Nucleons in the Medium

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Nuclear Chromo–Dynamic Studies with a Future Electron Ion Collider

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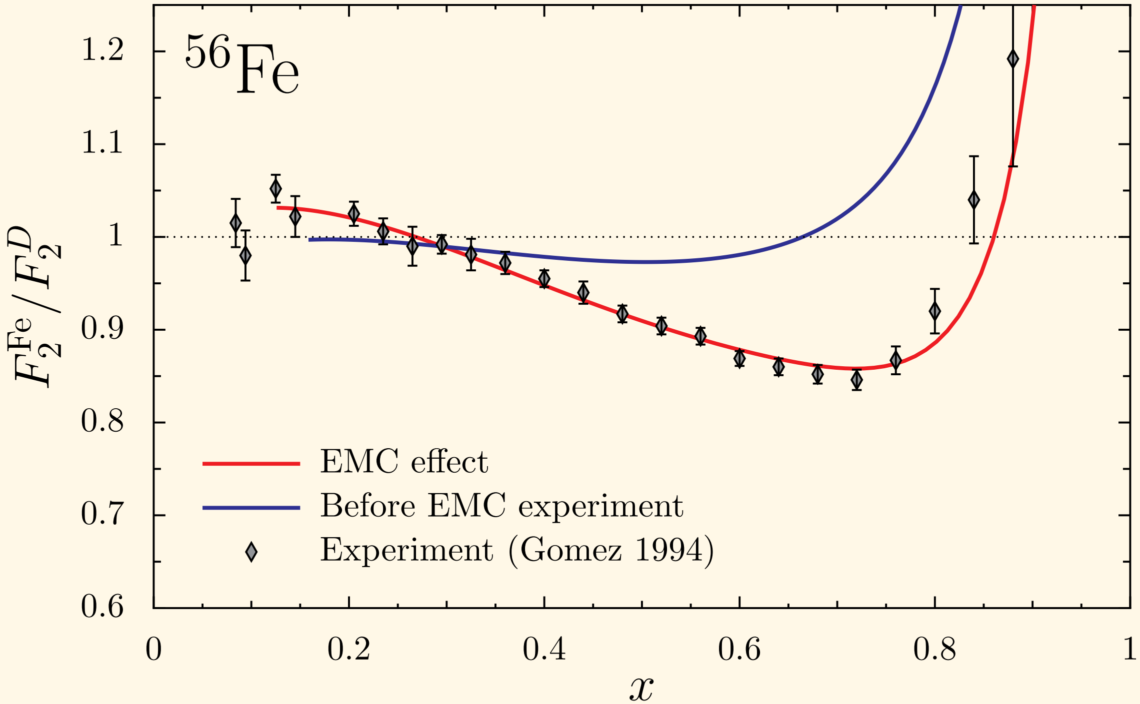
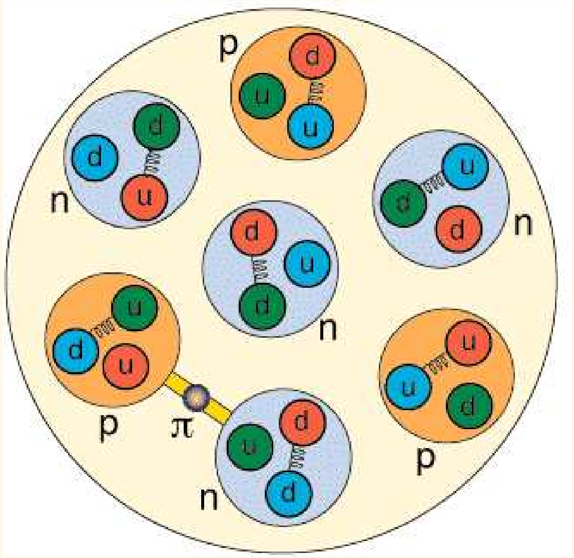
Theme

- Gain insight into nuclear structure from a QCD viewpoint
- Highlight opportunities provided by nuclear systems to study QCD
- Present complementary approach to traditional nuclear physics
  - formulated as a covariant quark theory
  - grounded in good description of mesons and baryons
  - at finite density self-consistent mean-field approach
- Fundamental difference
  - bound nucleons differ from free nucleons
  - medium modification – effects typically $\sim$10–15%
- Possible answers to many long standing questions: we address
  - the EMC effect [European Muon Collaboration]
  - the NuTeV anomaly [Neutrinos at the Tevatron]

EMC Effect





- J. J. Aubert *et al.* [European Muon Collaboration], Phys. Lett. B **123**, 275 (1983).
- Immediate parton model interpretation:
  - valence quarks in nucleus carry less momentum than in nucleon
- Nuclear effects seem to influence the quarks bound in the nucleons
- What is the mechanism? After 25 years no consensus
- EMC $\Longrightarrow$ medium modification

Medium Modification

- 50 years of traditional nuclear physics tells us that the nucleus is composed of nucleon-like objects
- However if a nucleon property is not protected by a symmetry its value may change in medium – for example:
  - mass, magnetic moment, size
  - quark distributions, form factors, GPDs, etc
- There must be medium modification:
  - nucleon propagator is changed in medium
  - off-shell effects ($p^2 \neq M^2$)
    - in-medium nucleon has 12 form factors instead of 2

$$\langle J^\mu \rangle = \sum_{\alpha,\,\beta=+,-} \Lambda^\alpha(p') \left[\gamma^\mu\, f_1^{\alpha\beta} + \frac{1}{2M} i\sigma^{\mu\nu} q_\nu\, f_2^{\alpha\beta} + q^\mu\, f_3^{\alpha\beta}\right] \Lambda^\beta(p)$$

- Need to understand these effects as first step toward QCD based understanding of nuclei

Medium Modification

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$$\langle J^\mu \rangle = \bar{u}(p') \left[\gamma^\mu F_1(Q^2) + \tfrac{1}{2M} i\sigma^{\mu\nu} q_\nu F_2(Q^2) \right] u(p)$$

- Need to understand these effects as first step toward QCD based understanding of nuclei

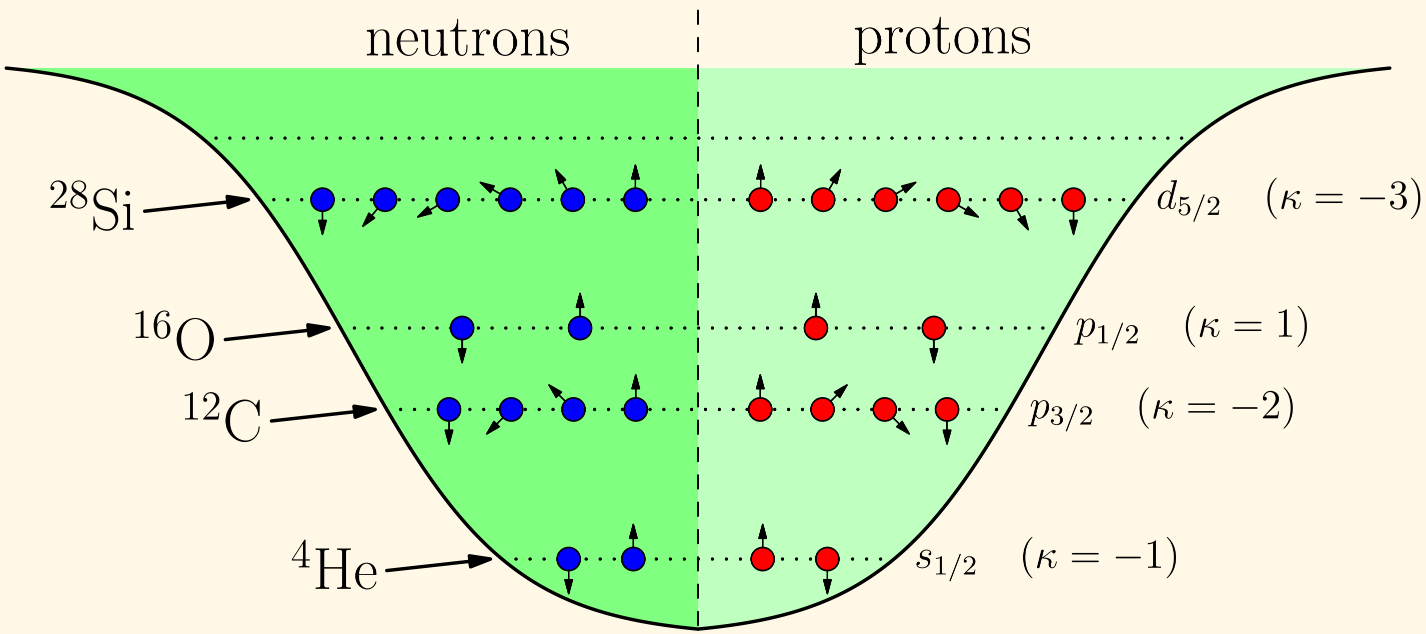
Finite nuclei quark distributions

- Definition of finite nuclei quark distributions

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

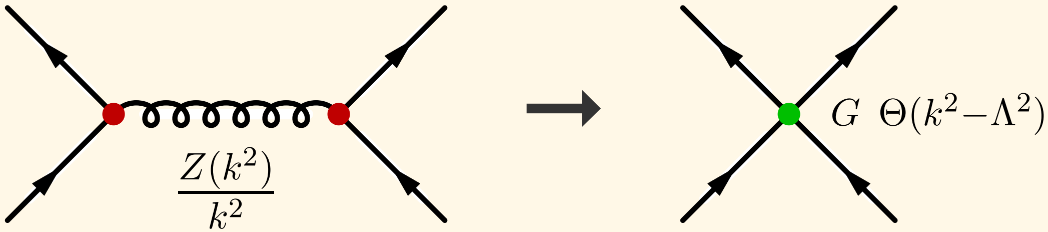
- Approximate using a modified convolution formalism

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

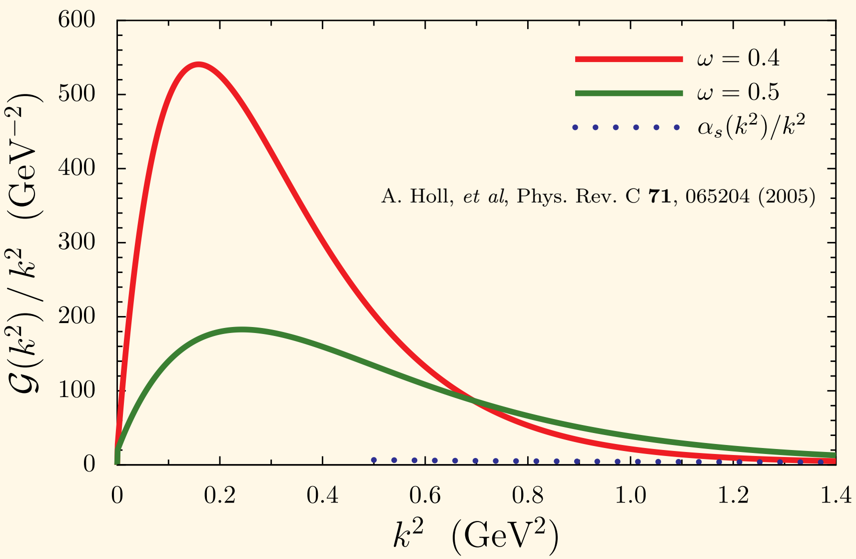


Nambu–Jona-Lasinio Model

- Interpreted as low energy chiral effective theory of QCD



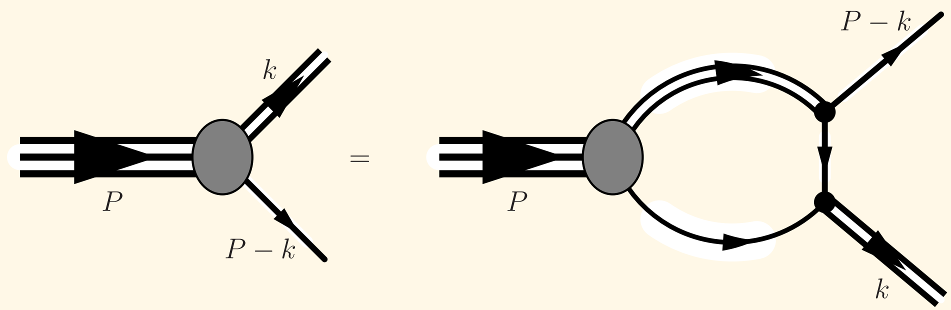
- Can be motivated by infrared enhancement of gluon propagator
  e.g. DSEs and Lattice QCD



- Investigate the role of quark degrees of freedom.
- NJL has same symmetries as QCD
- Lagrangian: $\mathcal{L}_{NJL} = \overline{\psi}\,(i\partial\!\!\!/ - m)\,\psi + G\,(\overline{\psi}\,\Gamma\,\psi)^2$

Nucleon in the NJL model

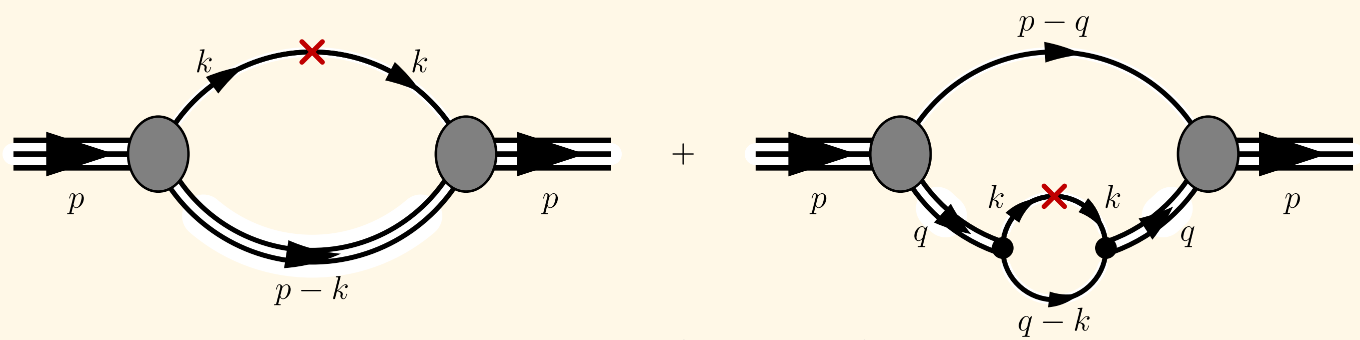
- Nucleon approximated as quark-diquark bound state
- Use relativistic Faddeev approach:



- Nucleon quark distributions

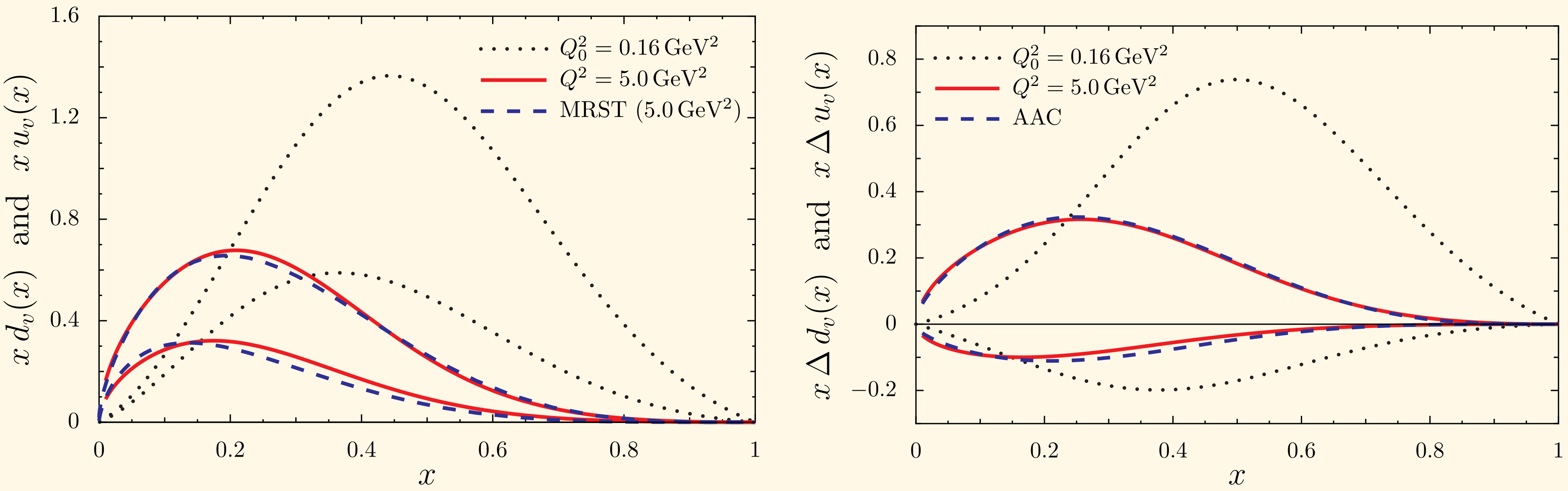
$$q(x) = p^+ \int \frac{d\xi^-}{2\pi} e^{i\,x\,p^+\xi^-} \langle p, s|\overline{\psi}_q(0)\gamma^+\psi_q(\xi^-)|p, s\rangle_c, \quad \Delta q(x) \quad = \langle \gamma^+\gamma_5\rangle$$

- Associated with a Feynman diagram calculation



❖ $[q(x), \Delta q(x), \Delta_T q(x)]$ ➞ $\mathsf{X} = \delta\left(x - \frac{k^+}{p^+}\right)\left[\gamma^+, \gamma^+\gamma_5, \gamma^+\gamma^1\gamma_5\right]$

Results: proton quark distributions

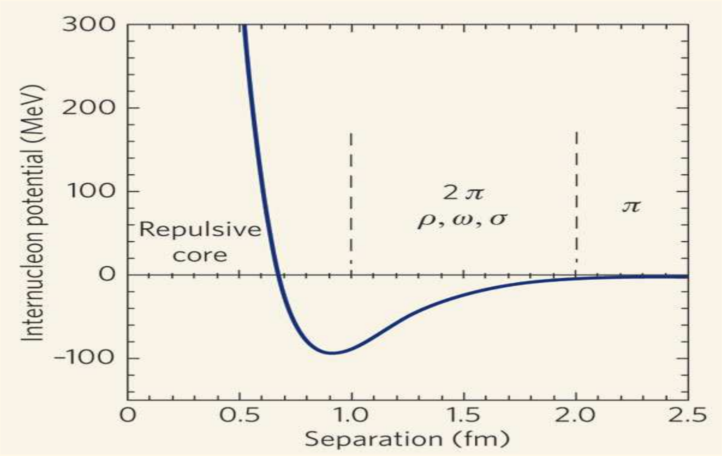


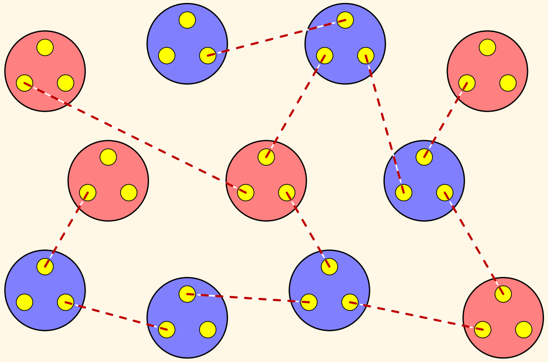
- Empirical distributions:
  - Martin, Roberts, Stirling and Thorne, Phys. Lett. B **531**, 216 (2002).
  - M. Hirai, S. Kumano and N. Saito, Phys. Rev. D **69**, 054021 (2004).
- NJL model gives good description of free nucleon quark distributions
- Approach is covariant, satisfies all sum rules & positivity constraints
- DGLAP equations [Dokshitzer (1977), Gribov-Lipatov (1972), Altarelli-Parisi (1977)]

$$\frac{\partial}{\partial \ln Q^2}\, q_v(x, Q^2) = \alpha_s(Q^2)\, P(z) \otimes q_v(y, Q^2)$$

Asymmetric Nuclear Matter

- Fundamental physics: mean fields couple to the quarks in nucleons





- Finite density mean-field Lagrangian: $\sigma, \ \omega, \ \rho$ fields

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

- σ: isoscalar-scalar – attractive
  ω: isoscalar-vector – repulsive
  ρ: isovector-vector – attractive/repulsive

- Finite density quark propagator

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

Effective Potential

- Hadronization → Effective potential

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

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

- Effective potential provides

$$\omega_0 = 6\,G_\omega\,(\rho_p + \rho_n)\,, \quad \rho_0 = 2\,G_\rho\,(\rho_p - \rho_n)\,, \quad \frac{\partial \mathcal{E}}{\partial M^*} = 0$$

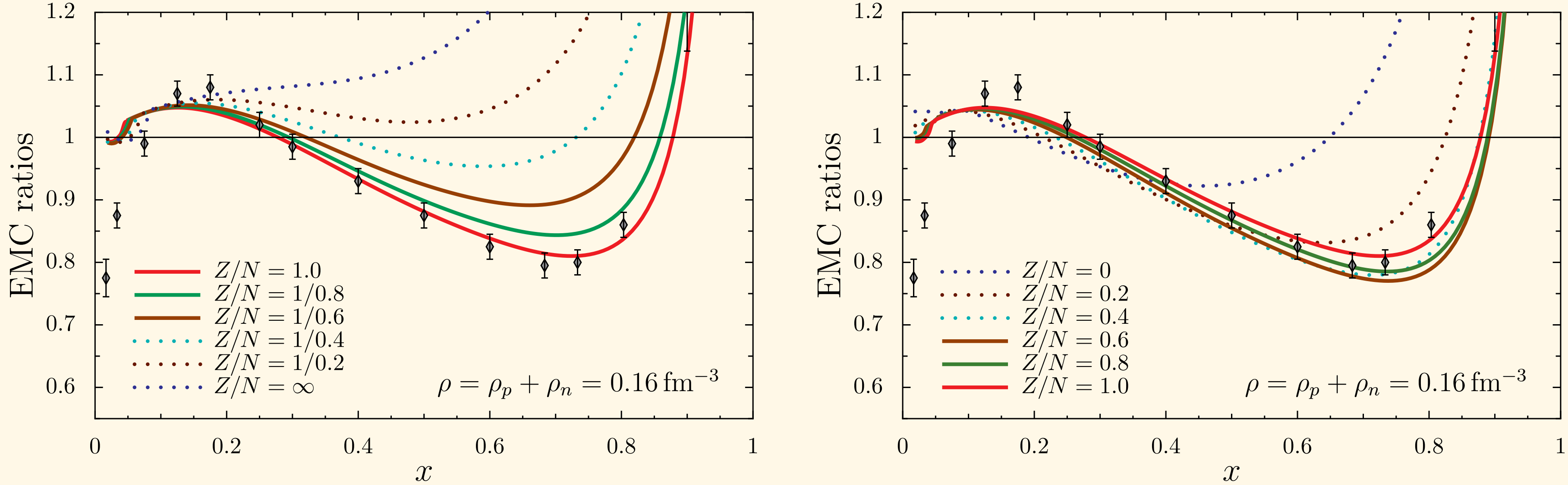
  - $G_\omega \Leftrightarrow Z = N$ saturation & $G_\rho \Leftrightarrow$ symmetry energy

- Quark vector fields:

$$V_{u(d)} = \omega_0 \pm \rho_0$$

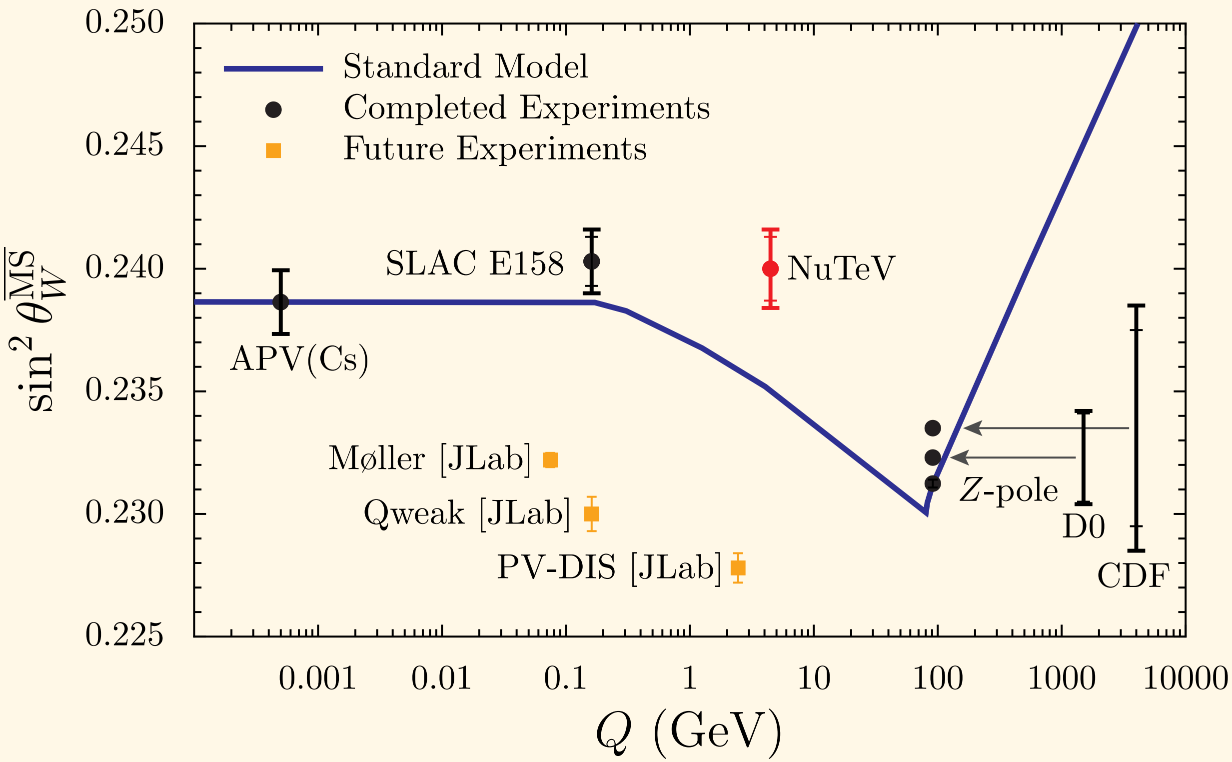
- Recall: quark propagator: $S_q(k) = \left[\not{k} - M^* - \not{V}_q\right]^{-1}$

Isovector EMC effect



- EMC ratio: $R = \frac{F_{2A}}{F_{2A}^{\text{naive}}} = \frac{F_{2A}}{Z\,F_{2p}+N\,F_{2n}} \sim \frac{4\ u_A(x)+d_A(x)}{4\ u_0(x)+d_0(x)}$
- Density is fixed only Z/N ratio is changing
  - non-trivial isospin dependence
- proton excess: u-quarks feel more repulsion than d-quarks
- neutron excess: d-quarks feel more repulsion than u-quarks
- Isovector interaction $\Longrightarrow$ isovector EMC Effect

Weak mixing angle and the NuTeV anomaly



- 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)
- World average $\sin^2\theta_W = 0.2227 \pm 0.0004$: 3 $\sigma \Longrightarrow$ "NuTeV anomaly"
- Huge amount of experimental & theoretical interest [over 400 citations]
- No universally accepted complete explanation

Paschos-Wolfenstein ratio

- Paschos-Wolfenstein ratio motivated the NuTeV study:

$$R_{PW} = \frac{\sigma_{NC}^{\nu A} - \sigma_{NC}^{\bar{\nu} A}}{\sigma_{CC}^{\nu A} - \sigma_{CC}^{\bar{\nu} A}}, \qquad NC \Longrightarrow Z^0, \quad CC \Longrightarrow W^{\pm}$$

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

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

- NuTeV "measured" R_{PW} on an Fe target ($Z/N \simeq 26/30$)
- $Z/N \neq 1 \quad \Longrightarrow$ need neutron excess corrections: $\Delta R_{PW} \neq 0$
- New realization concerning isovector EMC effect
  - isovector forces effect all u and d quarks in the nucleus
  - for $N > Z$ there is a shift in momentum from u to d quarks
- Must correct for this isovector EMC effect in NuTeV analysis

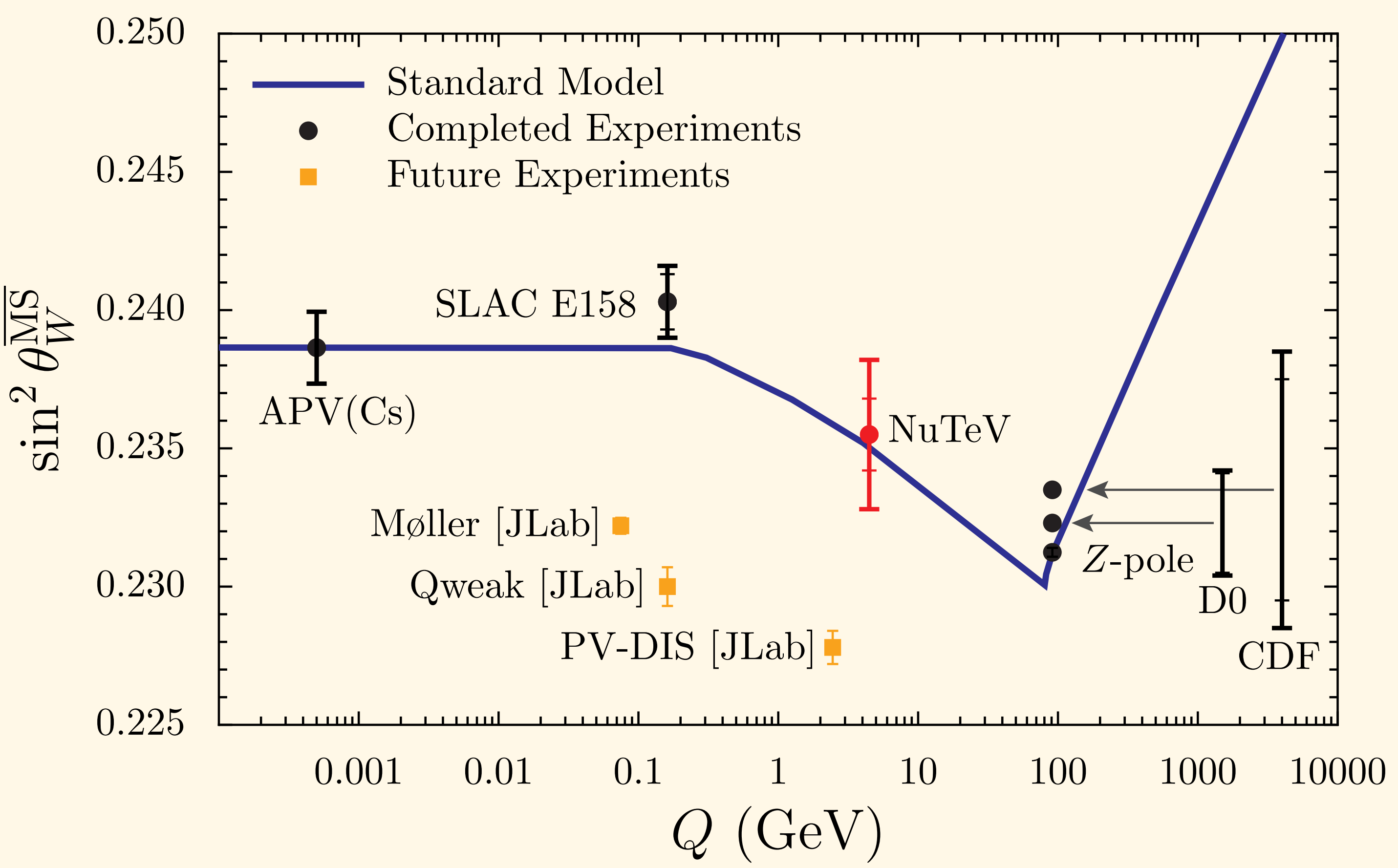
Summary of corrections to NuTeV Analysis

- Isovector EMC effect: $\Delta R^{\rho^0} = -0.0019 \pm 0.0006$
  - sign of correction is fixed by nature of vector fields

    $$q(x) = \frac{p^+}{p^+ - V^+}\, q_0\left(\frac{p^+}{p^+ - V^+}x - \frac{V_q^+}{p^+ - V^+}\right), \qquad N > Z \implies V_u < V_d$$

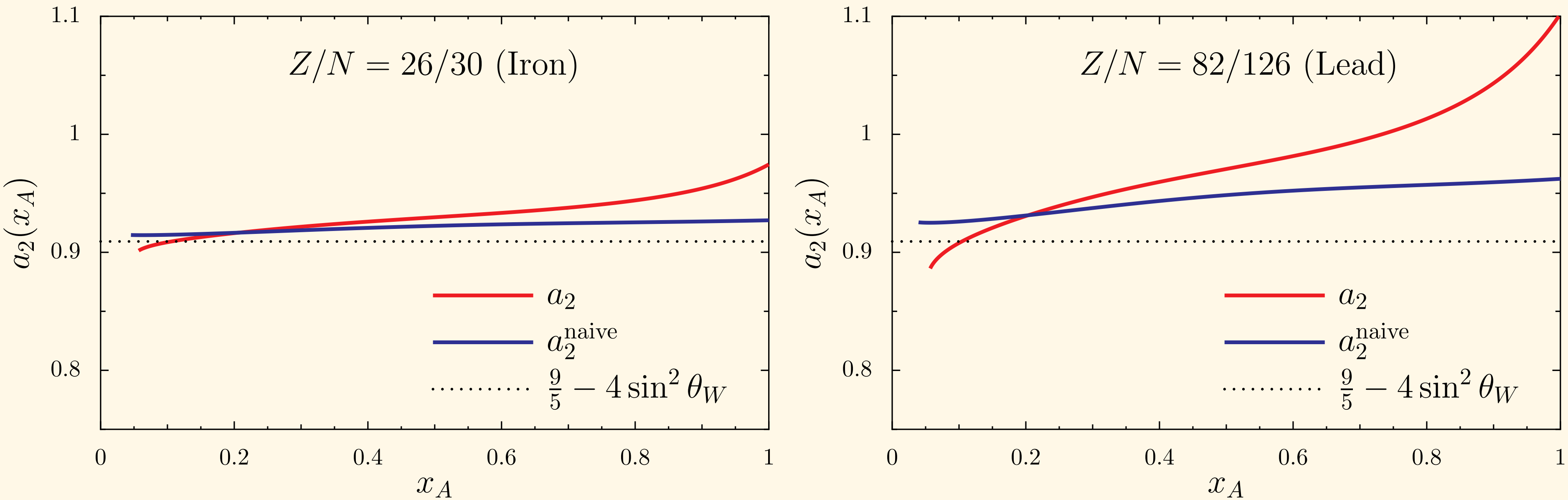
  - ρ^0-field shifts momentum from u to d quarks
  - size of correction is constrained by Nucl. Matt. symmetry energy
- Charge symmetry violation: $\Delta R^{CSV} = -0.0026 \pm 0.0011$
  - $m_u < m_d$ shifts momentum from u to d quarks
- Strange quarks: $\Delta R^s = 0.0 \pm 0.0018$
- All results include correction for NuTeV experimental acceptances, etc
- A negative ΔR_{PW} means $\sin^2\theta_W$ decreases
- Final result: $\sin^2\theta_W = 0.2232 \pm 0.0013(\text{stat}) \pm 0.0024(\text{syst})$

Total NuTeV correction



- No evidence for physics beyond the Standard Model
- Instead "NuTeV anomaly" is evidence for medium modification
  - Equally interesting
  - EMC effect has generated over 1000 papers

Observable elsewhere . . . Parity Violating DIS



- Isovector EMC effect can be observed in PV DIS [$\gamma\, Z^0$ interference]

$$A^{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} \propto [a_2(x) + \ldots]\,; \quad a_2(x) = g_A^e\, \frac{F_2^{\gamma Z}}{F_2^{\gamma}}$$

- For $N \simeq Z$ target

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

- Large x dependence of $a_2(x)$ even after naive correction
  - evidence for medium modification

Finite nuclei EMC effects

- EMC ratio

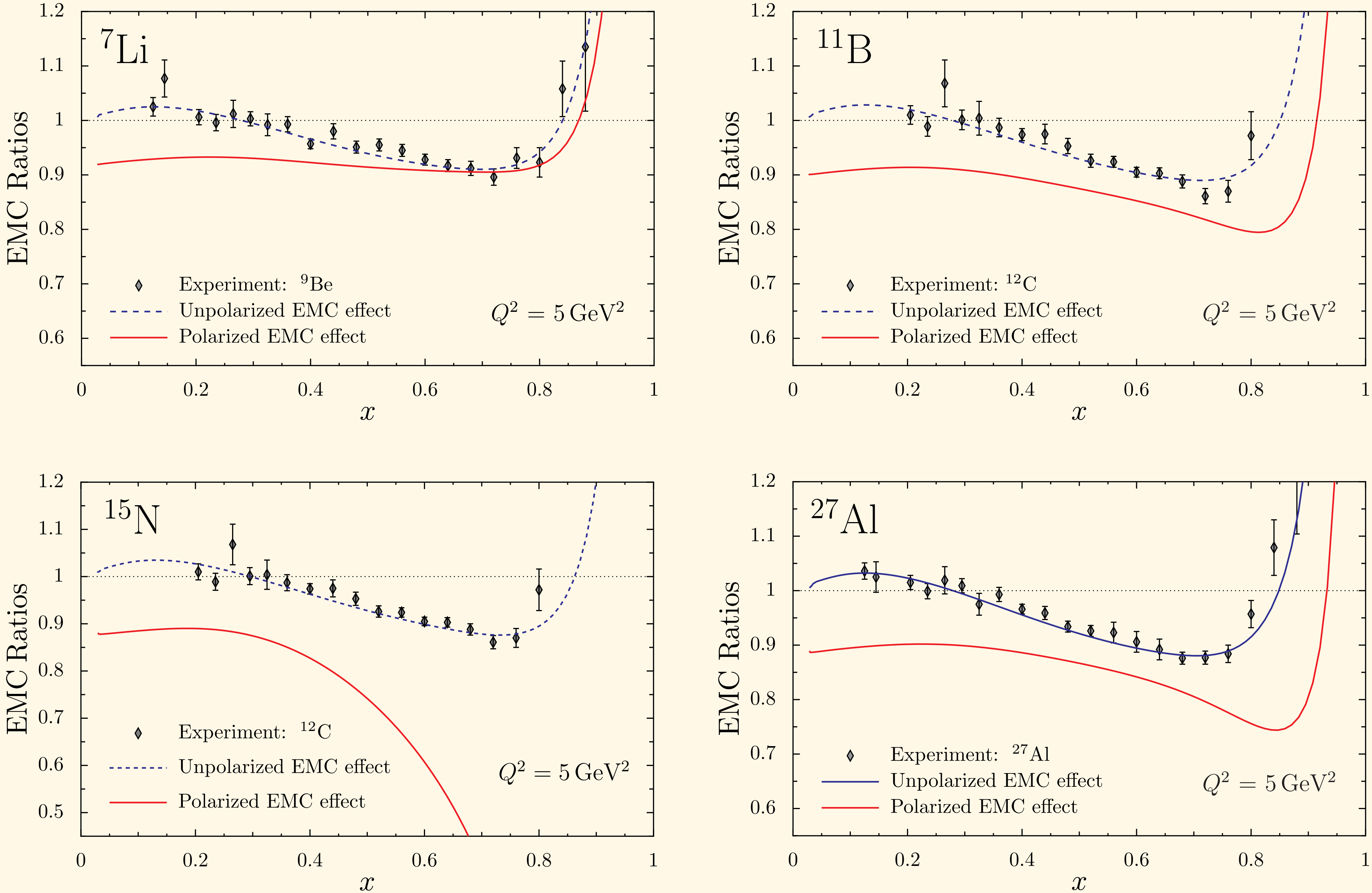
$$R = \frac{F_{2A}}{F_{2A}^{\text{naive}}} = \frac{F_{2A}}{Z\,F_{2p} + N\,F_{2n}}$$

- Polarized EMC ratio

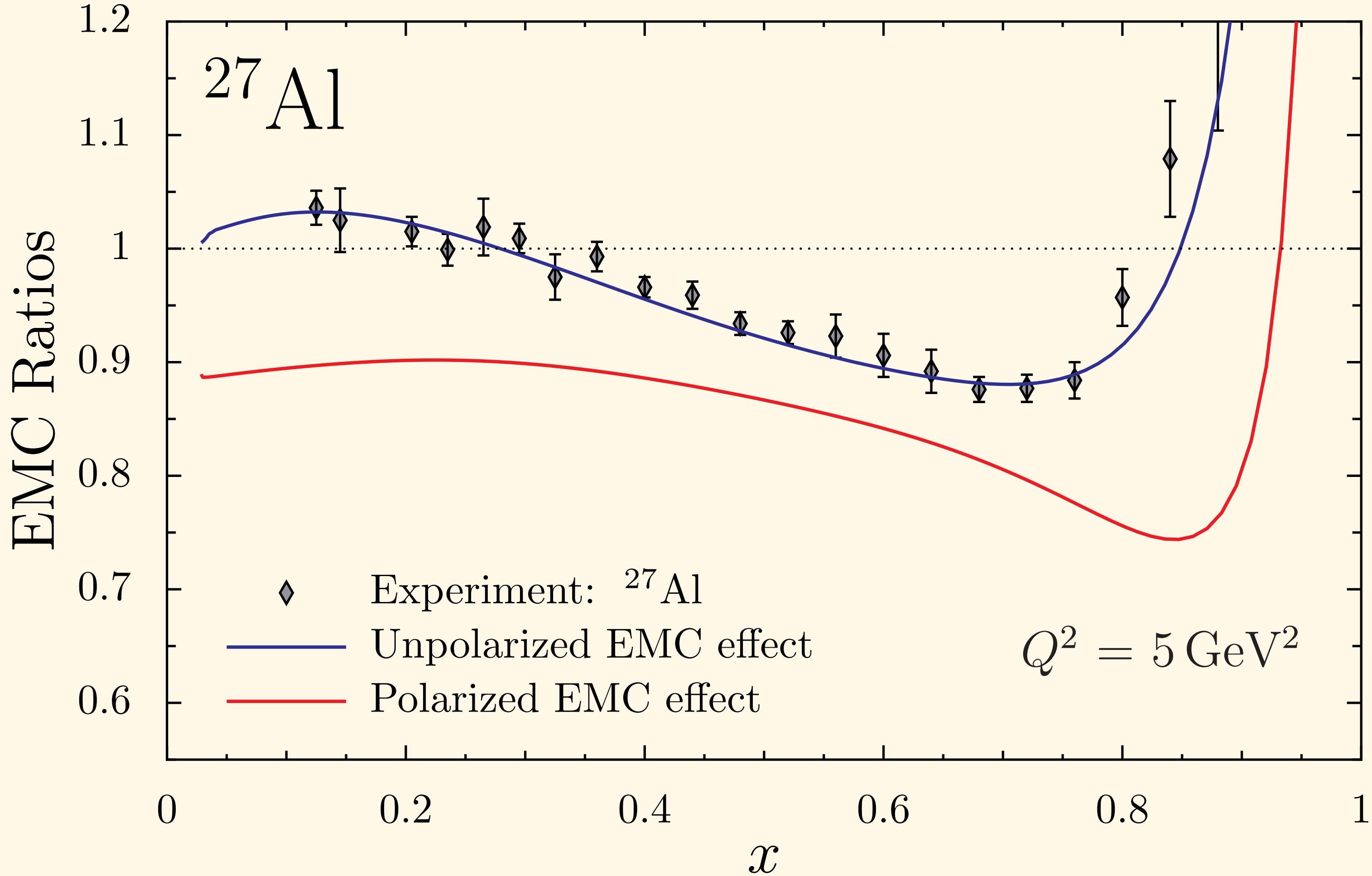
$$R_s^H = \frac{g_{1A}^H}{g_{1A}^{H,\text{naive}}} = \frac{g_{1A}^H}{P_p^H\,g_{1p} + P_n^H\,g_{1n}}$$

- Spin-dependent cross-section is suppressed by $1/A$
  - Must choose nuclei with $A \lesssim 27$
  - protons should carry most of the spin e.g. $\Longrightarrow$ ^{7}Li, ^{11}B, $\ldots$
- Ideal nucleus is probably ^{7}Li
  - From Quantum Monte–Carlo: $P_p^J = 0.86$ & $P_n^J = 0.04$
- Ratios equal 1 in non-relativistic and no-medium modification limit

EMC ratio ^{7}Li, ^{11}B, ^{15}N and ^{27}Al



Is there medium modification



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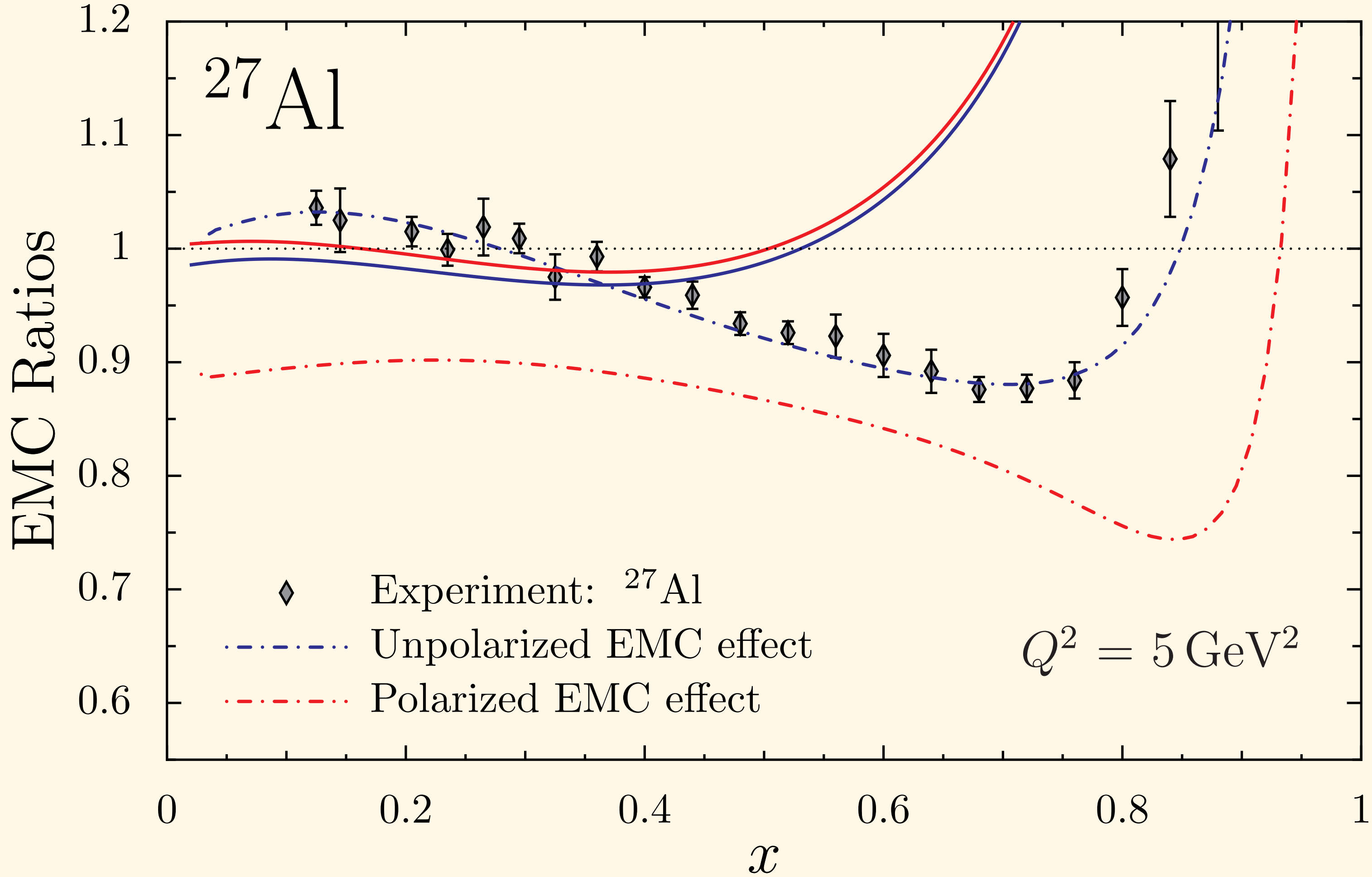

- Medium modification of nucleon has been switched off
- Relativistic effects remain
- Large splitting would be strong evidence for medium modification

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
- Conclusion: quark spin → orbital angular momentum in-medium

Conclusion

- Effective quark theories can be used to incorporate quarks into a traditional description of nuclei
  - complementary approach to traditional nuclear physics
- Major outstanding discrepancy with Standard Model predictions for Z^0 is NuTeV anomaly
  - may be resolved by CSV and isovector EMC effect corrections
- EMC effect and NuTeV anomaly are interpreted as evidence for medium modification of the bound nucleon wavefunction
- This result can be tested using PV DIS measurements
  - predict large medium modification in PV DIS
  - predict flavour dependence of EMC effect can be large
- In nuclei quark spin converted to orbital angular momentum
  - Polarized EMC effect