F_3(q^2)}{2m_N}]\,u\;e^{i\alpha(q^2)\gamma_5}$$

With $\sum_s u(p,s)\bar{u}(p,s) = \frac{(E\gamma_4 - ip\cdot\gamma + m)}{2E}$

The contribution to nEDM is given by $d_N = \dfrac{F_3(q^2=0)}{2m_N}$

Spinor transformation under Parity

	P, CP-even	P, CP-violating
Dirac Eq.	$\left(ip_\mu\gamma_\mu + m\right)u = 0$	$\left(ip_\mu\gamma_\mu + me^{-2i\alpha\gamma_5}\right)\tilde{u} = 0$
Parity Op.	$\boxed{\gamma_4}$ $u_{\vec{p}} \to \gamma_4 u_{-\vec{p}}$	$\boxed{e^{2i\alpha\gamma_5}\gamma_4}$ $\tilde{u}_{\vec{p}} \to e^{2i\alpha\gamma_5}\gamma_4\tilde{u}_{-\vec{p}}$

- Each CPV interactions ➔ phase in neutron mass term
  - γ_4 no longer parity op of neutron state
- Introduce new parity operator or
- Rotate neutron state so that γ_4 remains the parity op:

$$\boxed{\tilde{u} = e^{i\alpha\gamma_5}u, \qquad \bar{\tilde{u}} = \bar{u}e^{i\alpha\gamma_5}}$$

Abramczyk, et al., PRD96 (2017) 014501

Toolkit

- Use the gradient flow scheme
  - Remove short distance noise
  - Q → integers
- Integer values of Q → **no** operator renormalization required
- Variance reduction method
  - Analyze $X_{\epsilon}^{imp} = (X_{\epsilon} - X_{\epsilon=0})$ to exploit correlations

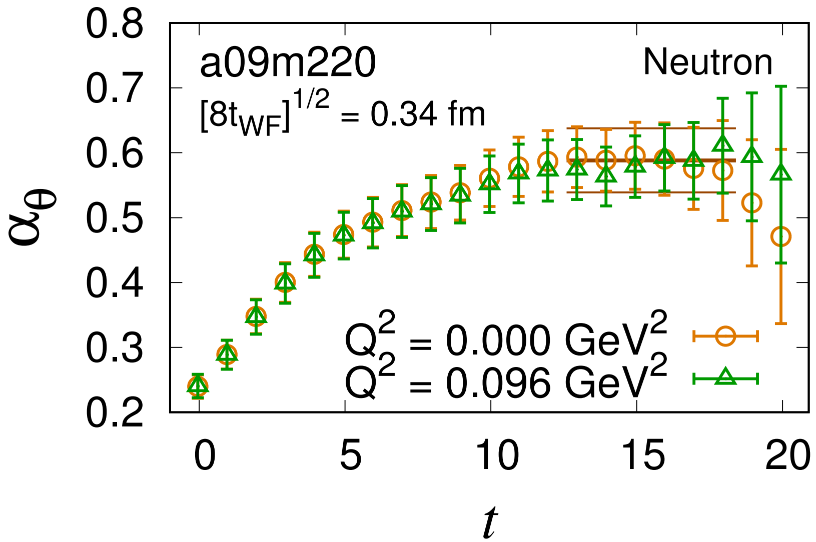
Determining α for the ground state

CPV Phase α

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

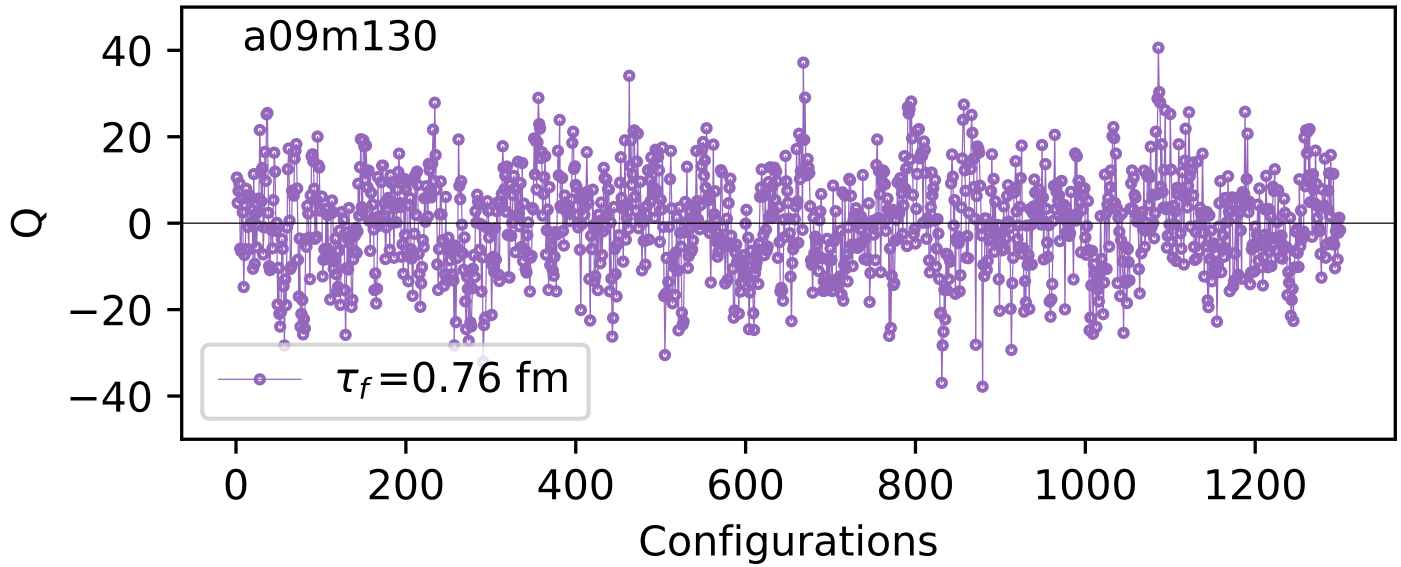
$$\frac{\mathrm{Im}C^{P}_{2\mathrm{pt}}(t)}{\mathrm{Re}C_{2\mathrm{pt}}(t)} \equiv \frac{\mathrm{Im\,Tr}\left[\gamma_5 \frac{1}{2}(1+\gamma_4)\langle N(t)\overline{N}(0)\rangle\right]}{\mathrm{Re\,Tr}\left[\frac{1}{2}(1+\gamma_4)\langle N(t)\overline{N}(0)\rangle\right]} = \frac{M_N \sin\left(2\alpha(t)\right)}{E_N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

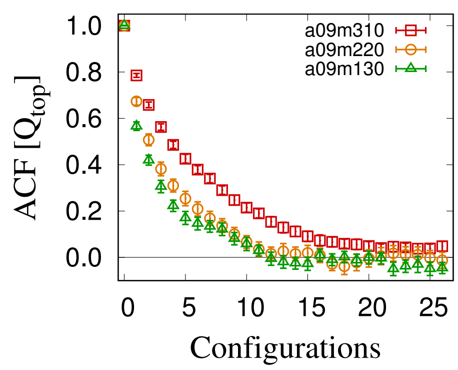
- Final α is obtained from plateau average over $\alpha(t \gg 1)$ where ESC is small

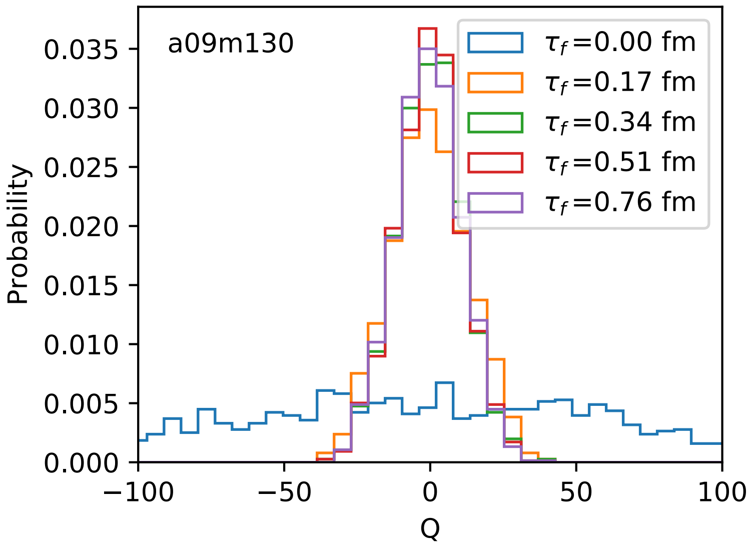


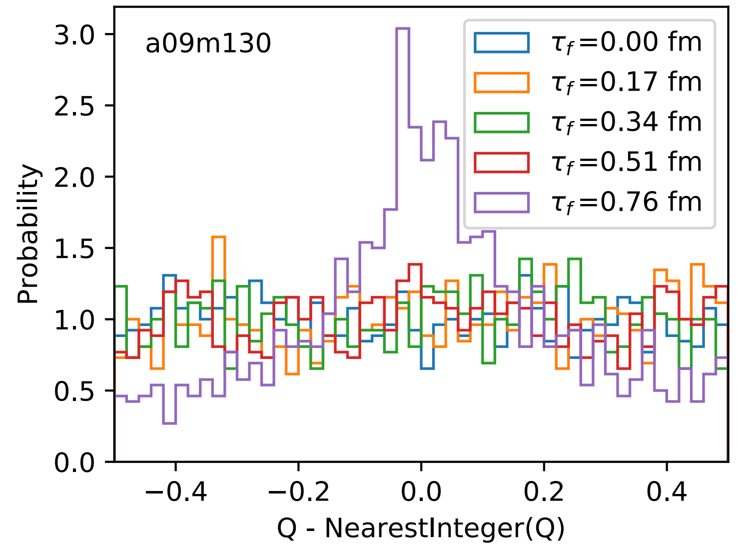
α is independent of Q^2

Time history/Distribution of Q

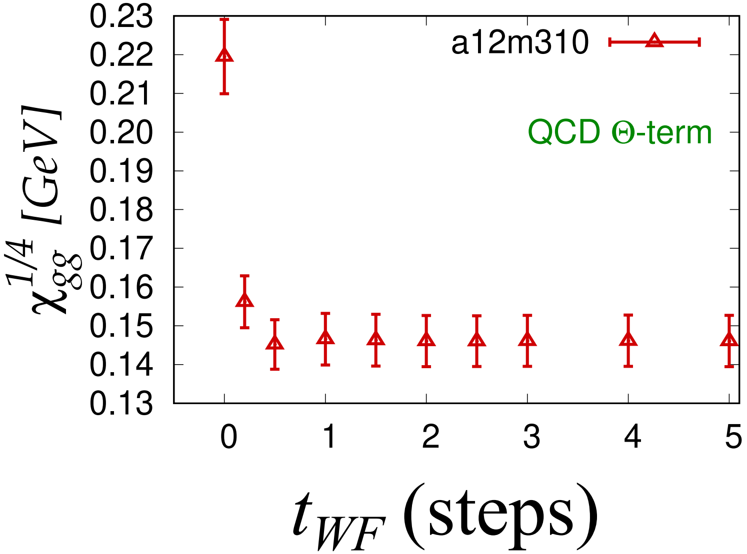


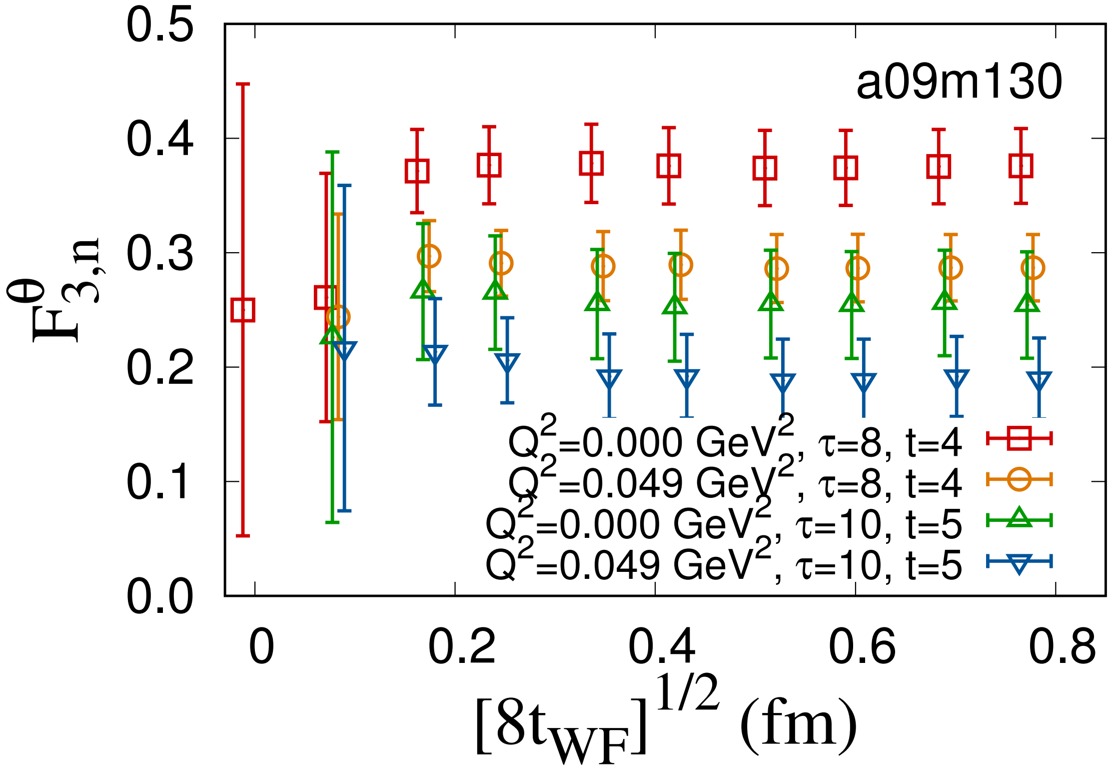




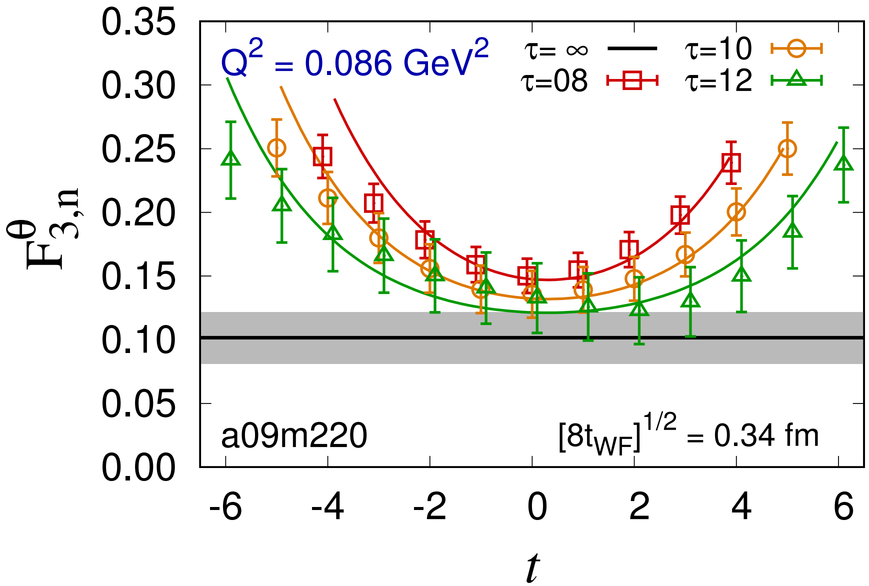


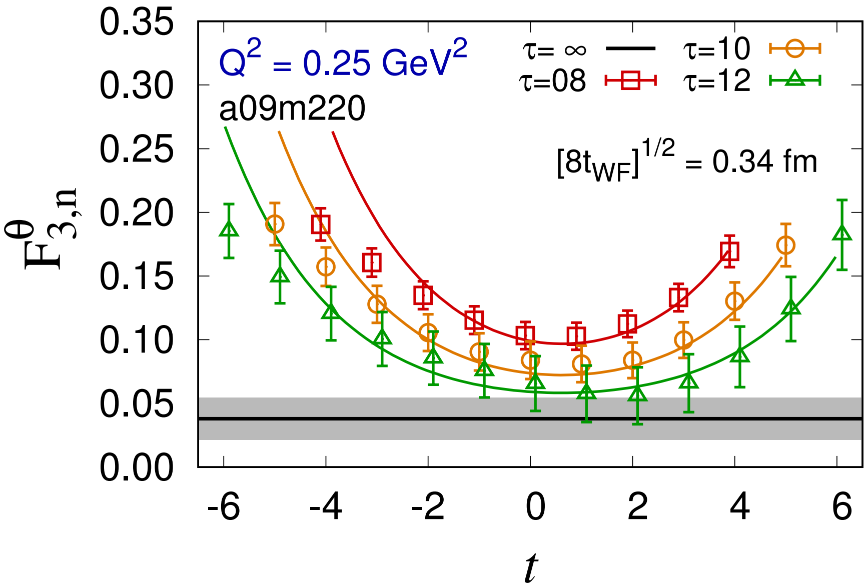
Results independent of flow time



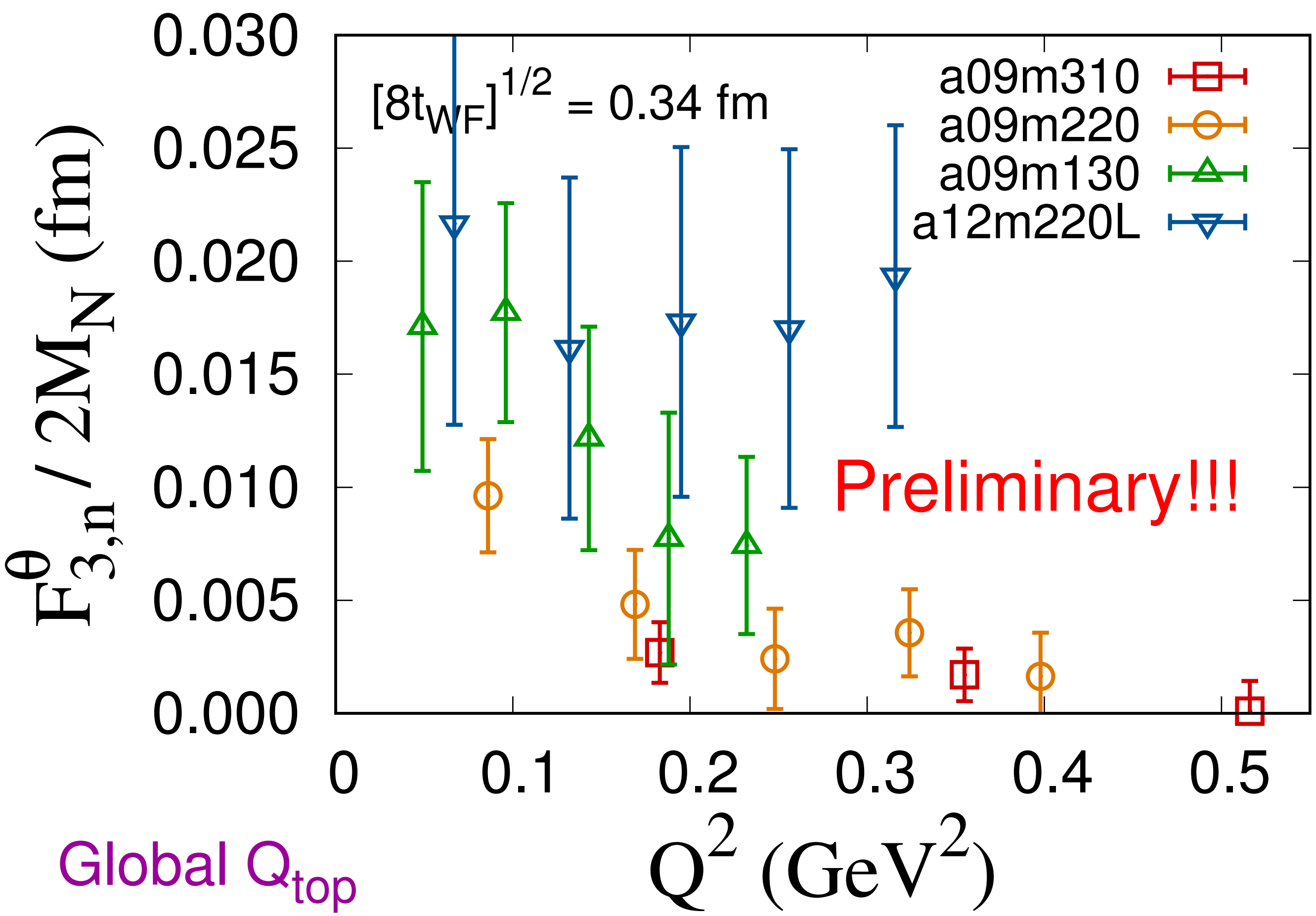


Removing excited state contamination (Under reanalysis)





Preliminary Results



Global Q_{top}

Need to

Resolve the Q^2 behavior

Determine the M_π^2 behavior

STATUS: d_n induced by the Θ-term

$$d_N = a\, M_\pi^2 + b\, M_\pi^2 \log M_\pi^2 + \cdots$$

Mereghetti et al, PLB696 (2011) 97

RBC/LHP (M_π = 330 MeV)

$$|2M_n\, d_n| = |F_{3n}(0)| \approx 0.05 \cdot \theta\, e$$

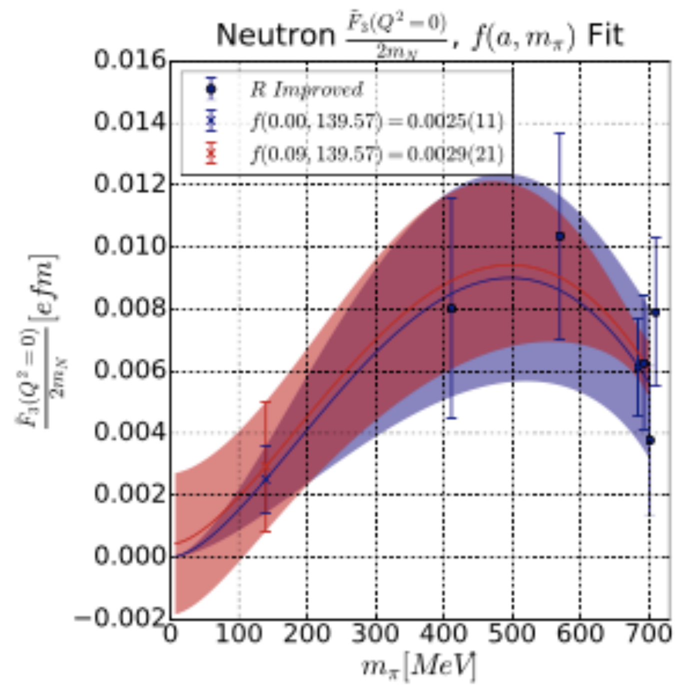
$$d_n \approx 0.005 \cdot \theta\, e\, fm$$

Need much higher statistics as $M_\pi \to 135$ MeV

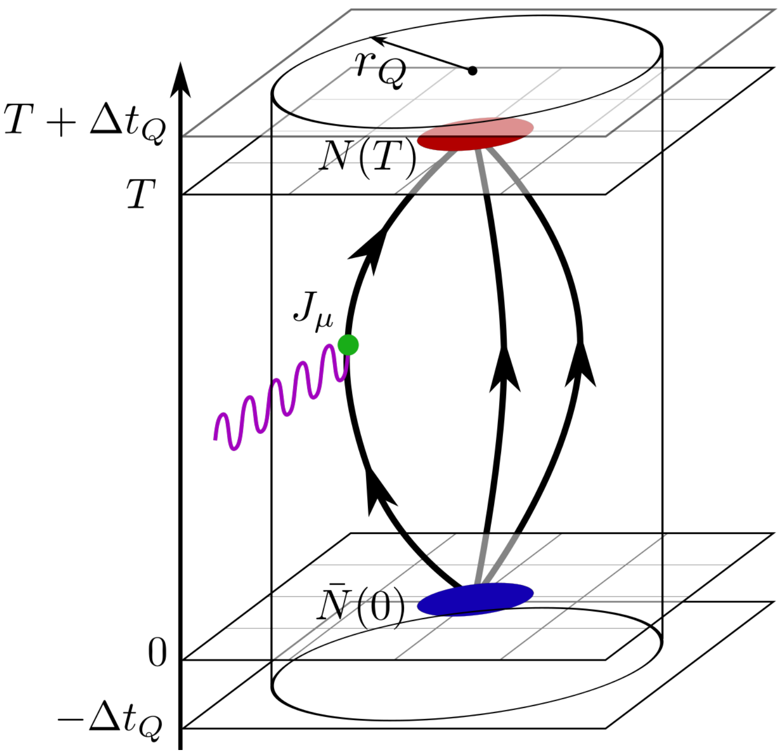
MSU/Juelich (arXiv:1902.03254)

M_π = 411, 570, 701 MeV

$$d_N = 0.0029(21)\, \Theta\, e\, fm$$

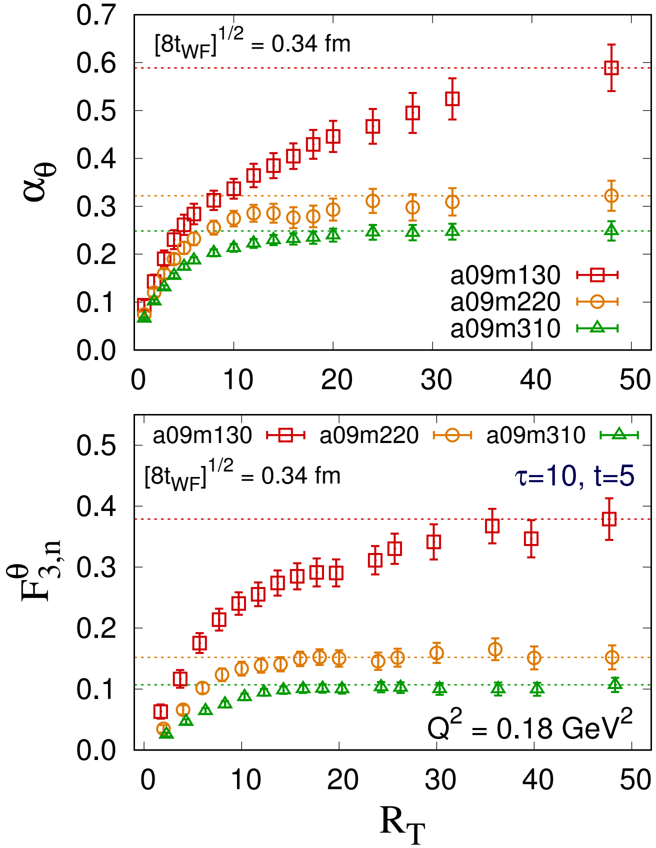


Can one improve the signal by integrating only over a 4-D cylinder of size $(r_Q \times R_T)$ without introducing a bias?



Volume used by Syritsyn et al

PNDME



$$|t_Q - t^N_{src}| \le R_T$$

Conclusions

- Precise results for quark EDM
- Have established signal in F_3 for the Θ-term
  - *Our variance reduction method works*
  - *Restricting* $Q_{top} \equiv \int d^4x\, G\tilde{G}(x)$ *to a "cylinder" may introduce a bias*
- Need to
  - Resolve the Q^2 behavior
  - Determine the M_π^2 behavior
  - Take the continuum limit