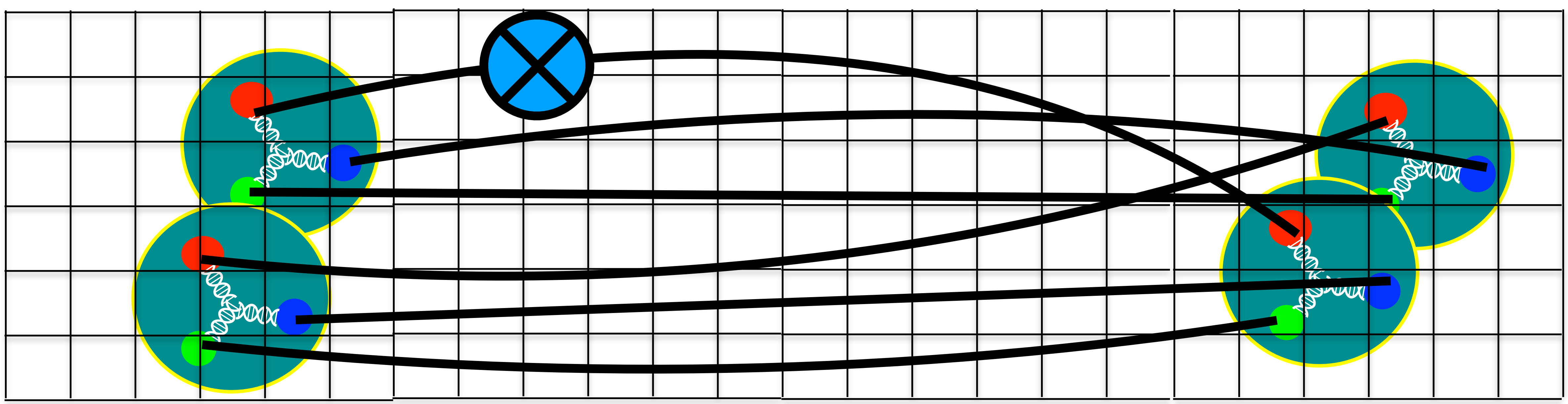
Nuclear Quark and Gluon Structure from Lattice QCD

Michael Wagman



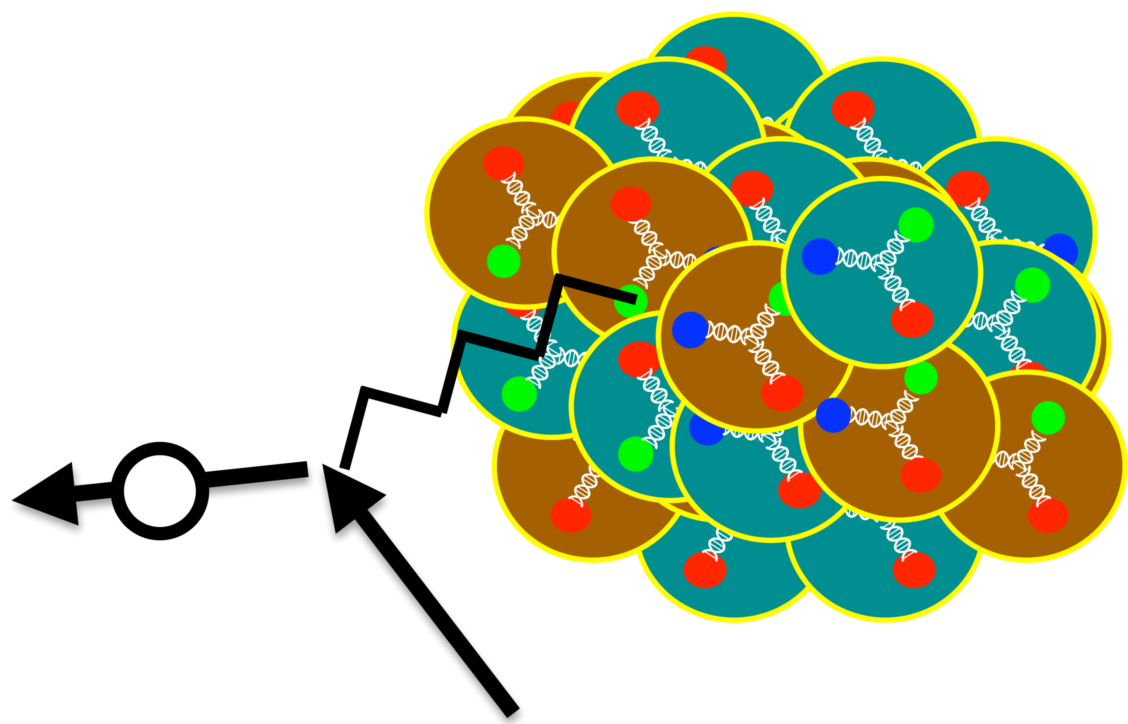
NPLQCD

QCD Evolution 2018

Nuclear Parton Structure

1) Nuclear physics adds "dirt":

— Nuclear effects obscure extraction of nucleon parton densities from nuclear targets (e.g. neutrino scattering)



2) Nuclear physics adds physics:

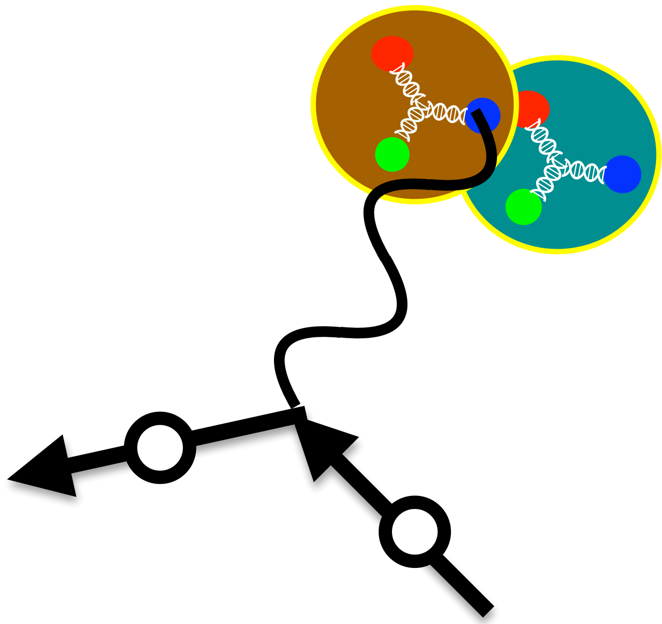
— Do partons in nuclei exhibit novel collective phenomena?

— Are gluons mostly inside nucleons in large nuclei?

Colliders and Lattices

Complementary roles in unraveling nuclear parton structure

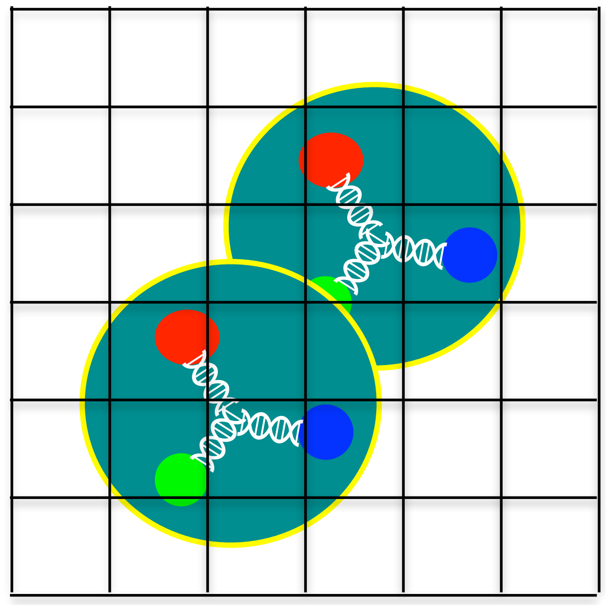
“Easy” for electron-ion collider:



Near lightcone kinematics

Electromagnetic charge weighted structure functions

“Easy” for lattice QCD:



Euclidean kinematics

Uncharged particles, full spin and flavor decomposition of structure functions

Structure Function Moments

Euclidean matrix elements of non-local operators connected to lightcone parton distributions

See talks by David Richards, Yong Zhao, Michael Engelhardt, Anatoly Radyushkin, and Joseph Karpie

Mellin moments of parton distributions are matrix elements of local operators

This talk: simple matrix elements in complicated systems

Gluon Transversity

$$O_{\nu_1\nu_2\mu_1\mu_2} = G_{\nu_1\mu_1}G_{\nu_2\mu_2}$$

Gluon Helicity

$$\tilde{O}_{\mu_1\mu_2} = \tilde{G}_{\mu_1\alpha}G_{\mu_2}^{\ \alpha}$$

Gluon Momentum

$$\overline{\mathcal{O}}_{\mu_1\mu_2} = G_{\mu_1\alpha}G_{\mu_2}^{\ \alpha}$$

Quark Transversity

$$\bar{q}\sigma_{\mu\nu}q$$

Quark Helicity

$$\bar{q}\gamma_\mu\gamma_5 q$$

Quark Mass

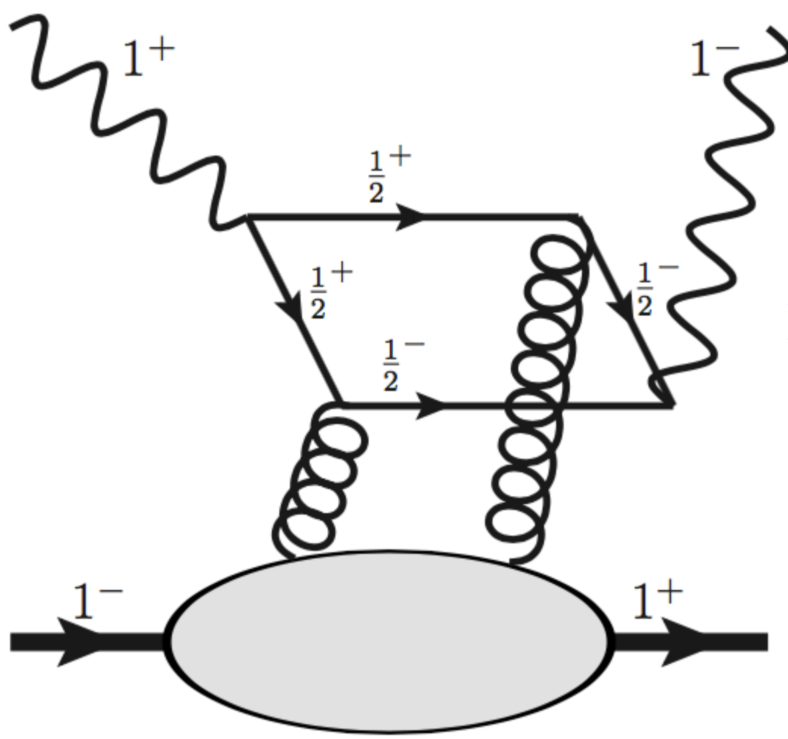
$$\bar{q}q$$

Nuclear Glue

Gluon transversity operator involves change in helicity by two units

In forward limit, only possible in spin 1 or higher targets

Jaffe, Manohar, PLB 223 (1989)



Detmold, Shanahan, PRD 94 (2016)

Gluon transversity probes nuclear ("exotic") gluon structure not present in a collection of isolated nucleons

Nucleon and Nuclear Structure

Spin 1+ nuclei have additional structure in forward limit

Spin 1/2 hadron (e.g. nucleon)

$$\langle h; p, s | \overline{\mathcal{O}}_{\mu_1 \mu_2} | h; p, s \rangle = b_2^{(h)}(\mu)\, S\left[p_{\mu_1} p_{\mu_2} \right] / m_h \qquad \langle h; p | \mathcal{O}_{\nu_1 \nu_2 \mu_1 \mu_2} | h; p \rangle = 0$$

Spin 1 hadron (e.g. deuteron)

Gluon momentum fraction

Polarized structure constant

$$\langle h; p, \epsilon | \overline{\mathcal{O}}_{\mu_1 \mu_2} | h; p, \epsilon \rangle = b_2^{(h)}(\mu)\, S\left[p_{\mu_1} p_{\mu_2} \right] / m_h + c_2^{(h)}(\mu)\, S\left[m_h^2 \epsilon_{\mu_1} \epsilon^*_{\mu_2} - \frac{1}{3} p_{\mu_1} p_{\mu_2} \right] / m_h$$

$$\langle h; p, \epsilon | \mathcal{O}_{\nu_1 \nu_2 \mu_1 \mu_2} | h; p, \epsilon \rangle = a_2^{(h)}(\mu)\, S\left[\left(p_{\nu_1} \epsilon_{\mu_1} - \epsilon_{\nu_1} p_{\mu_1} \right) \left(p_{\nu_2} \epsilon^*_{\mu_2} - \epsilon^*_{\nu_2} p_{\mu_2} \right) \right] / m_h$$

Double helicity flip constant

Nuclei on a Lattice

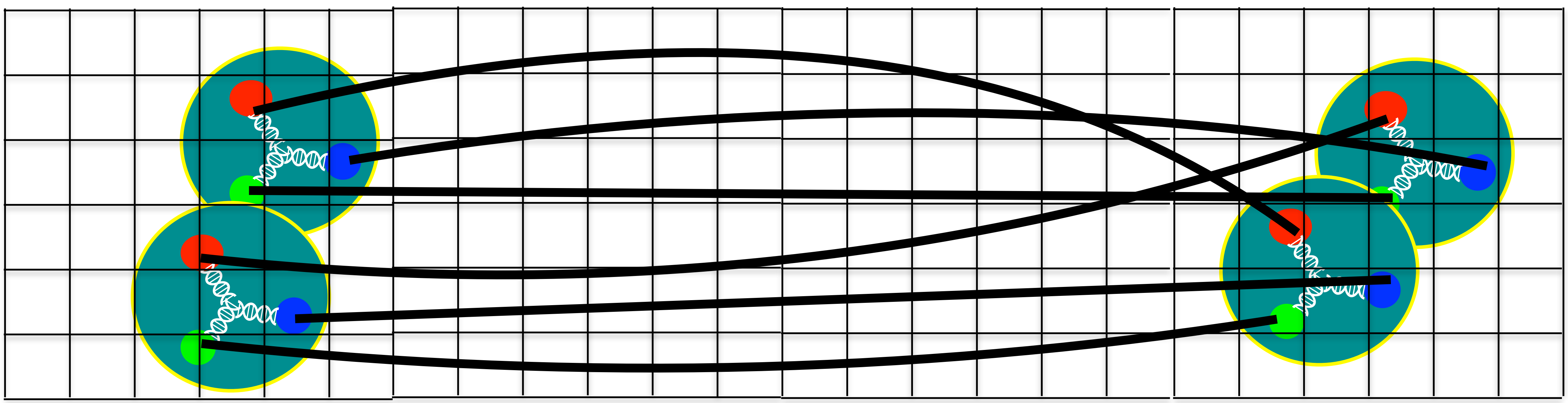
1) Ensemble of gluon fields (hybrid Monte Carlo)

2) Quark propagators in each gluon field (matrix inversion)

3) Correlation functions (baryon blocks and contractions)

Basak, Edwards, Fleming, Heller, Morningstar, Richards, Sato, Wallace, PRD 72 (2005)

Detmold, Orginos, PRD 87 (2013)



Spectrum determined by fitting correlation functions

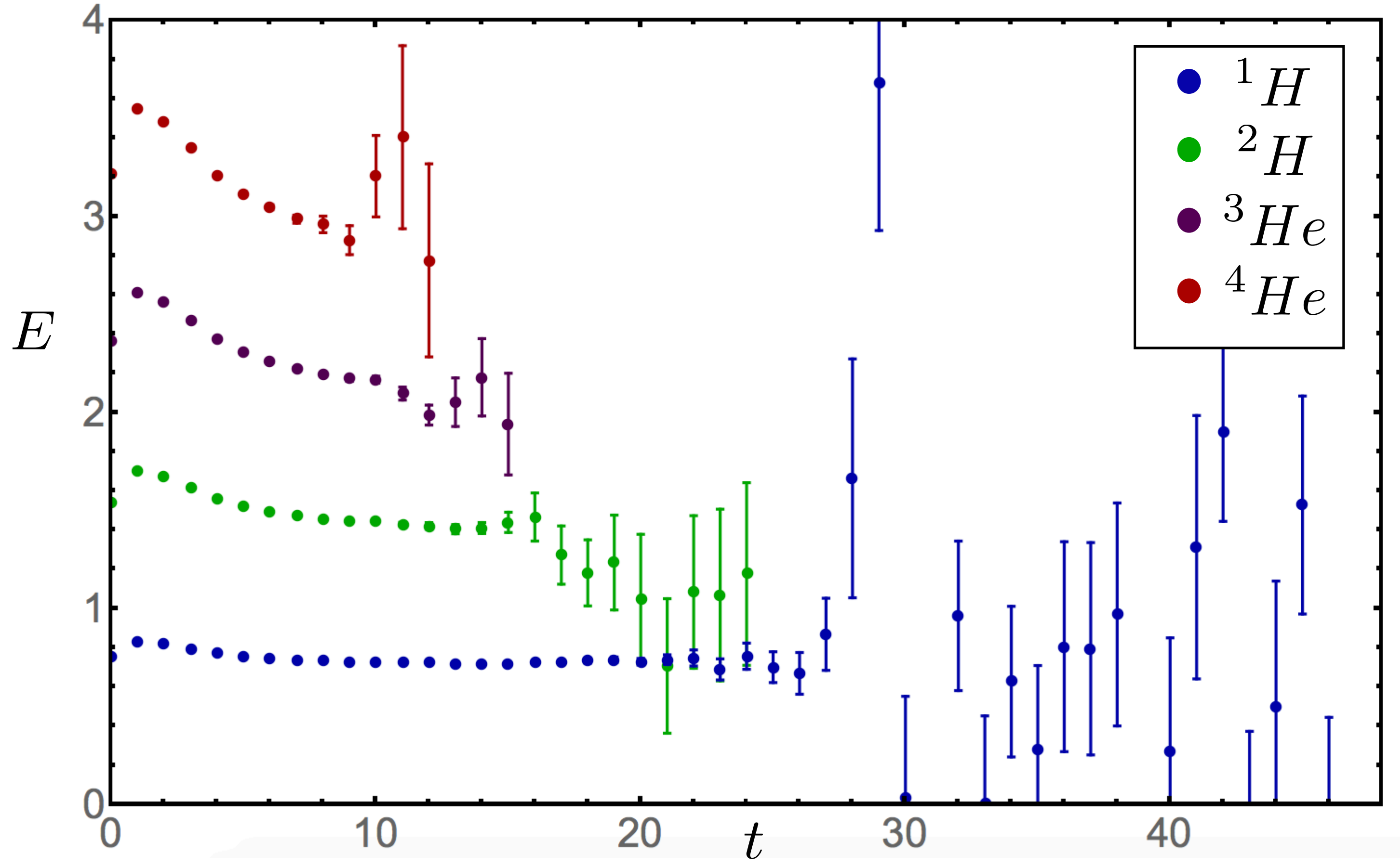
$$G_h^{2pt}(\mathbf{p}, t) = \langle h(t)\overline{h}(0)\rangle = \sum_n Z_h^n e^{-E_n t} + \tilde{Z}_h^n e^{-\tilde{E}_n(\beta - t)}$$

The Signal-to-Noise Problem

Baryon variance decays exponentially slower than mean

Signal-to-noise exponentially worse near chiral limit Lepage, TASI (1990)

Exploratory calculations use heavier quark masses



Nuclear correlation function magnitude set by pion mass, baryon mass arises from complex phase fluctuations (sign problem)

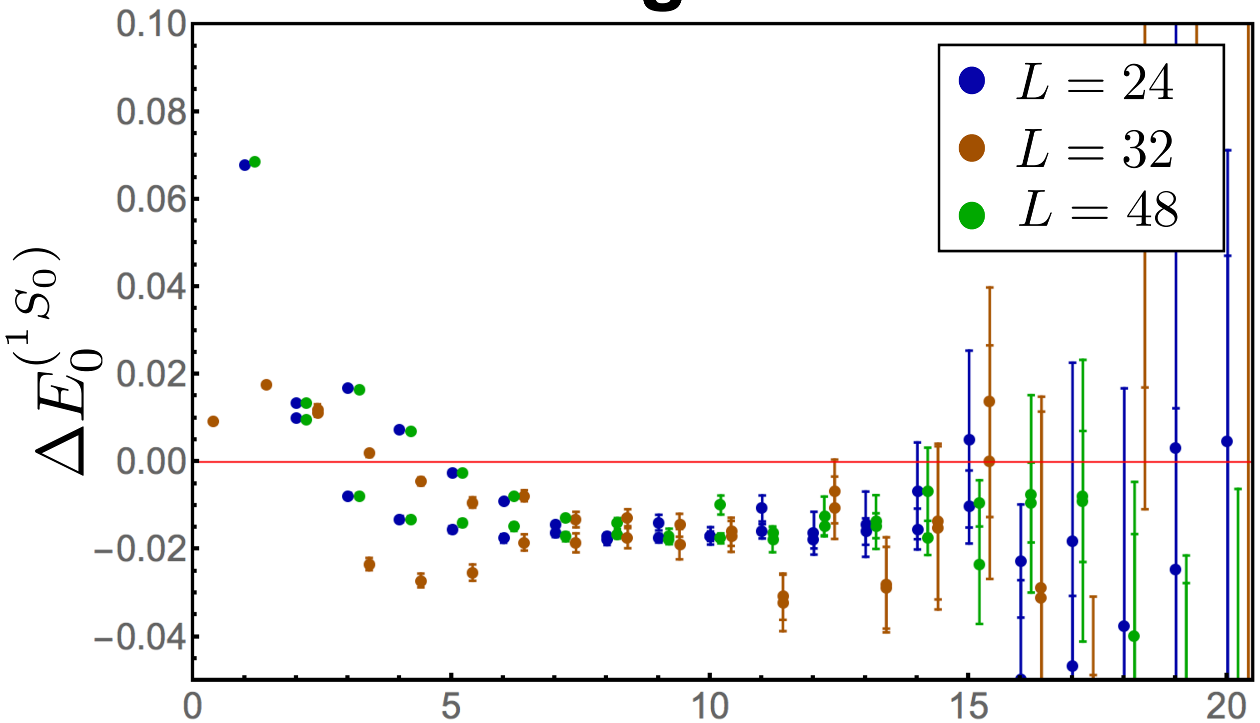
MW, Savage, PRD 96 (2017)

Nuclear Binding

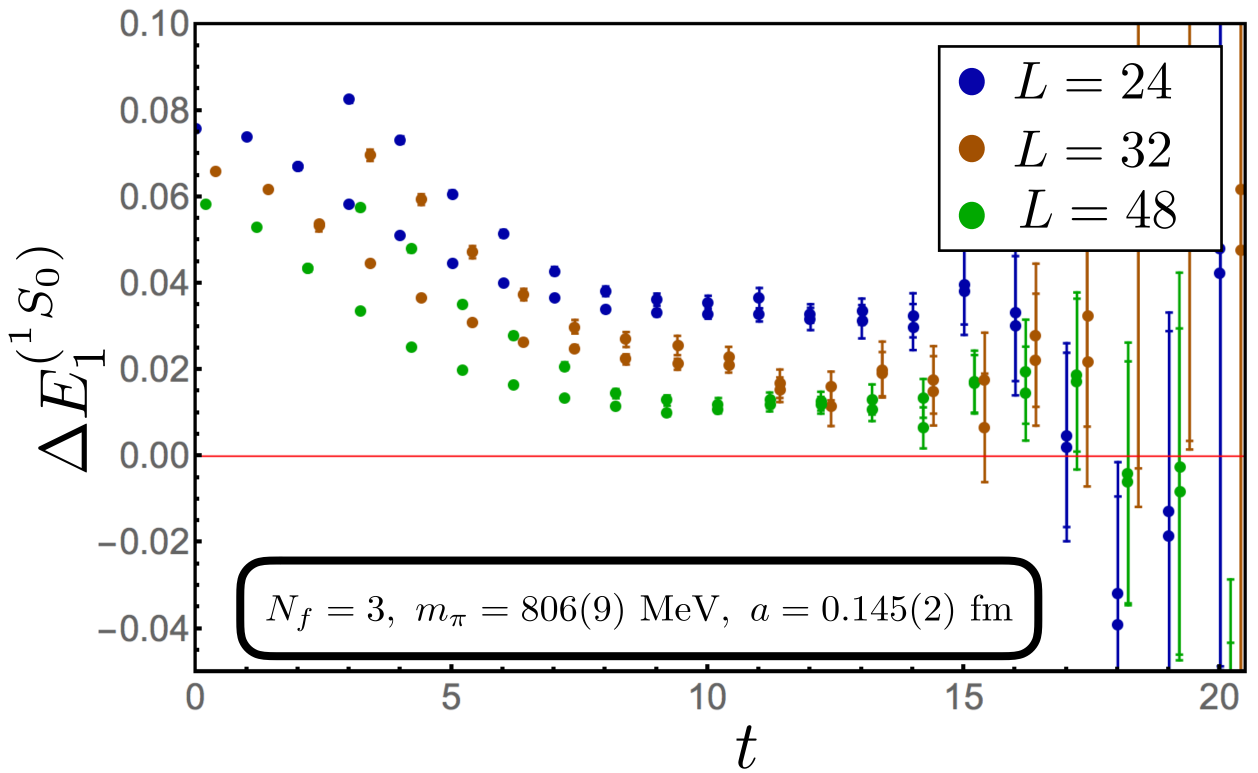
Finite-volume energies of bound states are exponentially close to infinite-volume bound state mass

Finite-volume scattering states include power-law energy shifts (interactions are more likely in smaller boxes)

Dineutron ground state



Dineutron excited state



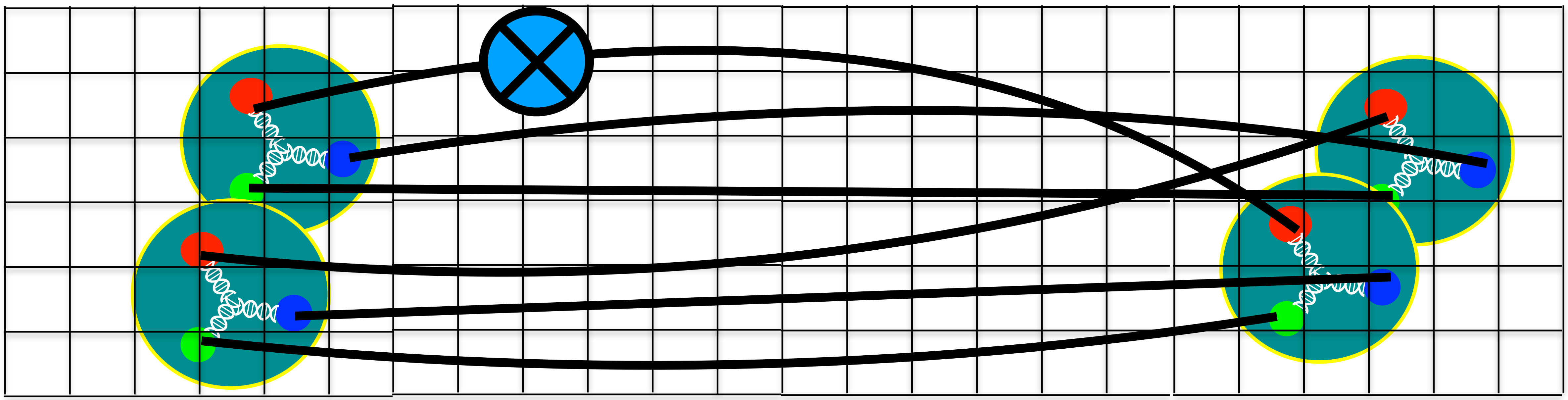
Deuteron, dineutron, ^3He and ^4He appear bound, $m_\pi \sim 806\ \mathrm{MeV}$

Beane, Chang, Cohen, Detmold, Lin, Luu, Orginos, Parreño, Savage, Walker-Loud, PRD 87 (2013)
Iritani, Aoki, Doi, Hatsuda, Ikeda, Inoue, Ishii, Nemura, Sasaki, PRD 96 (2017)
MW, Winter, Chang, Davoudi, Detmold, Orginos, Savage, Shanahan, PRD 96 (2017)

Nuclear Matrix Elements

Matrix elements determined from 3-point correlation functions including an operator insertion

Connected (quark only) and disconnected contractions arise



Matrix elements given by fitting 3pt and 2pt functions or ratios

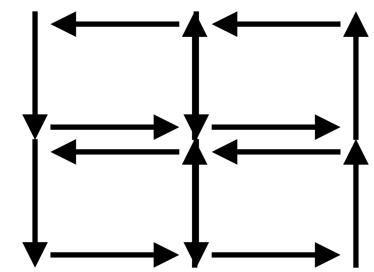
$$\frac{G_h^{3pt}(\mathbf{p},t,\tau,\mathcal{O})}{G_h^{2pt}(\mathbf{p},t)} = \langle \mathbf{p},h|\,\mathcal{O}\,|\mathbf{p},h\rangle + A_h e^{-\Delta_h t} + B_h e^{-\Delta_h \tau} + C_h e^{-\Delta_h (t-\tau)} + \ldots$$

Lattice Gluon Operators

Gluon fields expressed as gauge links / Wilson lines

$$G^{(E)}_{\mu\nu}(x) = \frac{1}{8}\left(P_{\mu\nu}(x) - P^{\dagger}_{\mu\nu}(x)\right)$$

$$P_{\mu\nu} =$$



$$\mathcal{O}^{(E)}_{\mu\nu\mu_1\mu_2} = G^{(E)}_{\mu\mu_1} G^{(E)}_{\nu\mu_2}$$

Operator mixing constrained by symmetries of hyper cubic Euclidean spacetime. Basis for hypercubic irreps:

$$\mathcal{O}^{(E)}_{1,1} = \frac{1}{8\sqrt{3}}\left(-2\mathcal{O}^{(E)}_{1122} + \mathcal{O}^{(E)}_{1133} + \mathcal{O}^{(E)}_{1144} + \mathcal{O}^{(E)}_{2233} + \mathcal{O}^{(E)}_{2244} - 2\mathcal{O}^{(E)}_{3344}\right)$$

$$\mathcal{O}^{(E)}_{1,2} = \frac{1}{8}\left(\mathcal{O}^{(E)}_{1144} + \mathcal{O}^{(E)}_{2233} - \mathcal{O}^{(E)}_{1133} - \mathcal{O}^{(E)}_{2244}\right)$$

Göckeler, Horsley, Ilgenfritz, Perlt, Rakow, Schierholz, Schiller, PRD 54 (1996)

Detmold, Shanahan, PRD 94 (2016)

Ratios and Renormalization

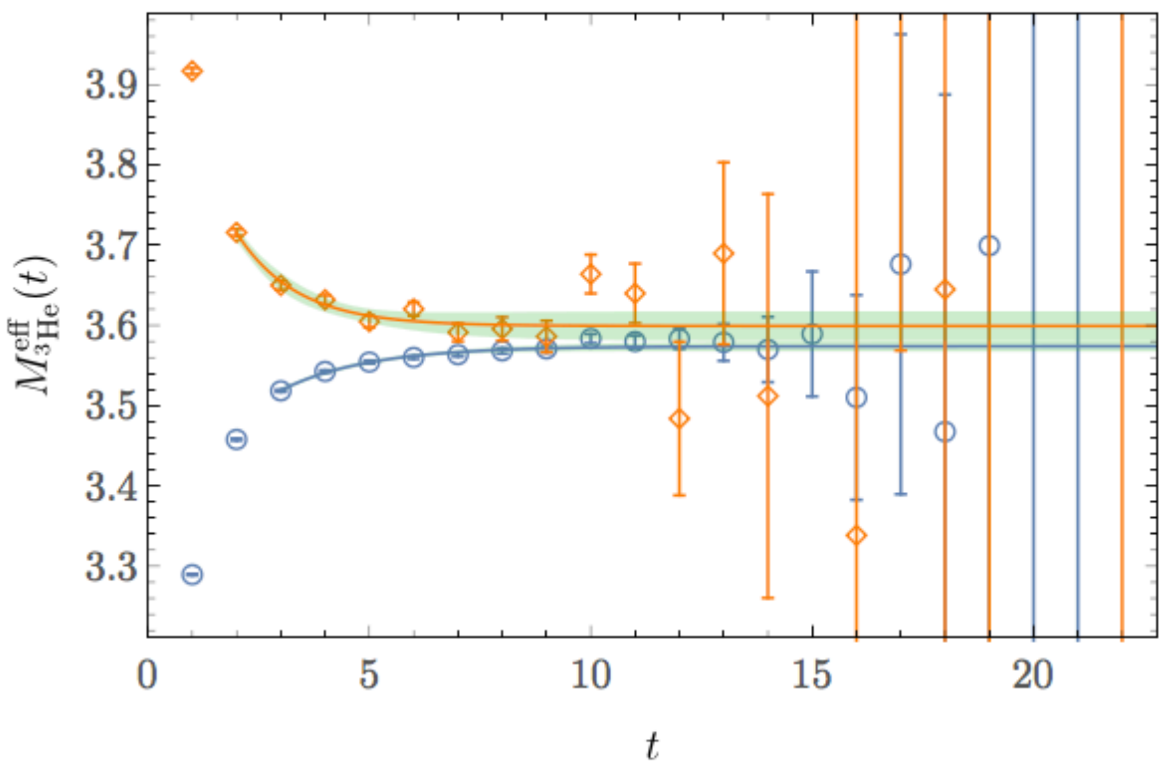
Renormalization factors (and other uncertainties) cancel in ratios of nuclear to nucleon matrix elements

Operator mixing leads to deviations between bare and renormalized matrix element ratios

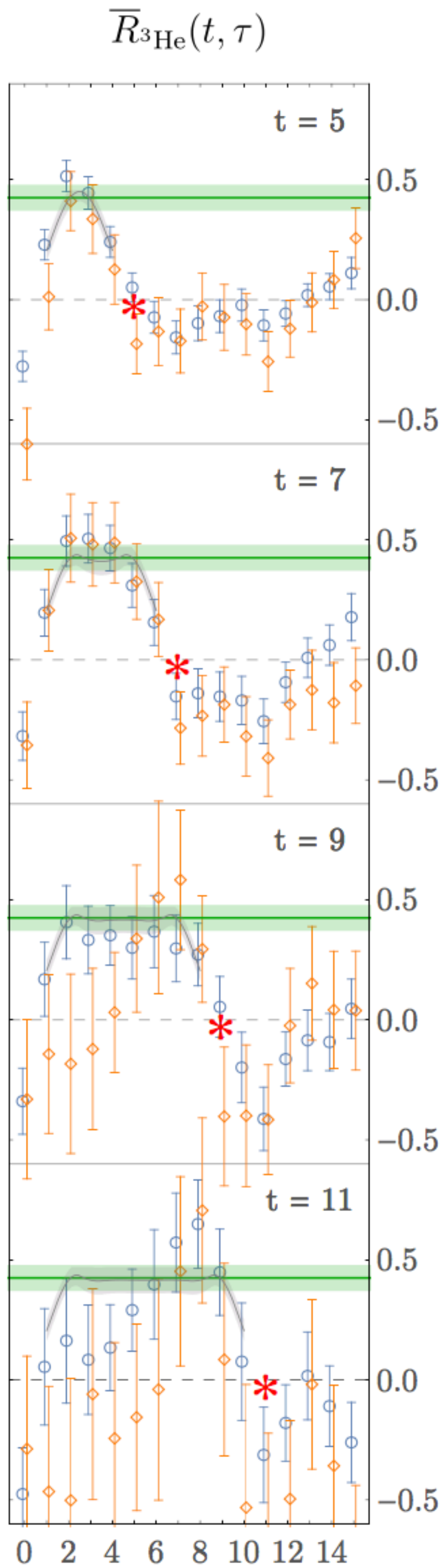
$$\frac{\langle h|\overline{\mathcal{O}}^{(E)}|h\rangle}{\langle N|\overline{\mathcal{O}}^{(E)}|N\rangle} = \frac{Z^{gg}\langle h|\overline{\mathcal{O}}^{\text{ren.}}|h\rangle + Z^{qg}\langle h|\overline{\mathcal{Q}}^{\text{ren.}}|h\rangle}{Z^{gg}\langle N|\overline{\mathcal{O}}^{\text{ren.}}|N\rangle + Z^{qg}\langle N|\overline{\mathcal{Q}}^{\text{ren.}}|N\rangle}$$
$$\approx \frac{\langle h|\overline{\mathcal{O}}^{\text{ren.}}|h\rangle}{\langle N|\overline{\mathcal{O}}^{\text{ren.}}|N\rangle}\left(1 + \frac{Z^{qg}}{Z^{gg}}\left[\frac{\langle h|\overline{\mathcal{Q}}^{\text{ren.}}|h\rangle}{\langle h|\overline{\mathcal{O}}^{\text{ren.}}|h\rangle} - \frac{\langle N|\overline{\mathcal{Q}}^{\text{ren.}}|N\rangle}{\langle N|\overline{\mathcal{O}}^{\text{ren.}}|N\rangle}\right]\right)$$

Mixing between spin-independent gluon and quark operators few percent effect

Gluon Momentum Fraction Analysis



Winter, Detmold, Gambhir, Orginos, Savage, Shanahan, MW, PRD 96 (2017)



Two-state model reliably describes 2pt functions with for $t \geq t_{min} \sim 2-3$

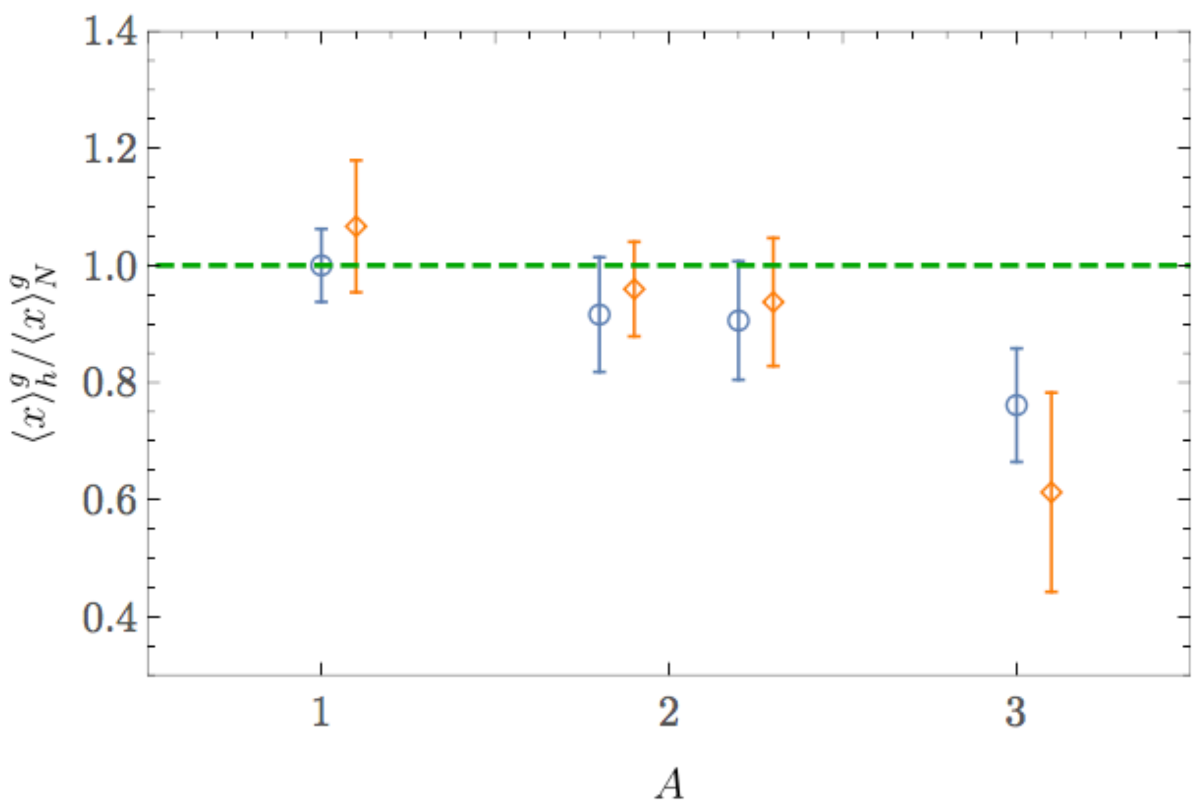
Trust two-state model for 3pt functions with $t \geq 2\ t_{min} \sim 5$

Fits at smaller t provide exponentially more precise but systematically biased results

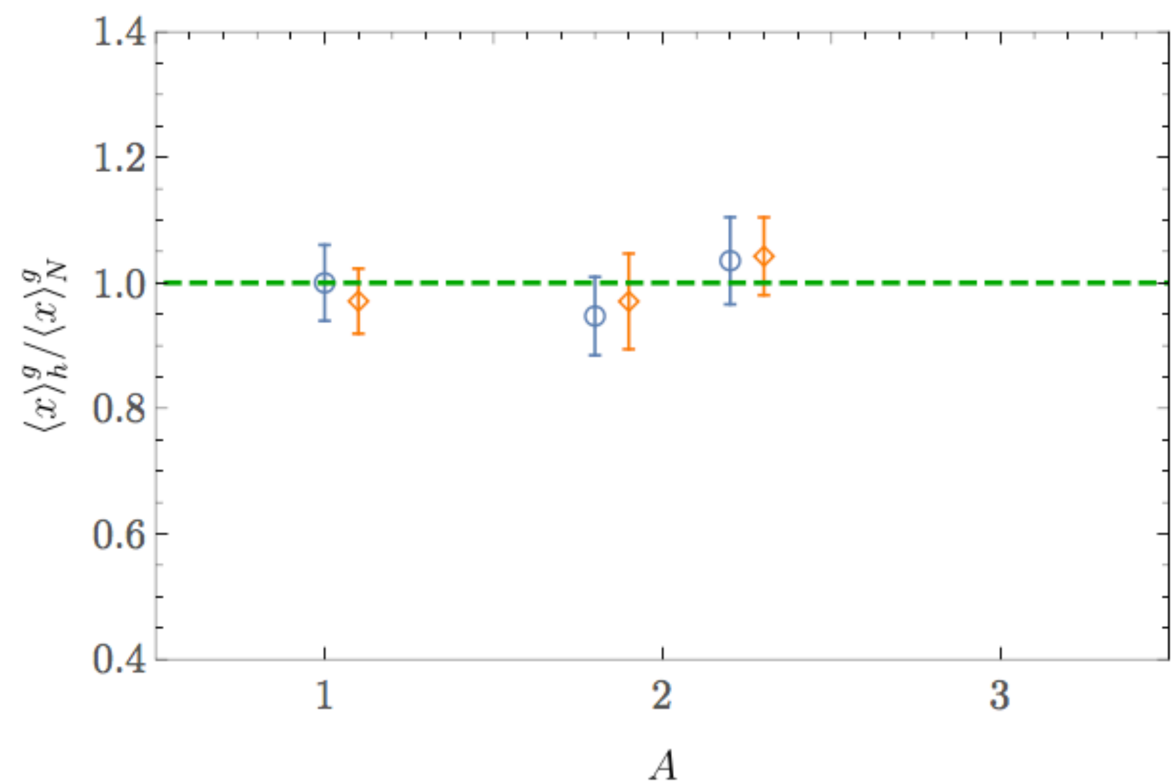
Gluon Momentum Fraction Results

Matrix element ratios allow calculations of gluonic analog of EMC effect

Results broadly consistent with < 10% nuclear effects though ^3He inconclusively hints at a reduction in tension with phenomenological expectations



$N_f = 3, \ m_\pi = 806(9) \text{ MeV}, \ a = 0.145(2) \text{ fm}$

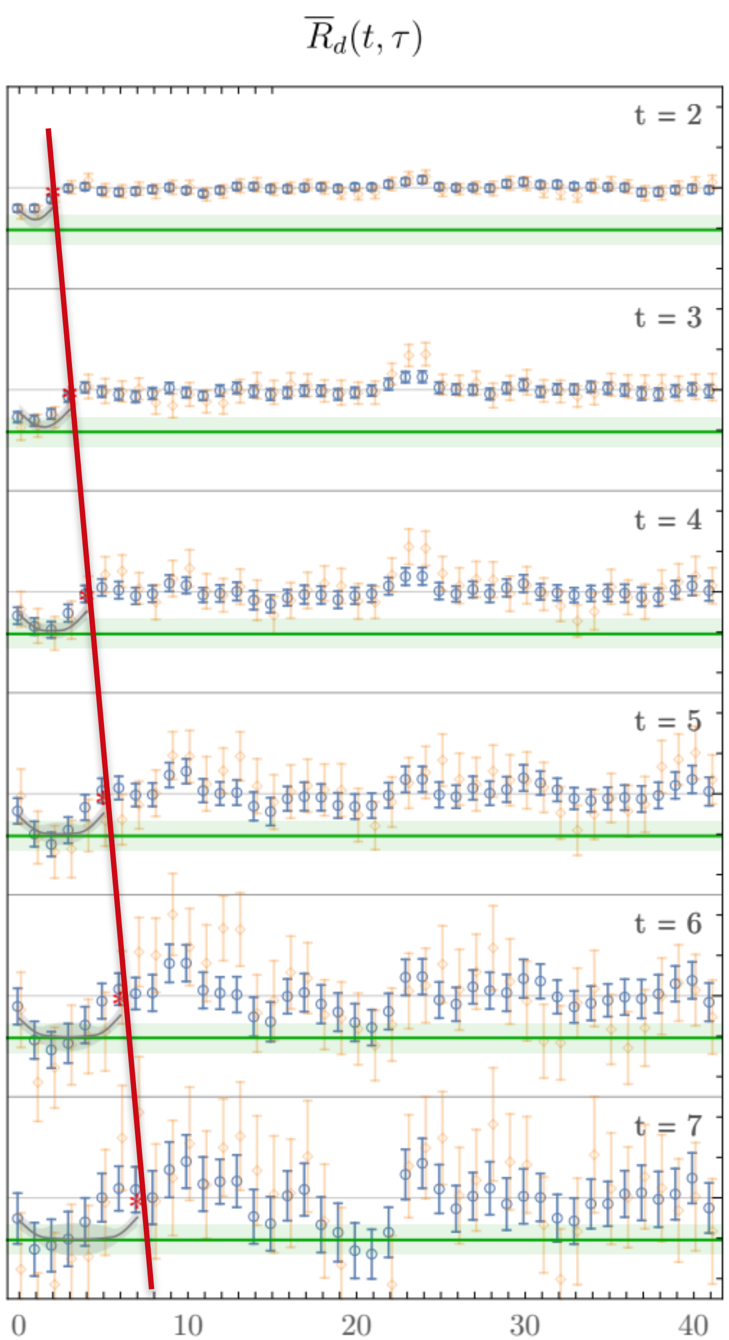


$N_f = 2+1, \ m_\pi = 450(5) \text{ MeV}, \ a = 0.112(2) \text{ fm}$

Gluon Transversity Results

Deuteron spin asymmetry consistent with zero: $c_2^{(d)}/b_2^{(d)} \lesssim 1/20$

Signal for deuteron transversity at $m_\pi \sim 806$ MeV



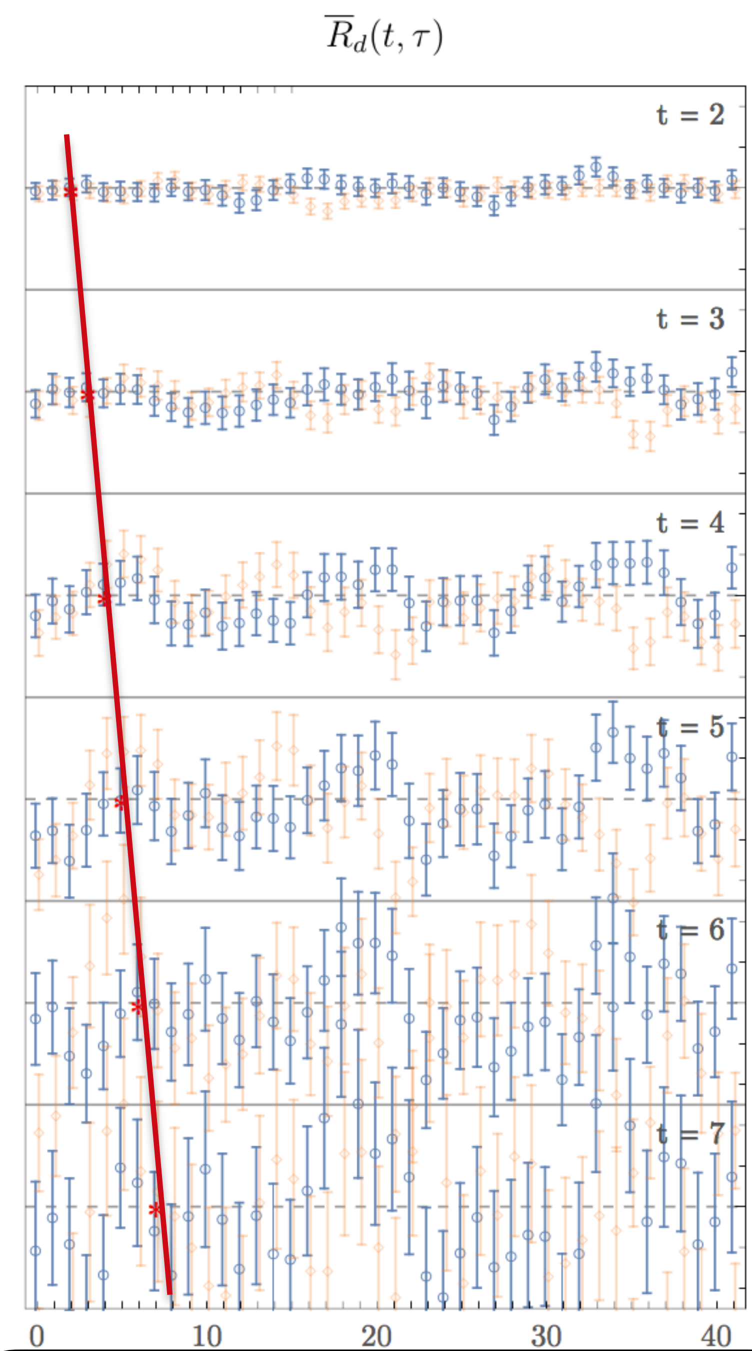
$N_f = 3,\ m_\pi = 806(9)$ MeV, $a = 0.145(2)$ fm

Unrenormalized (!):

$$\langle x \rangle_g^{(d)} = b_2^{(d)} = 0.51(5),$$

$$a_2^{(d)} = -0.010(3)$$

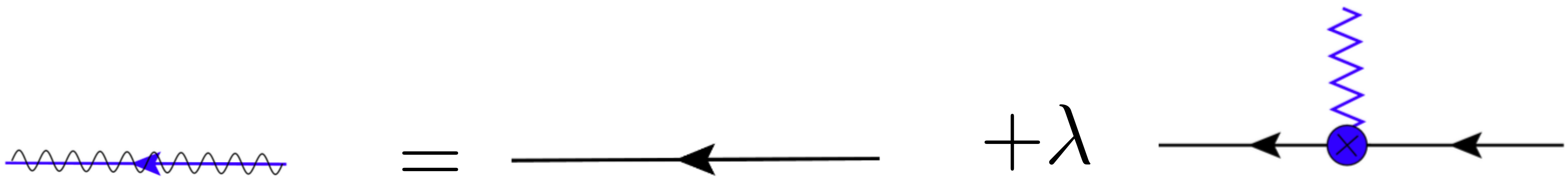
Order of magnitude transversity suppression consistent with $1/N_c^2$



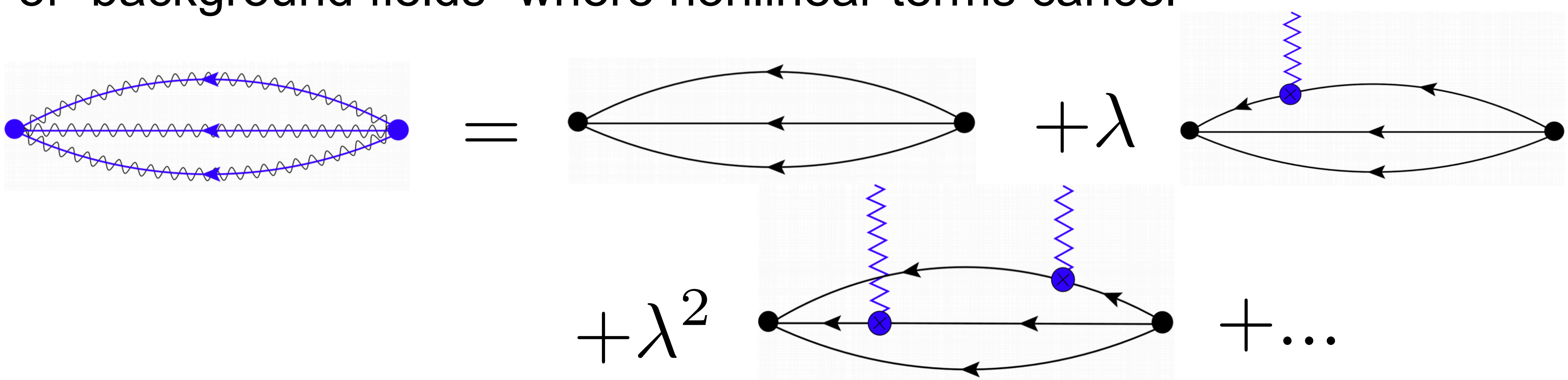
$N_f = 2+1,\ m_\pi = 450(5)$ MeV, $a = 0.112(2)$ fm

Quark Operators in Nuclei

Current operator insertions describing linear response to a background field can be added to quark propagators with sequential source techniques



Linear response of composite particles obtained from linear combinations of "background fields" where nonlinear terms cancel



Multi-baryon contractions of compound propagators can be performed straightforwardly

Savage, Shanahan, Tiburzi, MW, Winter, Beane, Chang, Davoudi, Detmold, Orginos, PRL 119 (2017)

Tiburzi, MW, Winter, Chang, Davoudi, Detmold, Orginos, Savage, Shanahan, PRD 96 (2017)

Nuclear Static Response

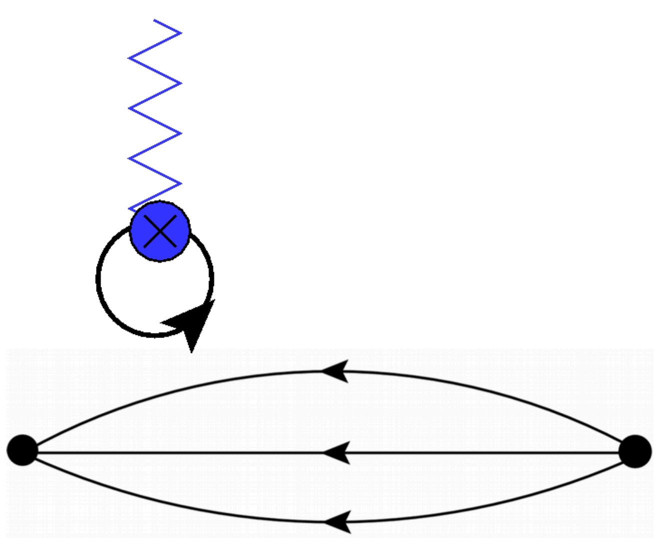
	d	pp	^{3}H	Expect.
$R_A^{(0)}$	1.98(1)	–	0.999(6)	$2S_3$
$R_A^{(3)}$	–	–	0.987(4)	$4T_3S_3$
$R_A^{(8)}$	1.983(4)	–	0.990(3)	$2S_3$
$R_A^{(s)}$	–	–	–	BS_3
$R_S^{(0)}$	1.97(2)	1.98(2)	2.87(4)	B
$R_S^{(3)}$	–	1.98(2)	0.96(2)	$2T_3$
$R_S^{(8)}$	1.98(1)	1.99(2)	2.90(2)	$2T_8$
$R_S^{(s)}$	1.93(9)	1.94(9)	2.70(14)	B
$R_T^{(0)}$	1.984(4)	–	0.990(2)	$2S_3$
$R_T^{(3)}$	–	–	1.002(2)	$4T_3S_3$
$R_T^{(8)}$	1.986(5)	–	0.991(3)	$2S_3$
$R_T^{(s)}$	–	–	–	BS_3

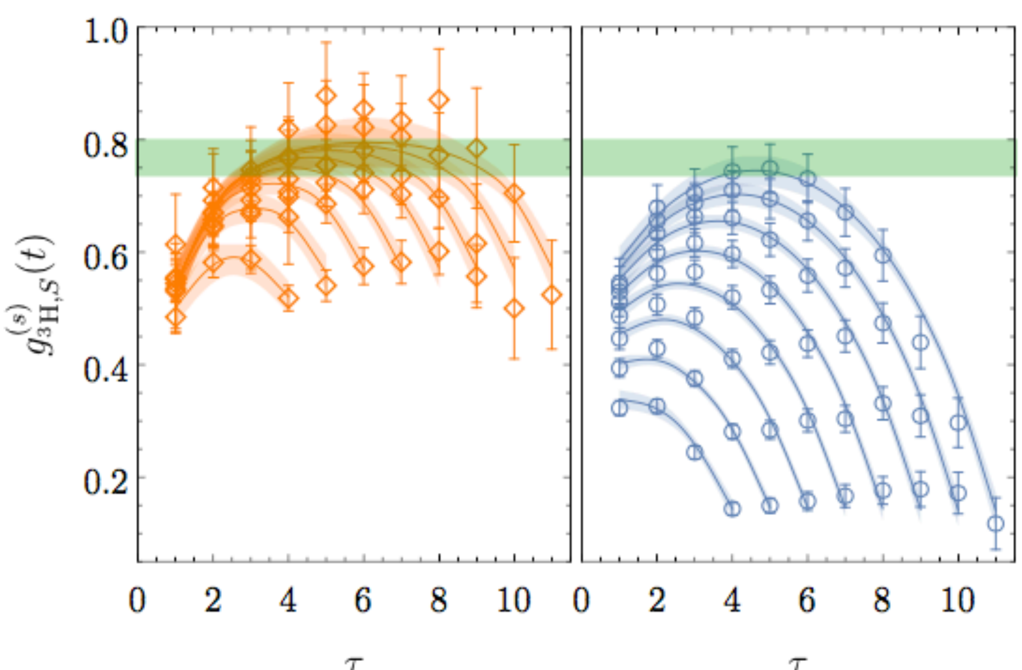
$N_f = 3,\ m_\pi = 806(9)$ MeV, $a = 0.145(2)$ fm

Complete spin-flavor decomposition of static responses of A=1-3 nuclei to external probe

Chang, Davoudi, Detmold, Gambhir, Orginos, Savage, Shanahan, Tibuzri, MW, Winter, PRL 120 (2018)

Disconnected diagrams contribute significantly to scalar matrix elements





Gambhir, Stathopulos, Orginos, J. Sci. Comput. 39 (2017)

Polarized Nuclear Quark Structure

Helicity:

Isovector quark spin reduced by 1.3(4)% in ^3H vs proton at $m_\pi \sim 806$ MeV

Experimental tritium beta-decay, 4.89(13)% reduction at $m_\pi \sim 135$ MeV

No statistically significant nuclear effects on isoscalar quark spin
* anomaly-induced mixing with gluons neglected

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$R_A^{(0)}$	1.98(1)	–	0.999(6)	$2S_3$
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$N_f = 3,\ m_\pi = 806(9)\ \mathrm{MeV},\ a = 0.145(2)\ \mathrm{fm}$

Transversity:

Nuclear effects lead to O(1%) reduction of tensor charge in deuteron and triton

Do nuclear effects always reduce quark charges?

— Isovector tensor charge possible counter-example

Scalar Structure of Nuclei

- Nuclear effects on scalar charge much larger: 4(1)% reduction of triton isoscalar charge at $m_\pi \sim 806\ \mathrm{MeV}$

- Scalar fields couple coherently to all baryons in a nucleus — nuclear effects on scalar charge could be large in large nuclei

	d	pp	$^3\mathrm{H}$	Expect.
$R_A^{(0)}$	1.98(1)	–	0.999(6)	$2S_3$
$R_A^{(3)}$	–	–	0.987(4)	$4T_3S_3$
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$R_T^{(s)}$	–	–	–	BS_3

$N_f = 3,\ m_\pi = 806(9)\ \mathrm{MeV},\ a = 0.145(2)\ \mathrm{fm}$

- Affects interpretation of spin-independent dark matter direct detection (constraints on nucleon cross-section could be weaker than expected)

- Physical quark mass LQCD calculations needed

- Can we measure scalar structure experimentally?

Summary and Outlook

Mellin moments of structure functions can be precisely calculated in LQCD, extra input for global fits of structure functions

LQCD predicts gluonic EMC effect modest ($\lesssim$10%) at heavy quark mass

Non-zero gluon transversity signals nuclear gluons not associated with individual nucleons are present in the deuteron

LQCD predicts ~1% polarized EMC effects on quark helicity and transversity at heavy quark mass

Quark scalar matrix elements show larger nuclear effects that could affect interpretation of dark matter searches

Onward to physical quark masses! …signal-to-noise problem?