Nucleon Electric Dipole Moment From Chiral Fermions on the Lattice

梁剑

华南师范大学量子物质研究院

(χQCD collaboration)

01/23/2021 第五届强子谱和强子结构研讨会 @ 中山大学（线上）

Outlines

A. Backgrounds
B. Current Status
C. Our Efforts
D. Summary and Outlook

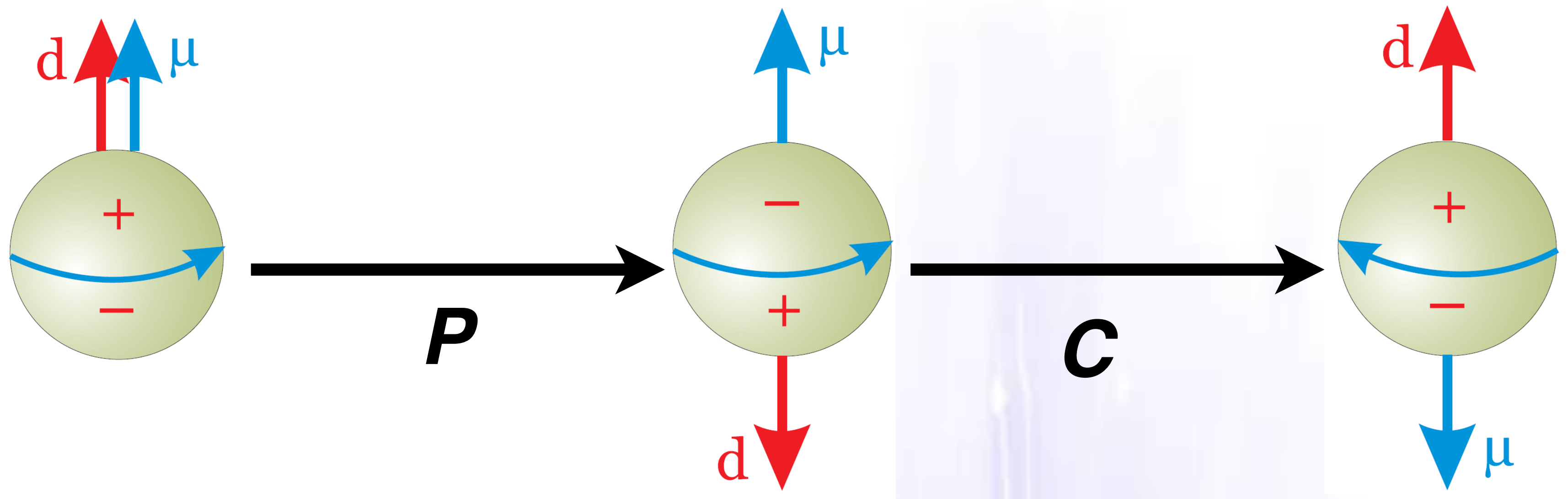
EDM and CP-violation

- The CP violation allowed in the SM (the CKM phase) is insufficient for Baryogenesis under Sakharov conditions, BSM interactions?

A. D. Sakharov, JETP Lett. 5 24-27 (1967)

- QCD with non-vanishing theta term and the strong CP problem.

- A non-zero intrinsic electric dipole moment (EDM) of a fundamental particle violates the CP(T) symmetry.



- Nucleon EDM (nEDM) is a sensitive probe of BSM: the contribution to the nEDM from the weak CP-violating (CPV) phase is ~ 10^{-31} e·cm, 10^{-5} of the current experimental limit.

Experiments

First experiment: $|d_n| < 5 \times 10^{-20}$ **e·cm**

Smith et al., RP108:120-122 (1957)

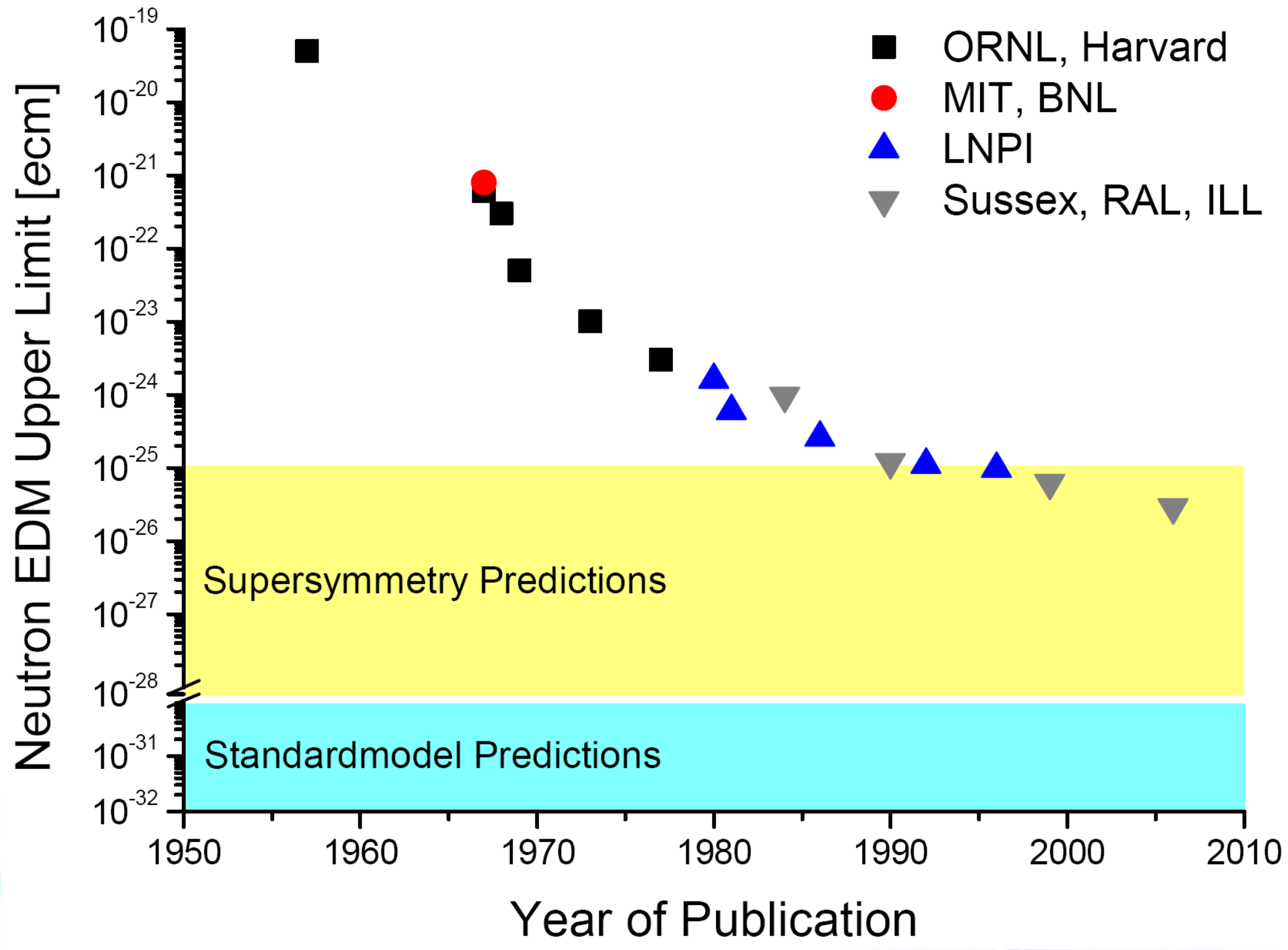
Current neutron EDM limits: 10^{-26} **e·cm**

Baker et al, PRL97:131801 (2006)

Graner et al, PRL116:161601 (2016)

Most recent result: $0.0(1.1)(0.2) \times 10^{-26}$ **e·cm**

C. Abel et al., PRL124:081803 (2020)



During the past ~~50~~ 60+ years of experiments, six orders of magnitude have been covered.

Many experiments are aiming at improving the limit down to 10^{-28} **e·cm in the next ~10 years. It is still a long way to trek to finally detect a non-zero nEDM, but this leaves plenty of room for the theta term and BSM physics.**

CP-Violating Operators (P and CP Violation)

Operators at the energy scale of hadronic matter

- ✦ 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, e.g., $\bar{\psi}\gamma_5\psi\bar{\psi}\psi$, dim-6

Hard due to renormalization and mixing

R. Gupta, arXiv:1904.00323

How to distinguish the contributions of different operators if we do observe a non-zero EDM in experiments?

CP-Violating Operators (P and CP Violation)

- $iG_{\mu\nu}\tilde{G}_{\mu\nu}$
- $i\bar{\psi}[\tilde{F}_{\mu\nu}\sigma^{\mu\nu}]\psi$
- $i\bar{\psi}[\tilde{G}_{\mu\nu}\sigma^{\mu\nu}]\psi$
- $f^{abc}\tilde{G}^{a}_{\mu}{}^{\nu}G^{a}_{\nu}{}^{\rho}G^{a}_{\rho}{}^{\mu}$
- $\bar{\psi}\gamma_5\psi\bar{\psi}\psi$

nEDM

Lattice QCD: first-principles connection between the CPV interactions (theta term and BSM interactions) and the nEDM.

General Lattice Methodology

Introducing CPV interactions

- ✦ MC simulation with an imaginary θ term
- ✦ Taylor expansion in terms of small couplings (theta term and Weinberg term)
- ✦ Modifying the Dirac operator for inversions and re-weighting (quark bilinear terms)

Lattice observables

- ✦ CPV EM from factor (FF) from nucleon matrix element
- ✦ Nucleon energy shift in the present of a background electric field

Detailed Formula

✦ **Taylor expansion in terms of small couplings**

$$\mathcal{L}^E = \bar{\psi}\left(\not{D}^E + m\right)\psi + \frac{1}{4}F^{E,a}_{\mu\nu}F^{E,\mu\nu}_a - i\bar{\theta}\frac{g^2}{32\pi^2}F^E_{\mu\nu}\tilde{F}^{E,\mu\nu}$$

$$\begin{aligned}&\int DA\cdot\mathrm{Det}\,[M]\,e^{-S_g+i\theta Q_t}\\=&\int DA\cdot\mathrm{Det}\,[M]\,e^{-S_g}+i\theta\int DA\cdot\mathrm{Det}\,[M]\,Q_t e^{-S_g}\end{aligned}$$

$${}_\theta\langle\ldots\rangle_\theta = \langle\ldots\rangle + i\theta\langle\ldots Q_t\rangle$$

Detailed Formula

✦ **CPV EM from factor (FF) from nucleon matrix element**

$$G_2^\theta = G_2 + i\theta G_2^Q \qquad G_2^Q = ZZ'^\dagger e^{-Et}\frac{m}{E}\alpha^1\gamma_5$$

$$G_3^\theta = G_3 + i\theta G_3^Q$$

$$G_3^Q = \alpha^1\gamma_5 W_\mu^{\text{even}}\frac{-i\not{p}_i + m}{2m} + \frac{-i\not{p}_f + m}{2m}W_\mu^{\text{even}}\alpha^1\gamma_5 + \frac{-i\not{p}_f + m}{2m}W_\mu^{\text{odd}}\frac{-i\not{p}_i + m}{2m}$$

$$W_\mu^{\text{odd}} = -\sigma_{\mu\nu}q_\nu\gamma_5\frac{F_3(q^2)}{2m_N} \qquad d_n = \frac{F_3(0)}{2m_N}\theta$$

Outlines

A. Backgrounds

B. Current Status

C. Our Efforts

D. Summary and Outlook

“OLD” Lattice Calculations

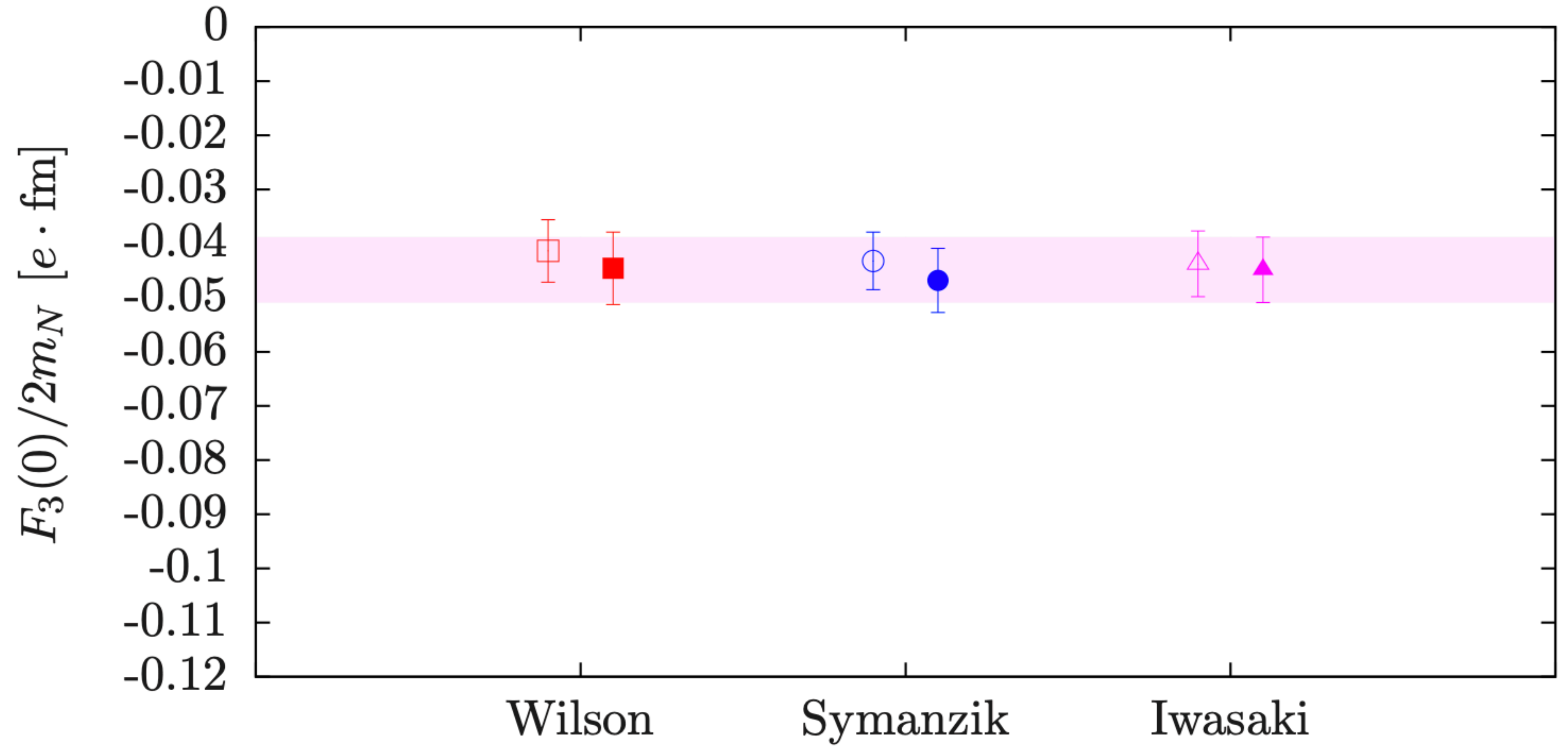
[10] E. Shintani, S. Aoki, N. Ishizuka, K. Kanaya, Y. Kikukawa, Y. Kuramashi, M. Okawa, Y. Tanigchi, A. Ukawa, and T. Yoshie. Neutron electric dipole moment from lattice QCD. *Phys. Rev.*, D72:014504, 2005.

[11] F. Berruto, T. Blum, K. Orginos, and A. Soni. Calculation of the neutron electric dipole moment with two dynamical flavors of domain wall fermions. *Phys. Rev.*, D73:054509, 2006.

[12] F. K. Guo, R. Horsley, U. G. Meissner, Y. Nakamura, H. Perlt, P. E. L. Rakow, G. Schierholz, A. Schiller, and J. M. Zanotti. The electric dipole moment of the neutron from 2+1 flavor lattice QCD. *Phys. Rev. Lett.*, 115(6):062001, 2015.

[13] Eigo Shintani, Thomas Blum, Taku Izubuchi, and Amarjit Soni. Neutron and proton electric dipole moments from $N_f = 2+1$ domain-wall fermion lattice QCD. *Phys. Rev.*, D93(9):094503, 2016.

[14] C. Alexandrou, A. Athenodorou, M. Constantinou, K. Hadjiyiannakou, K. Jansen, G. Koutsou, K. Ottnad, and M. Petschlies. Neutron electric dipole moment using $N_f = 2+1+1$ twisted mass fermions. *Phys. Rev.*, D93(7):074503, 2016.



Correction to the CPV FF

The CPV terms alter the Dirac equation and spinors

$$(i\not{p} + m' e^{-2i\alpha(\theta)\gamma_5}) u'(p,s) = 0 \qquad u' = e^{i\alpha^1\theta\gamma_5} u \qquad \bar{u}' = \bar{u} e^{i\alpha^1\theta\gamma_5}$$

$$\langle N(p') | \bar{\psi}\gamma_\mu\psi | N(p) \rangle_{\not{CP}} = \bar{u}(p') \left[F_1(q^2)\gamma_\mu - \left[F_2(q^2) + i\theta F_3(q^2)\gamma_5 \right] \frac{i\sigma_{\mu\nu}q_\nu}{2m_N} \right] u(p)$$

$$\langle N(p') | \bar{\psi}\gamma_\mu\psi | N(p) \rangle_{\not{CP}} = \bar{u}'(p') \left[F_1(q^2)\gamma_\mu - \left[F_2(q^2) + i\theta F_3(q^2)\gamma_5 \right] \frac{i\sigma_{\mu\nu}q_\nu}{2m_N} \right] u'(p)$$

$$u(p) \to u(\tilde{p}) = \gamma_4 u(p)$$

$$u'(p) \to u'(\tilde{p}) = e^{i\alpha^1\theta\gamma_5}\gamma_4 u(p)$$

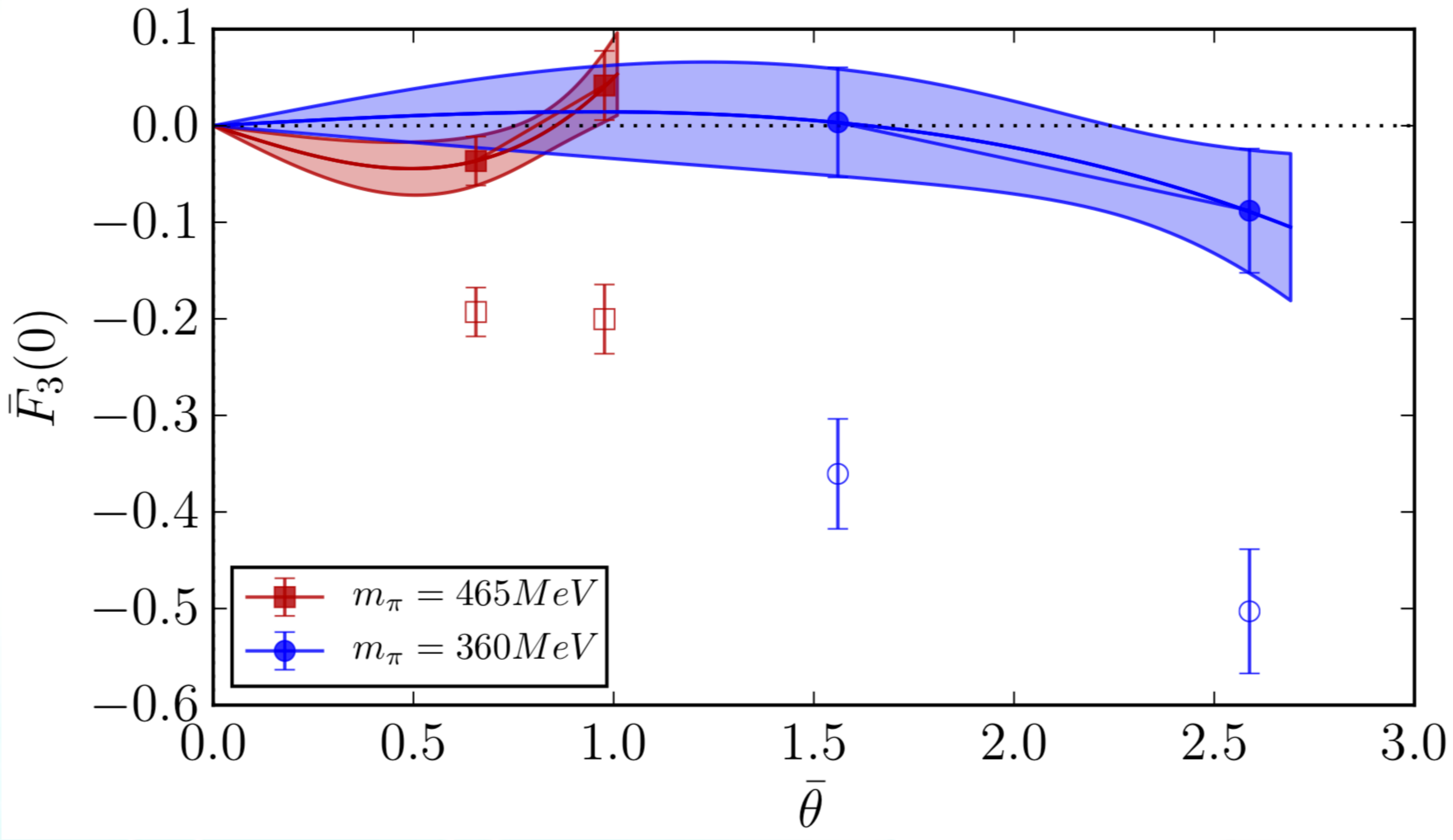
$$F^{\not{CP}} = F_3 + 2\alpha^1 F_2$$

*Abramczyk et al., PRD96:014501 (**2017**)*

Correction to the CPV FF

$$\langle N(p')|\bar{\psi}\gamma_\mu\psi|N(p)\rangle_{\not{CP}} = \bar{u}'(p')\left[F_1(q^2)\gamma_\mu - \left[F_2(q^2) + i\theta F_3(q^2)\gamma_5\right]\frac{i\sigma_{\mu\nu}q_\nu}{2m_N}\right]u'(p)$$

$$F^{\not{CP}} = F_3 + 2\alpha^1 F_2$$



More Crucial to Reduce the uncertainties!

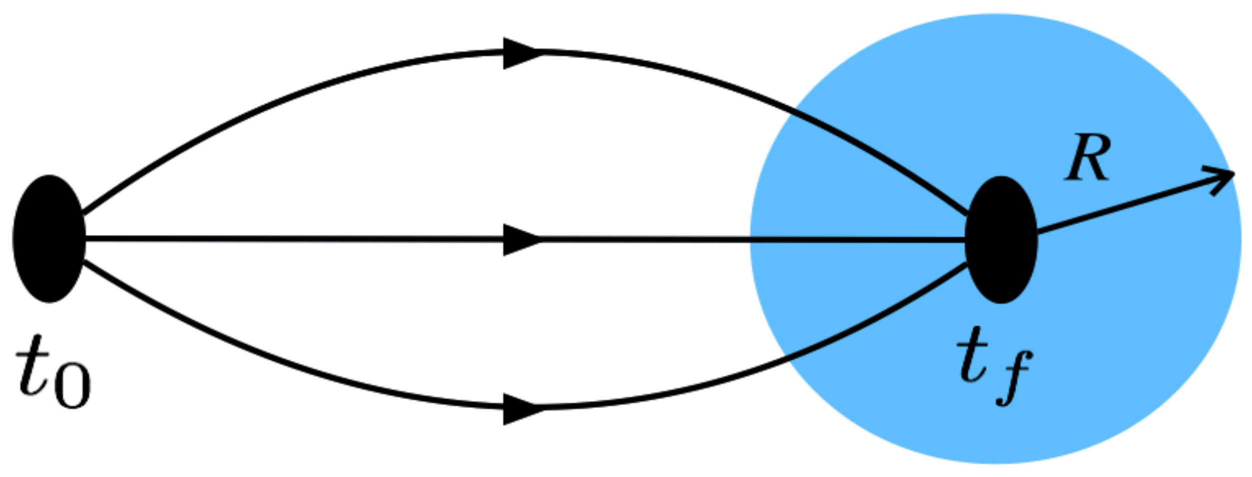
*Abramczyk et al., PRD96:014501 (**2017**)*

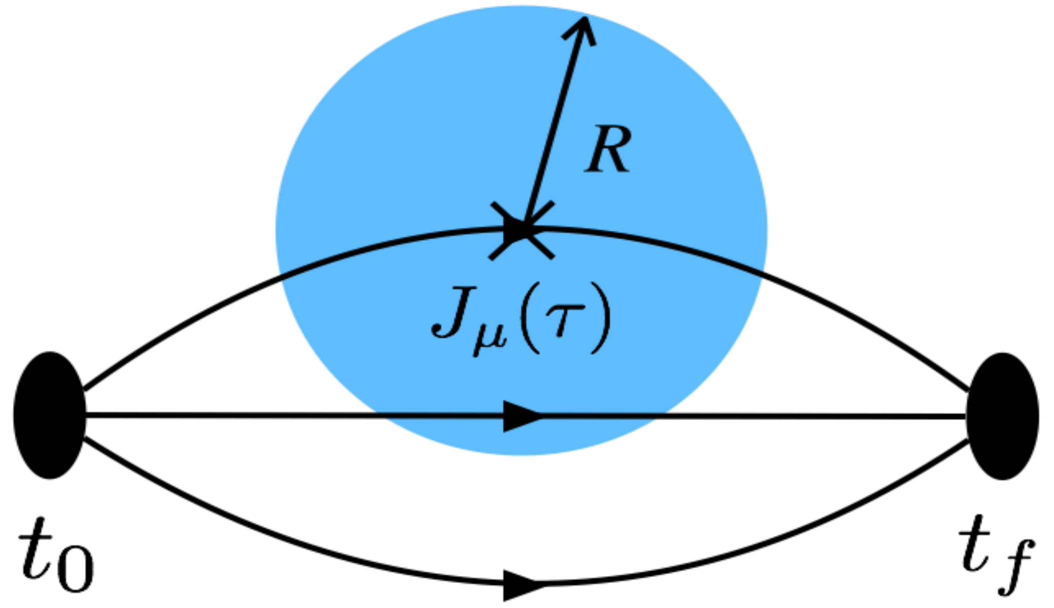
Error Reduction

The cluster decomposition error reduction (CDER):

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

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





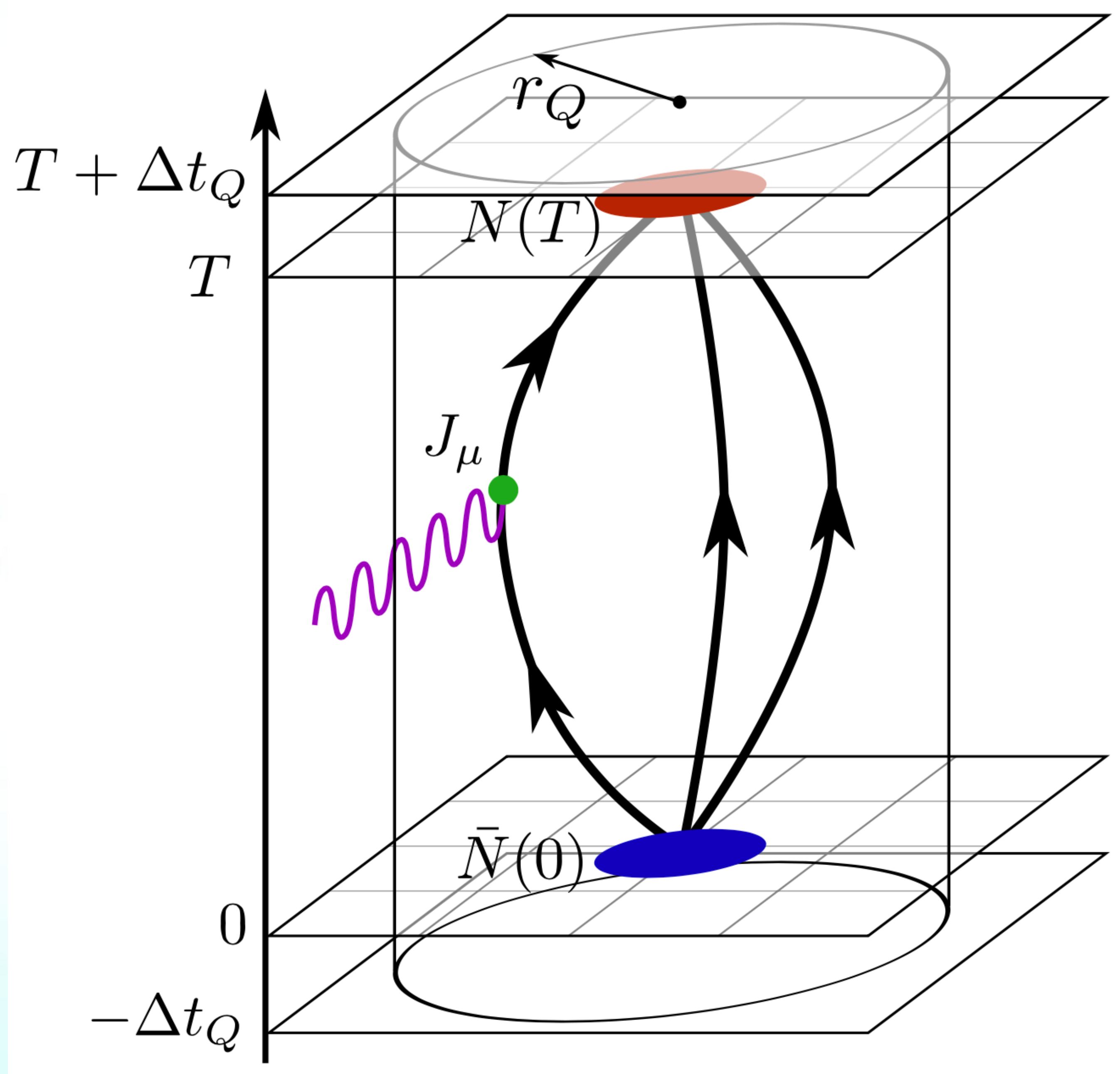
$$C_3^Q(t_f, R) = \sum_{\vec{x}} \left\langle \sum_r^{|r|\leq R} q(x+r)\chi(x)\bar{\chi}(0) \right\rangle \quad C_4^Q(t_f, \tau, R) = \sum_{\vec{x}\vec{y}} e^{-i\vec{p}\cdot\vec{x}} e^{i\vec{q}\cdot\vec{y}} \left\langle \chi(x) \sum_r^{|r|\leq R} q(y+r) J_\mu(y) \bar{\chi}(0) \right\rangle$$

Bind the topological density to the sink or to the current

Error Reduction

Cylinder shape cutoff on the topological charge

T. Izubuchi, H. Ohki and S. Syritsyn, arXiv:2004.10449



Truncation in *t*-direction

J. Dragos et al., arXiv:1902.03254

$$\overline{G}_3^{(\overline{Q})}(\boldsymbol{p}', t, \boldsymbol{q}, \tau, \Pi, \gamma_\mu, t_f, t_s)$$

$$= a \sum_{\frac{\tau_Q}{a}=0}^{t_s/a} \Big[\Delta_3^{(\overline{Q})}(\boldsymbol{p}', t, \boldsymbol{q}, \tau, \tau_Q, \Pi, \gamma_\mu, t_f) + \Delta_3^{(\overline{Q})}(\boldsymbol{p}', t, \boldsymbol{q}, \tau, T - \tau_Q, \Pi, \gamma_\mu, t_f) \Big]$$

Recent Results (Theta Term)

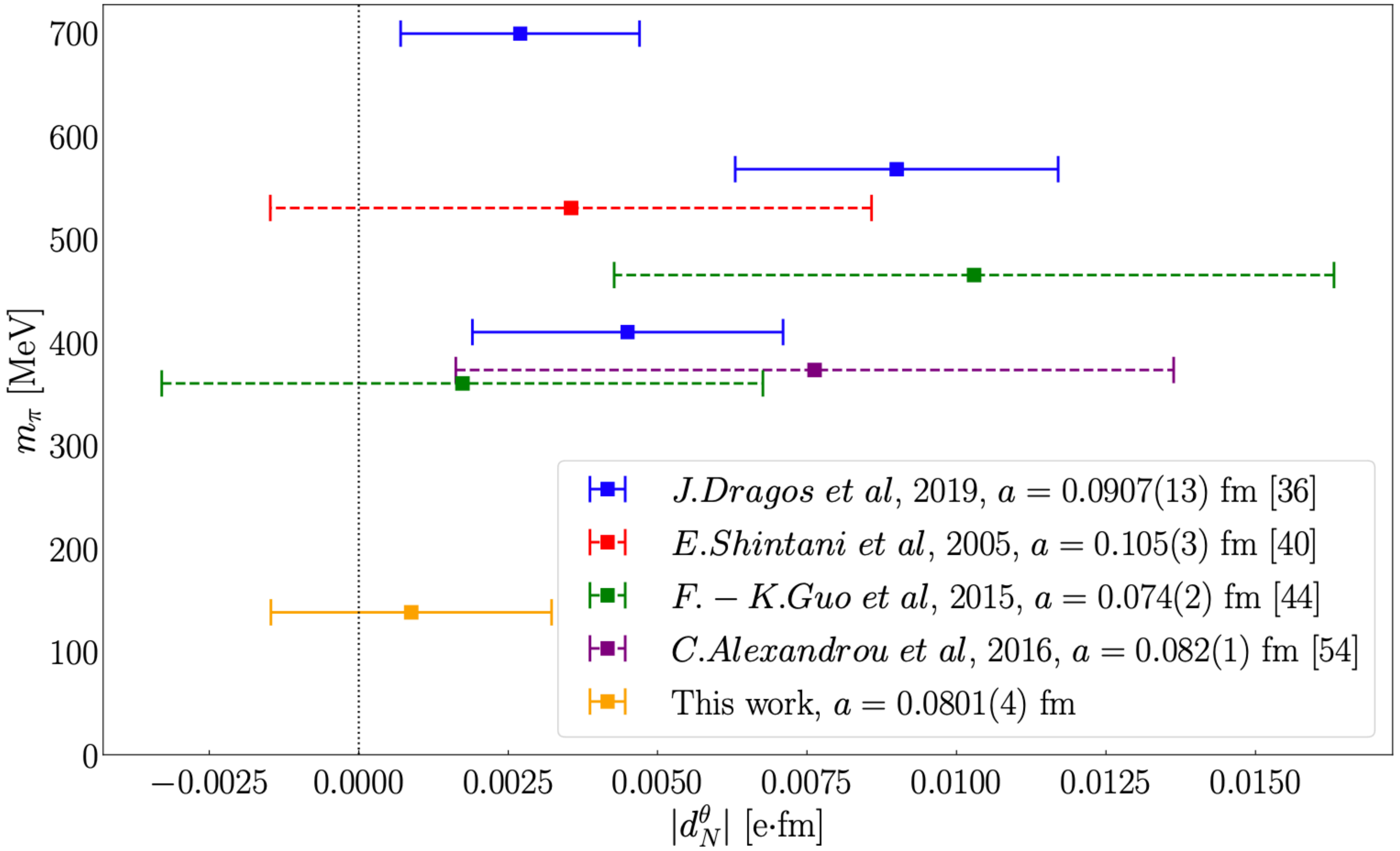


Figure 10: Comparison with other lattice QCD determinations of nEDM present in literature. Values from Refs. [40, 44, 54] (dashed error bars) are not the ones from their original papers but are taken from Table III of Ref. [45], where the spurious contribution coming from $F_2(Q^2)$ is subtracted. See Ref. [45] for further details.

C. Alexandrou et. at., arXiv:2011.01084

	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 $N\pi$	$d_n = -0.028(18)(54)$	$d_p = 0.068(25)(120)$
ETMC [66]	$\|d_n\| = 0.0009(24)$	–
Dragos et al. [44]	$d_n = -0.00152(71)$	$d_p = 0.0011(10)$
Syritsyn et al. [67]	$d_n \approx 0.001$	–

T. Bhattacharya et. at., arXiv:2101.07230

Outlines

A. Backgrounds

B. Current Status

C. Our Efforts

D. Summary and Outlook

Overlap Fermions

Nielsen-Ninomiya NO-GO theorem: No chiral fermions can be accommodated on the lattice without doubles, if the lattice action has Translational invariance, Hermiticity and locality.

Ginsparg-Wilson relation: $\{\gamma_5, D\} = aD\gamma_5 D$. It defines the lattice version of chiral symmetry, which is restored in a naive continuum limit.

The overlap fermion $D_{\rm ov} = \frac{1}{a}[1 + \gamma_5 {\rm sgn}(H)]$ with ${\rm sgn}(H) = \frac{H}{\sqrt{H^2}}$ and $H = \gamma_5 D_w$ is an exact solution to the GW relation.

Effective propagator: $D^{-1} = \frac{1 - \frac{1}{2}D_{\rm ov}}{D_{\rm ov}(m)} = \frac{1}{\frac{D_{\rm ov}}{1 - \frac{1}{2}D_{\rm ov}} + m} \equiv \frac{1}{D_c + m}$; D_c is continuum-like: $\{\gamma_5, D_c\} = 0$.

Theta QCD With Chiral Fermions

For overlap fermions, the anomalous Ward identity (AWI) has been proven (with chiral axial vector current) and numerically checked (with local axial current plus a normalization constant the same as the iso-vector case) at finite lattice spacings.

P. Hasenfratz, et. al., NPB643:280 (2002)
***J. Liang** et. al., PRD98:074505 (2018)*

With the AWI, it can be shown that the topological charge term can be replaced with the $2mP$ term, which grantees that $d_n \to 0$ when $m_q \to 0$ even at finite lattice spacings.

D. Guadagnoli, et. al., JHEP 0304, 019 (2003)

Topological charge can be defined from the overlap operator: $\frac{1}{2}\mathrm{Tr}[\gamma_5 D_{\mathrm{ov}}]$

Lattice Setups

Overlap fermions on three domain wall gauge ensembles

label	$L^3 \times T$	a (fm)	L (fm)	$m_{\pi,s}$ (MeV)	N_{cfg}
24I005	$24^3 \times 64$	0.1105(3)	2.65	339	203
24I010	$24^3 \times 64$	0.1105(3)	2.65	432	143
24I020	$24^3 \times 64$	0.1105(3)	2.65	560	100

Multiple valence pion masses by using the Multi-Mass algorithm

label	$m_{\pi,v}$ (MeV)			
24I005	282	321	348	389
24I010	391	426	519	600
24I020	397	432	525	606

Our Strategy (Using Chiral Fermions)

A. Heavy pion masses and chiral extrapolation at finite lattice spacing.

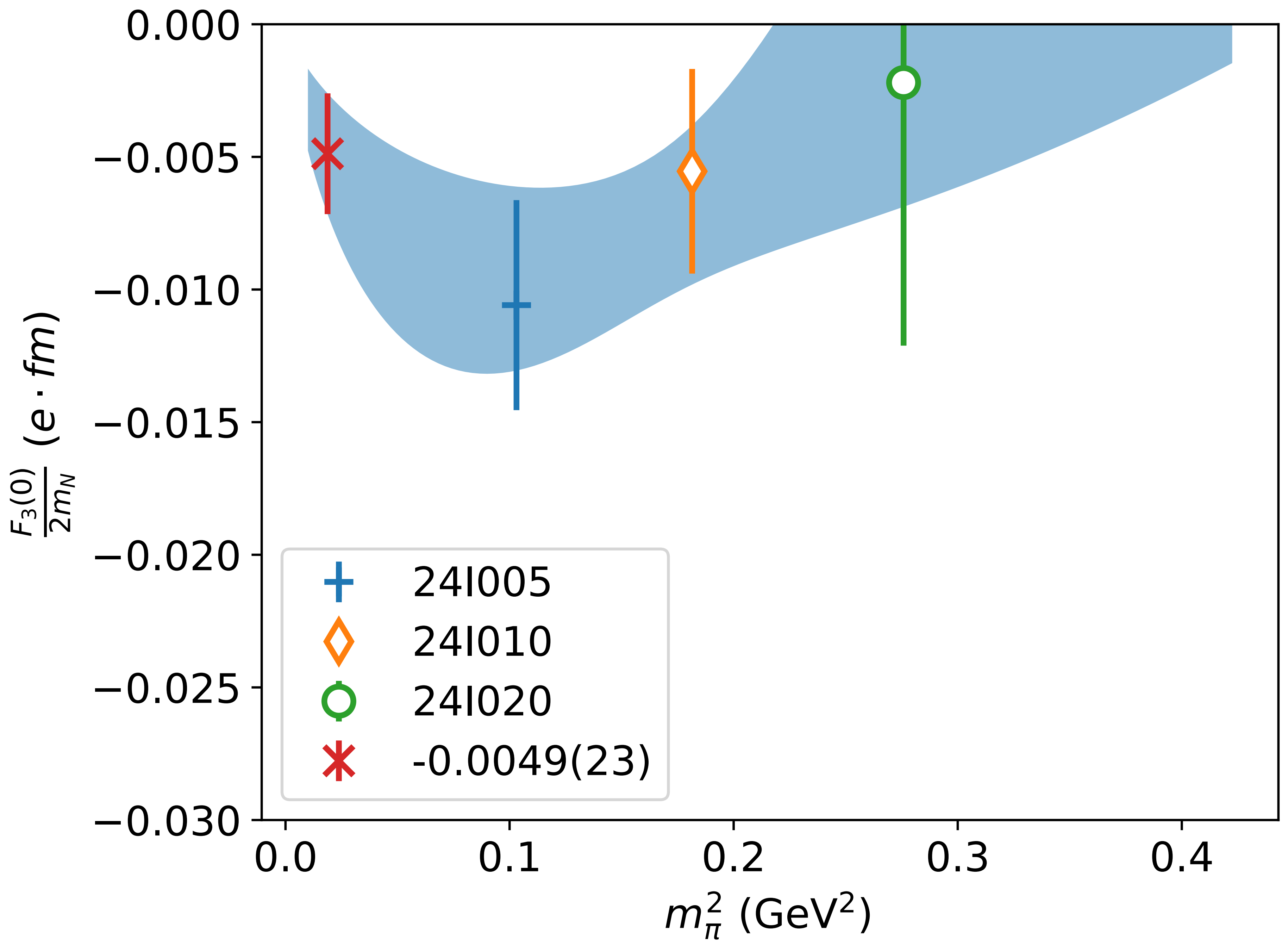
B. Additional valence (partially-quenched) pion mass points in the extrapolation.

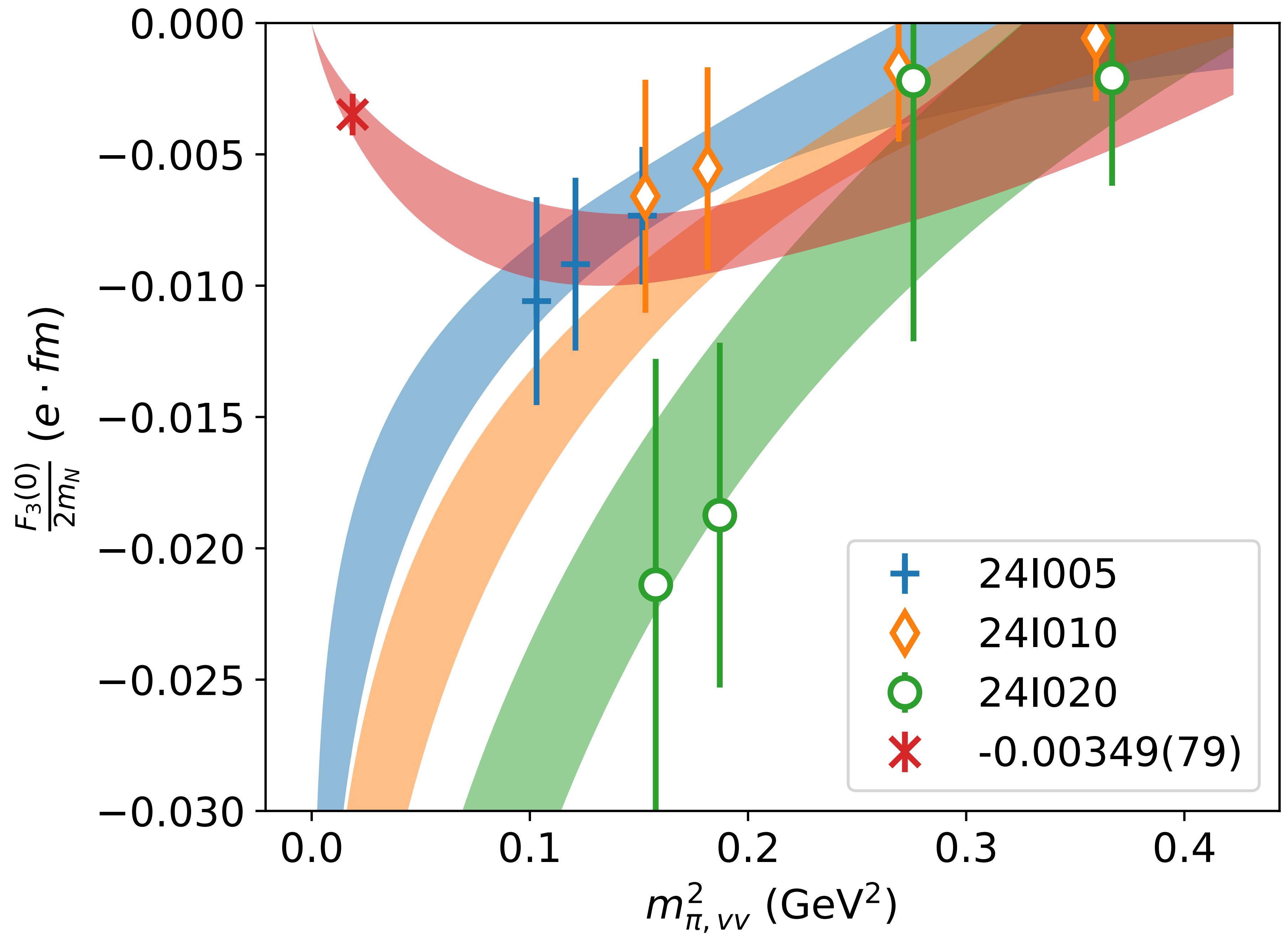
C. The cluster decomposition error reduction (CDER).

D. Smaller source-sink separations (hoping the excited-state effects are not larger than the statistical errors).

E. Overlap defined topological charge density.

Preliminary Results





$$d_{p/n}(m_\pi) = C_1\ m_\pi^2 + C_2\ m_\pi^2 \log(\frac{m_\pi^2}{m_{N,phys}^2})$$

W. H. Hockings and U. van Kolck, PLB605, 273 (2005)

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

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

Chiral fermions + partially-quenched valence points really help

Data points are from source-sink separation ~ 0.9 fm (excited-state contaminations!)

Outlines

A. Backgrounds
B. Current Status
C. Our Efforts
D. Summary and Outlook

Summary and Outlook

CP Violation is an important physical topic, but getting the nucleon (neutron) EDM on the lattice (especially directly at the physical point) is really hard.

We have tried a lot and made some progress. Hopefully, with the help of chiral fermions, we may finally be able to have non-zero results at the physical pion mass limit.

The excited-state contaminations are quite important to study in order to have controlled systematic uncertainties.

Different lattice spacings and light pion masses will be included in the next stage.

Thank you for your attention!

SNSC
Southern Nuclear Science Computing Center

Backup and Old Slides

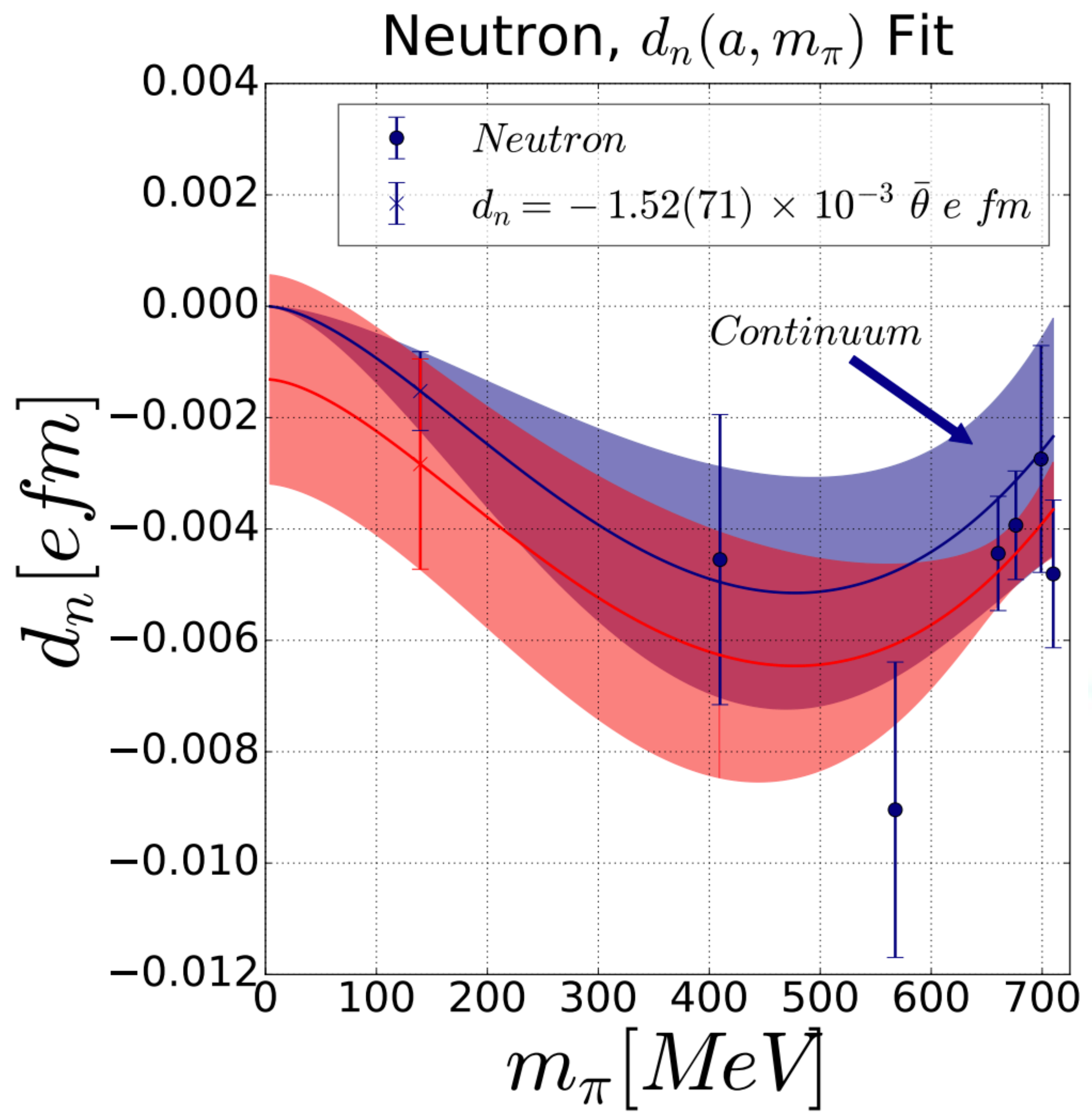
南方核科学计算中心

SNSC
Southern Nuclear Science Computing Center

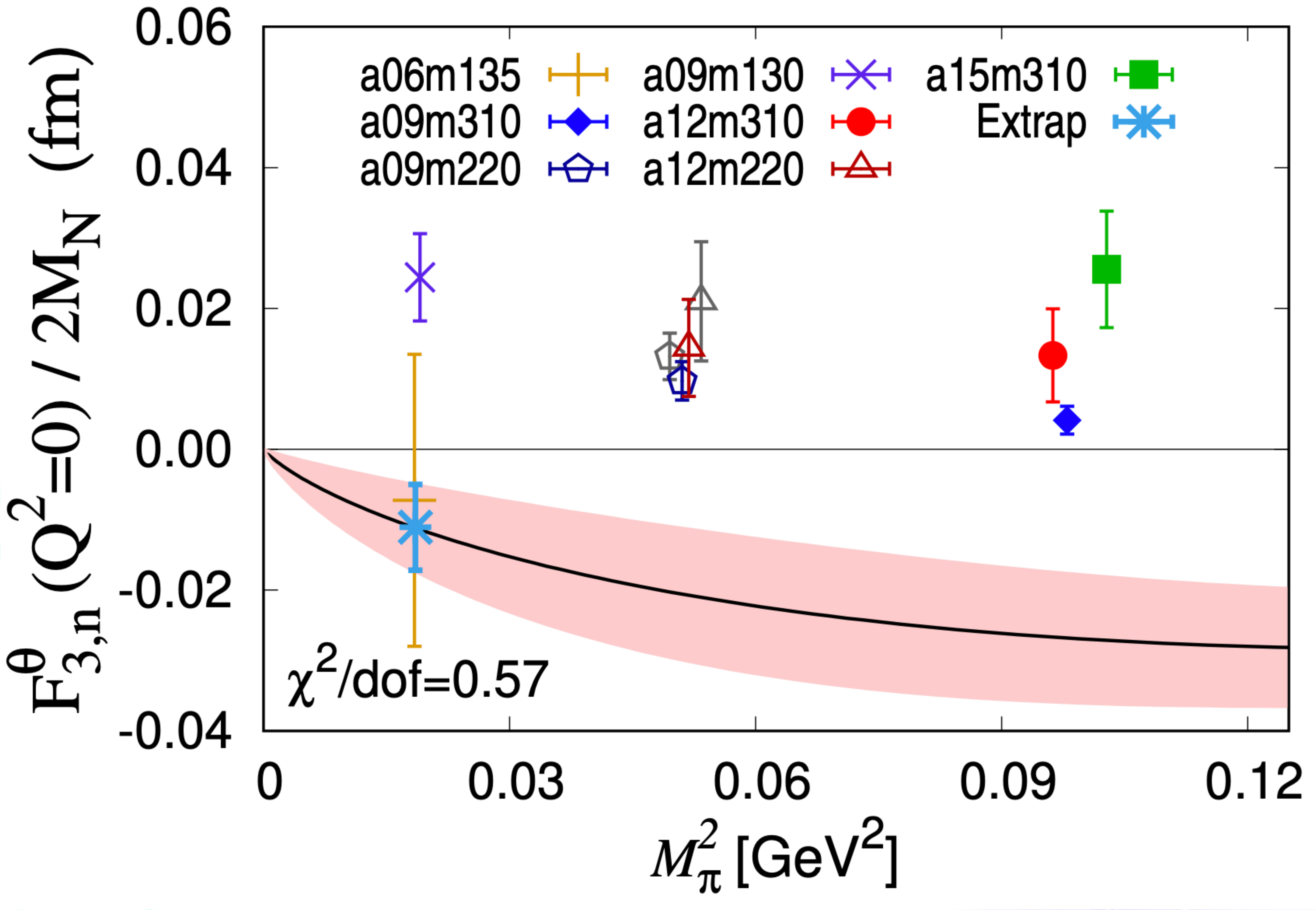
目前：2 DGX2节点 + 8 GPU8节点，96 V100 GPUs，~750T 峰值双精浮点计算能力

最终目标：～170 GPU节点，～10P 峰值双精浮点计算能力，中国乃至世界核物理研究方向最强大的计算平

Recent Results (Theta Term)



J. Dragos et al., arXiv:1902.03254

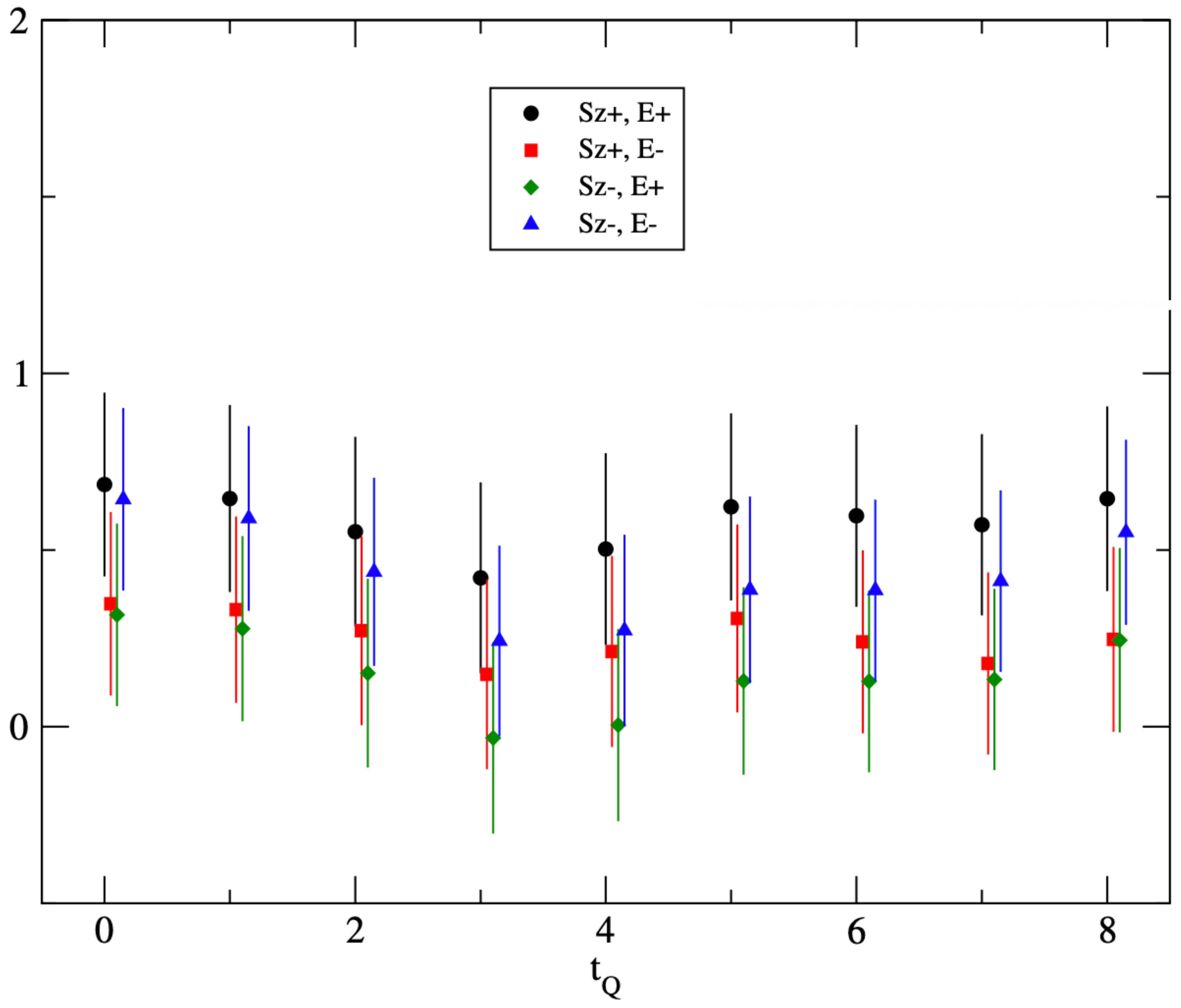


B. Yoon et. al., arXiv:2003.05390

Chiral extrapolation with heavy pion masses and with non-chiral fermion

Non-zero signal at the physical point, but large order *a* extrapolation

Recent Results (Theta Term)



T. Izubuchi, H. Ohki and S. Syritsyn, arXiv:2004.10449

Energy shift method in the presence of a background electric field with local topological charge (no momentum transfer extrapolation is required): F3(0) at pion mass ~330 MeV

Recent Results (Theta Term)

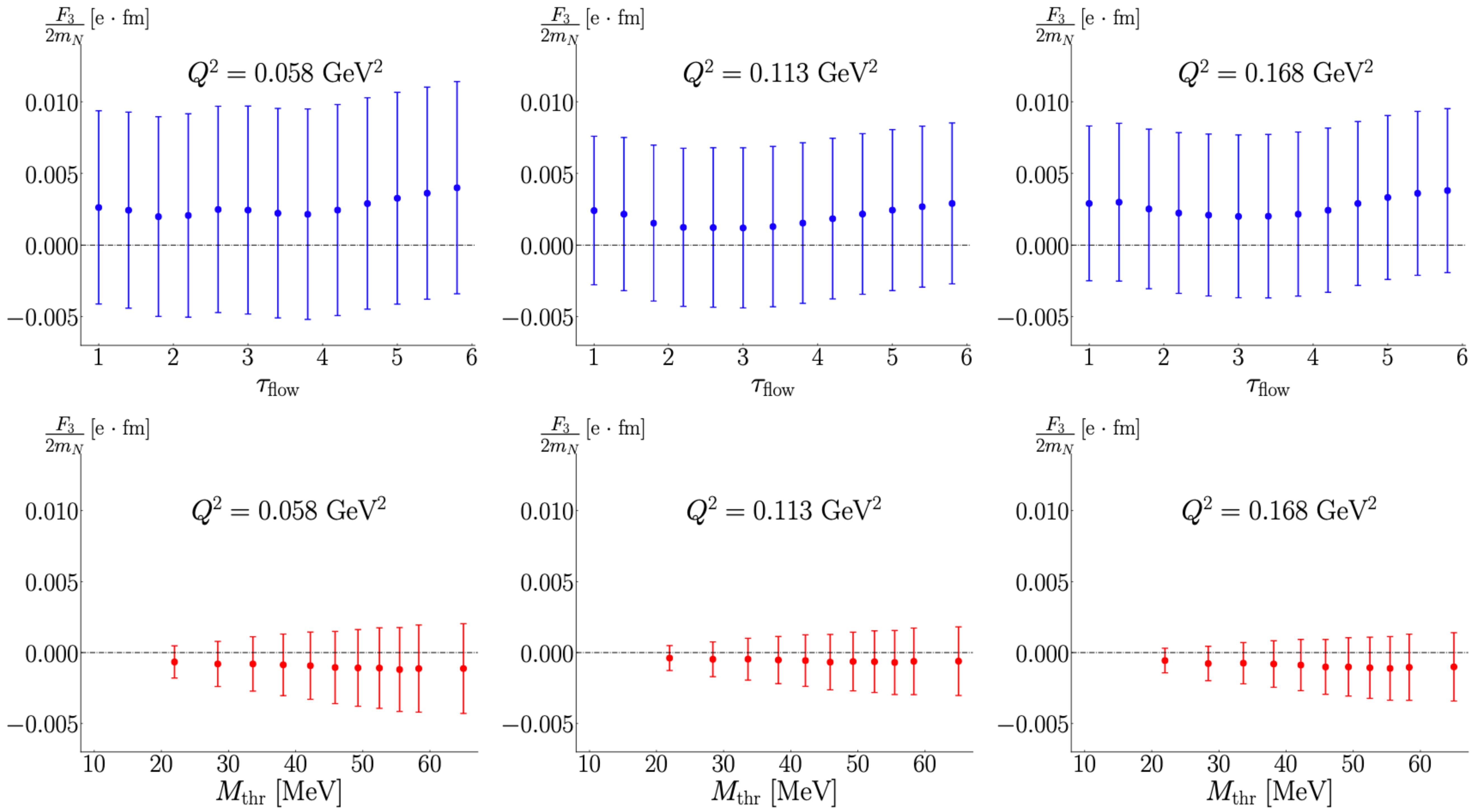


Figure 9: Dependence of the $F_3(0)$ on the smoothing scale τ_{flow} for the gluonic (upper row) and cut-off M_{thr} for the fermionic (bottom row) definitions used in computation of the topological charge, for the three smaller values of the momentum transfer squared.

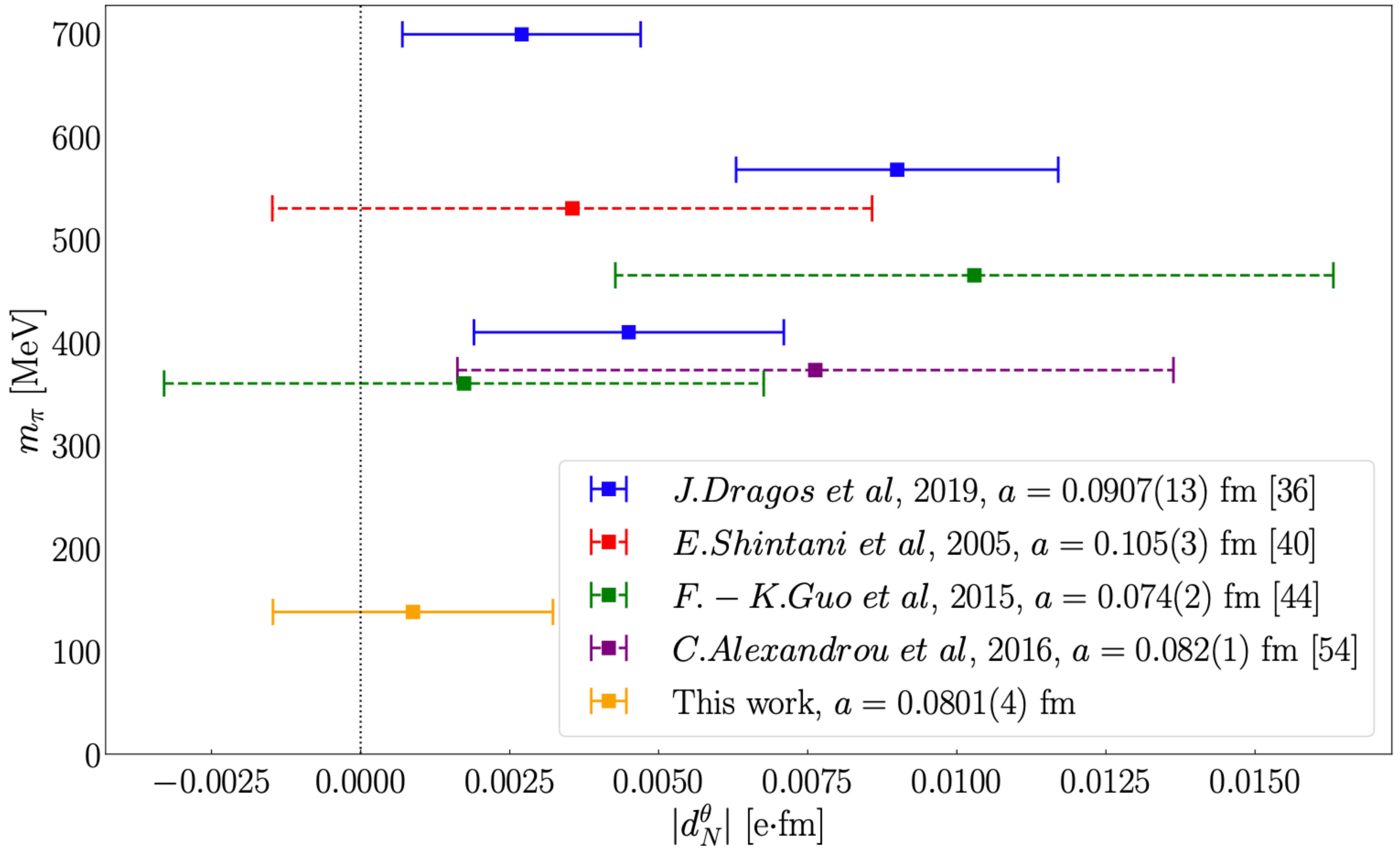
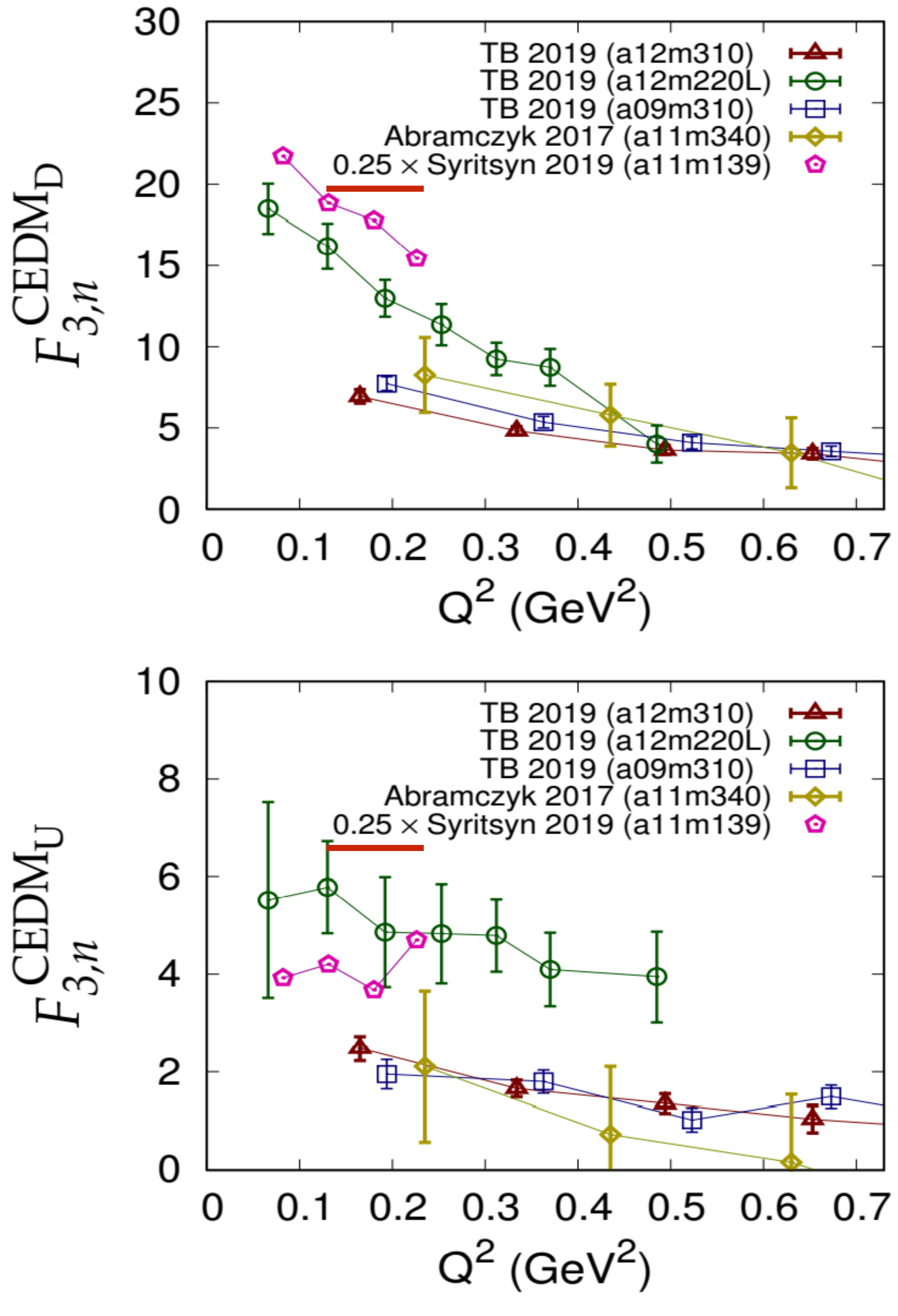


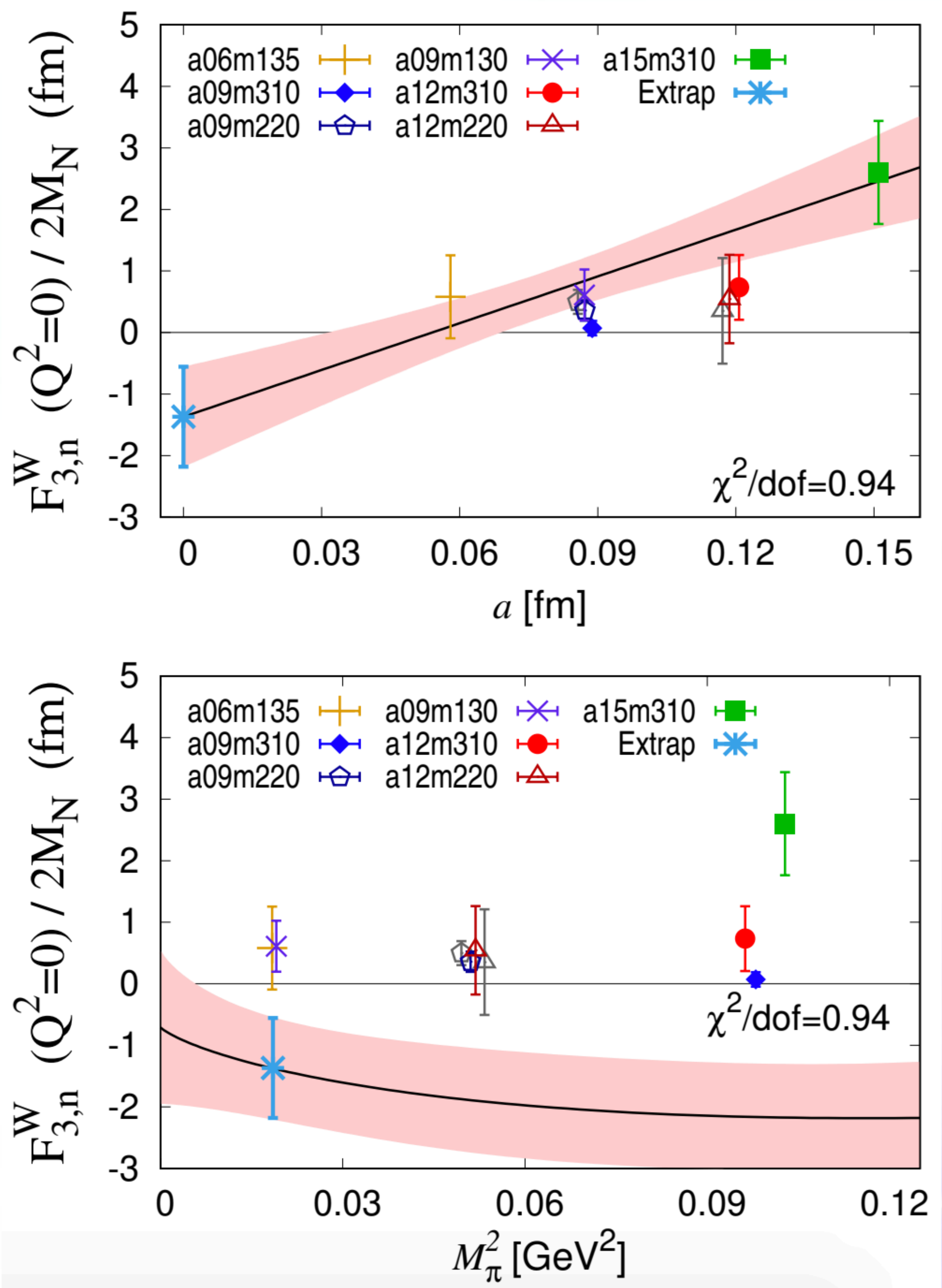
Figure 10: Comparison with other lattice QCD determinations of nEDM present in literature. Values from Refs. [40, 44, 54] (dashed error bars) are not the ones from their original papers but are taken from Table III of Ref. [45], where the spurious contribution coming from $F_2(Q^2)$ is subtracted. See Ref. [45] for further details.

C. Alexandrou et. at., arXiv:2011.01084

Physical pion mass directly, no signal…

Recent Results (BSM)





B. Yoon et. al., arXiv:2003.05390

M. Abramczyk et. al., PRD96: 014501 (2017)
T. Bhattacharya, R. Gupta and B. Yoon, arXiv:2003.08490
S. Syritsyn, T. Izubuchi and H. Ohki, ArXiv:1901.05455

Strong quark mass dependence (or other unknown systematic uncertainties) of cEDM

Large statistical error in the Weinberg term case

Chirality

The term **chirality** originated from a Greek word which means **the hand.**

In geometry, an object is chiral if it is not identical to its **mirror image**.

Chiral Symmetry in QCD

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}(i\not{D} + m)\psi + \mathcal{L}_{\mathrm{g}}$$

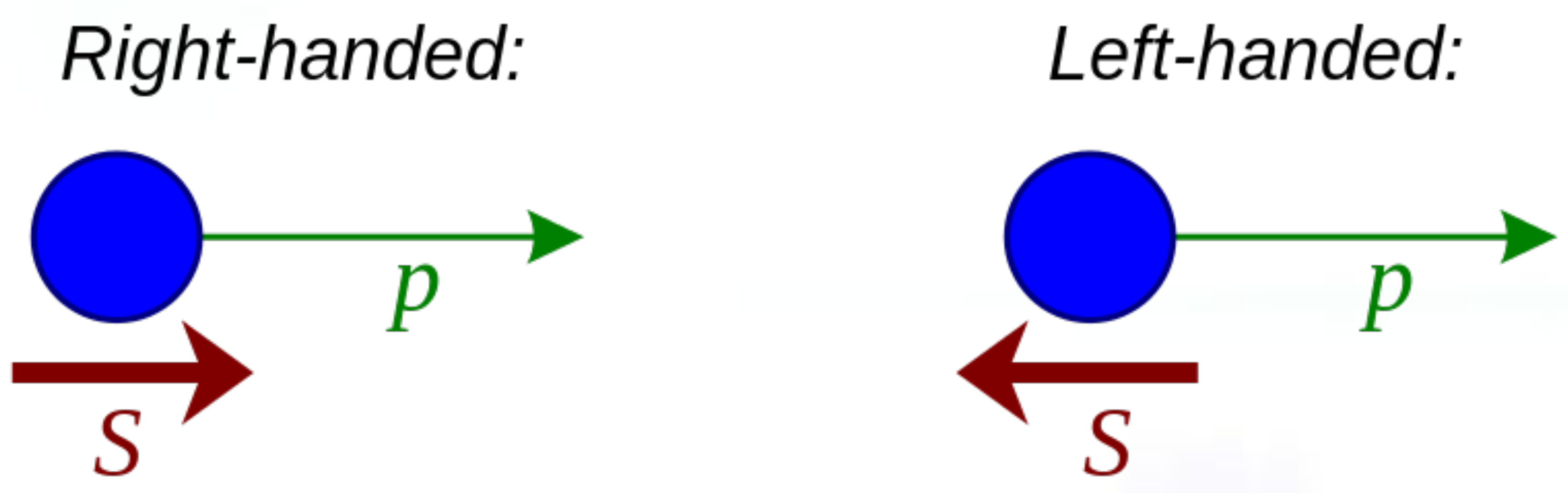
$$\psi \rightarrow \psi_L = \frac{1-\gamma_5}{2}\psi \qquad \psi \rightarrow \psi_R = \frac{1+\gamma_5}{2}\psi$$

$$\bar{\psi} \rightarrow \bar{\psi}_L = \bar{\psi}\frac{1+\gamma_5}{2} \qquad \bar{\psi} \rightarrow \bar{\psi}_R = \bar{\psi}\frac{1-\gamma_5}{2}$$

$$\gamma_5\psi_L = -\psi_L \qquad \gamma_5\psi_R = +\psi_R$$

$$\mathcal{L}_{\mathrm{QCD}}(m=0) \rightarrow \bar{\psi}_L i\not{D}\psi_L + \bar{\psi}_R i\not{D}\psi_R + \mathcal{L}_{\mathrm{g}}$$

$$\psi_L \rightarrow e^{i\theta_L}\psi_L \qquad \psi_R \rightarrow e^{i\theta_R}\psi_R$$

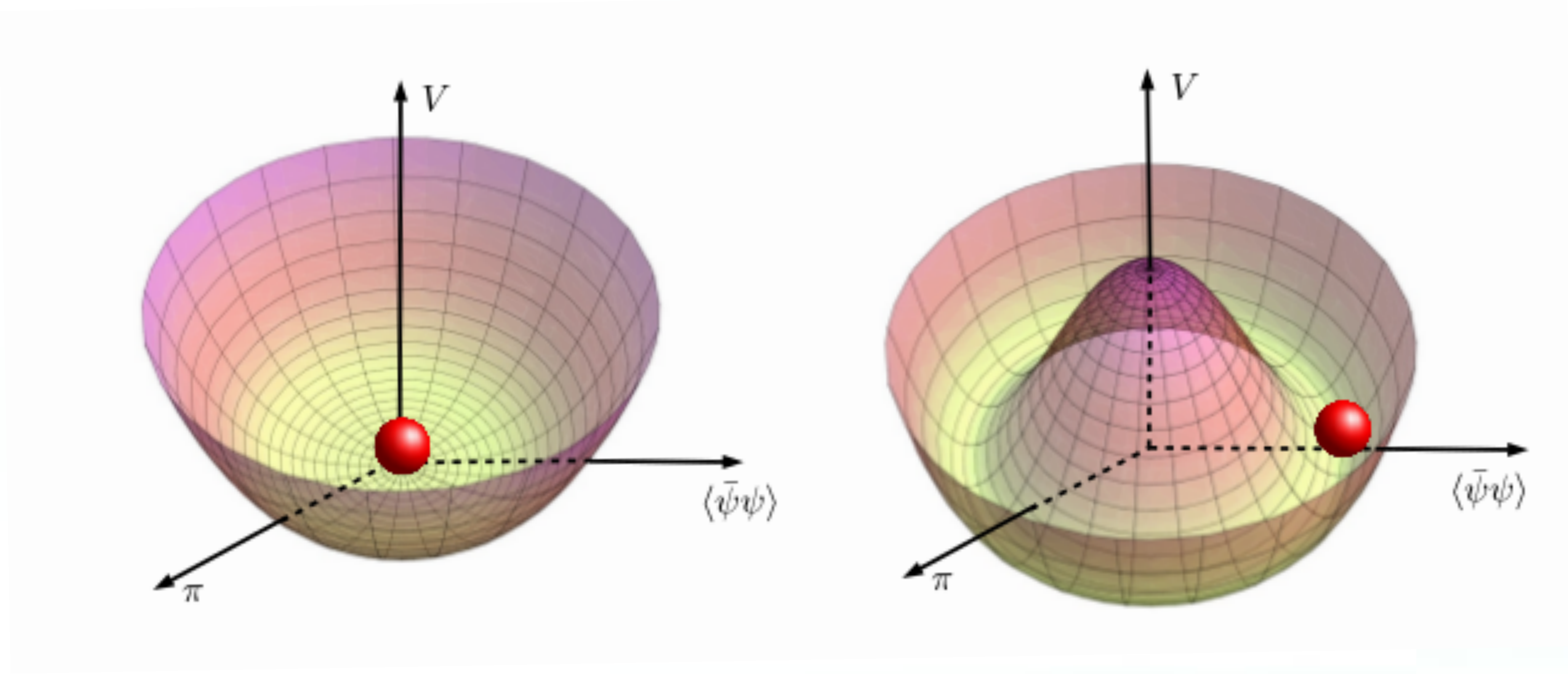


$$SU(3)_L \times SU(3)_R \times U(1)_V \times U(1)_A$$

$$\theta_L = \theta_R \qquad \theta_L = -\theta_R$$

Spontaneous Chiral Symmetry Breaking

Due to the gluon dynamics, the condensate $\langle\bar{\psi}\psi\rangle \neq 0$ makes the QCD vacuum **NOT invariant** under chiral transformation.



https://www.quora.com/What-is-an-intuitive-explanation-of-chiral-symmetry-breaking

$SU(3)_L \times SU(3)_R \rightarrow SU(3)_V$ 8 (Pseudo-)Goldstone bosons

It gives the theory an **intrinsic scale**.

It explains the bulk of hadron masses, and, the bulk of the **mass of the visible universe**.

$U(1)_A \rightarrow \cancel{U(1)_A}$ Ninth one? Axial anomaly

Chiral Symmetry on the Lattice

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

$$D_w = \ldots + \frac{4}{a}\bar{\psi}\psi$$

the Wilson term fails in preserving chiral symmetry

Other ways to remove the doublers?

Nielsen-Ninomiya NO-GO theorem: **No** chiral fermions (in terms of the anti-commutator) can be accommodated on the lattice without doubles, if the lattice action has

Translational invariance **Hermiticity** **locality**

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

the chiral symmetry is restored in a **naive continuum limit**

Ginsparg-Wilson Relation:

$$\{\gamma_5, D\} = aD\gamma_5 D$$

$$\gamma_5 \to \hat{\gamma}_5 = \gamma_5(1 - aD)$$

$$\psi \to \psi_L = \frac{1 - \hat{\gamma}_5}{2}\psi \qquad \psi \to \psi_R = \frac{1 + \hat{\gamma}_5}{2}\psi$$

$$\hat{\gamma}_5\psi_L = -\psi_L \qquad \hat{\gamma}_5\psi_R = +\psi_R$$

$$\mathscr{L}_{\rm QCD}(m=0) \to \bar{\psi}_L D\psi_L + \bar{\psi}_R D\psi_R + \mathscr{L}_{\rm g}$$

It defines the **lattice version of the chiral symmetry**.

$$\gamma_5 D^{-1}(y,x) + D^{-1}(y,x)\gamma_5 = a\gamma_5\delta(y,x)$$

only a **contact term**

The Overlap Fermion

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

$$\text{sgn}^2(H) = 1 \qquad [1 + \gamma_5 \text{sgn}(H)]\gamma_5[1 + \gamma_5 \text{sgn}(H)] = [1 + \gamma_5 \text{sgn}(H)]\gamma_5 + [\text{sgn}(H) + \gamma_5]$$

Exponentially local:

$|D(y,x)| \leq Ce^{-\gamma|x-y|}$ and C and γ are independent of lattice spacing (gauge field).

The evaluation of the sign function is costly, deflation + polynomial

PRD82:114501 (2010)

Massive Overlap Fermions and D_c

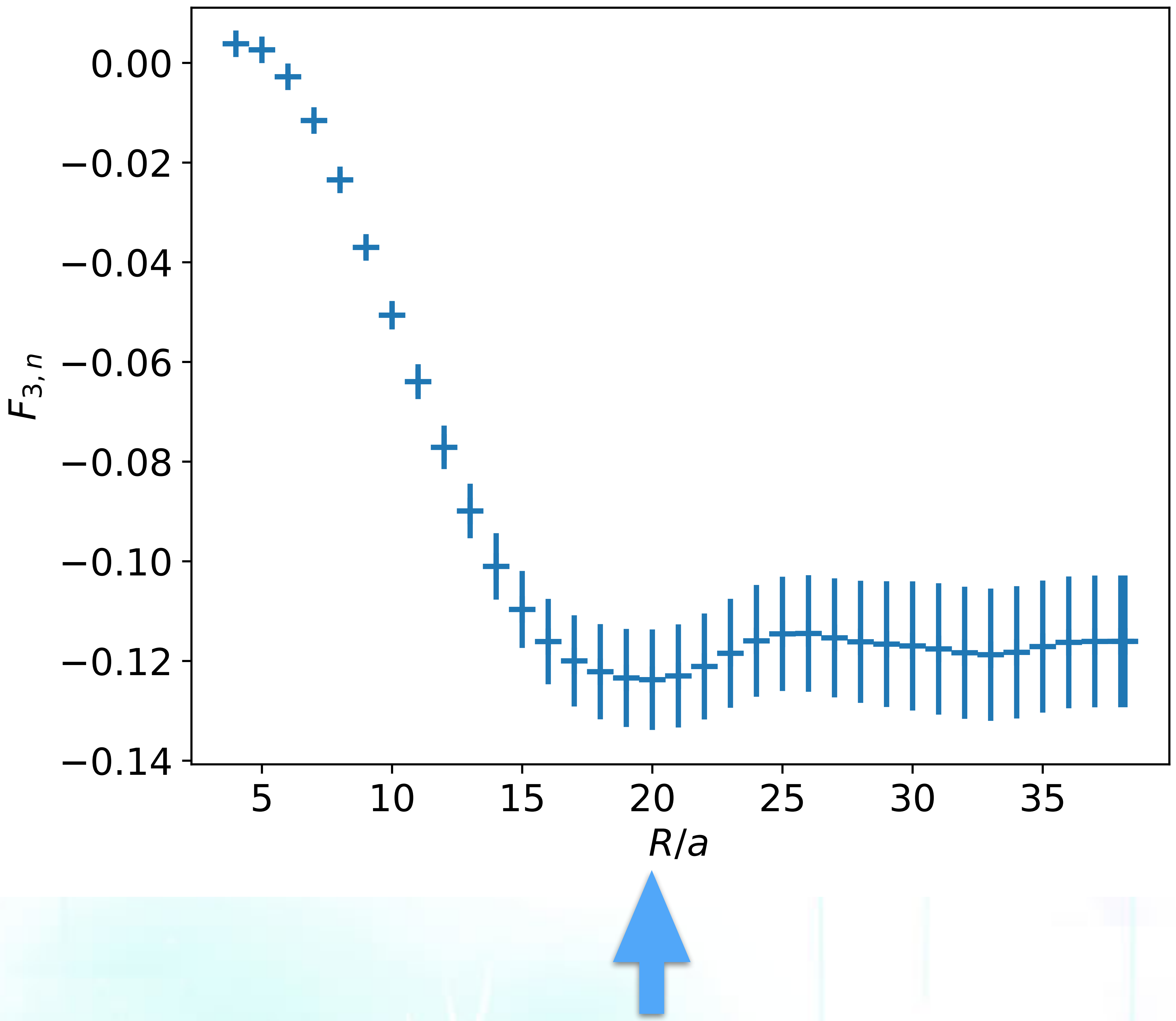
Massless overlap Dirac operator: $\rho D_{\text{ov}}(\rho)$ $\qquad \{\gamma_5, D_{\text{ov}}\} = \frac{1}{\rho} D_{\text{ov}} \gamma_5 D_{\text{ov}}$

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

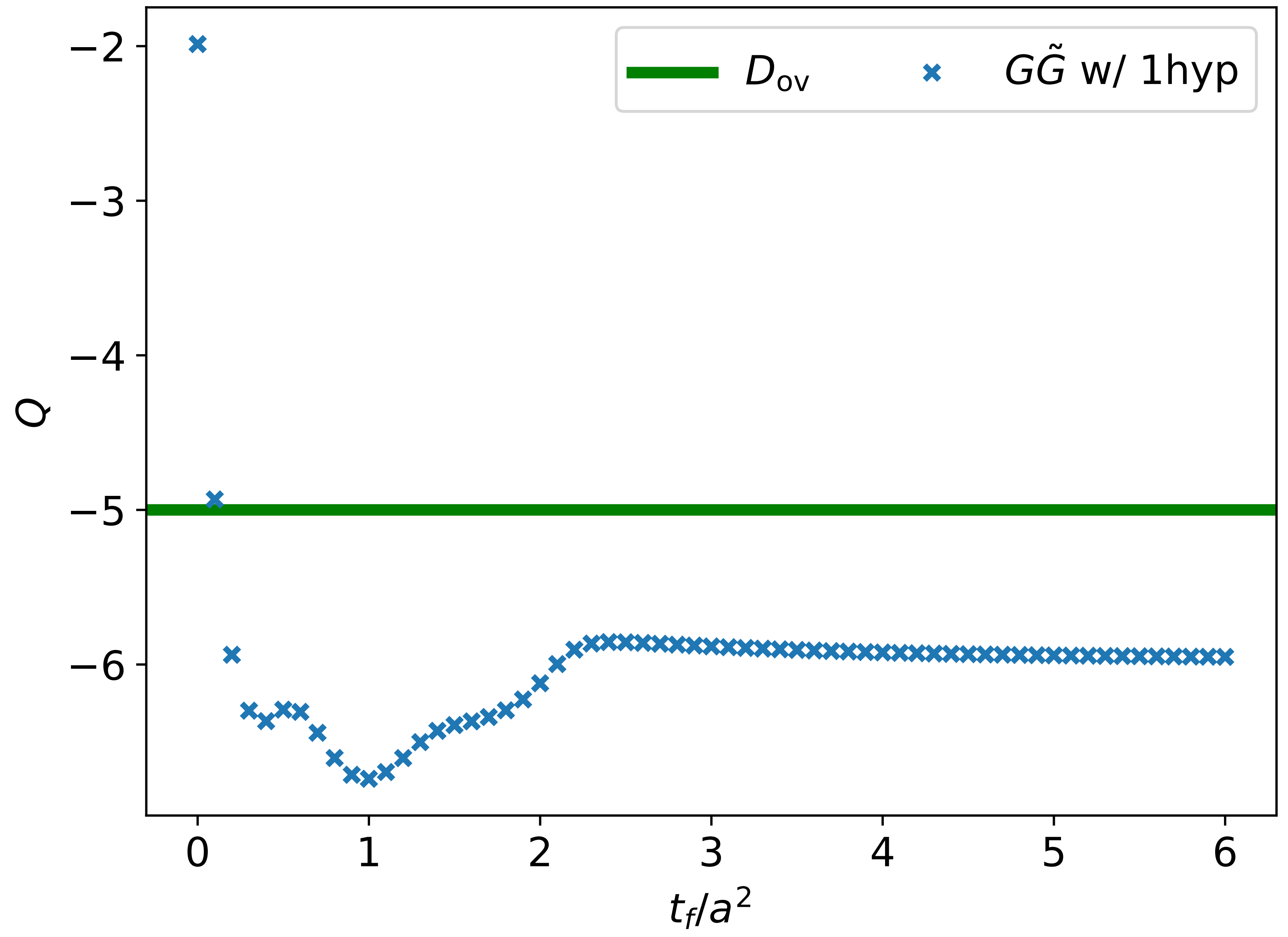
D_c is **continuum-like**.

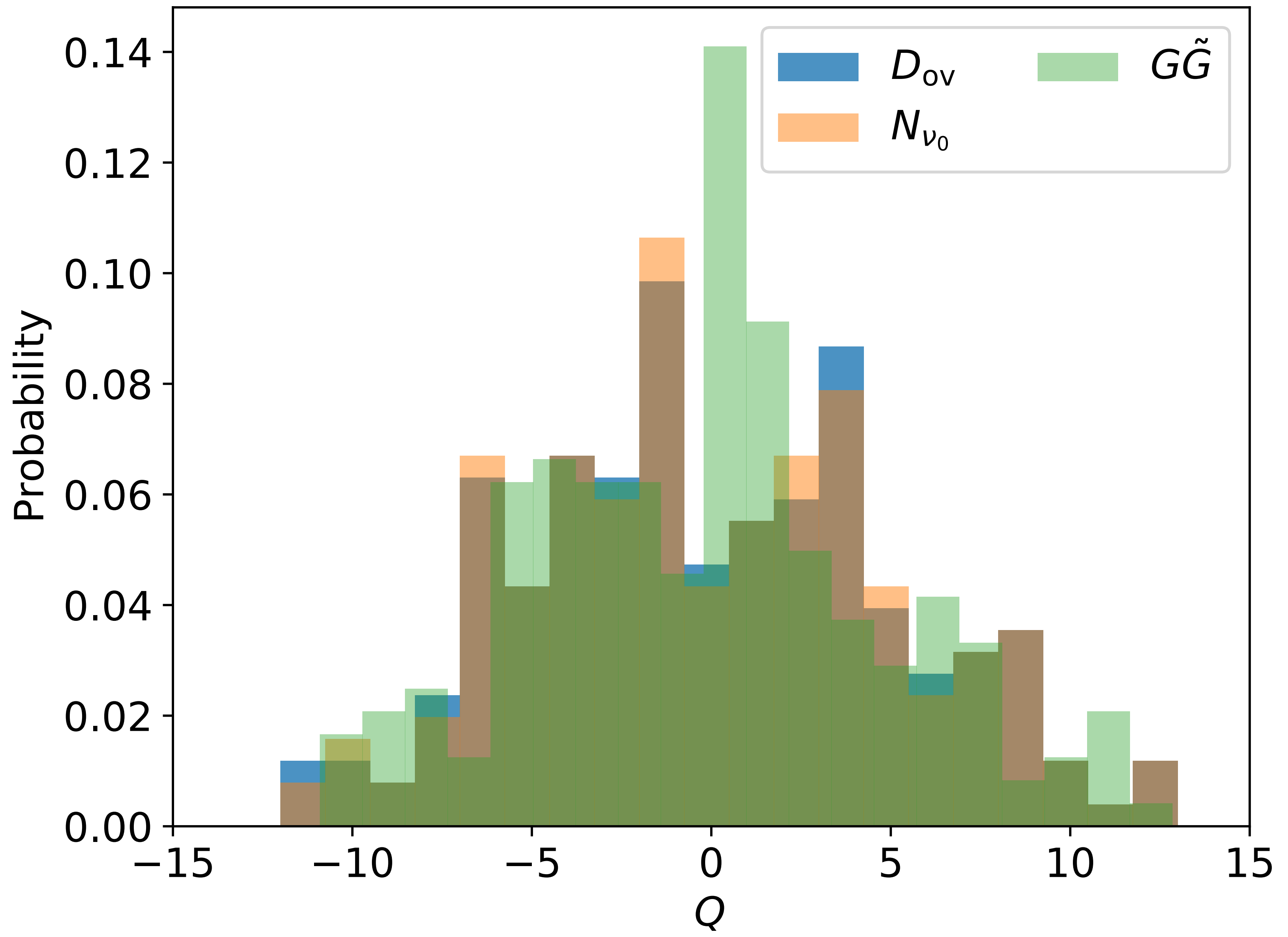
CDER

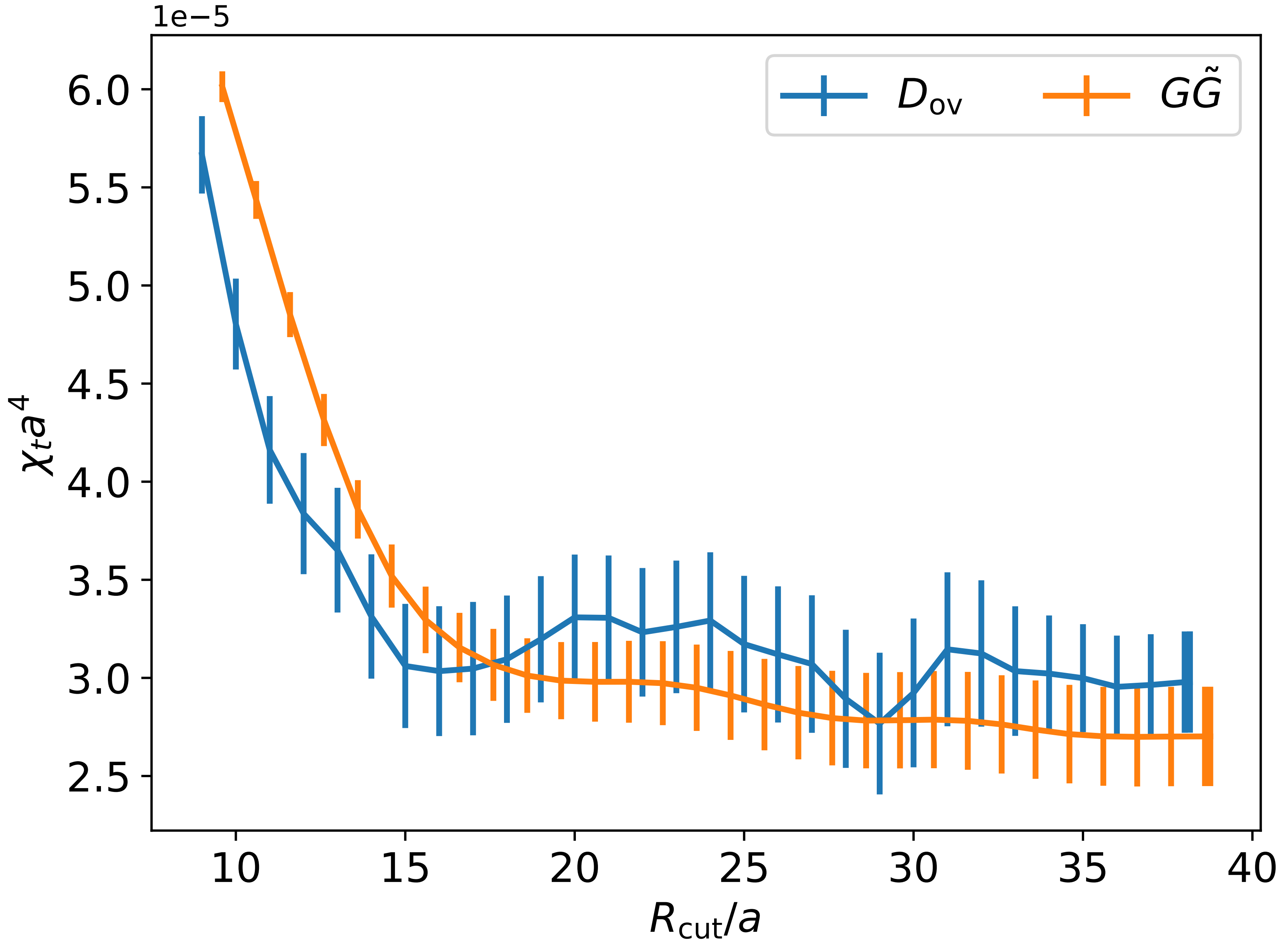


For this small lattice (~2.64 fm), we can reduce the error by half.

Topological Charges



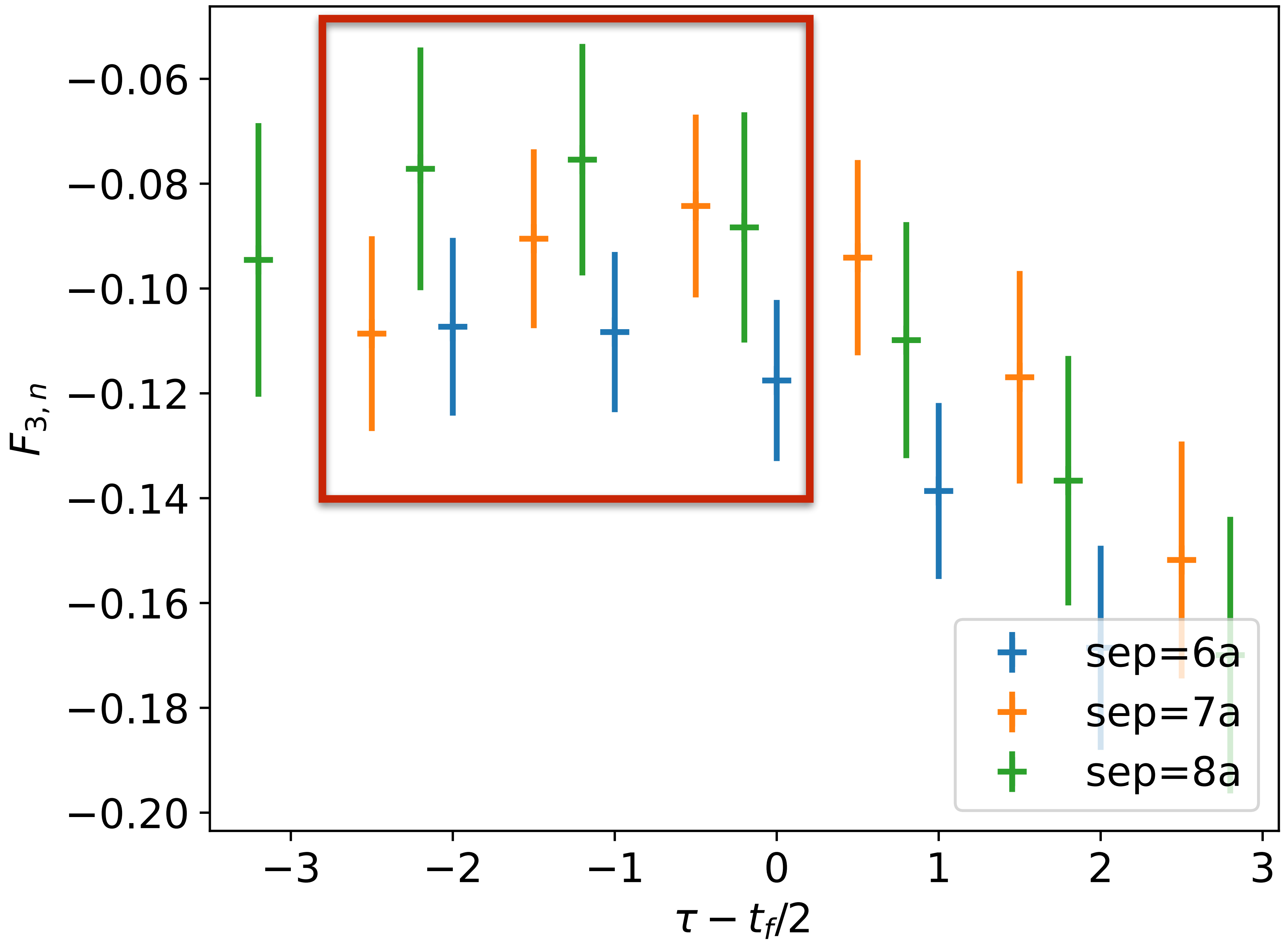


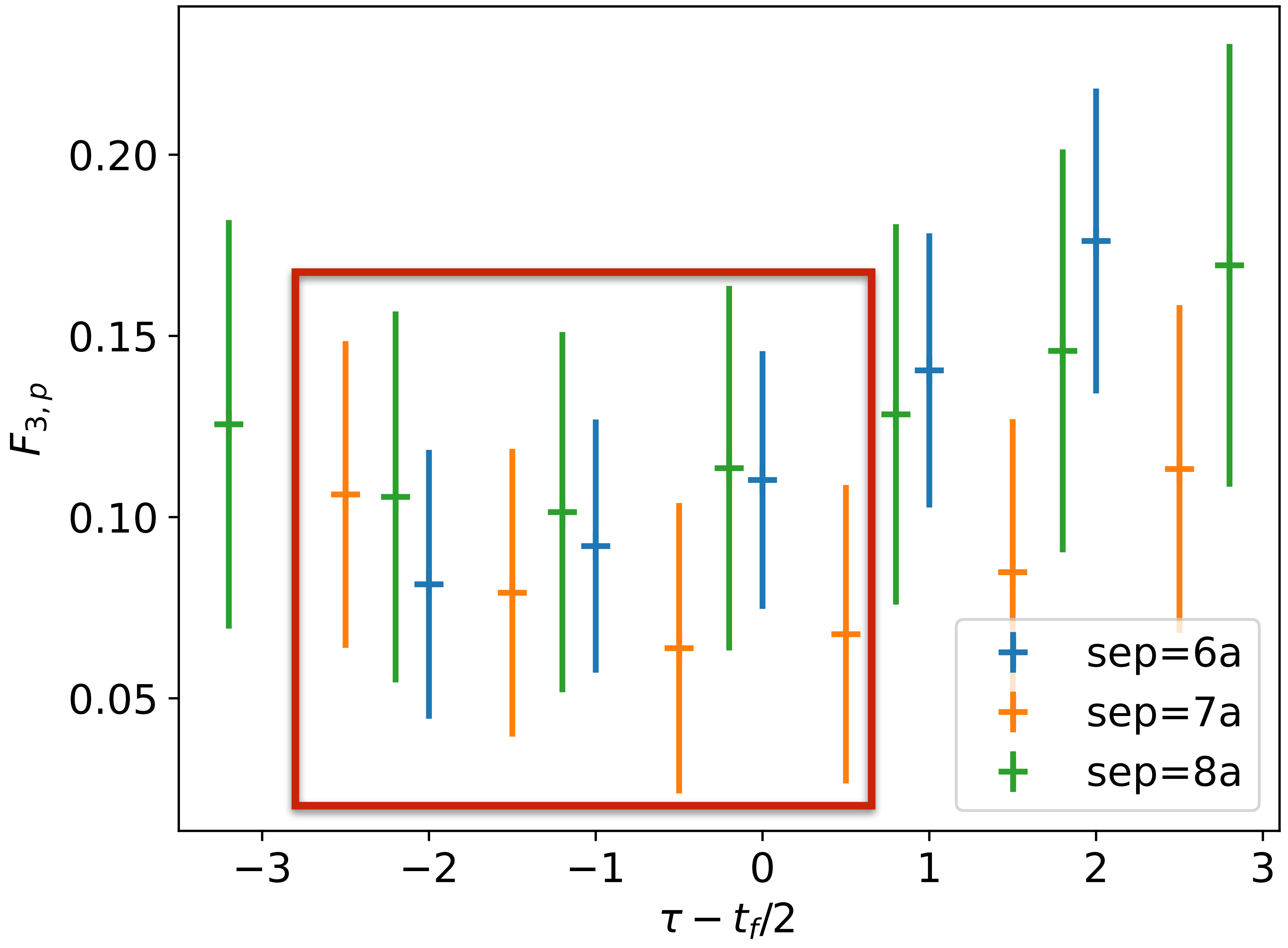


The topological charges of individual configurations with different definitions are different, which is natural as they involve different regulations. Distributions are similar.

For physical quantities such as the topological susceptibility, different definitions agree within statistical errors.

Excited-State Effects





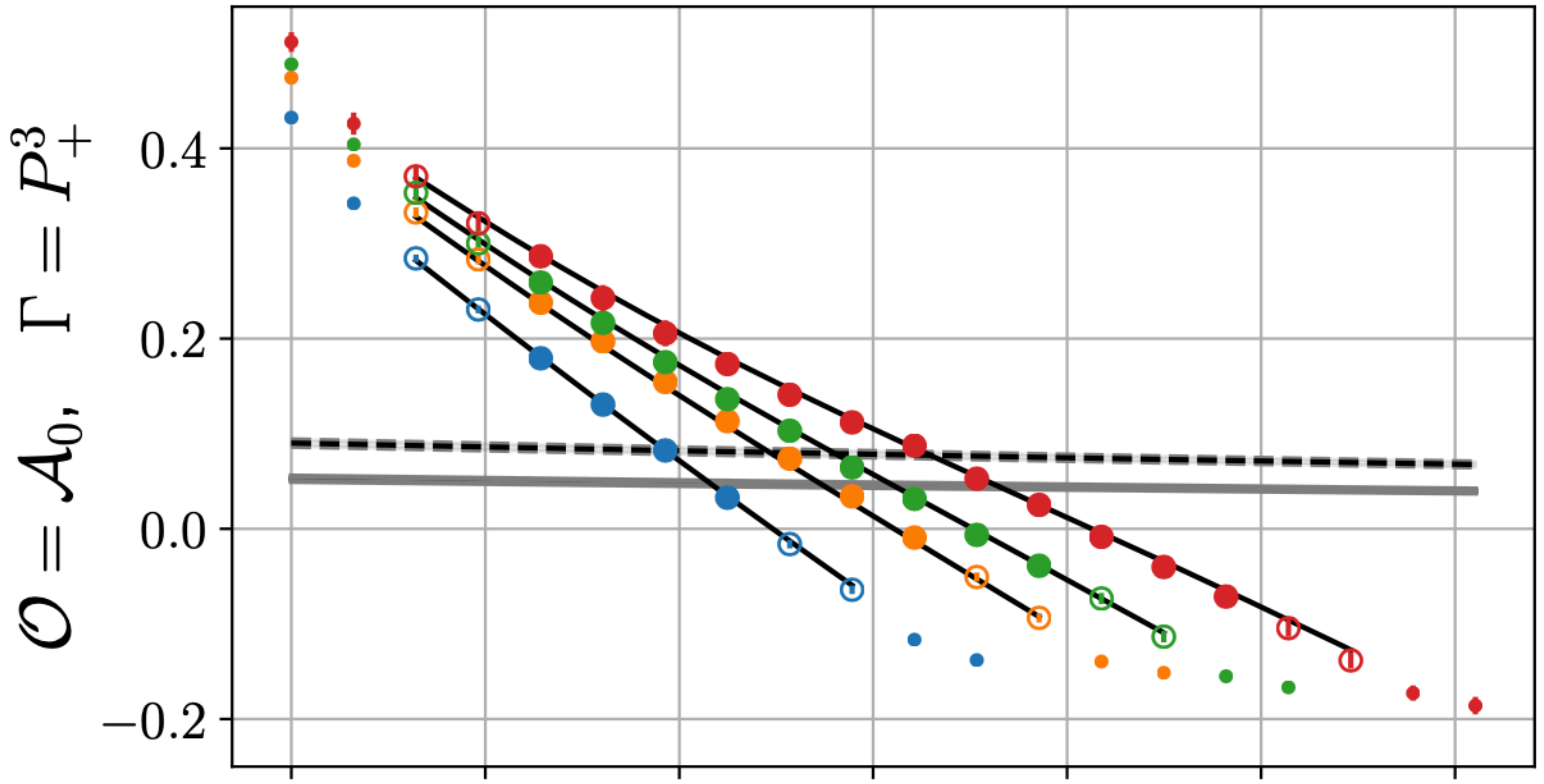
Smeared source to point sink!

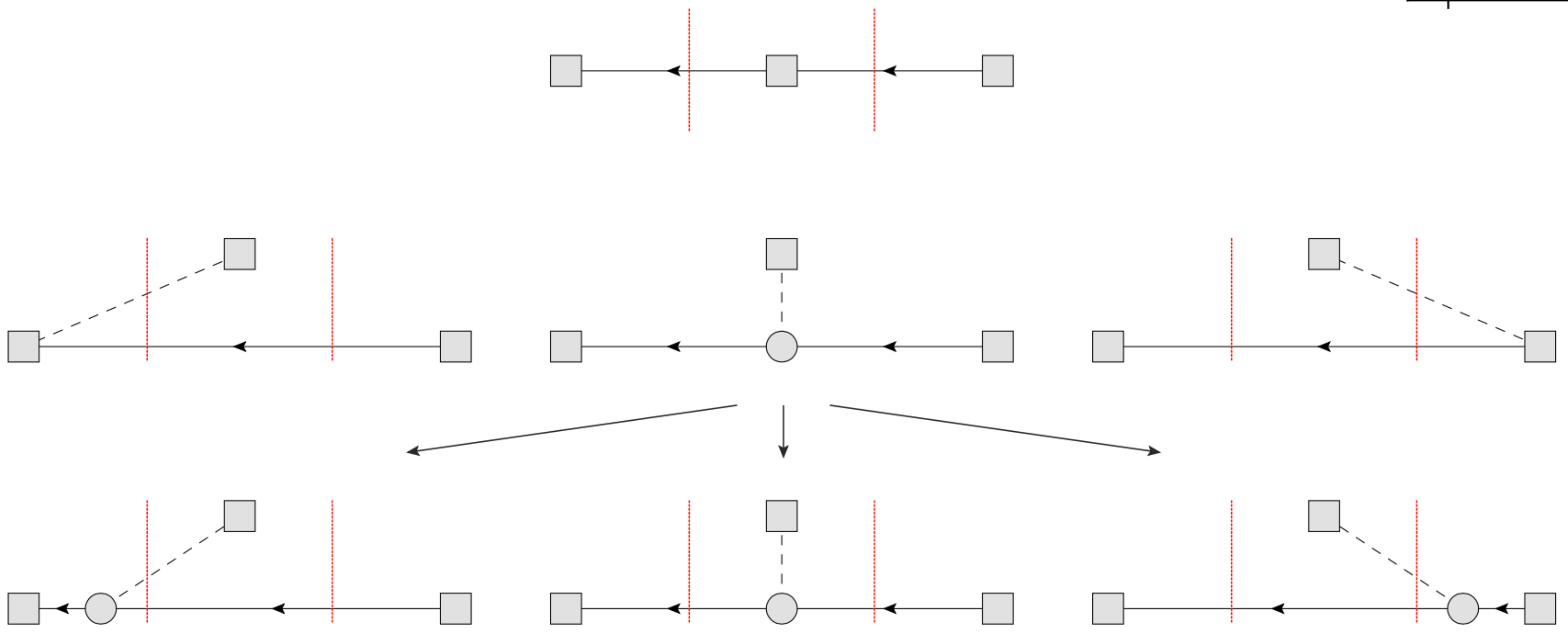
After having more statistics, the excited-states contamination seems obvious, at least on the sink side.

The Pion-Nucleon-State Effects

$$\langle J_N A_4(P) \bar{J}_N \rangle$$

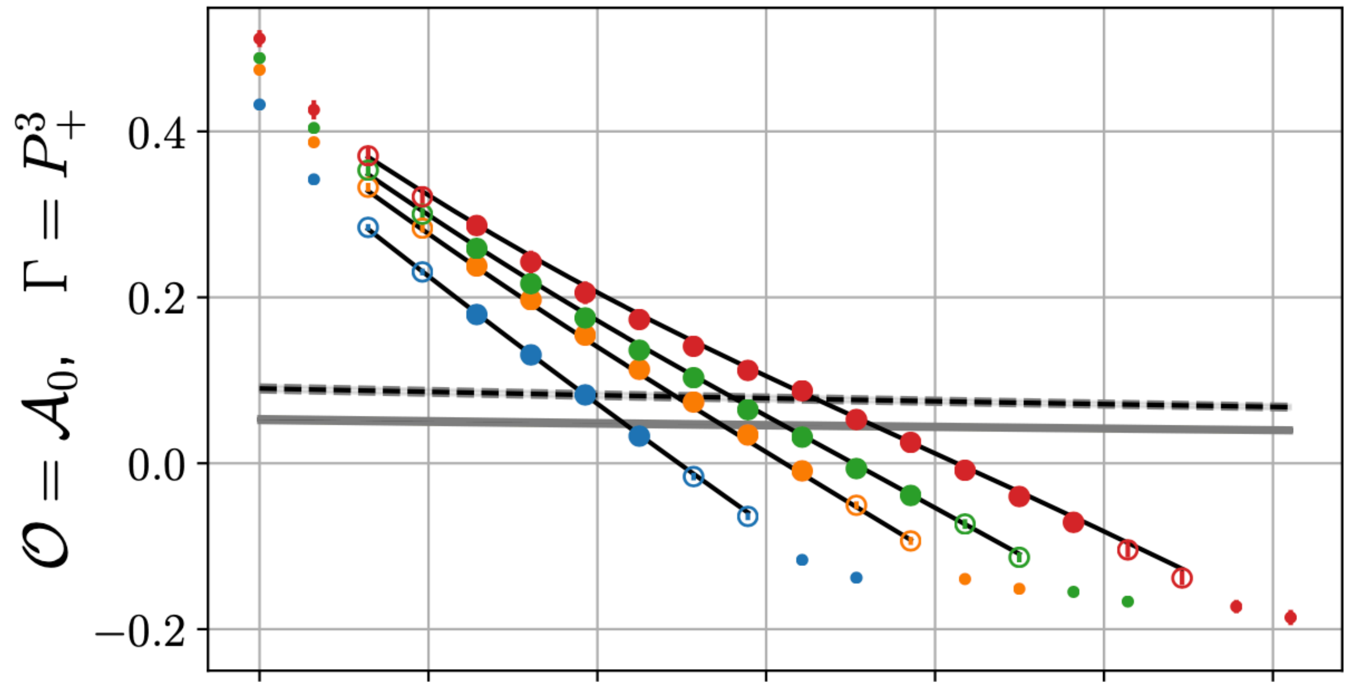
$$\frac{1}{2}^+ \quad 0^- \quad \frac{1}{2}^+$$





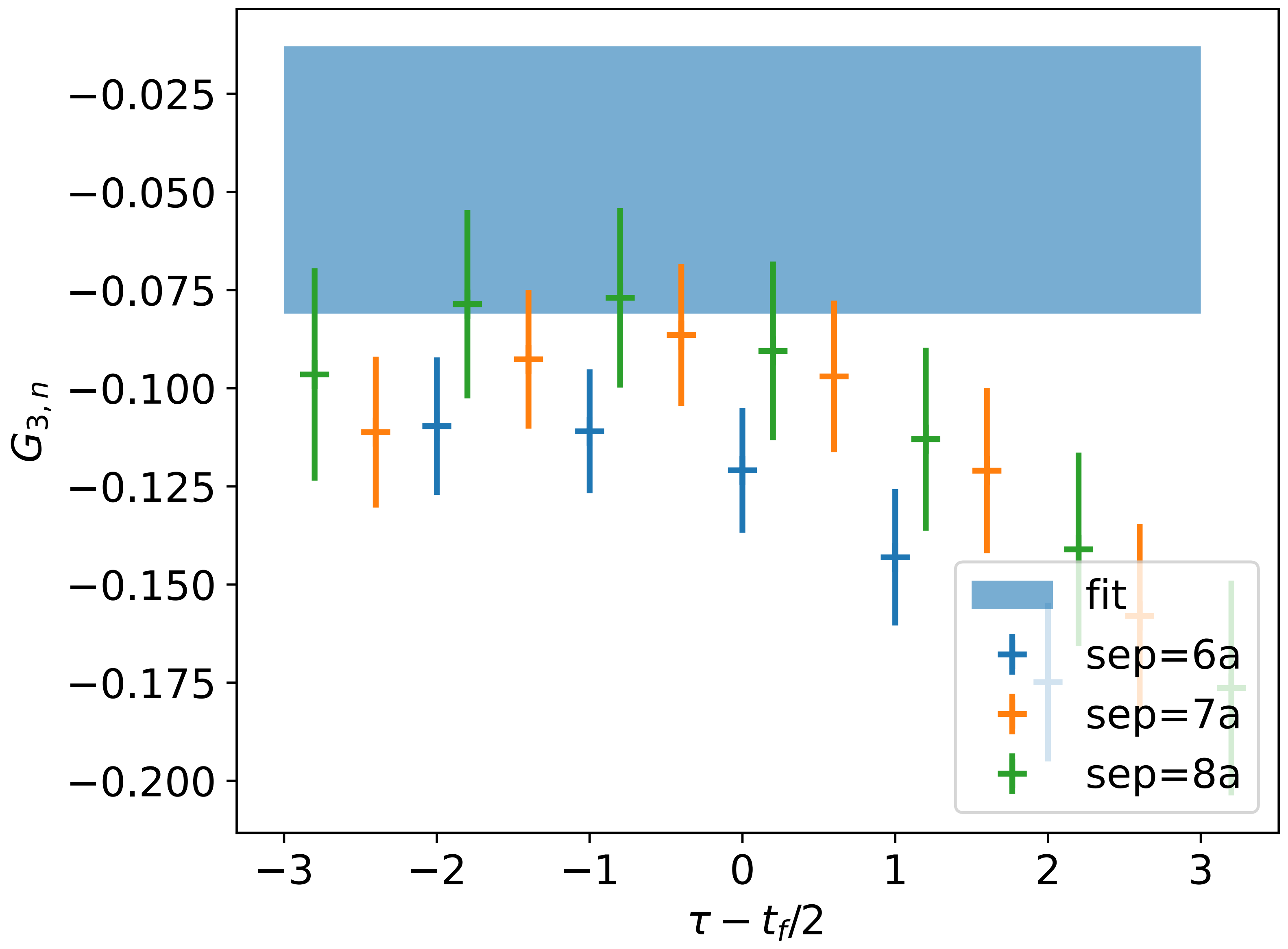
G. S. Bali et al., JHEP05(2020)126

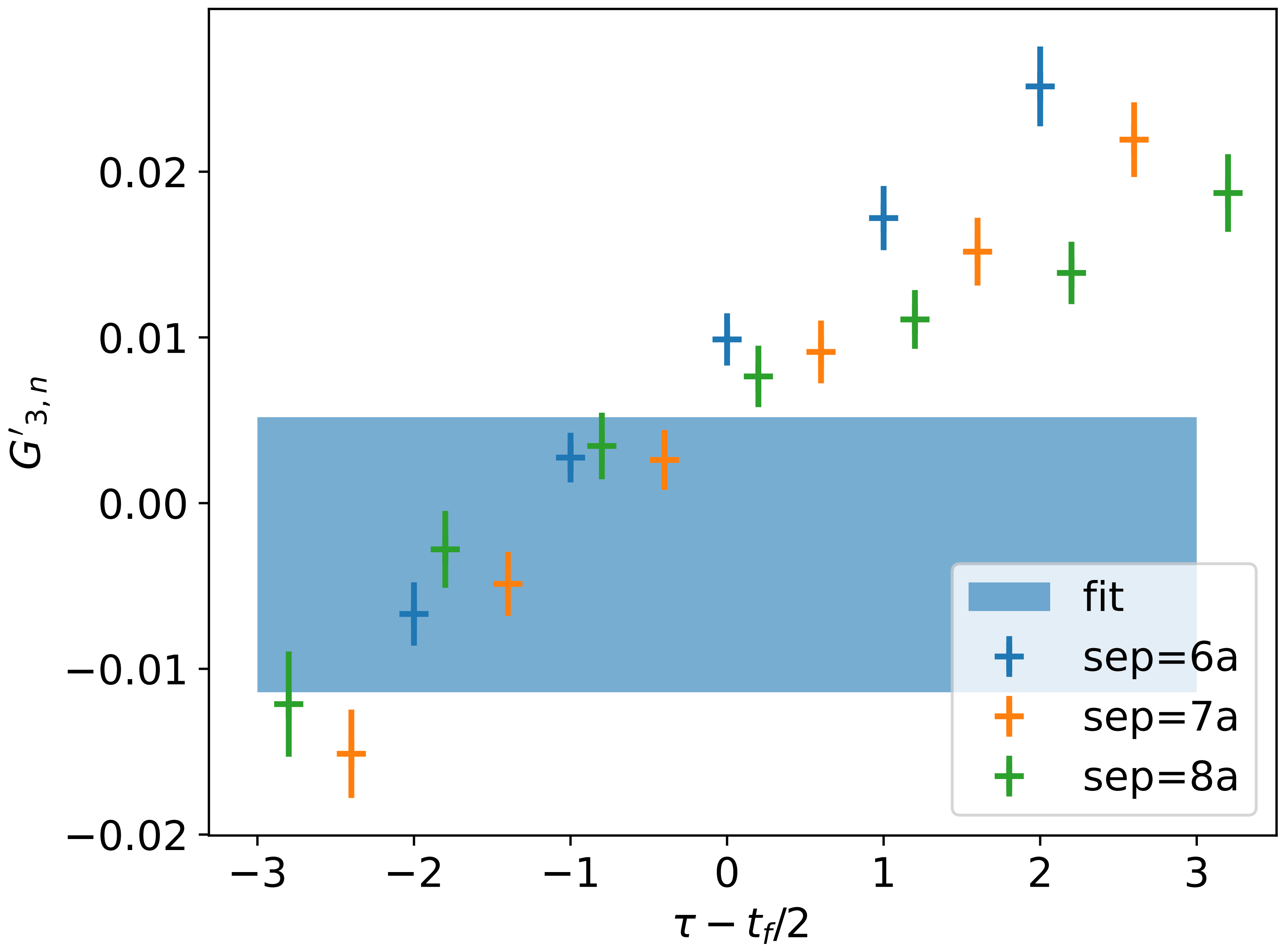
The Pion-Nucleon-State Effects



$$C^{\mathbf{p}',\mathbf{p},\mathcal{A}^\mu}_{3\mathrm{pt},P^i_+} = \frac{\sqrt{Z'}\sqrt{Z}}{2E'\,2E} e^{-E'(t-\tau)} e^{-E\tau} \times \Big[B^{\mathbf{p}',\mathbf{p}}_{P^i_+,\mathcal{A}^\mu} \Big(1 + B_{10} e^{-\Delta E'(t-\tau)} + B_{01} e^{-\Delta E\tau} + B_{11} e^{-\Delta E'(t-\tau)} e^{-\Delta E\tau}\Big) + e^{-\Delta E'_{N\pi}(t-\tau)} \frac{E'}{E_\pi} r^\mu_+ \Big(c' p^i + d' q^i\Big) + e^{-\Delta E_{N\pi}\tau} \frac{E}{E_\pi} r^\mu_- \Big(c\, p'^i + d\, q^i\Big) \Big],$$

G. S. Bali et al., JHEP05(2020)126





$$\langle J_N A_4(P) \bar{J}_N \rangle \quad \frac{1}{2}^+ \; 0^- \; \frac{1}{2}^+$$

$$\langle J_N V_4 \bar{J}_N Q \rangle \quad \frac{1}{2}^\pm \; 0^\pm \; \frac{1}{2}^\pm \; ?$$

$$\langle J_N V_i \bar{J}_N Q \rangle \quad \frac{1}{2}^\pm \; 1^\mp \; \frac{1}{2}^\pm \; ?$$

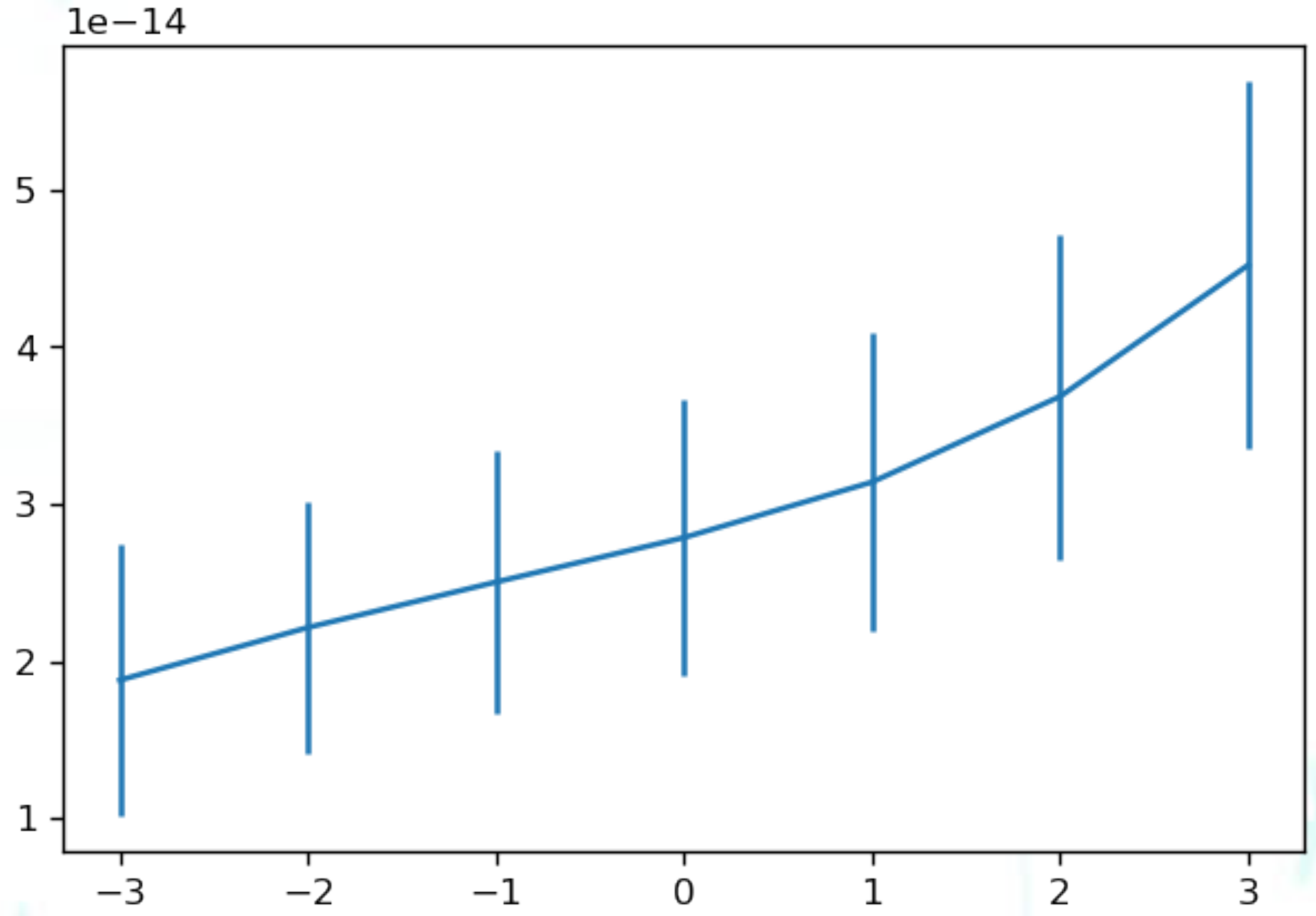
$$R_3^{\mathrm{EM}\theta}(\Gamma_i, \gamma_4) = \frac{\mathrm{Tr}\left[\Gamma_i G_3^\theta(\gamma_4)\right]}{\mathrm{Tr}\left[\Gamma_e G_2(\vec{p}=0)\right]}$$

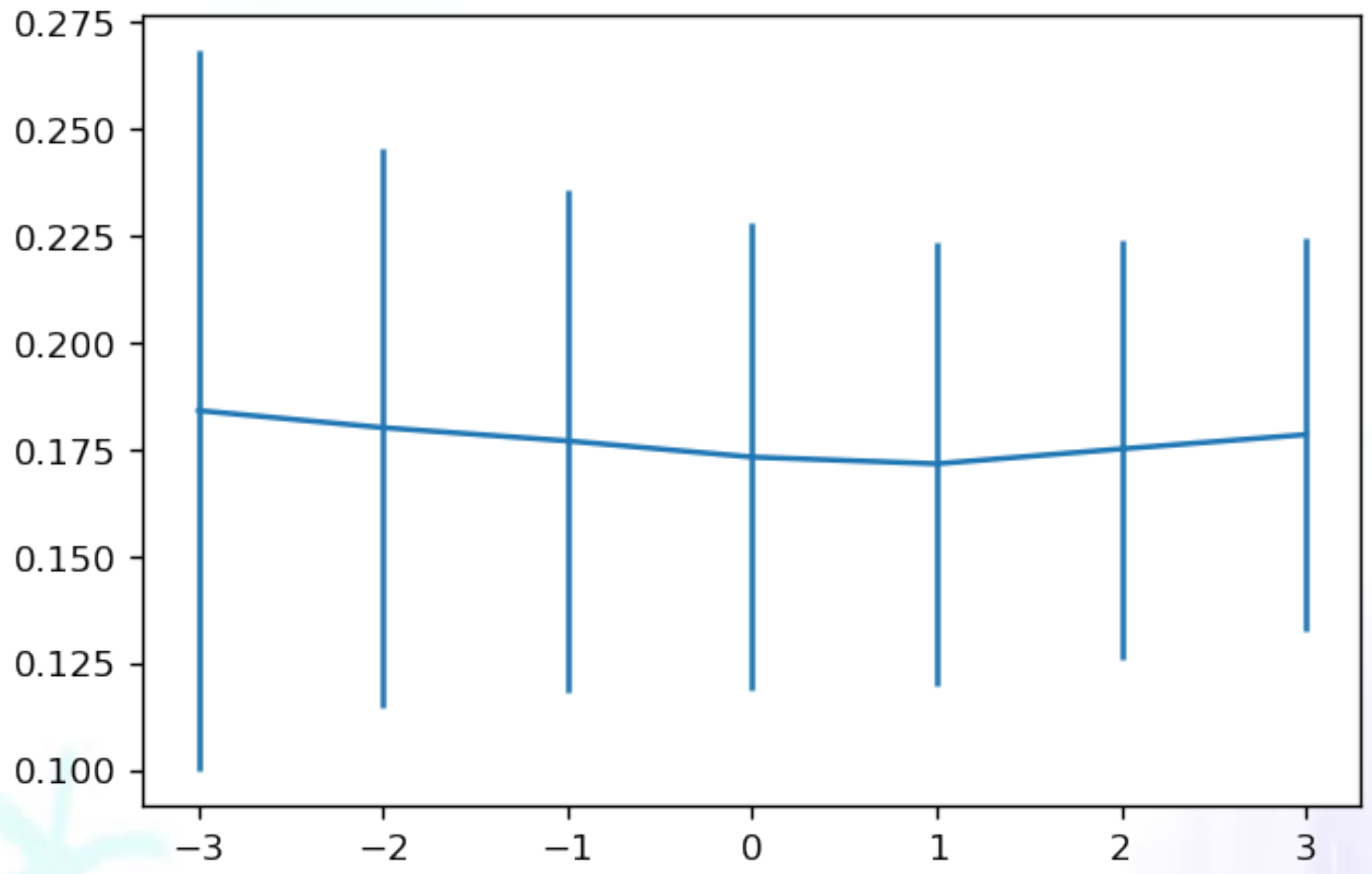
$$R_3^{\mathrm{EM}\theta 2}(\Gamma_i, \gamma_i) = \frac{\mathrm{Tr}\left[\Gamma_i G_3^\theta(\gamma_i)\right]}{\mathrm{Tr}\left[\Gamma_e G_2(\vec{p}=0)\right]}$$

Interesting Behavior!

Can eta contribution explain?

Smeared-to-Smeared Case





source-sink separation ~ 0.9 fm, Seems very promising!