EMC Effect:
Isospin dependence and PVDIS

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Quantitative challenges in EMC and SRC Research and Data-Mining

Massachusetts Institute of Technology

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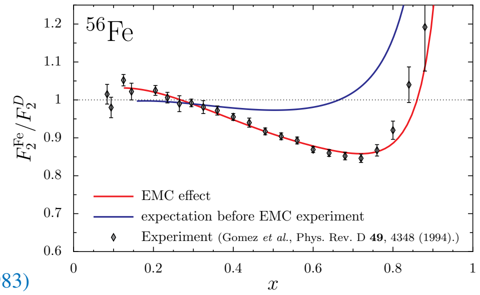
The EMC effect

- 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)

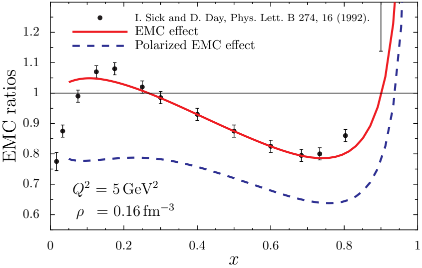


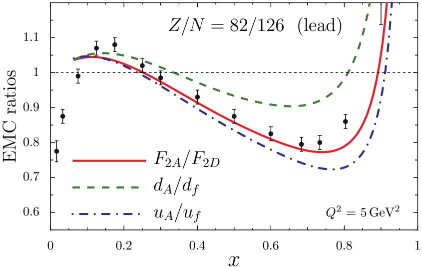
"The results are in complete disagreement with the calculations ... We are not aware of any published detailed prediction presently available which can explain behavior of these data."

- 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

Understanding the EMC effect

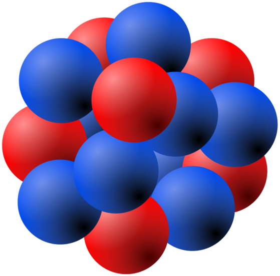
- *The puzzle posed by the EMC effect will only be solved by conducting new experiments that expose novel aspects of the EMC effect*
- Measurements should help distinguish between explanations of EMC effect
  e.g. whether *all nucleons* are modified by the medium or only those in SRCs
- Important examples are:
  - *EMC effect in polarized structure functions*
  - *flavour dependence of EMC effect*
- JLab DIS experiment on ^{40}Ca & ^{48}Ca sensitive to flavour dependence
  but to truely access flavour dependence PVDIS must play a pivotal role



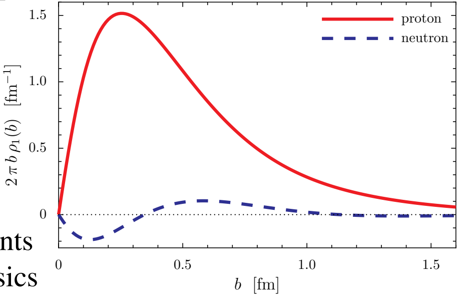


Nucleons in Nuclei

- 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 25% 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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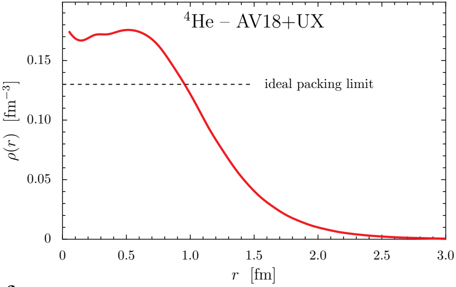

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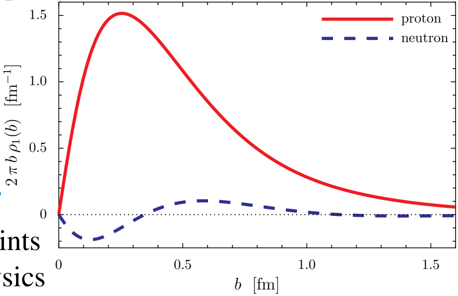

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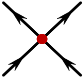
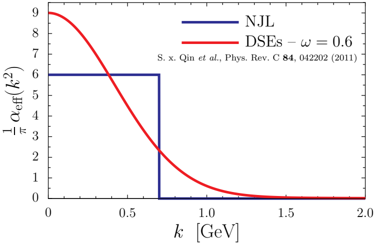
– *a new paradigm or deep insights into colour confinement in QCD*

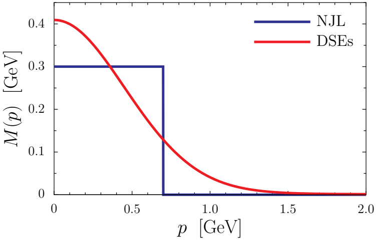
Quarks, Nuclei and the NJL model

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

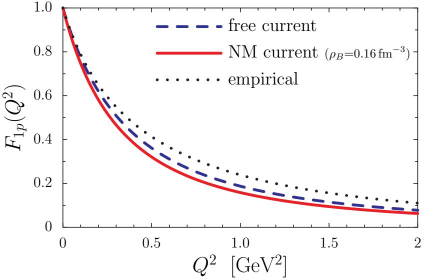
- Quark confinement is implemented via proper-time regularization
  - quark propagator: $[\not{p} - m + i\varepsilon]^{-1} \quad \rightarrow \quad Z(p^2)[\not{p} - M + i\varepsilon]^{-1}$
  - wave function renormalization vanishes at quark mass-shell: $Z(p^2 = M^2) = 0$
  - *confinement is critical for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

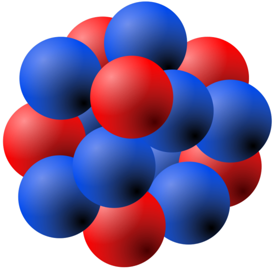




Nucleons in the Nuclear Medium

- 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 $F_{2p}/2M_N$ largely constant – μ_p almost constant





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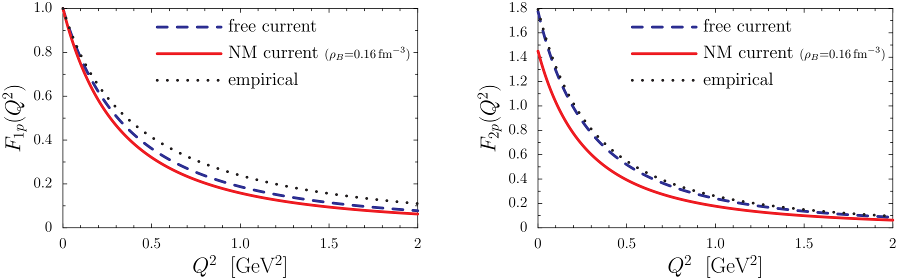
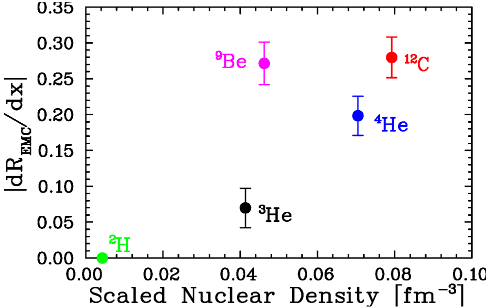
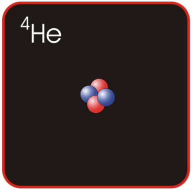
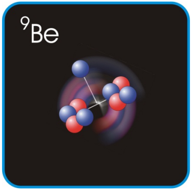
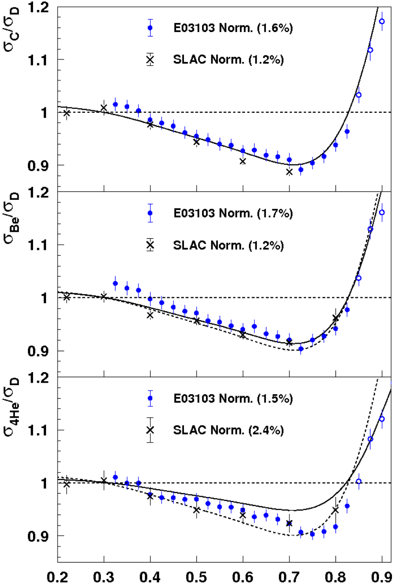








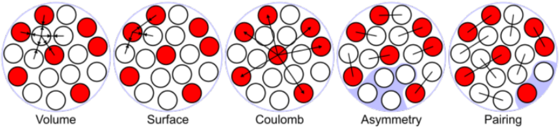
[J. Seely *et al.*, PRL **103**, 202301 (2009)]



- EMC effect determined by *local density*
- *^{9}Be consistent with our mean-field approach*

- Why should we expect a (large) isovector EMC effect?
- Consider the Bethe–Weizsäcker mass formula

$$E_B = a_V\,A - a_S\,A^{2/3} - a_C\,\frac{Z^2}{A^{1/3}} - a_A\,\frac{(A-2\,Z)^2}{A} \pm \delta(A,Z)$$



$a_V = 15.75 \quad a_S = 17.8 \quad a_C = 0.711 \quad a_A = 23.7 \quad a_P = 11.8$ [J. W. Rohlf (1994)]

- There is a trivial isovector EMC effect from: $N \neq Z \implies u_A \neq d_A$
  - non-trivial effect must remain after isoscalarity correction to have a flavour dependent EMC effect

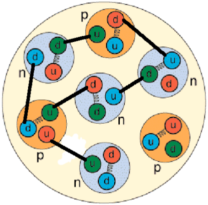
$$f_A^{\rm ISO}(x) = \frac{A}{2}\,\frac{F_{2p} + F_{2n}}{Z\,F_{2p} + N\,F_{2n}}$$

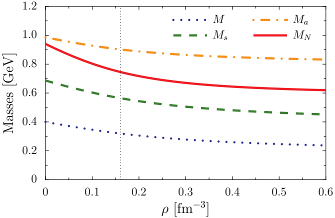
NJL at Finite Density

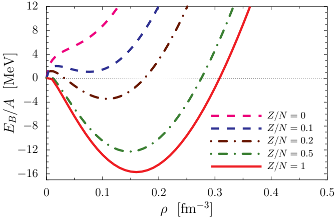
- Finite density (mean-field) Lagrangian: $\bar{q}q$ interaction in $\sigma,\ \omega,\ \rho$ channels

$$\mathcal{L} = \overline{\psi}_q \left(i\,\not{\partial} - M^* - \not{V}_q\right)\psi_q + \mathcal{L}'_I$$

- *Fundamental physics – mean fields couple to the quarks in nucleons*







- Quark propagator: $S(k)^{-1} = \not{k} - M + i\varepsilon \ \rightarrow\ S_q(k)^{-1} = \not{k} - M^* - \not{V}_q + i\varepsilon$

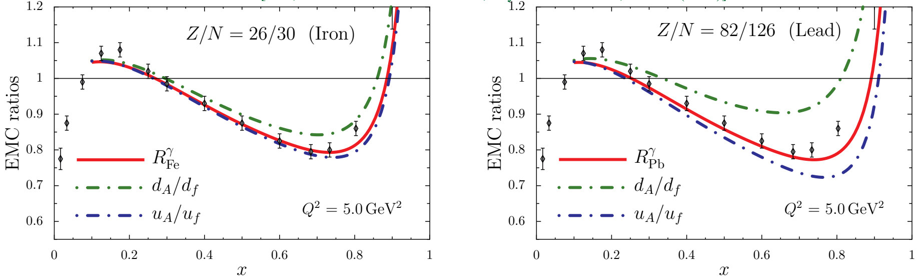
- Hadronization + mean–field $\Longrightarrow$ effective potential

$$V_{u(d)} = \omega_0 \pm \rho_0, \qquad \omega_0 = 6\,G_\omega\,(\rho_p + \rho_n)\,, \qquad \rho_0 = 2\,G_\rho\,(\rho_p - \rho_n)$$

  - $G_\omega \Longleftrightarrow Z = N$ saturation & $G_\rho \Longleftrightarrow$ symmetry energy

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* – medium modification from SRCs needs to compensate for this

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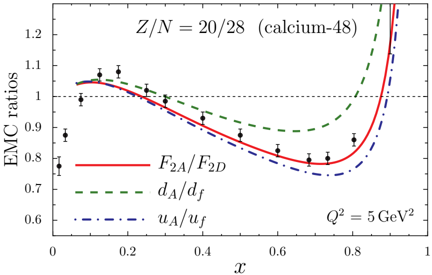

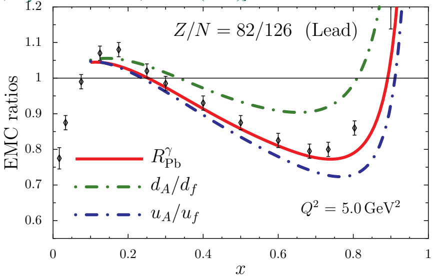

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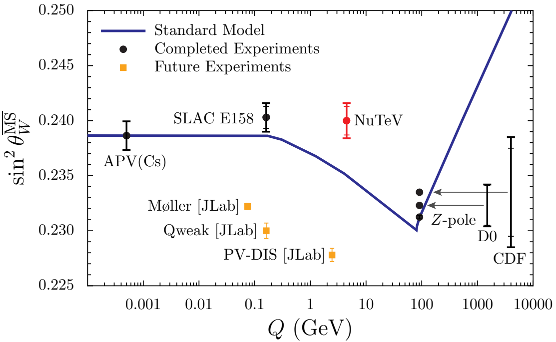
Weak mixing angle and the NuTeV anomaly



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 widely accepted *complete* explanation

Paschos-Wolfenstein ratio

- Paschos-Wolfenstein ratio motivated the NuTeV study:

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

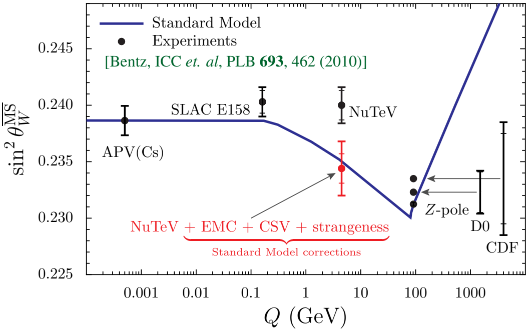
  - $\langle x_A\, q_A^- \rangle$ fraction of target momentum carried by valence quarks of flavor q

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

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

- 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

A Reassessment of the NuTeV anomaly



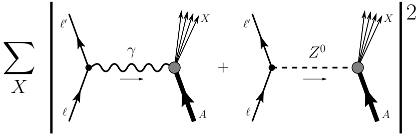
- Paschos-Wolfenstein ratio motivated NuTeV study:

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

- 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: $\sin^2\theta_W = 0.2227 \pm 0.0004$ $\Leftrightarrow 3\sigma \implies$ "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

New insights from Parity-Violating DIS

- PVDIS can test this explanation for the NuTeV anomaly & provide much needed new insight into the EMC effect



- $\gamma\, Z$ interference gives non-zero asymmetry; in Bjorken limit:

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{G_F\, Q^2}{4\sqrt{2}\,\alpha_{\rm em}} \left[a_2(x) + \frac{1-(1-y)^2}{1+(1-y)^2}\, a_3(x) \right]$$

$$a_2(x) = -2\, g_A^e\, \frac{F_2^{\gamma Z}}{F_2^{\gamma}} \simeq \frac{6\, u^+ + 3\, d^+}{4\, u^+ + d^+} - 4 \sin^2\theta_W$$

$$a_3(x) = -2\, g_V^e\, \frac{x\, F_3^{\gamma Z}}{F_2^{\gamma}} \simeq 3\left(1 - 4\sin^2\theta_W\right) \frac{2\, u^- + d^-}{4\, u^+ + d^+}$$

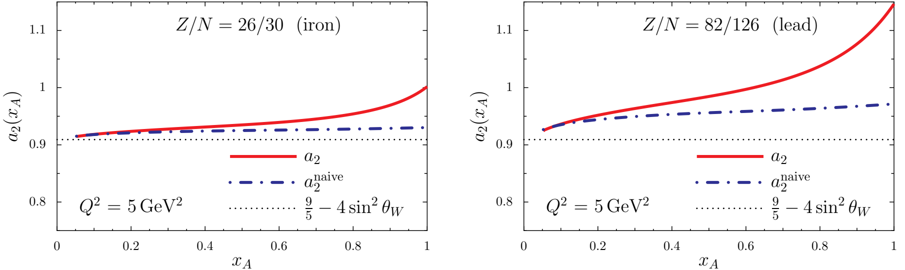
- Parton model expressions

$$\left[F_2^{\gamma},\ F_2^{\gamma Z}\right] = x \sum\nolimits_q \left[e_q^2,\ 2\, e_q\, g_V^q\right] (q + \bar{q}) \qquad F_3^{\gamma Z} = 2 \sum\nolimits_q e_q\, g_A^q\ (q - \bar{q})$$

$$g_V^q = \pm\frac{1}{2} - 2\, e_q\ \sin^2\theta_W \qquad g_A^q = \pm\frac{1}{2}$$

Isovector Effects in Nuclei

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



- PVDIS – $\gamma\, Z$ interference:

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

- 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 $a_2(x)$ of ^{48}Ca was deferred twice …

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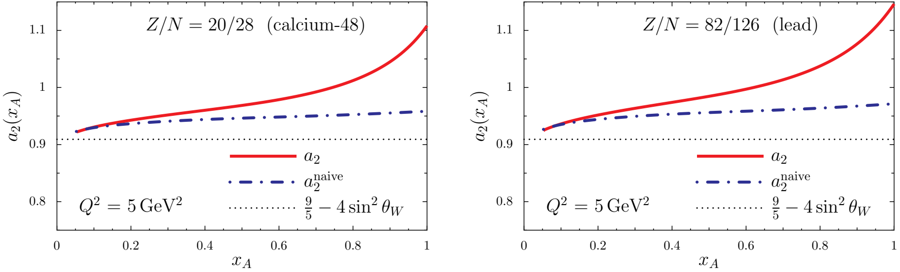

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Anti-Quarks & Gluons in Nuclei

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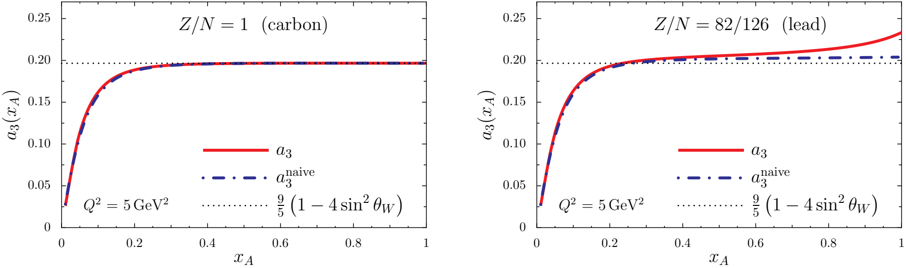

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- $a_3(x)$ is a sensitive measure of anti-quarks in nucleons and nuclei
- Under DGLAP the numerator evolves as a non-singlet – *independent of the gluons* – whereas denominator evolution involves the gluon PDF
  - given a large Q^2 lever arm $a_3(x)$ can help constrain the gluon PDF
  - this is a key goal of Jefferson Lab and a future EIC

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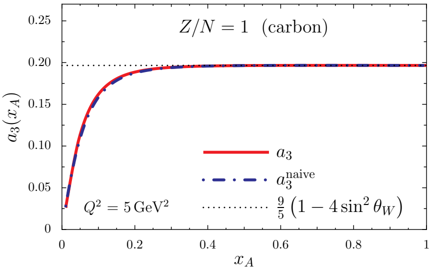
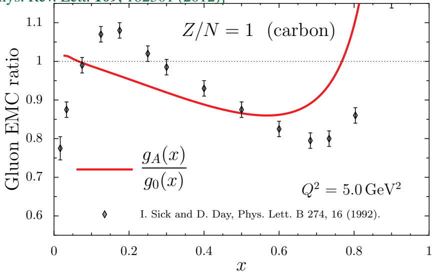




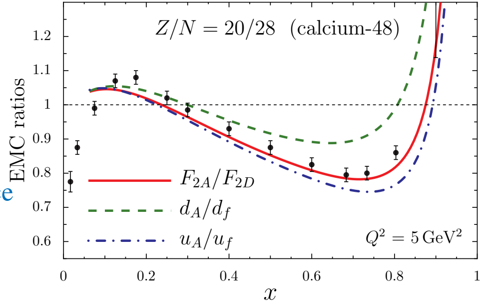
- PVDIS – $\gamma\, Z$ interference:

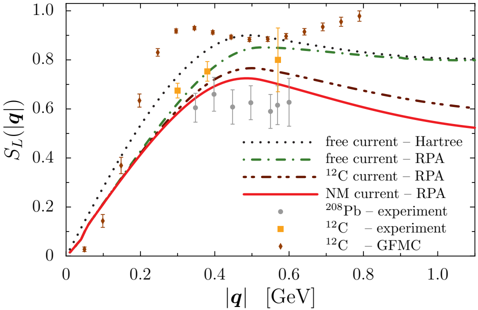
$$a_3(x) = -2\, g_V^e\, \frac{x\, F_3^{\gamma Z}(x)}{F_2^{\gamma}(x)} \overset{N\sim Z}{\simeq} \frac{9}{5}\left(1 - 4\sin^2\theta_W\right) \frac{u_A^-(x) + d_A^-(x)}{u_A^+(x) + d_A^+(x)}$$

- $a_3(x)$ is a sensitive measure of anti-quarks in nucleons and nuclei
- Under DGLAP the numerator evolves as a non-singlet – *independent of the gluons* – whereas denominator evolution involves the gluon PDF
  - given a large Q^2 lever arm $a_3(x)$ can help constrain the gluon PDF
  - this is a key goal of Jefferson Lab and a future EIC

Conclusion

- Need new experiments that provide clean access to new aspects of the EMC effect
  - PVDIS experiment on ^{48}Ca deferred twice – would provide critical information on the flavour dependence of the EMC effect
- NuTeV anomaly can be explained by an isovector EMC effect & CSV
- *To make progress with the JLab PAC on approving experiments to help solve the EMC effect it is essential to identify at most a handful of must do experiments*
- Coulomb Sum Rule another key observable to shed light on medium modification



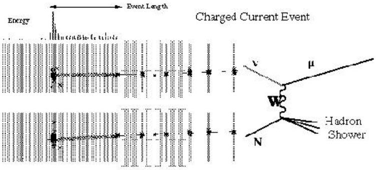


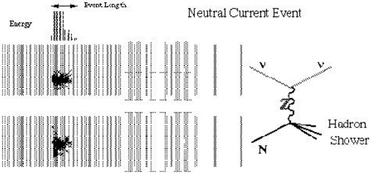
Backup Slides

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

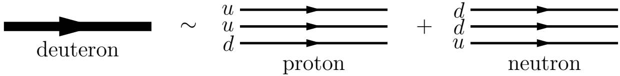
CSB Correction to NuTeV

- Two sources of charge symmetry breaking (CSB) corrections
  - quark mass differences: $\delta m = m_d - m_u \sim 4\,\text{MeV}$
  - quark charge differences: $e_u^2 \neq e_d^2$ [QED splitting/QED evolution of PDFs]
- CSB correction to Paschos-Wolfenstein ratio:

$$\Delta R_{PW}^{CSB} \simeq \left(1 - \tfrac{7}{3}\sin^2\theta_W\right) \frac{\langle x\, u_A^- - x\, d_A^- \rangle}{\langle x\, u_A^- + x\, d_A^- \rangle} \longrightarrow \tfrac{1}{2}\left(1 - \tfrac{7}{3}\sin^2\theta_W\right) \frac{\langle x\, \delta u^- - x\, \delta d^- \rangle}{\langle x\, u_p^- + x\, d_p^- \rangle}$$

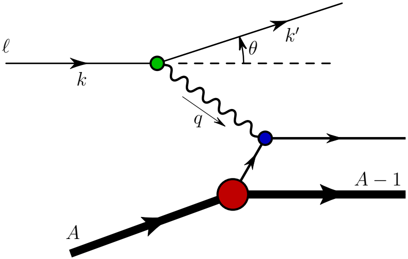
$$\delta d^-(x) = d_p^-(x) - u_n^-(x) \qquad \delta u^-(x) = u_p^-(x) - d_n^-(x)$$

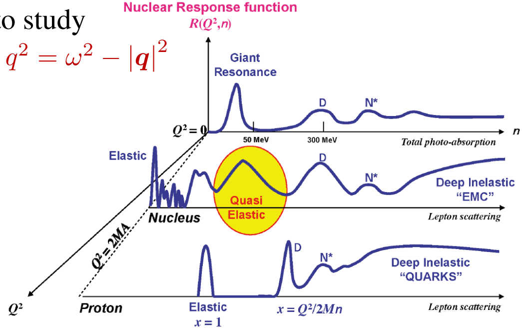
- Mass differences – what do we expect? Consider deuteron:



  - therefore since: $m_u < m_d \implies \langle x\, u_A^- \rangle < \langle x\, d_A^- \rangle$
- $e_u^2 > e_d^2 \implies$ u-quarks lose momentum faster than d-quarks to γ-field
- Expect CSB corrections reduce NuTeV discrepancy with Standard Model

- 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

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

  - 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 $F_2(x, Q^2)$

Quasi-elastic scattering

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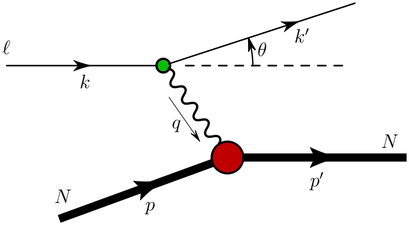

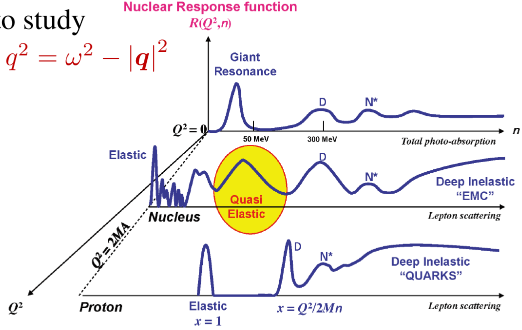

- The cross-section for this process reads

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

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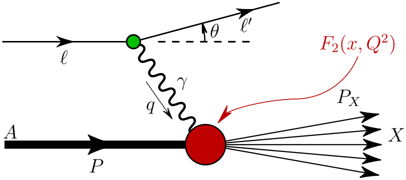

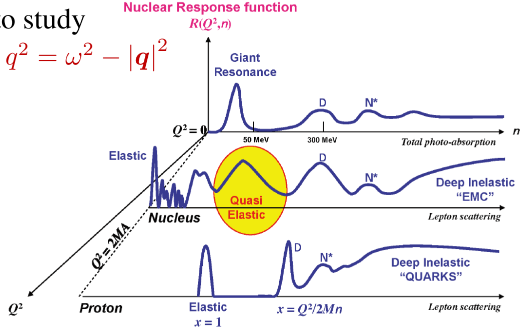

- The cross-section for this process reads

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

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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 $F_2(x, Q^2)$

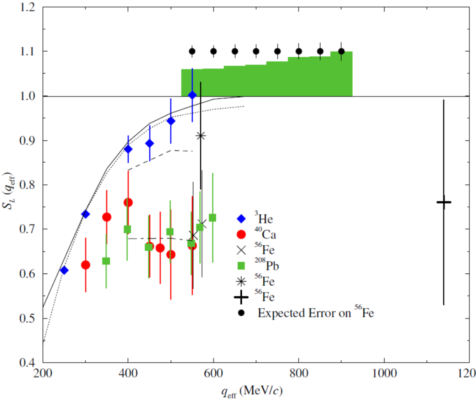
Coulomb Sum Rule

- The "Coulomb Sum Rule" reads

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

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

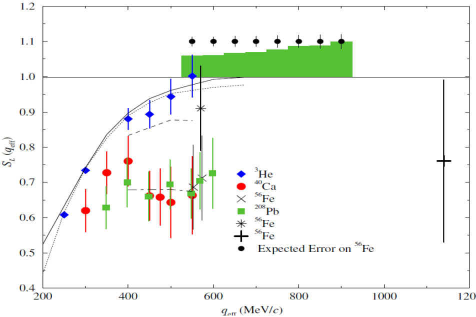
- Non-relativistic expectation – as $|\boldsymbol{q}|$ becomes large – $S_L(|\boldsymbol{q}| \gg p_F) \to 1$
  - CSR counts number of charge carriers

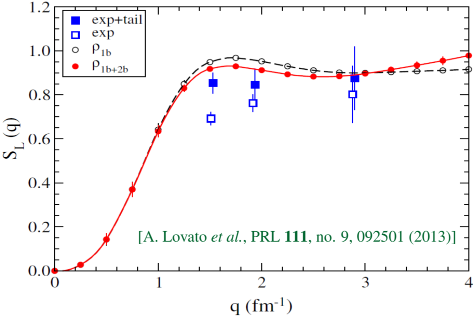


- The CSR was first measured at MIT Bates in 1980 then at Saclay in 1984
  - both experiments observed significant *quenching* of the CSR
- Two plausible explanations: 1) *nucleon structure is modified in the nuclear medium;* 2) *experiment/analysis is flawed e.g. Coulomb corrections*
- A number of influential physicists have argued very strongly for the latter

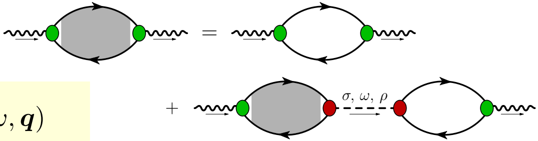
Coulomb Sum Rule Today

- 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



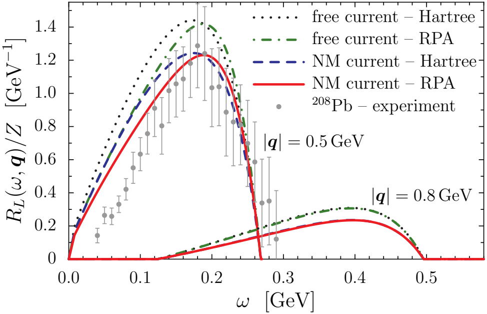


- In nuclear matter response function given by



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

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

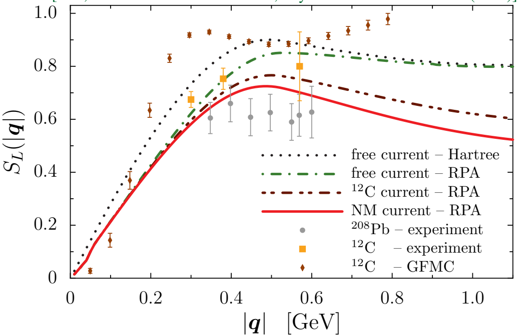


Coulomb Sum Rule

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

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

[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