The Polarized EMC Effect

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Polarized light-ion physics with an EIC

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U.S. DEPARTMENT OF ENERGY | Office of Science

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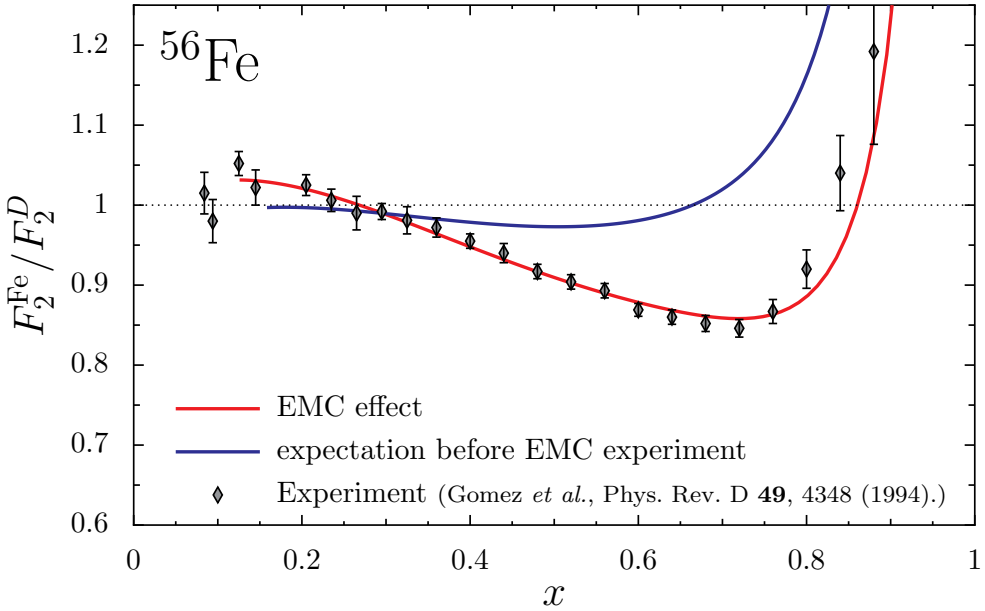
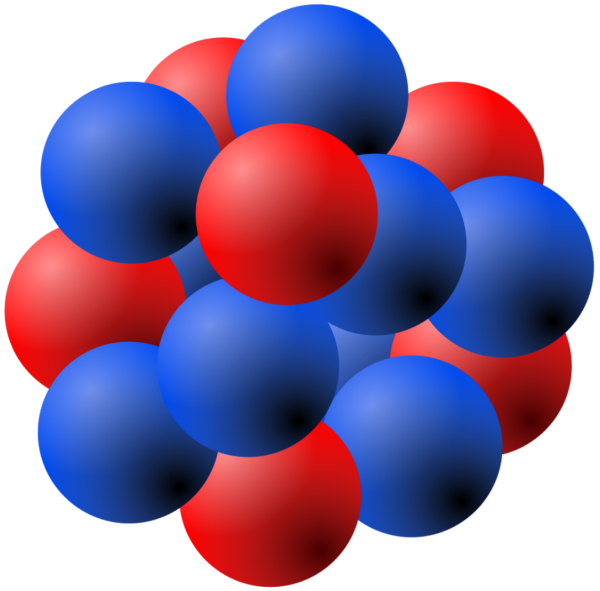
The EMC Effect

- 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?*
- Many nuclear physicists think nuclear structure provides explanation





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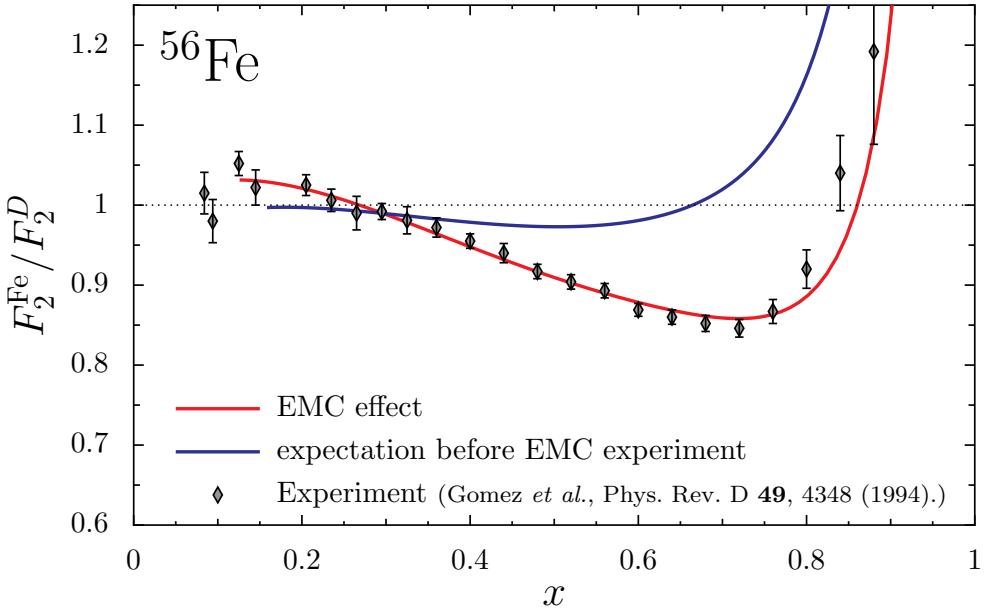
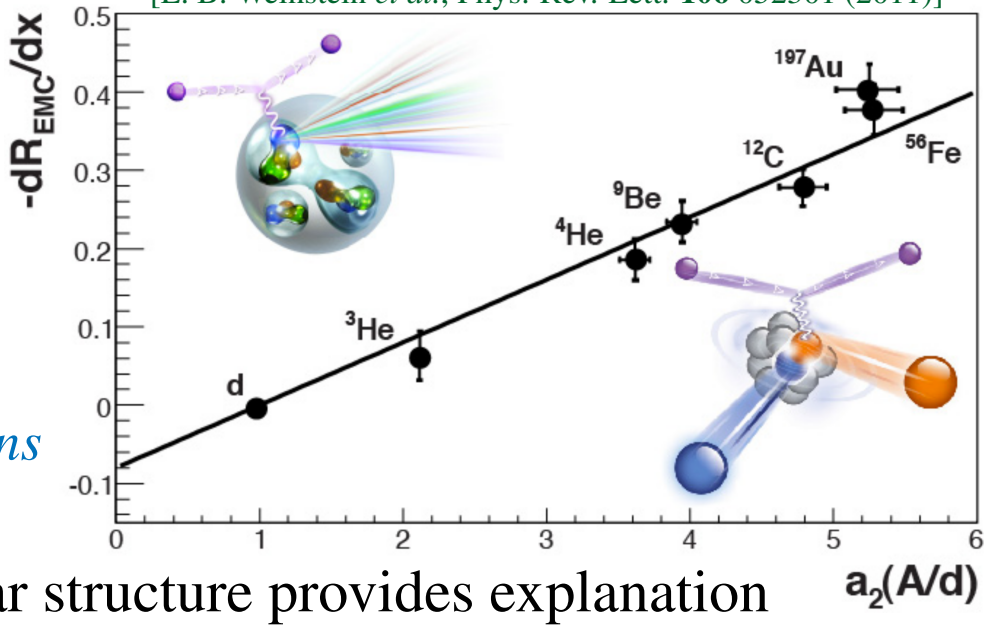


[L. B. Weinstein *et al.*, Phys. Rev. Lett. **106** 052301 (2011)]



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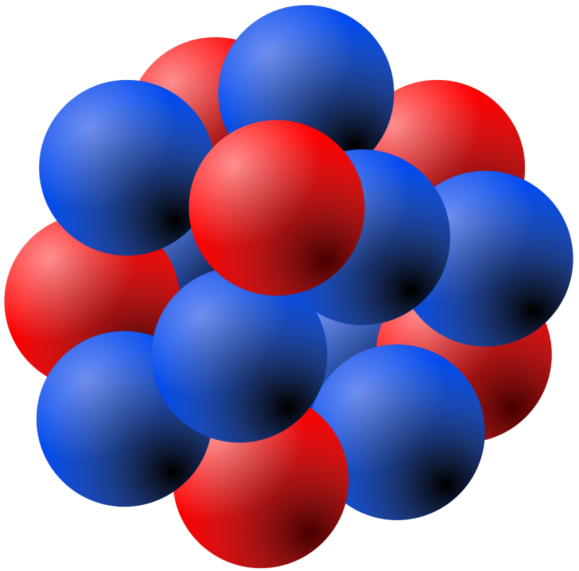
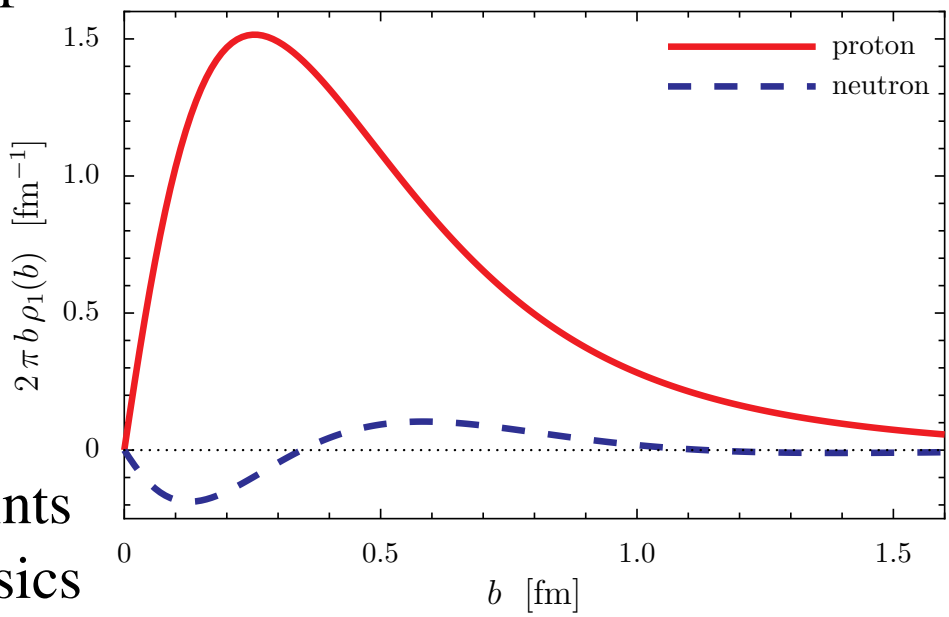
Nucleons in Nuclei

- Nuclei are extremely dense:
  - proton rms radius is $r_p \simeq 0.85\,\mathrm{fm}$, corresponds hard sphere $r_p \simeq 1.10\,\mathrm{fm}$
  - ideal packing gives $\rho \simeq 0.13\,\mathrm{fm}^{-3}$; nuclear matter density is $\rho \simeq 0.16\,\mathrm{fm}^{-3}$
  - 20% of nucleon volume inside other nucleons – nucleon centers $\sim 2\,\mathrm{fm}$ apart



- For realistic charge distribution 25% of proton charge at distances $r > 1\,\mathrm{fm}$
- *Natural to expect that nucleon properties are modified by nuclear medium – even at the mean-field level*
  - in contrast to traditional nuclear physics



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

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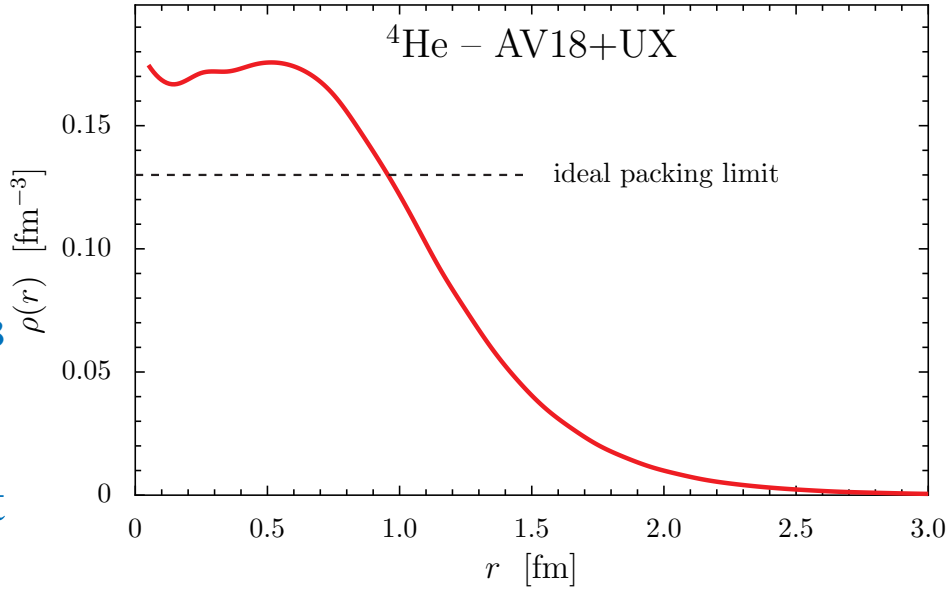

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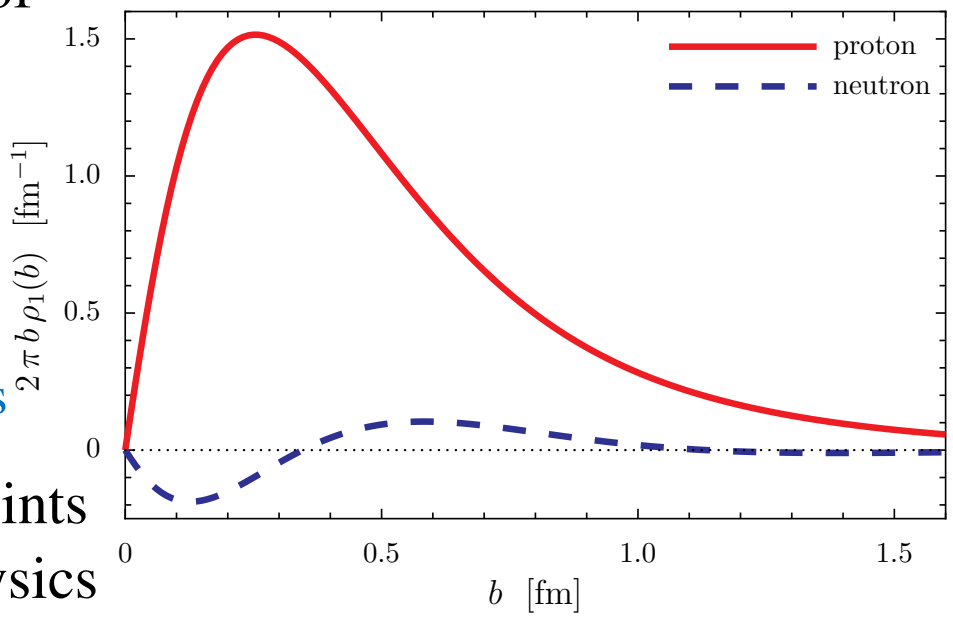
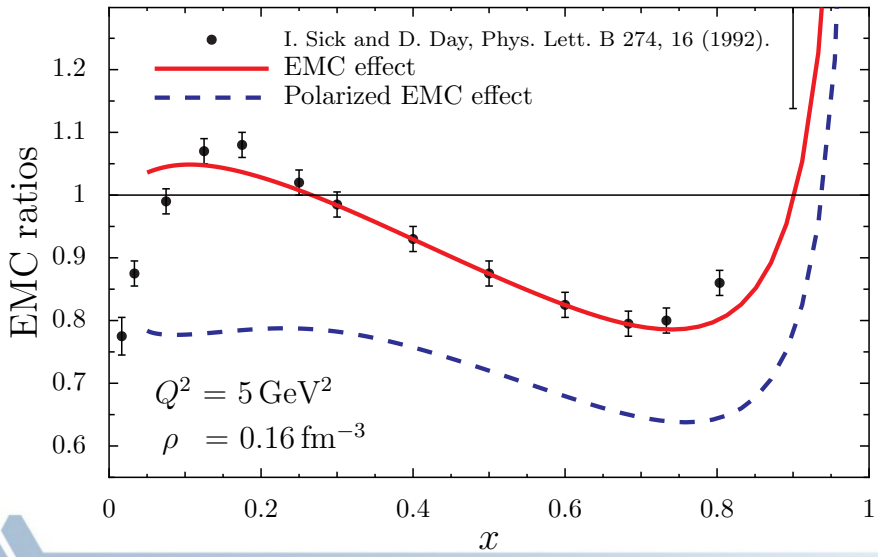
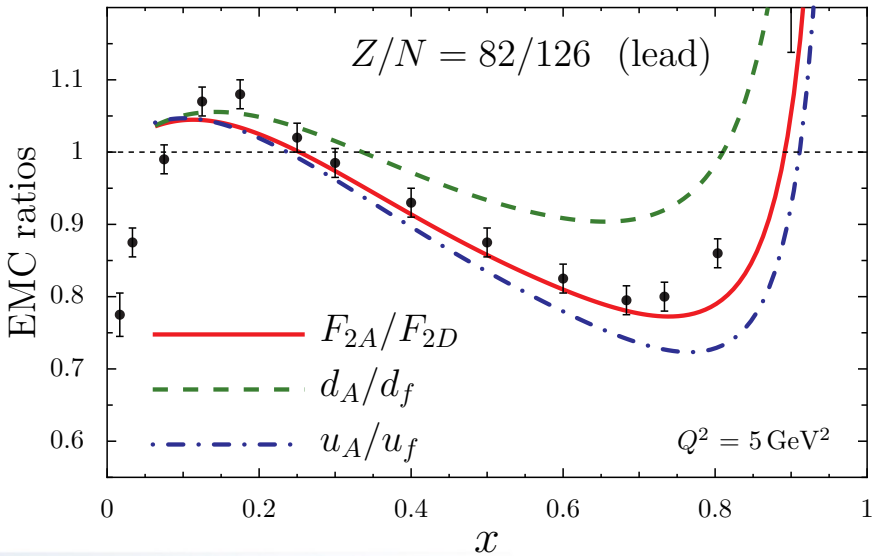


- Understanding validity of two viewpoints remains key challenge for nuclear physics
  – *a new paradigm or deep insights into color confinement in QCD*

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 *flavor dependence of EMC effect*
- A JLab experiment has been approved to measure the spin structure of ^{7}Li
- Flavor dependence will be accessed via JLab DIS experiments on ^{40}Ca & ^{48}Ca – *but parity violating DIS stands to play the pivotal role (maybe at EIC)*





Theory approaches to EMC effect

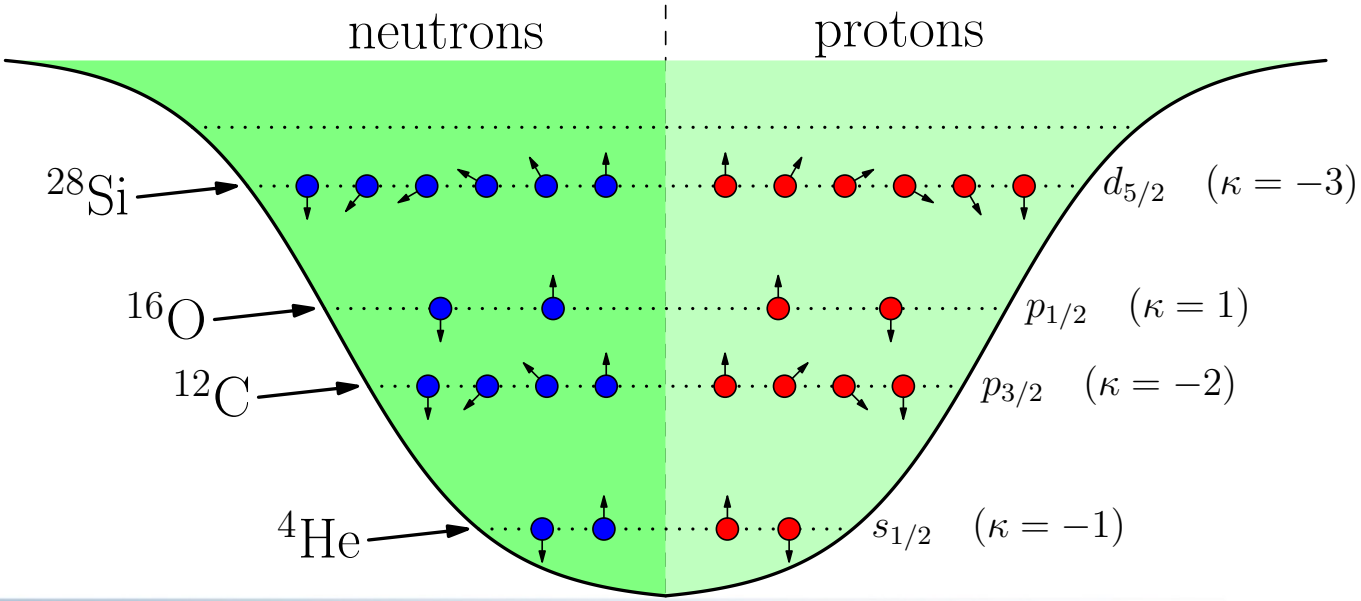
- To address the EMC effect must determine nuclear quark distributions:

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

- Common to approximate using convolution formalism

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

  - $\alpha =$ (bound) protons, neutrons, pions, deltas. . . .



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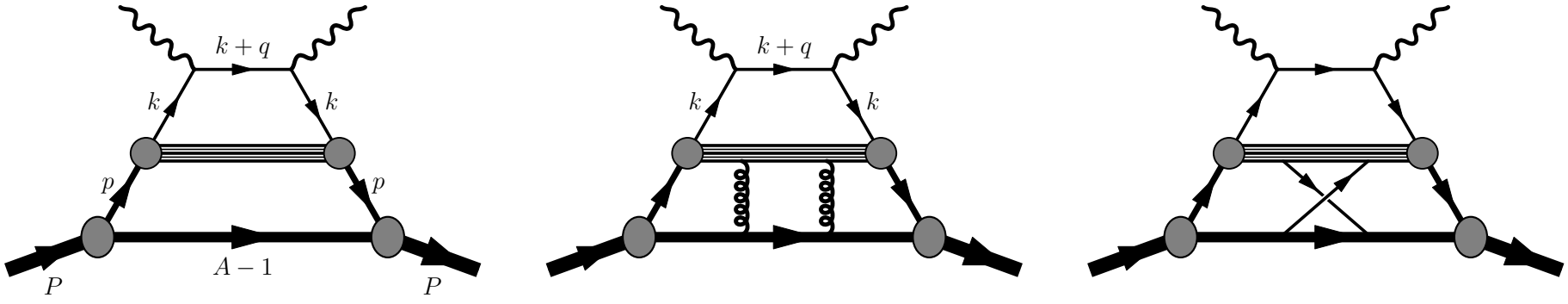
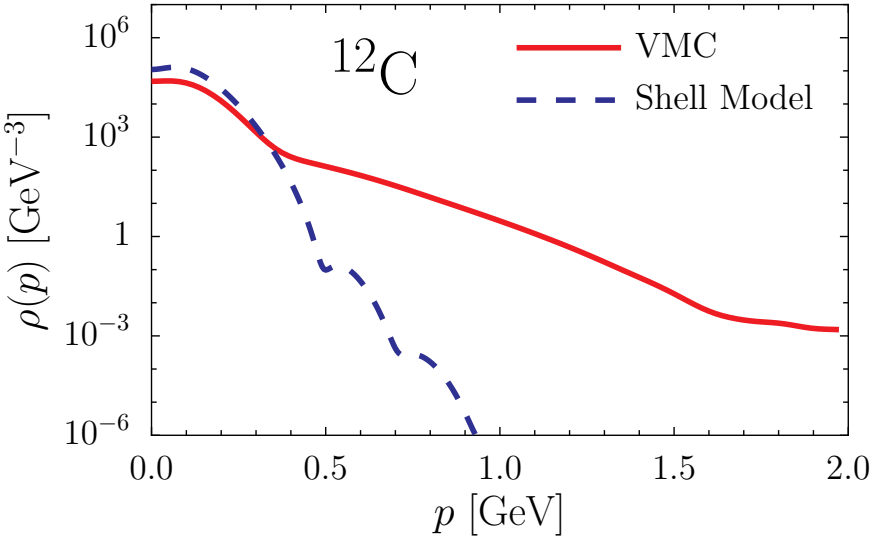
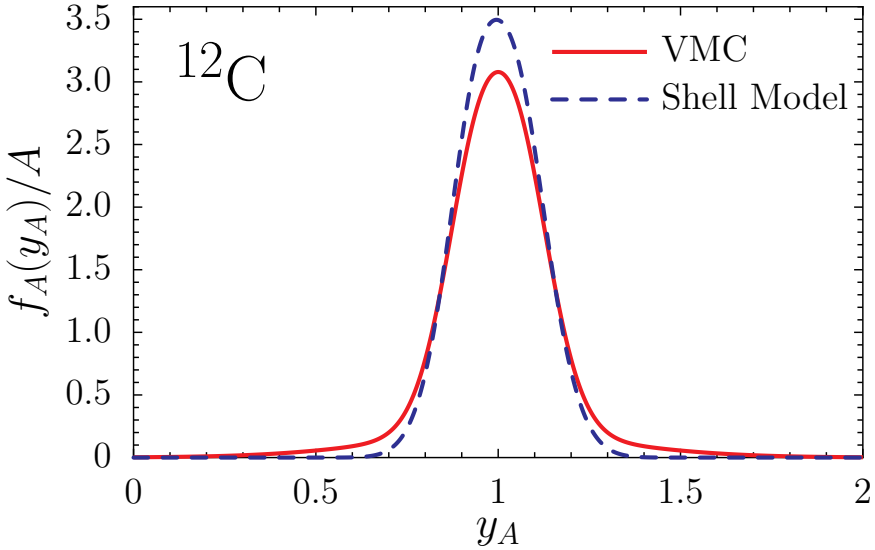
  - $\alpha =$ (bound) protons, neutrons, pions, deltas. . . .
  - $q_\alpha\left(x\right)$ light-cone distribution of quarks q in bound hadron α
  - $f_\alpha(y_A)$ light-cone distribution of hadrons α in nucleus



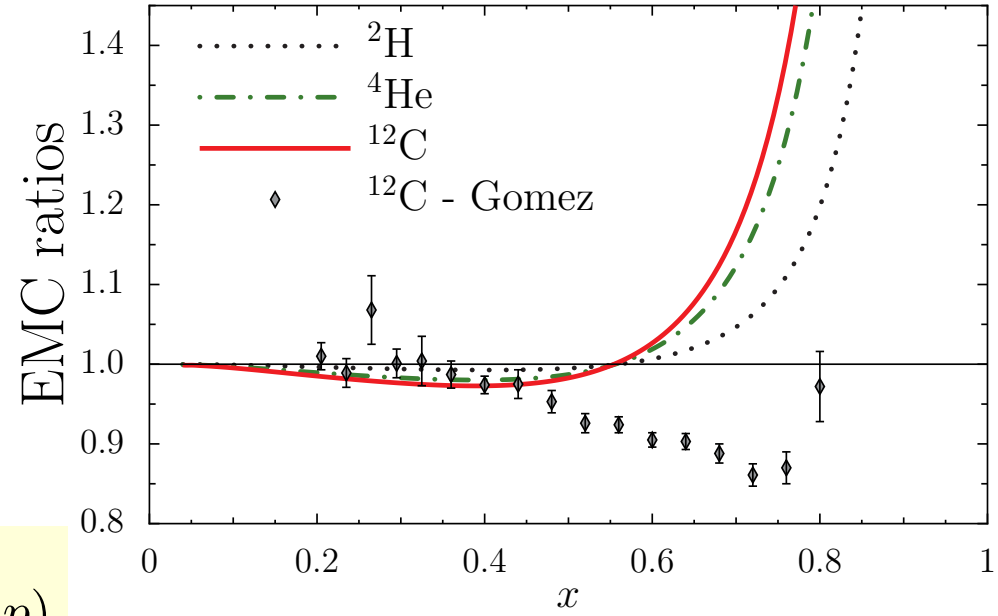
Nuclear Wave Functions





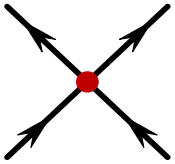
- Modern GFMC or VMC nucleon momentum distributions have significant high momentum tails
  - indicates momentum distributions contain SRCs: ∼20% for ^{12}C
- Light-cone momentum distribution of nucleons in nucleus is given by

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



Quarks, Nuclei, and the NJL model

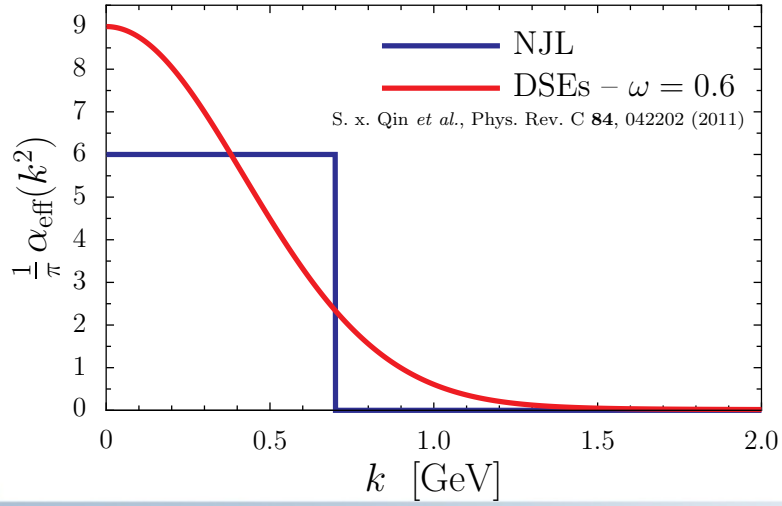
QCD *"integrate out gluons"* →

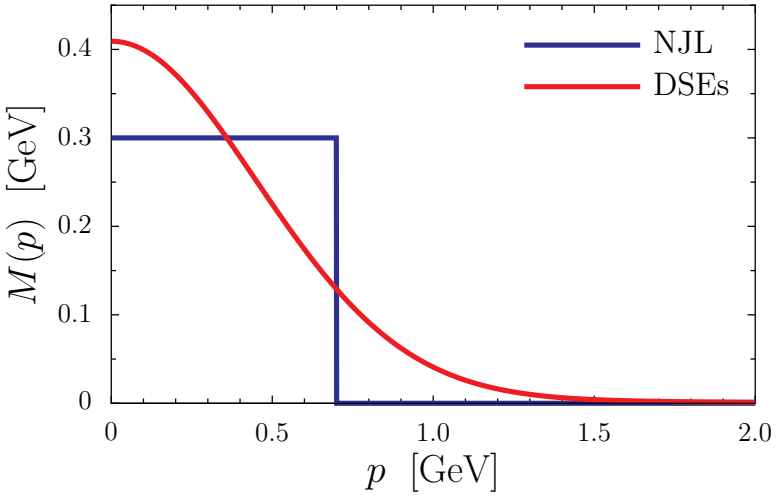


$\frac{1}{m_g^2}\ \Theta(\Lambda^2 - k^2)$

- 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

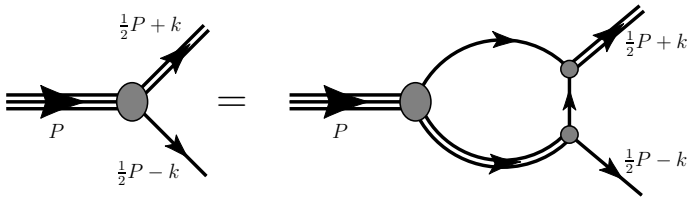
- Quark confinement is implemented via proper-time regularization
  - quark propagator: $[\not{p} - m + i\varepsilon]^{-1} \rightarrow Z(p^2)[\not{p} - M + i\varepsilon]^{-1}$
  - wave function renormalization vanishes at quark mass-shell: $Z(p^2 = M^2) = 0$
  - *confinement is critical for our description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

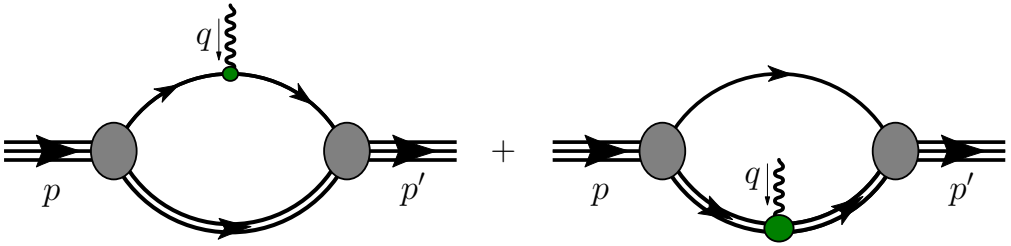




Nucleon Electromagnetic Form Factors

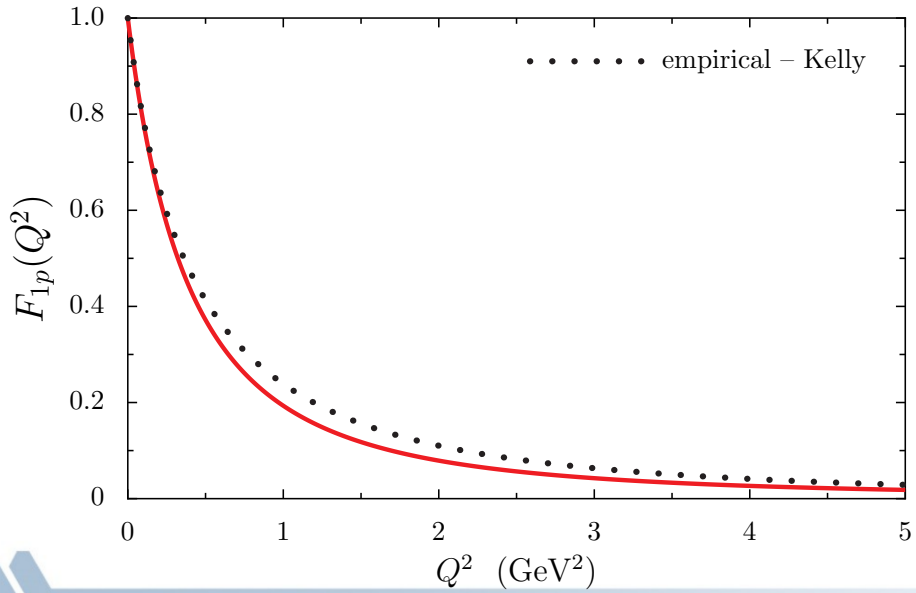
- Nucleon = quark+diquark
- Form factors given by Feynman diagrams:

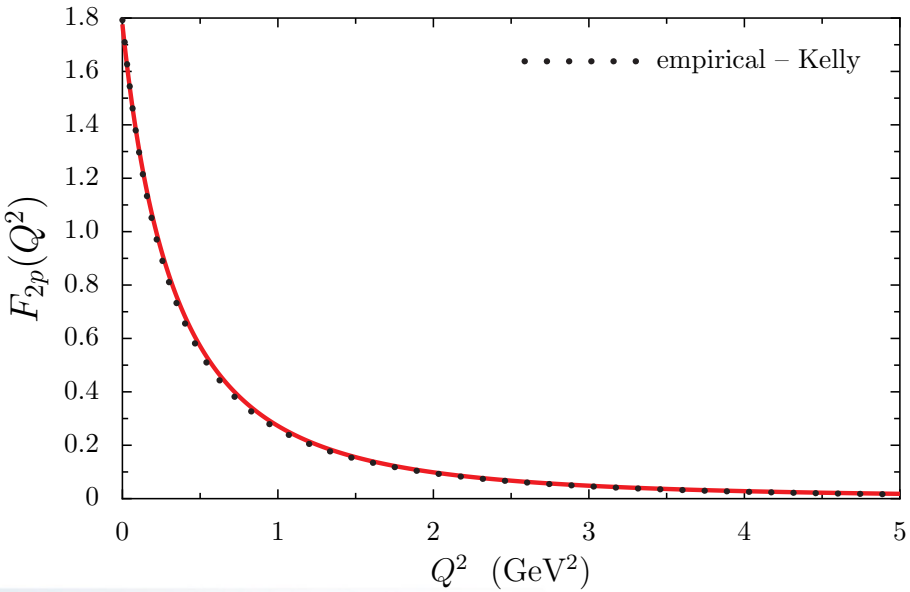




- Calculation satisfies electromagnetic gauge invariance; includes
  - dressed quark–photon vertex with ρ and ω contributions
  - contributions from a pion cloud

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





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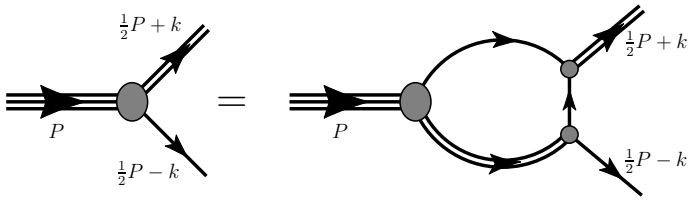

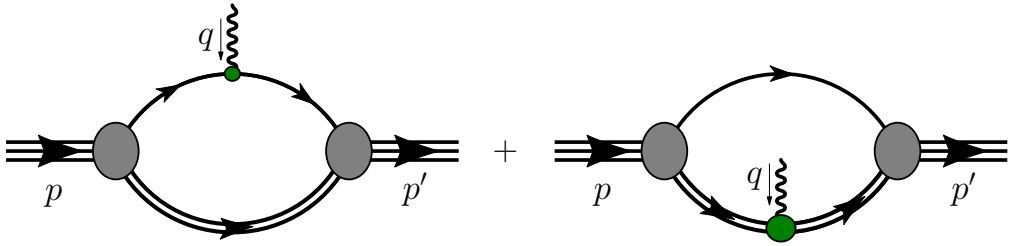

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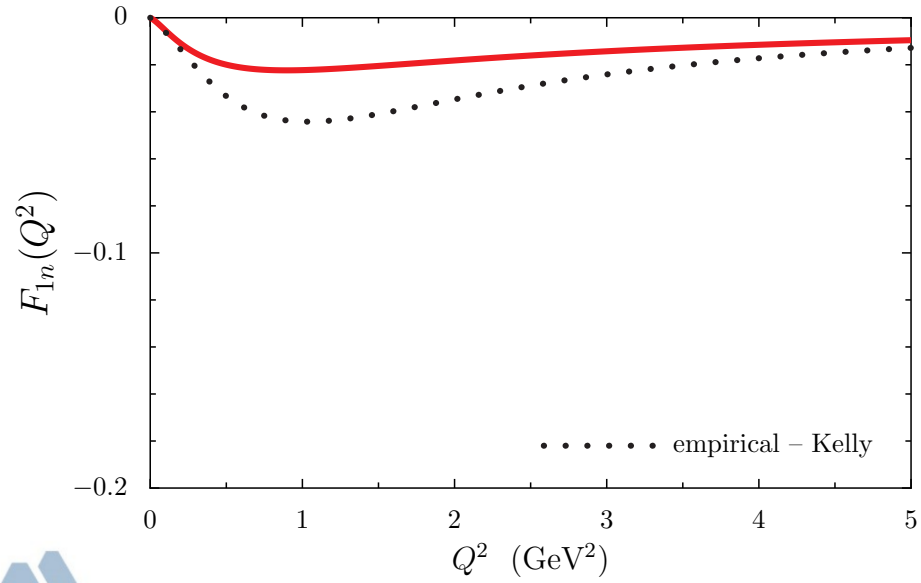
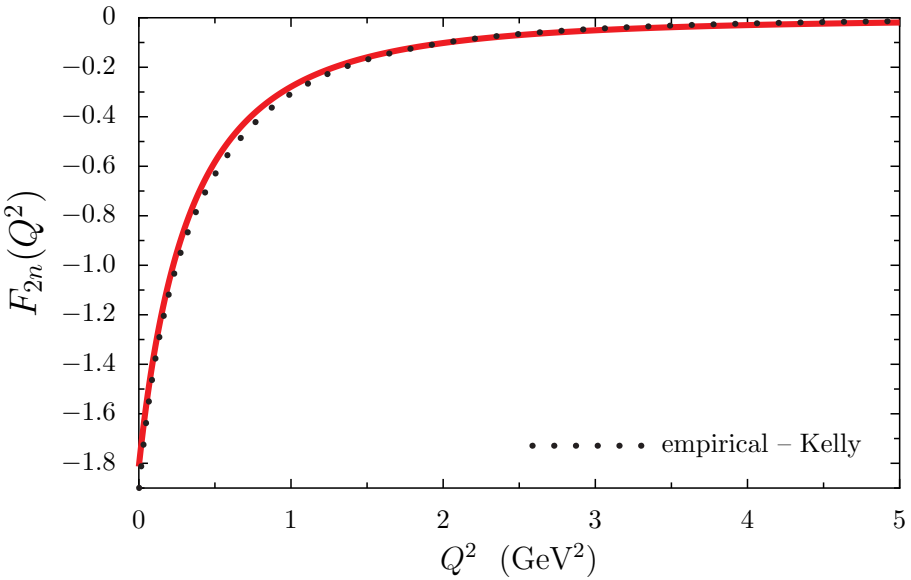
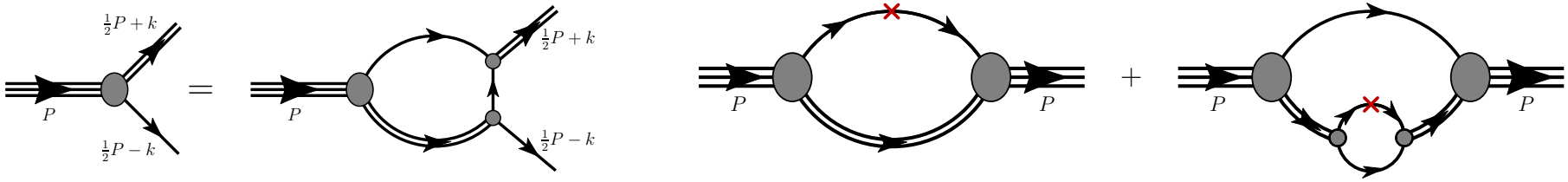




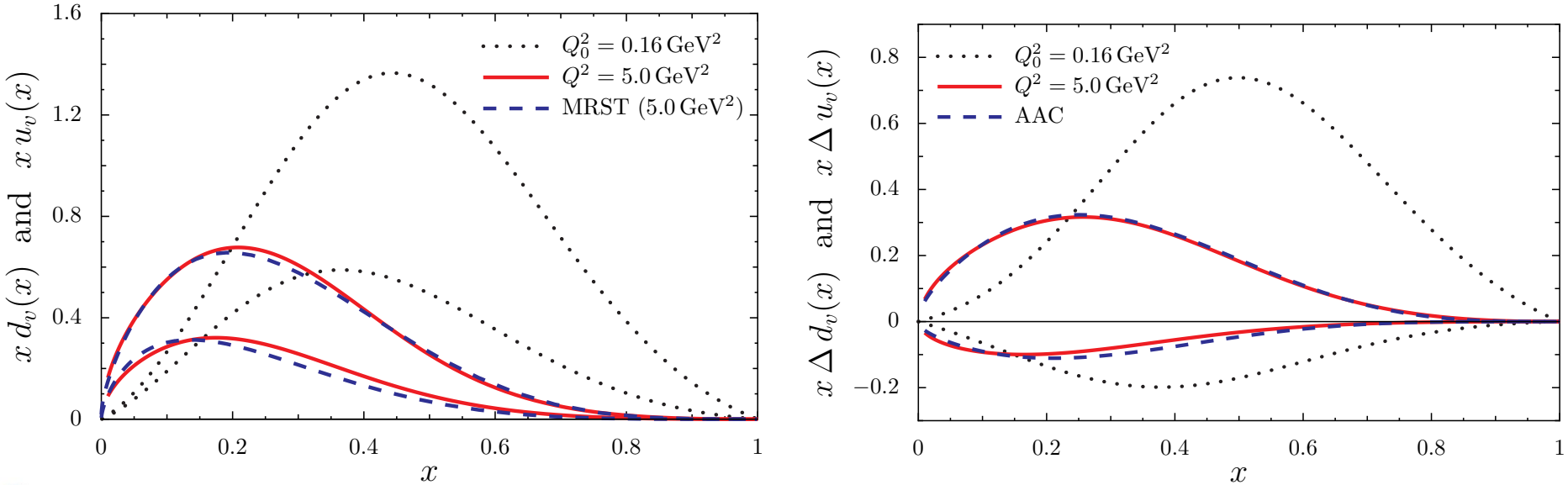
Nucleon quark distributions

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



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

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



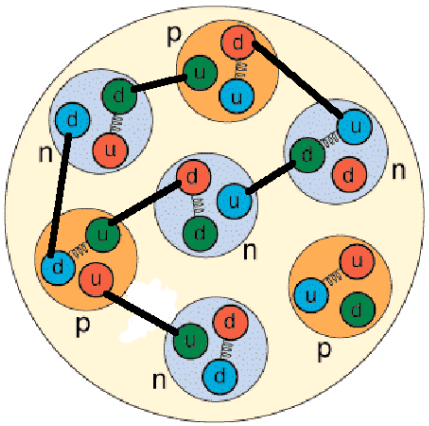
[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **621**, 246 (2005)]

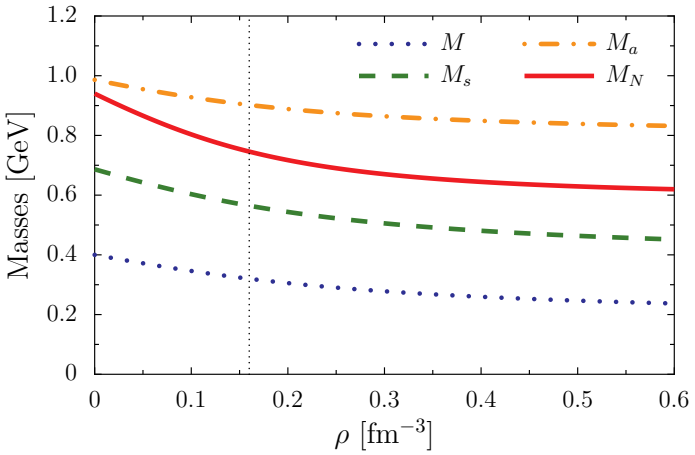
NJL at Finite Density

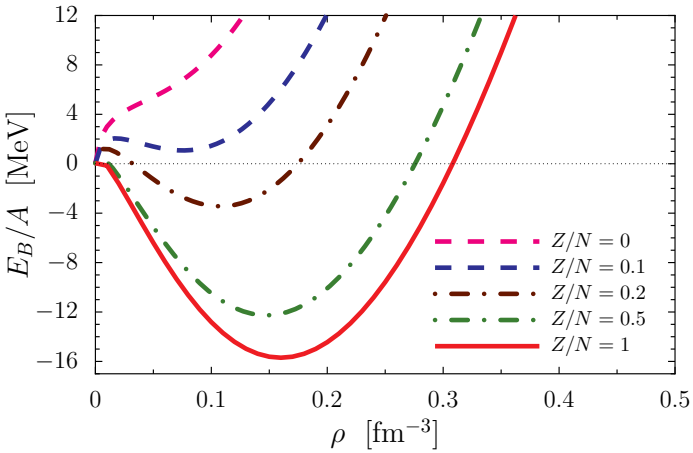
- Finite density (mean-field) Lagrangian: $\bar{q}q$ interaction in $\sigma,\ \omega,\ \rho$ channels

$$\mathcal{L} = \overline{\psi}_q \left(i\,\partial\!\!\!/ - M^* - V\!\!\!/_q\right)\psi_q + \mathcal{L}'_I$$

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







- Quark propagator: $S(k)^{-1} = k\!\!\!/ - M + i\varepsilon \rightarrow S_q(k)^{-1} = k\!\!\!/ - M^* - V\!\!\!/_q + i\varepsilon$

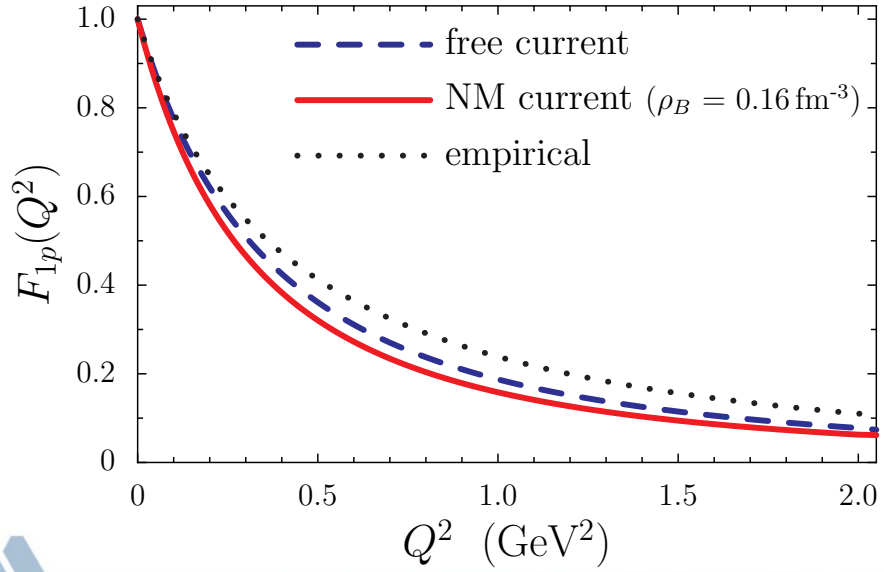
- Hadronization + mean–field $\Longrightarrow$ effective potential (solve self-consistently)

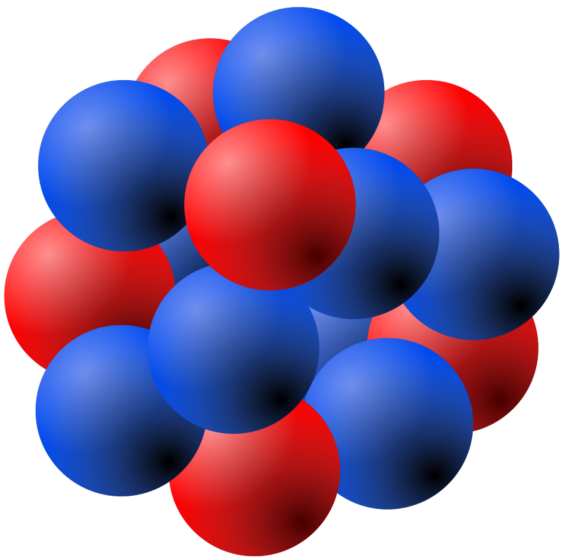
$$\mathcal{E} = \mathcal{E}_V + \mathcal{E}_p + \mathcal{E}_n - \frac{\omega_0^2}{4\,G_\omega} - \frac{\rho_0^2}{4\,G_\rho}$$

  - $\mathcal{E}_V$ = vacuum energy
  - $\mathcal{E}_{p(n)}$ = energy of nucleons moving in $\sigma,\ \omega,\ \rho$ mean-fields

Nucleons in the Nuclear Medium

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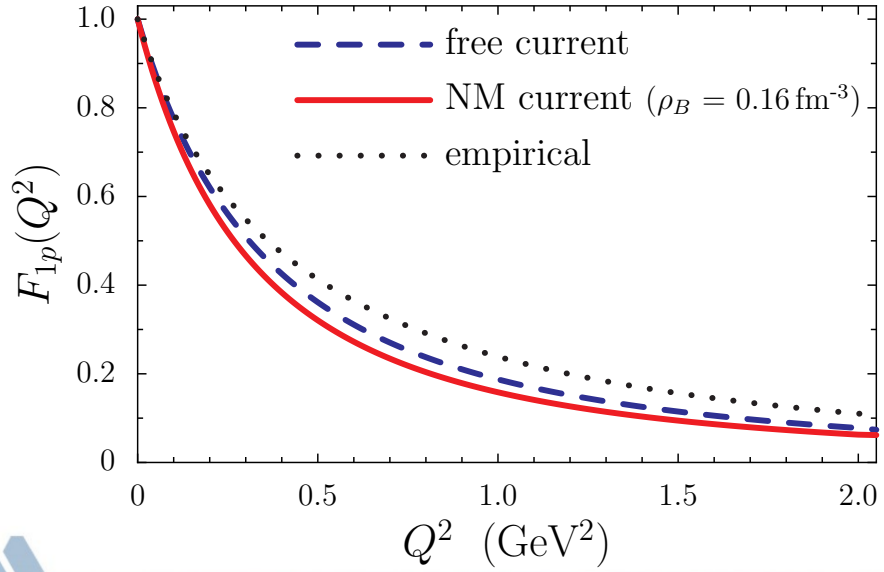
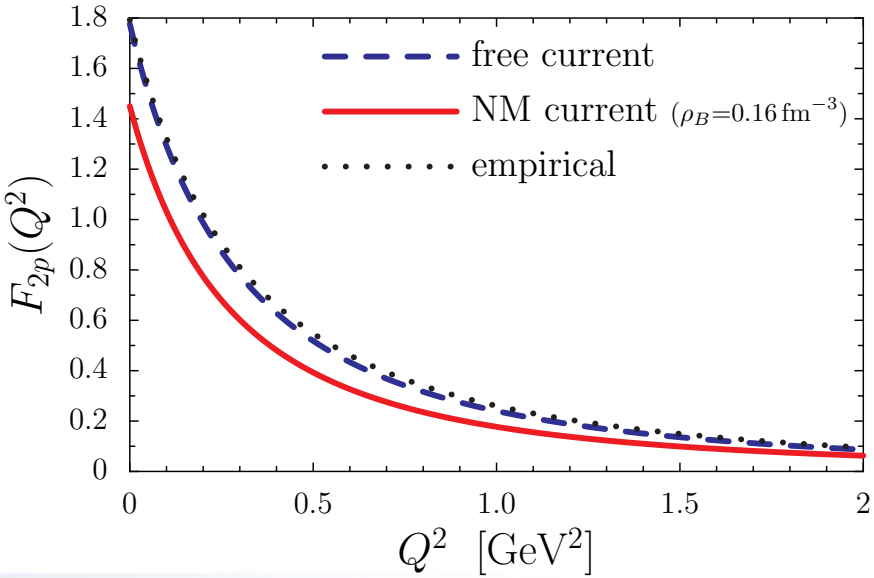
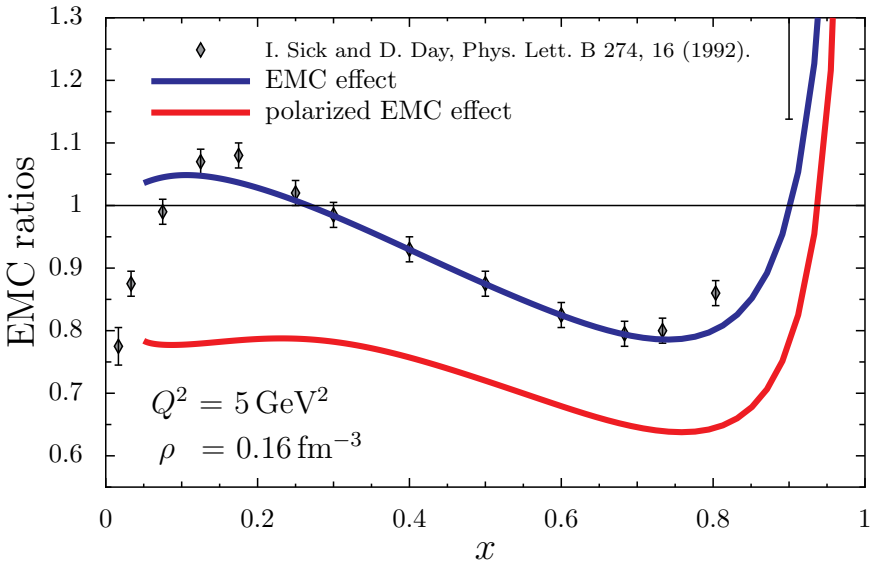


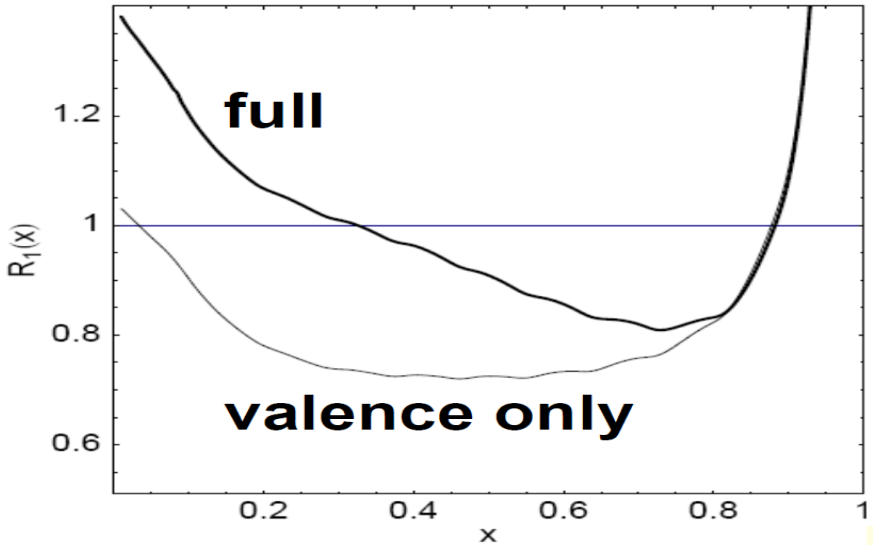


EMC and Polarized EMC effects

[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)]



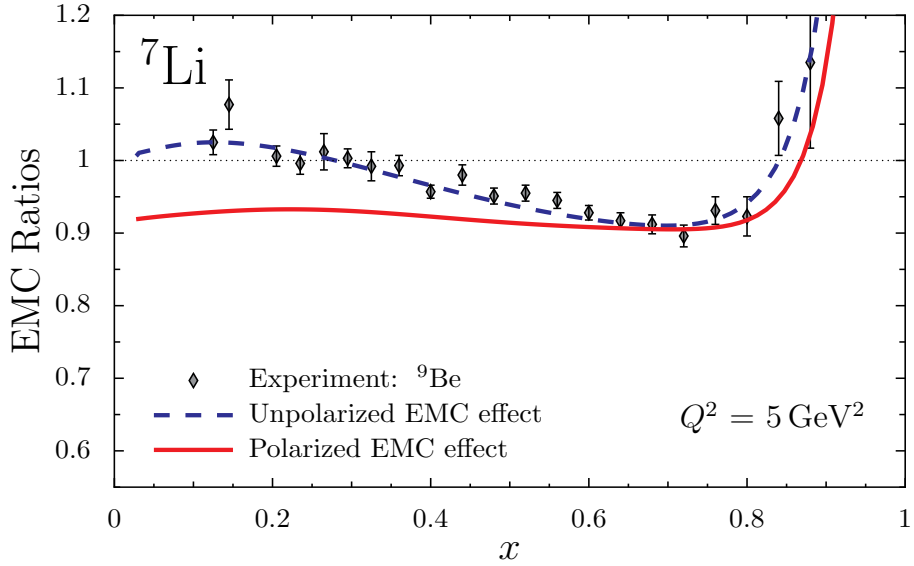
- Definition of polarized EMC effect:
  - ratio equals unity if no medium effects

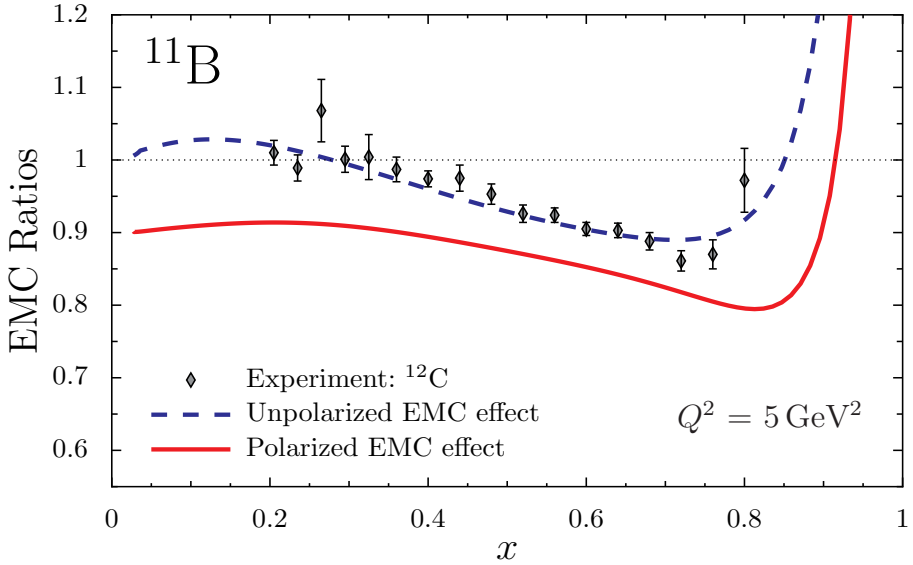
$$\Delta R = \frac{g_{1A}}{g_{1A}^{\text{naive}}} = \frac{g_{1A}}{P_p\, g_{1p} + P_n\, g_{1n}}$$

- 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 many other explanations of the EMC effect

EMC effects in Finite Nuclei

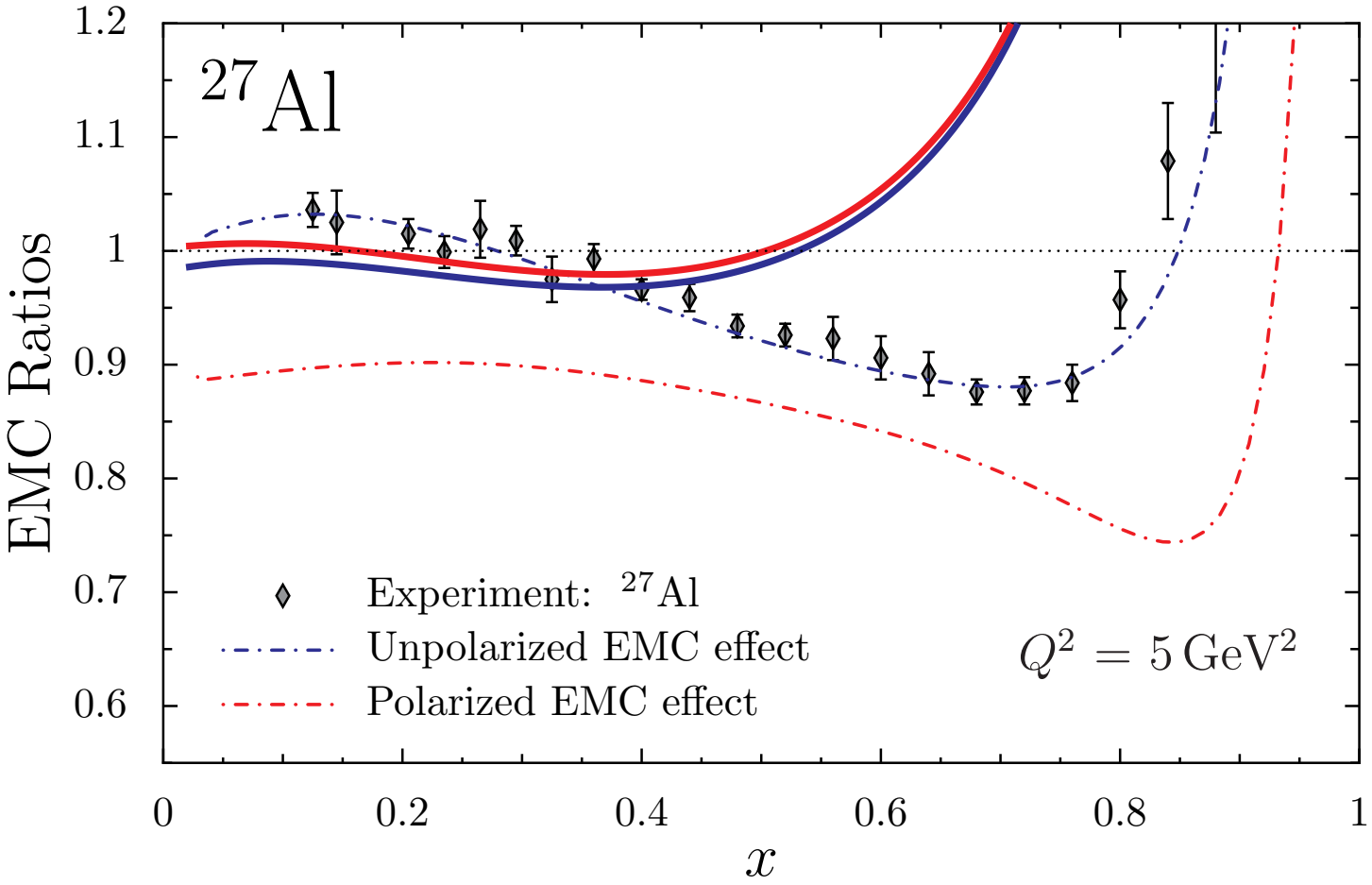
[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **642**, 210 (2006)]





- 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

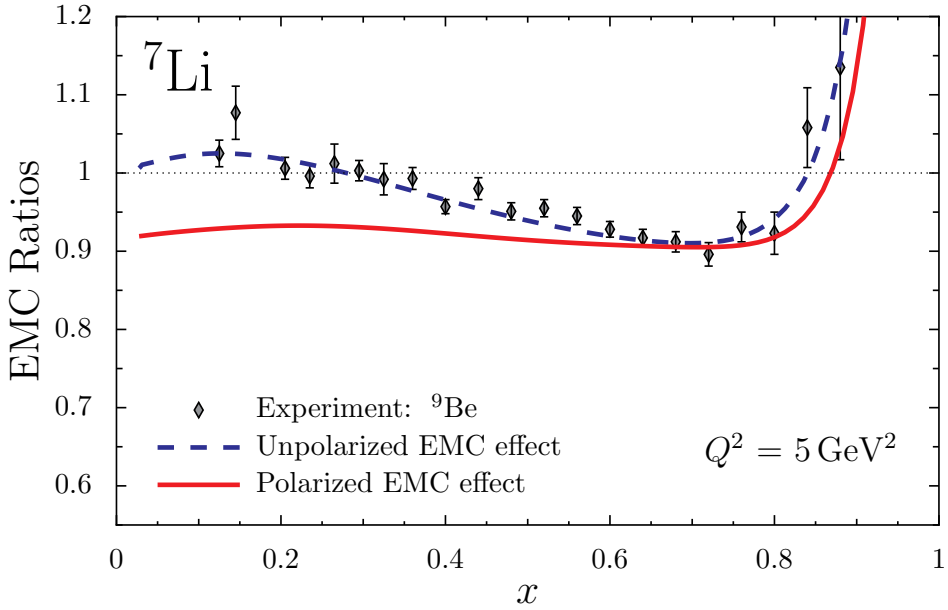
Nuclear spin sum

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

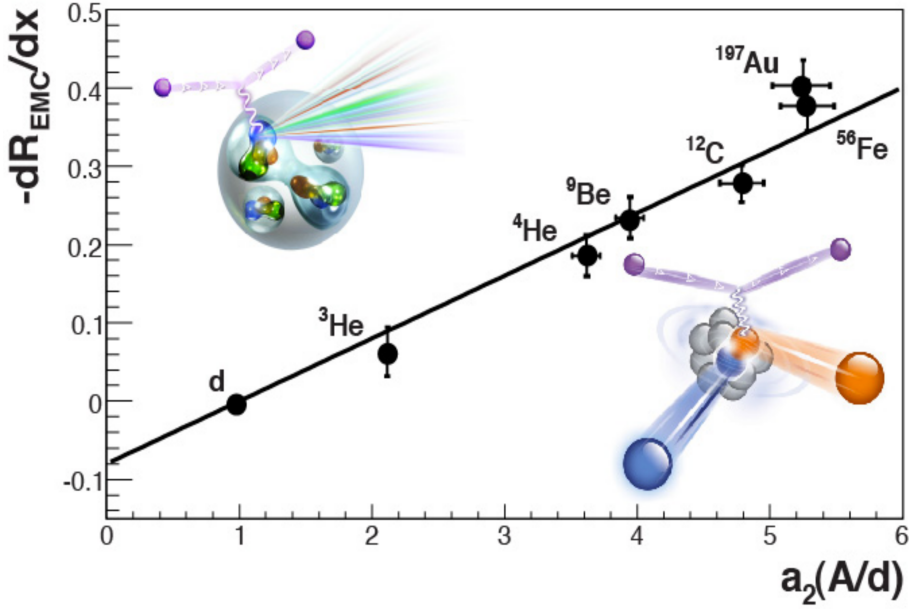
- Angular momentum of nucleon: $J = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$
  - in medium $M^* < M$ and therefore quarks are more relativistic
  - lower components of quark wavefunctions are enhanced
  - quark lower components usually have larger angular momentum
  - $\Delta q(x)$ very sensitive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

Mean-field vs SRC induced Medium Modification

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



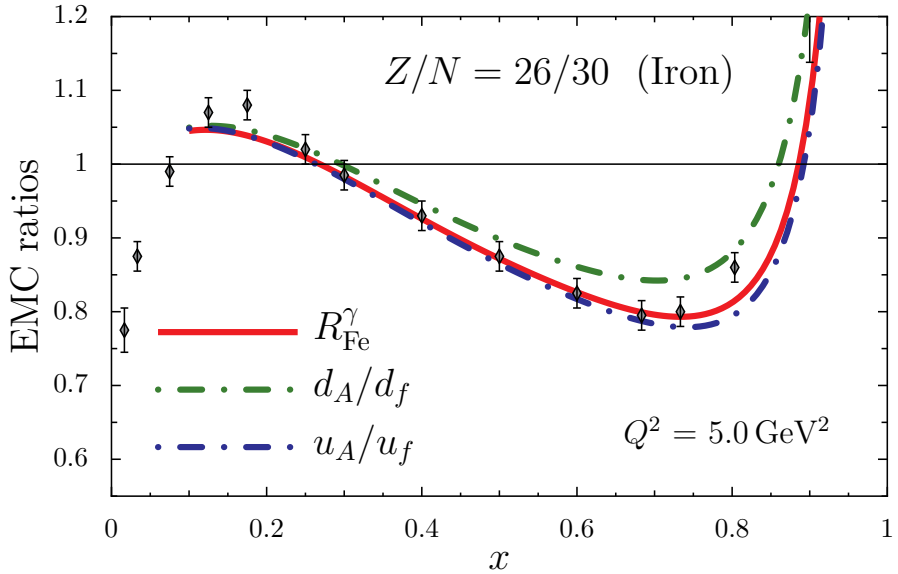
[L. B. Weinstein *et al.*, Phys. Rev. Lett. **106** 052301 (2011)]

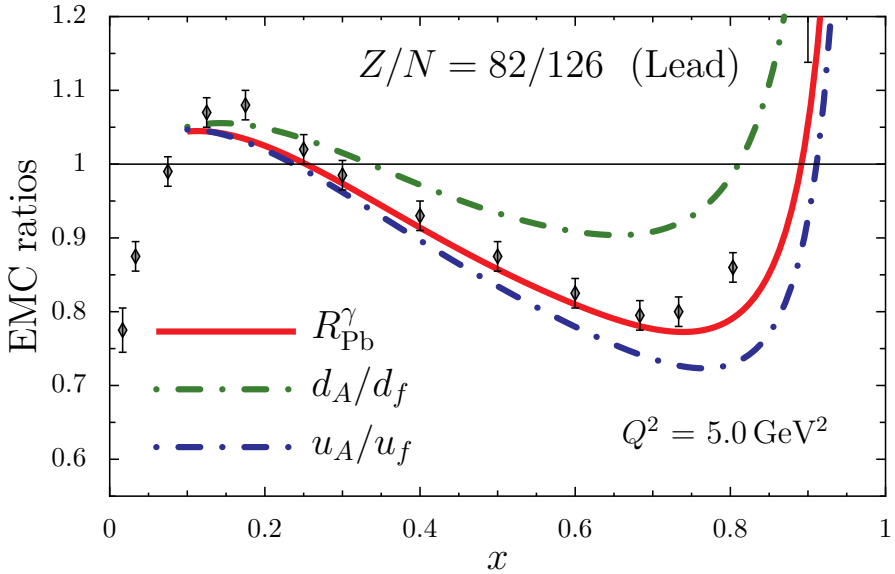


- Explanations of EMC effect using SRCs also invoke medium modification
  - since about 20% of nucleons are involved in SRCs, need medium modifications about 5 times larger than in mean-field models
- For polarized EMC effect only 2–3% of nucleons are involved in SRCs
  - it would therefore be natural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

Flavor 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* – SRCs are also predominately isoscalar

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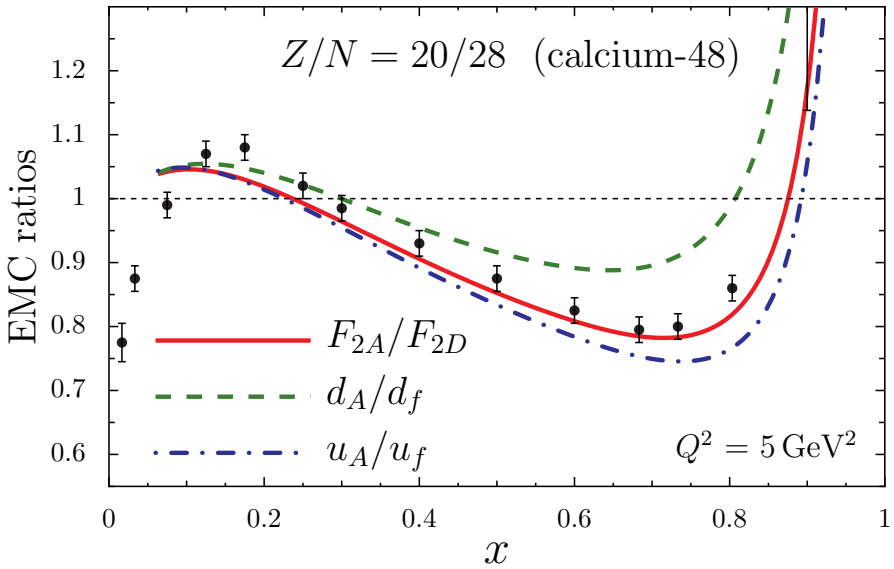

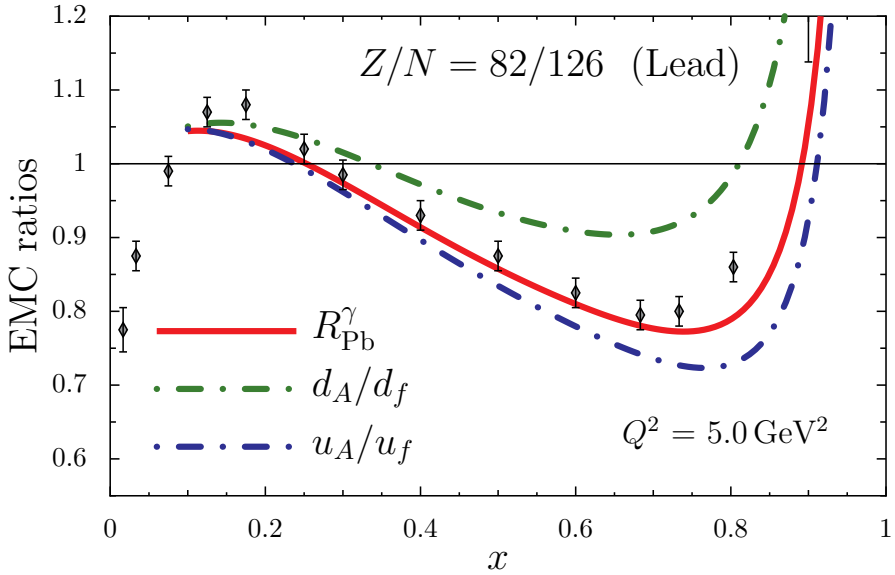

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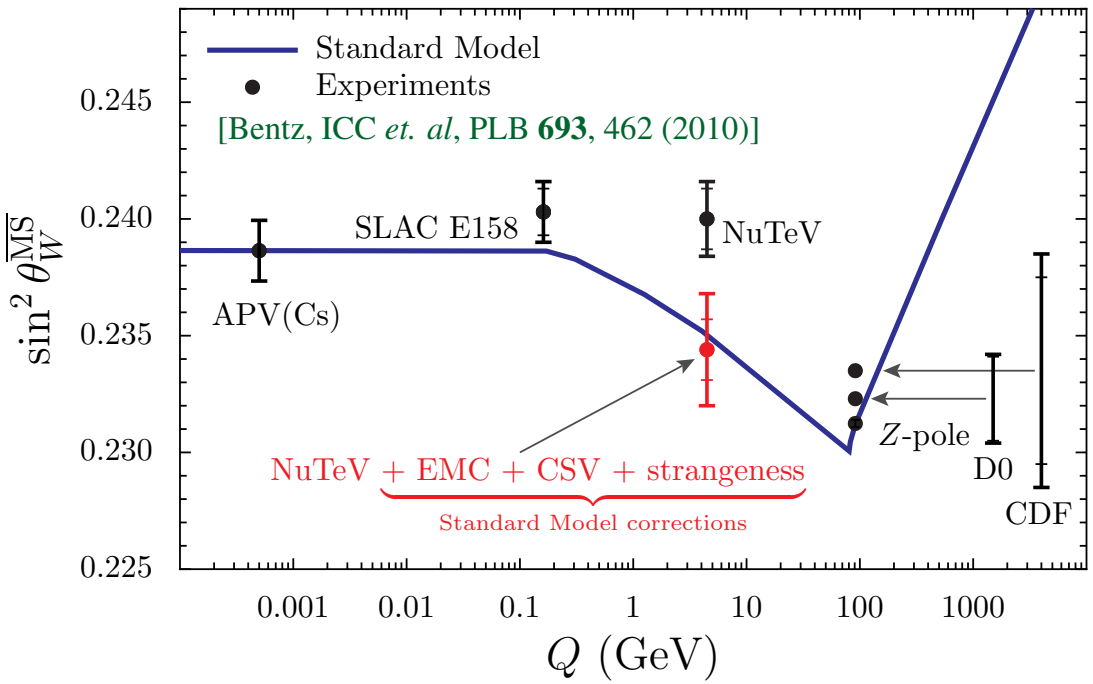
A Reassessment of the NuTeV anomaly



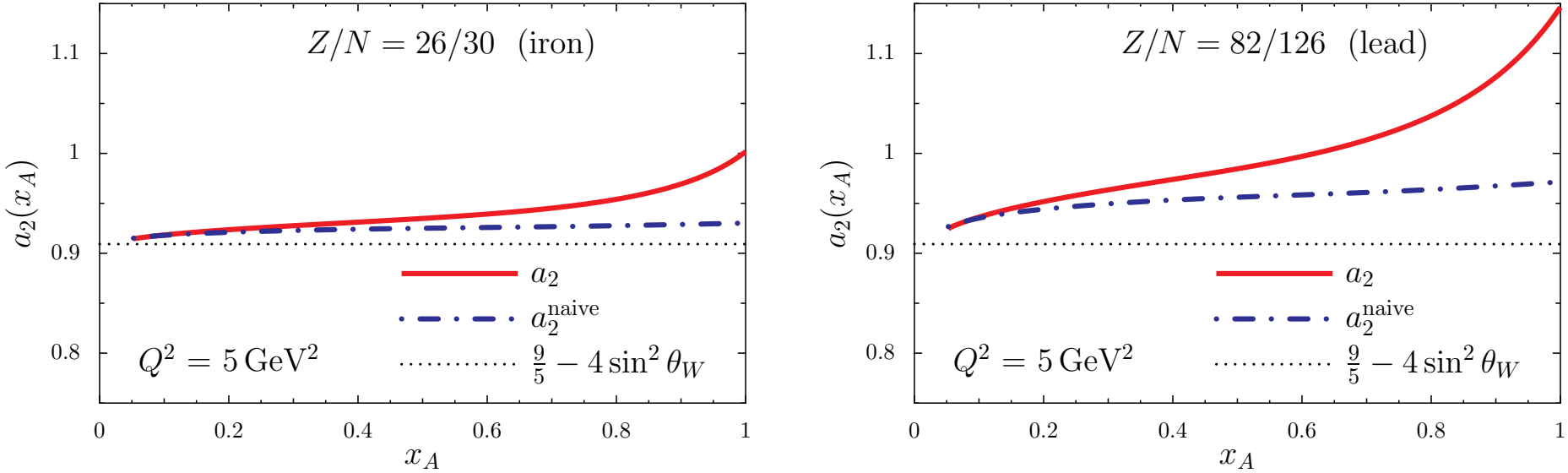
- Paschos-Wolfenstein ratio motivated NuTeV study:

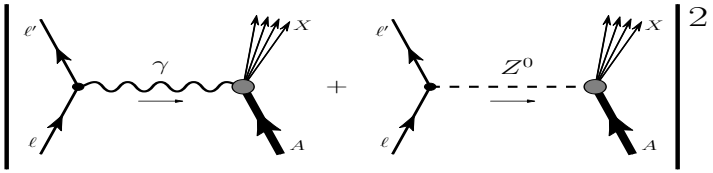
$$R_{PW} = \frac{\sigma_{NC}^{\nu\,A} - \sigma_{NC}^{\bar\nu\,A}}{\sigma_{CC}^{\nu\,A} - \sigma_{CC}^{\bar\nu\,A}} \overset{N\sim Z}{=} \frac{1}{2} - \sin^2\theta_W + \left(1 - \frac{7}{3}\sin^2\theta_W\right)\frac{\langle x\,u_A^- - x\,d_A^-\rangle}{\langle x\,u_A^- + x\,d_A^-\rangle}$$

- 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: $\sum_X$ 

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

- 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

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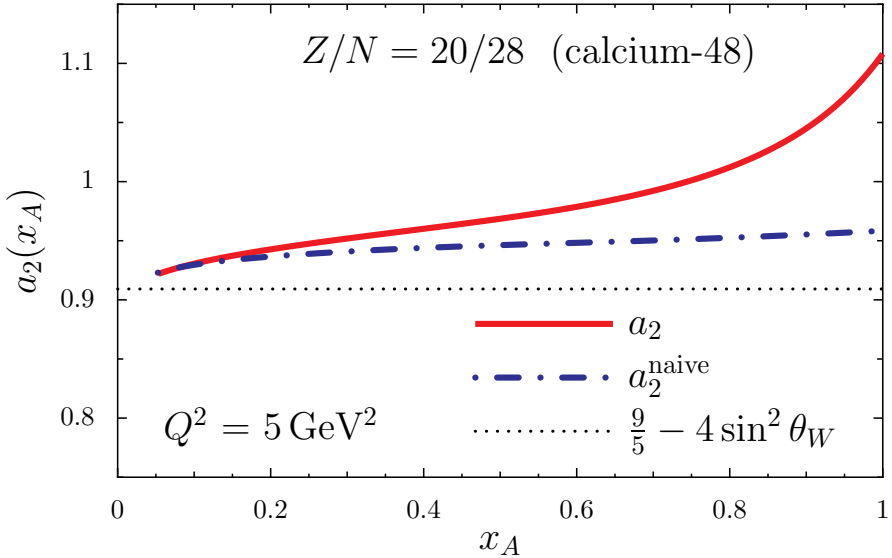
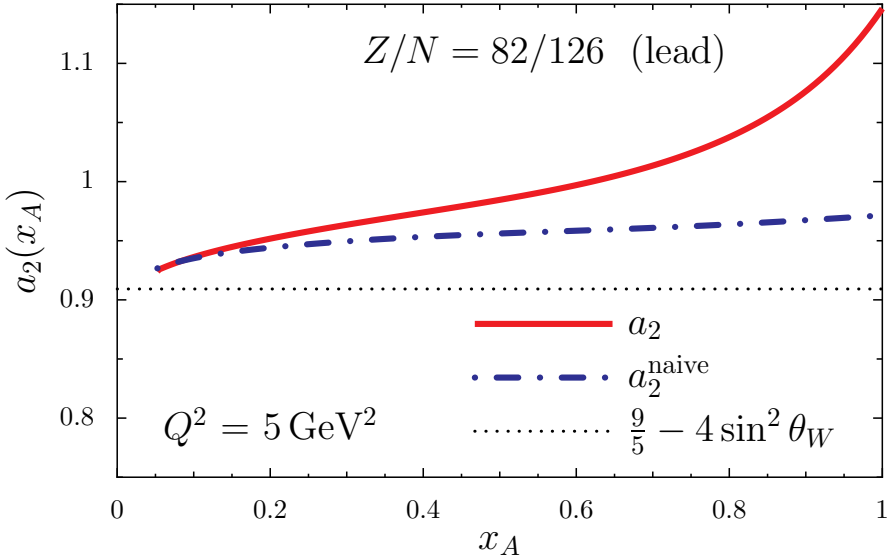
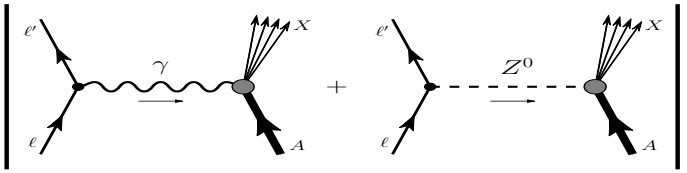




- PV DIS – $\gamma\, Z$ interference: $\sum_X \Big|$  $\Big|^2$

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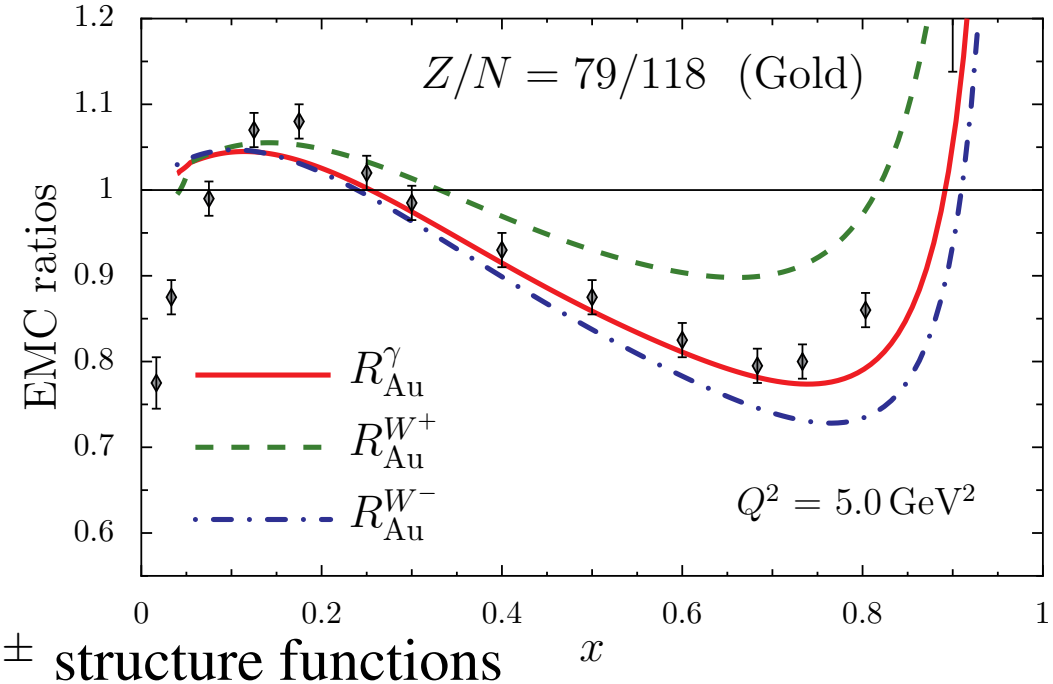
Charged Current Processes

- 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

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

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

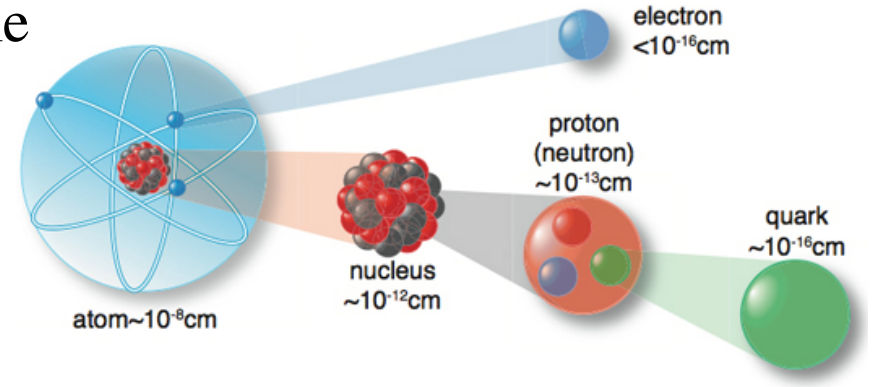
- Would provide much needed data on flavour structure of both valence and sea quark distribution functions
- Flavor dependence can also be test using e.g. SIDIS, π^+/π^- Drell-Yan, PVDIS, ν-DIS & W-production at RHIC

Quasi-Elastic Scattering

- First hints for QCD effects in nuclei came from quasi-elastic electron scattering:

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

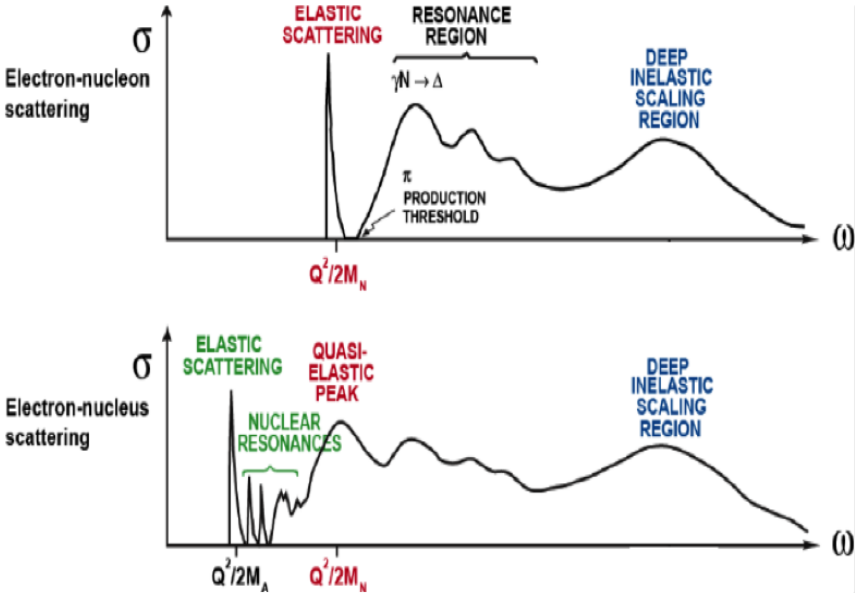
  - in measurements at MIT Bates in 1980 on Fe, which were later confirmed at Saclay in 1984



- These experiments, and *most* others following, observed a *quenching* of the Coulomb Sum Rule (CSR):

$$S_L(|\boldsymbol{q}|) = \int_{\omega^+}^{|\boldsymbol{q}|} d\omega\, \frac{R_L(\omega,|\boldsymbol{q}|)}{Z\, G_{Ep}^2(Q^2) + N\, G_{En}^2(Q^2)}$$

  - despite widespread expectation that the CSR should approach unity for $|\boldsymbol{q}| \gg k_F$



- Observation of quenching began one of the most controversial issues in nuclear physics – which remains to this day

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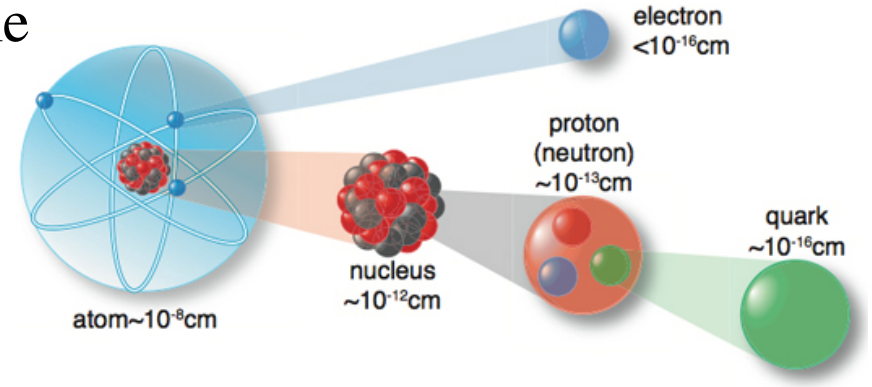

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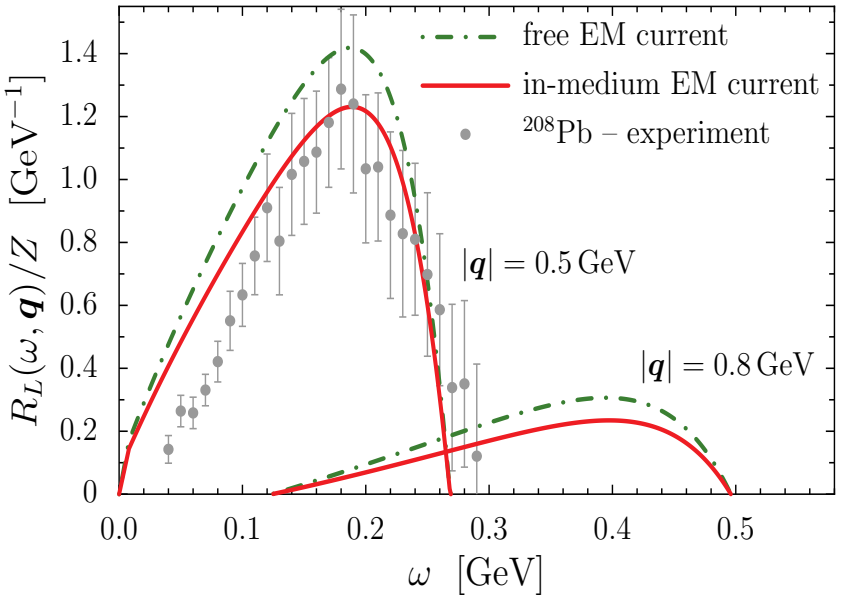

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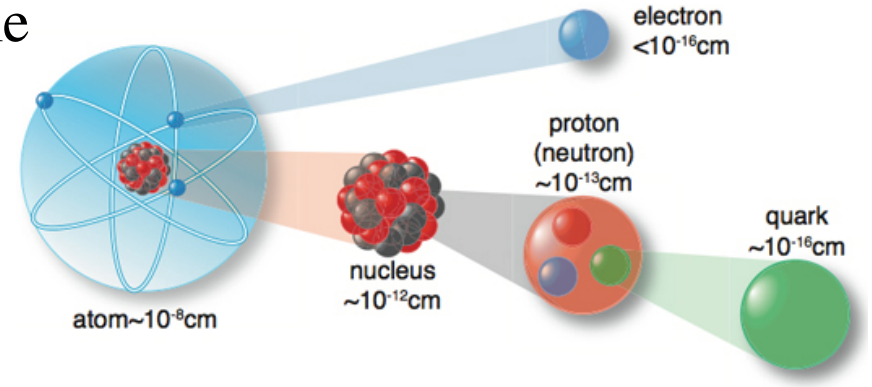

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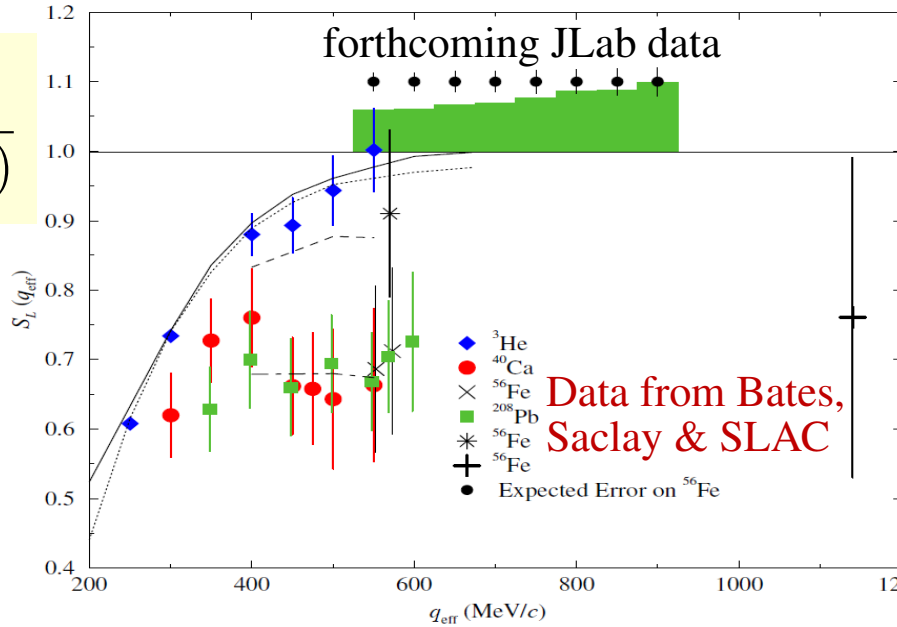

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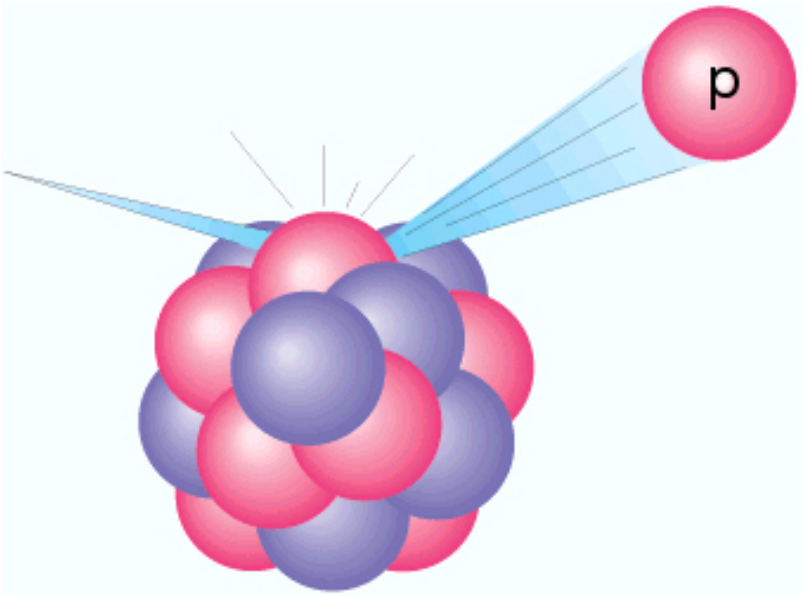
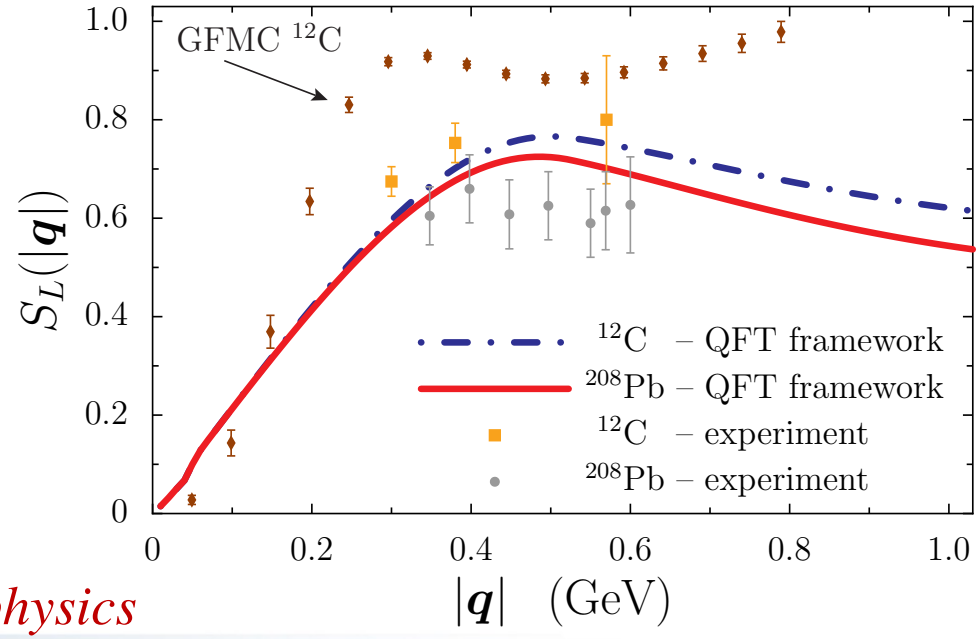
Coulomb Sum Rule

- QE scattering is sensitive to internal structural properties of bound nucleons
  - quenching of the CSR can be naturally explained by slight modification of bound nucleon EM form factors
  - natural consequence of QCD models
- Two state-of-the-art theory results exist, both from Argonne:
  - the GFMC result, with no explicit QCD effects, finds no quenching
  - QCD motivated framework finds a dramatic quenching; 50% relativistic effects & 50% medium modification
- Jefferson Lab has revisited QE scattering & this impasse stands to be resolved shortly
  - *confirmation of either result will be an important milestone in QCD nuclear physics*





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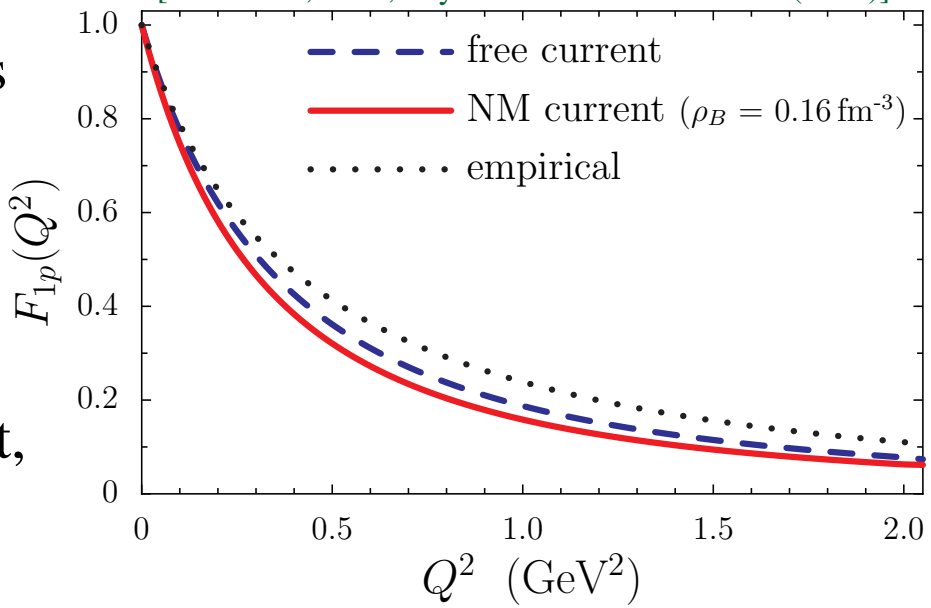
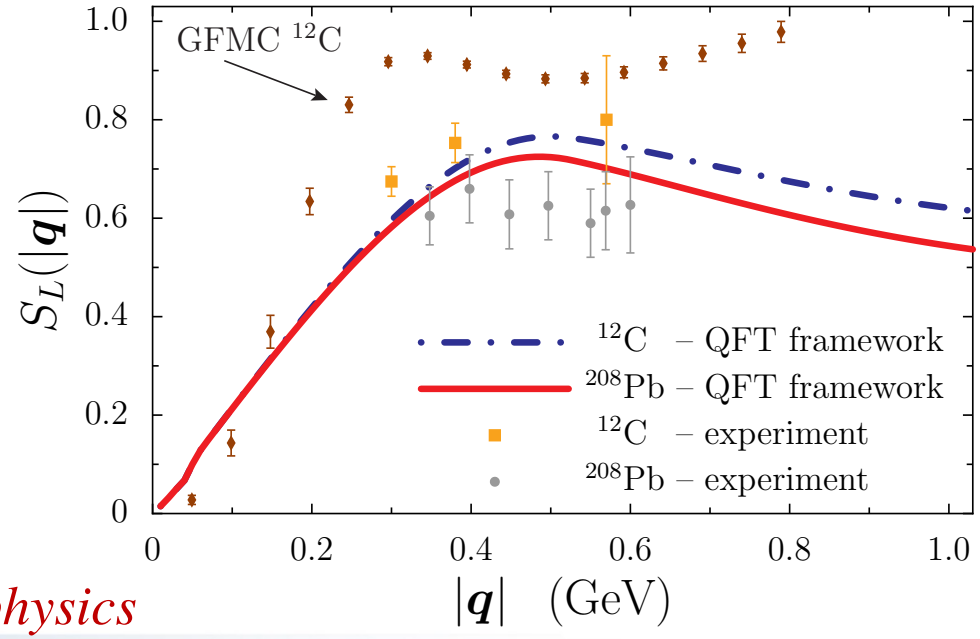
[I. C. Cloët, *et al.*, Phys. Rev. Lett. **116** 032701 (2016)]

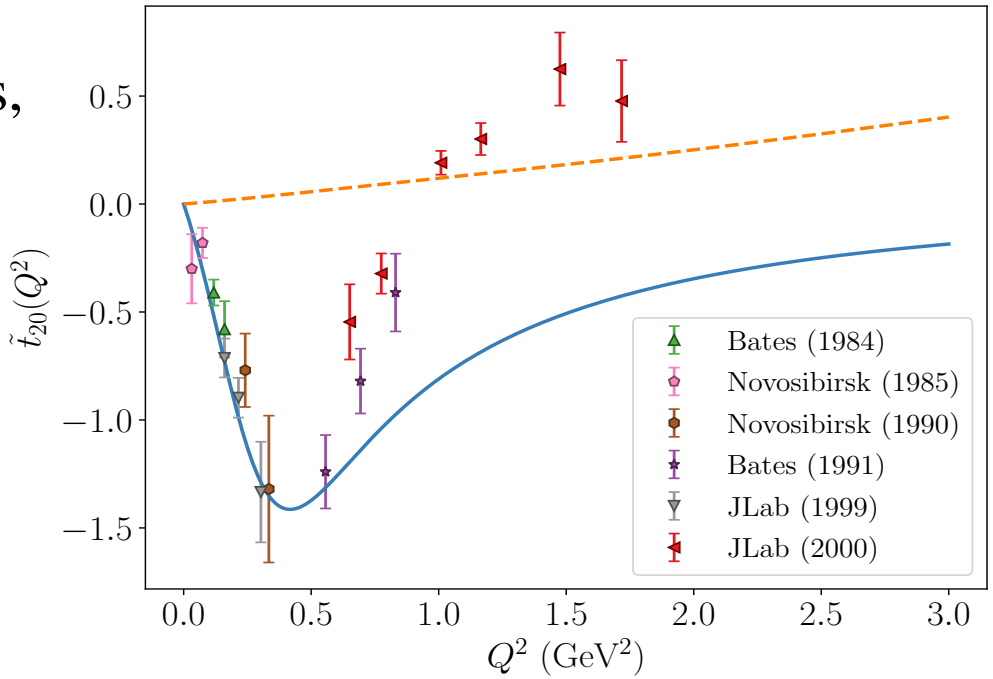


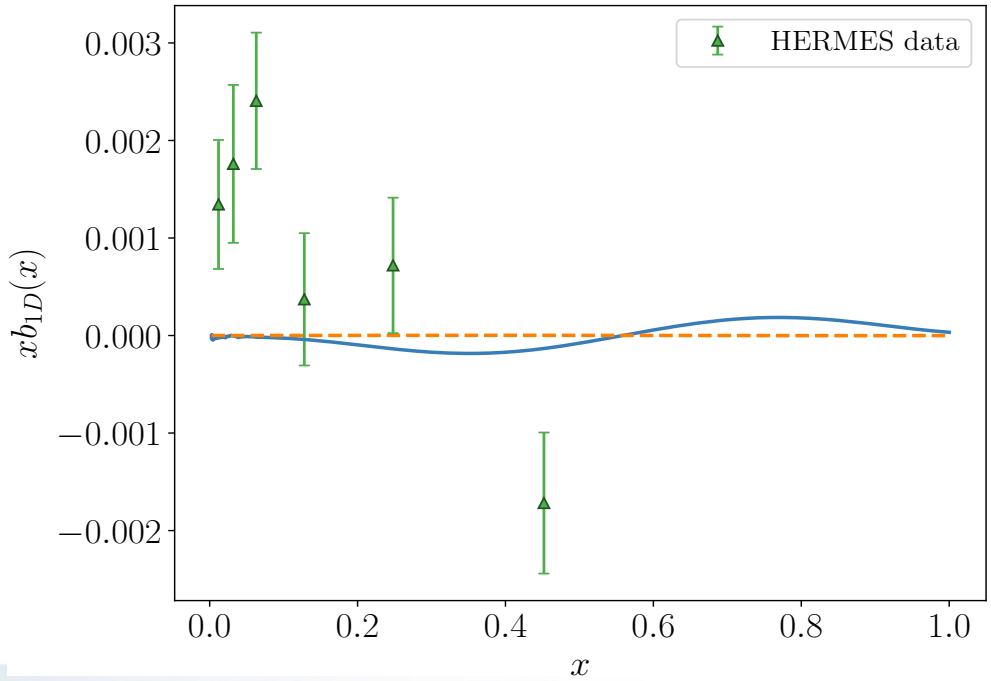


Deuteron

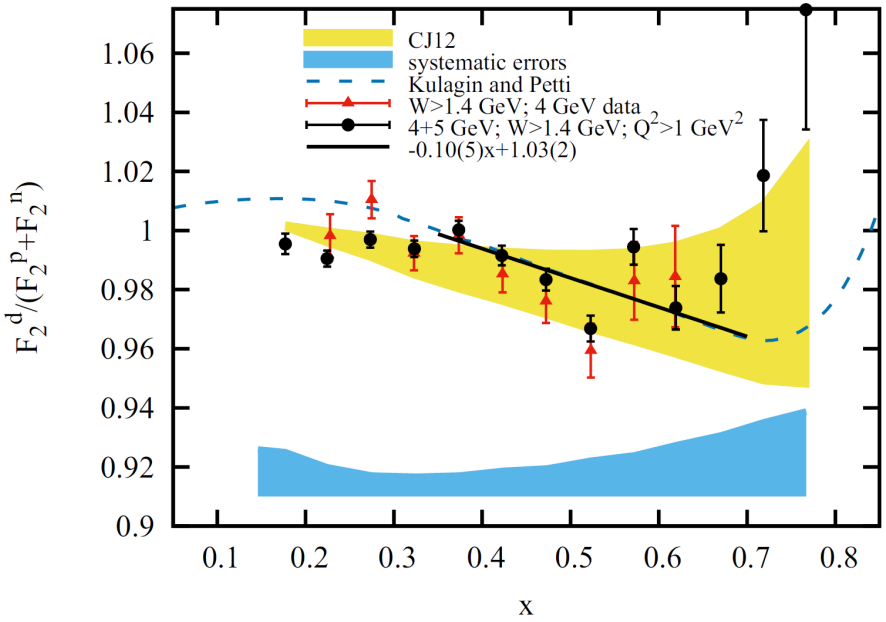
The Deuteron

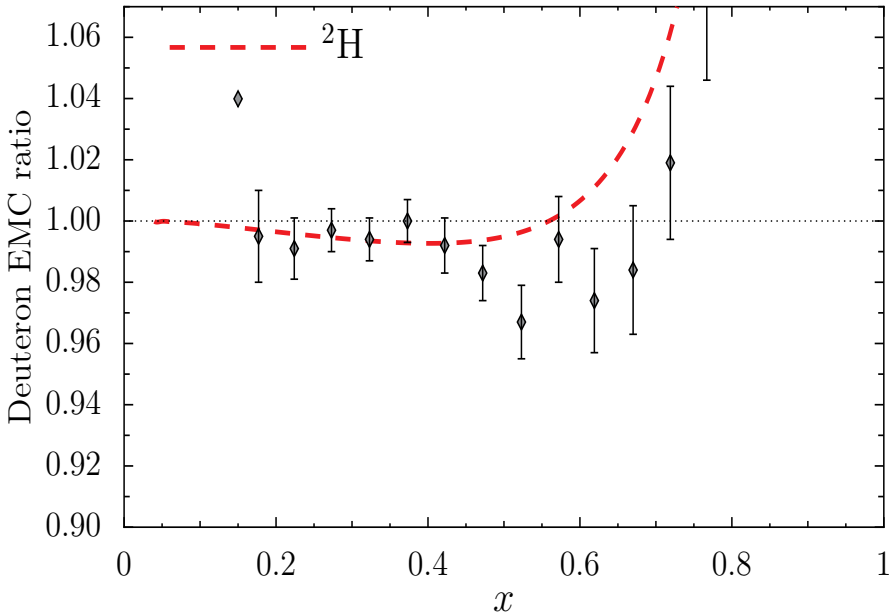
- The deuteron is the simplest nucleus, consisting primarily of a proton + neutron with 2.2 MeV binding
  - however the deuteron is greater than the sum of its parts – it has numerous properties not found in either of its primary constituents
- Unique properties of deuteron:
  - a quadrupole moment
  - has additional spin-independent leading-twist PDF called $b_1^q(x)$
  - gluon transversity PDF
  - has numerous additional TMDs and GPDs associated with tensor polarization
- Deuteron is the idea system to study QCD aspects of NN interaction





Deuteron DIS Structure





- BONuS data suggestive of an EMC effect that is difficult to explain with traditional nuclear physics
- For DIS on spin-1 target 4 additional structure functions $b_{1\ldots4}(x)$ appear; in Bjorken limit just one $b_1(x)$ [Hoodbhoy, Jaffe and Manohar, Nucl. Phys. B **312**, 571 (1989)]

$$b_1(x) = \sum_q e_q^2 \left[b_1^q(x) + b_1^{\bar{q}}(x)\right], \quad b_1^q = \tfrac{1}{2}\,\theta_q = \tfrac{1}{4}\left[2\,q^{(\lambda=0)} - q^{(\lambda=1)} - q^{(\lambda=-1)}\right]$$

- Seems impossible to explain HERMES data with only bound nucleon degrees of freedom

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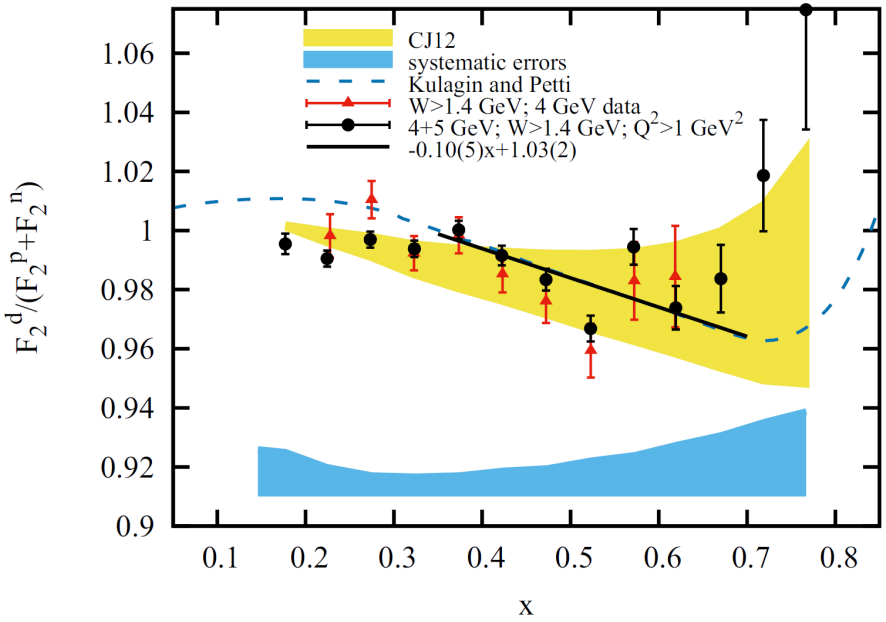

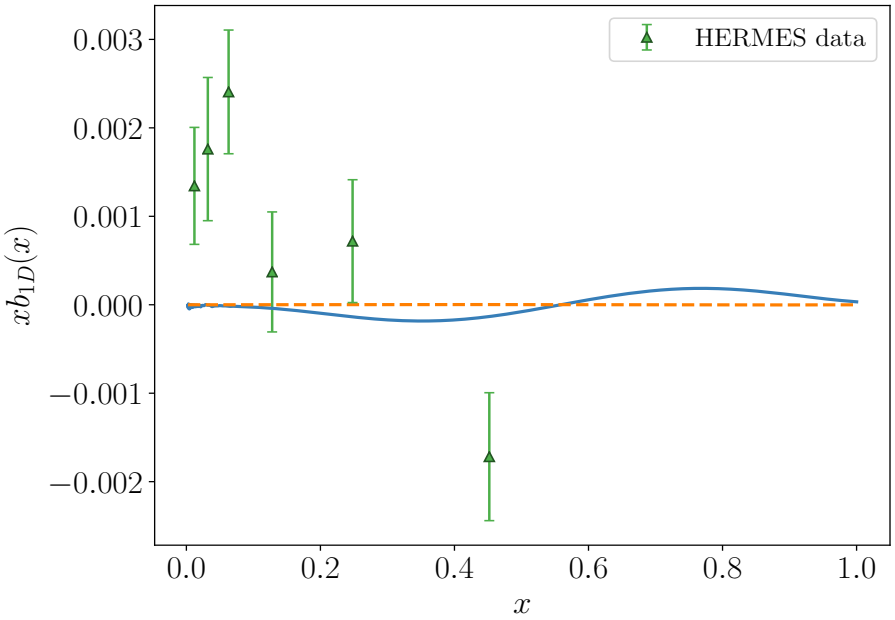

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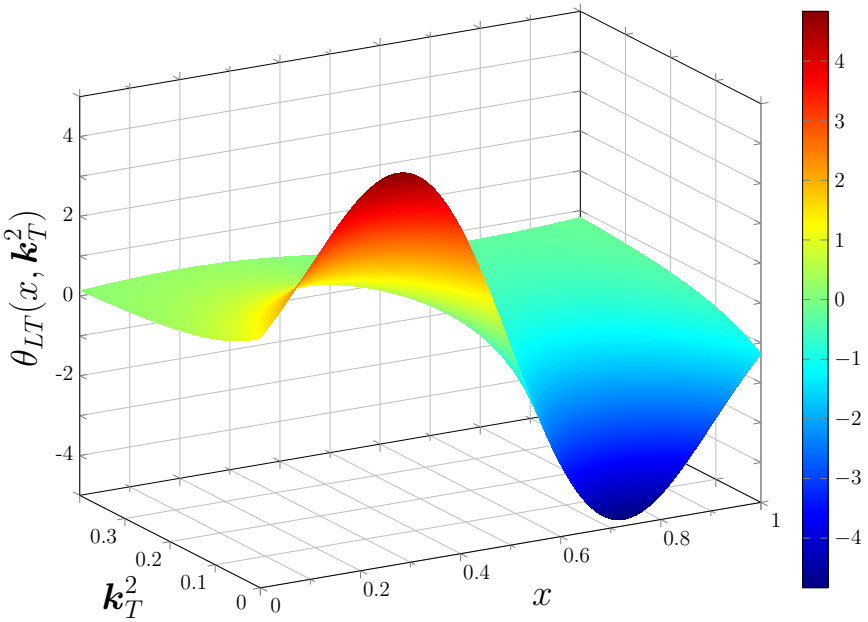
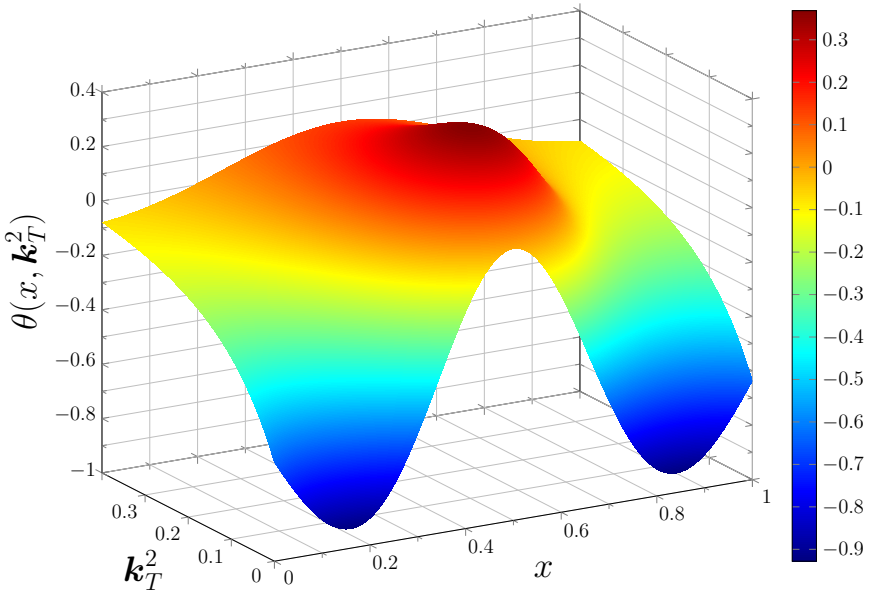
Spin-1 TMDs – Tensor Polarization





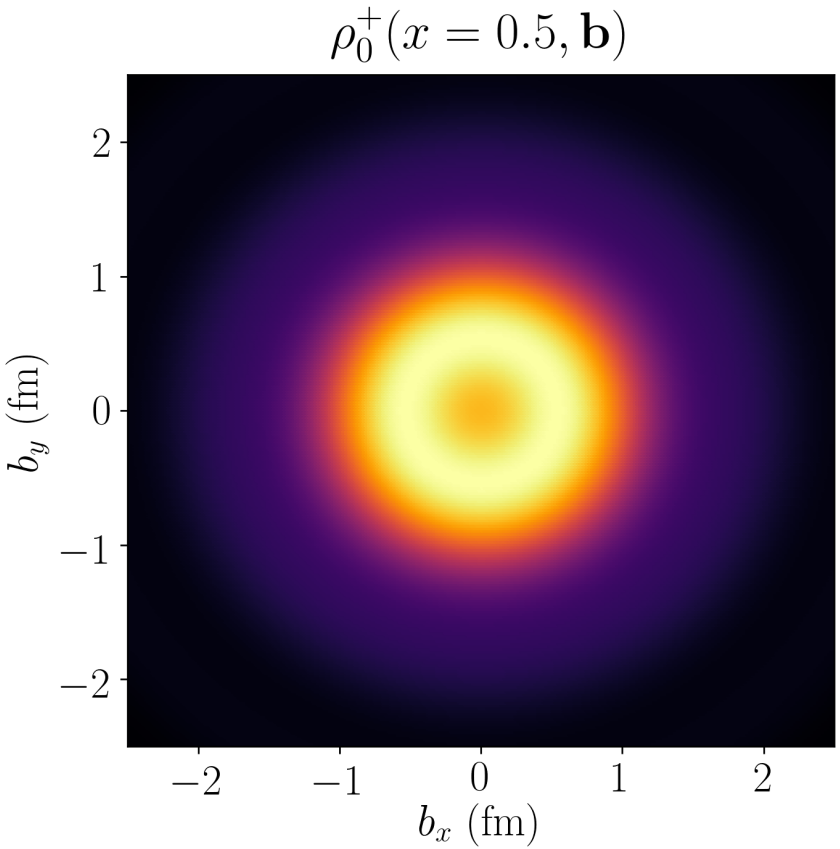
- Tensor polarized TMDs have a number of surprising features

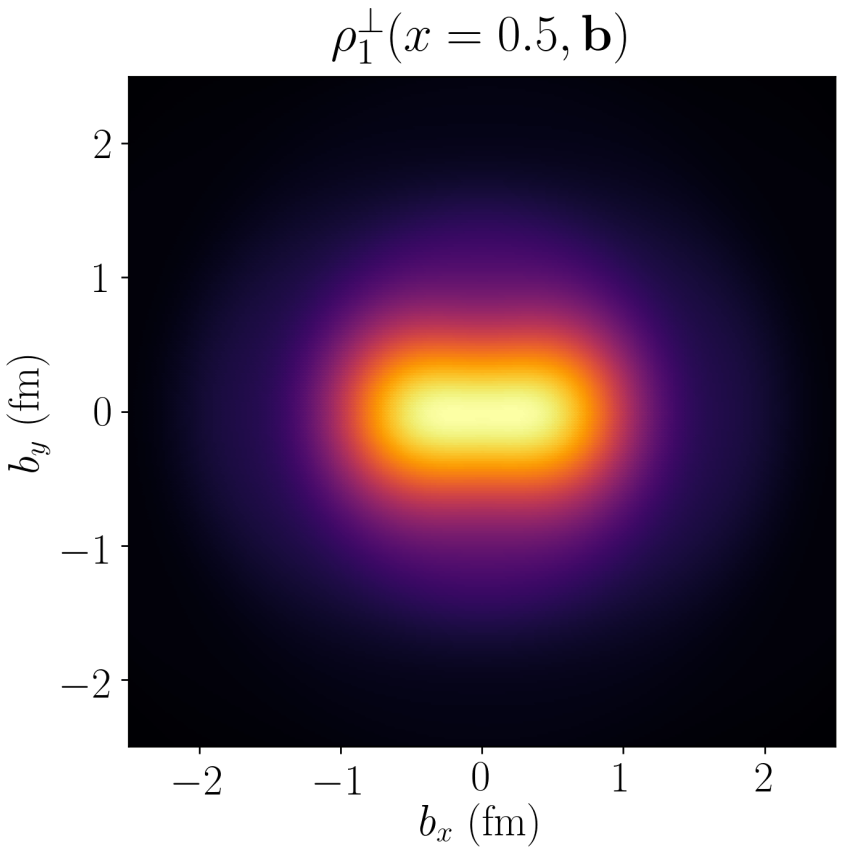
$$\theta(x, \boldsymbol{k}_T^2) = \theta_{LL}(x\, \boldsymbol{k}_T^2) - \frac{\boldsymbol{k}_T^2}{2\, m_h^2}\, \theta_{TT}(x\, \boldsymbol{k}_T^2)$$

- TMDs $\theta_{LL}(x\, \boldsymbol{k}_T^2)$ & $\theta_{LT}(x\, \boldsymbol{k}_T^2)$ identically vanishes at $x = 1/2$ for all $\boldsymbol{k}_T^2$
  - $x = 1/2$ corresponds to zero relative momentum between (the two) constituents, that is, s-wave contributions
  - therefore θ_{LL} & θ_{LT} only receive contributions from $L \geqslant 1$ components of the wave function – *sensitive measure of orbital angular momentum*
- Features hard to determine from a few moments – difficult for lattice QCD

Deuteron Tomography

[Adam Freese, I. C. Cloët, *to appear*]





- Deuteron spin-independent impact-parameter PDFs
  - tensor polarized along z-axis – donut shape is clear
  - longitudinally polarized along x-axis
- Does the gluon *donut* align with the quark *donut* – does this change with x – incredible insight into NN interaction possible at an EIC

Conclusion

- Understanding the EMC effect is a critical step towards a QCD based description of nuclei
  - approved JLab experiment to measure polarized EMC effect in ^{7}Li
  - PVDIS experiment on ^{48}Ca would provide critical information on flavor dependence of the EMC effect
- EIC would be transformational for understanding QCD and nuclei
  - quark and gluon GPDs and TMDs of: proton, deuteron, triton, ^{3}He, ^{4}He
  - quark and gluon PDFs of ^{7}Li, ^{11}B, ^{19}F
  - must have flavor separation – e.g. s-quarks
- Unprecedented opportunity to study NN interaction and nuclei with QCD d.o.f