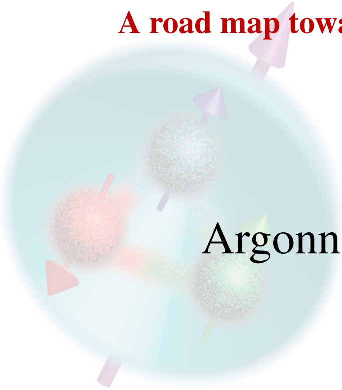
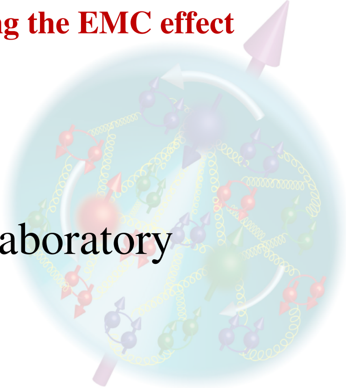
Nuclear Structure Functions

A road map toward understanding the EMC effect





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Nucleon Structure at Large Bjorken-x – HiX2014

Laboratori Nazionali di Frascati

November 17-21, 2014

U.S. DEPARTMENT OF ENERGY | Office of Science

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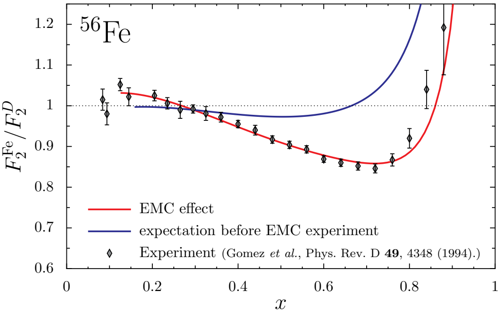
Why Nuclear Targets?

- Understanding nuclei within QCD remains one of the most important challenges in fundamental science; *not sufficient to study hadrons alone*
- Nuclei give access to numerous novel aspects of QCD:
  - neutron target, targets with $J \geqslant 1$, colour transparency, hidden colour, etc
- Unambiguous evidence for quark & gluon effects in nuclei remains elusive
  - important candidates are the EMC effect & recently proton knockout reactions
- Success of *standard nuclear theory* must be related to confinement in QCD
- Measurement of *EMC effect* destroyed particle-physics paradigm regarding QCD & nuclear structure
  - a broad consensus regarding an explanation is still lacking
  - *valence quarks in a nucleus carry less momentum than in a nucleon*



Progress using Lattice QCD

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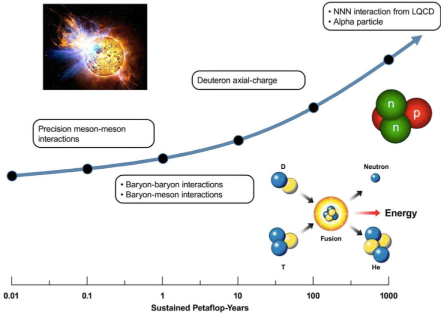
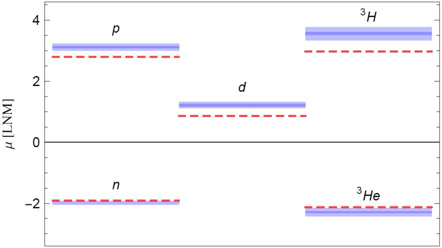
[S. R. Beane, *et al.*, Prog. Part. Nucl. Phys. **66**, 1-40 (2011)]



[S. R. Beane, *et al.* (NPLQCD), arXiv:1409.3556 [hep-lat]]



$[m_\pi \simeq 800\,\text{MeV}]$

- Lattice QCD is beginning to make progress in the study of very light nuclei
- However calculations require huge computational resources and it will likely take 10-20 years before light nuclei studies match those of the nucleon today
- Lattice QCD will not calculate an EMC effect for the foreseeable future
  - not clear if lattice will explain why there is an EMC effect

Nuclear Structure Functions

- A novel aspect of DIS on nuclei is that they are the only targets with $J > \frac{1}{2}$
  - numerous extra structure functions are possible
  - in the *Bjorken limit* there are $2J+1$ *DIS structure functions*, assuming *Callen-Gross-like* relations ($F_2 = 2x\,F_1$) [e.g. deuteron b_1 structure function]
- For target with helicity H *hadronic tensor*, in Bjorken limit, takes the form

$$W^H_{\mu\nu}(p',p) = \left(g_{\mu\nu}\frac{p\cdot q}{q^2} + \frac{p_\mu p_\nu}{p\cdot q}\right) F_2^H(x,Q^2) + \frac{i\varepsilon_{\mu\nu\lambda\sigma}q^\lambda p^\sigma}{p\cdot q}\, g_1^H(x,Q^2)$$

  - parity invariance implies: $F_2^H = F_2^{-H}$ & $g_1^H = -g_1^{-H}$
  - measurement of F_2^H requires a polarized target; g_1^H also needs a polarized beam
  - the familiar F_2 structure function is obtained by averaging F_2^H over helicities
  - the deuteron b_1 structure function e.g., is given by: $2\,b_1(x) = F_1^0(x) - F_1^1(x)$
- Nuclear parton distributions are defined in the usual manner and e.g.

$$F_2^H(x) = x\sum_q e_q^2\left[q^H(x) + \bar{q}^H(x)\right] \qquad g_1^H(x) = \frac{1}{2}\sum_q e_q^2\left[\Delta q^H(x) + \Delta\bar{q}^H(x)\right]$$

Nuclear Multipole Quark Distributions

- Useful to consider multipole structure functions/quark distributions, e.g.

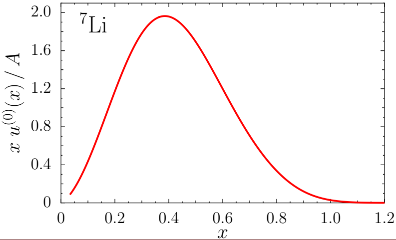
$$q^{(K)}(x) \equiv \sum_H (-1)^{J-H} \sqrt{2K+1} \begin{pmatrix} J & J & K \\ H & -H & 0 \end{pmatrix} q^H(x), \quad K = 0, 2, \ldots, 2J$$

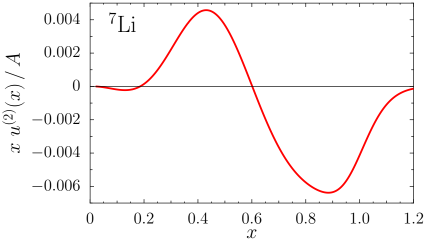
  - better (irreducible) transformation properties under rotations
  - e.g. $J = 1: \; b_1 = -\sqrt{\frac{3}{2}} F_1^{(2)}; \quad J = \frac{3}{2}: \; q^{(0)} = q^{\frac{3}{2}} + q^{\frac{1}{2}}, \quad q^{(2)} = q^{\frac{3}{2}} - q^{\frac{1}{2}}$
  - higher multipoles encapsulate differences between helicity distributions

- Sum rules [Jaffe and Manohar, Nucl. Phys. B **321**, 343 (1989)]

$$\int dx x^{n-1} q^{(K)}(x) = 0 \quad K, n \text{ even} \quad 2 \leqslant n < K \qquad \int dx\, x^{n-1} \Delta q^{(K)}(x) = 0 \quad K, n \text{ odd} \quad 1 \leqslant n < K$$

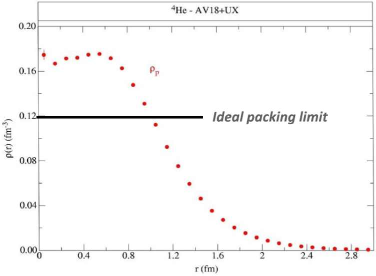
- Large $K > 1$ multipole PDFs would be very surprising, may imply: non-nucleon components; large off-shell effects; etc





Nuclei and the EMC effect

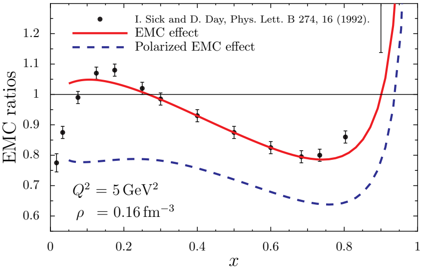
- Nuclei are extremely dense – 10^{14} times denser that ordinary matter
  - proton rms radius is $r_p \simeq 0.85$ fm, corresponds to hard sphere $r_p \simeq 1.15$ fm
  - ideal packing gives $\rho = 0.12\,\text{fm}^{-3}$; nuclear matter density is $\rho \simeq 0.16\,\text{fm}^{-3}$
  - bound nucleon wave functions often overlapping

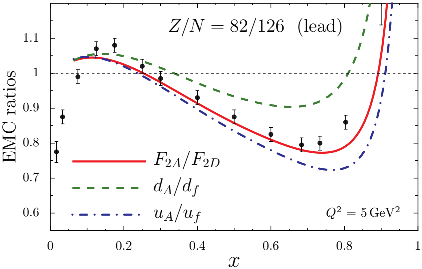


- Important question: *How do the internal structural properties of protons and neutrons change when they form complex nuclei and what is the cause?*
- In modern *ab inito* approaches to nuclear structure – e.g. VMC, GFMC, no-core shell model – nucleon properties are unchanged in nuclei
- In quark level approaches *self-consistent coupling to nuclear mean-fields* naturally results in *medium modification of all nucleons in a nucleus*
- Medium modification has also been attributed to SRCs; with $\sim 20\,\%$ of nucleons involved, amount of modification must be much greater
- *Only quark level approaches have provided robust explanation EMC effect*

Understanding the EMC effect

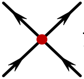
- *The puzzle posed by the EMC effect will only be solved by conducting new experiments that expose novel aspects of the EMC effect*
- Measurements must help distinguish between explanations of EMC effect; e.g. whether *all nucleons* are modified by the medium or only those in SRCs
- Important examples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





Continuum QCD

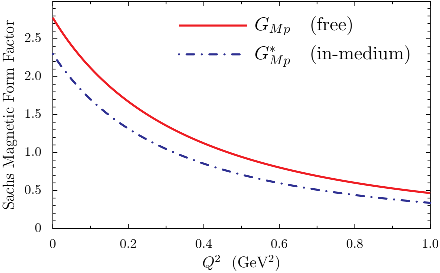
"*integrate out gluons*" →



$\frac{1}{m_G^2}\,\Theta(\Lambda^2 - k^2)$

- this is just a modern interpretation of the Nambu–Jona-Lasinio (NJL) model
- model is a Lagrangian based covariant QFT, exhibits dynamical chiral symmetry breaking & quark confinement; elements can be QCD motivated via the DSEs

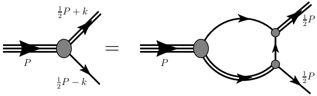
- For nuclei, we find that quarks bind together into color singlet nucleons
  - however contrary to traditional nuclear physics approaches these quarks feel the presence of the nuclear environment
  - *as a consequence bound nucleons are modified by the nuclear medium*

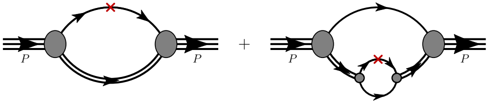


- Modification of the bound nucleon wave function by the nuclear medium is a *natural consequence* of quark level approaches to nuclear structure

Nucleon quark distributions

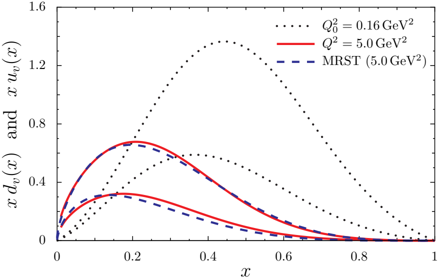
- Nucleon = quark+diquark
- PDFs given by Feynman diagrams: $\langle\gamma^+\rangle$

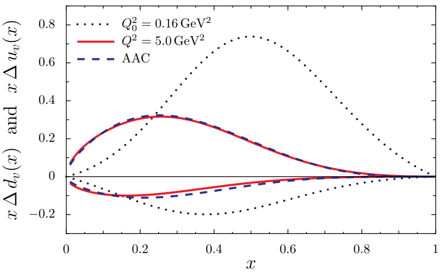




- Covariant, correct support; satisfies sum rules, Soffer bound & positivity

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

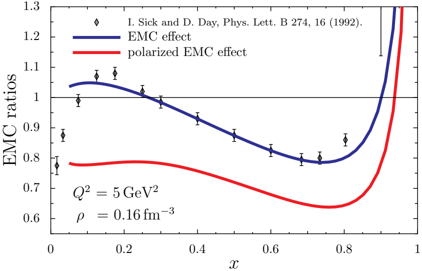




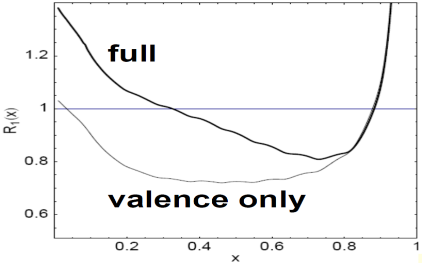
[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **621**, 246 (2005)]

EMC and Polarized EMC effects

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



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



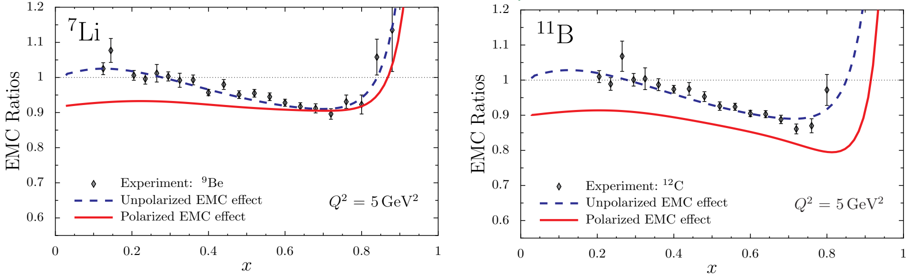
- Definition of polarized EMC effect:
  - ratio equals 1 if no medium effects

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

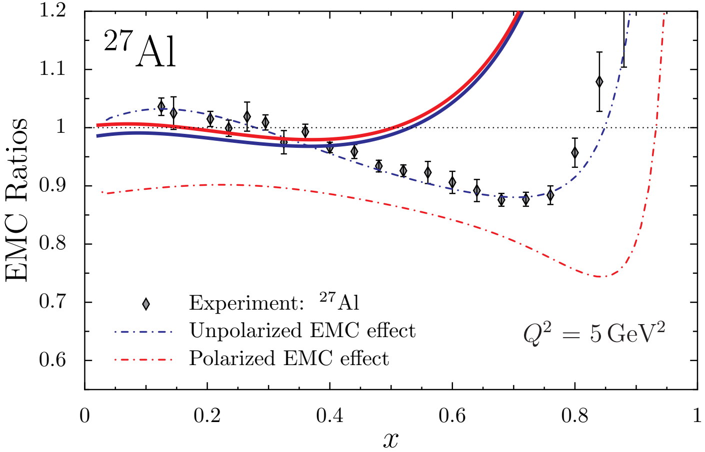
- Large polarized EMC effect results because in-medium quarks are more relativistic ($M^* < M$)
  - lower components of quark wave functions are enhanced and these usually have larger orbital angular momentum
  - *in-medium we find that quark spin is converted to orbital angular momentum*
- A large polarized EMC effect would be difficult to accommodate within standard nuclear theory and (as we shall see) from SRCs

EMC effects in Finite Nuclei

[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **642**, 210 (2006)]



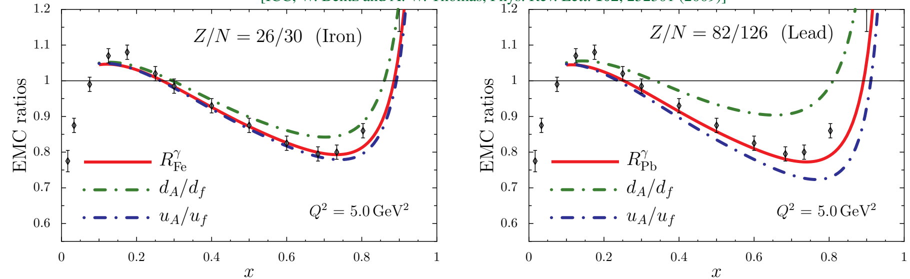
- Spin-dependent cross-section is suppressed by $1/A$
  - should choose light nucleus with spin carried by proton e.g. $\Longrightarrow$ ^{7}Li, ^{11}B, ...
- Effect in ^{7}Li is slightly suppressed because it is a light nucleus and proton does not carry all the spin (simple WF: $P_p = 13/15$ & $P_n = 2/15$)
- Experiment just approved at JLab (E12-14-001) to measure spin structure functions of ^{7}Li (GFMC: $P_p = 0.86$ & $P_n = 0.04$)
- *Everyone with their favourite explanation for the EMC effect should make a prediction for the polarized EMC effect in ^{7}Li*



- Without medium modification both EMC & polarized EMC effects disappear
- Polarized EMC effect is smaller than the EMC effect; this is natural within standard nuclear theory and also from SRC perspective
- Large splitting very difficult without *mean-field* medium modification

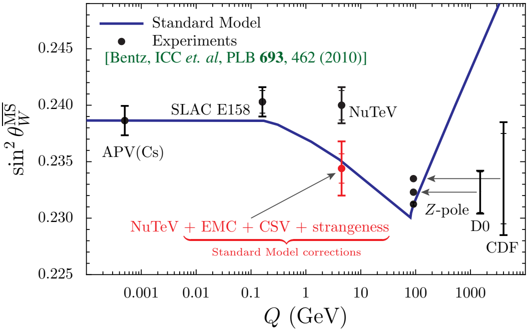
Flavour dependence of EMC effect

[ICC, W. Bentz and A. W. Thomas, Phys. Rev. Lett. **102**, 252301 (2009)]



- Find that EMC effect is basically a result of binding at the quark level
  - for $N > Z$ nuclei, d-quarks feel more repulsion than u-quarks: $V_d > V_u$
  - therefore u quarks are more bound than d quarks
- Find isovector mean-fields shift momentum *from* u-quarks *to* d-quarks
- For $N > Z$ nuclei protons more likely to be involved in SRCs
  - in this picture expect u-quarks to be more modified than d-quarks
- However, since SRCs give protons a larger momentum than neutrons for $N > Z$ nuclei, may expect momentum shifted *from* d-quarks *to* u-quarks
- Hints will be given by approved JLab DIS experiment on ^{40}Ca and ^{48}Ca

The NuTeV anomaly



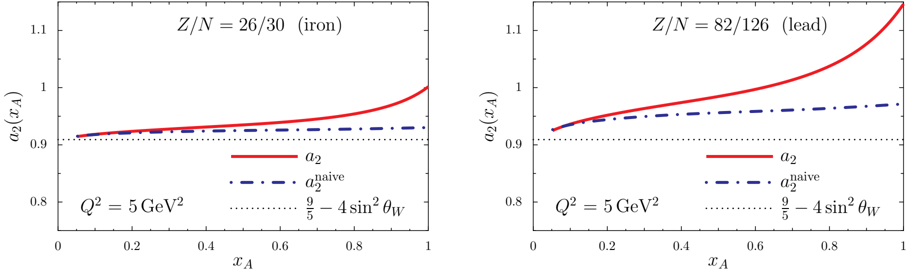
- Paschos-Wolfenstein ratio motivated NuTeV study:

$$R_{PW} = \frac{\sigma_{NC}^{\nu A} - \sigma_{NC}^{\bar\nu A}}{\sigma_{CC}^{\nu A} - \sigma_{CC}^{\bar\nu A}} \overset{N \sim Z}{=} \frac{1}{2} - \sin^2\theta_W + \left(1 - \frac{7}{3}\sin^2\theta_W\right)\frac{\langle x\, u_A^- - x\, d_A^-\rangle}{\langle x\, u_A^- + x\, d_A^-\rangle}$$

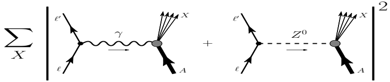
- NuTeV: $\sin^2\theta_W = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$ [Zeller *et al.* PRL. **88**, 091802 (2002)]
- Standard Model: $\sin^2\theta_W = 0.2227 \pm 0.0004$ $\Leftrightarrow 3\sigma \Longrightarrow$ "NuTeV anomaly"
- At the time widely thought as evidence for physics beyond Stardard Model
- Corrections from the EMC effect ($\sim 1.5\,\sigma$) and charge symmetry violation ($\sim 1.5\,\sigma$) brings NuTeV result into agreement with the Standard Model
  - consistent with mean-field expectation – momentum shifted *from u to d*-quarks

Parity-Violating DIS

[ICC, W. Bentz and A. W. Thomas, Phys. Rev. Lett. **109**, 182301 (2012)]



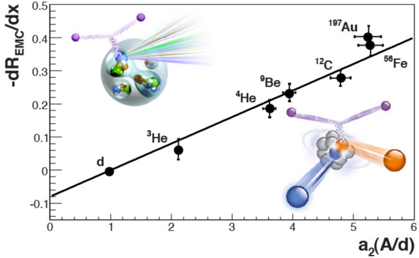
- PV DIS – $\gamma\, Z$ interference:



$$A_{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} \propto a_2(x) = -\,2 g_A^e \frac{F_2^{\gamma Z}}{F_2^{\gamma}} \stackrel{N\simeq Z}{=} \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\,\frac{u_A^+(x) - d_A^+(x)}{u_A^+(x) + d_A^+(x)}$$

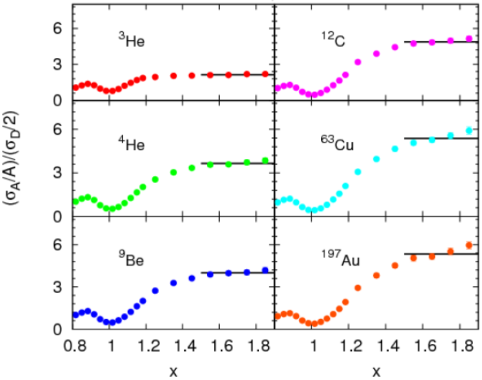
- Deviation from naive expectation: momentum shifted *from* u *to* d*-quarks*
- $F_2^{\gamma Z}(x)$ has markedly different flavour dependence compared with $F_2^{\gamma}(x)$
  - a measurement of both enables an extraction of $u(x)$ and $d(x)$ separately
- Proposal to measure a_2 of ^{48}Ca was deferred – will likely be approved soon

Short-Range Correlations



- Plateaus associated with nucleons with $p \gtrsim 270\,\text{MeV}$:
  $\Longrightarrow$ short-range correlations

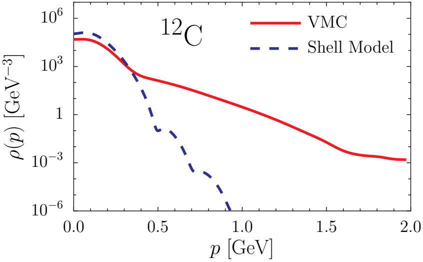
[N. Fomin *et al.*, Phys. Rev. Lett. **108** 092052 (2012)]

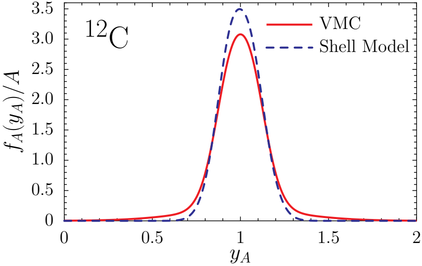


- *Empirical correlation between slope of EMC effect and quasi-elastic scattering plateaus has resulted in a renaissance of the EMC effect*
- Many convinced SRC $\Longrightarrow$ EMC effect: [Klaus Rith arXiv:1402.5000 [hep-ex]]

  "It is rather unlikely that this correlation is purely accidental and one can therefore rather safely assume that a large fraction of the strength of the EMC effect in the valence quark region is due to short-range nucleon-nucleon correlations"

Nuclear Wave Functions

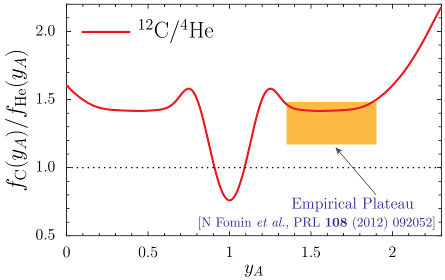


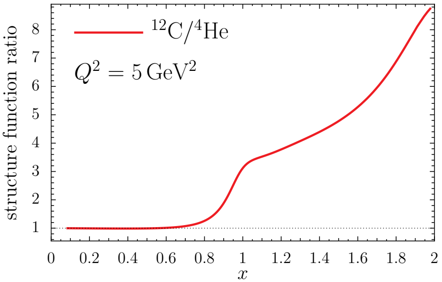


- Modern GFMC or VMC nuclear WFs have large high momentum tails
  - indicates wave function has large SRC component; ~20% for ^{12}C
- Light cone momentum distribution of nucleons in nucleus is given by

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

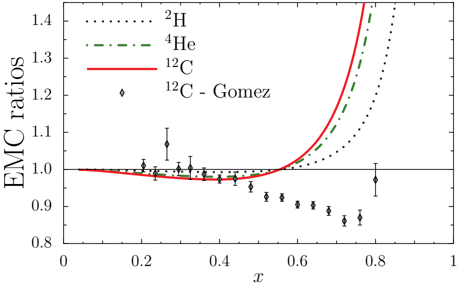
	^{2}H	^{3}H	^{3}He	^{4}He	^{7}Li	^{9}Be	^{11}B	^{12}C
proton (%)	4.3	5.8	9.0	12.9	12.2	13.5	15.6	19.5
neutron (%)	4.3	9.2	5.7	12.9	10.3	11.8	14.6	19.5

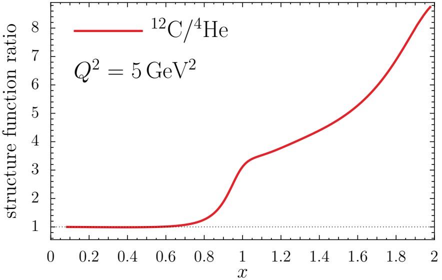




- Ratio of variational Monte Carlo (VMC) light cone wave function exhibits distinct plateau which agrees with experiment
- Using VMC light cone wave functions and convolution model with empirical nucleon PDFs to obtain nuclear structure functions and hence EMC effect
  - plateau still prominent in DIS regime
  - nucleon SRCs alone from VMC wave functions cannot explain EMC effect
- Demonstrates that SRC plateau need not be related to the EMC effect
  - correlation may just be accidental

SRCs and Medium Modification

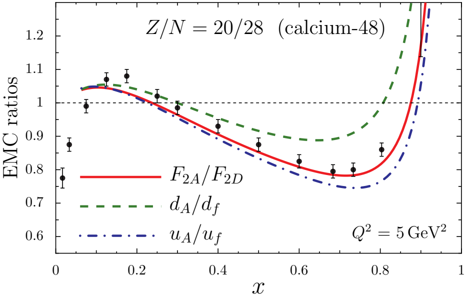




- Explanations of EMC effect using SRCs also invoke medium modification
  - since about 20% of nucleons are involved in SRCs, need medium modifications about 5 times larger than in mean-field models
- For polarized EMC effect only 2–3% of nucleons are involved in SRCs
  - it would therefore be natural for SRCs to produce a smaller polarized EMC effect
- Observation of a large polarized EMC effect would imply that SRCs are less likely to be the mechanism responsible for the EMC effect

Conclusion

- Understanding the EMC effect is a critical step towards a QCD based description of nuclei
- Data on flavour & spin dependence of the EMC effect is critical
  - will help differentiate between various explanations

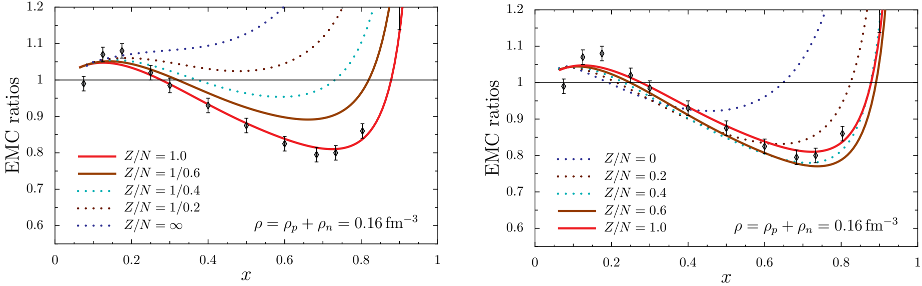


- Approved JLab experiments will measure the polarized EMC effect in ^{7}Li & DIS on ^{40}Ca and ^{48}Ca is sensitive to flavour dependence; PVDIS important!
- *Everyone with their favourite model for the EMC effect should make predictions for the polarized and flavour dependent EMC effects*
- NuTeV anomaly can be explained by an isovector EMC effect and CSV
- Using state-of-the-art nuclear wave functions demonstrated that SRCs can give plateau but do not necessarily lead to an explanation for the EMC effect
- QCD town meeting: "... *must solve problem posed by the EMC effect ...*"

Backup Slides

Isovector EMC effect

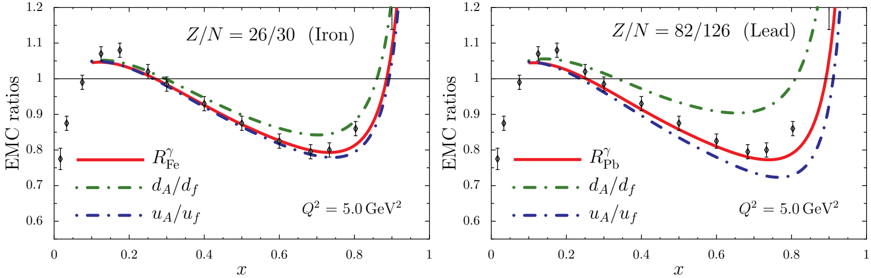
[ICC, W. Bentz and A. W. Thomas, Phys. Rev. Lett. **102**, 252301 (2009)]



- EMC ratio: $R = \frac{F_{2A}}{F_{2A,\text{naive}}} = \frac{F_{2A}}{Z\,F_{2p} + N\,F_{2n}} \simeq \frac{4\,u_A(x) + d_A(x)}{4\,u_f(x) + d_f(x)}$
- Density is fixed only changing Z/N ratio [therefore only ρ_0 is changing]
- EMC effect essentially a consequence of binding at the quark level
- proton excess: u-quarks feel more repulsion than d-quarks ($V_u > V_d$)
- neutron excess: d-quarks feel more repulsion than u-quarks ($V_d > V_u$)

Flavour dependence of (Isovector) EMC effect

[ICC, W. Bentz and A. W. Thomas, Phys. Rev. Lett. **109**, 182301 (2012)]



- Flavour dependence: $F_2^{\gamma} = \sum e_q^2\, x\, q^+(x), \quad F_2^{\gamma Z} = 2 \sum e_q\, g_V^q\, x\, q^+(x)$
- $N > Z \implies$ d-quarks feel more repulsion than u-quarks: $V_d > V_u$
  - u quarks are more bound than d quarks
  - ρ^0 field has shifted momentum from u to d quarks

$$q(x) = \frac{p^+}{p^+ - V^+}\, q_0 \left(\frac{p^+}{p^+ - V^+}\, x - \frac{V_q^+}{p^+ - V^+} \right)$$

- If observed would imply strong evidence for medium modification

New Sum Rules

- Sum rules for multipole quark distributions:
  - Jaffe & Manohar, *DIS from arbitrary spin targets*, Nucl. Phys. B **321**, 343 (1989).

$$\int dx\, x^{n-1}\; q^{(K)}(x) = 0, \quad K, n \text{ even}, \quad 2 \leqslant n < K,$$

$$\int dx\, x^{n-1}\, \Delta q^{(K)}(x) = 0, \quad K, n \text{ odd}, \quad 1 \leqslant n < K.$$

- Examples:

$$J = \tfrac{3}{2} \implies \left\langle \Delta q^{(3)}(x) \right\rangle = 0$$

$$J = 2 \implies \left\langle q^{(4)}(x) \right\rangle = \left\langle \Delta q^{(3)}(x) \right\rangle = 0$$

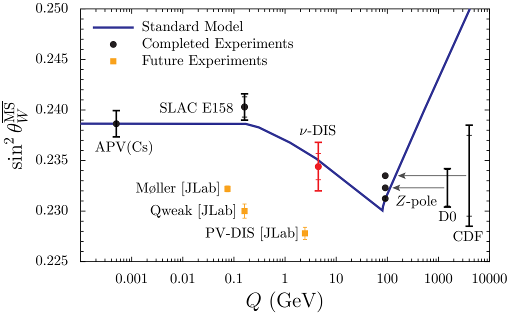
$$J = \tfrac{5}{2} \implies \left\langle q^{(4)}(x) \right\rangle = \left\langle \Delta q^{(3)}(x) \right\rangle = \left\langle \Delta q^{(5)}(x) \right\rangle = \left\langle x^2\, \Delta q^{(5)}(x) \right\rangle = 0$$

- Sum rules place tight constraints on multipole PDFs

A Reassessment of the NuTeV anomaly

- Also include corrections:
  - charge symmetry violation:

    $m_u \neq m_d \quad \& \quad e_u \neq e_d$
  - strange quarks
- Use NuTeV functionals
- "NuTeV anomaly" is evidence for medium modification



[Bentz, ICC, Londergan & Thomas, Phys. Lett. B **693**, 462 (2010)]

- Model dependence?
  - sign of correction is fixed by nature of vector fields

    $$q(x) = \frac{p^+}{p^+ - V^+}\, q_0 \left(\frac{p^+}{p^+ - V^+}\, x - \frac{V_q^+}{p^+ - V^+} \right), \qquad N > Z \implies V_d > V_u$$
  - ρ^0-field shifts momentum from u to d quarks
  - R_{PW} correction term negative $\implies$ $\sin^2\theta_W$ decreases
  - size of correction is constrained by nuclear matter symmetry energy
- ρ_0 vector field reduces NuTeV anomaly – model independent!

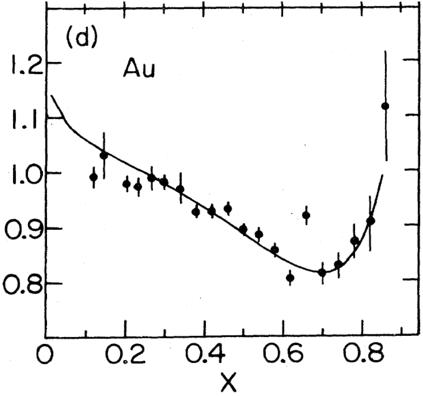
Sea-Quarks & Pion Excess in Nuclei

- Pions are responsible for (*inter alia*) the long range part of NN interaction
- Natural to expect pions are important for the EMC effect

  [Ericson & Thomas (1983); Llewellyn Smith (1983); Berger, Coester & Wiringa (1984)]
- Pions are light – $m_\pi/M_A \ll M_N/M_A$ – so shift momentum to small x
  - introduce light cone distribution for pions:

    $$f_\pi(y_A); \quad \int dy_A\, f_\pi(y_A) = n_\pi$$

[E. L. Berger & F. Coester, Phys. Rev. D **32**, 1071 (1985)]



- To explain EMC effect in Gold, for example, need: $n_\pi = 0.114$

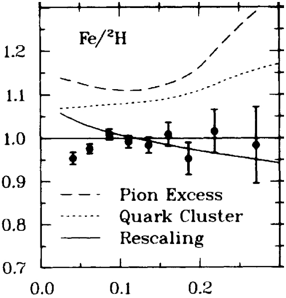
  $\Longrightarrow \langle y_A \rangle = 0.061$ per-nucleon
- *A consequence of pion excess is a sizeable enhancement in the sea-quark distributions in nuclei*

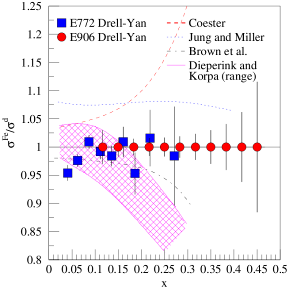
Nuclear Sea-Quarks and Drell-Yan

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

- Proton induced Drell-Yan used to access nuclear anti-quark PDFs

$\sim \dfrac{\bar{u}_{\mathrm{Fe}}}{\bar{u}_D}$





- Proposed in:

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

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

- Experiment 772 at Fermilab found no anti-quark enhancement compared to the free nucleon

PERSPECTIVES

Where Are the Nuclear Pions?

George F. Bertsch, Leonid Frankfurt, Mark Strikman

[Science, 1993]

- *"Made a persuasive case that virtual pions with momenta greater than about 400 MeV/c are not very important in a nucleus"*

- New Fermilab Drell-Yan experiment 906 currently running