The EMC effect: Past, Present and Future

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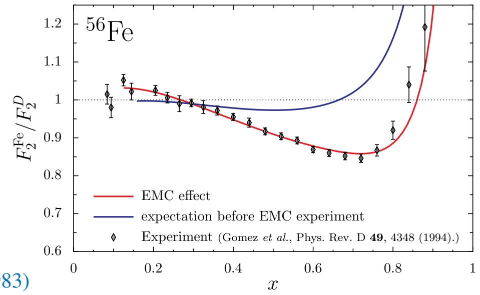
EMC effect

- In the early 80s physicists at CERN thought that nucleon structure studies using DIS could be enhanced (by a factor A) using nuclear targets
- The European Muon Collaboration (EMC) conducted DIS experiments on an iron target
  - J. J. Aubert *et al.*, Phys. Lett. B **123**, 275 (1983)

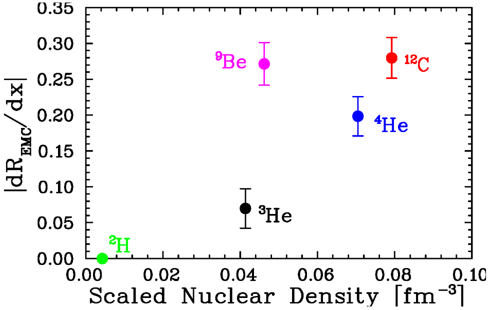


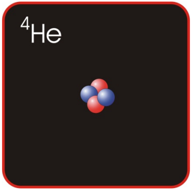
"The results are in complete disagreement with the calculations ... We are not aware of any published detailed prediction presently available which can explain behavior of these data."

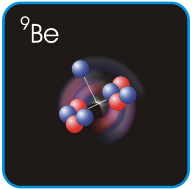
- Measurement of the *EMC effect* destroyed a particle-physics paradigm regarding QCD and nuclear structure
  - more than 30 years after discovery a broad consensus on explanation is lacking
  - what is certain: *valence quarks in nucleus carry less momentum than in a nucleon*
- One of the most important nuclear structure discoveries since advent of QCD
  - understanding its origin is critical for a QCD based description of nuclei

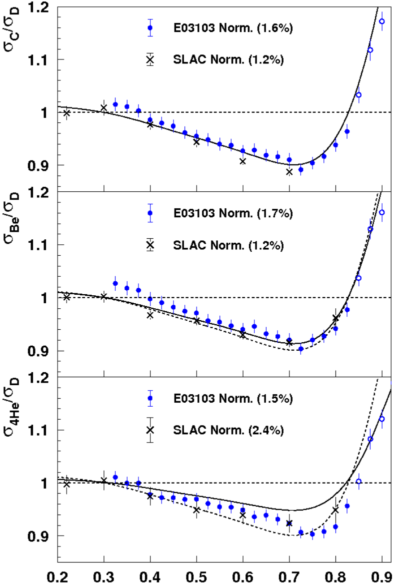
Recent data for EMC effect in light nuclei

- Size of EMC effect determined by the *local density* not the average density or A: $R_{\mathrm{He}} \simeq R_{\mathrm{Be}} \simeq R_{\mathrm{C}}$





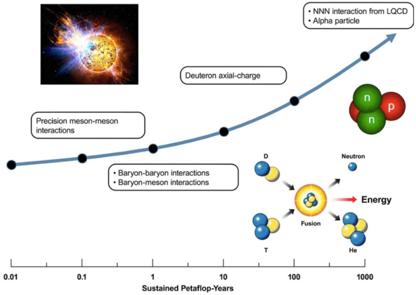




[J. Seely *et al.*, Phys. Rev. Lett. **103**, 202301 (2009).]

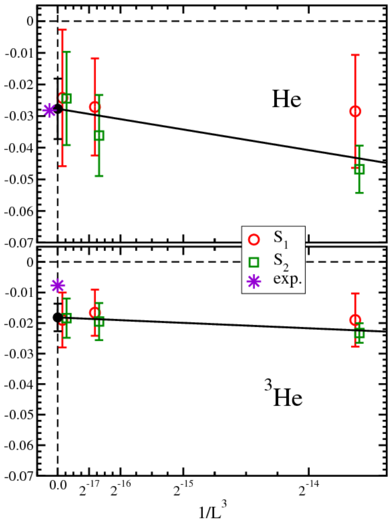
Lattice QCD and nuclear physics

- Lattice QCD is beginning to make inroads into nuclear physics
- Calculations require huge computational resources
- Lattice QCD will not calculate an EMC effect in foreseeable future
  - importantly lattice will NOT explain why there is an EMC effect



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

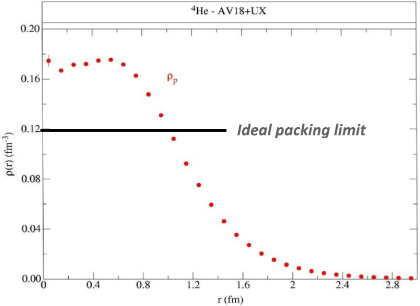
[PACS-CS Collaboration, Phys. Rev. **D81**, 111504 (2010).]

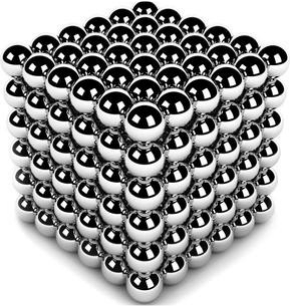


- Quenched with $m_\pi \sim 0.8\,\text{GeV}$

What do we know about nuclei?

- Nuclei are complex, strongly-interacting many-body systems
  - effective description in terms of bound nucleons and mesons works well
  - typical velocities for nucleons in nuclei are $\sim$30% speed of light
- Nuclei are extremely dense, 10^{14} times denser that ordinary matter
  - proton rms radius is $r_p \simeq 0.85\,\text{fm}$, corresponds to hard sphere with $r_p \simeq 1.15\,\text{fm}$
  - ideal packing gives $\rho = 0.12\,\text{fm}^{-3}$, nuclear matter has density $\rho \simeq 0.16\,\text{fm}^{-3}$
  - bound nucleon wave functions must be overlapping





Theoretical approaches to EMC effect

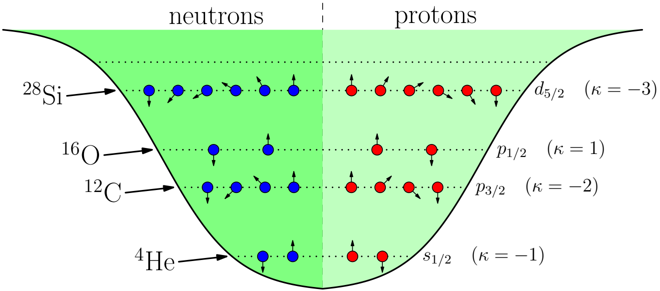
- In general must determine nuclear quark distributions:

$$q_A\,(x_A) = \frac{P^+}{A}\int \frac{d\xi^-}{2\pi} e^{iP^+\,x_A\,\xi^-/A}\langle A,P|\overline{\psi}_q(0)\,\gamma^+\,\psi_q(\xi^-)|A,P\rangle$$

- Approximate using convolution formalism

$$q_A\,(x_A) = \sum_\alpha \int_0^A dy_A \int_0^1 dx\;\delta(x_A - y_A\,x)\;\;f_\alpha(y_A)\;q_\alpha\,(x)$$

  - α = (bound) protons, neutrons, pions, deltas. . . .



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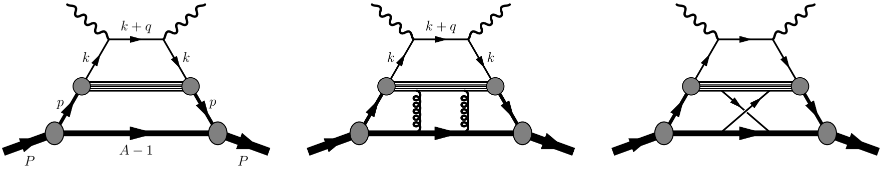
  - $\alpha =$ (bound) protons, neutrons, pions, deltas. . . .
  - $q_\alpha(x)$ lightcone distribution of quarks q in bound hadron α
  - $f_\alpha(y_A)$ lightcone distribution of hadrons α in nucleus



Convolution Formalism and Sum Rules

- Recall convolution model:

$$q_A(x_A) = \sum_\alpha \int_0^A dy_A \int_0^1 dx\ \delta(x_A - y_A\, x)\ \ f_\alpha(y_A)\ q_\alpha(x)$$

- All credible explanations of the EMC effect must satisfy baryon number and momentum sum rules:

$$\int_0^A dx_A\, u_A^-(x_A) = 2\,Z + N, \qquad \int_0^A dx_A\, d_A^-(x_A) = Z + 2\,N,$$

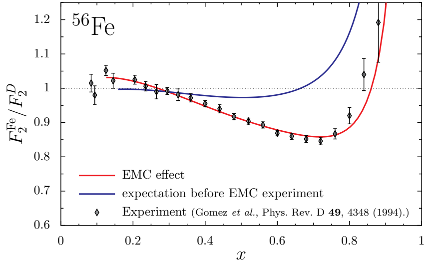
$$\int_0^A dx_A\, x_A\left[u_A^+(x_A) + d_A^+(x_A) + \ldots + g_A(x_A)\right] = Z + N = A,$$

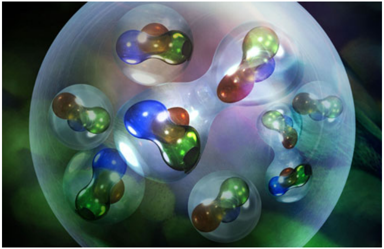
- In convolution formalism these sum rules imply

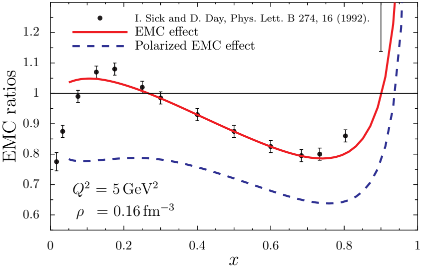
$$\sum_\alpha n_B \int_0^A dy_A\, f_\alpha(y_A) = A \quad \sum_\alpha \int_0^A dy_A\, y_A\, f_\alpha(y_A) = A$$

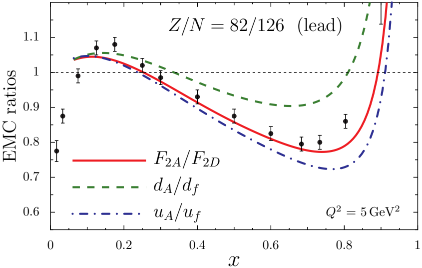
  - quark distributions $q_\alpha(x)$ should satisfy baryon number and momentum sum rules for hadron α

- Explanations of EMC effect include:
  - Nuclear binding and Fermi motion
  - Pion excess in nuclei
  - Dynamical rescaling
  - Multi-quark clusters, e.g. 6, 9, . . . quark bags
  - Nucleon swelling and suppresion of point-like configurations
  - Medium modification of bound nucleon wave functions
  - Short-range nucleon-nucleon correlations
- After 30 years data has ruled out almost none of these explanations!





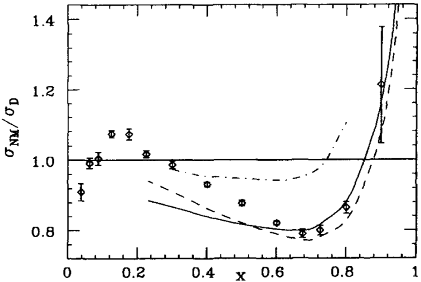




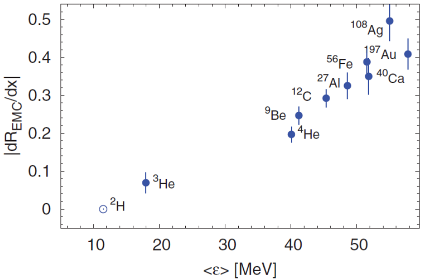
- *The puzzle posed by the EMC effect will only be solved by conducting new experiments that expose novel aspects of the EMC effect*
- Two important measurements are:
  - the flavour dependence of the EMC effect – Isovector EMC effect
  - the EMC effect in spin-dependent structure functions – Polarzied EMC effect
- Proposed explanations predict various behaviours for these new EMC effects
- New experiments at e.g. Jefferson Lab will measure both these EMC effects

Nuclear Binding

[O. Benhar *et al.*, Phys. Lett. B **410**, 79 (1997)]



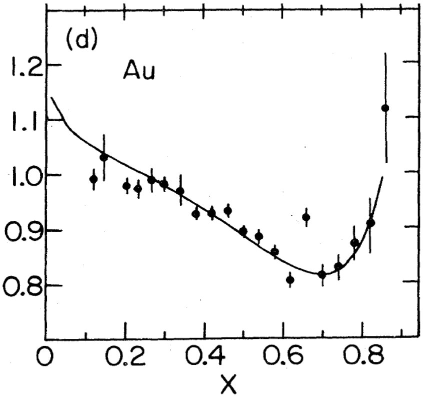
[J. Arrington *et al.*, Phys. Rev. C **86**, 065204 (2012)]



- Nucleons are bound inside a nucleus, therefore binding, Fermi motion and off-shell corrections must be considered in any explanation of EMC effect
- Binding energy (∼8 MeV) is too small to explain EMC effect; therefore average nucleon separation energy usually considered
  - Koltan sum rule: $\frac{E_A}{A} = \frac{1}{2}\left[\langle t\rangle + \langle \varepsilon\rangle\right]$; total binding energy for ^{4}He = 28 MeV
- Approach does not satisfy momentum sum rule – completely unconstrained
- The spin structure of nuclei is dominated by the valence nucleons, therefore binding would predict a small polarized EMC effect

Pion Excess

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



- Pions are responsible for (*inter alia*) long range part of NN interaction
- Natural to expect pions are important for EMC effect [Ericson & Thomas (1983); Llewellyn Smith (1983); Berger, Coester & Wiringa (1984)]
- Introduce lightcone distribution for pions in a nucleus:

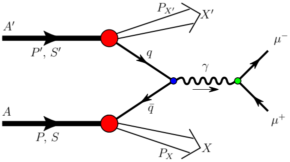
  $f_\pi(y_A); \quad \int dy_A\, f_\pi(y_A) = n_\pi$

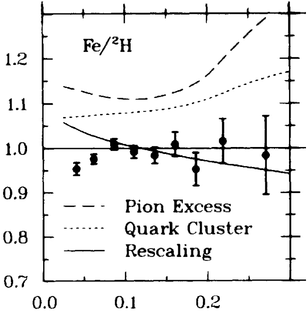
- Momentum conservation now implies:

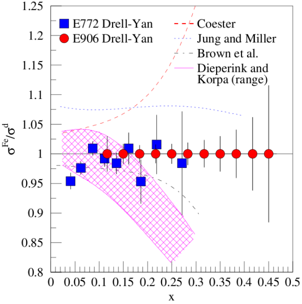
$$\int_0^A dy_A\, y_A\, f_N(y_A) + \int_0^A dy_A\, y_A\, f_\pi(y_A) = A$$

  - can explain EMC effect; e.g. for Au: $n_\pi = 0.114, \quad \langle y_A \rangle = 0.061$ per-nucleon
- Pion excess predicts large enhancement in sea-quark distributions in nuclei
- Because $\Delta f_\pi(y_A) = 0$ pion excess predicts small polarized EMC effect

Anti-quarks in nuclei and Drell-Yan







- Pions play a fundamental role in traditional nuclear physics
  - may expect pion (anti-quark) enhancement in nuclei compared to nucleon
- Drell-Yan experiment set up to probe anti-quarks in target nucleus
  - $\bar{q}q \to \mu^+\mu^-$ – E906: running Fermilab, [E772: Alde *et al.*, PRL. **64**, 2479 (1990).]

    [*proposed in* R. P. Bickerstaff, M. C. Birse and G. A. Miller, Phys. Rev. Lett. **53**, 2532 (1984).]
  - no anti-quark enhancement compared to free nucleon was observed
- Important to understand anti-quarks in nuclei: Drell-Yan & PV DIS

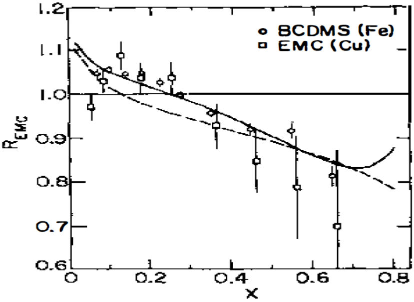
Dynamical Rescaling

[E. L. Berger & F. Coester, Ann. Rev. Nucl. Part. Sci. **37**, 463 (1987)]

- Idea arises from observation:

$$F_{2A}(x,Q^2) \simeq F_{2N}(x,\, \xi_A(Q^2)\, Q^2)$$

  - where $\xi_A(Q^2) > 1$
  - empirically $\xi \simeq 2$ at $Q^2 = 20\,\text{GeV}^2$
  - promoted by several "luminaries" e.g. O. Nachtmann, H. Pirner; F. E. Close, R. G. Roberts, G. G. Ross; R. L. Jaffe



- Attributed to increase in confinement radius of bound nucleon; which is associated with change in factorization scale: $r_A\,\mu_A = r_N\,\mu_N;\;\; \mu_A < \mu_N$
- Assuming $q_A(x, Q^2 = \mu_A^2) = q_N(x, Q^2 = \mu_N^2)$ LO QCD implies

$$\xi_A(Q^2) = \left(\mu_N^2/\mu_A^2\right)^{\alpha_s(\mu_N^2)/\alpha_s(Q^2)}; \qquad \xi \sim 2 \implies r_A/r_N \sim 1.15$$

- Dynamical rescaling predicts a polarized and usual EMC effect of a similar size; since DGLAP evolution is flavour bind no isovector EMC effect

Medium Modification

- 50 years of traditional nuclear physics tells us that the nucleus is composed of nucleon-like objects
- However if a nucleon property is not protected by a symmetry its value may change in medium – e.g.
  - mass, magnetic moment, size
  - quark distributions, form factors, GPDs, etc
- There must be medium modification:
  - nucleon propagator is changed in medium
  - off-shell effects ($p^2 \neq M^2$)
  - Lorentz covariance implies bound nucleon has 12 EM form factors

$$\langle J^\mu \rangle = \sum\nolimits_{\alpha,\,\beta=+,-} \Lambda^\alpha(p') \left[\gamma^\mu\, f_1^{\alpha\beta} + \tfrac{1}{2M} i\sigma^{\mu\nu} q_\nu\, f_2^{\alpha\beta} + q^\mu\, f_3^{\alpha\beta}\right] \Lambda^\beta(p)$$

- Need to understand these effects as first step toward QCD based understanding of nuclei

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  - mass, magnetic moment, size
  - quark distributions, form factors, GPDs, etc
- There must be medium modification:
  - nucleon propagator is changed in medium
  - off-shell effects ($p^2 \neq M^2$)
  - Becomes two form factors for on-shell nucleon

$$\langle J^\mu \rangle = \bar{u}(p') \left[\gamma^\mu \, F_1(Q^2) + \frac{1}{2M} i\sigma^{\mu\nu} q_\nu \, F_2(Q^2) \right] u(p)$$

- Need to understand these effects as first step toward QCD based understanding of nuclei

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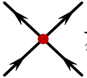
Continuum QCD

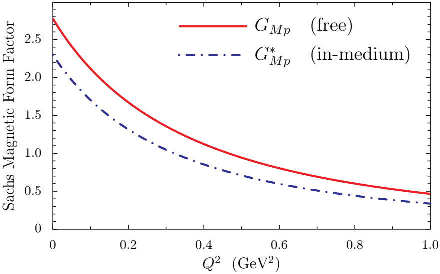
"integrate out gluons" →



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

- 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

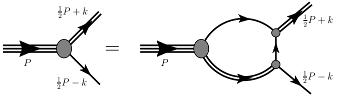
- For nuclei, we find that quarks bind together into color singlet nucleons
  - however contrary to traditional nuclear physics approaches these quarks feel the presence of the nuclear environment
  - *as a consequence bound nucleons are modified by the nuclear medium*



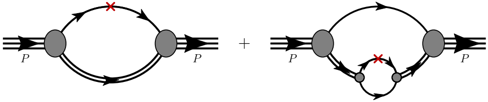
- Modification of the bound nucleon wave function by the nuclear medium is a *natural consequence* of quark level approaches to nuclear structure
- These studies provide a complementary approach to more traditional nuclear physics research (e.g. GFMC conducted here at Argonne)

Nucleon quark distributions

- Nucleon = quark+diquark



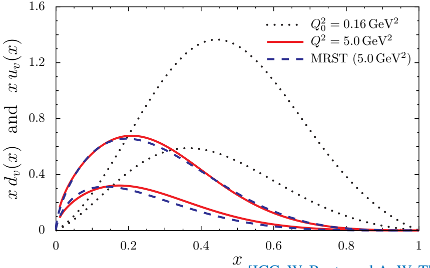
- PDFs given by Feynman diagrams: $\langle\gamma^+\rangle$

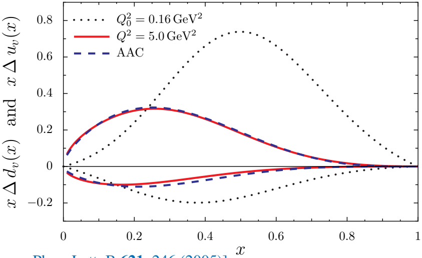


- Covariant, correct support; satisfies sum rules, Soffer bound & positivity

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

- $q(x)$: probability strike quark of favor q with momentum fraction x of target

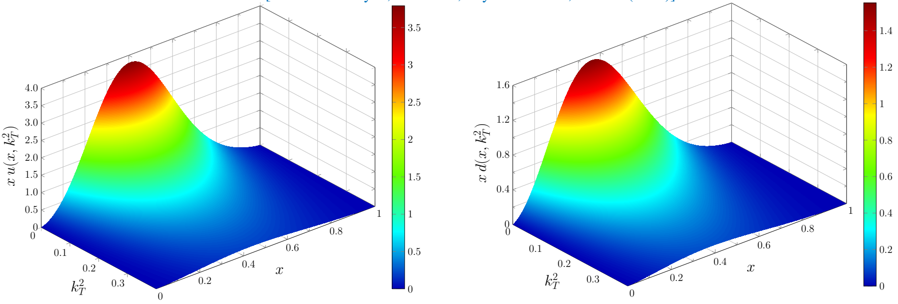




[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **621**, 246 (2005)]

Transverse Momentum Dependent PDFs

[H. H. Matevosyan, ICC *et al.*, Phys. Rev. D **85**, 014021 (2012)]



- So far only considered the simplest spin-averaged TMDs – $q(x,k_T^2)$
- In phenomenology common to work with parametrization of the form:

$$q(x,k_T^2) = q(x)\,\frac{e^{-k_T^2/\langle k_T^2\rangle_0}}{\pi\,\langle k_T^2\rangle_0}$$

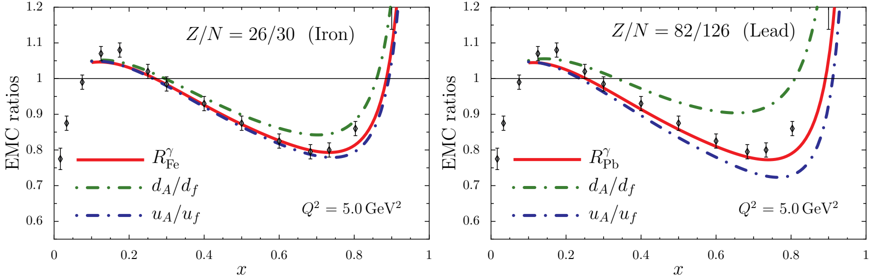
$$\langle k_T^2\rangle^{Q^2=Q_0^2} = 0.36^2\,\text{GeV}^2 \sim M^2$$

$$\langle k_T^2\rangle = 0.56^2\,\text{GeV}^2\ _{\text{[HERMES]}},\quad 0.64^2\,\text{GeV}^2\ _{\text{[EMC]}}$$

- Gaussian ansatz fits our results well
  - argeement with experiment reasonable as $\langle k_T^2\rangle$ grows with Q^2

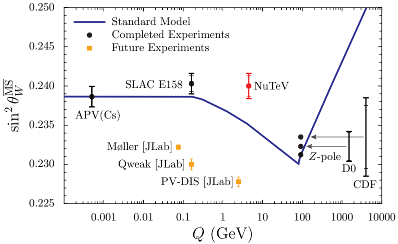
Flavour dependence of (Isovector) EMC effect

[I. C. Cloët *et. al*, Phys. Rev. Lett. **109**, 182301 (2012)]



- Model provides a natural explanation of the EMC effect
- Predicts that isovector nuclear forces result in a large quark flavor dependence of the EMC effect
  - parity-violating DIS experiments at JLab are sensitive to this flavor dependence
- $N > Z \implies d$-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
- If observed would provide strong evidence for medium modification

Weak mixing angle and the NuTeV anomaly



- NuTeV: $\sin^2\theta_W = 0.2277 \pm 0.0016$
  - G. P. Zeller *et al.* Phys. Rev. Lett. **88**, 091802 (2002).
- SM: $\sin^2\theta_W = 0.2227 \pm 0.0004$
- Evidence for physics beyond Standard Model?

- Paschos-Wolfenstein ratio motivated NuTeV study:

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

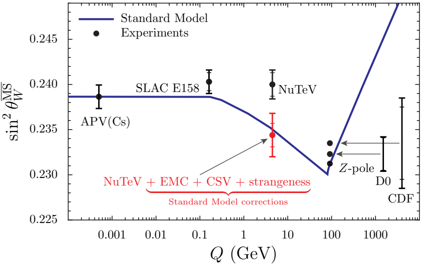
- NuTeV used a steel target – $Z/N \simeq 26/30$
  - correct for neutron excess $\Longleftrightarrow$ flavour dependent EMC effect
- Use our medium modified *Iron* quark distributions

$$\Delta R_{PW} = \Delta R_{PW}^{\text{naive}} + \Delta R_{PW}^{\text{EMC effect}} = -\left(0.0107 + 0.0032\right).$$

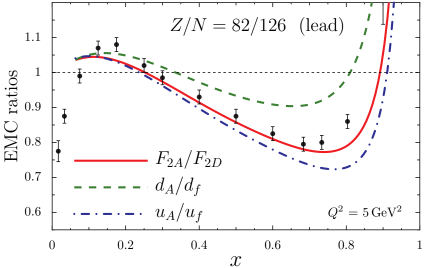
- Flavour dependence of EMC effect explains up to 65% of anomaly

Isovector EMC effect & the NuTeV Anomaly

[W. Bentz *et. al* [including Cloët], Phys. Lett. B **693**, 462 (2010)]



[I. C. Cloët *et. al*, Phys. Rev. Lett. **109**, 182301 (2012)]



- 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
  - NuTeV anomaly interpreted as evidence that nucleon structure is modified by the nuclear medium
- NuTeV anomaly provides no evidence from physics beyond Stardard Model
  - from 2001 press conference: "99.75% probability that the neutrinos are not behaving like other particles . . . only 1 in 400 chance that our measurement is consistent with prediction . . . room full of physicists fell silent"

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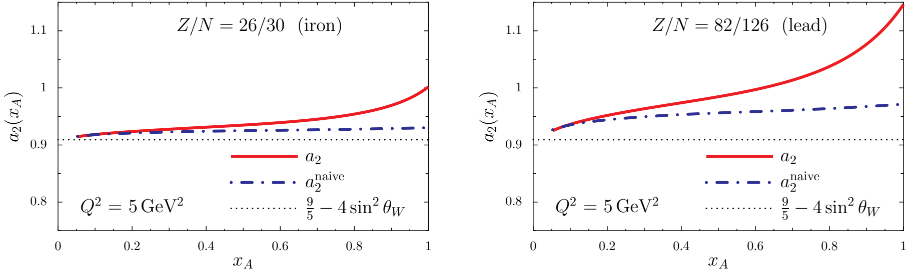
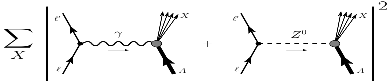
[ICC, W. Bentz and A. W. Thomas, Phys. Rev. Lett. **109**, 182301 (2012)]



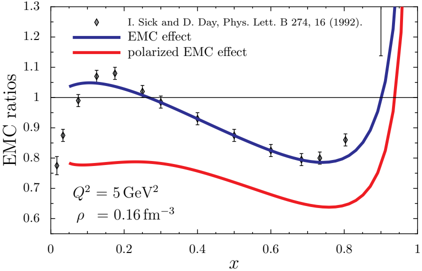
- PV DIS – $\gamma\, Z$ interference: 

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

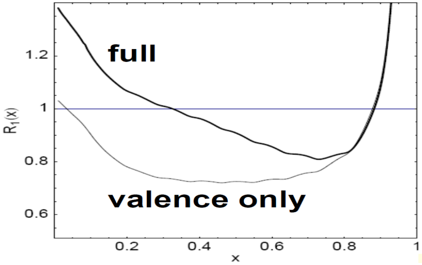
- Large x dependence of $a_2(x)$ ➞ evidence for medium modification
- $a_2(x)$ is also a excellent way to measure $\sin^2\theta_W$
- Predictions will be tested at Jefferson Lab

Polarized EMC effect

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



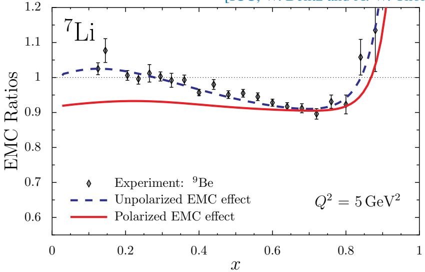
[J. R. Smith and G. A. Miller, Phys. Rev. C **72**, 022203(R) (2005)]

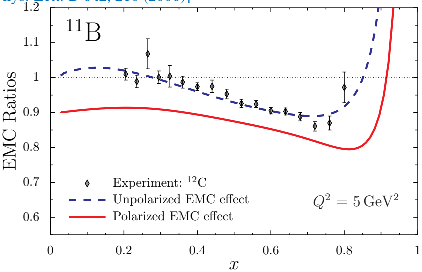


- Polarized EMC ratio: $$\Delta R = \frac{g_{1A}}{g_{1A}^{\text{naive}}} = \frac{g_{1A}}{P_p\, g_{1p} + P_n\, g_{1n}}$$
- Spin-dependent cross-section is suppressed by $1/A$
  - must choose nuclei with $A \lesssim 27$
  - protons should carry most of the spin e.g. $\Longrightarrow$ ^{7}Li, ^{11}B, …
- Ideal nucleus is probably ^{7}Li
  - from Quantum Monte–Carlo: $P_p = 0.86$ & $P_n = 0.04$
- Ratios equal 1 in limit of no nuclear effects

Polarized EMC effect

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





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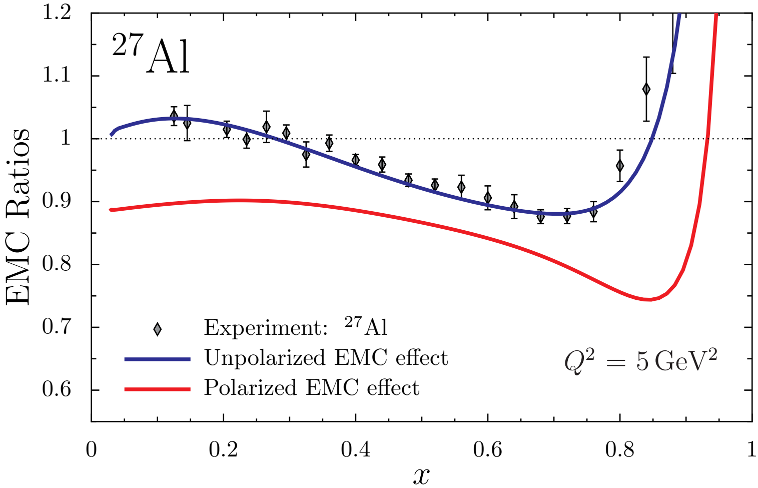
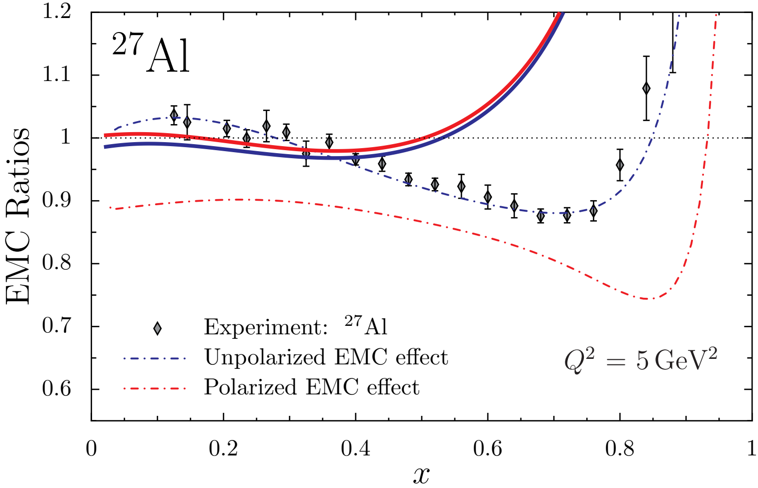
  - from Green Function Quantum Monte–Carlo: $P_p = 0.86 \quad \& \quad P_n = 0.04$
- Ratios equal 1 in limit of no nuclear effects

Is there medium modification



Is there medium modification



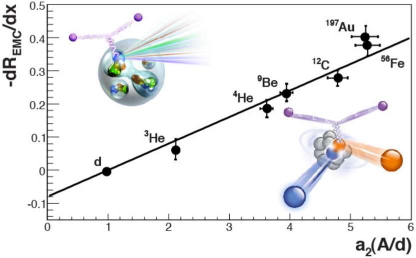
- Medium modification of nucleon has been switched off
- Relativistic effects remain
- Large splitting very difficult without medium modification

Nuclear spin sum

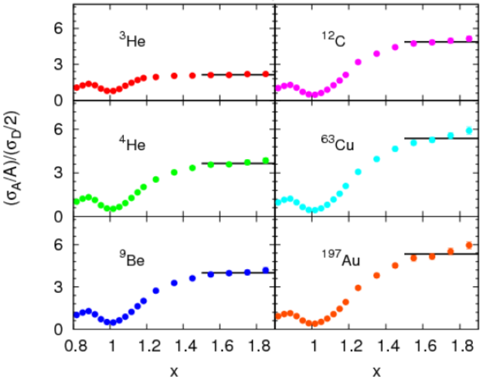
Proton spin states	Δu	Δd	Σ	g_A
p	0.97	-0.30	0.67	1.267
^{7}Li	0.91	-0.29	0.62	1.19
^{11}B	0.88	-0.28	0.60	1.16
^{15}N	0.87	-0.28	0.59	1.15
^{27}Al	0.87	-0.28	0.59	1.15
Nuclear Matter	0.79	-0.26	0.53	1.05

- Angular momentum of nucleon: $J = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$
  - in medium $M^* < M$ and therefore quarks are more relativistic
  - lower components of quark wavefunctions are enhanced
  - quark lower components usually have larger angular momentum
  - $\Delta q(x)$ very sensitive to lower components
- Therefore, in-medium quark spin → orbital angular momentum

Short-Range Correlations



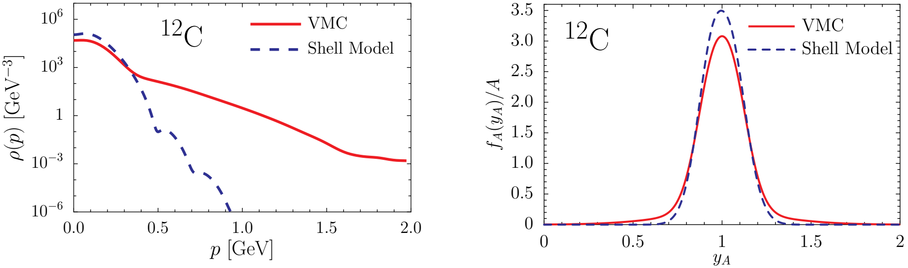
[N. Fomin *et al.*, Phys. Rev. Lett. **108** (2012) 092052]



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

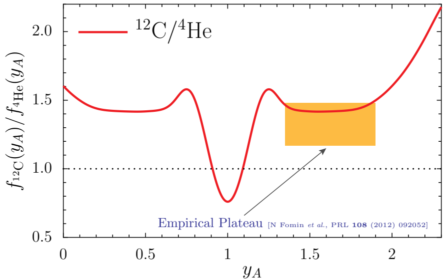


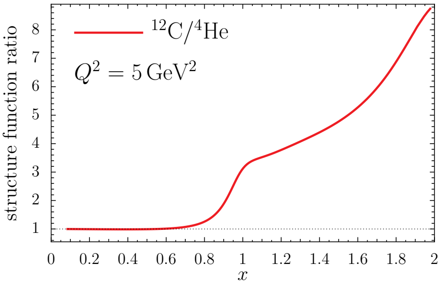
- Modern GFMC or VMC nuclear WFs have large high momentum tails
  - indicates wave function has large SRC component; ∼20% for ^{12}C
- Lightcone momentum distribution of nucleons in nucleus is given by

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

	^{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

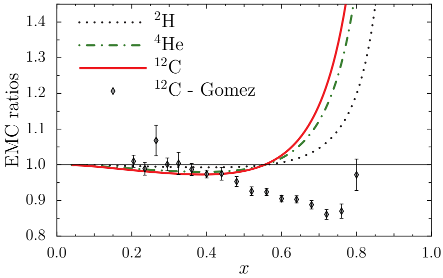
EMC effect and Short-Range Correlations

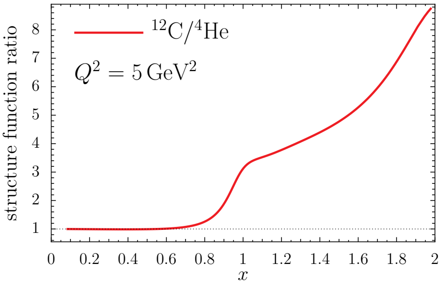




- Ratio of Variational Monte-Carlo (VMC) lightcone wave function exhibits distinct plateau which agrees with experiment
- Using VMC lightcone wave functions and convolution model with empirical nucleon PDFs to obtain nuclear structure functions and hence EMC effect
  - plateau still prominant in DIS 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 5 times larger than in mean-field models
- For polarized EMC effect only 2–3% of nucleons are involved in SRCs
  - for large polarized EMC effect need medium modification from SRCs about 20 times larger than in mean-field models
- Observation of large polarized EMC effect would imply SRCs less likely to be mechanism responsible for EMC effect

Conclusion

- Highlight the importance of understanding the EMC effect as a critical step towards a QCD based description of nuclei
- Measurements of the flavour dependence of the EMC effect and the polarized EMC effect will provide critical new insights
  - will help differentiate between the various models
- EMC effect and NuTeV anomaly are interpreted as evidence for medium modification of the bound nucleon wavefunction
  - predictions will be tested using PV DIS
- Using state-of-the-art nuclear wave functions demonstarted that SRCs do not necessary led to an explanation for the EMC effect
  - correlation between slope of EMC effect and quasi-elastic plateau may just be coincidental
- Exciting new experiments will expose novel aspects of the EMC effect:
  - PV DIS, pion induced Drell-Yan, tagged DIS, SIDIS, DVCS, DVMP
- Slowly building a QCD based understanding of nuclear structure