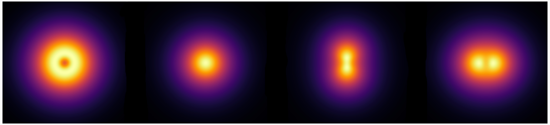
Transverse Motion of Quarks in Nuclear Matter

Ian Cloët

Argonne National Laboratory

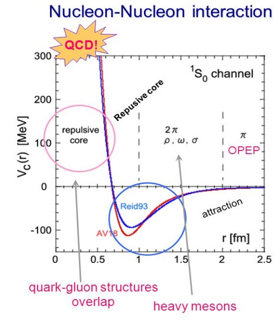


XVIth Quark Confinement and the Hadron Spectrum

18-24 August 2024, Cairns, Queensland, Australia

Why Nuclei?

- Nuclei give access to numerous aspects of QCD not found in a single proton
  - neutron target via deuteron or ^{3}He and mirror nuclei such as ^{3}H – ^{3}He
  - only targets with $J \geqslant 1$, new PDFs, form factors, TMDs, GPDs, etc.
  - color transparency, hidden color, correlations
  - isospin & baryon density effects, e.g., partial chiral symmetry restoration and possible changes in confinement length scales between quarks and gluons
  - enhance numerous Standard Model effects: gluon saturation, QED, neutrino cross-sections, etc.

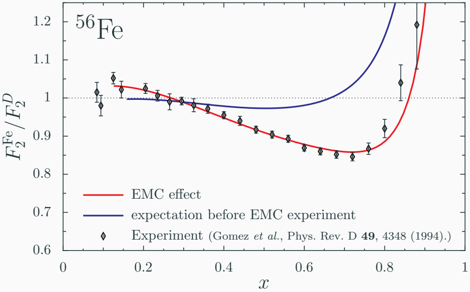


- At a fundamental level nuclear tomography (deuteron, ^{3}H, ^{3}He, ^{4}He, ^{7}Li, . . .) can help address several key questions: *How does the nucleon-nucleon interaction arise from QCD?*

> *“No story of modern physics is more intriguing than the history of the theory of nuclear forces.”*
> Ruprecht Machleidt, Weinberg’s proposal of 1990: A very personal view

EMC Effect

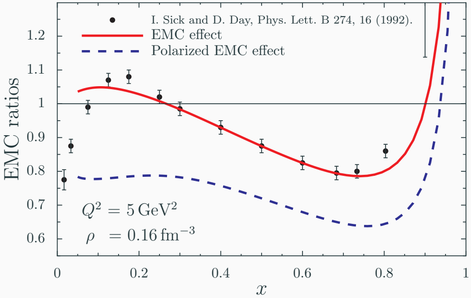
- Understanding origin of the EMC effect is critical for a QCD based description of nuclei
  - 40+ years after discovery a broad consensus on explanation is lacking
  - Valence quarks in nucleus carry less momentum than in a nucleon
- Important question: *In what processes, and at what energy scales, do quarks and gluons become the effective degrees of freedom in nuclei?*
- Modern explanations of EMC effect are based around medium modification of the bound nucleons
  - Is modification caused by *mean-fields* which modify all nucleons all of the time or by *SRCs* which modify some nucleons some of the time?

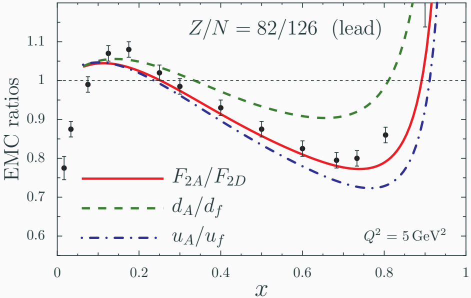


long- and short-range *NN* interactions

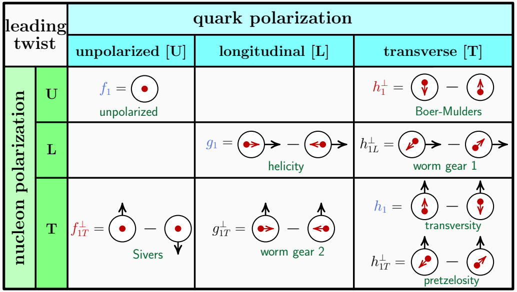
Understanding the EMC Effect

- *The puzzle posed by the EMC effect will only be solved by conducting new experiments that expose novel aspects of the EMC effect*
- Measurements should help distinguish between explanations of EMC effect e.g. whether *all nucleons* are modified by the medium or only those in SRCs
- Important examples are measurements of the *EMC effect in polarized structure functions* & the *flavor dependence of EMC effect*
- A JLab experiment has been approved to measure the spin structure of ^{7}Li
- Flavor dependence can be accessed via JLab DIS experiments on ^{40}Ca & ^{48}Ca – *but parity violating DIS stands to play the pivotal role*

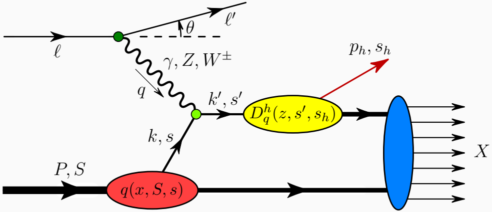




Probing Transverse Momentum



leading twist		quark polarization		
		unpolarized [U]	longitudinal [L]	transverse [T]
nucleon polarization	U	$f_1 =$ unpolarized		$h_1^\perp =$ − Boer-Mulders
	L		$g_1 =$ − helicity	$h_{1L}^\perp =$ − worm gear 1
	T	$f_{1T}^\perp =$ − Sivers	$g_{1T}^\perp =$ − worm gear 2	$h_1 =$ − transversity $h_{1T}^\perp =$ − pretzelosity



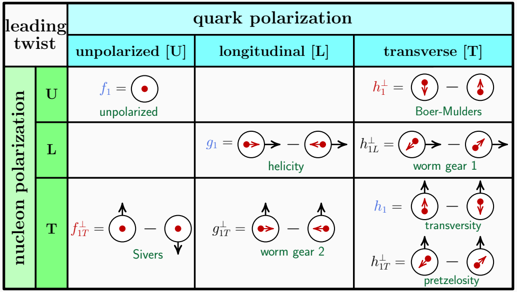
- Semi-Inclusive DIS (SIDIS) cross-section on nucleon has 18 structure functions – factorize as:

$$F(x, z, P_{h\perp}^2, Q^2) \propto \sum f^q(x, \boldsymbol{k}_T^2) \otimes D_q^h(z, \boldsymbol{p}_T^2) \otimes H(Q^2)$$

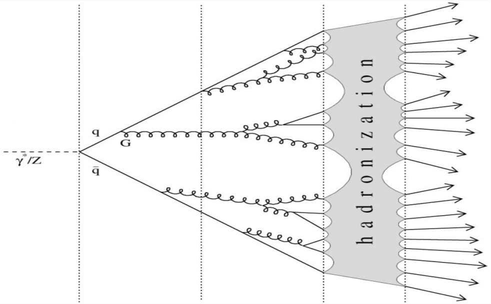
  - reveals correlations between parton transverse momentum, its spin, and target spin

- Fragmentation functions are particularly important but also challenging
  - *can potentially shed new light on confinement and DCSB – because they describe how a fast moving quark or gluon becomes a tower of hadrons*

Probing Transverse Momentum



leading twist		quark polarization		
		unpolarized [U]	longitudinal [L]	transverse [T]
nucleon polarization	U	$f_1 =$ unpolarized		$h_1^\perp = \quad - \quad$ Boer-Mulders
	L		$g_1 = \quad - \quad$ helicity	$h_{1L}^\perp = \quad - \quad$ worm gear 1
	T	$f_{1T}^\perp = \quad - \quad$ Sivers	$g_{1T}^\perp = \quad - \quad$ worm gear 2	$h_1 = \quad - \quad$ transversity $h_{1T}^\perp = \quad - \quad$ pretzelosity



- Semi-Inclusive DIS (SIDIS) cross-section on nucleon has 18 structure functions – factorize as:

$$F(x, z, P_{h\perp}^2, Q^2) \propto \sum f^q(x, \boldsymbol{k}_T^2) \otimes D_q^h(z, \boldsymbol{p}_T^2) \otimes H(Q^2)$$

  - reveals correlations between parton transverse momentum, its spin, and target spin

- Fragmentation functions are particularly important but also challenging
  - *can potentially shed new light on confinement and DCSB – because they describe how a fast moving quark or gluon becomes a tower of hadrons*

Theory approaches to EMC Effect and Nuclear Imaging

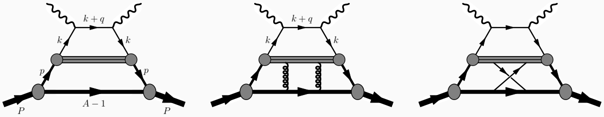
- To address origins of EMC effect must determine e.g. nuclear PDFs, TMDs, GPDs:

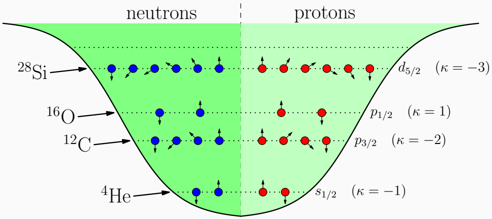
$$q_A(x_A, \boldsymbol{k}_T^2) = \frac{P^+}{A} \int \frac{d\xi^- \boldsymbol{\xi}_T}{2\pi} e^{ix_A P\cdot\xi/A} \langle A, P \left| \overline{\psi}_q(0)\, \gamma^+ \, \psi_q(\xi^-, \boldsymbol{\xi}_T) \right| A, P \rangle \Big|_{\xi^+=0}$$

- Common to approximate using convolution formalism

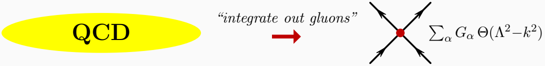
$$q_A(x_A, \boldsymbol{k}_T^2) = \sum_\alpha \int_0^A dy_A \int_0^1 dz\ \delta(x_A - y_A z) \int d^2\boldsymbol{q}_T \int d^2\boldsymbol{\ell}_T$$
$$\delta(\boldsymbol{\ell}_T - \boldsymbol{k}_T + z\,\boldsymbol{q}_T)\ f_A^\alpha(y_A, \boldsymbol{q}_T^2)\ q_\alpha(z, \boldsymbol{q}_T, \boldsymbol{\ell}_T^2)$$

  - $\alpha =$ (bound) protons, neutrons, pions, deltas ...
  - $q_\alpha\left(z, \boldsymbol{q}_T, \boldsymbol{\ell}_T^2\right)$ TMDs of quarks q in bound hadron α that has transverse momentum $\boldsymbol{q}_T$
  - $f_\alpha\left(y_A, \boldsymbol{q}_T^2\right)$ TMDs of hadron in nucleus





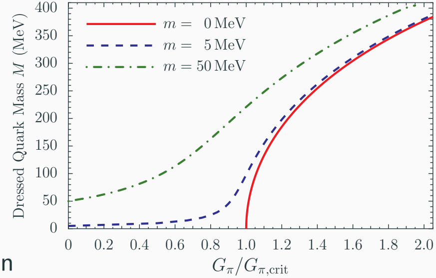
The Nambu–Jona-Lasinio Model



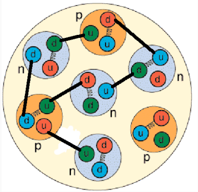
QCD

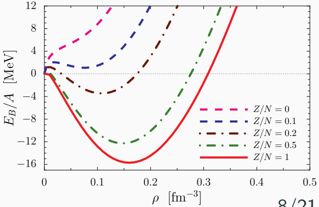
"integrate out gluons"

$\sum_\alpha G_\alpha \Theta(\Lambda^2 - k^2)$



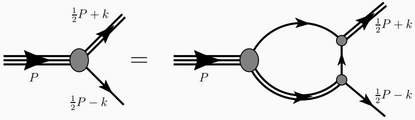
- NJL model is a Lagrangian based covariant QFT, exhibits dynamical chiral symmetry breaking, & aspects of confinement
  - Calculations proceed via bound state equations: gap, Bethe-Salpeter, Faddeev, ...
- Quark confinement is implemented via proper-time regularization
  - Quark propagator: $[\not{p} - m + i\varepsilon]^{-1} \quad \to \quad Z(p^2)[\not{p} - M + i\varepsilon]^{-1}$
  - Wave function renormalization vanishes at quark mass-shell: $Z(p^2 = M^2) = 0$
- Finite density calculations are possible at mean-field level with interactions in $\sigma,\ \omega,\ \rho, \ldots$ channels
  - Effective *NN* potential is derived via hadronization methods and calculations are done self-consistently
  - Model exhibits correct saturation of nuclear matter is symmetry energy



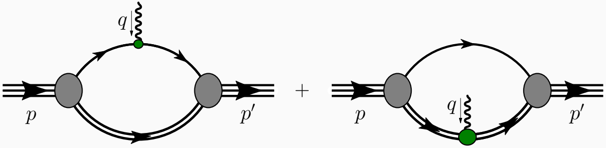


Nucleon Electromagnetic Form Factors

- Nucleon = quark+diquark

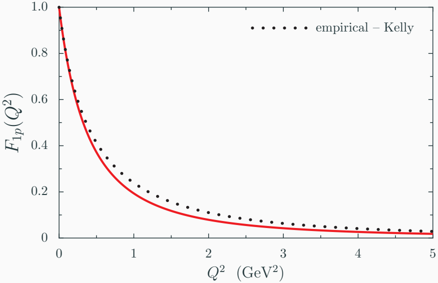


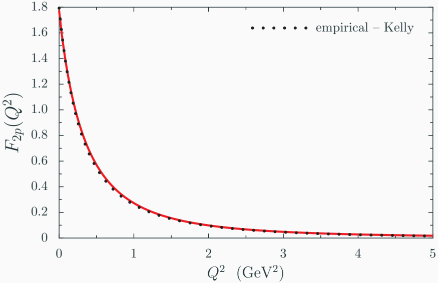
- Form factors given by Feynman diagrams:



- Calculation satisfies electromagnetic gauge invariance; includes
  - dressed quark–photon vertex with ρ and ω contributions
  - contributions from a pion cloud

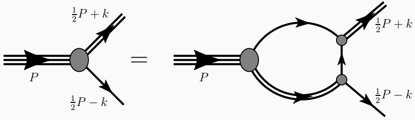
[ICC, W. Bentz and A. W. Thomas, Phys. Rev. C **90**, 045202 (2014)]



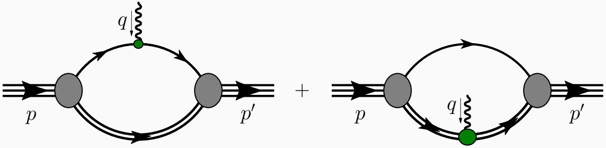


Nucleon Electromagnetic Form Factors

- Nucleon = quark+diquark

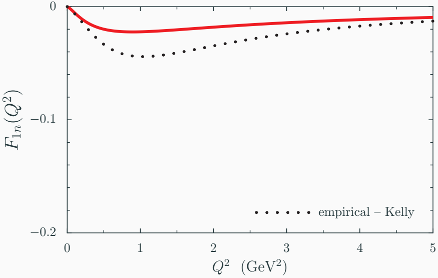


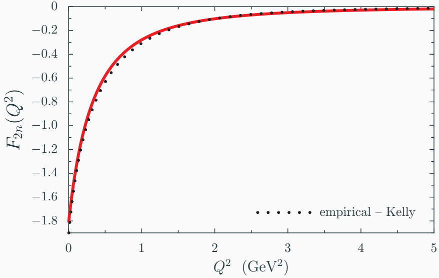
- Form factors given by Feynman diagrams:



- Calculation satisfies electromagnetic gauge invariance; includes
  - dressed quark–photon vertex with ρ and ω contributions
  - contributions from a pion cloud

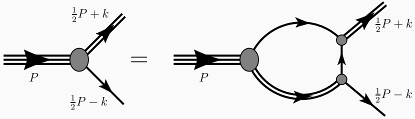
[ICC, W. Bentz and A. W. Thomas, Phys. Rev. C **90**, 045202 (2014)]



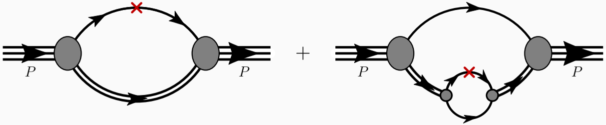


Nucleon quark distributions

- Nucleon = quark+diquark



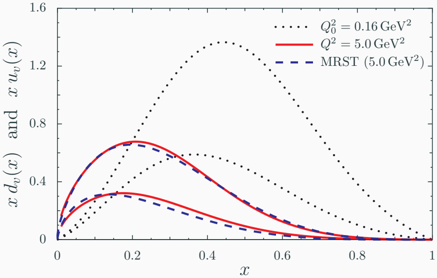
- PDFs given by Feynman diagrams: $\langle\gamma^+\rangle$

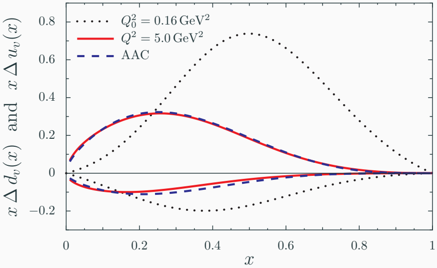


- Covariant, correct support; satisfies sum rules, Soffer bound & positivity

$$\langle q(x)-\bar{q}(x)\rangle = N_q, \quad \langle x\,u(x) + x\,d(x) + \ldots\rangle = 1, \quad |\Delta q(x)|\,, \quad |\Delta_T q(x)| \leqslant q(x)$$

[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **621**, 246 (2005)]





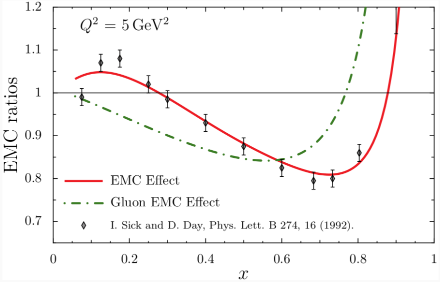
Gluon and Spin EMC Effects

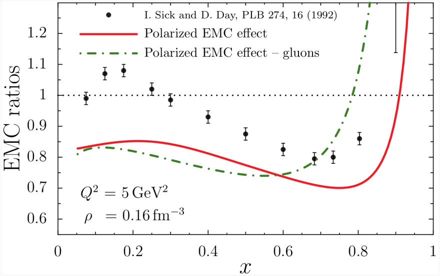
- To solve puzzle of EMC effect need new observables, e.g., gluon and spin EMC effects
  - Can help distinguish between different explanations of the EMC effect
  - Mean-field and SRC make different predictions for spin EMC effect
- The gluon EMC effect can be defined as

$$R_g(x) = \frac{g_A(x)}{Z\, g_p(x) + N\, g_n(x)}$$

  - Analogous definition for gluon spin EMC effect, with, $Z \to P_p$ and $N \to P_n$
- Results obtained in mean-field model that describes the EMC effect and predicts spin EMC effect
  - Gluons are generated purely perturbatively
  - Provides a baseline for comparison and understanding of future measurements

[X. G. Wang, W. Bentz, ICC, and A. W. Thomas, J. Phys. G **49**, (2022)]





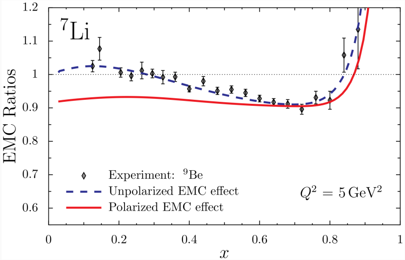
Polarized EMC Effect – Update

- Proposal "*The EMC Effect in Spin Structure Functions*" for ^{7}Li completed jeopardy process in PAC 48 (2020)
  - scientific rating went from B^+ to A^- — almost unheard of — thanks to a lot of work from Will Brooks and Sebastian Kuhn
- Spin/Polarized EMC effect experiments are just measurements of the spin structure function(s) of a nucleus – exactly analogous to nucleon DIS
- Polarized EMC effect provides insight into QCD effects in nuclei

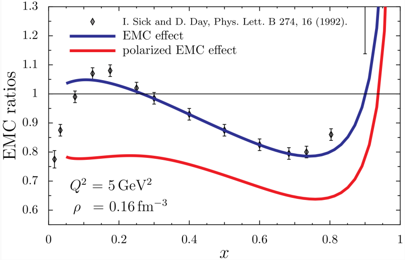
$$\Delta R(x) = \frac{g_{1A}(x)}{g_{1A}^{\text{naive}}(x)} = \frac{g_{1A}(x)}{P_p\, g_{1p}(x) + P_n\, g_{1n}(x)}$$

  - P_p & P_n effective polarizations of protons/neutrons in nucleus
- JLab will hopefully soon run polarized ^{7}Li DIS experiment
  - Ideal target should have spin dominated by protons and small A
  - Candidate nuclei include ^{3}H ($J = \frac{1}{2}$), ^{7}Li ($J = \frac{3}{2}$), ^{11}B ($J = \frac{3}{2}$), . . .

[ICC, W. Bentz and A. W. Thomas, PLB 642, 210 (2006)]

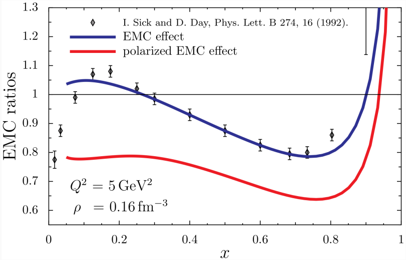


[ICC, W. Bentz and A. W. Thomas, PRL **95**, 052302 (2005)]

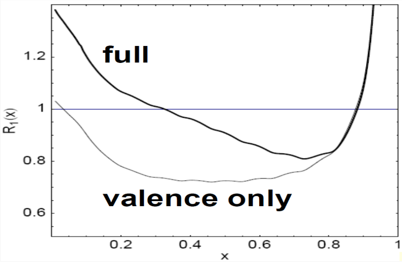


Mean-Field Calculations of Polarized EMC Effect

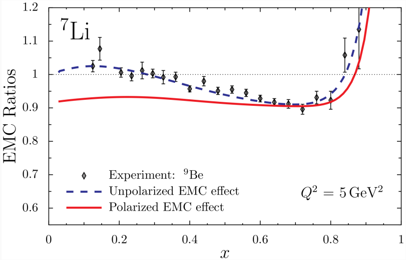
- Several relativistic mean-field calculations of polarized EMC effect
  - all calculations find polarized EMC same size or larger than EMC effect
- Large polarized EMC effect results because in-medium quarks are more relativistic ($M^* < M$)
  - quark lower components are enhanced
  - in-medium we find that quark spin is converted to orbital angular momentum



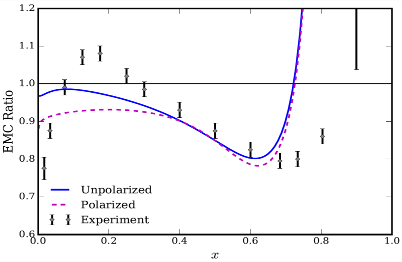
[ICC, W. Bentz and A. W. Thomas, PRL **95**, 052302 (2005)]



[J. R. Smith and G. A. Miller, Phys. Rev. C **72**, 022203(R) (2005)]

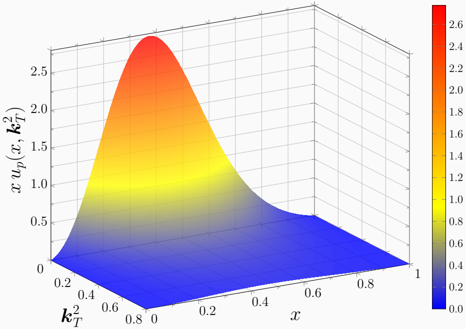


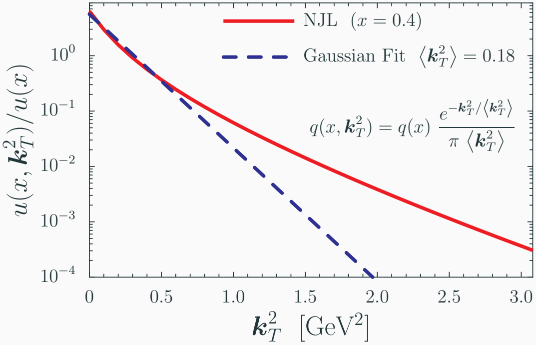
[ICC, W. Bentz and A. W. Thomas, PLB 642, 210 (2006)]



[Tronchin, Matevosyan and Thomas, PLB **783**, 247-252 (2018)]

Nucleon TMDs, Diquarks, & Flavor Dependence

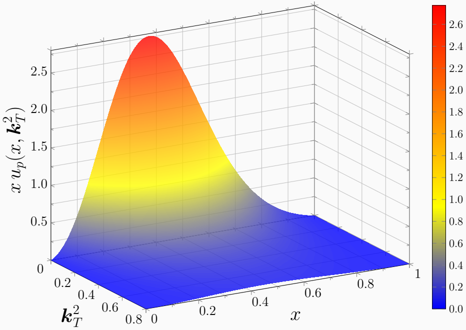


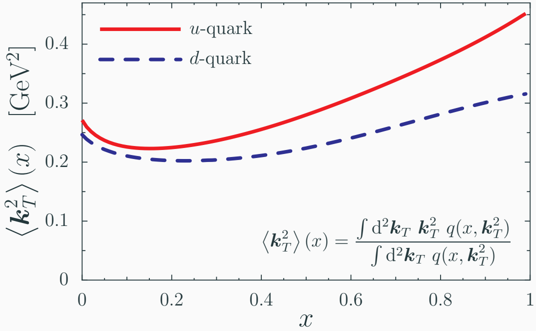


- Rigorously included transverse momentum of diquark correlations in TMDs
- This has numerous consequences:
  - scalar diquark correlations greatly increase $\langle \boldsymbol{k}_T^2 \rangle$
  - find deviation from Gaussian anzatz and that TMDs do not factorize in x & $\boldsymbol{k}_T^2$
  - diquark correlations introduce a significant flavor dependence in $\langle \boldsymbol{k}_T^2 \rangle(x)$

$$\langle \boldsymbol{k}_T^2 \rangle^{\mu_0^2} = 0.47^2\,\text{GeV}^2 \quad \langle \boldsymbol{k}_T^2 \rangle = 0.56^2\,\text{GeV}^2\,[\text{HERMES}], \quad 0.64^2\,\text{GeV}^2\,[\text{EMC}]$$

Nucleon TMDs, Diquarks, & Flavor Dependence

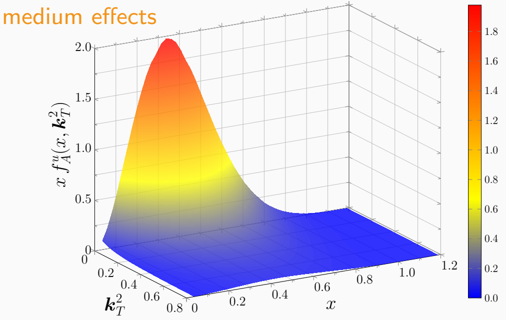




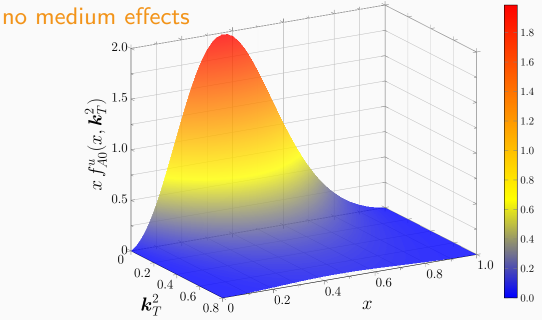
- Rigorously included transverse momentum of diquark correlations in TMDs
- This has numerous consequences:
  - scalar diquark correlations greatly increase $\langle \boldsymbol{k}_T^2 \rangle$
  - find deviation from Gaussian anzatz and that TMDs do not factorize in x & $\boldsymbol{k}_T^2$
  - diquark correlations introduce a significant flavor dependence in $\langle \boldsymbol{k}_T^2 \rangle (x)$

$$\langle \boldsymbol{k}_T^2 \rangle^{\mu_0^2} = 0.47^2\ \text{GeV}^2 \quad \langle \boldsymbol{k}_T^2 \rangle = 0.56^2\ \text{GeV}^2\ [\text{HERMES}], \quad 0.64^2\ \text{GeV}^2\ [\text{EMC}]$$

TMDs in Isoscalar Nuclear Matter



medium effects



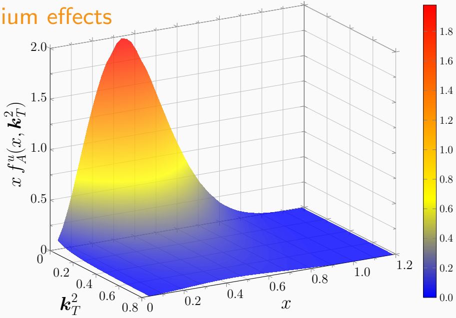
no medium effects

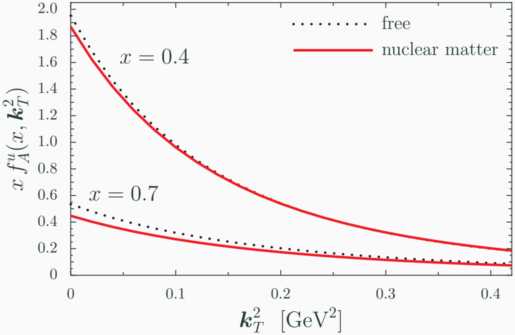
- So far only considered the simplest spin-averaged TMDs – $q(x, k_T^2)$
  - Integral of these TMDs over $\boldsymbol{k}_T$ gives the PDFs and reproduces the EMC effect

- Medium effects have only a minor impact on $\boldsymbol{k}_T^2$ dependence of TMD
  - scalar field causes $M^* < M$ but also $r_N^* > r_N$, net effect $\langle \boldsymbol{k}_T^2 \rangle$ slightly decreases
  - fermi motion has a minor impact – analogous to x-dependence in EMC effect
  - vector field only has zeroth component, no direct effect on $\boldsymbol{k}_T^2$

TMDs in Isoscalar Nuclear Matter

medium effects



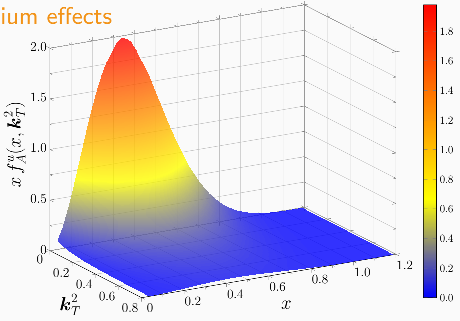


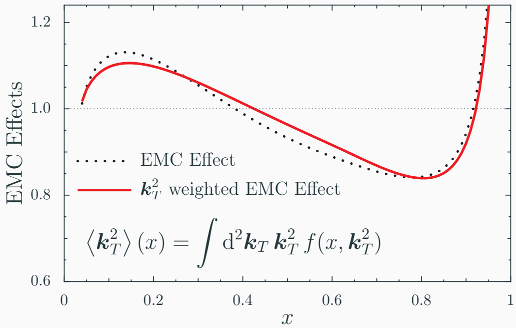
- So far only considered the simplest spin-averaged TMDs – $q(x, k_T^2)$
  - Integral of these TMDs over $\boldsymbol{k}_T$ gives the PDFs and reproduces the EMC effect

- Medium effects have only a minor impact on $\boldsymbol{k}_T^2$ dependence of TMD
  - scalar field causes $M^* < M$ but also $r_N^* > r_N$, net effect $\langle \boldsymbol{k}_T^2 \rangle$ slightly decreases
  - fermi motion has a minor impact – analogous to x-dependence in EMC effect
  - vector field only has zeroth component, no direct effect on $\boldsymbol{k}_T^2$

TMDs in Isoscalar Nuclear Matter

medium effects



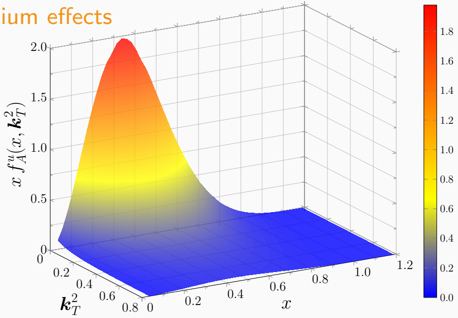


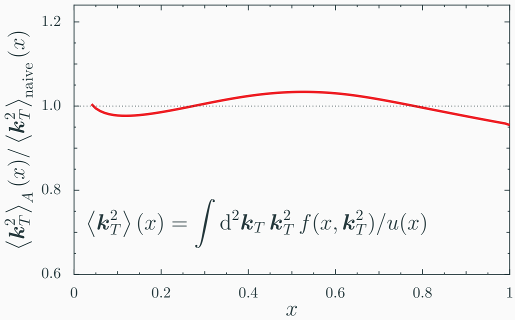
- So far only considered the simplest spin-averaged TMDs – $q(x, k_T^2)$
  - Integral of these TMDs over $\boldsymbol{k}_T$ gives the PDFs and reproduces the EMC effect

- Medium effects have only a minor impact on $\boldsymbol{k}_T^2$ dependence of TMD
  - scalar field causes $M^* < M$ but also $r_N^* > r_N$, net effect $\langle \boldsymbol{k}_T^2 \rangle$ slightly decreases
  - fermi motion has a minor impact – analogous to x-dependence in EMC effect
  - vector field only has zeroth component, no direct effect on $\boldsymbol{k}_T^2$

TMDs in Isoscalar Nuclear Matter

medium effects



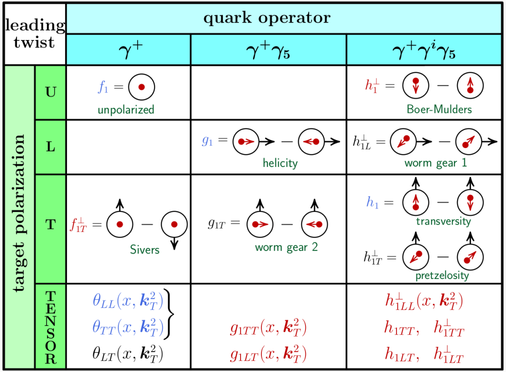


- So far only considered the simplest spin-averaged TMDs – $q(x, k_T^2)$
  - Integral of these TMDs over $\boldsymbol{k}_T$ gives the PDFs and reproduces the EMC effect

- Medium effects have only a minor impact on $\boldsymbol{k}_T^2$ dependence of TMD
  - scalar field causes $M^* < M$ but also $r_N^* > r_N$, net effect $\langle \boldsymbol{k}_T^2 \rangle$ slightly decreases
  - fermi motion has a minor impact – analogous to x-dependence in EMC effect
  - vector field only has zeroth component, no direct effect on $\boldsymbol{k}_T^2$

TMDs of Spin-1 Targets

- A spin-1 target can have tensor polarization $[\lambda = 0]$
  - 3 additional T-even and 7 additional T-odd quark TMDs compared to nucleon
- Analogous situation for gluon TMDs
  - to fully expose role of quarks and gluons in nuclei need polarized nuclear targets (transverse and longitudinal) with all spin projections, e.g., for $J = 1$: ^{2}H, ^{6}Li
- Spin 4-vector of a spin-one particle moving in z-direction, with spin quantization axis $\boldsymbol{S} = (\boldsymbol{S}_T, S_L)$, reads: $S^\mu(p) = \left(\frac{p_z}{m_h} S_L, \boldsymbol{S}_T, \frac{p_0}{m_h} S_L\right)$
  - for given direction $\boldsymbol{S}$ the particle has the three possible spin projections $\lambda = \pm 1, 0$
  - longitudinal polarization $\Longrightarrow \boldsymbol{S}_T = 0, S_L = 1$; transverse $\Longrightarrow |\boldsymbol{S}_T| = 1, S_L = 0$



leading twist		quark operator		
		γ^+	$\gamma^+\gamma_5$	$\gamma^+\gamma^i\gamma_5$
target polarization	U	$f_1 =$ unpolarized		$h_1^\perp =$ Boer-Mulders
	L		$g_1 =$ helicity	$h_{1L}^\perp =$ worm gear 1
	T	$f_{1T}^\perp =$ Sivers	$g_{1T} =$ worm gear 2	$h_1 =$ transversity $h_{1T}^\perp =$ pretzelosity
	TENSOR	$\left.\begin{matrix}\theta_{LL}(x, \boldsymbol{k}_T^2)\\ \theta_{TT}(x, \boldsymbol{k}_T^2)\end{matrix}\right\}$ $\theta_{LT}(x, \boldsymbol{k}_T^2)$	$g_{1TT}(x, \boldsymbol{k}_T^2)$ $g_{1LT}(x, \boldsymbol{k}_T^2)$	$h_{1LL}^\perp(x, \boldsymbol{k}_T^2)$ $h_{1TT}, \quad h_{1TT}^\perp$ $h_{1LT}, \quad h_{1LT}^\perp$

- Associated quark correlation function:

$$\langle\gamma^+\rangle_{\boldsymbol{S}}^{(\lambda)}(x, \boldsymbol{k}_T) \equiv f(x, \boldsymbol{k}_T^2) - \frac{3\lambda^2 - 2}{2}\left[\left(S_L^2 - \frac{1}{3}\right)\theta_{LL}(x, \boldsymbol{k}_T^2) + \frac{(\boldsymbol{k}_T \cdot \boldsymbol{S}_T)^2 - \frac{1}{3}\boldsymbol{k}_T^2}{m_h^2}\theta_{TT}(x, \boldsymbol{k}_T^2) + S_L \frac{\boldsymbol{k}_T \cdot \boldsymbol{S}_T}{m_h}\theta_{LT}(x, \boldsymbol{k}_T^2)\right]$$

Measuring TMDs of Spin-1 Targets

- Need longitudinal and transverse polarized spin-1 targets ($\lambda = \pm 1, 0$), e.g., deuteron and ^{6}Li

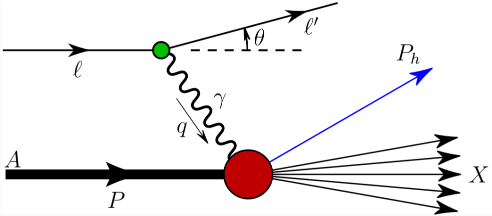
- For SIDIS there are 41 structure functions; 18 for U+L which also appear for spin-half and 23 associated with tensor polarization

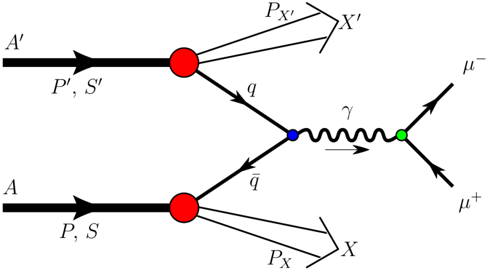
  [W. Cosyn, M. Sargsian and C. Weiss, PoS DIS **2016**, 210 (2016)]

- For proton + deuteron Drell-Yan there are 108 structure functions; 60 associated with tensor structure of deuteron

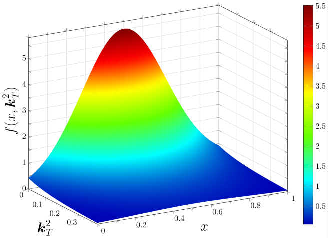
  [S. Kumano, J. Phys. Conf. Ser. **543**, no. 1, 012001 (2014)]

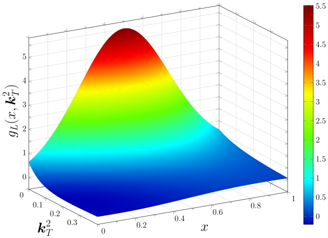
- Challenging experimentally
  - Need solid physics motivation

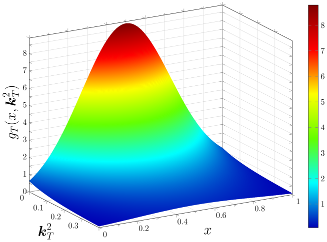


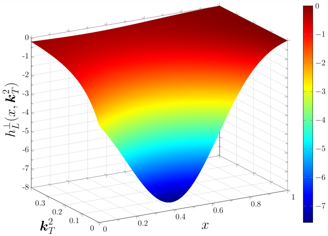


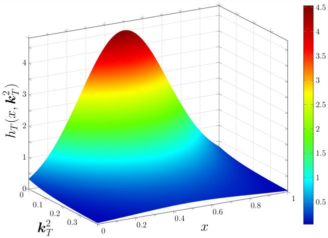
Spin-1 Target TMDs – with Nucleon Analogs

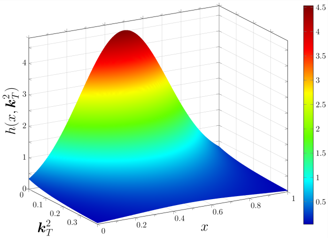

unpolarized


helicity


worm gear 2


worm gear 1


pretzelosity


transversity

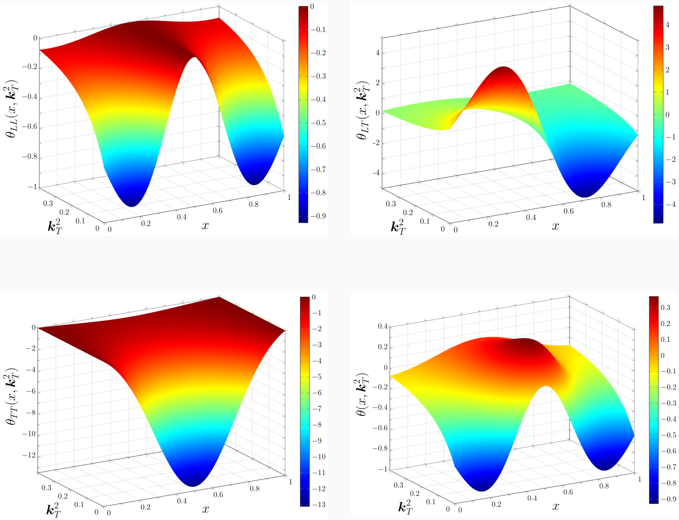
[Yu Ninomiya, ICC and Wolfgang Bentz, Phys. Rev. C **96**, no.4, 045206 (2017)]

Spin-1 Target TMDs – Tensor Polarization

- Calculations assume point-like nucleons but nevertheless show tensor polarized TMDs have many surprising features

- TMDs $\theta_{LL}(x\, \boldsymbol{k}_T^2)$ & $\theta_{LT}(x\, \boldsymbol{k}_T^2)$ identically vanish at $x = 1/2$ for all $\boldsymbol{k}_T^2$
  - $x = 1/2$ corresponds to zero relative momentum between (the two) constituents, that is, *s*-wave contributions
  - therefore θ_{LL} & θ_{LT} primarily receive contributions from $L \geqslant 1$ components of the wave function – *sensitive to orbital angular momentum*

- Features hard to determine from a few moments – difficult for traditional lattice QCD methods



[Yu Ninomiya, ICC and Wolfgang Bentz, Phys. Rev. C **96**, no.4, 045206 (2017)]

Gravitational Structure of Nucleons and Nuclear Matter

- The nucleon has 3 gravitational form factors

$$\langle p' \,|\, T^{\mu\nu} \,|\, p\rangle = \bar{u}(p')\left[A(t)\,\frac{P^{\mu}P^{\nu}}{M} + D(t)\,\frac{\Delta^{\mu}\Delta^{\nu} - \Delta^{2} g^{\mu\nu}}{4\,M} + J(t)\,\frac{P^{\{\mu} i\sigma^{\nu\}\alpha}\Delta_{\alpha}}{2\,M}\right] u(p)$$

  - related to mass and angular momentum distributions $J(t) = \frac{1}{2}\left[A(t) + B(t)\right]$, and pressure and shear forces

- Gravitational form factors are related to GPDs

$$\sum_{i=q,g}\int_{-1}^{1} \mathrm{d}x\, x\,\left[H_i(x,\xi,t), E_i(x,\xi,t)\right] = \left[A(t) + \xi^2 D(t),\; B(t) - \xi^2 D(t)\right]$$

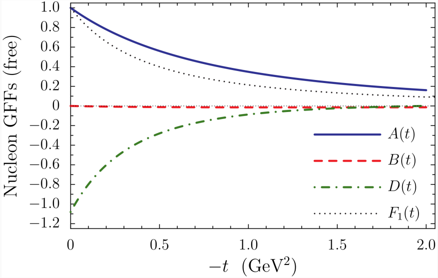
- We find (light front) charge and mass radii of:

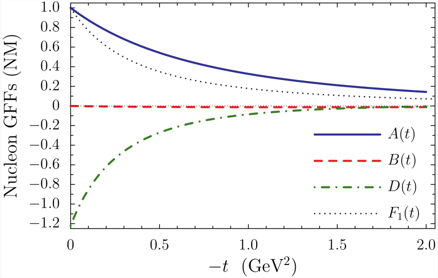
free $\langle r^2\rangle_C = (0.61\,\mathrm{fm})^2, \quad \langle r^2\rangle_A = (0.45\,\mathrm{fm})^2, \quad D(0) = -1.08$

NM $\langle r^2\rangle_C = (0.66\,\mathrm{fm})^2, \quad \langle r^2\rangle_A = (0.46\,\mathrm{fm})^2, \quad D(0) = -1.21$

  - mass radius changes much less than the charge radius
  - pressure and shear forces on the nucleon increase by around 10%
  - small mass radius may help explain success of traditional NP

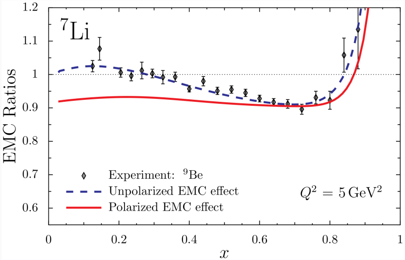
[Adam Freese and ICC, *to appear* (2024)]

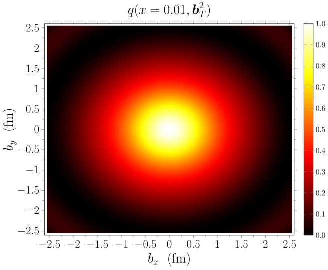


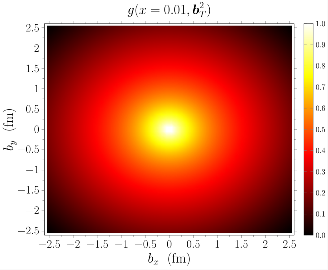


Conclusion and Outlook

- JLab is motivated to measure polarized EMC effect in ^{7}Li
    - features in a new "opportunities" document for JLab
- Tremendous opportunity for the JLab and EIC to transform our understanding of QCD and nuclei via 3D imaging
    - quark & gluon GPDs and TMDs of: p, D, ^{3}H, ^{3}He, ^{4}He, ...
    - quark & gluon PDFs of ^{7}Li, ^{11}B, ^{56}Fe, ...
    - flavor separation, e.g., s-quarks
- Key physics questions: How does the NN interaction arise from QCD? How do quark/gluon confinement length scales change in medium?
- Can explore these question by imaging nuclei and comparing quarks and gluons for slices in x, $\boldsymbol{k}_T^2$, and $\boldsymbol{b}_T^2$
    - correlations between quarks and gluons in nuclei provide insights into color confinement







BACKUP SLIDES

Mean-Field vs SRC Expectations

- To explain EMC effect need medium modification of bound nucleons — or equivalently significant non-nucleonic components in nucleus
  - leading explanation for EMC effect is medium modification from mean-field and/or SRC
- Polarized EMC effect provides a means to possibility distinguish between mean-field and SRC effects
- For SRCs to give large polarized EMC — SRC pairs need to have a significant polarization correlated with spin of nucleus
  - QMC calculations using Argonne v18 potential show very little net polarization for high momentum nucleons
  - integrating distributions shows that only ∼2% net polarization from high momentum nucleons
- See also "Reflections on the Origin of the EMC Effect" (A. W. Thomas) for explanation on how SRCs depolarize participants

[Bob Wiringa `www.phy.anl.gov/theory/research/momenta/`]