Isospin dependence of the EMC effect

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Introduction

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- Effective chiral quark theories are powerful tools to describe quark distributions and structure functions of nucleons.
- Nuclear EMC effect showed: Nucleon properties are modified in the medium $\Rightarrow$ Use chiral quark theories to assess also medium modifications.
- Our earlier work: Interesting results and predictions for the unpolarized and polarized EMC ratios for $N \simeq Z$ nuclei:

$$R(x) = \frac{F_{2A}(x_A)}{ZF_{2p}(x) + NF_{2n}(x)} \xrightarrow{\text{NR,no-medium}} 1$$

$$R_s^H(x) = \frac{g_{1A}^H(x_A)}{P_p^H g_{1p}(x) + P_n^H g_{1n}(x)} \xrightarrow{\text{NR,no-medium}} 1$$

Here $x_A = A\frac{Q^2}{2M_A\nu} = x\frac{M_N}{M_A/A} \equiv xM_N/\overline{M}_N$, and $H = J_z$ is the helicity of nucleus A.

Here: We point out some interesting effects for $N \neq Z$!

Previous results: EMC in finite nuclei

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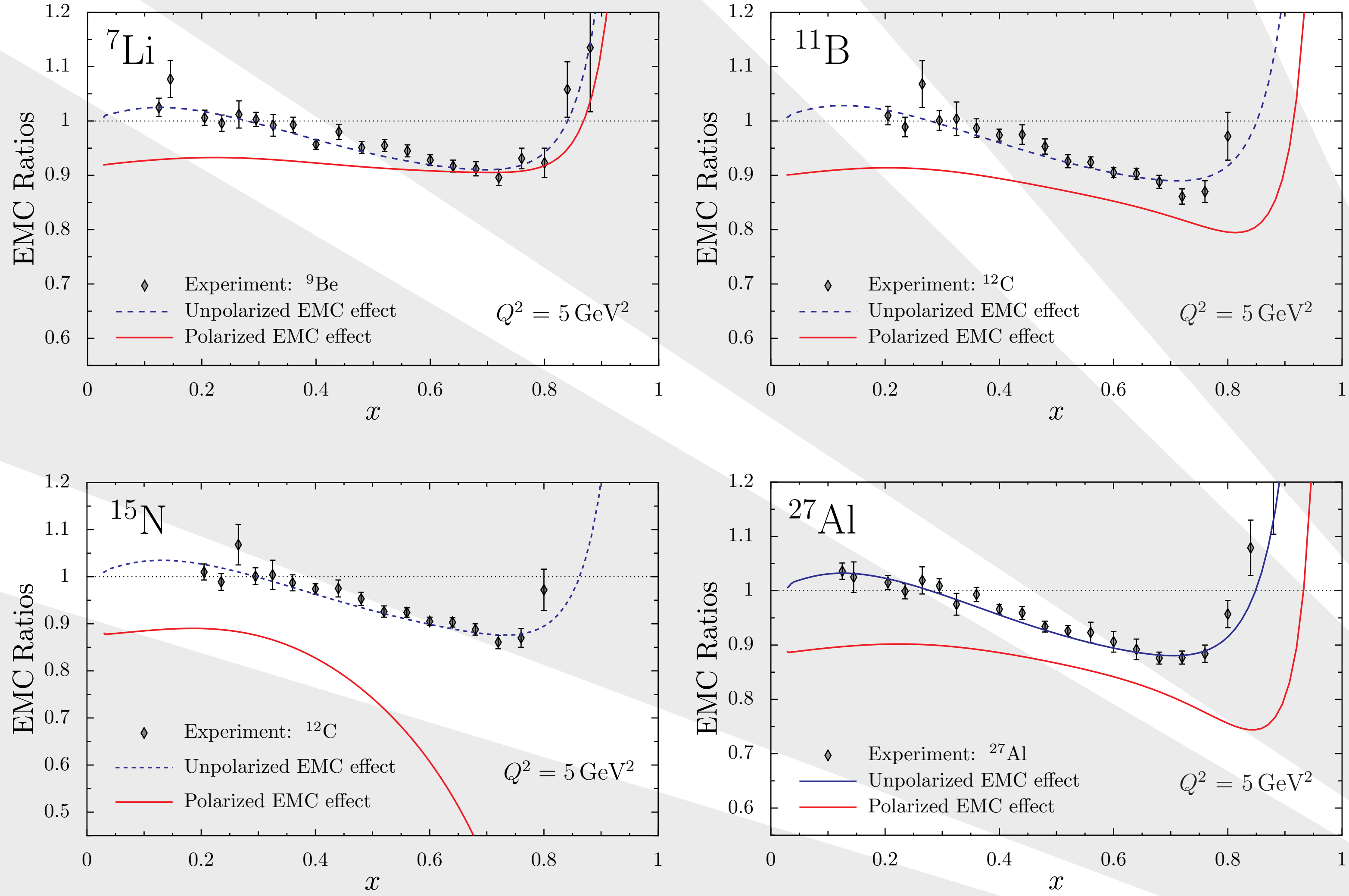

- Spin independent case: Nuclear vector potential leads to rescaling of Bjorken x, and plays the essential role!
- Spin dependent case: Nuclear scalar potential (smaller quark mass) leads to quenching of quark spin sum and enhancement of quark orbital angular momentum!

Previous results: EMC in nuclear matter

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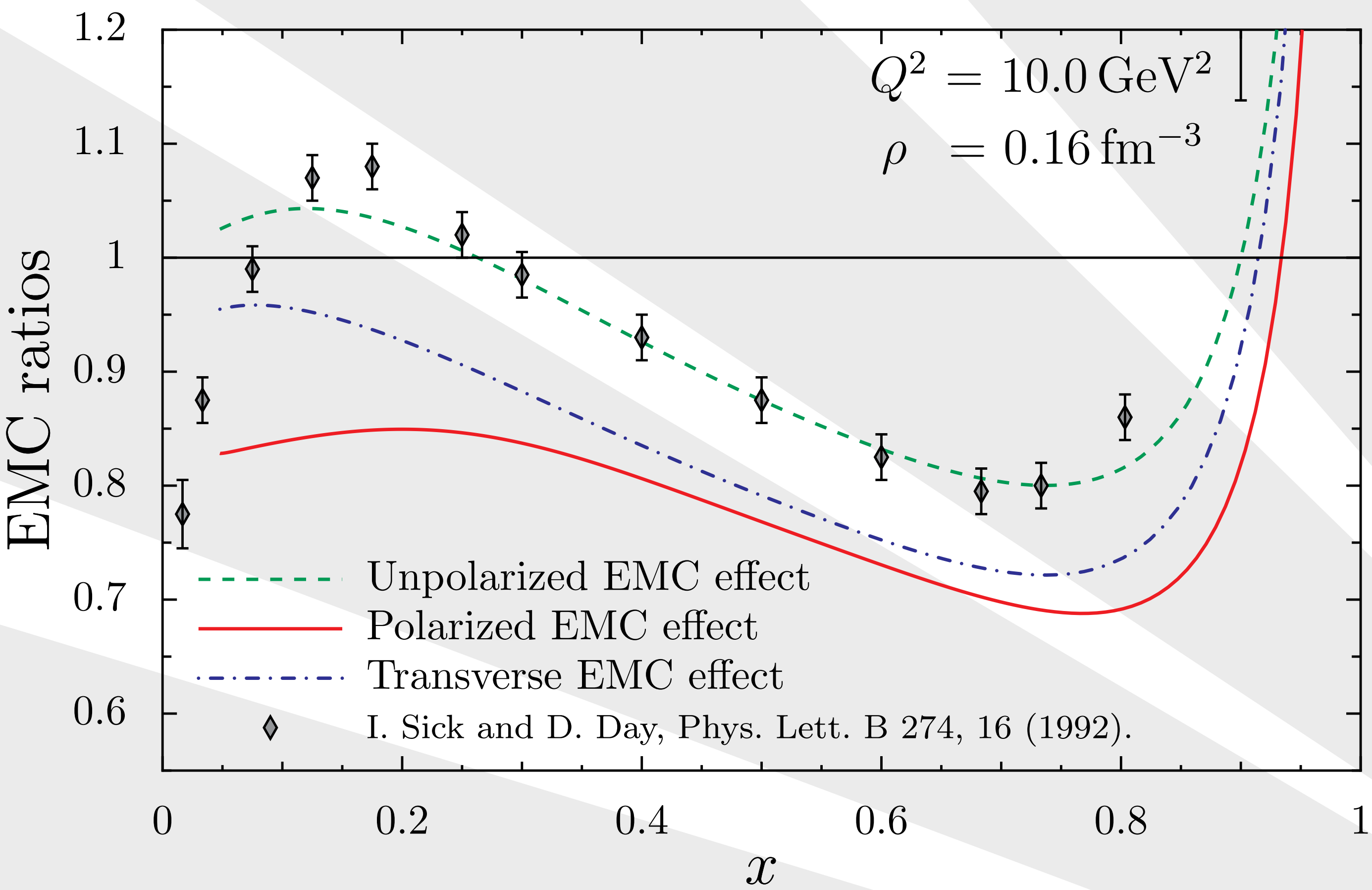

“Transverse EMC ratio” is defined here by replacing $\Delta q(x) \to \Delta_T q(x)$ in the spin-dependent EMC ratio.

Model: Single nucleon

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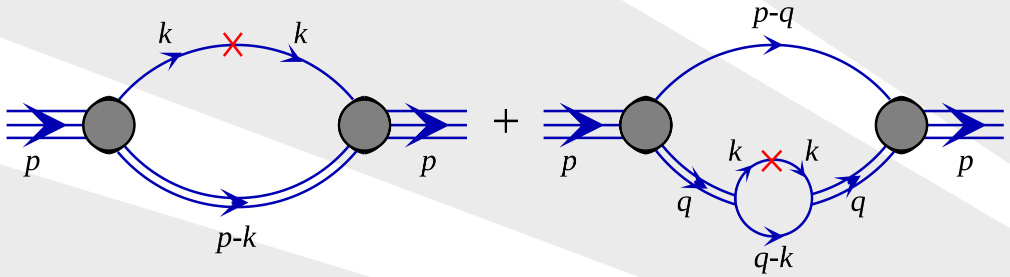
- Effective quark theory for single nucleon:
  Nambu-Jona-Lasinio (NJL) model, quark-diquark description based on the Faddeev method.

  (see: N. Ishii et al, NPA **587** (1995) 617.)

  We include scalar (0^+) and axial vector (1^+) diquarks.

- Quark distributions $(q_N(x), \Delta q_N(x), \Delta_T q_N(x))$ in the nucleon calculated from Feynman diagrams



where X $= (\gamma^+, \gamma^+\gamma_5, \gamma^+\gamma^1\gamma_5)\, \delta(x - \frac{k_-}{p_-})$.
Good agreement with empirical parametrizations!
Scalar and vector nuclear mean fields can be included in the quark propagators!

Model: Nuclear matter

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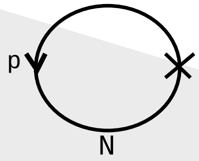
- Nuclear matter equation of state constructed in mean field approximation. Mean self consistent scalar and vector fields couple to the quarks in the nucleon. For example, the energy density for N=Z becomes

$$E(M) = E_{\mathrm{vac}}(M) + \gamma_N \int^{p_F} \frac{\mathrm{d}^3 k}{(2\pi)^3} \sqrt{M_N(M)^2 + k^2} + E_\omega$$

$M_N(M) \ldots$ nucleon mass vs. constituent quark mass.

- For $N \neq Z$, an isovector vector field (ρ^0) is included.
- After minimization, one obtains all masses as functions of density $\Rightarrow$ Calculate quark distributions in the nucleon, nucleon distributions in medium (s. diagram below), and (by convolution) quark distributions in medium.



Operator insertion (spin indep. case): $\gamma^+ \delta \left(y_A - \frac{\epsilon_p + p^3}{\overline{M}_N} \right)$, where ϵ_p = nucleon energy, $\overline{M}_N$ = mass per nucleon.

Binding energy of nuclear matter

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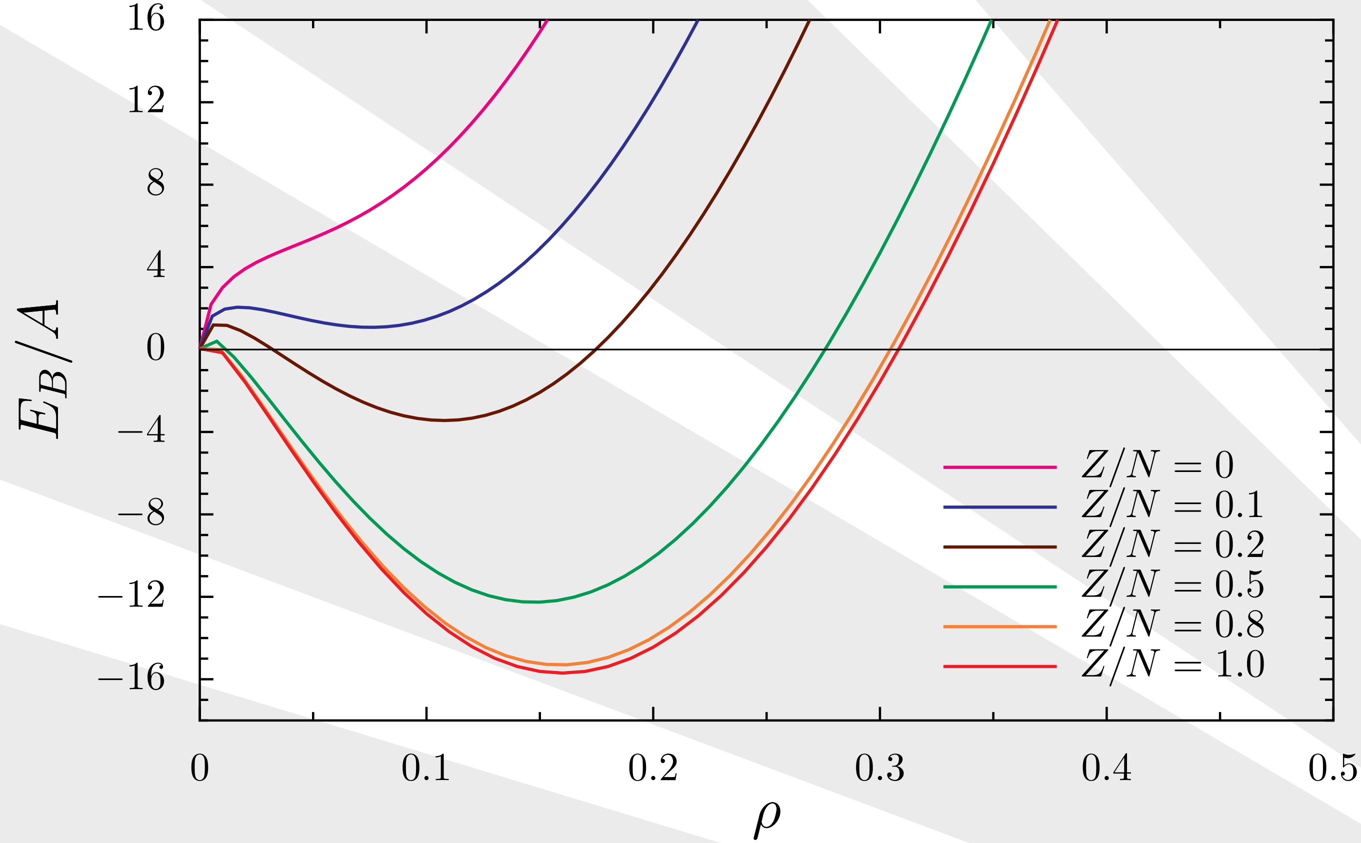

Mean vector fields: $\omega^0 = 2G_\omega\langle\psi^\dagger\psi\rangle\,, \quad \rho^0 = 2G_\rho\langle\psi^\dagger\tau_3\psi\rangle$

Vector potentials: $V_{p(n)} = 3\omega^0 \pm \rho^0\,, \quad V_{u(d)} = \omega^0 \pm \rho^0$

$G_\omega \Leftrightarrow$ saturation point for $Z = N$, $G_\rho \Leftrightarrow$ symmetry energy.

Effective masses in nuclear matter

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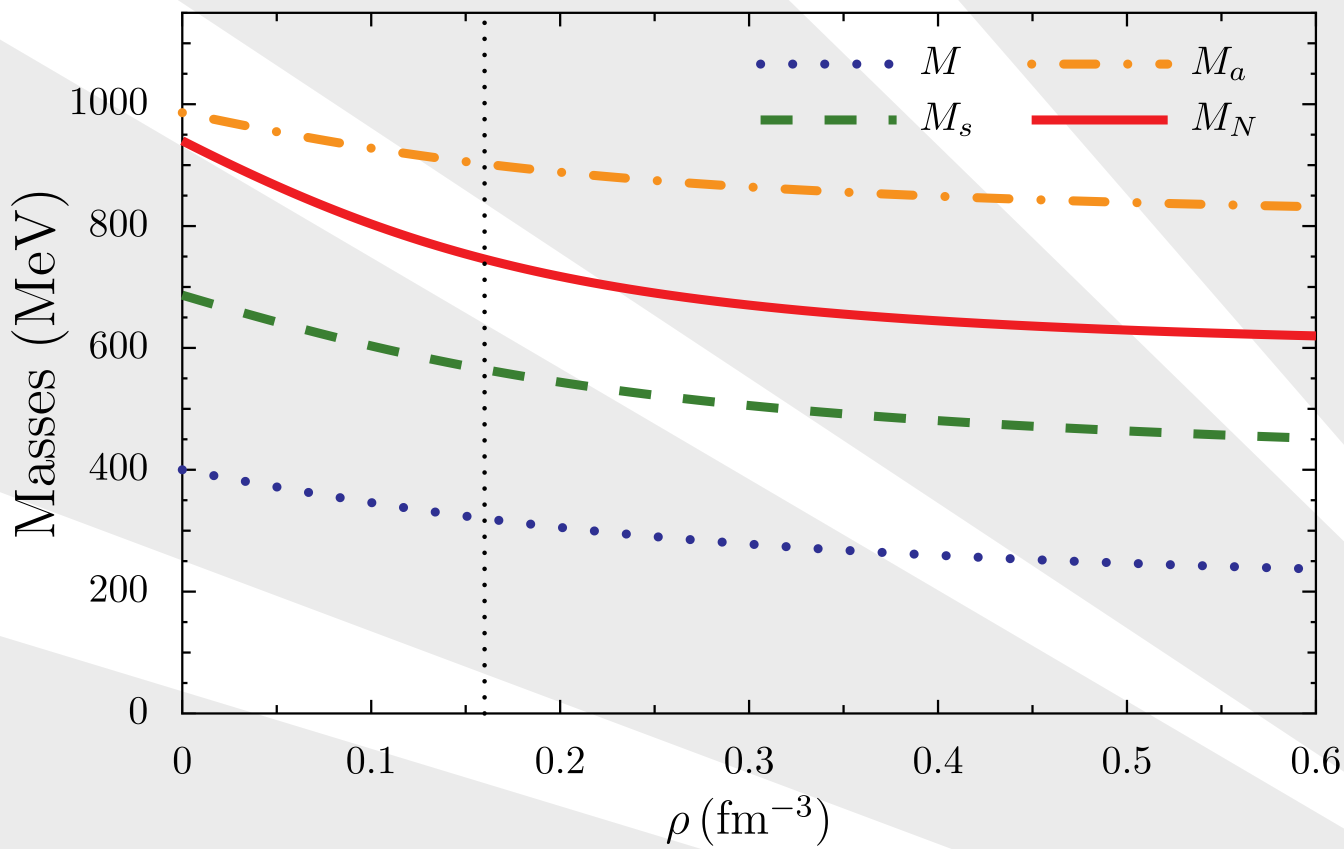

M ... constituent quark mass $(M = m - 2G_\pi \langle\overline{\psi}\psi\rangle)$
$M_{s(a)}$ ... scalar (axial vector) diquark mass (pole of qq t-matrix)
M_N ... nucleon mass (pole of q-diquark t-matrix).

Distributions in nuclear matter ($r_{pn} = Z/N$)

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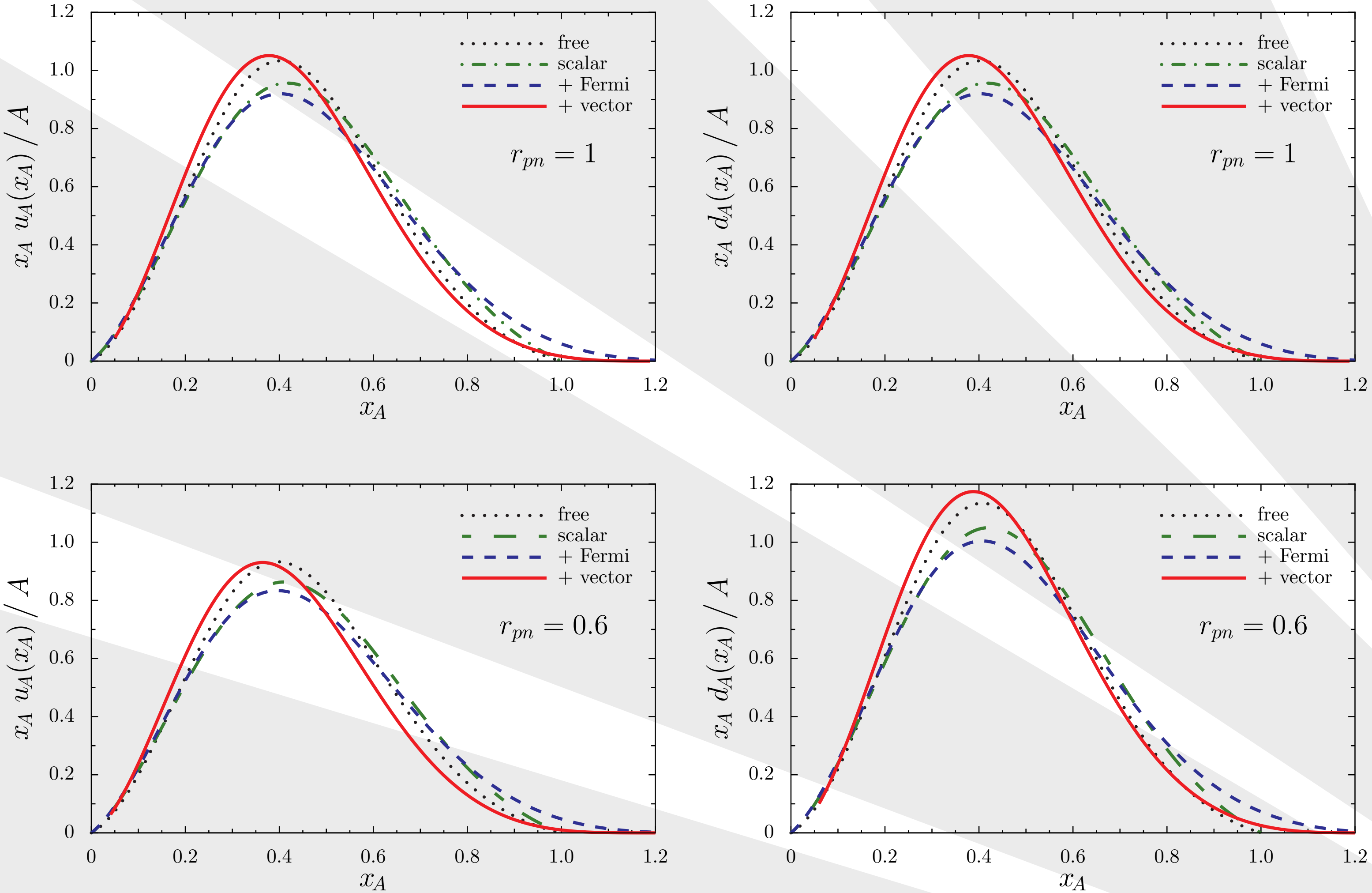

- In-medium distributions softer than free ones: Binding effect on quark level.
- For $N > Z$, u-quarks feel additional binding (symmetry energy!) $\Rightarrow$ larger medium effects for u-quarks in neutron rich matter.

EMC in nuclear matter: Dependence on Z/N

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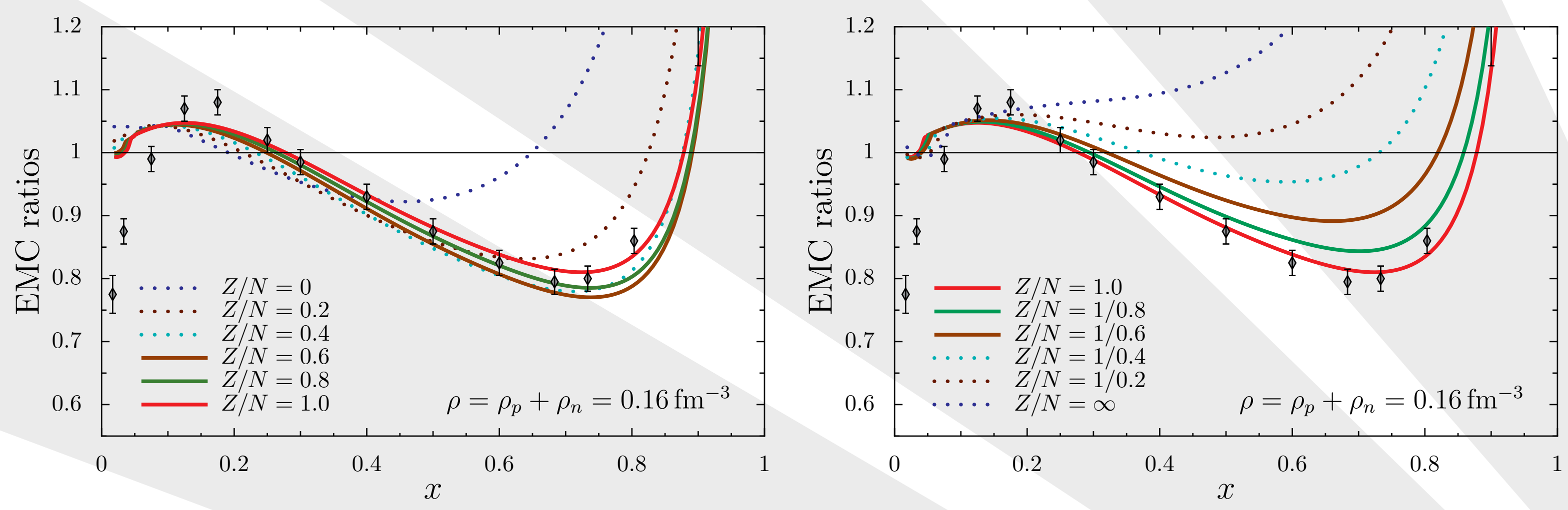

- Case $N > Z$: When matter becomes neutron-rich, medium-modification of u-quarks increases, but their number decreases $\Rightarrow$ EMC effect becomes more pronounced as Z/N decreases from 1 to 0.6, but for $Z/N < 0.6$ the EMC effect becomes smaller because d-quarks begin to dominate.

- Case $N < Z$: When matter becomes proton-rich, medium modification of u-quarks decreases and their number increases $\Rightarrow$ EMC effect becomes smaller.

Simple estimate of the isospin dependence

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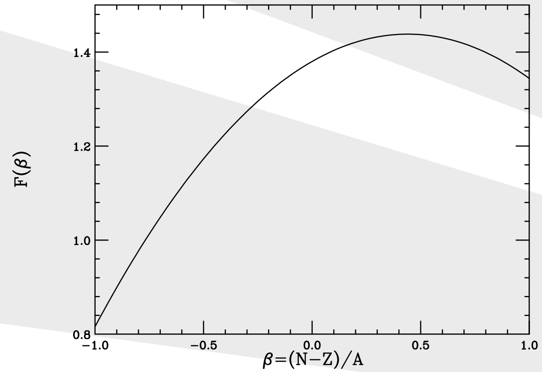
Make this argument a bit more quantitative:

- Assume: EMC effect $\propto$ binding energy of quarks (E_u, E_d) weighted by their numbers and squared charges:
  $F(\beta) \equiv \mathrm{const} \times (4N_u E_u + N_d E_d)$, where
  $\beta = (N - Z)/A$.
- Use $E_q = M_0 - \mu_q$, where $M_0 = 400$ MeV, and the chemical potentials follow from energy density as:
  $\mu_{d(u)} = \frac{1}{3}\overline{M}_N \pm 2\beta a_4$, where $\overline{M}_N = (940 - 15)$ MeV,
  $a_4 = 30$ MeV.



Note: Maximum at $\beta = 0.44$ ($Z/N = 0.4$).

Paschos-Wolfenstein Ratio (1)

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In 2002, the NuTeV collaboration measured the ratio

$$R = \frac{\sigma\left(\nu\mathrm{Fe} \to \nu\mathrm{X}\right) - \sigma\left(\overline{\nu}\mathrm{Fe} \to \overline{\nu}\mathrm{X}\right)}{\sigma\left(\nu\mathrm{Fe} \to \mu^{-}\mathrm{X}\right) - \sigma\left(\overline{\nu}\mathrm{Fe} \to \mu^{+}\mathrm{X}\right)} = \frac{\mathrm{NC}}{\mathrm{CC}}$$

(All cross sections integrated over Bjorken-x and $y = q_0/E$, $Q^2 \simeq 20$ GeV^2.) In terms of nuclear valence quark distributions,

$$R = \frac{\int \mathrm{d}x_A\, x_A\left(\alpha u_A(x_A) + \beta d_A(x_A)\right)}{\int \mathrm{d}x_A\, x_A\left(d_A(x_A) - \frac{1}{3}u_A(x_A)\right)}$$

where $\alpha = \frac{2}{3}\left(\frac{1}{4} - \frac{2}{3}\sin^2\Theta_W\right)$, $\beta = \frac{2}{3}\left(\frac{1}{4} - \frac{1}{3}\sin^2\Theta_W\right)$. For small isospin asymmetry,

$$R = R_0 + \left(1 - \frac{7}{3}\sin^2\Theta_W\right)\frac{f_-}{f_+} \equiv R_0 + \delta R$$

where $R_0 = \frac{1}{2} - \sin^2\Theta_W, \quad f_\pm = \int \mathrm{d}x_A x_A\left(u_A \pm d_A\right)$.

Paschos-Wolfenstein Ratio (2)

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- NuTeV estimated f_-/f_+ by using "free" parton distributions ($q_{Af} = Zq_{pf} + Nq_{nf}$, $q = u, d$), and extracted $\sin^2\Theta_W$. Their result was $\sin^2\Theta_W = 0.2277$, which is different from Standard Model value $\sin^2\Theta_W = 0.2227$.
  (⇒ "NuTeV anomaly": $R - \delta_f R \neq \frac{1}{2} - \sin^2\Theta_W$.)

- However: Use the Standard Model value of $\sin^2\Theta_W$ (⇒ $R_0 = 0.2773$), but take into account medium ("med") and charge symmetry breaking ("csb") corrections: $\delta R = \delta_f R + \delta_{\text{med}} R + \delta_{\text{csb}} R$. Then we get for $R - \delta_f R = R_0 + \delta_{\text{med}} R + \delta_{\text{csb}} R$:

free	+ med	+ csb*	NuTeV
0.2773	0.2741	0.2724	0.2723

$*$ Arising from $m_d > m_u$, from: J.T. Londergan, Eur. Phys. J. **A 32** (2007) 415.

- Result: Measured PW ratio is consistent with the Standard Model value of $\sin^2\Theta_W$: There is no "anomaly".

Parity - violating (PV) EMC effect (1)

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Compare parton model expressions for usual EMC ratio and PV EMC ratio ($\gamma - Z$ interference effect):

$$R^{\gamma} = \frac{F_{2A}}{F_{2A,\text{naive}}} = \frac{4u_A + d_A}{4u_{Af} + d_{Af}}$$

$$R^{\gamma Z} = \frac{F_{2A}^{\gamma Z}}{F_{2A,\text{naive}}^{\gamma Z}} = \frac{1.15u_A + d_A}{1.15u_{Af} + d_{Af}}$$

(Remember: $q_{Af} = Zq_{pf} + Nq_{nf}, \quad q = u, d$.)

- For $N = Z$ and Coulomb neglected:
  $u_A = d_A \quad \Rightarrow R^{\gamma Z} = R^{\gamma}$.
- For $N > Z$: $u_A < d_A$, but u_A has stronger medium modifications because of additional binding from symmetry energy. (Remember: This was the reason why usual EMC effect increases as Z/N decreases from 1 to 0.6.)
- The ratio $R^{\gamma Z}$ is less dominated by u quarks $\Rightarrow$ PV EMC effect will decrease as Z/N decreases.

F_2^γ and $F_2^{\gamma Z}$ $(r_{pn} = Z/N)$

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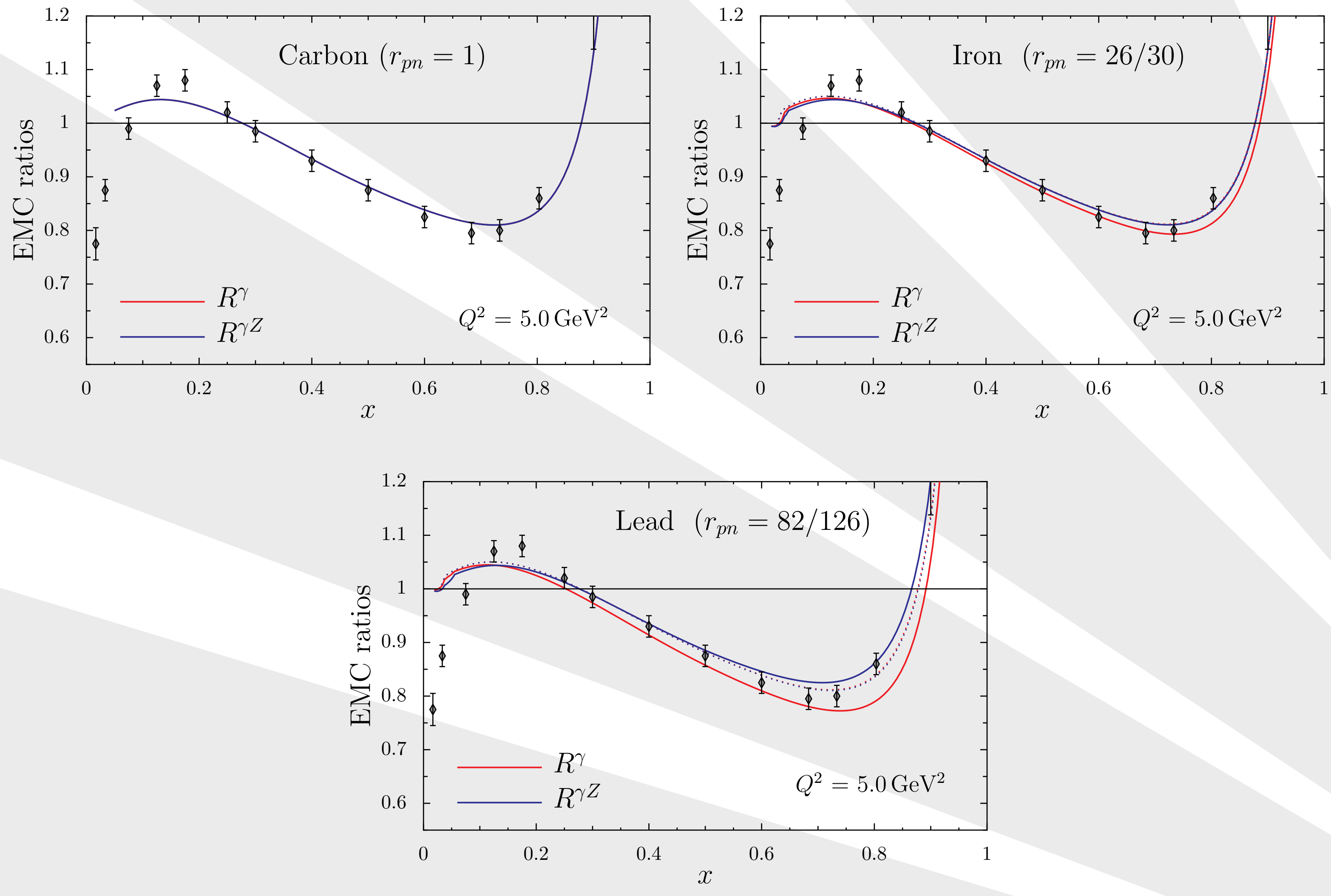

$$R^\gamma = \frac{4u_A + d_A}{4u_{Af} + d_{Af}}\,, \quad R^{\gamma Z} = \frac{1.15u_A + d_A}{1.15u_{Af} + d_{Af}}.$$

PV DIS a_1 ratios

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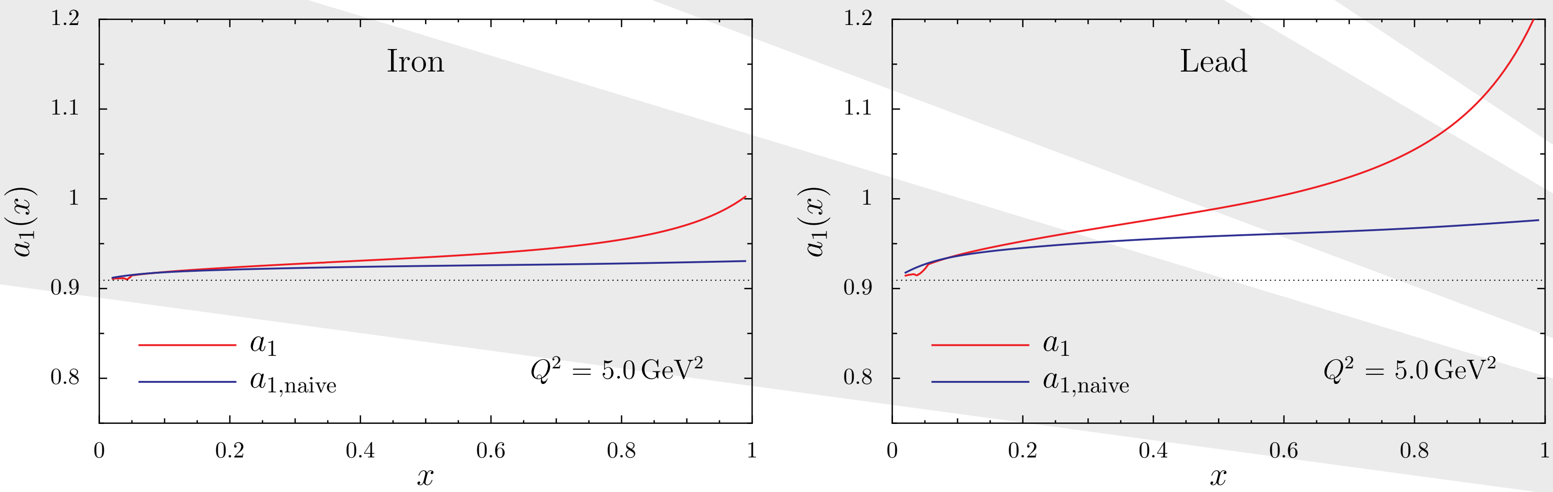
Single-spin asymmetry (arising from vector part of quark current) in PV DIS is proportional to:

$$a_1 \equiv \frac{F_2^{\gamma Z}}{F_2^{\gamma}} \simeq 2.11\,\frac{1.15\,u_A(x) + d_A(x)}{4\,u_A(x) + d_A(x)}$$

$$\Rightarrow \frac{a_1}{a_{1,\text{naive}}} = \frac{R^{\gamma Z}}{R^{\gamma}} > 1\,.$$

This ratio is expected to increase with increasing isospin asymmetry.



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For nuclear systems with neutron excess, the symmetry energy leads to additional attraction (repulsion) for up (down) quarks. This gives rise to interesting new medium modifications:

- EMC effect increases with increasing isospin asymmetry (in the range $0.6 < \frac{Z}{N} < 1$).
- "NuTeV anomaly" (Paschos-Wolfenstein ratio for $\nu - A$ DIS) is no longer an anomaly: The experimental PW ratio can be explained by nuclear effects arising from neutron excess, and charge symmetry breaking effects.
- Parity violating EMC effect is predicted to be different from the usual EMC effect. Single-spin asymmetries are expected to increase with increasing isospin asymmetry.