The Polarized EMC Effect

Ian Cloët

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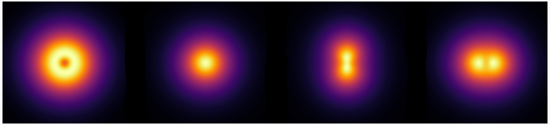


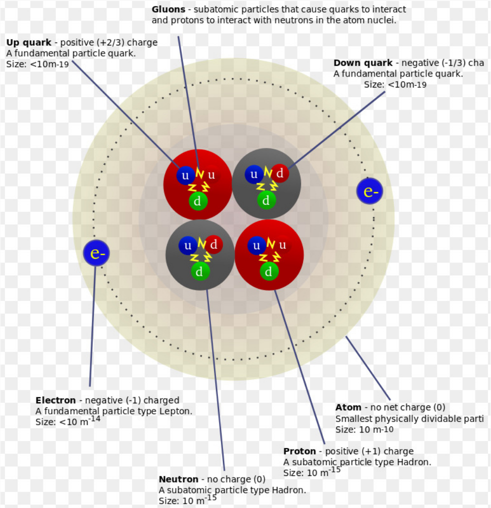
Polarized Ion Sources and Beams at EIC

10—13 March 2025

Center for Frontiers in Nuclear Science, Stony Brook University

QCD and Nuclei

- There is a gap—perhaps a big gap—between traditional picture of a nucleus and a QCD picture
  - this gap manifests in the valence region — EMC effect
- Where to start? ^{4}He can be consider the lightest *"real"* nucleus $\left[{}^4\mathrm{He}_{\mathrm{BE}} = 7.1\,\mathrm{MeV/A}\right]$ and EMC effect is fully manifest $\left[{}^{208}\mathrm{Pb}_{\mathrm{BE}} = 7.9\,,\ {}^3\mathrm{He}_{\mathrm{BE}} = 2.6\,,{}^3\mathrm{H}_{\mathrm{BE}} = 2.8\,\mathrm{MeV/A}\right]$
- ^{4}He is a key constituent of nuclei — α clustering
  - "standard candle" for QCD and nuclei
- Many foundational QCD questions to address
  - Are the quarks and gluons confined to nucleon-like objects? Does this depend on, e.g., the momentum filter x?
  - What are the quark and gluon mass radii for ^{4}He and how does this contrast with the nucleon?
  - What are the pressure and shear forces in ^{4}He?
- EIC can help bridge this gap



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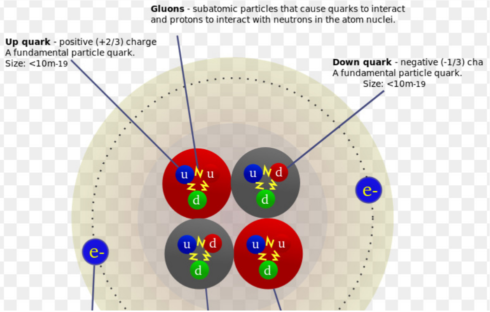

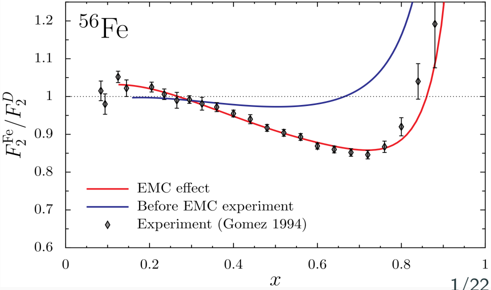

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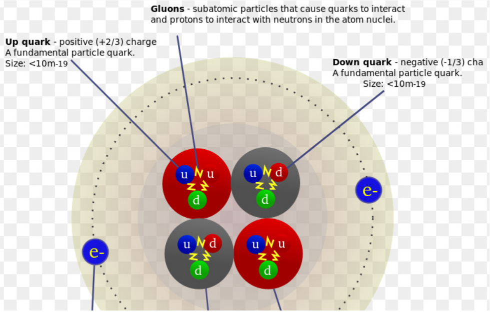

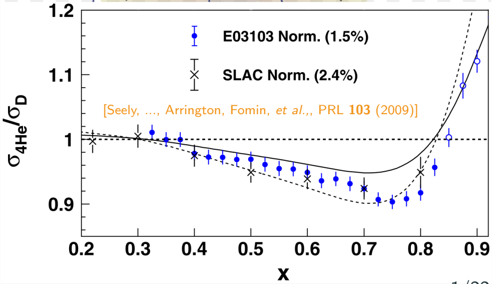

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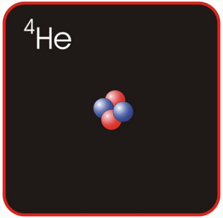
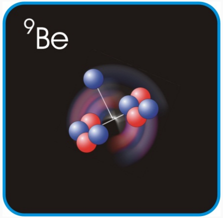
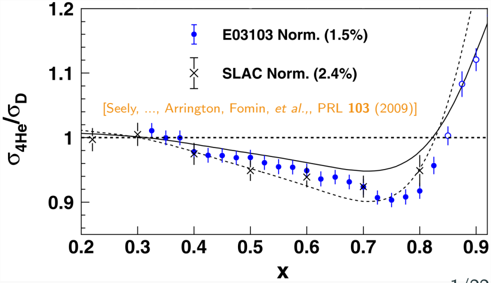
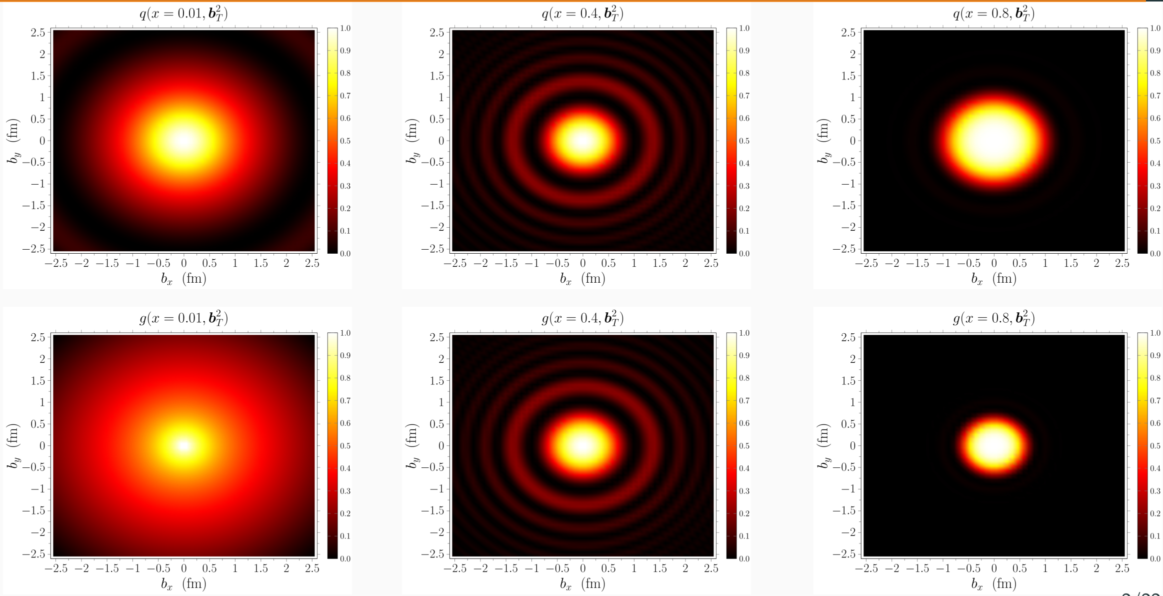




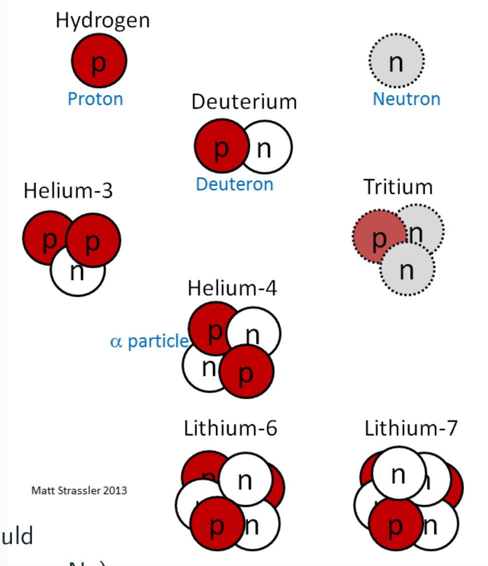


A More Realistic Impression of ^{4}He — Spatial Tomography



QCD and Imaging of Light Nuclei

- Nuclei provide a QCD laboratory with characteristics not avaliable from protons alone
- Program build around imaging of light nuclei would have tremedous impact and reveal many novel aspects of QCD
  - How is gluon dynamics modified by the nuclear medium?
  - $J \geqslant 1$ targets $\Rightarrow$ new PDFs, form factors, TMDs, GPDs, etc.
  - Exotic gluonic components from gluon transversity PDFs
  - Color transparency, hidden color, NN correlations, fast quarks
  - Isospin & baryon density effects, e.g., partial restoration of chiral symmetry and possible changes in confinement length scales between quarks and gluons
- Key question: *How does the nucleon-nucleon interaction arise from QCD?*
- EIC's unique capabilities for polarized proton structure should apply equally to nuclei (ideally p, D, ^{3}H, ^{3}He, ^{6}Li, ^{7}Li, ^{7}Be, ..., Ne)



QCD and Imaging of Light Nuclei

- Nuclei provide a QCD laboratory with characteristics not avaliable from protons alone
- Program build around imaging of light nuclei would have tremedous impact and reveal many novel aspects of QCD
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> *"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

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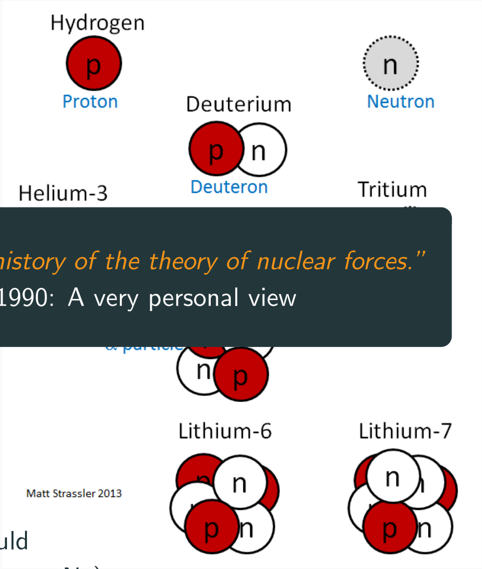
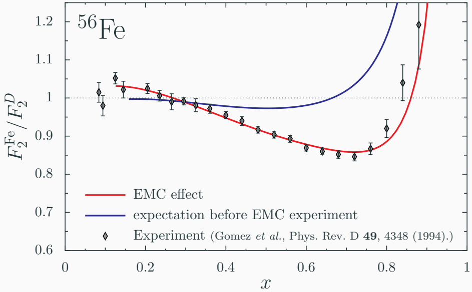


EMC Effect

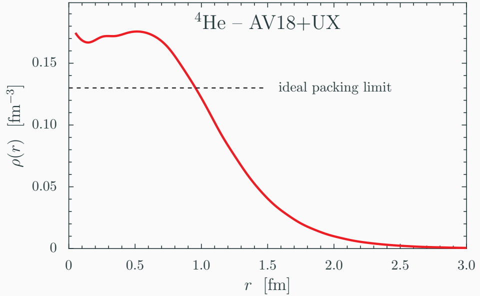
- Understanding origin of the EMC effect is critical for a QCD based description of nuclei
  - 40+ years after discovery a broad consensus on explanation is lacking
  - Valence quarks in nucleus carry less momentum than in a nucleon
- Important question: *In what processes, and at what energy scales, 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?

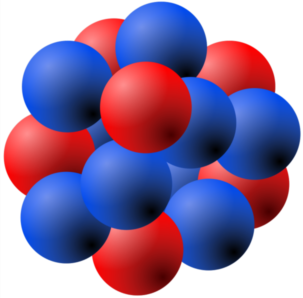


long- and short-range *NN* interactions

Nucleons in Nuclei

- Nuclei are extremely dense:
  - proton rms radius is $r_p \simeq 0.85\,\text{fm}$, corresponds hard sphere $r_p \simeq 1.10\,\text{fm}$
  - ideal packing gives $\rho \simeq 0.13\,\text{fm}^{-3}$; nuclear matter density is $\rho \simeq 0.16\,\text{fm}^{-3}$
  - 20% of nucleon volume inside other nucleons – nucleon centers $\sim 2\,\text{fm}$ apart
- For realistic charge distribution 25% of proton charge at distances $r > 1\,\text{fm}$ (scalar radius?)
- *Natural to expect that nucleon properties are modified by nuclear medium*
  - in contrast to traditional nuclear physics
- Understanding validity of two viewpoints remains key challenge for nuclear physics – *a new paradigm or deep insights into color confinement in QCD*





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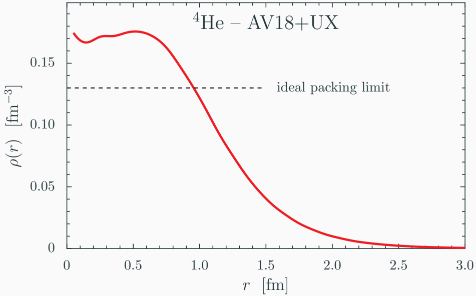
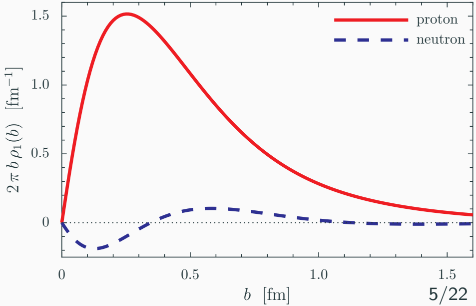
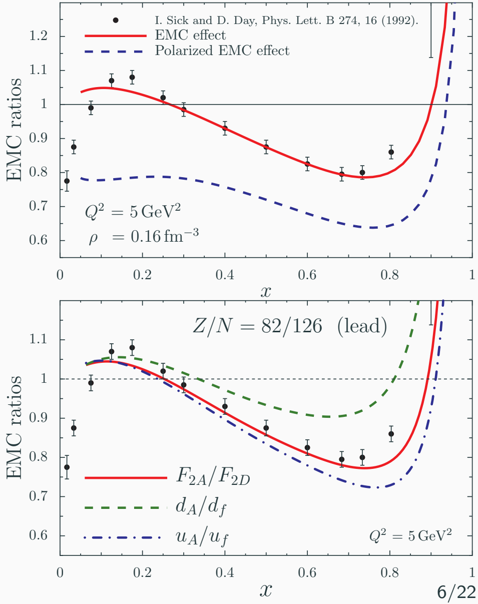




Understanding the EMC Effect

- *The puzzle posed by the EMC effect will only be solved by conducting new experiments that expose new aspects*
- 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 has been accessed via JLab DIS experiments on ^{40}Ca & ^{48}Ca – *but parity violating DIS stands to play the pivotal role*



Theory approaches to EMC Effect

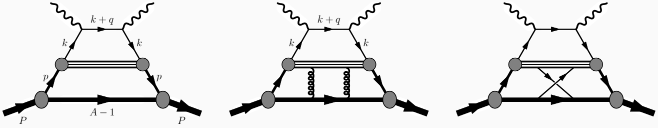
- To address origins of EMC effect must determine e.g. nuclear PDFs, TMDs, GPDs:

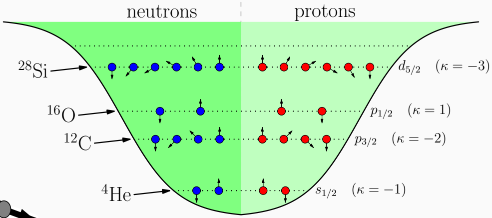
$$q_A(x_A) = \frac{P^+}{A} \int \frac{d\xi^-}{4\pi} e^{ix_A P\cdot\xi/A} \left\langle A, P \left| \overline{\psi}_q(0)\, \gamma^+ \, \psi_q(\xi^-, \boldsymbol{\xi}_T) \right| A, P \right\rangle \Big|_{\xi^+=0}$$

- Common to approximate using convolution formalism

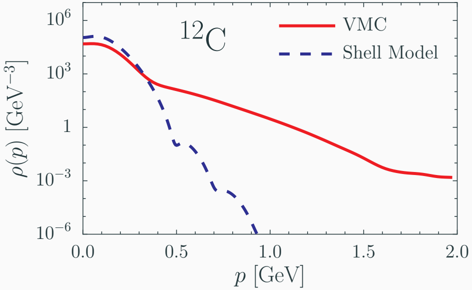
$$q_A(x_A) = \sum_\alpha \int_0^A dy_A \int_0^1 dz\ \delta(x_A - y_A z)\ f_A^\alpha(y_A)\ q_\alpha(z)$$

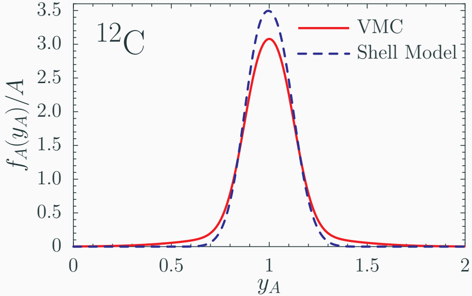
  - $\alpha =$ (bound) protons, neutrons, pions, deltas ...
  - $q_\alpha\,(z)$ PDFs of quarks q in bound hadron α
  - $f_\alpha\,(y_A)$ PDFs of hadron in nucleus



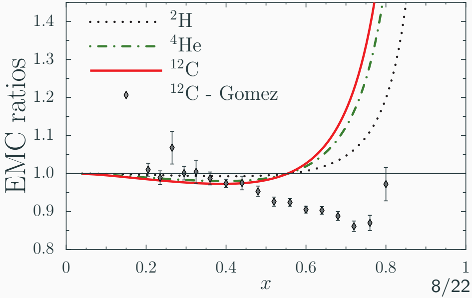


Nucleon Momentum Distributions in Nuclei





- Modern GFMC or VMC nucleon momentum distributions have significant high momentum tails
  - indicates presence of SRCs: $\sim$20% for ^{12}C

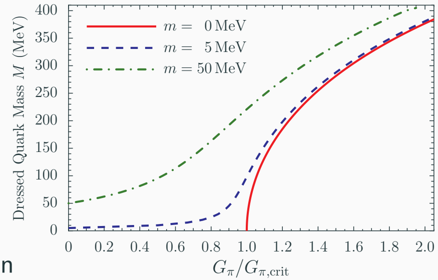


- Light-cone momentum distribution:

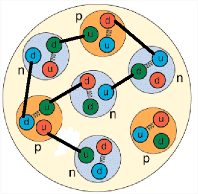
$$f(y_A) = \int \frac{d^3\vec{p}}{(2\pi)^3}\, \delta\left(y_A - \frac{p^+}{P^+}\right)\, \rho(p)$$

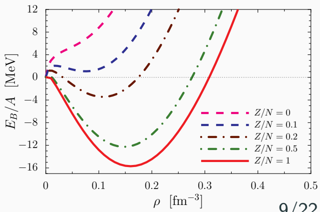
- *Naive SRCs introduce effect of opposite sign to EMC effect*

The Nambu–Jona-Lasinio Model



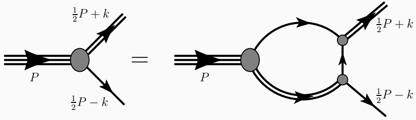
- NJL model is a Lagrangian based covariant QFT, exhibits dynamical chiral symmetry breaking, & aspects of confinement
  - Calculations proceed via bound state equations: gap, Bethe-Salpeter, Faddeev, ...
- Quark confinement is implemented via proper-time regularization
  - Quark propagator: $[\not{p} - m + i\varepsilon]^{-1} \quad \rightarrow \quad Z(p^2)[\not{p} - M + i\varepsilon]^{-1}$
  - 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 σ, ω, $\rho, \ldots$ 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



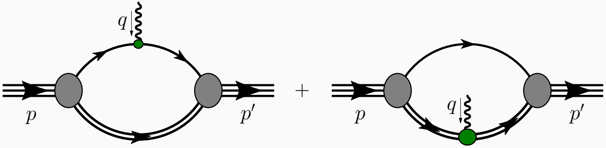


Nucleon Electromagnetic Form Factors

- Nucleon = quark+diquark

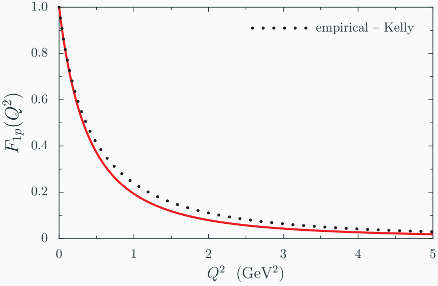


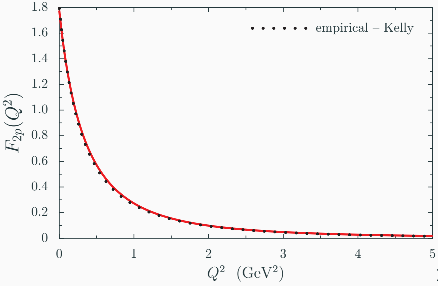
- Form factors given by Feynman diagrams:



- 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)]





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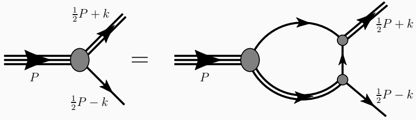

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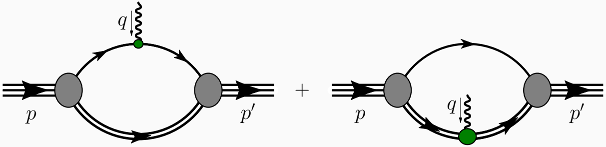

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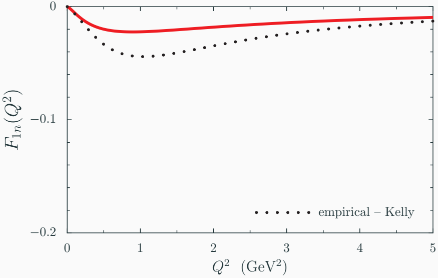
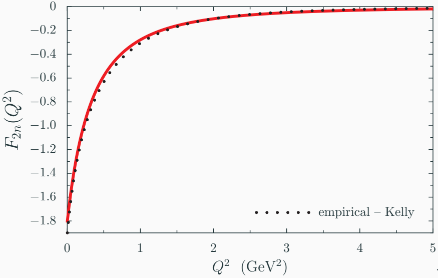
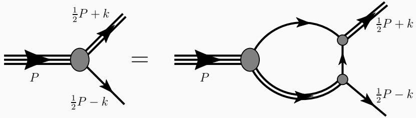


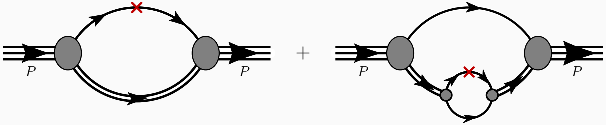


Nucleon quark distributions

- Nucleon = quark+diquark



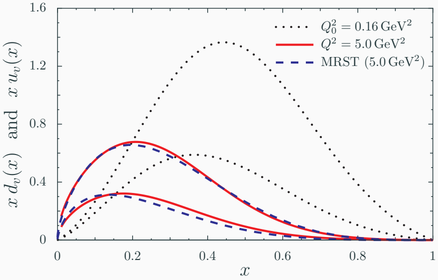
- PDFs given by Feynman diagrams: $\langle\gamma^+\rangle$

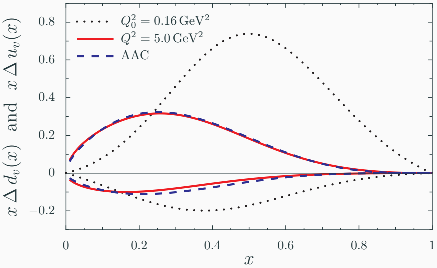


- Covariant, correct support; satisfies sum rules, Soffer bound & positivity

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

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





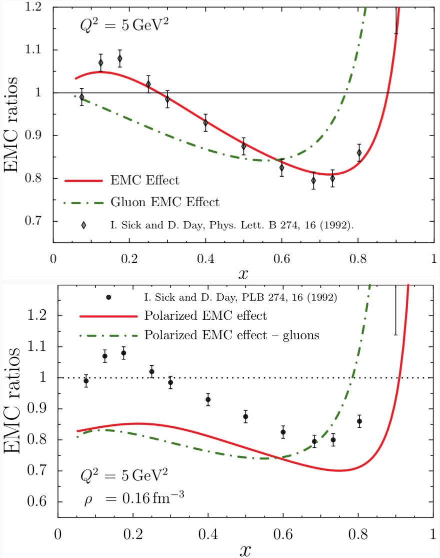
Spin and Gluon EMC Effects

- 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)]



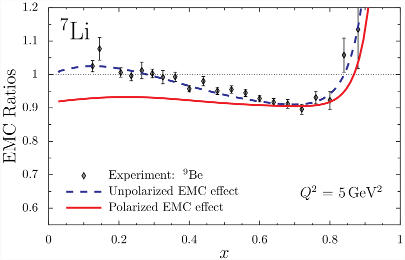
Polarized EMC Effect – Update

- 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

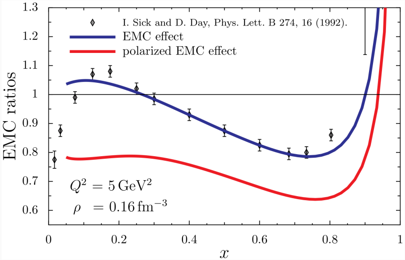
$$\Delta R(x) = \frac{g_{1A}(x)}{g_{1A}^{\text{naive}}(x)} = \frac{g_{1A}(x)}{P_p\, g_{1p}(x) + P_n\, g_{1n}(x)}$$

  - 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)]



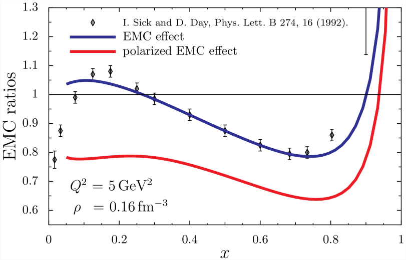
[ICC, W. Bentz and A. W. Thomas, PRL **95**, 052302 (2005)]



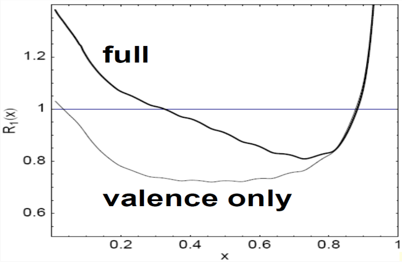
Mean-Field Calculations of Polarized EMC Effect

- 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

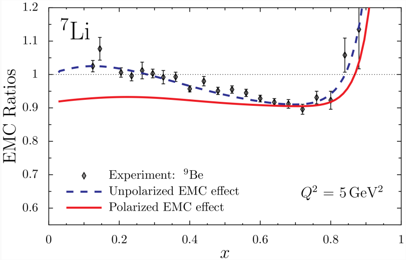
[ICC, W. Bentz and A. W. Thomas, PRL **95**, 052302 (2005)]



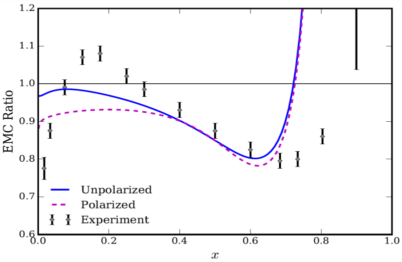
[J. R. Smith and G. A. Miller, Phys. Rev. C **72**, 022203(R) (2005)]



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



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

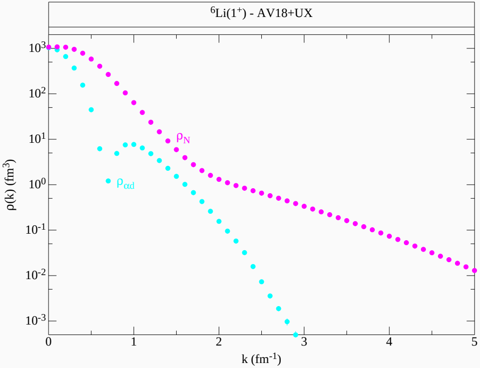


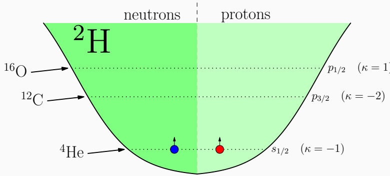
EMC and Polarized EMC in Spin-1 Nuclei

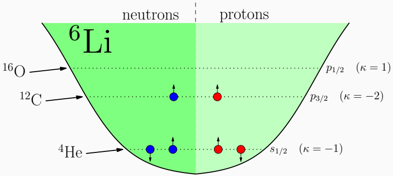
- Of the 250+ stable nuclei only 3 have spin-one: ^{2}H (deuteron), ^{6}Li, and ^{14}N
- Spin of each of these nuclei us primarily carried by the two valence nucleon
- For ^{6}Li nucleons in $p_{3/2}$ and ^{14}N nucleons in $p_{1/2}$, so each nucleon has one unit of orbitial angular momentum

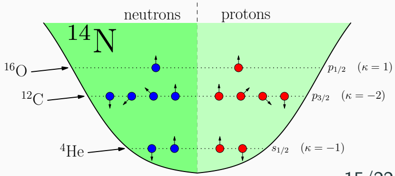
$$\Psi^{11}_{^6\mathrm{Li}} = \sqrt{\frac{3}{10}}\left[p^{3/2}n^{-1/2}\right] + \sqrt{\frac{3}{10}}\left[p^{-1/2}n^{3/2}\right] - \sqrt{\frac{2}{5}}\left[p^{1/2}n^{1/2}\right]$$

- For deuteron nucleon is s-wave, so very interesting to compare polarized EMC effect for these nuclei









Polarized EMC Effect for Spin-One Nuclei

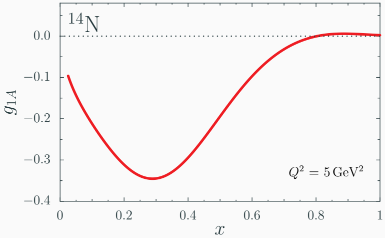
- Recall that the polarized EMC effect is defined by

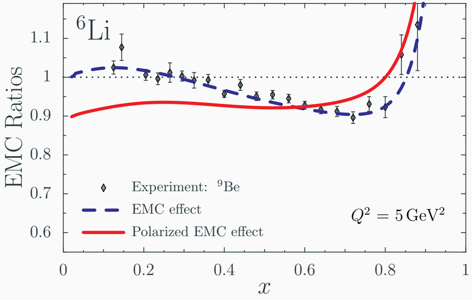
$$\Delta R(x) = \frac{g_{1A}(x)}{g_{1A}^{\text{naive}}(x)} = \frac{g_{1A}(x)}{P_p\, g_{1p}(x) + P_n\, g_{1n}(x)}$$

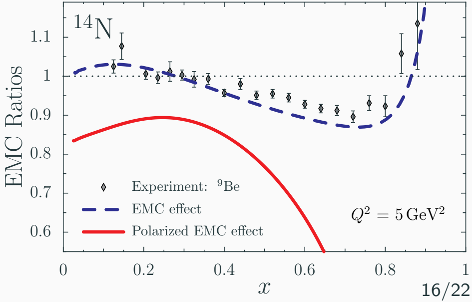
  - P_p & P_n effective polarizations of protons/neutrons

- ^{6}Li polarized EMC effect similar to that of ^{7}Li
  - effective polarizations: $P_p = P_n = 1/3$

- In ^{14}N valence nucleons in $p_{1/2}$ state
  - causes zero-crossing in numerator of $\Delta R(x)$





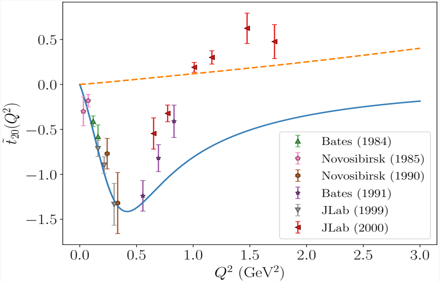


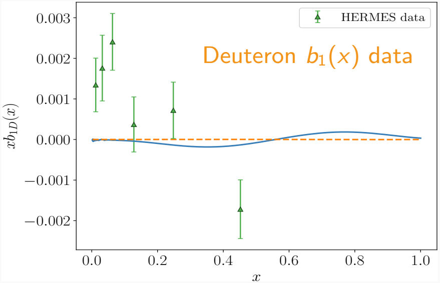
The Deuteron

- The deuteron is the simplest nucleus – naively consisting of a proton + neutron with 2.2 MeV binding
  - however deuteron is greater than sum of its parts, having many properties not found in either of its primary constituents
  - deuteron is also finally tuned — making it an interesting target to isolate QCD effects
- Unique properties of deuteron:
  - a quadrupole moment and gluon transversity PDF
  - many TMDs and GPDs associated with tensor polarization
- Additional spin-independent leading-twist PDF called $b_1^q(x)$

$$b_1(x) = e_q^2 \left[b_1^q(x) + b_1^{\bar{q}}(x) \right], \quad \int_0^1 dx \left[b_1^q(x) - b_1^{\bar{q}}(x) \right] = 0$$

- Need tensor polarized target to measure $b_1(x)$ – (HERMES)
  - impossible to explain HERMES data with only bound nucleon degrees of freedom — need exotic QCD states, 6q bags, etc.
  - Hall C has an approved proposal (J.-P. Chen, *et al.*)





TMDs of Spin-1 Targets

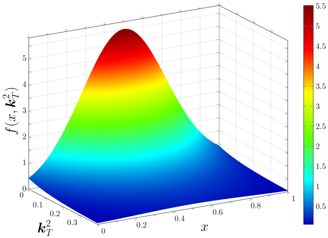
- A spin-1 target can have tensor polarization $[\lambda = 0]$
  - 3 additional T-even and 7 additional T-odd quark TMDs compared to nucleon
- Analogous situation for gluon TMDs
  - to fully expose role of quarks and gluons in nuclei need polarized nuclear targets (transverse and longitudinal) with all 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 $\Longrightarrow |\boldsymbol{S}_T| = 1, S_L = 0$
- Associated quark correlation function:

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

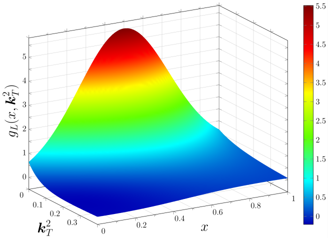
leading twist		quark operator: γ^+	$\gamma^+\gamma_5$	$\gamma^+\gamma^i\gamma_5$
target polarization	U	$f_1 =$ unpolarized		$h_1^\perp =$ − Boer-Mulders
	L		$g_1 =$ − helicity	$h_{1L}^\perp =$ − worm gear 1
	T	$f_{1T}^\perp =$ − Sivers	$g_{1T} =$ − worm gear 2	$h_1 =$ − transversity $h_{1T}^\perp =$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

Spin-1 Target TMDs – with Nucleon Analogs

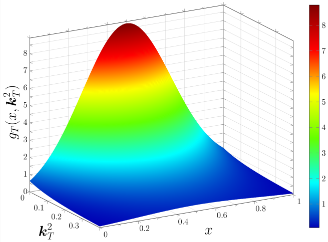
unpolarized



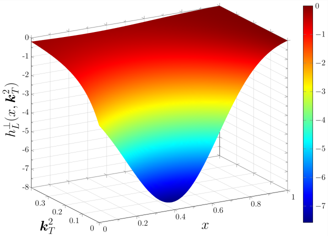
helicity



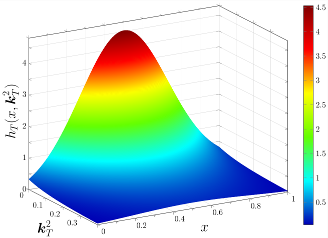
worm gear 2



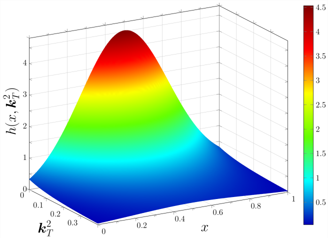
worm gear 1



pretzelosity



transversity



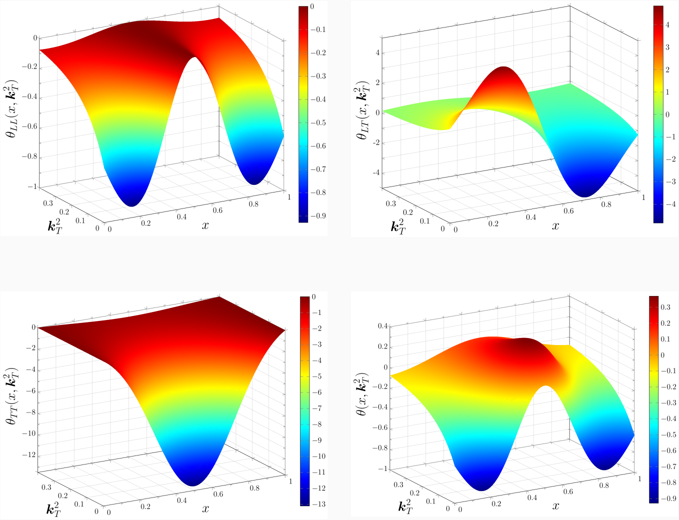
[Yu Ninomiya, ICC and Wolfgang Bentz, Phys. Rev. C **96**, no.4, 045206 (2017)]

Spin-1 Target TMDs – Tensor Polarization

- Calculations assume point-like nucleons but nevertheless show tensor polarized TMDs have some 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 — challenge for traditional lattice QCD methods

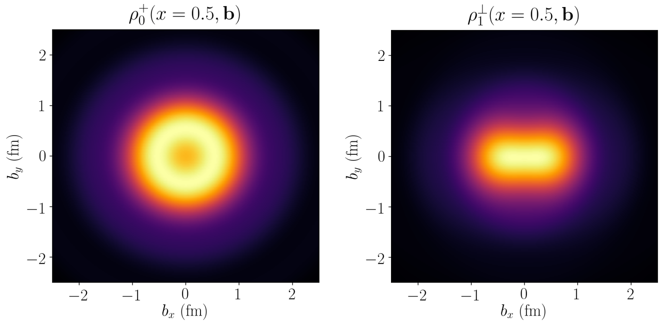


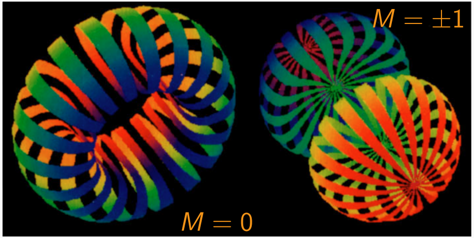
[Yu Ninomiya, ICC and Wolfgang Bentz, Phys. Rev. C **96**, no.4, 045206 (2017)]

Deuteron GPDs

- The deuteron has a rich GPD structure
- The impact parameter PDFs provide a spatial tomography for various x slices
  - tensor polarized along z-axis — clear donut shape
  - longitudinally polarized along x-axis — clear dumbbell shape
- These quantities provide an interesting connection to traditional nuclear physics results for the deuteron
  - nuclear spatial densities have donut and dumbbell shapes
- Does the gluon donut align with the quark donut – does this change with x? Incredible insight into NN interaction possible

[A. Freese, W. Bentz, and ICC, *to appear 2025*]





J. Carlson, R. Schiavalla, Rev. Mod. Phys. **70** 743 (1998)

J. L. Forrest *et al.* Phys. Rev. **C54** 646 (1996)

Conclusion and Outlook

- Tremendous opportunity for EIC to transform understanding of QCD in nuclei
  - GPDs and TMDs of light nuclei
  - medium effects on gluon structure via J/ψ production
  - Anti-shadowing region and its A dependence
  - $b_1(x)$ and gluon transversity in deuteron and ^{6}Li
- Key physics questions: How does the NN interaction arise from QCD? How do quark/gluon confinement length scales change in medium?
- Can explore these questions by imaging light 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