QCD and Nuclei

From the Coulomb Sum Rule to the EMC effect

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Argonne National Laboratory

New Directions in Subatomic Physics

Workshop to celebrate the 60th birthday of Tony Williams

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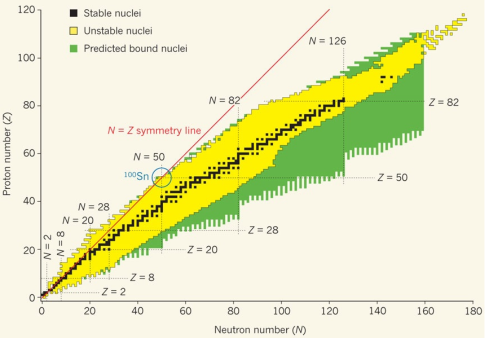
Why are Nuclei Interesting?

- Nuclei encapsulate and accentuate much of Standard Model physics
  - QED has a dramatic affect on, e.g. the valley of stability as the number of protons increase
  - weak interactions have a dramatic affect on e.g. the stability of nuclei
  - proton decay occurs inside nuclei:

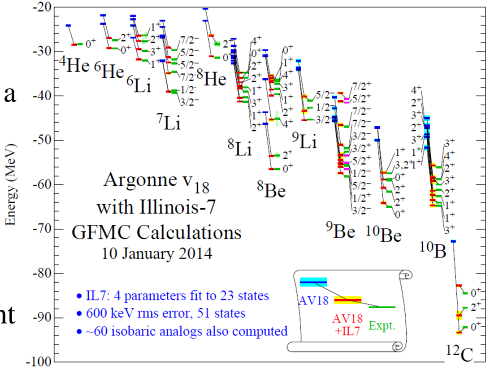
$$^{23}_{12}\mathrm{Mg} \to {}^{23}_{11}\mathrm{Na} + e^+ + \nu_e$$



- However, the properties of nuclei are dominated by the strong interaction
  - understanding the properties of nuclei within QCD remains one of the most important challenges in fundamental science
  - *too understand QCD it is not sufficient to study hadrons alone*
- Nuclei are used in many searches for physics beyond the Standard Model
  - electric dipole moment in mercury, radium, etc
  - neutrinoless double β decay
- BSM searches can be hindered by a lack of understanding of QCD & nuclei

Traditional Nuclear Physics

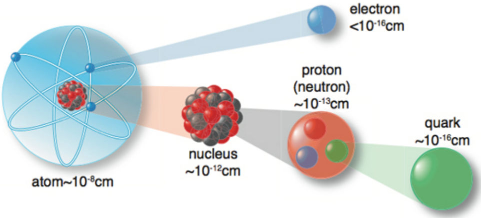
- In traditional nuclear physics the nucleus is viewed as a collection of *elementary* nucleons interacting via a phenomenological potential
  - this picture began with the discovery of the neutron in 1932
  - on firm ground with establishment of the nuclear shell model in 1940s
- Interim has seen steady improvement
  - largely independent of QCD



- State-of-the-art today are sophisticated *non-relativistic* quantum-many-body approaches – VMC and GFMC – using e.g. the Argonne V_{18} potential
  - V_{18} + IL-7 potential has 44 parameters fit to NN scattering data, . . .
  - remarkably successful at describing numerous properties of light nuclei
- *Key assumption of ab initio approaches is that the nucleons which comprise a nucleus have the same internal structural properties as free nucleons*

Nuclear Targets

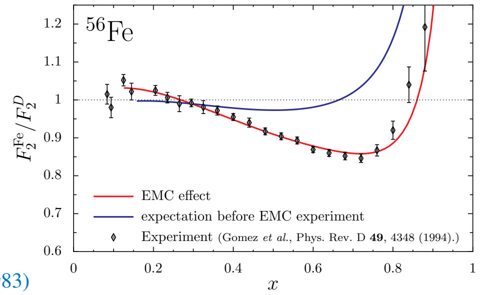
- Nuclei give access to numerous novel aspects of QCD:
  - neutron target, targets with $J \geqslant 1$
  - colour transparency, hidden colour
  - hypernuclei, gluon saturation, etc



- Important question: *How do the internal structural properties of protons and neutrons change when they form complex nuclei and what is the cause?*
- In quark level approaches *self-consistent coupling to nuclear mean-fields* naturally results in *medium modification of all nucleons in a nucleus*
  - for example, the dressed quark mass function changes with temperature and baryon chemical potential
  - very difficult to avoid medium modification in these approaches
- Unambiguous evidence for quark & gluon effects in nuclei remains elusive
  - important candidates are the EMC effect
  - Quasi-elastic scattering, the Coulomb Sum Rule & proton knockout reactions

The 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."

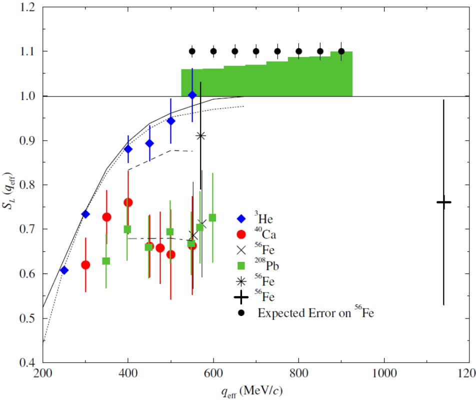
- Measurement of the *EMC effect* created a new paradigm regarding QCD and nuclear structure
  - more than 30 years after discovery a broad consensus on explanation is lacking
  - what is certain: *valence quarks in nucleus carry less momentum than in a nucleon*
- One of the most important nuclear structure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

Coulomb Sum Rule

- The "Coulomb Sum Rule" reads

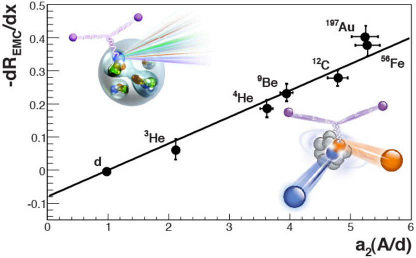
$$S_L(|\boldsymbol{q}|) = \int_{\omega^+}^{|\boldsymbol{q}|} d\omega \, \frac{R_L(\omega, |\boldsymbol{q}|)}{\tilde{G}_E^2(Q^2)}$$

$$\tilde{G}_E^2 = Z\, G_{Ep}^2(Q^2) + N\, G_{En}^2(Q^2)$$

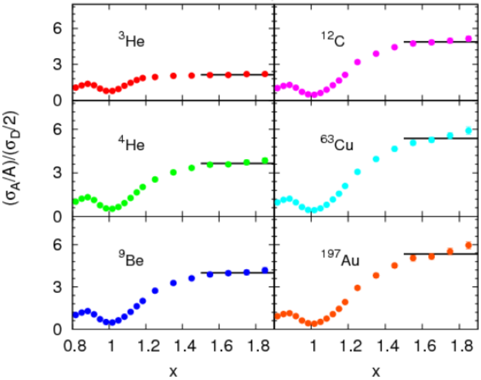


- Non-relativistic expectation – as $|\boldsymbol{q}|$ becomes large – $S_L(|\boldsymbol{q}| \gg p_F) \to 1$
  - CSR counts number of charge carriers
- The CSR was first measured at MIT Bates in 1980 then at Saclay in 1984
  - both experiments observed significant *quenching* of the CSR
- Two plausible explanations: 1) *nucleon structure is modified in the nuclear medium;* 2) *experiment/analysis is flawed e.g. Coulomb corrections*
- A number of influential physicists have argued very strongly for the latter

Short-Range Correlations



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



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

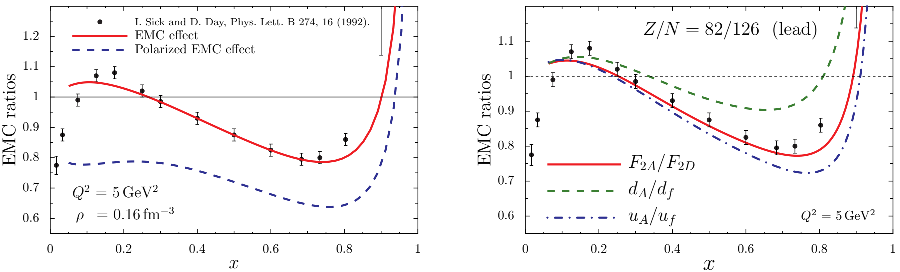
- *Empirical correlation between slope of EMC effect and quasi-elastic scattering plateaus has resulted in a renaissance of the EMC effect*

- 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"

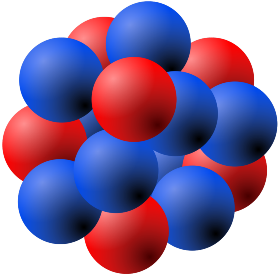
Understanding the EMC effect

- *The puzzle posed by the EMC effect will only be solved by conducting new experiments that expose novel aspects of the EMC effect*
- Measurements should help distinguish between explanations of EMC effect e.g. whether *all nucleons* are modified by the medium or only those in SRCs
- Important examples are measurements of the *EMC effect in polarized structure functions* & the *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 – *but parity violating DIS stands to play the pivotal role*

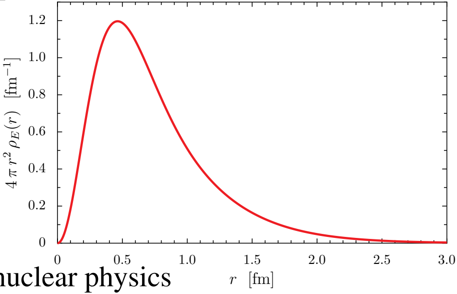


Nucleons in Nuclei

- 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 22% of proton charge at distances $r > 1\,\text{fm}$
- *Natural to expect that nucleon properties are modified by nuclear medium – even at the mean-field level*
  - in contrast to traditional nuclear physics



- Understanding validity of two viewpoints remains key challenge for nuclear physics

– *a new paradigm or deep insights into colour confinement in QCD*

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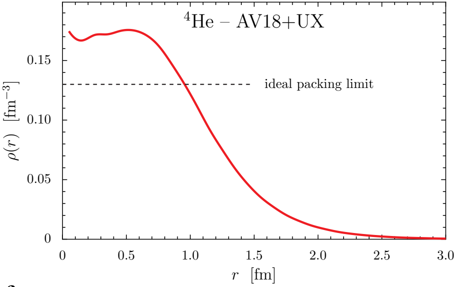

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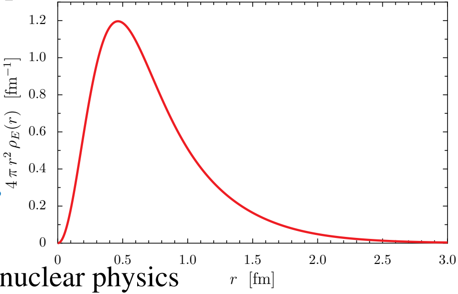

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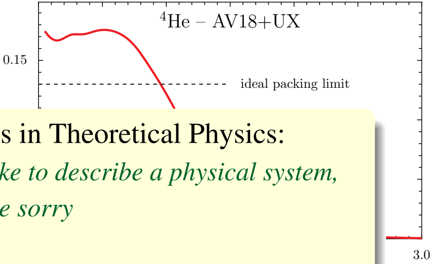


Weinberg's Third Law of Progress in Theoretical Physics:

you may use any degrees of freedom you like to describe a physical system, but if you choose the wrong ones, you'll be sorry

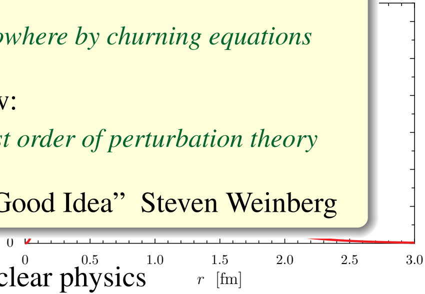
First Law:

Conservation of Information: You'll get nowhere by churning equations

Second Law:

Do not trust arguments based on the lowest order of perturbation theory

"Why the Renormalization Group is a Good Idea" Steven Weinberg



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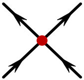
Quarks, Nuclei and the NJL model

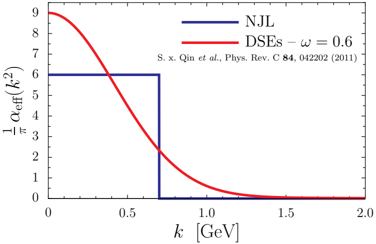
Continuum QCD "*integrate out gluons*" →

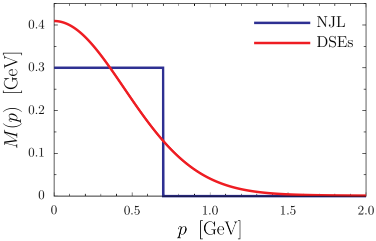


$\frac{1}{m_g^2}\ \Theta(\Lambda^2 - k^2)$

- 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

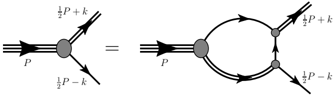
- Quark confinement is implemented via proper-time regularization
  - quark propagator: $[\not{p} - m + i\varepsilon]^{-1} \quad \to \quad Z(p^2)[\not{p} - M + i\varepsilon]^{-1}$
  - wave function renormalization vanishes at quark mass-shell: $Z(p^2 = M^2) = 0$
  - *confinement is critical for our description of nuclei and nuclear matter*

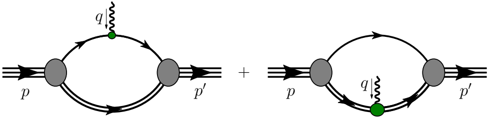




Nucleon Electromagnetic Form Factors

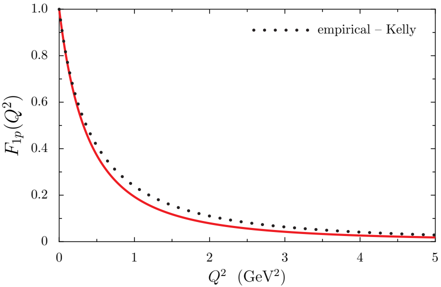
- Nucleon = quark+diquark
- Form factors given by Feynman diagrams:

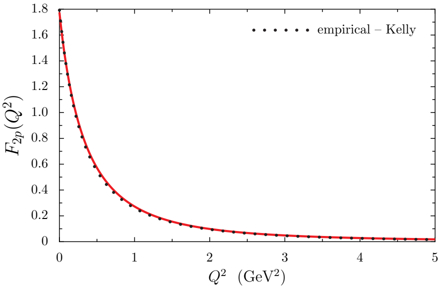




- Calculation satisfies electromagnetic gauge invariance; includes
  - dressed quark–photon vertex with ρ and ω contributions
  - contributions from a pion cloud

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





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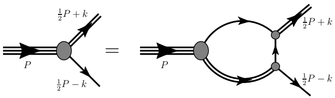

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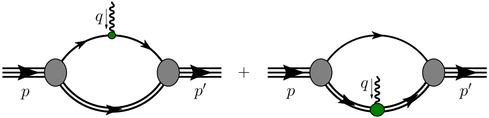

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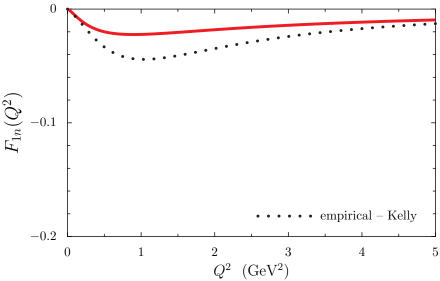
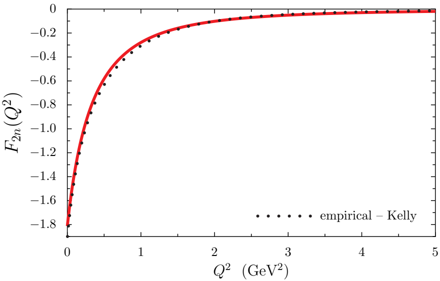
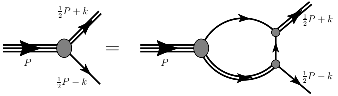
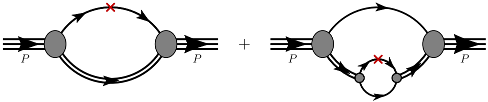




Nucleon quark distributions

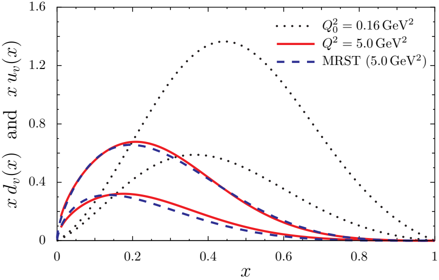
- Nucleon = quark+diquark
- PDFs given by Feynman diagrams: $\langle\gamma^+\rangle$

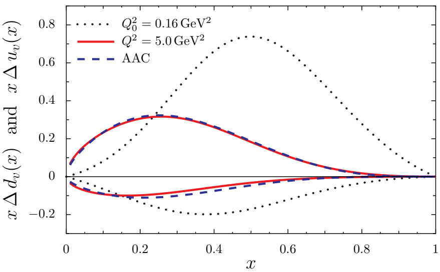




- Covariant, correct support; satisfies sum rules, Soffer bound & positivity

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

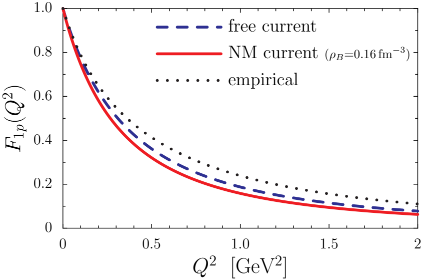


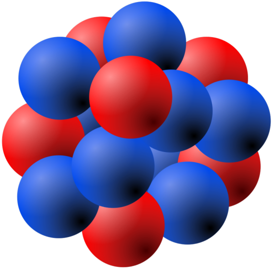


[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **621**, 246 (2005)]

Nucleons in the Nuclear Medium

- For nuclei, we find that quarks bind together into colour 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
- For a proton in nuclear matter find
  - Dirac & charge radii each increase by about 8%; Pauli & magnetic radii by 4%
  - $F_{2p}(0)$ decreases; however $F_{2p}/2M_N$ almost constant – μ_p almost constant





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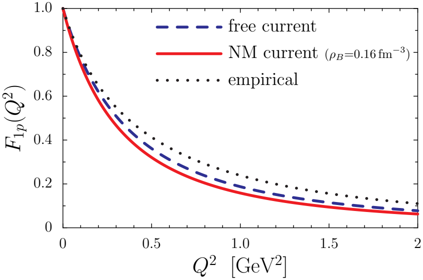
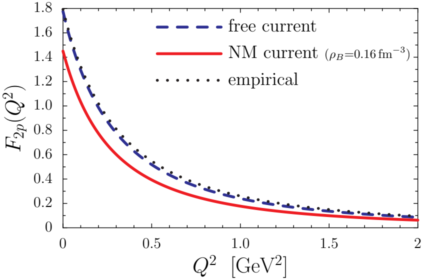
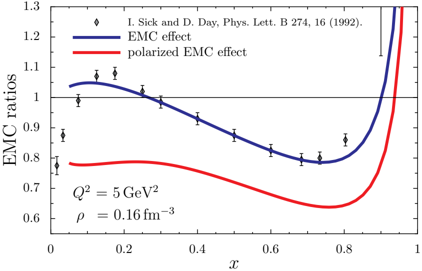


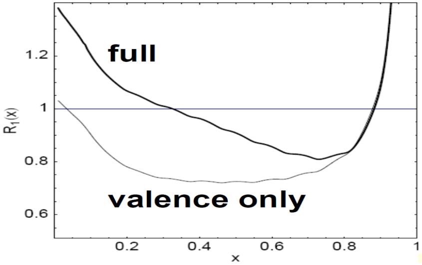


EMC and Polarized EMC effects

[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)]



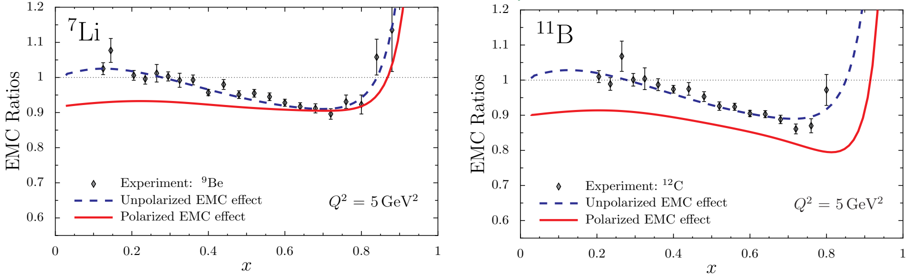
- Definition of polarized EMC effect:
  - ratio equals unity if no medium effects

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

- 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 traditional nuclear physics and numerous other explanations of the EMC

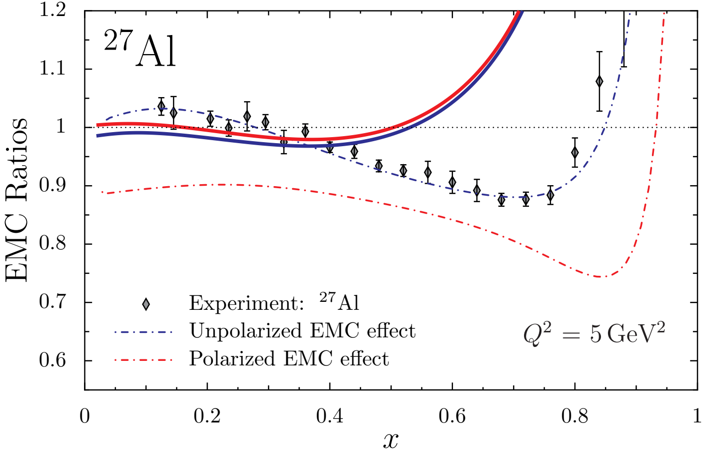
EMC effects in Finite Nuclei

[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 now 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*

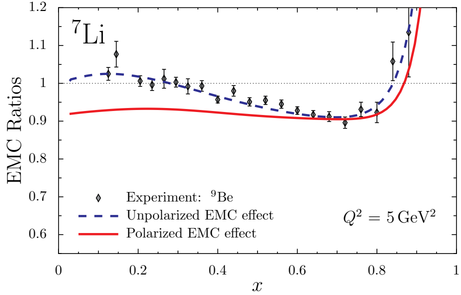
Turning off Medium Modification



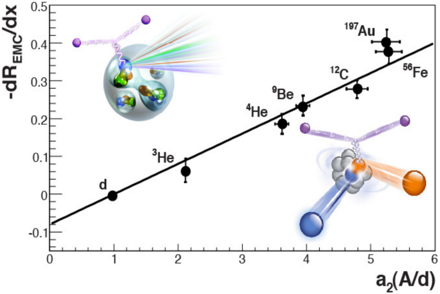
- Without medium modification both EMC & polarized EMC effects disappear
- Polarized EMC effect is smaller than the EMC effect – this is natural within standard nuclear theory and also from SRC perspective
- Large splitting very difficult without *mean-field* medium modification

Mean-field vs SRC induced Medium Modification

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



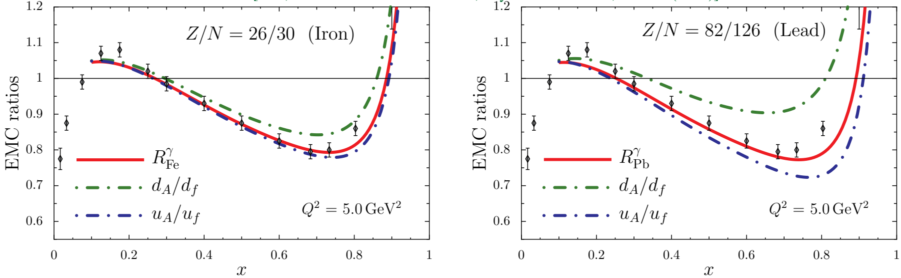
[L. B. Weinstein *et al.*, Phys. Rev. Lett. **106** 052301 (2011)]



- 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

Flavour dependence of EMC effect

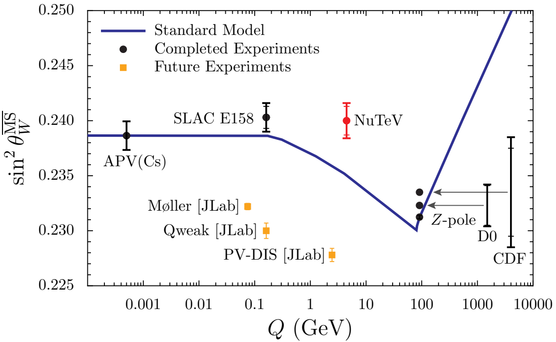
[ICC, W. Bentz and A. W. Thomas, Phys. Rev. Lett. **102**, 252301 (2009)]



- 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-field shifts momentum *from* u-quarks *to* d-quarks

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

- SRCs shift momentum from n to p – *therefore opposite to mean-field* – but since SRCs are isoscalar cannot give an isovector EMC effect



Fermilab 2001 press release:

"The predicted value was 0.2227. The value we found was 0.2277, a difference of 0.0050. It might not sound like much, but the room full of physicists fell silent when we first revealed the result"

"99.75% probability that the neutrinos are not behaving like other particles . . . only 1 in 400 chance that our measurement is consistent with prediction"

- NuTeV: $\sin^2\theta_W = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$

[G. P. Zeller *et al.* Phys. Rev. Lett. **88**, 091802 (2002)]

- Standard Model: $\sin^2\theta_W = 0.2227 \pm 0.0004 \Leftrightarrow 3\sigma \Longrightarrow$ "NuTeV anomaly"
- Huge amount of experimental & theoretical interest [600+ citations]
- Evidence for physics beyond the Standard Model?
- No universally accepted *complete* explanation

Paschos-Wolfenstein ratio

- Paschos-Wolfenstein ratio motivated the NuTeV study:

$$R_{PW} = \frac{\sigma_{NC}^{\nu A} - \sigma_{NC}^{\bar{\nu} A}}{\sigma_{CC}^{\nu A} - \sigma_{CC}^{\bar{\nu} A}} = \frac{\left(\frac{1}{6}-\frac{4}{9}\sin^2\theta_W\right)\left\langle x_A\, u_A^-\right\rangle + \left(\frac{1}{6}-\frac{2}{9}\sin^2\theta_W\right)\left\langle x_A\, d_A^- + x_A\, s_A^-\right\rangle}{\left\langle x_A\, d_A^- + x_A\, s_A^-\right\rangle - \frac{1}{3}\left\langle x_A\, u_A^-\right\rangle}$$

  - $\left\langle x_A\, q_A^-\right\rangle$ fraction of target momentum carried by valence quarks of flavor q

- For an isoscalar target $u_A \simeq d_A$ and if $s_A \ll u_A + d_A$

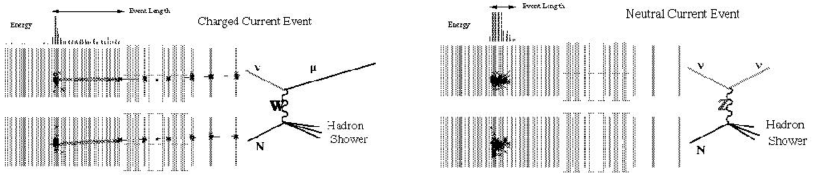
$$R_{PW} = \frac{1}{2} - \sin^2\theta_W + \Delta R_{PW}; \;\; \Delta R_{PW} = \left(1 - \frac{7}{3}\sin^2\theta_W\right)\frac{\left\langle x_A\, u_A^- - x_A\, d_A^- - x_A\, s_A^-\right\rangle}{\left\langle x_A\, u_A^- + x_A\, d_A^-\right\rangle}$$

- ΔR_{PW} well constrained $\Longrightarrow$ excellent way to measure weak mixing angle
- NuTeV "result" for R_{PW} is smaller than Standard Model value
- Studies suggest that largest contributions to ΔR_{PW} maybe:
  - strange quarks
  - charge symmetry violation (CSV) $\Longrightarrow$ $u_p \neq d_n, \;\; d_p \neq u_n$
  - nuclear effects
- NuTeV target was 690 tons of steel $\stackrel{?}{\Longrightarrow}$ non-trivial nuclear corrections

The NuTeV experiment

- Paschos-Wolfenstein ratio was not directly measured:

$$R_{PW} = \frac{\sigma^{\nu}_{NC} - \sigma^{\bar{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\bar{\nu}}_{CC}} \implies R^{\nu} = \frac{\sigma^{\nu}_{NC}}{\sigma^{\nu}_{CC}}, \quad R^{\bar{\nu}} = \frac{\sigma^{\bar{\nu}}_{NC}}{\sigma^{\bar{\nu}}_{CC}}; \quad R_{PW} = \frac{R^{\nu} - r\,R^{\bar{\nu}}}{1 - r}$$



- NuTeV measured: $R^{\nu}_{\text{NuTeV}} = 0.3916(7)$ & $R^{\bar{\nu}}_{\text{NuTeV}} = 0.4050(16)$

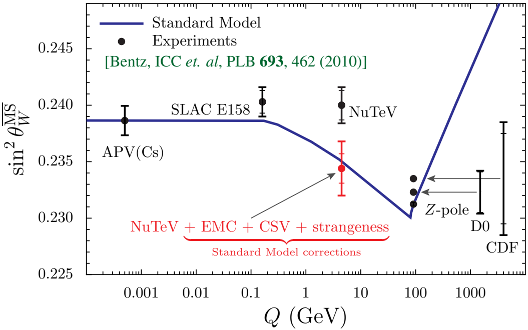
" Corrections to $R^{\nu(\bar{\nu})}$ result from the presence of heavy quarks in the sea, the production of heavy quarks in the target, higher order terms in the cross section, and any isovector component of the light quarks in the target. In particular, in the case where a final-state charm quark is produced from a d or s quark in the nucleon, there are large . . .

[G. P. Zeller *et al.*, arXiv:hep-ex/0110059]

- NuTeV then performed a sophisticated Monte-Carlo analysis using constraints from the Paschos-Wolfenstein ratio

A Reassessment of the NuTeV anomaly

Argonne NATIONAL LABORATORY



- Paschos-Wolfenstein ratio motivated NuTeV study:

$$R_{PW} = \frac{\sigma_{NC}^{\nu A} - \sigma_{NC}^{\bar{\nu} A}}{\sigma_{CC}^{\nu A} - \sigma_{CC}^{\bar{\nu} A}}$$

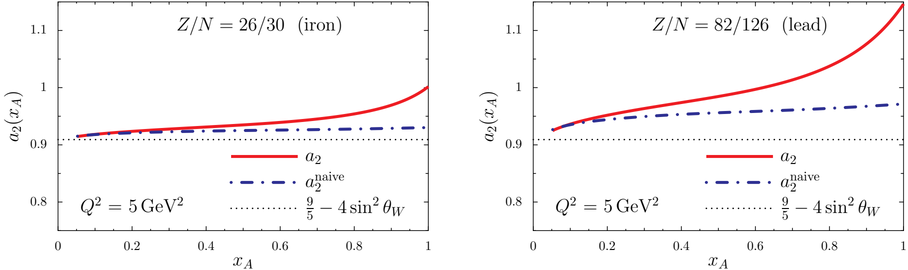
$$\overset{N \sim Z}{=} \frac{1}{2} - \sin^2\theta_W$$

$$+ \left(1 - \frac{7}{3}\sin^2\theta_W\right) \frac{\langle x\, u_A^- - x\, d_A^- \rangle}{\langle x\, u_A^- + x\, d_A^- \rangle}$$

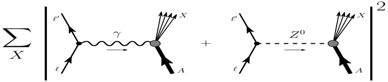
- NuTeV: $\sin^2\theta_W = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$ [Zeller *et al.* PRL. **88**, 091802 (2002)]
- Standard Model: $\sin^2\theta_W = 0.2227 \pm 0.0004 \Leftrightarrow 3\sigma \Longrightarrow$ "NuTeV anomaly"
- Using NuTeV *functionals*: $\sin^2\theta_W = 0.2221 \pm 0.0013(\text{stat}) \pm 0.0020(\text{syst})$
- 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:



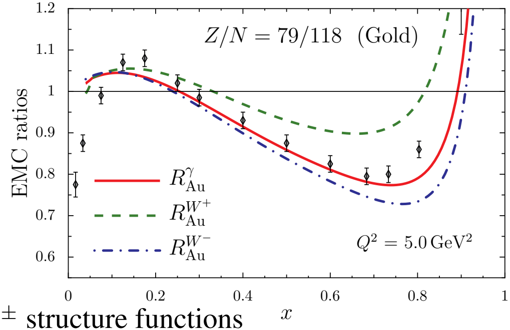
$$A_{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} \propto a_2(x) = -2g_A^e \frac{F_2^{\gamma Z}}{F_2^{\gamma}} \overset{N\sim Z}{=} \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\,\frac{u_A^+(x) - d_A^+(x)}{u_A^+(x) + d_A^+(x)}$$

- 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

Opportunities at an EIC

Argonne NATIONAL LABORATORY

- The reaction $e^{\mp}\,A \longrightarrow \nu\,(\bar{\nu})\,X$ has incredible promise for shedding new light on nucleon and nuclear PDFs
  - at EIC neutrino energy can be reconstructed from final state



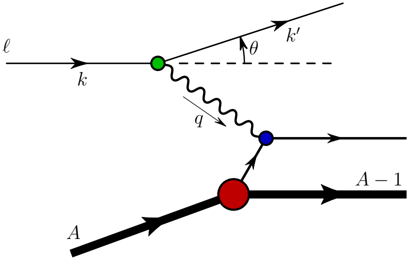
- Parton model expressions for $W^{\pm}$ structure functions

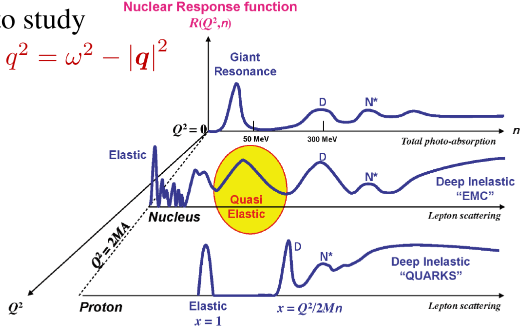
$$F_1^{W^+} = \bar{u} + d + s + \bar{c} \qquad F_3^{W^+} = -\bar{u} + d + s - \bar{c}$$
$$F_1^{W^-} = u + \bar{d} + \bar{s} + c \qquad F_3^{W^-} = u - \bar{d} - \bar{s} + c$$

- Would provide much needed data on flavour structure of both valence and sea quark distribution functions
- Flavour dependence can also be test using e.g. SIDIS, π^+/π^- Drell-Yan, PVDIS, ν-DIS & W-production at RHIC

Quasi-elastic scattering

- Quasi-elastic scattering is used to study nucleon properties in a nucleus: $q^2 = \omega^2 - |\boldsymbol{q}|^2$





- The cross-section for this process reads

$$\frac{d^2\sigma}{d\Omega\, d\omega} = \sigma_{\text{Mott}} \left[\frac{q^4}{|\boldsymbol{q}|^4} R_L(\omega, |\boldsymbol{q}|) + \left(\frac{q^2}{2\,|\boldsymbol{q}|^2} + \tan^2\frac{\theta}{2} \right) R_T(\omega, |\boldsymbol{q}|) \right]$$

  - response functions are accessed via Rosenbluth separation

- In the DIS regime – $Q^2, \omega \to \infty \quad x = Q^2/(2\, M_N\, \omega) = \text{constant}$ – response functions are proportional to the structure functions $F_1(x, Q^2)$ and $F_2(x, Q^2)$

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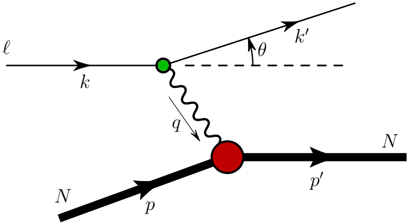

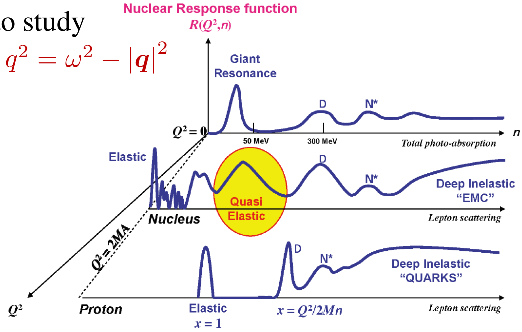

- The cross-section for this process reads

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{\text{Mott}}}{1+\tau}\left[G_E^2(Q^2) + G_M^2(Q^2)\right]$$

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- In the DIS regime – $Q^2, \omega \to \infty \quad x = Q^2/(2\,M_N\,\omega) = \text{constant}$ – response functions are proportional to the structure functions $F_1(x, Q^2)$ and $F_2(x, Q^2)$

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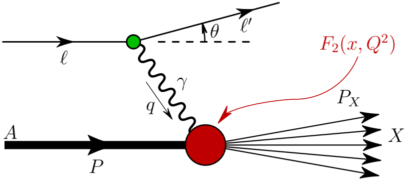
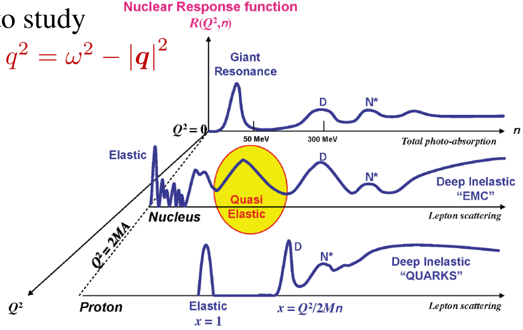




- The cross-section for this process reads

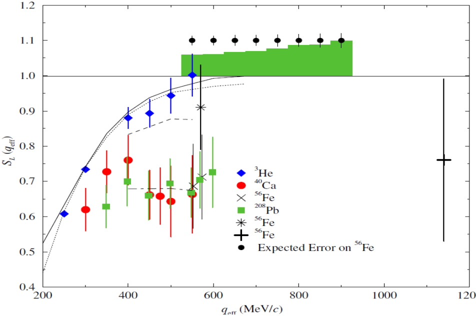
$$\frac{d\sigma}{dx\, dQ^2} = \frac{2\pi\, \alpha_e^2}{x\, Q^4} \left[\left(1 + (1+y)^2\right) F_2(x, Q^2) - y^2 F_L(x, Q^2) \right]$$

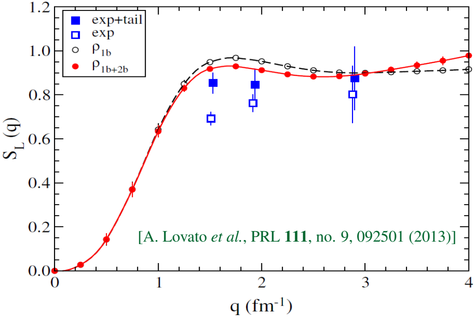
  - response functions are accessed via Rosenbluth separation

- In the DIS regime – $Q^2, \omega \to \infty \quad x = Q^2/(2\, M_N\, \omega) = \text{constant}$ – response functions are proportional to the structure functions $F_1(x, Q^2)$ and $F_2(x, Q^2)$

Coulomb Sum Rule Today

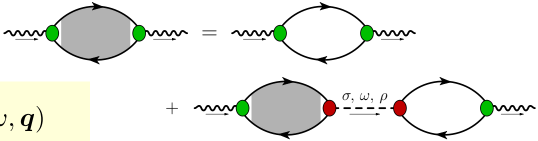
- No new data on the CSR since SLAC data from early 1990s
- The *quenching* of the CSR has become one of the most contentious observations in all of nuclear physics
- Experiment E05-110 was performed at Jefferson Lab in 2005 – should settle controversy of CSR *quenching* once and for all
  - publication of results expected soon
- State-of-the-art traditional nuclear physics (GFMC) calculations find no quenching





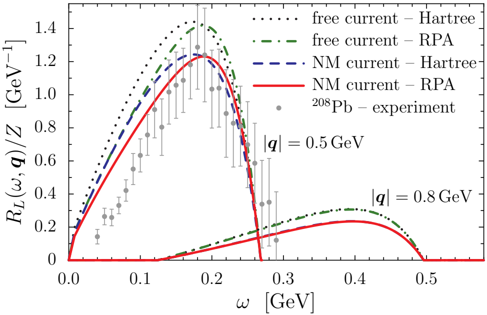
Longitudinal Response Function

- In nuclear matter response function given by



$$R_L(\omega, \boldsymbol{q}) = -\frac{2\,Z}{\pi\,\rho_B}\,\mathrm{Im}\,\Pi_L\,(\omega, \boldsymbol{q})$$

- Longitudinal polarization – Π_L – is obtained by solving a Dyson equation
- We consider two cases: (1) *the electromagnetic current is that if a free nucleon;* (2) *the current is modified by the nuclear medium*
- The *in-medium* nucleon current causes a sizeable quenching of the longitudinal response
  - driver of this effect is modification of the proton Dirac form factor
- Nucleon RPA correlations play almost no role for $|\boldsymbol{q}| \gtrsim 0.7\,\mathrm{GeV}$

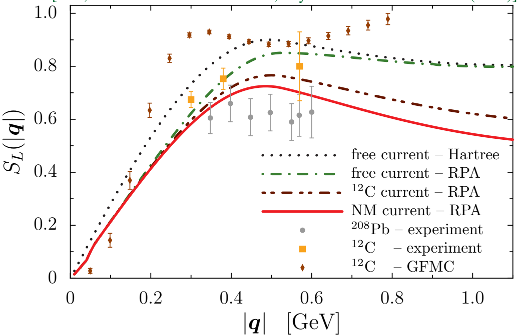


Coulomb Sum Rule

$$S_L(|\boldsymbol{q}|) = \int_{\omega^+}^{|\boldsymbol{q}|} d\omega \; \frac{R_L(\omega, |\boldsymbol{q}|)}{\tilde{G}_E^2(Q^2)}$$

$$\tilde{G}_E^2 = Z\, G_{Ep}^2(Q^2) + N\, G_{En}^2(Q^2)$$

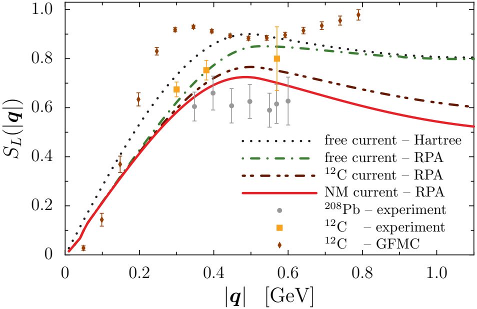
[ICC, W. Bentz and A. W. Thomas, Phys. Rev. Lett. **116** 032701 (2016)]

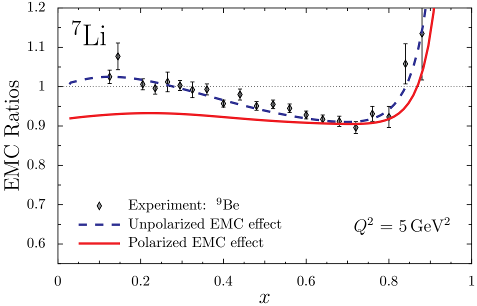


- Recall that the non-relativistic expectation is unity for $|\boldsymbol{q}| \gg p_F$
- GFMC ^{12}C results are consistent with this expectation
- For a *free nucleon current* find relativistic corrections of 20% at $|\boldsymbol{q}| \simeq 1\,\text{GeV}$
  - in the non-relativistic limit our CSR result does saturate at unity
- An *in-medium nucleon current* induces a further 20% correction to the CSR
  - good agreement with exisiting ^{208}Pb data – although this data is contested
- Our ^{12}C result is in stark contrast to the corresponding GFMC prediction
  - forthcoming Jefferson Lab should break this impasse

Conclusion

- New Jefferson Lab results for the CSR are expected soon
  - confirmation or otherwise of the quenching of the CSR will have a dramatic impact
- Two state-of-the-art calculations predict vastly different results *– for well understood reasons –*
- Understanding the EMC effect is a another critical step towards a QCD based description of nuclei
  - approved JLab experiments will measure the polarized EMC effect in ^{7}Li; PVDIS also important!
- Next frontier is GPDs and TMDs of nuclei at JLab12 and an EIC





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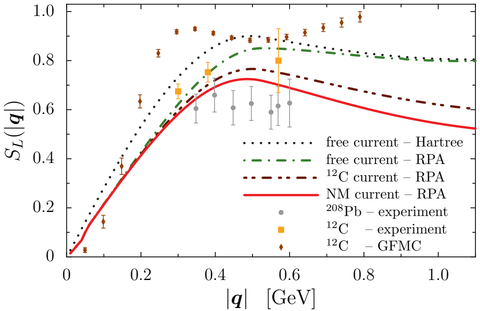
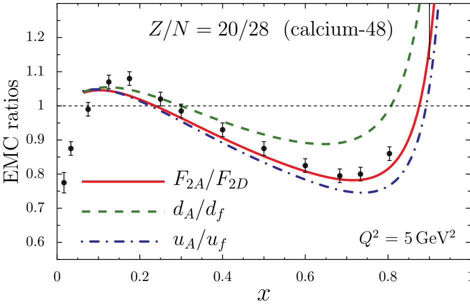
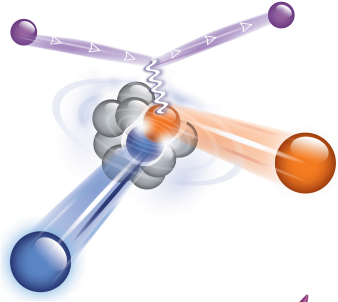


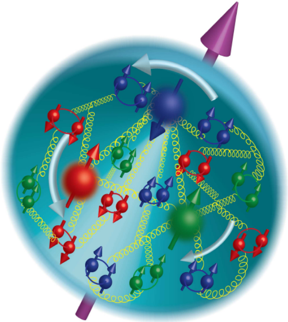


Backup Slides

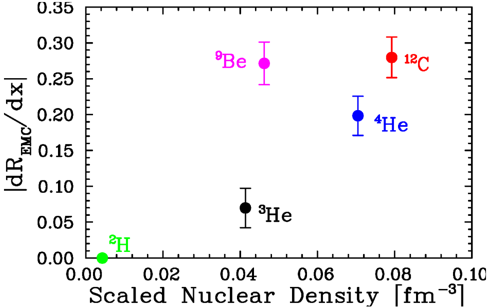
Explanations of the EMC effect

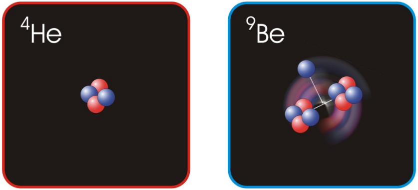
- Traditional explanations include:
  - nuclear binding and Fermi motion
  - pion excess in nuclei
- QCD motivated explanations include:
  - dynamical rescaling
  - multi-quark clusters, e.g. 6, 9, . . . quark bags
  - nucleon swelling and suppression of point-like configurations
  - medium modification of bound nucleon wave functions
- Hybrid explanations include:
  - short-range nucleon-nucleon correlations (SRCs)
- After 30 years data has ruled out almost none of these explanations!

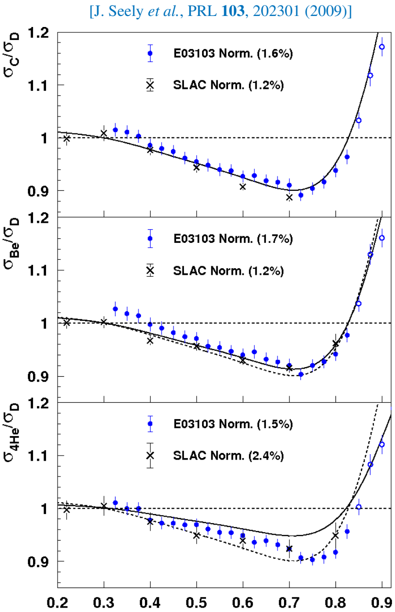




EMC effect in light nuclei







- EMC effect determined by *local density* not the *average density*: $R_{He} \sim R_{Be} \sim R_{C}$ [future: E12-10-008]

Sea-Quarks & Pion Excess in Nuclei

- Pions are responsible for (*inter alia*) the long range part of NN interaction

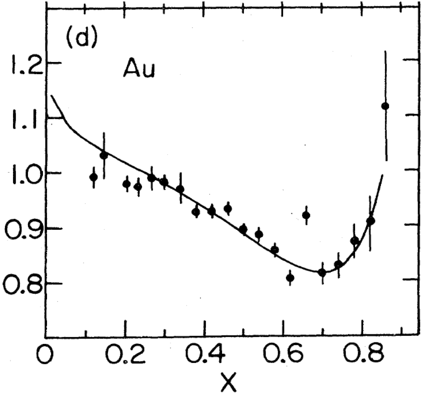
- Natural to expect pions are important for the EMC effect

  [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)]

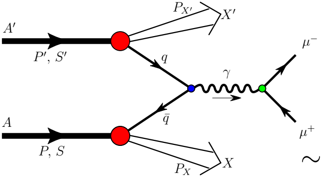


- To explain EMC effect in Gold, for example, need: $n_\pi = 0.114$

  $\implies \langle y_A \rangle = 0.061$ per-nucleon

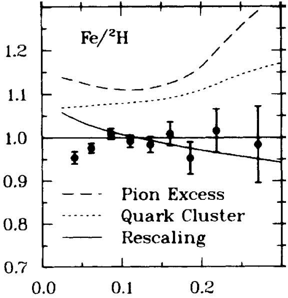
- *A consequence of pion excess is a sizeable enhancement in the sea-quark distributions in nuclei*

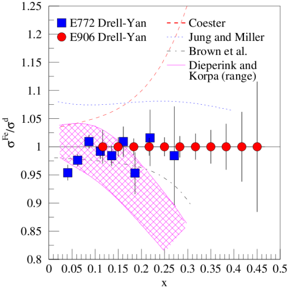
Nuclear Sea-Quarks and Drell-Yan



$$\sim \frac{\bar{u}_{\text{Fe}}}{\bar{u}_D}$$

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





- 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

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

PERSPECTIVES

Where Are the Nuclear Pions?

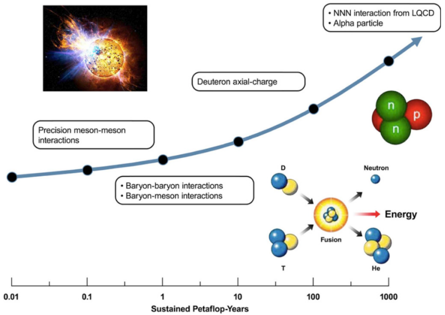
George F. Bertsch, Leonid Frankfurt, Mark Strikman

[Science, 1993]

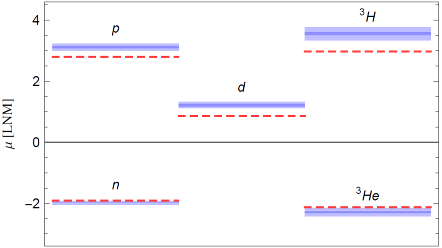
- New Fermilab Drell-Yan experiment 906 currently running

Progress using Lattice QCD

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



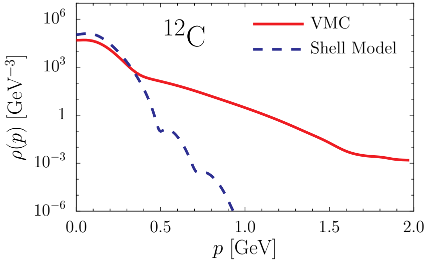
[S. R. Beane *et al.* (NPLQCD), PRL **113**, 252001 (2014)]

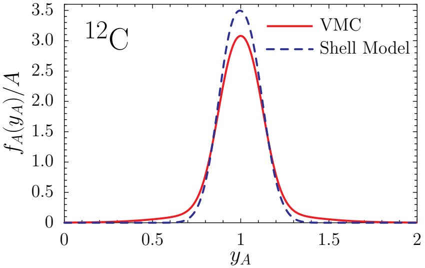


[$m_\pi \simeq 800\,\mathrm{MeV}$]

- 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 can only provide limited physical insight into nuclear structure
  - it cannot tell us what the relevant degrees of freedom are in nuclei

Nuclear Wave Functions



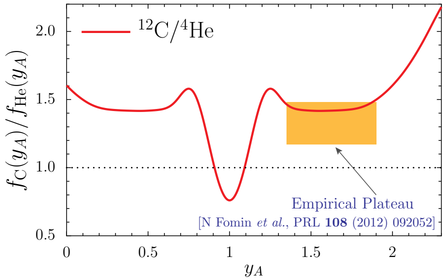


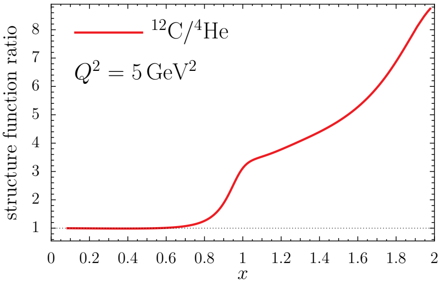
- Modern GFMC or VMC nuclear WFs have large high momentum tails
  - indicates wave function has large SRC component; ∼20% for ^{12}C
- Light cone momentum distribution of nucleons in nucleus is given by

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

	^{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

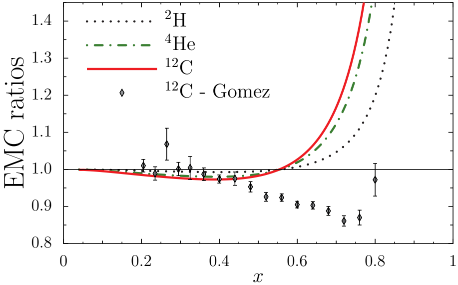
EMC effect and Short-Range Correlations

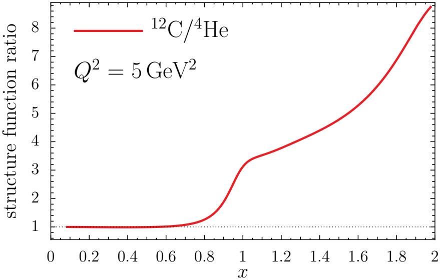




- Ratio of variational Monte Carlo (VMC) light cone wave function exhibits distinct plateau which agrees with experiment
- Using VMC light cone wave functions and convolution model with empirical nucleon PDFs to obtain nuclear structure functions and hence EMC effect
  - plateau still prominent in DIS 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