The Polarized EMC effect

Ian Cloët

(Argonne National Lab)

Collaborators

Wolfgang Bentz (Tokai Uni.) and Tony Thomas (JLab)

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Theme

- Are nucleon properties modified by the nuclear medium?
  - Of fundamental importance.
  - Remains an open question.
- Areas where medium modifications seem important:
  - Quenching of g_A in-medium
  - Nuclear magnetic moments
  - Nuclear Form Factors (e.g.^{4}He)
- Most importantly nuclear structure functions, that is, the EMC and potentially the Polarized EMC effects
  - Spin observables $\Longleftrightarrow$ lower components

Hadronic Tensor

- Bjorken limit and Callen-Gross gives:
  - For $J=\frac{1}{2}$ target

$$W_{\mu\nu}=\left(g_{\mu\nu}\frac{P\cdot q}{q^2}+\frac{p_\mu p_\nu}{\nu}\right)F_2(x_A,Q^2)+i\,\frac{\varepsilon_{\mu\nu\lambda\sigma}q^\lambda s^\sigma}{\nu}\,g_1(x_A,Q^2)$$

  - For arbitrary J ($2J+1$ structure functions)

$$W^H_{\mu\nu}=\left(g_{\mu\nu}\frac{P\cdot q}{q^2}+\frac{p_\mu p_\nu}{\nu}\right)F_2^{JH}(x_A,Q^2)+i\,\frac{\varepsilon_{\mu\nu\lambda\sigma}q^\lambda s^\sigma}{\nu}\,g_1^{JH}(x_A,Q^2)$$

$$F_2^{JH}=F_2^{J\,-H}\qquad g_1^{JH}=-g_1^{J\,-H}$$

- Parton model expressions

$$g_{1A}^{JH}(x)=\frac{1}{2}\sum_q e_q^2\left[\Delta q_A^{JH}(x)+\Delta\bar{q}_A^{JH}(x)\right].$$

Calculation

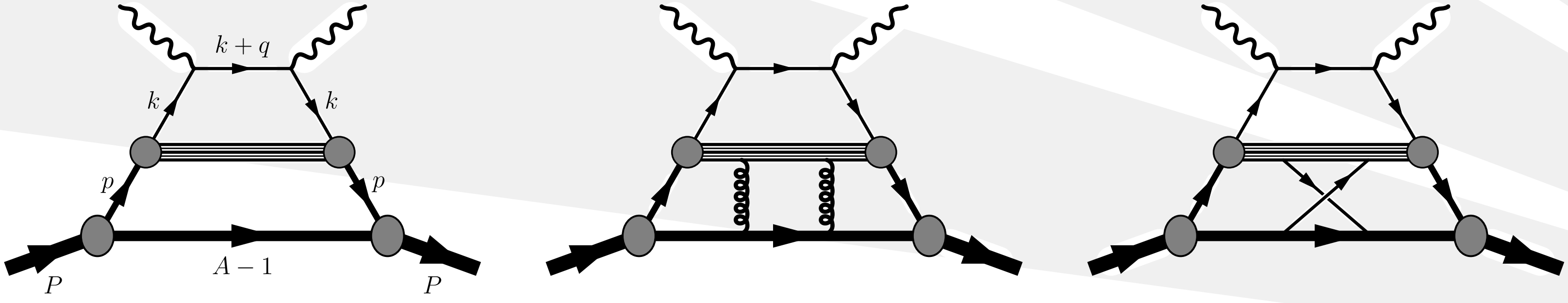
- Finite Nuclei quark distributions

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

- Using Modified Convolution formalism

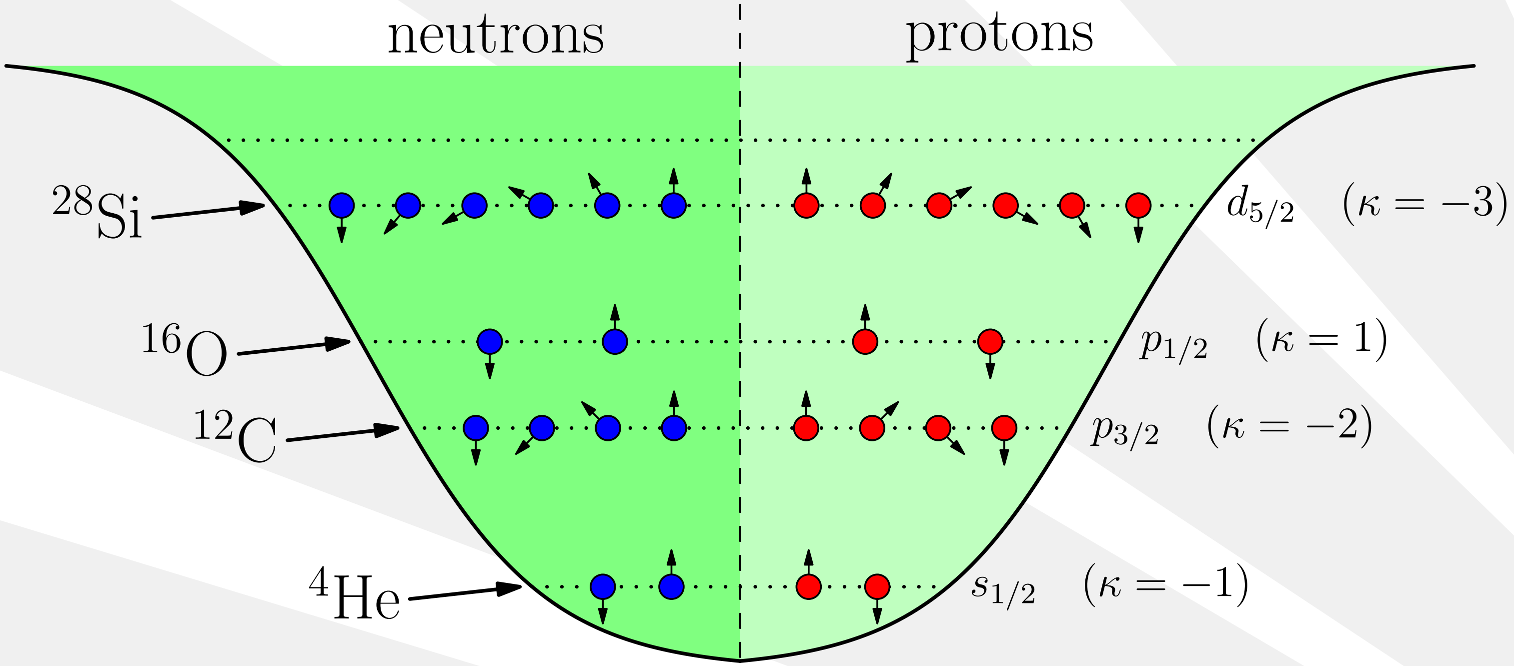
$$q_A^{JH}(x_A) = \sum_{\kappa,m} \int dy_A \int dx\ \delta(x_A - y_A\, x)\ f_{\kappa,m}^{(JH)}(y_A)\ q_\kappa(x)\,.$$

- Diagrammatically



(a) (b) (c)

Shell Model



$$q_A^{JH}(x_A) = \sum_{\kappa,m} \int dy_A \int dx\ \delta(x_A - y_A\, x)\ f^{(JH)}_{\kappa,m}(y_A)\ q_\kappa(x)\,.$$

Quark Multipole Distributions

- ❖ Theme
- ❖ Hadronic Tensor
- ❖ Calculation
- ❖ Quark Dis.
- ❖ NJL model
- ❖ Finite Density
- ❖ Nucleon Dis.
- ❖ Nucleon Dis. ^{11}B
- ❖ Quark Dis. ^{27}Al
- ❖ Quark Dis. ^{27}Al
- ❖ Polarized EMC
- ❖ Conclusions

- Multipole distributions

$$q^{(JK)}(x) \equiv \sum_{H} (-1)^{J-H} \sqrt{2K+1} \begin{pmatrix} J & J & K \\ H & -H & 0 \end{pmatrix} q^{JH}(x)$$

- New Sum Rules

$$\int_0^A x^{n-1}\ q^{(JK)}(x)dx = 0, \qquad \int_0^A x^{n-1}\, \Delta q^{(JK)}(x)dx = 0$$

$K,\ n$ even, $2 \leqslant n < K$ $\qquad$ $K,\ n$ odd, $1 \leqslant n < K$

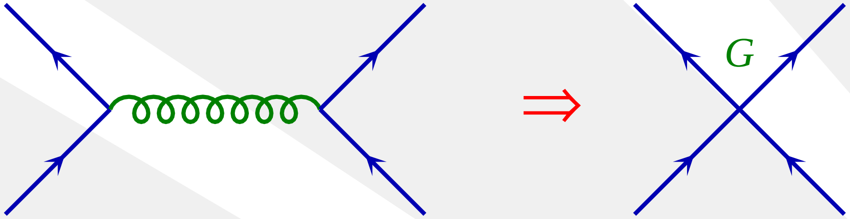
❖ Example: $J = 3/2$ $\quad \int_0^A dx\, \Delta q^{(\frac{3}{2}3)}(x) = 0$

- Example: ^{7}Li, ^{11}B, $\ldots$

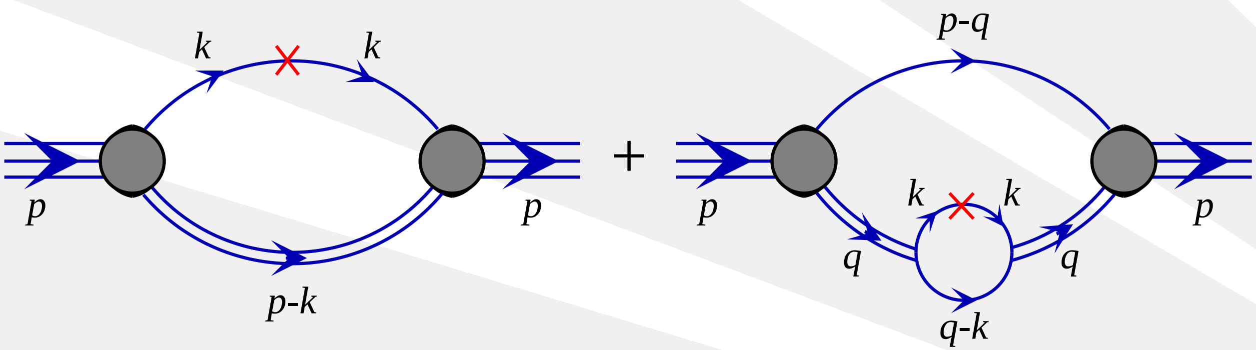
$$u_A^{\frac{3}{2}\frac{3}{2}} \simeq u_A^{\frac{3}{2}\frac{1}{2}} \Longrightarrow u_A^{(\frac{3}{2}0)} \simeq 2u_A^{\frac{3}{2}\frac{3}{2}}, \quad u_A^{(\frac{3}{2}2)} \simeq 0$$

Nambu–Jona-Lasinio Model

- Low energy effective theory



- Nucleon quark distributions



- $[q(x), \Delta q(x), \Delta_T q(x)] \quad \rightarrow \quad \delta(x - \frac{k^+}{p^+}) \left[\gamma^+, \gamma^+\gamma_5, \gamma^+\gamma^1\gamma_5\right]$

- Covariant, satisfy sum rules and gives correct support.

$u_v(x)$ and $d_v(x)$ distributions

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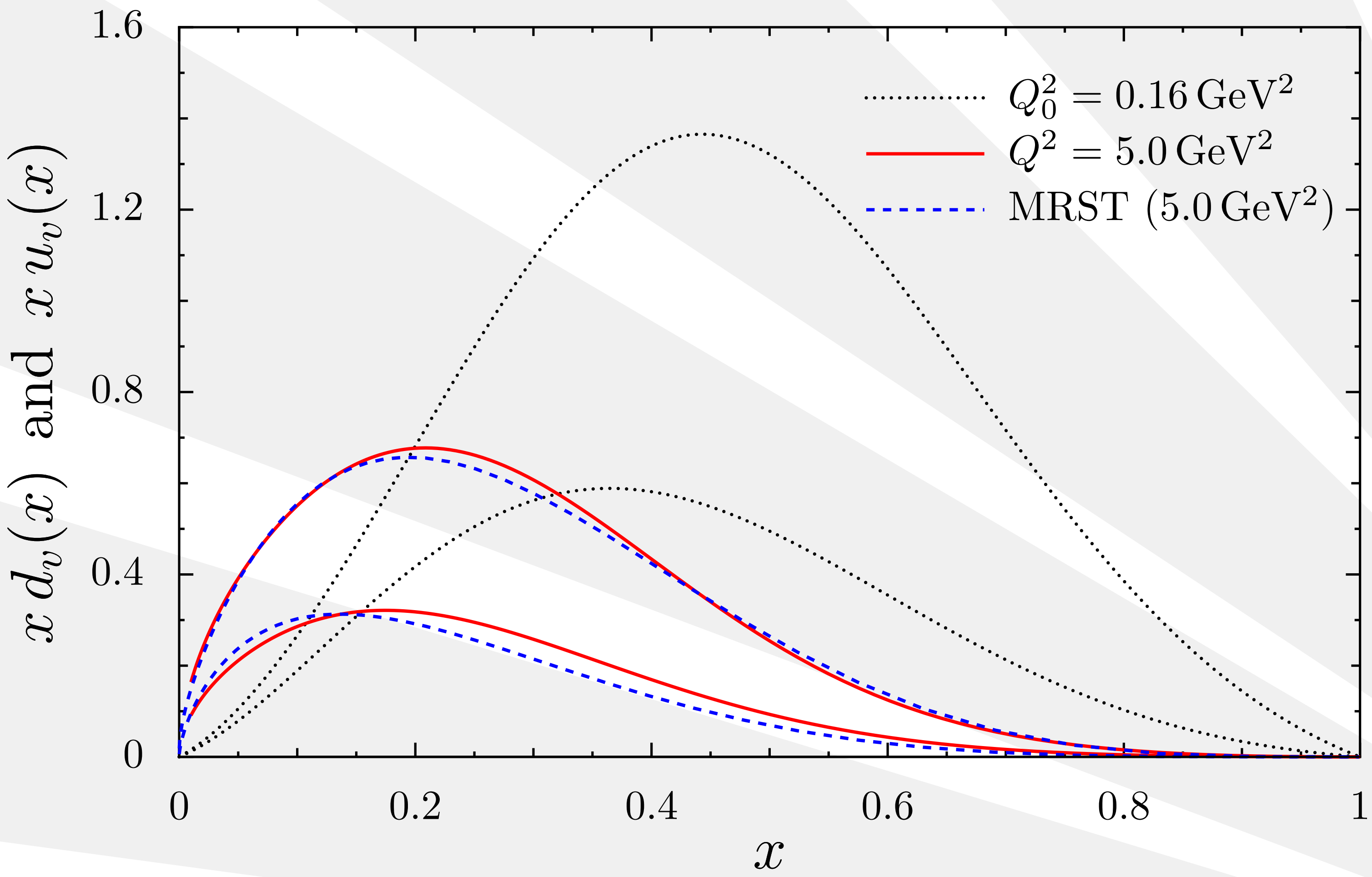


● MRST, Phys. Lett. B **531**, 216 (2002).

NJL Model at Finite Density

- Re-calculate diagrams

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

- Equivalent to:
  - ✧ Scalar field: via effective masses
  - ✧ Fermi motion: via convolution
  - ✧ Vector field: via scale transformation
- Vector field, Finite Nuclei:

$$q_{A,\kappa}(x_A) = \frac{\overline{M}_N}{\hat{M}_N}\, q_{A0,\kappa}\left(\frac{\overline{M}_{N\kappa}}{\hat{M}_{N\kappa}} x_A - \frac{V_\kappa}{\hat{M}_{N\kappa}}\right)$$

$$\hat{M}_{N\kappa} = \overline{M}_N - 3V_\kappa, \qquad \overline{M}_N = M_A/A$$

Nucleon distribution functions

- Definition

$$f_{\kappa m}(y_A) = \frac{\sqrt{2}\,\overline{M}_N}{A} \int \frac{d^3p}{(2\pi)^3}$$
$$\delta\left(p^3 + \varepsilon_\kappa - \overline{M}_N\, y_A\right) \overline{\Psi}_{\kappa m}(\vec{p})\ \gamma^+\, \Psi_{\kappa\, m}(\vec{p})\,,$$

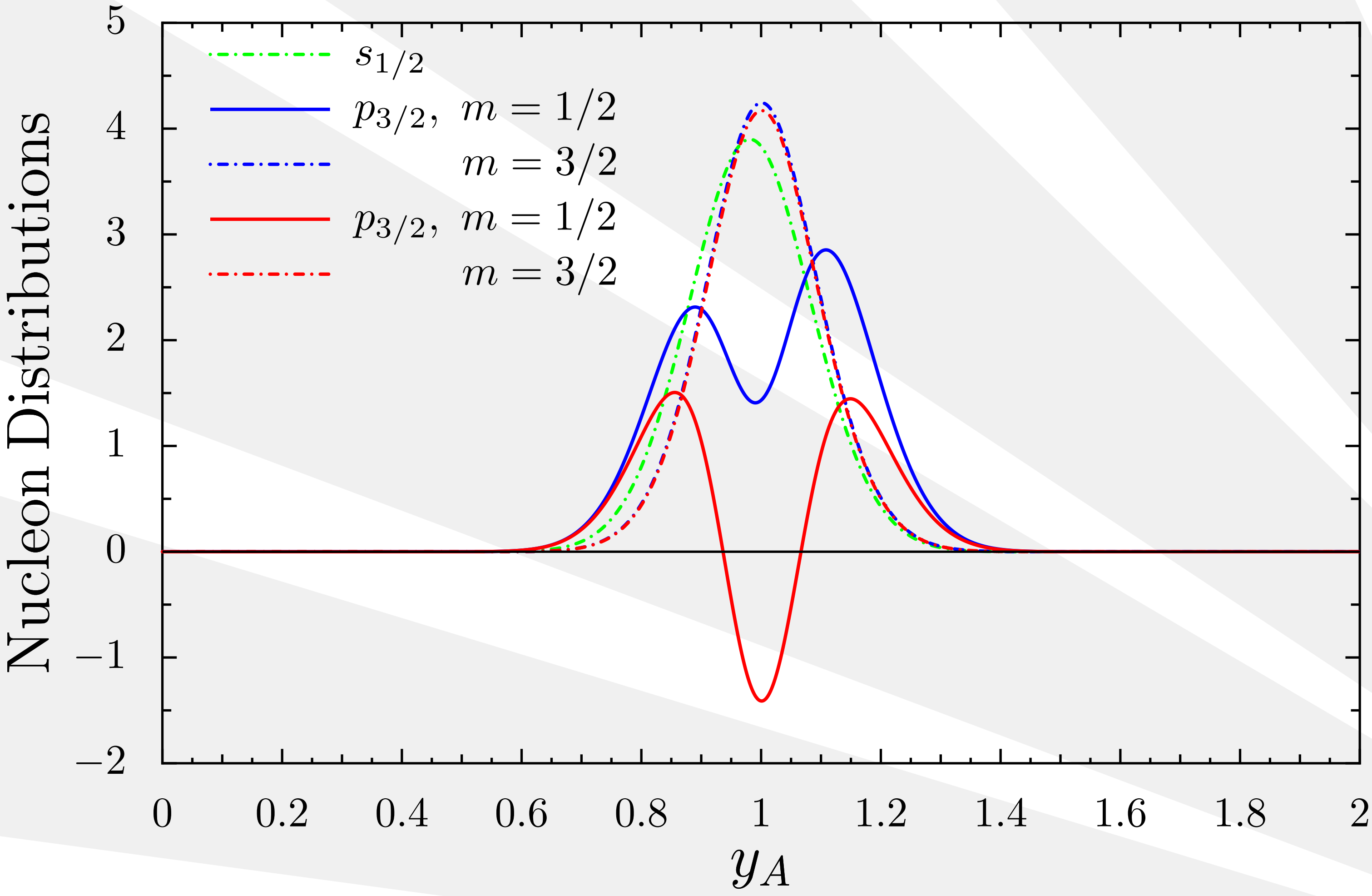
- Central Potential Dirac eigenfunctions

$$\Psi_{\kappa m}(\vec{p}) = (-i)^\ell \begin{bmatrix} F_\kappa(p)\, \Omega_{\kappa m}(\theta,\phi) \\ -G_\kappa(p)\, \Omega_{-\kappa m}(\theta,\phi) \end{bmatrix},$$

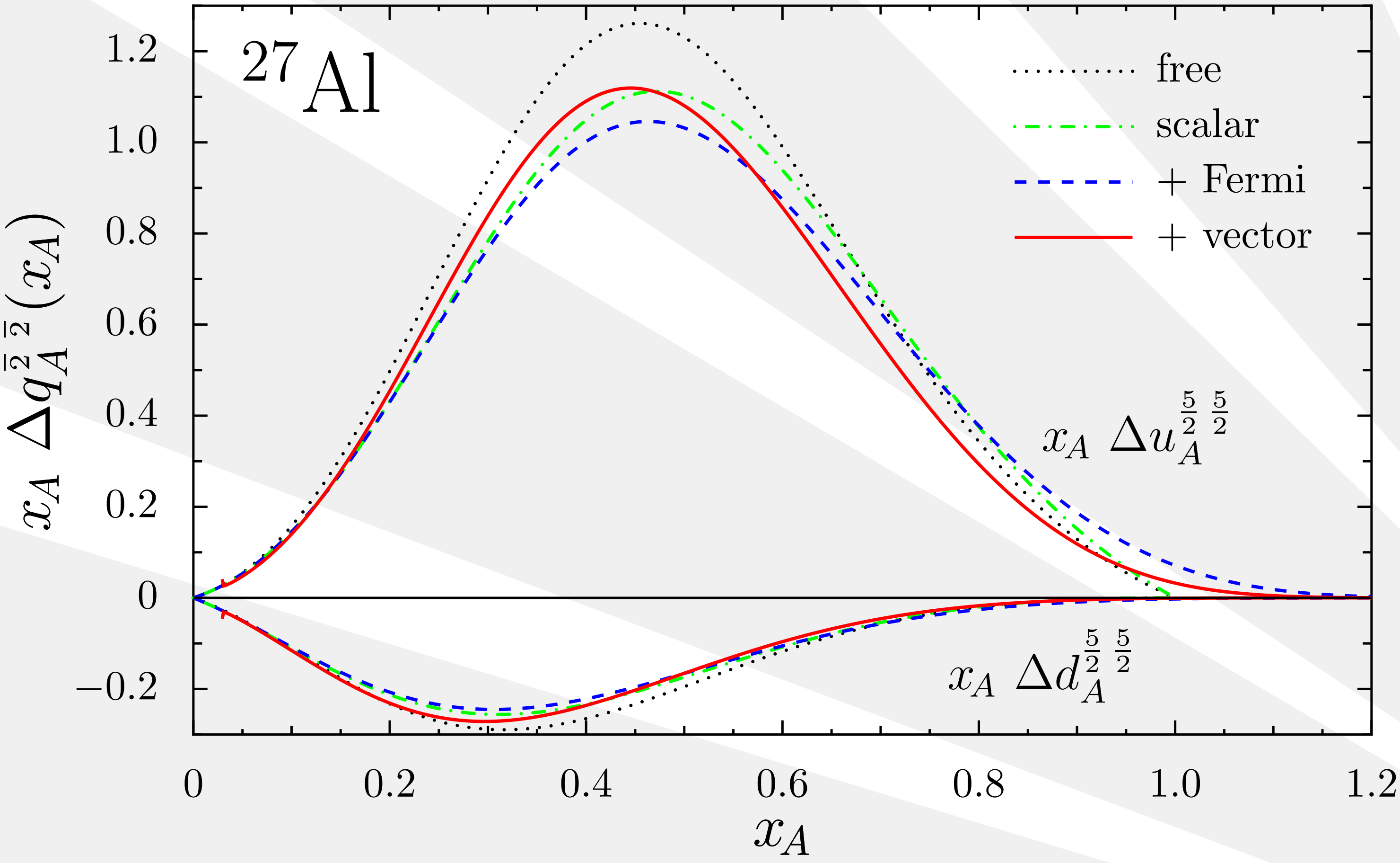
❖ Dirac Equation

$$\left[-i\,\vec{\alpha}\cdot\vec{\nabla} + \beta\left[M(r) - V_s(r)\right] + V_v(r)\right] \psi_\kappa(r) = \varepsilon_\kappa\, \psi_\kappa(r)$$

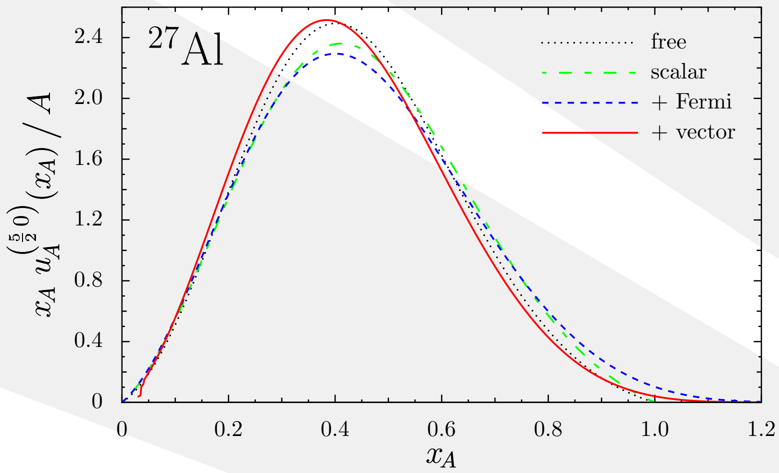
Nucleon distributions: ^{11}B

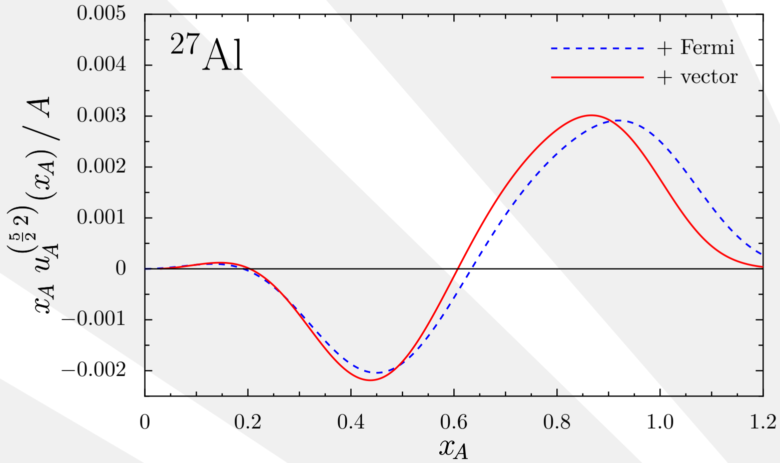


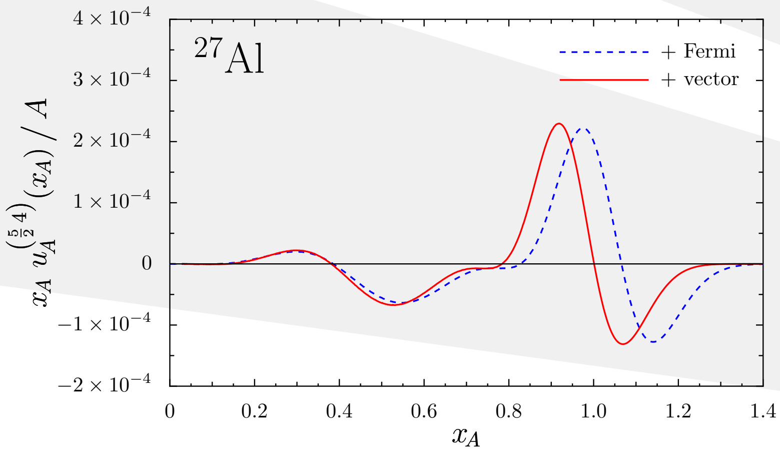
Quark distributions in ^{27}Al

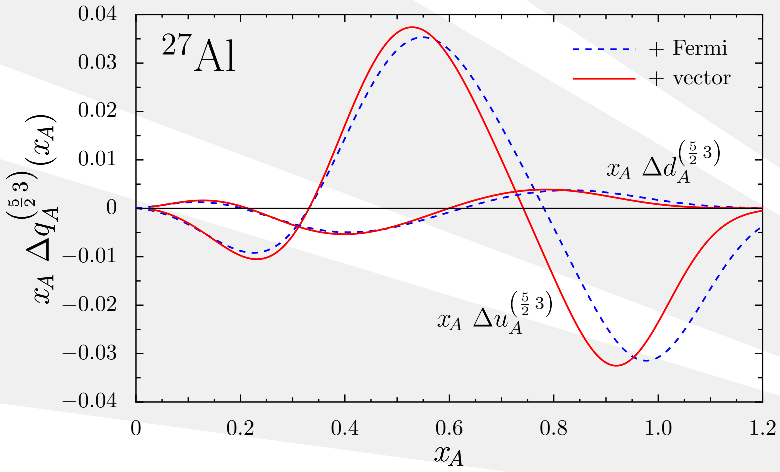


Multipole distributions in ^{27}Al









Definition: Polarized EMC effect

- EMC ratio

$$R = \frac{F_{2A}}{F_{2A}^{\text{naive}}} = \frac{F_{2A}}{Z\,F_{2p} + (A - Z)\,F_{2n}}$$

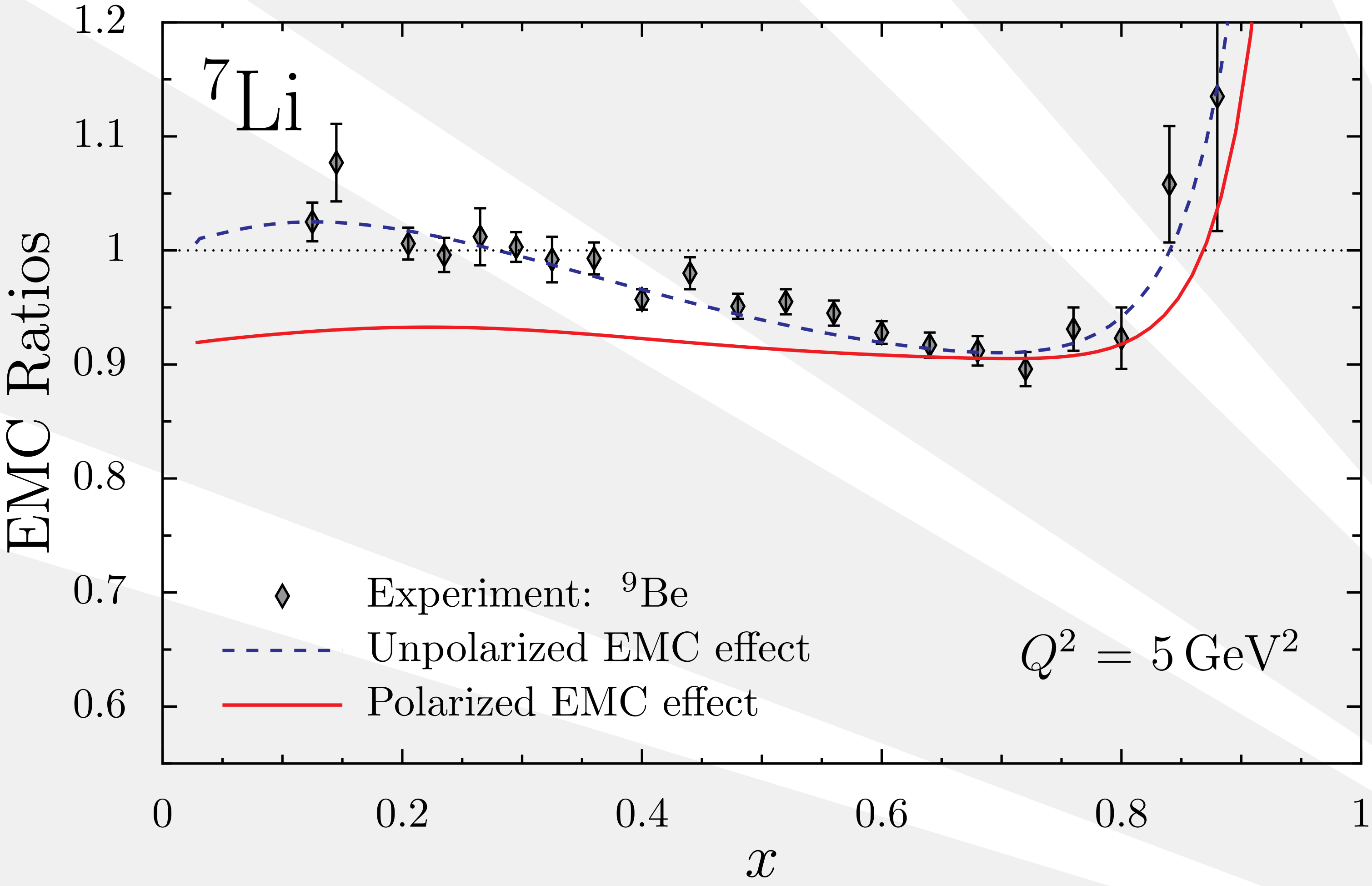
- Polarized EMC ratio

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

$$R_s^{(J1)} = \frac{g_{1A}^{(J1)}}{P_p^{(J1)}\,g_{1p} + P_n^{(J1)}\,g_{1n}}$$

- $1/A$ effect, i.e. $A \lesssim 27$, “proton states”, $\Longrightarrow$ ^{7}Li, ^{11}B, $\ldots$
- Ratios equal 1 in non-relativistic and no-medium modification limit.

Polarized EMC ratio ^{7}Li



Polarized EMC ratio ^{7}Li

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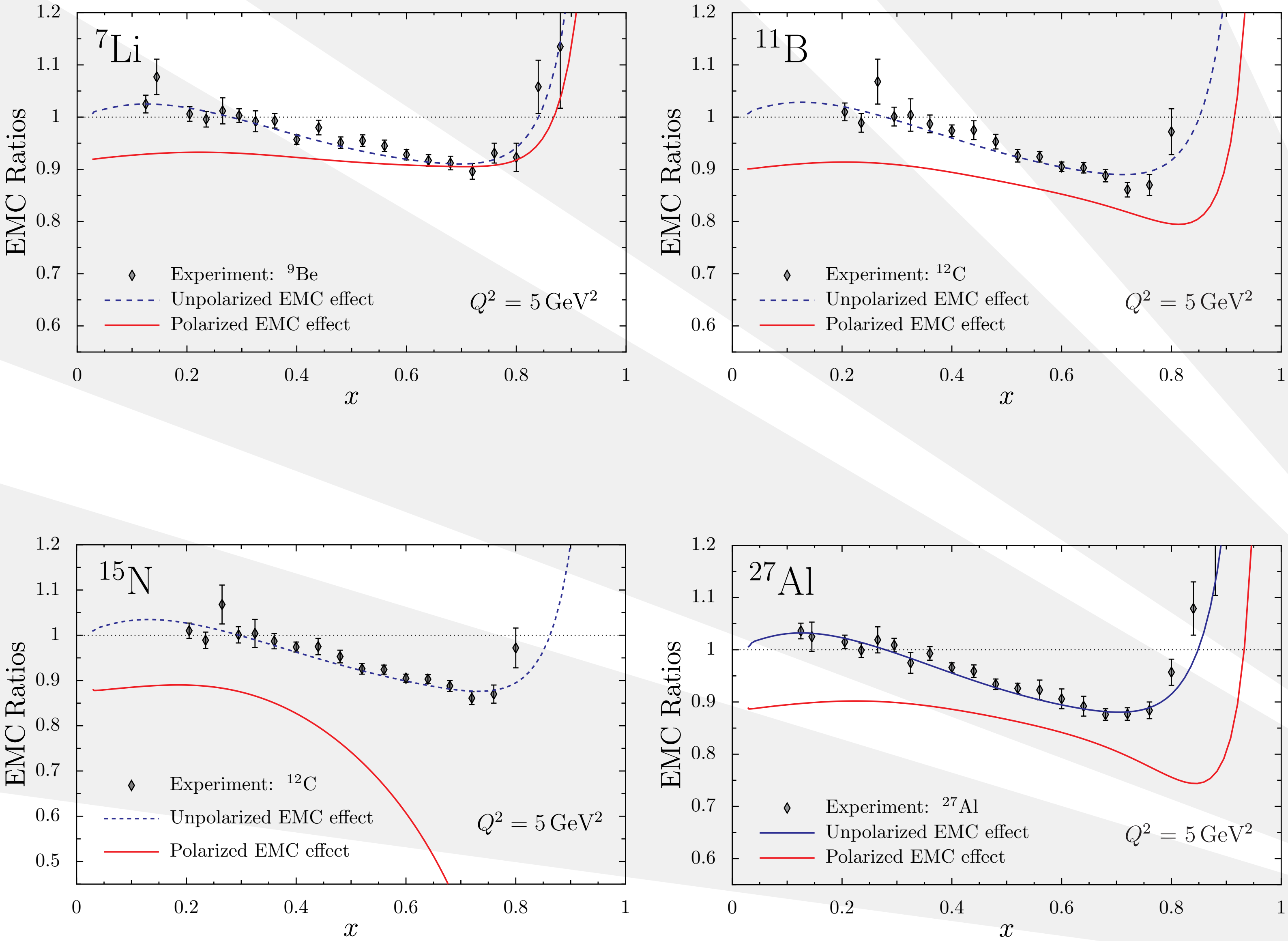
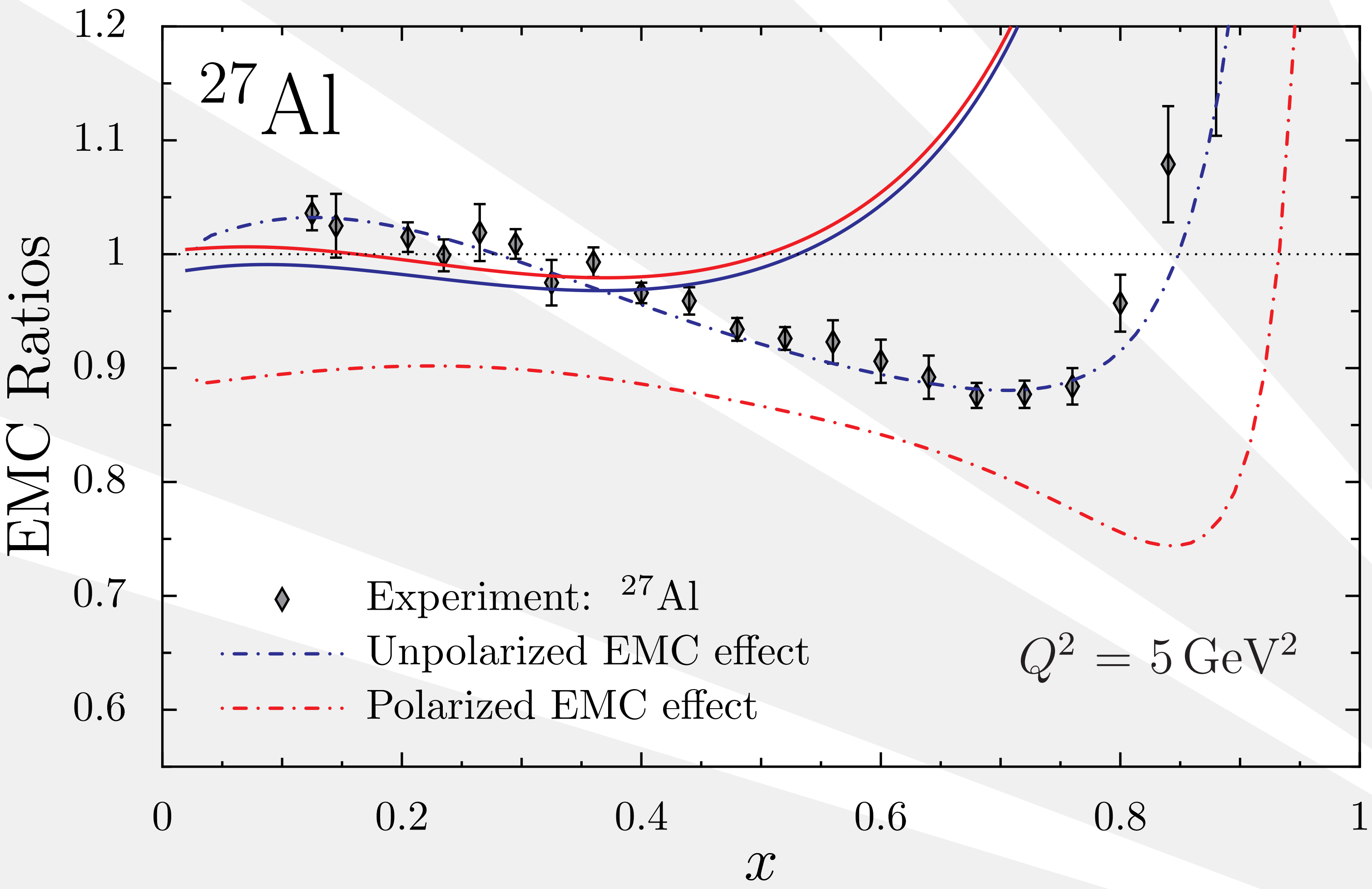


Is there medium modification



Conclusions

- Effective chiral quark theories can be used to incorporate quarks into many-body physics.
- Higher multipoles are very small for $A \gtrsim 7$.
  - Large F^{JK}, $K \geqslant 2$, would indicate break down of convolution formalism.
- Binding of quarks to mean scalar and vector fields can largely explain the EMC effect.
- Calculated the Polarized EMC effect in nuclei.
  - pEMC effect about twice EMC effect
  - Experimental conformation would yield important insights on quark dynamics in nuclear medium.

Nuclear Spin Sum

- Definitions $(H = J)$:

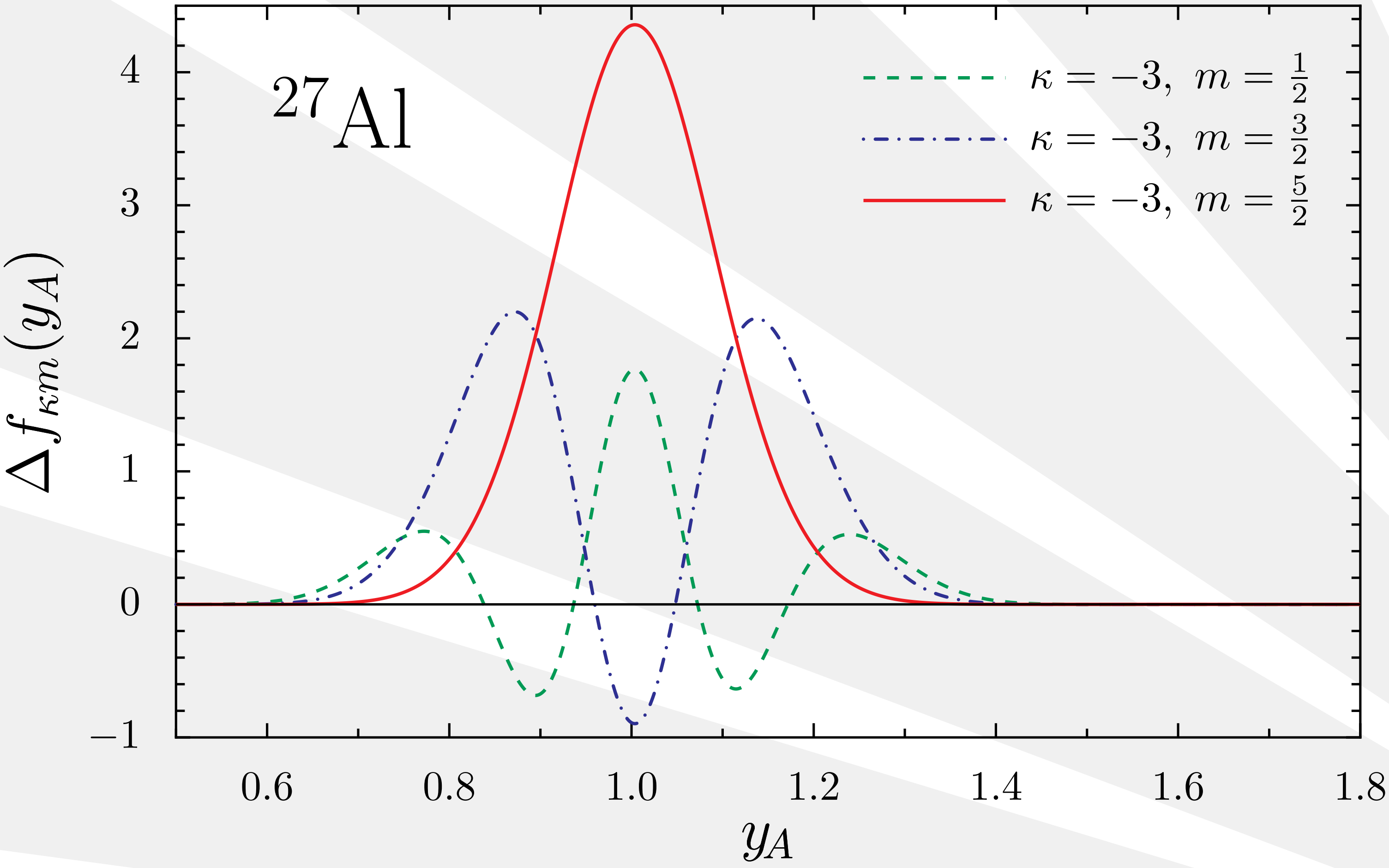
$$\Sigma^{(A)} = \Delta u_A + \Delta d_A \equiv \Sigma\,(P_p + P_n)$$

$$g_A^{(A)} = \Delta u_A - \Delta d_A \equiv g_A\,(P_p - P_n)$$

	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

- Quark Spin $\Longrightarrow$ orbital angular momentum

Nucleon distributions: ^{27}Al



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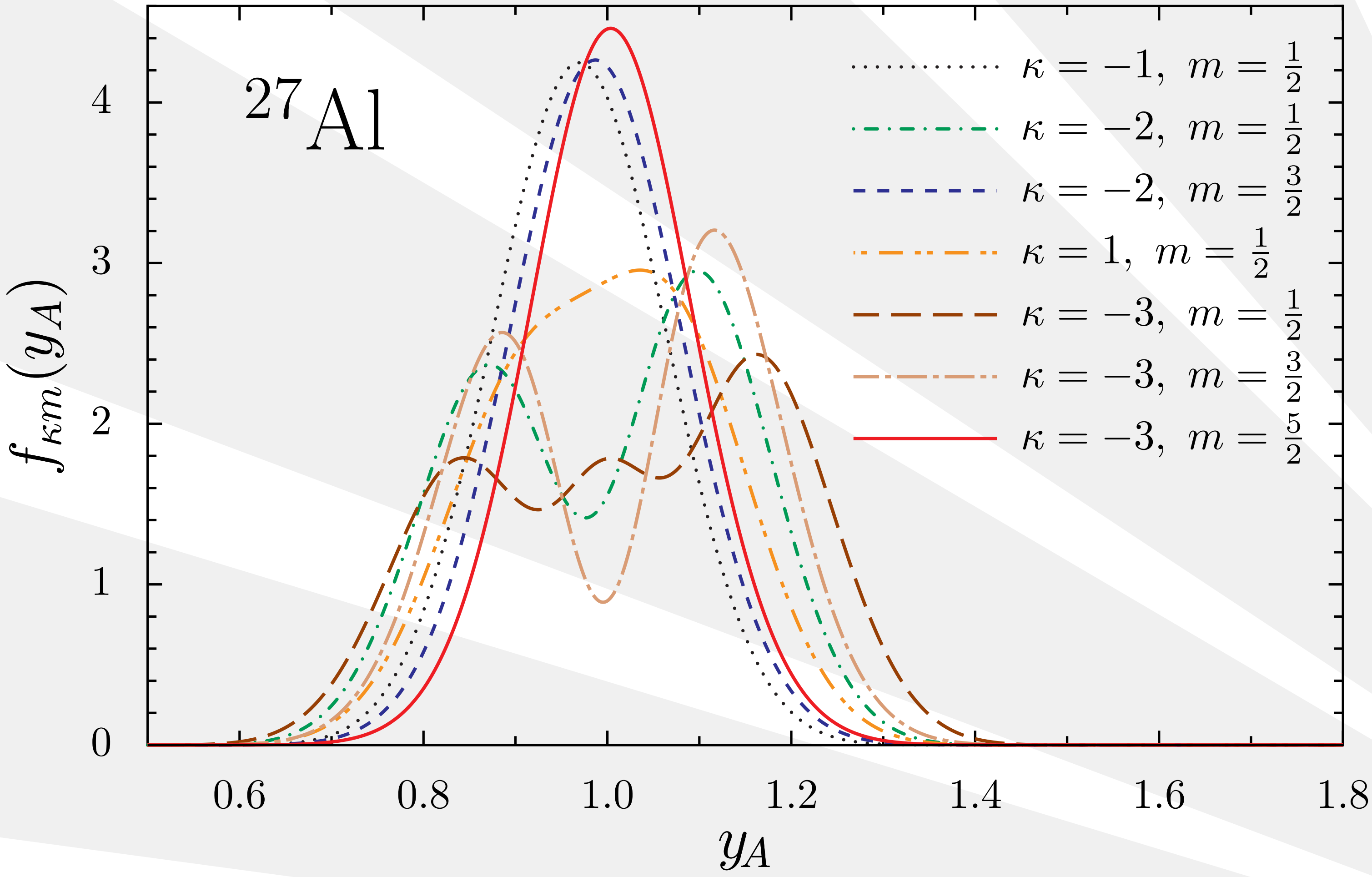
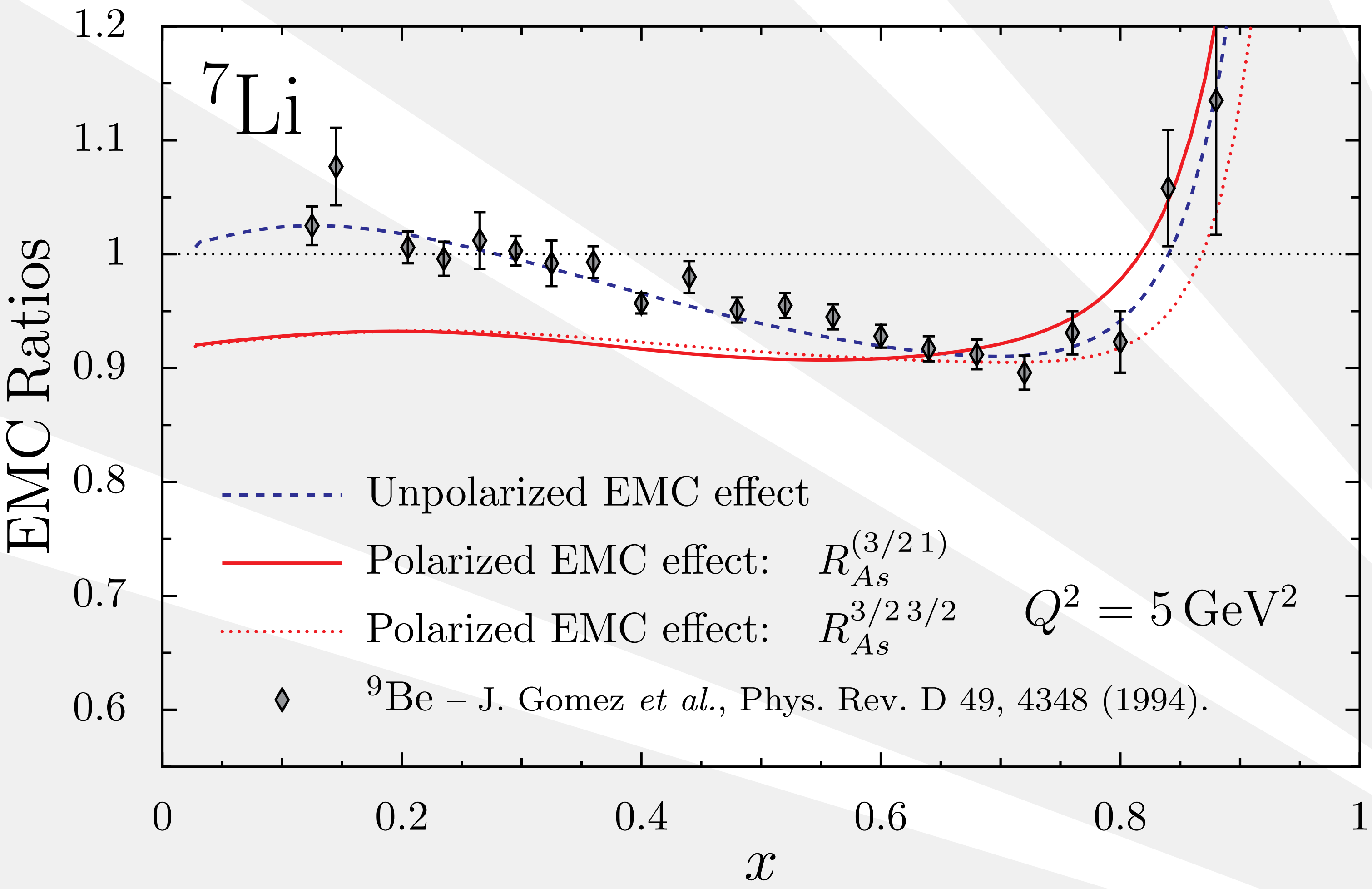
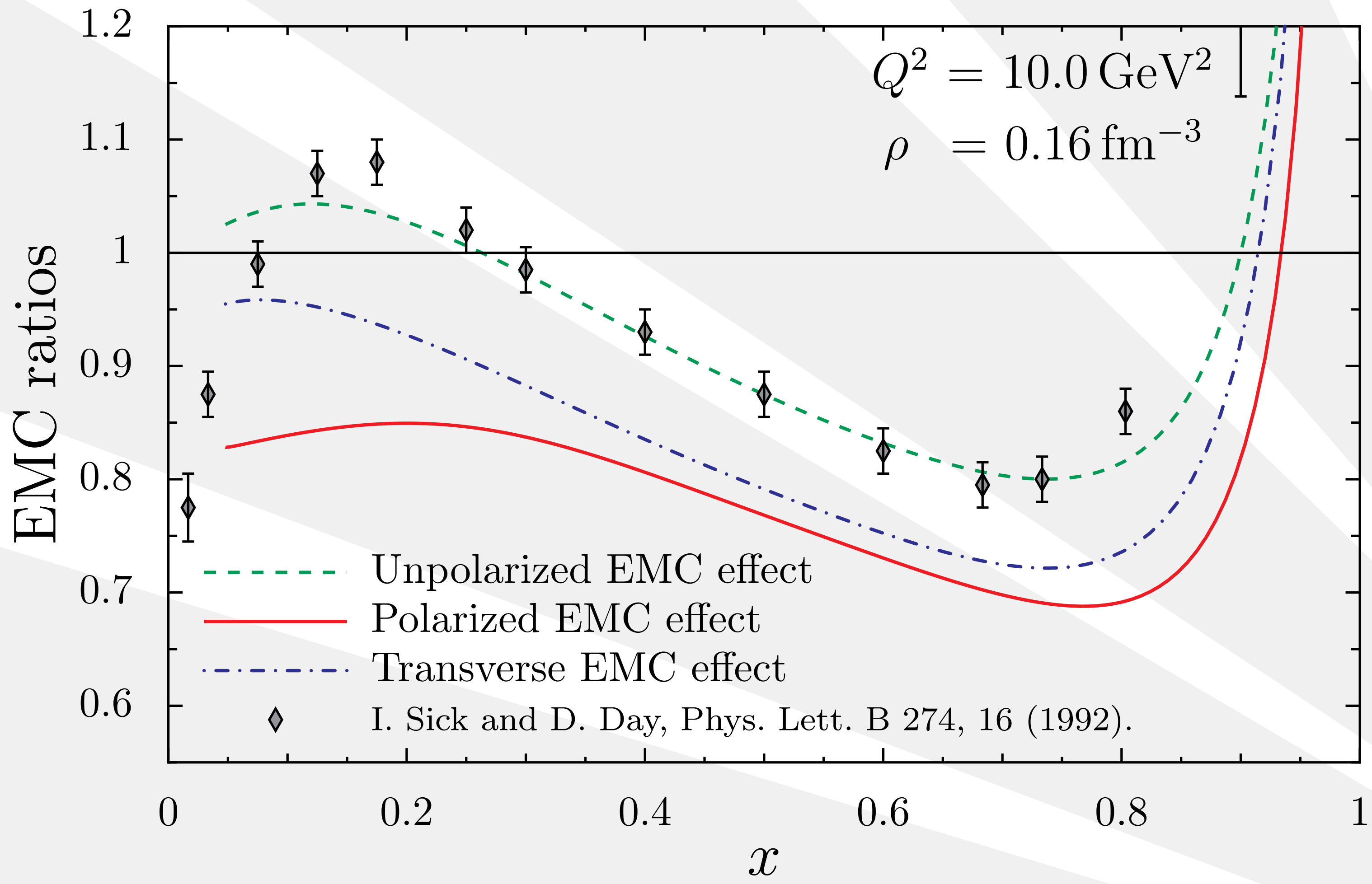


EMC ratios ^{7}Li



Nuclear Matter



Regularization

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- Proper-time regularization

$$\frac{1}{X^n} = \frac{1}{(n-1)!} \int_0^\infty d\tau \, \tau^{n-1} \, e^{-\tau X}$$

$$\longrightarrow \quad \frac{1}{(n-1)!} \int_{1/(\Lambda_{UV})^2}^{1/(\Lambda_{IR})^2} d\tau \, \tau^{n-1} \, e^{-\tau X} .$$

- Λ_{IR} eliminates unphysical thresholds for the nucleon to decay into quarks: $\longrightarrow$ simulates confinement.

  ✥ G. Hellstern, R. Alkofer and H. Reinhardt, Nucl. Phys. A **625**, 697 (1997).

- Needed for: nuclear matter saturation, Δ baryon.

  ✥ W. Bentz, A.W. Thomas, Nucl. Phys. A **696**, 138 (2001)

Model Parameters

- Free Parameters: Λ_{IR}, Λ_{UV}, M_0, G_π, G_s and G_a.
- Constraints:
  - $f_\pi = 93$ MeV, $m_\pi = 140$ MeV and $M_N = 940$ MeV
  - $(\rho, E_B/A) = (0.16\,\text{fm}^{-3}, -15.7$ MeV$)$
  - $\int_0^1 dx\ (\Delta u_v(x) - \Delta d_v(x)) = g_A = 1.267$
- We obtain:
  - $\Lambda_{IR} = 240$ MeV, $\Lambda_{UV} = 644$ MeV, $M_0 = 400$ MeV
  - $G_\pi = 19$ GeV^{-2}, $G_s = 7.5$ GeV^{-2}, $G_a = 2.8$ GeV^{-2}
  - $M_s = 690$ MeV, $M_a = 990$ MeV,