Theory Perspective – Mysteries of the Anti-shadowing region

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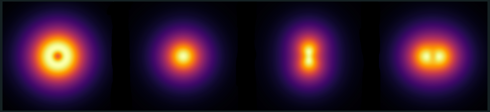

High Energy Workshop Series 2022: Science at Mid x – Anti-Shadowing and the Role of the Sea

22–23 July 2022, Jefferson Lab

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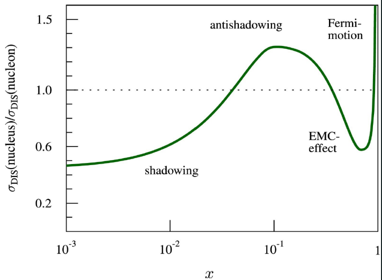
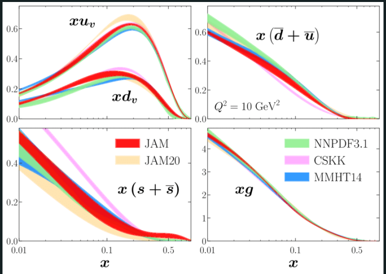
Nuclear Structure Functions

- Nuclear structure functions have four distinct features relative to the nucleon — some easy to understand and others that continue to challenge physicists 40 years after discovery
  - **Fermi motion:** standard nuclear effect caused by NN interactions
  - **Shadowing:** caused by multi-nucleon interference effects
  - **EMC Effect:** no universally accepted explanation, leading explanation is medium modification caused by mean-fields and/or SRCs
  - **Anti-Shadowing:** less studied, perhaps caused by flavor-dependent Reggeon exchange or a coherent effect from other mechanisms
- Anti-Shadowing region ($0.1 \lesssim x \lesssim 0.3$) is roughly equally dominated by valence quarks, sea-quarks, and gluons
  - precision measurements in this region on mirror nuclei, and nuclei across A, N, and Z would shed important light on partonic structure of nuclei, e.g., nuclear gluons, anti-quarks in nuclei, and spin/flavor dependent effects



[JAM Collaboration]



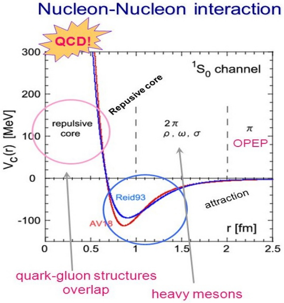
Pion Excess in Nuclei & Nuclear Sea-Quarks

- Pions are responsible for many aspects of the *NN* interaction
- Natural to expect pions important EMC effect [Ericson & Thomas (83); Llewellyn Smith (83)]
- Pions are light, should dominantly contribute to anti-shadowing region $x_\pi \simeq m_\pi / M_N \simeq 0.15$
  - nuclear pions shift momentum to small x
- Models introduce pion momentum distribution

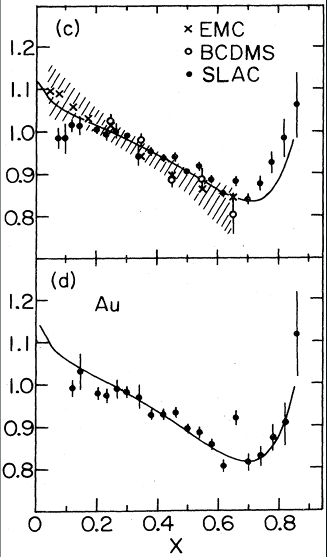
$$\int dz\, z \left[f_{N/A}(z) + f_{\pi/A}(z)\right] = 1$$

momentum sum rule

  - to satisfy sum rule pions must introduce coherent effect across all x
- A small number of pions can explain EMC effect: $\int dz\, f_{\pi/A}(z) = n_\pi$
  - for gold $n_\pi = 0.114$ which shifts 6% of momentum from nucleons to pions
  - adding shadowing effects could explain DIS data
- *Pion excess introduces sizeable enhancement in nuclear sea-quark PDFs*



[Berger and Coester, PRD **32**, 1071 (1985)]



Nuclear Sea-Quarks and Drell-Yan

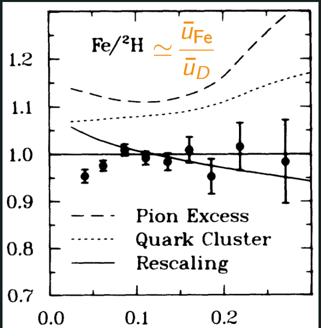
- A few authors suggested proton-induced Drell-Yan on nuclear targets to study nuclear sea-quark PDFs

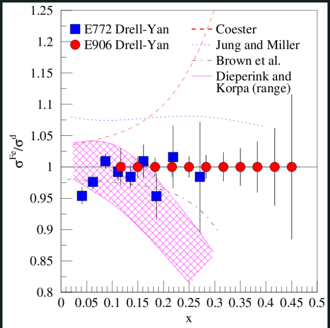
  Ericson & Thomas, PLB **148**, 191 (1984)

  Bickerstaff, Birse & Miller, PRL **53**, 2532 (1984)

- In 1990 Fermilab E772 experiment found no anti-quark enhancement in nuclei across ^{2}H, C, Ca, Fe, and W
  - Fermilab E906/SeaQuest experiment has taken updated data on nuclear targets

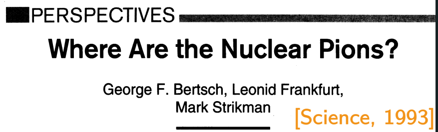
[Alde *et al.*, PRL. **64**, 2479 (1990)]





- This experiment, and others, killed the "pion excess" explanation of the EMC effect:

  "Unexpected results in a number of experiments . . . are chipping away one of the cornerstones of nuclear physics, namely the pi meson as a dominant carrier of the nuclear force."


PERSPECTIVES

Where Are the Nuclear Pions?

George F. Bertsch, Leonid Frankfurt, Mark Strikman

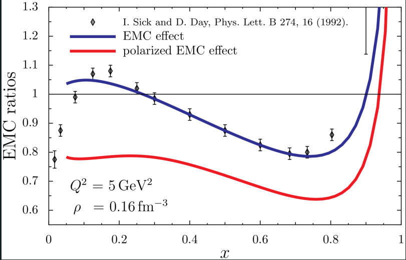
[Science, 1993]

- *Is there still a puzzle with nuclear anti-quarks?* [Also charged pion electroproduction ^{1,2}H, ^{3}He (Gaskell PRL 2001)]

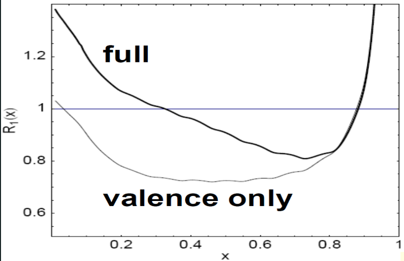
Mean-Field Calculations of Polarized Nuclear PDFs

- Several relativistic mean-field calculations of polarized Nuclear PDFs
  - all calculations find polarized EMC same size or larger than EMC effect
  - effects are as large or larger in anti-shadowing region
- Large effects in polarized nuclear PDFs results because in-medium quarks are more relativistic ($M^* < M$)
  - in-medium we find that quark spin is converted to orbital angular momentum

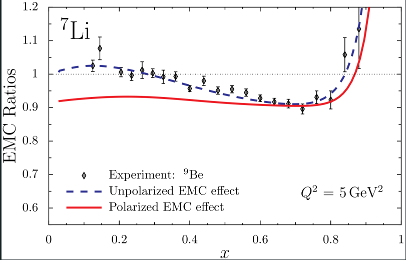
[ICC, W. Bentz and A. W. Thomas, PRL **95**, 052302 (2005)]



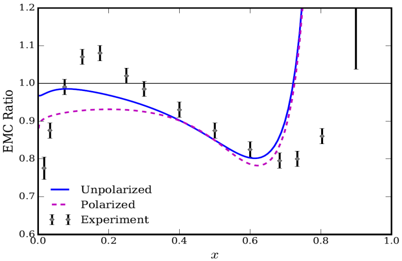
[J. R. Smith and G. A. Miller, Phys. Rev. C **72**, 022203(R) (2005)]



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



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

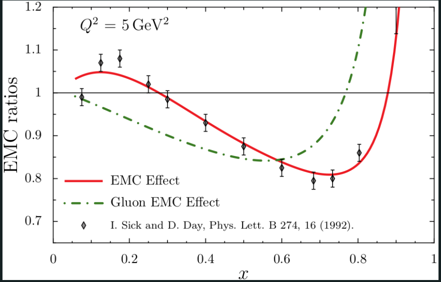


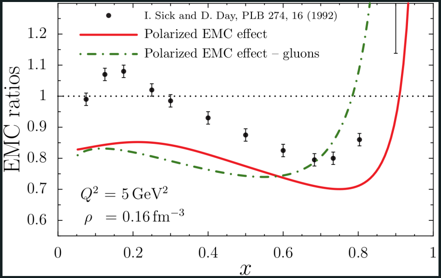
Gluon and Spin Nuclear PDFs

- 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 opposite 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 EIC measurements





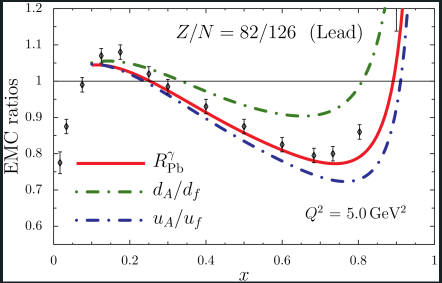
Flavor Dependence Nuclear PDFs

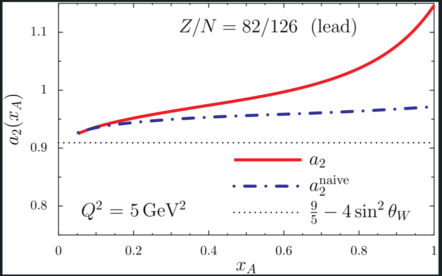
- In mean-field model with isovector forces find a flavor dependence to the EMC effect
  - for $N > Z$ nuclei, d-quarks feel more repulsion than u-quarks and therefore u quarks are more bound than d quarks
  - can explain large fraction of NuTeV anomaly
- Parity-violating DIS is particularly sensitive to isovector effects

$$a_2(x) = -2g_A^e \frac{F_2^{\gamma Z}}{F_2^{\gamma}} \overset{N\sim Z}{=} \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+(x) - d_A^+(x)}{u_A^+(x) + d_A^+(x)}$$

  - momentum is shifted from u to d quarks, however, flavor dependence effect largest in EMC region
- Isovector EMC effect recently observed in analysis of MARATHON data
  - has same sign as mean-field predictions
- Find that flavor dependence is small in anti-shadowing region
  - potentially provides opportunity to isolate Reggeon physics

[ICC, Bentz and Thomas, PRL **109**, 182301 (2012)]





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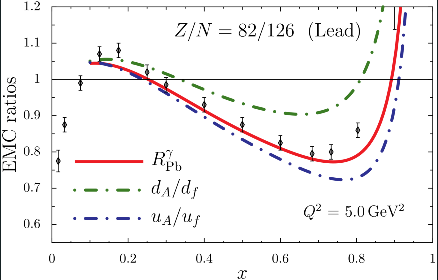
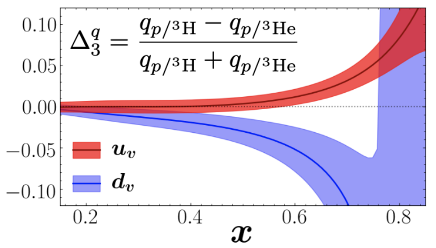


[Cocuzza *et al.*, PRL **127**, 242001 (2021)]

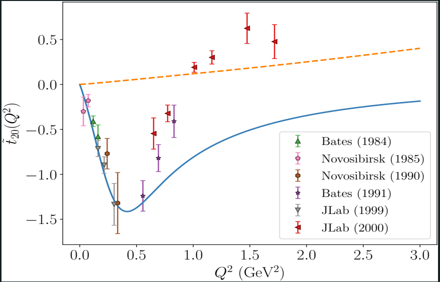


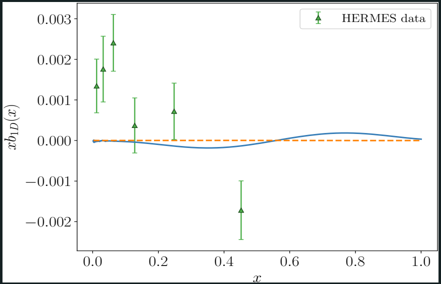
The Deuteron

- The deuteron is the simplest nucleus – consisting primarily of a proton + neutron with 2.2 MeV binding
  - however the deuteron is greater than the sum of its parts, having many properties not found in either of its primary constituents
  - the 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.



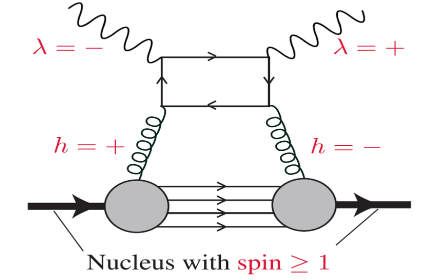


Gluon Transversity PDF

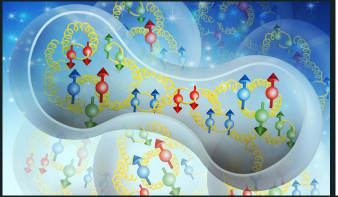
- Transversity PDFs are associated with double-helicity flip:

$$g_T(x) \;\propto\; \mathcal{A}_{+-,-+} + \mathcal{A}_{-+,+-}$$

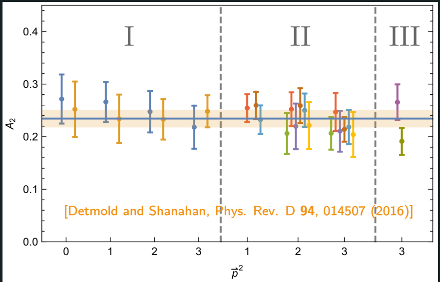
  - helicity conservation forbids this helicity amplitude for a gluon in a nucleon — no gluon transversity PDF in nucleon
  - need $J \geq 1$, so targets such as deuteron, ^{6}Li, …(ω, ρ, Δ, etc.)
  - Jaffe & Manohar, *"Nuclear Gluonometry"*, PLB **223**, 218 (1989)
  - LoI at JLab: J. Maxwell, *et al.* [arXiv:1803.11206 [nucl-ex]]



- Observation of a gluon transversity distribution in deuteron would be first direct evidence for non-nucleonic components in nuclei
  - exotic glue, $\Delta\Delta$ component, etc.

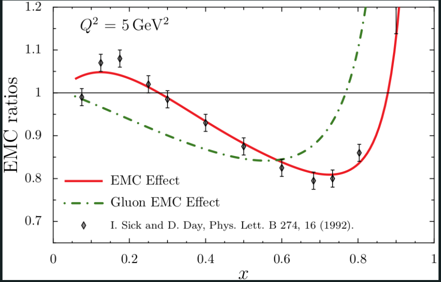


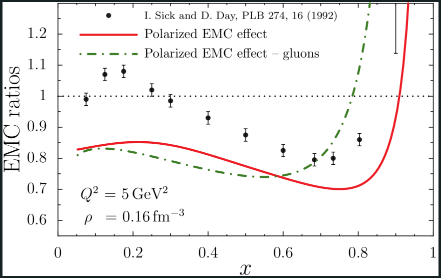
- Lattice calculations find significant gluon transversity in ϕ meson



Conclusion and Outlook

- There is still much to learn about the origin of the EMC effect and the connection to the anti-shadowing region
  - nuclear anti-quark PDFs and the connection to the expected pion excess in nuclei is still a mystery
  - anti-quark and gluon PDFs, together with their spin and flavor dependence, of great interest in the anti-shadowing region
- Key physics questions: How does the *NN* interaction arise from QCD? How do quark/gluon confinement length scales change in medium?
- Deuteron provide pathway to address some of these questions
  - additional spin-independent leading-twist PDF, $b_1^q(x)$, associated with tensor polarization – cannot explain current HERMES data with just nucleon dof
  - deuteron also has gluon transversity distribution, which is not possible in the nucleon





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