The EMC and EMC-like Effects

Exposing the partonic structure of nuclei

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Next generation nuclear physics with JLab12 and EIC

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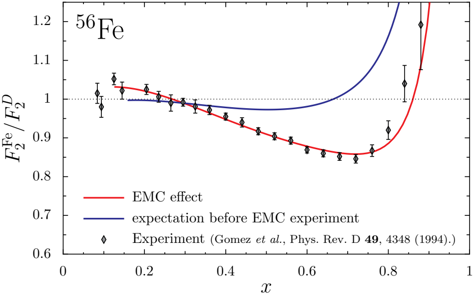
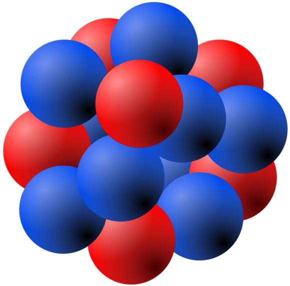
The EMC Effect

- Measurement of the *EMC effect* created a new paradigm regarding QCD and nuclear structure
  - 30+ years after discovery a broad consensus on explanation is lacking
  - *valence quarks in nucleus carry less momentum than in a nucleon*



- Understanding origin is critical for a QCD based description of nuclei

- Modern QCD motivated explanations based around medium modification of the bound nucleons
  - *is modification caused by mean-fields which modify all nucleons all the time or by SRCs which modify some nucleons some of the time?*



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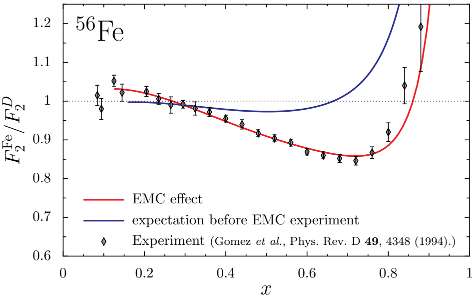
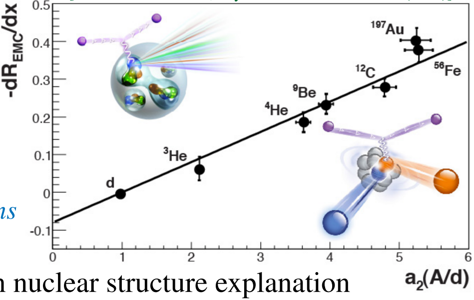


[L. B. Weinstein *et al.*, Phys. Rev. Lett. **106** 052301 (2011)]



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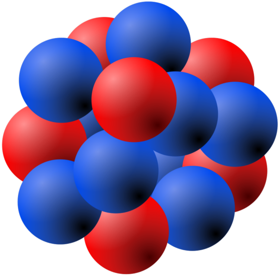
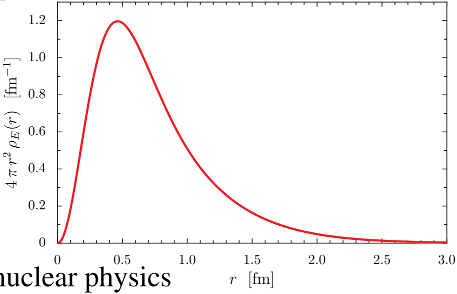
Mean-Field Medium Modification

- Nuclei are extremely dense:
  - proton rms radius is $r_p \simeq 0.85$ fm, corresponds hard sphere $r_p \simeq 1.10$ 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 ~ 2 fm apart



- For realistic charge distribution 22% of proton charge at distances $r > 1$ 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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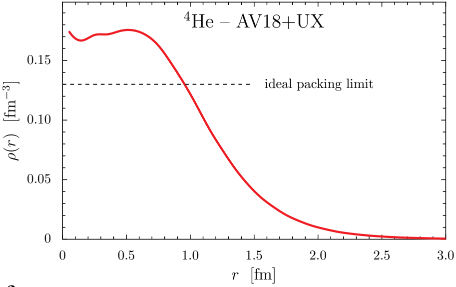

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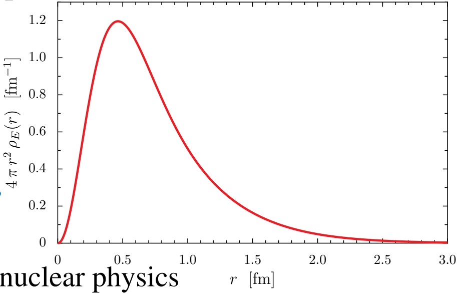
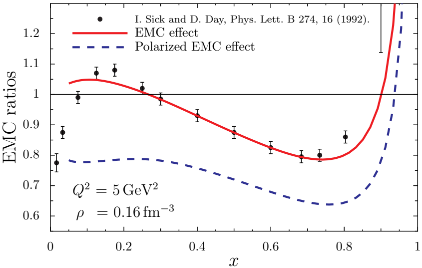
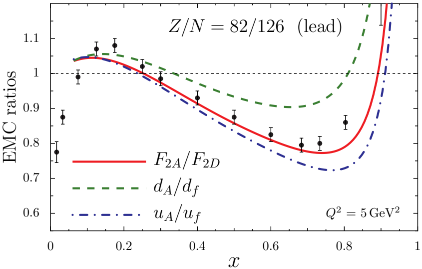


– *a new paradigm or deep insights into colour confinement in QCD*

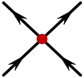
Understanding the EMC effect

- *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*





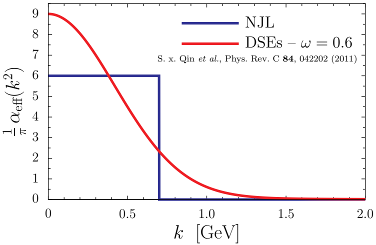
Continuum QCD *"integrate out gluons"* →

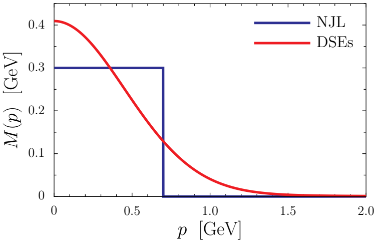


$\frac{1}{m_g^2}\ \Theta(\Lambda^2 - k^2)$

- 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

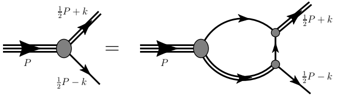
- Quark confinement is implemented via proper-time regularization
  - quark propagator: $[\not{p} - m + i\varepsilon]^{-1} \rightarrow Z(p^2)[\not{p} - M + i\varepsilon]^{-1}$
  - wave function renormalization vanishes at quark mass-shell: $Z(p^2 = M^2) = 0$
  - *confinement is critical for our description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



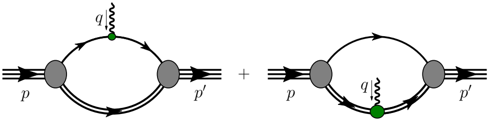


Nucleon Electromagnetic Form Factors

- Nucleon = quark+diquark

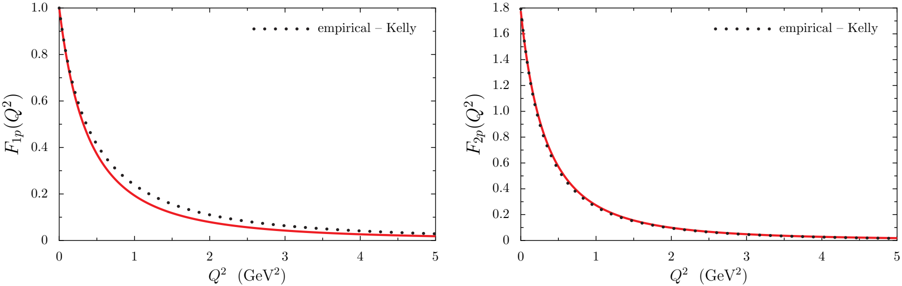


- Form factors given by Feynman diagrams:



- 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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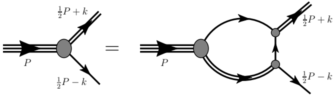
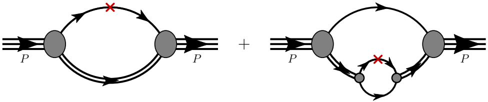
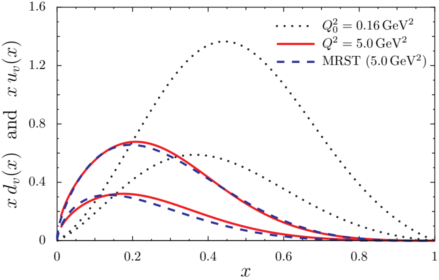


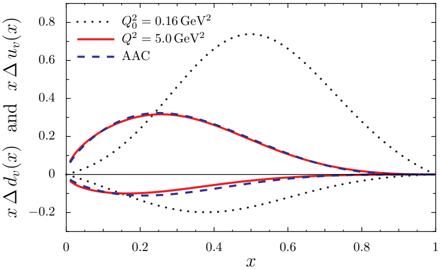
- PDFs given by Feynman diagrams: $\langle\gamma^+\rangle$



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

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

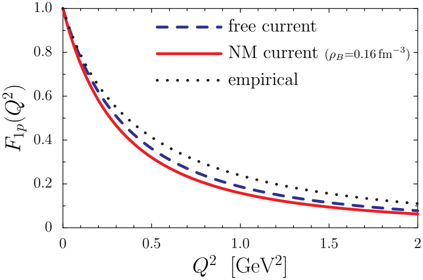


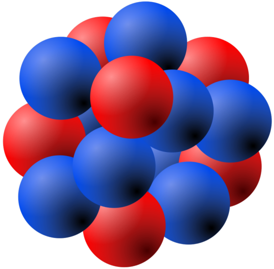


[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **621**, 246 (2005)]

A Nucleon 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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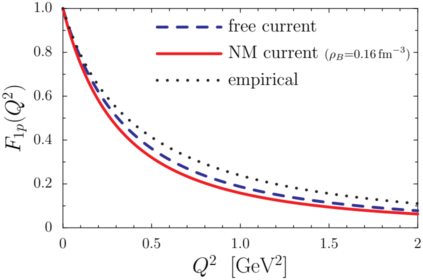
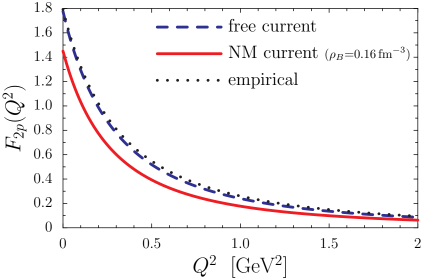
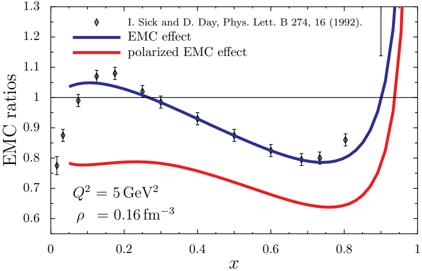


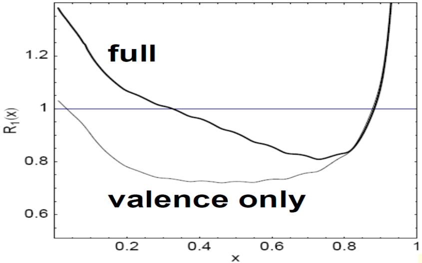


EMC and Polarized EMC effects

[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)]



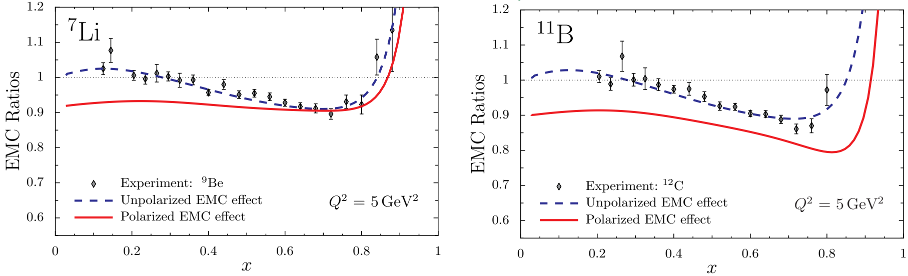
- Definition of polarized EMC effect:
  - ratio equals unity if no medium effects

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

- 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

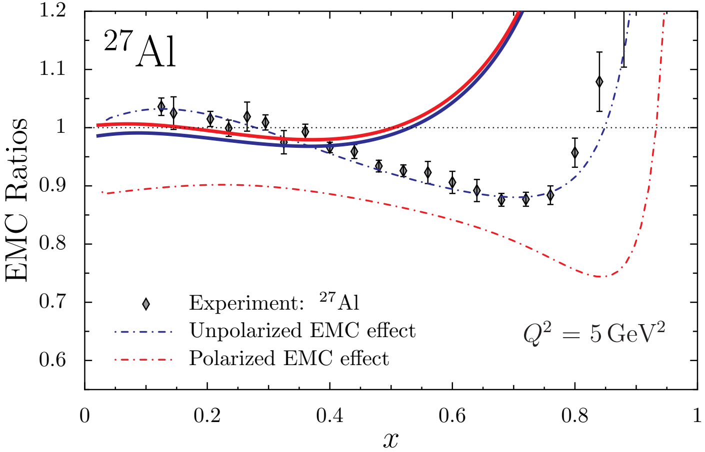
EMC effects in Finite Nuclei

[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*

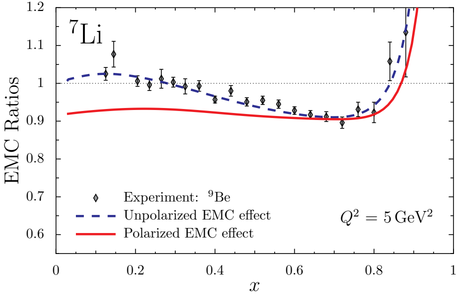
Turning off Medium Modification



- 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)]



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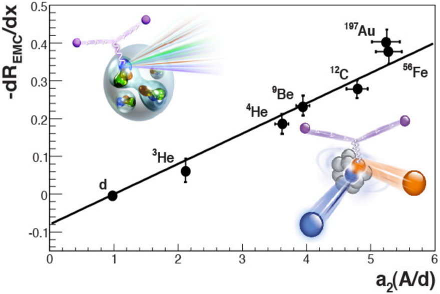
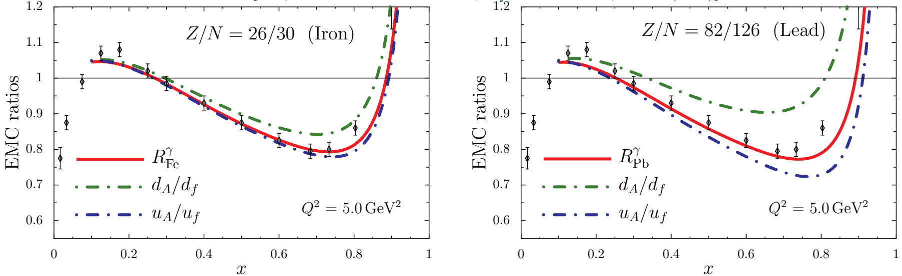


- Explanations of EMC effect using SRCs also invoke medium modification
  - since about 20% of nucleons are involved in SRCs, need medium modifications about 5 times larger than in mean-field models
- For polarized EMC effect only 2–3% of nucleons are involved in SRCs
  - it would therefore be natural 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)]

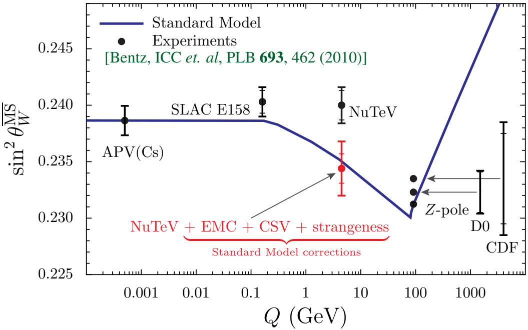


- Find that EMC effect is basically a result of binding at the quark level
  - for $N > Z$ nuclei, d-quarks feel more repulsion than u-quarks: $V_d > V_u$
  - therefore u quarks are more bound than d quarks
- Find isovector mean-field shifts momentum *from* u-quarks *to* d-quarks

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

  - therefore, from protons to neutrons – *this is opposite to SRCs, however unknown medium modification may still shift momentum from u to d*

The NuTeV anomaly



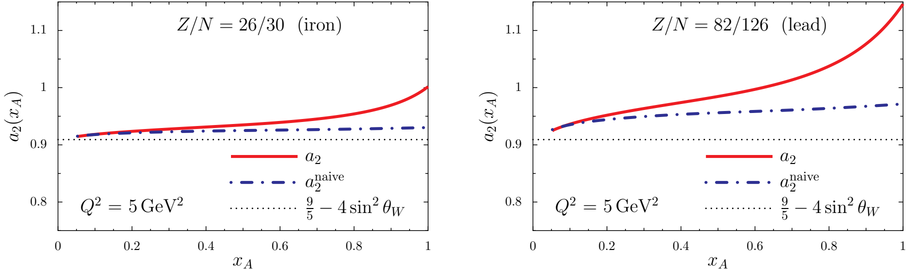
- Paschos-Wolfenstein ratio motivated NuTeV study:

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

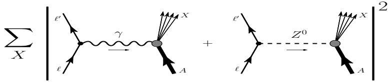
- NuTeV: $\sin^2\theta_W = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$ [Zeller *et al.* PRL. **88**, 091802 (2002)]
- Standard Model: $\sin^2\theta_W = 0.2227 \pm 0.0004$ $\Leftrightarrow 3\sigma \Longrightarrow$ "NuTeV anomaly"
- At the time widely thought as evidence for physics beyond 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
  - mean isovector field shifts momentum *from u to d*-quarks [therefore from p to n]

Parity-Violating DIS

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



- PV DIS – $\gamma\, Z$ interference:

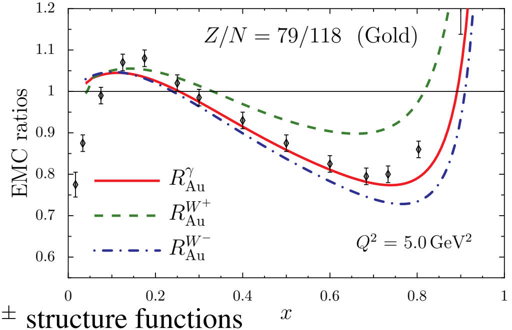


$$A_{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} \propto a_2(x) = -2g_A^e \frac{F_2^{\gamma Z}}{F_2^{\gamma}} \overset{N \sim Z}{=} \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\,\frac{u_A^+(x) - d_A^+(x)}{u_A^+(x) + d_A^+(x)}$$

- 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 – hopefully approved soon

Opportunities at an EIC

- 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



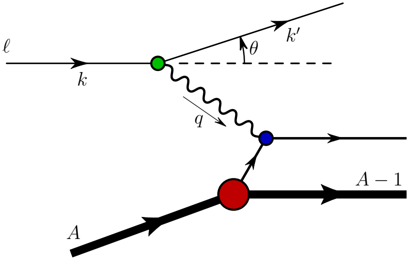
- Parton model expressions for $W^{\pm}$ structure functions

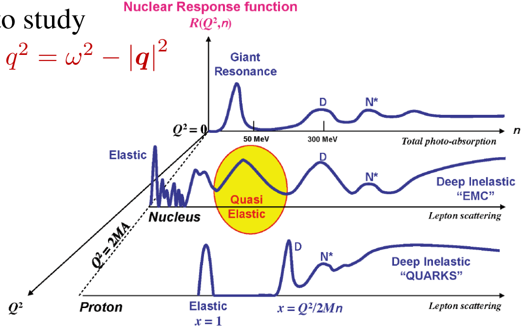
$$F_1^{W^+} = \bar{u} + d + s + \bar{c} \qquad F_3^{W^+} = -\bar{u} + d + s - \bar{c}$$
$$F_1^{W^-} = u + \bar{d} + \bar{s} + c \qquad F_3^{W^-} = u - \bar{d} - \bar{s} + c$$

- 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 $F_2(x, Q^2)$

Coulomb Sum Rule

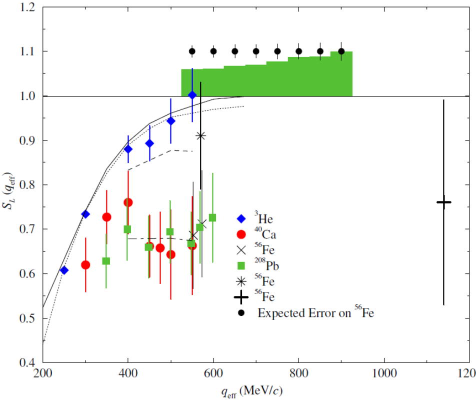
- The "Coulomb Sum Rule" reads

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

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

- Non-relativistic expectation – as $|\boldsymbol{q}|$ becomes large – $C(|\boldsymbol{q}| \gg p_F) \to 1$
  - CSR counts number of charge carriers

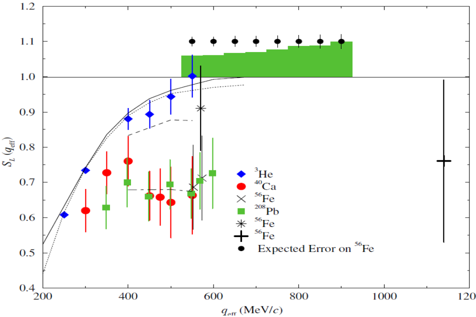
- The CSR was first measured at MIT Bates in 1980 then at Saclay in 1984
  - both experiments observed significant *quenching* of the CSR

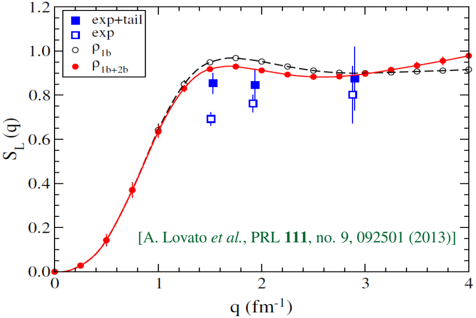


- Two plausible explanations: 1) *nucleon structure is modified in the nuclear medium;* 2) *experiment/analysis is flawed e.g. Coulomb corrections*

- A number of influential physicists have argued very strongly for the latter

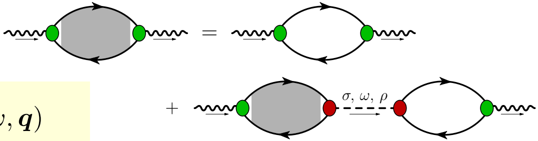
- No new data on the CSR since SLAC data from early 1990s
- The *quenching* of the CSR has become one of the most contentious observations in all of nuclear physics
- Experiment E05-110 was performed at Jefferson Lab in 2005 – should settle controversy of CSR *quenching*
- State-of-the-art traditional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





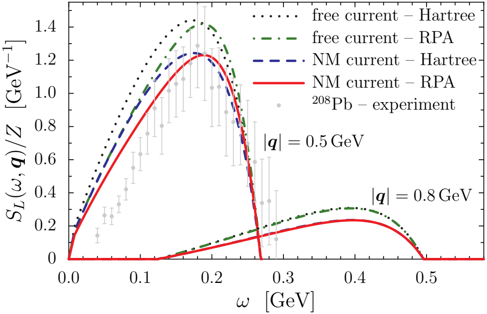
Longitudinal Response Function

- In nuclear matter response function given by



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

- 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 $|\boldsymbol{q}| \gtrsim 0.7\,\mathrm{GeV}$

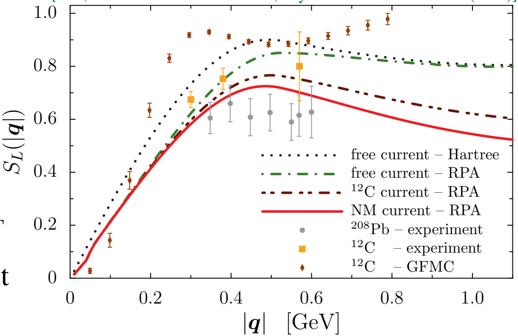


Coulomb Sum Rule

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

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

[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 $|\boldsymbol{q}| \simeq 1\,$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
  - 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 experiment will measure the polarized EMC effect in ^{7}Li; PVDIS also important!
- The next frontier is GPDs and TMDs of nuclei at JLab12 or an EIC