Parton distributions in nuclear systems

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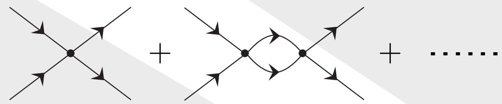
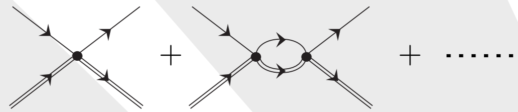
Introduction

- Our earlier work: We used an effective quark theory - the Nambu-Jona-Lasinio (NJL) model - to calculate **parton distribution functions** in **free** and **bound** nucleons.
  We obtained interesting results and predictions for the unpolarized and polarized **EMC effects**.

- Here: We point out new effects for $N \neq Z$:
  - **Flavor dependence** of nuclear parton distributions
  - **Parity violation** in $e - A$ deep inelast. scattering (DIS)
  - **Paschos-Wolfenstein ratio** in $\nu - A$ DIS.

Model

- Free nucleon: quark-diquark description based on the Faddeev method.
  We include scalar (0^+) and axial vector (1^+) diquarks.

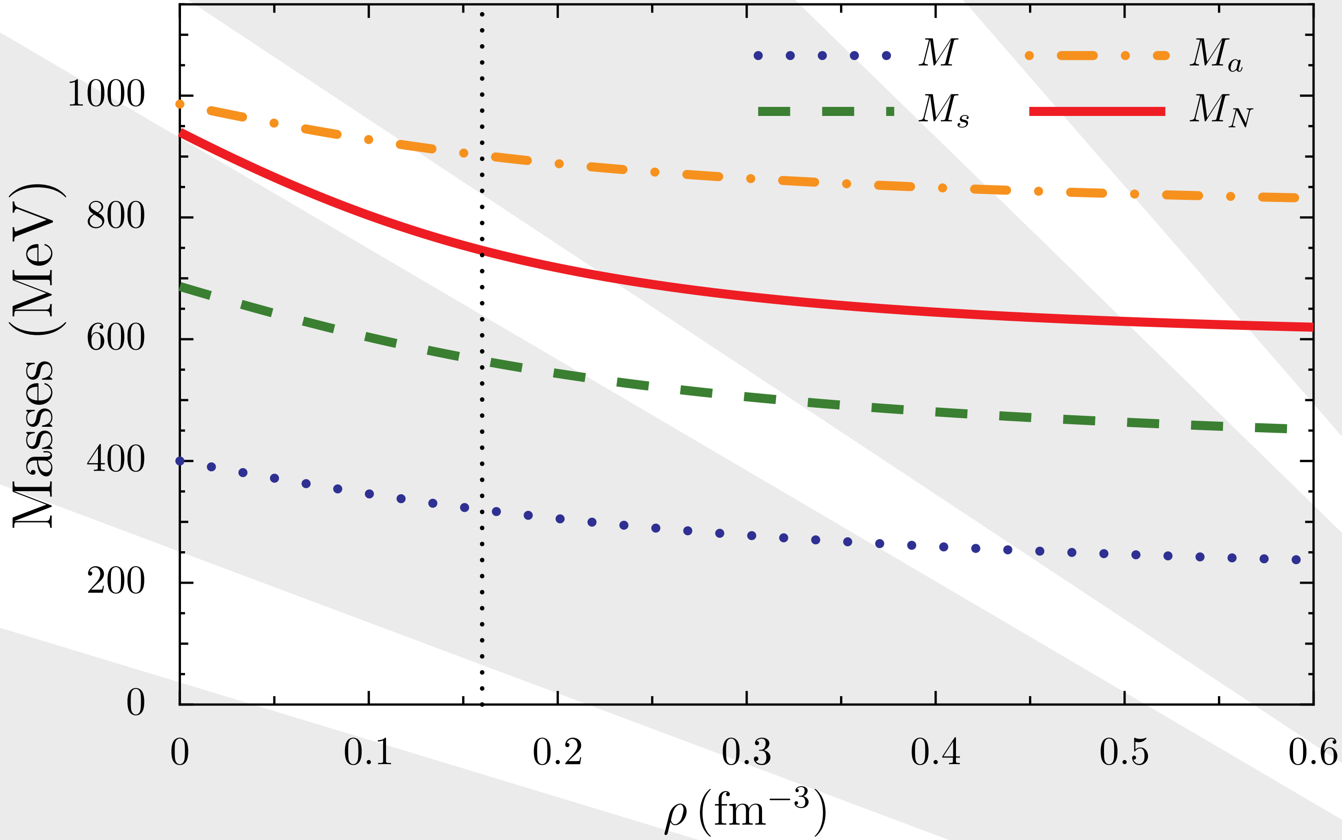
  diquark:  nucleon: 

  $\Rightarrow$ Calculate **parton distributions in the free nucleon**.

- Nuclear matter described in mean field approximation:
  Self consistent mean scalar and vector fields couple to the quarks in the nucleon!
  We include the following mean fields:
  $M = m - 2G_\pi \langle \overline{\psi}\psi \rangle$,
  $\omega_0 = 2G_\omega \langle \overline{\psi}\gamma_0\psi \rangle$, $\rho_0 = 2G_\rho \langle \overline{\psi}\gamma_0\tau_3\psi \rangle$.

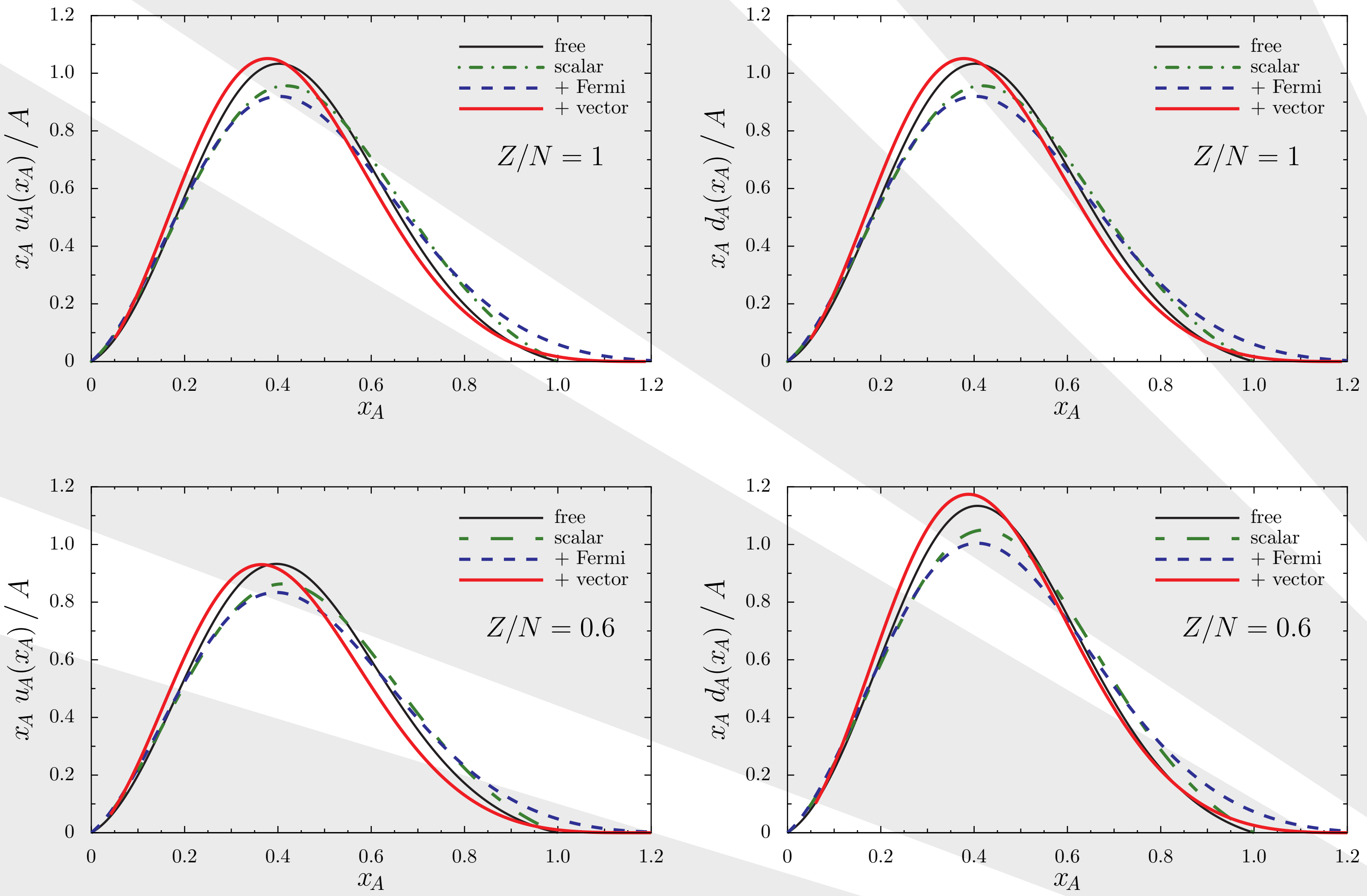
- Incorporate these mean fields in the quark propagators to calculate parton distributions in the bound nucleon.
  Use the convolution formalism to get the parton distributions in nuclear matter.

Effective masses in symmetric nuclear matter



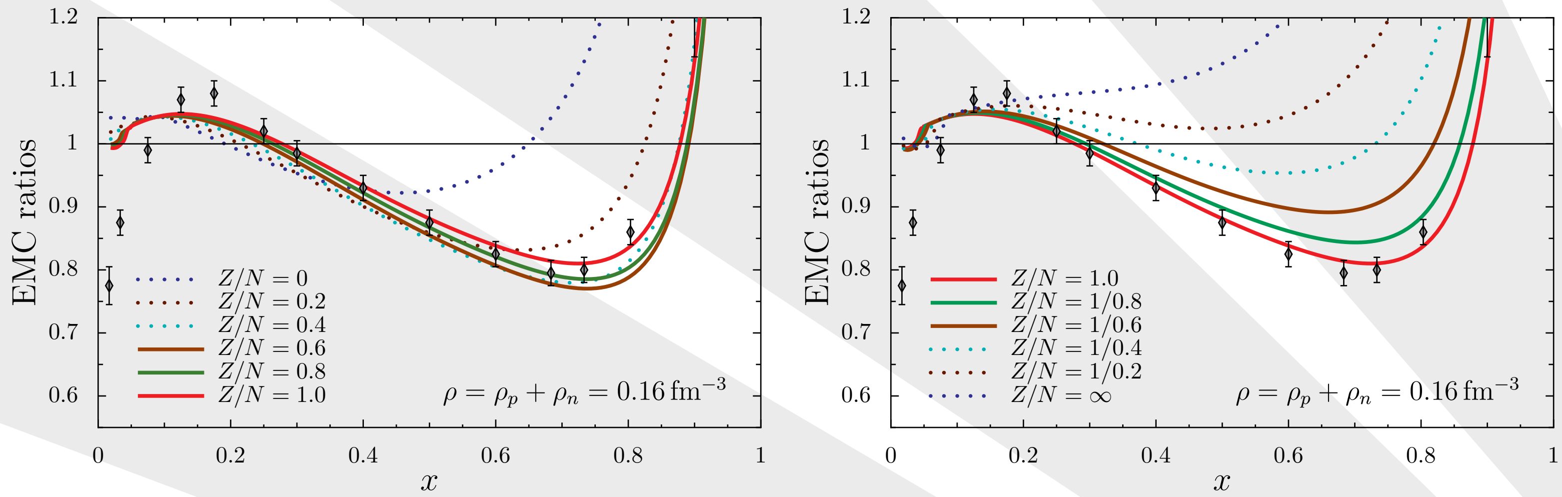
M . . . constituent quark mass $(M = m - 2G_\pi \langle\overline{\psi}\psi\rangle)$
$M_{s(a)}$ . . . scalar (axial vector) diquark mass (pole of qq t-matrix)
M_N . . . nucleon mass (pole of q-diquark t-matrix).

In-medium flavor dependence



- 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.** (This effect is caused mainly by the ρ^0 field.)

Isospin dependence of EMC effect



EMC ratio = $\frac{F_{2A}}{F_{2A,\text{naive}}} \simeq \frac{4u_A + d_A}{4u_{A\text{f}} + d_{A\text{f}}}$, where $q_{A\text{f}} = Zq_{p\text{f}} + Nq_{n\text{f}}$.

- 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.

Applications

This flavor dependence should show up in many places, e.g.,
$e + A \to e' + \pi^{\pm} + X, \quad \pi^{\pm} + A \to (\ell^+\ell^-) + X$.

Here: Consider some physical quantity R, which is a ratio of nuclear parton distributions:

$$R = \frac{c_1 u_A + c_2 d_A}{c_3 u_A + c_4 d_A} \simeq A + B\,\frac{d_A - u_A}{d_A + u_A} \equiv R_0 + \delta_{\rm naive} R + \delta_{\rm med} R$$

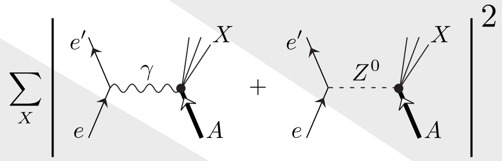
A, B = known constants, $R_0 = A =$ value for $N = Z$,
$\delta_{\rm naive} R =$ **neutron excess correction** obtained from **free** (no-medium) parton distributions.

- If R could be measured, any deviation from the "**naive value**" $R_0 + \delta_{\rm naive} R$ would be an indication for the in-medium flavor dependence $\delta_{\rm med} R$.

Note: Effects of **charge symmetry breaking** should also be considered.

Application 1: Parity-violating DIS

Parity violation from $\gamma - Z^0$ **interference**:

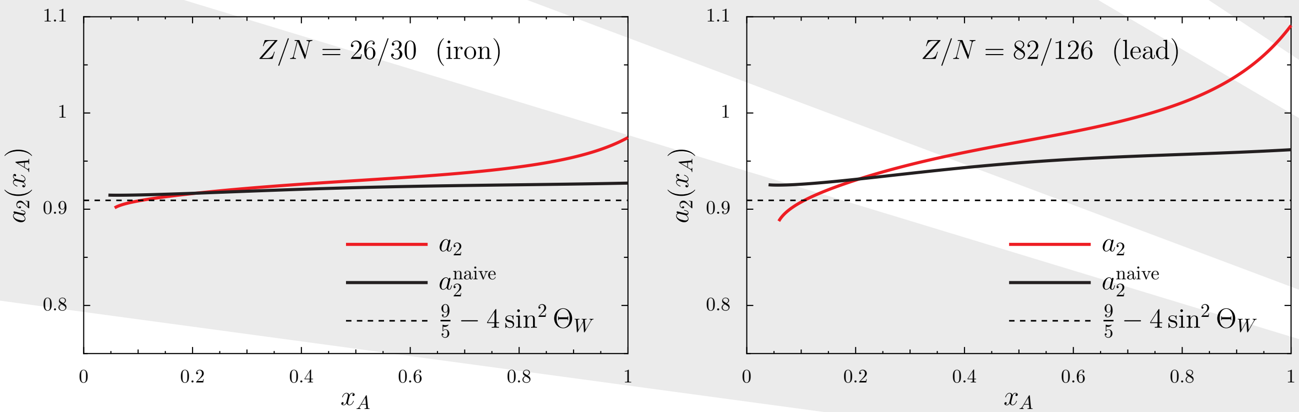


$$W^{\mu\nu} = \frac{1}{4\pi} \sum_X < X|J^\mu|N >^* < X|J^\nu|N > \times (2\pi)^4 \delta(p_X - p - q)$$

leads to electron spin asymmetry $\frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$ for unpolarized targets:

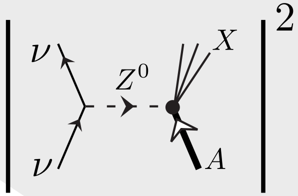
$$A_{PV} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} [a_2(x_A) + \text{small corrections}]$$

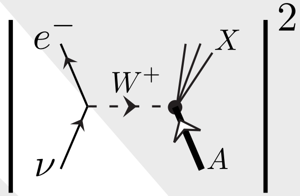
$$a_2 \simeq \left(\frac{9}{5} - 4\sin^2\Theta_W\right) + \frac{12}{25}\frac{d_A - u_A}{d_A + u_A}$$



Note: a_2^{naive} is the naive estimate of neutron excess effects, using the “free” distributions u_{Af} and d_{Af}.

Application 2: DIS of neutrinos

NC: $\sum_X$ 

CC: $\sum_X$ 

In 2002, the NuTeV collaboration measured the following Paschos-Wolfenstein ratio (all cross sections integrated over x_A and y):

$$
\begin{aligned}
R &= \frac{\sigma(\nu \mathrm{Fe} \to \nu \mathrm{X}) - \sigma(\overline{\nu}\mathrm{Fe} \to \overline{\nu}\mathrm{X})}{\sigma(\nu \mathrm{Fe} \to \mu^- \mathrm{X}) - \sigma(\overline{\nu}\mathrm{Fe} \to \mu^+ \mathrm{X})} \\
&\simeq \left(\frac{1}{2} - \sin^2\Theta_W\right) - \left(1 - \frac{7}{3}\sin^2\Theta_W\right)\frac{\langle x_A d_A - x_A u_A\rangle}{\langle x_A d_A + x_A u_A\rangle} \\
&\equiv R_0 + \delta_{\mathrm{naive}} R + \delta_{\mathrm{med}} R
\end{aligned}
$$

- If the Standard Model value of $\sin^2\Theta_W$ is used: Measured R deviates from the "naive value" $R_0 + \delta_{\mathrm{naive}} R$ ($\Rightarrow$ "NuTeV anomaly").
- However: Including medium effects, and also charge symmetry breaking effects ($m_d > m_u$), the measured value of R is reproduced with the Standard Model value of $\sin^2\Theta_W$: **There is no anomaly!**

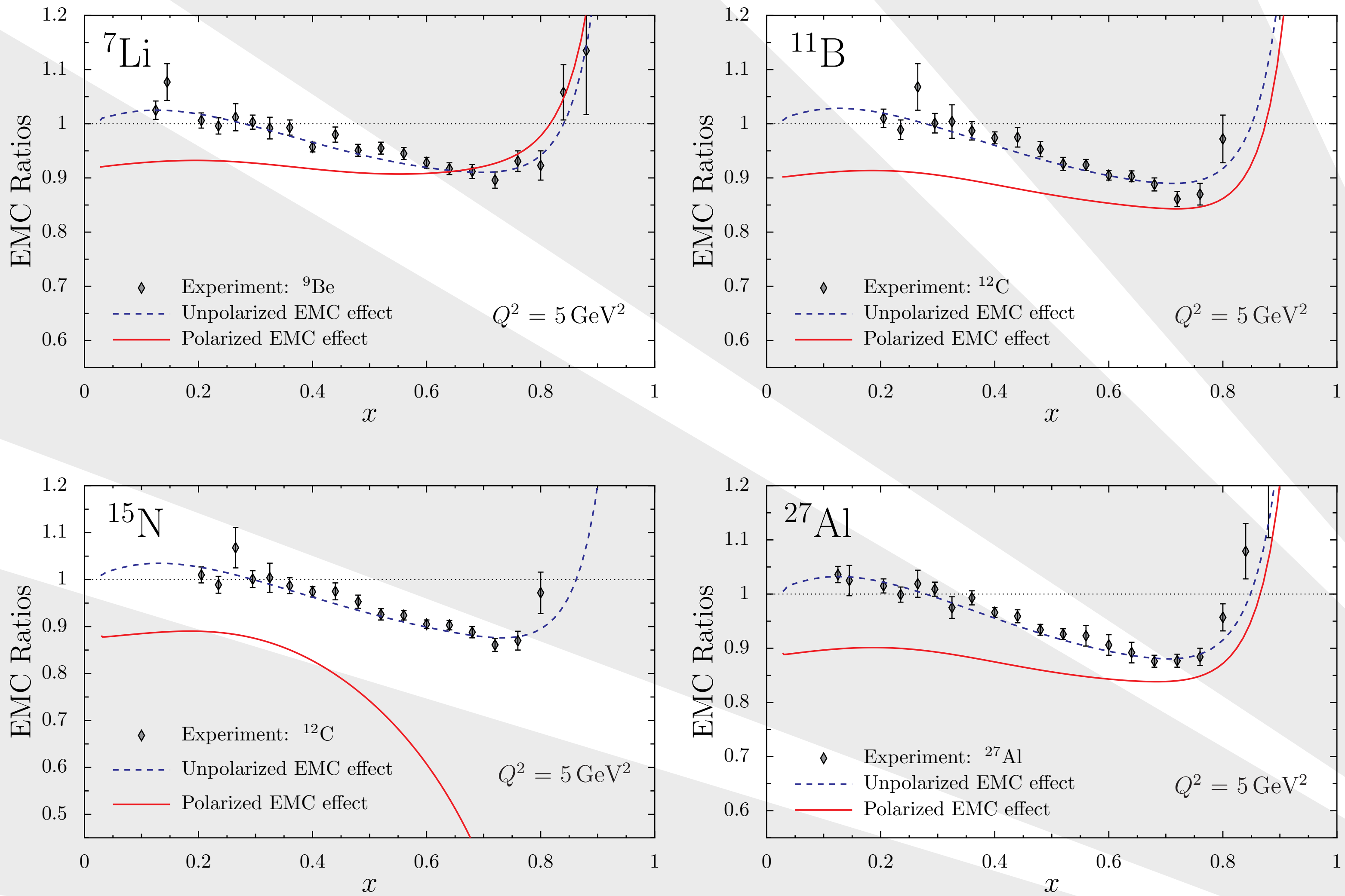
Summary

For nuclear systems with neutron excess, the isovector mean field gives rise to interesting new medium modifications:

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

Our earlier work: EMC effect

- ❖ Introduction
- ❖ Model
- ❖ Isospin dependence
- ❖ PVDIS
- ❖ PVDIS
- ❖ Neutrinos
- ❖ Summary



- **Polarized case**: Nuclear scalar potential (smaller quark mass) leads to enhancement of quark orbital angular momentum in the medium!

Results for spin sums:

	Δu	Δd	Σ	g_A
p	0.97	-0.30	0.67	1.27
^{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
nucl. matt.	0.74	-0.25	0.49	0.99

- Isoscalar spin sum: $\Delta u_A + \Delta d_A \equiv \Sigma \cdot (P_p + P_n)$, where $\Sigma \equiv \Delta u + \Delta d$ is the **isoscalar spin sum for a nucleon bound in the valence level**.
- Isovector spin sum: $\Delta u_A - \Delta d_A \equiv g_A \cdot (P_p - P_n)$, where $g_A \equiv \Delta u - \Delta d$ is the **isovector (Bjorken) spin sum for a nucleon bound in the valence level**.