Nuclear structure functions

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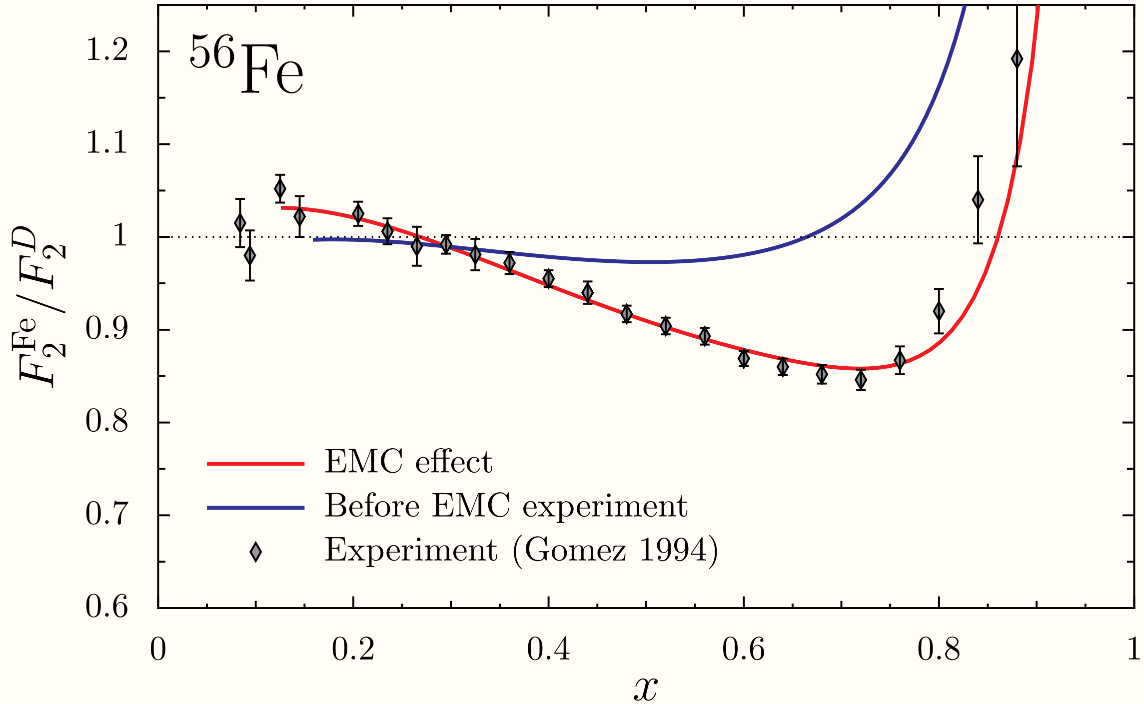
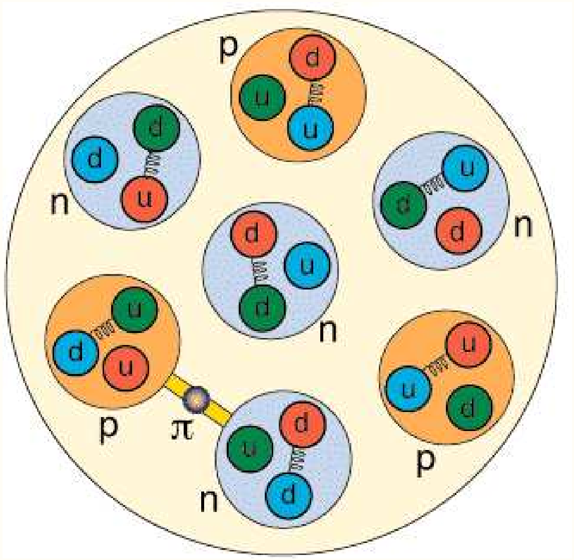
Theme

- Aspects of DIS on nuclear targets $\Longrightarrow$ nuclear structure functions
  - Highlight opportunities provided by nuclear systems to study QCD
  - Gain insight into nuclear structure from a QCD viewpoint
- 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
  - bound nucleons differ from free nucleons
- Possible answers to many long standing questions: we address
  - EMC effect & NuTeV anomaly
- Highlight the unique opportunities provided by PV DIS on nuclei

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 in the bound 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 ($p^2 \neq M^2$)
  - Lorentz covariance implies bound nucleon has 12 EM form factors

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

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

Medium Modification

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- There must be medium modification:
  - nucleon propagator is changed in medium
  - off-shell effects ($p^2 \neq M^2$)
  - Becomes 2 form factors for on-shell nucleon

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

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

DIS on Nuclear Targets

- Why nuclear targets?
  - only targets with $J \geqslant 1$ are nuclei
  - study QCD and nucleon structure at finite density
- Hadronic Tensor: in Bjorken limit & Callen-Gross ($F_2 = 2x\, F_1$)
  - For $J = \frac{1}{2}$ target

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

  - For arbitrary J: $-J \leqslant H \leqslant J$ [$2J+1$ structure functions]

$$W^H_{\mu\nu} = \left(g_{\mu\nu} \frac{p \cdot q}{q^2} + \frac{p_\mu p_\nu}{p \cdot q} \right) F^H_{2A}(x_A, Q^2) + \frac{i\varepsilon_{\mu\nu\lambda\sigma} q^\lambda p^\sigma}{p \cdot q} g^H_{1A}(x_A, Q^2)$$

- Parton model expressions [$2J+1$ quark distributions]

$$F^H_{2A}(x_A) = \sum\nolimits_q e_q^2\, x_A \left[q^H_A(x_A) + \bar{q}^H_A(x_A) \right]; \quad \text{parity} \quad \Longrightarrow \quad F^H_{2A} = F^{-H}_{2A}$$

DIS on Nuclear Targets

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$$F_{2A}(x) = \frac{1}{2J+1} \sum_{H=-J}^{J} F^H_{2A}(x)$$

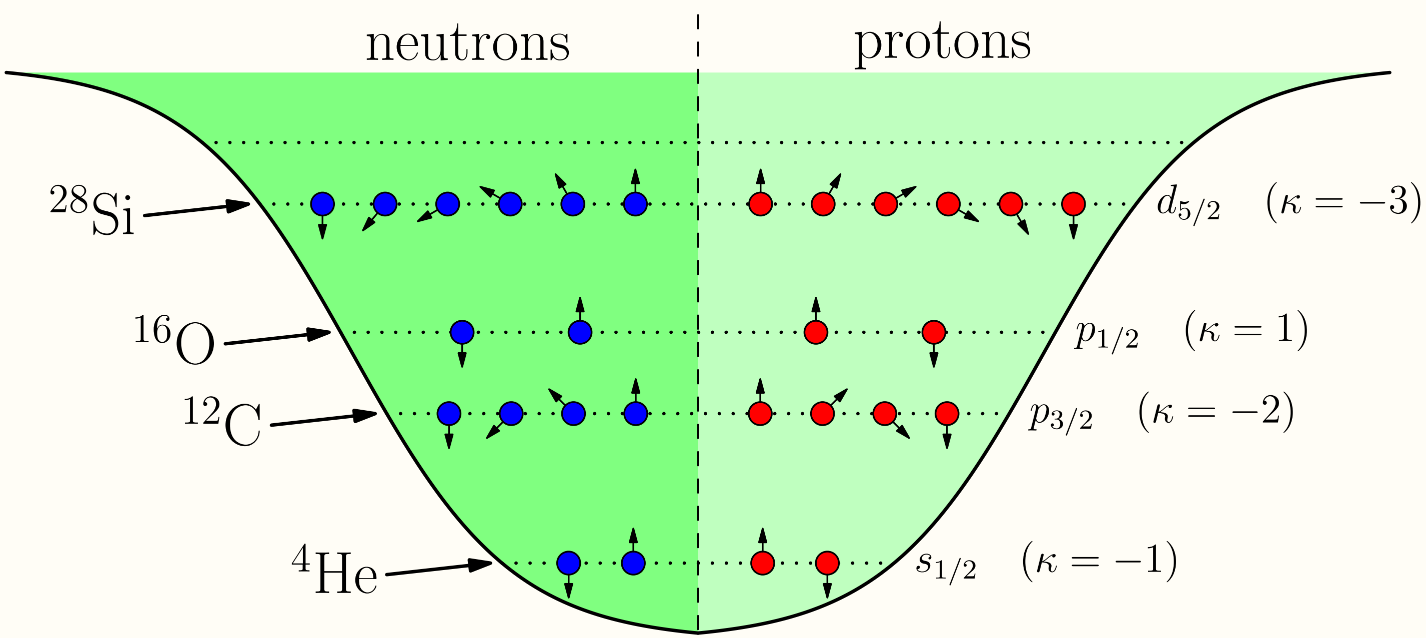
Finite nuclei quark distributions

- Definition of finite nuclei quark distributions

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

- Approximate using a modified convolution formalism

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



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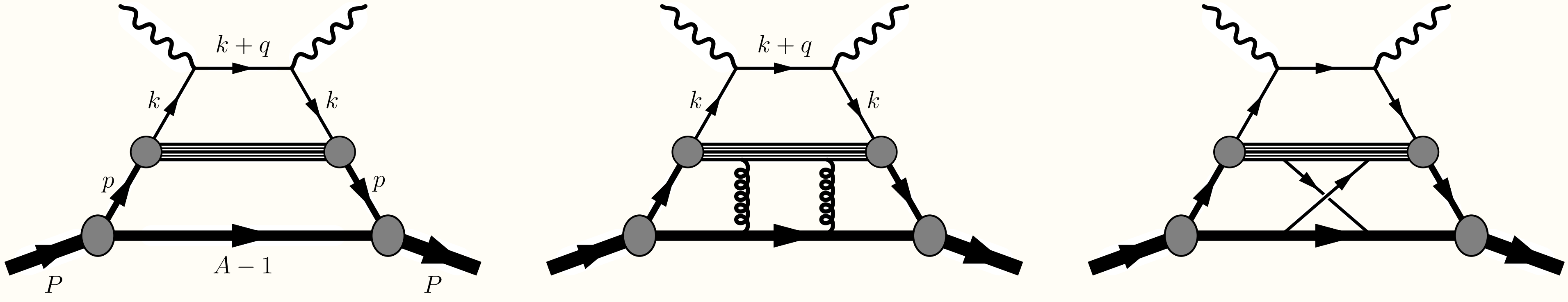
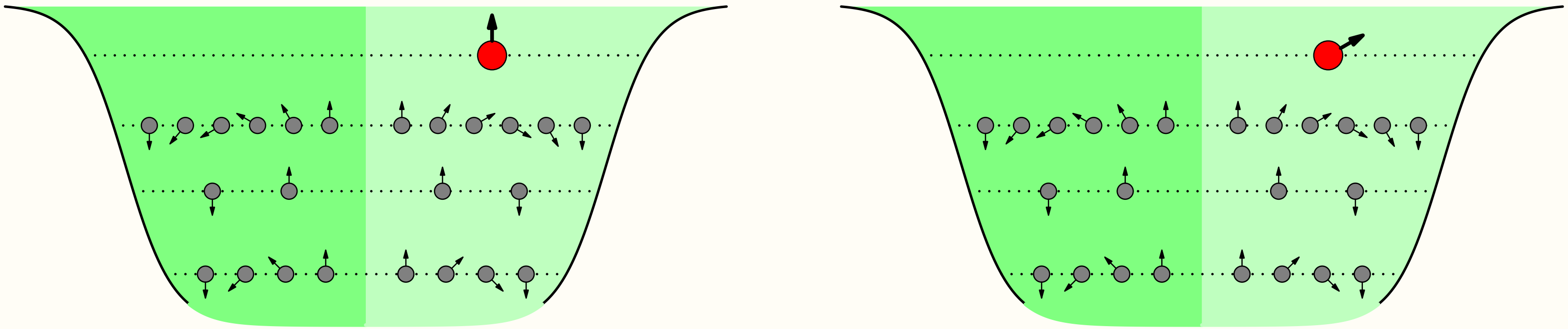
- Convolution formalism diagrammatically:



Convolution Formalism: implications

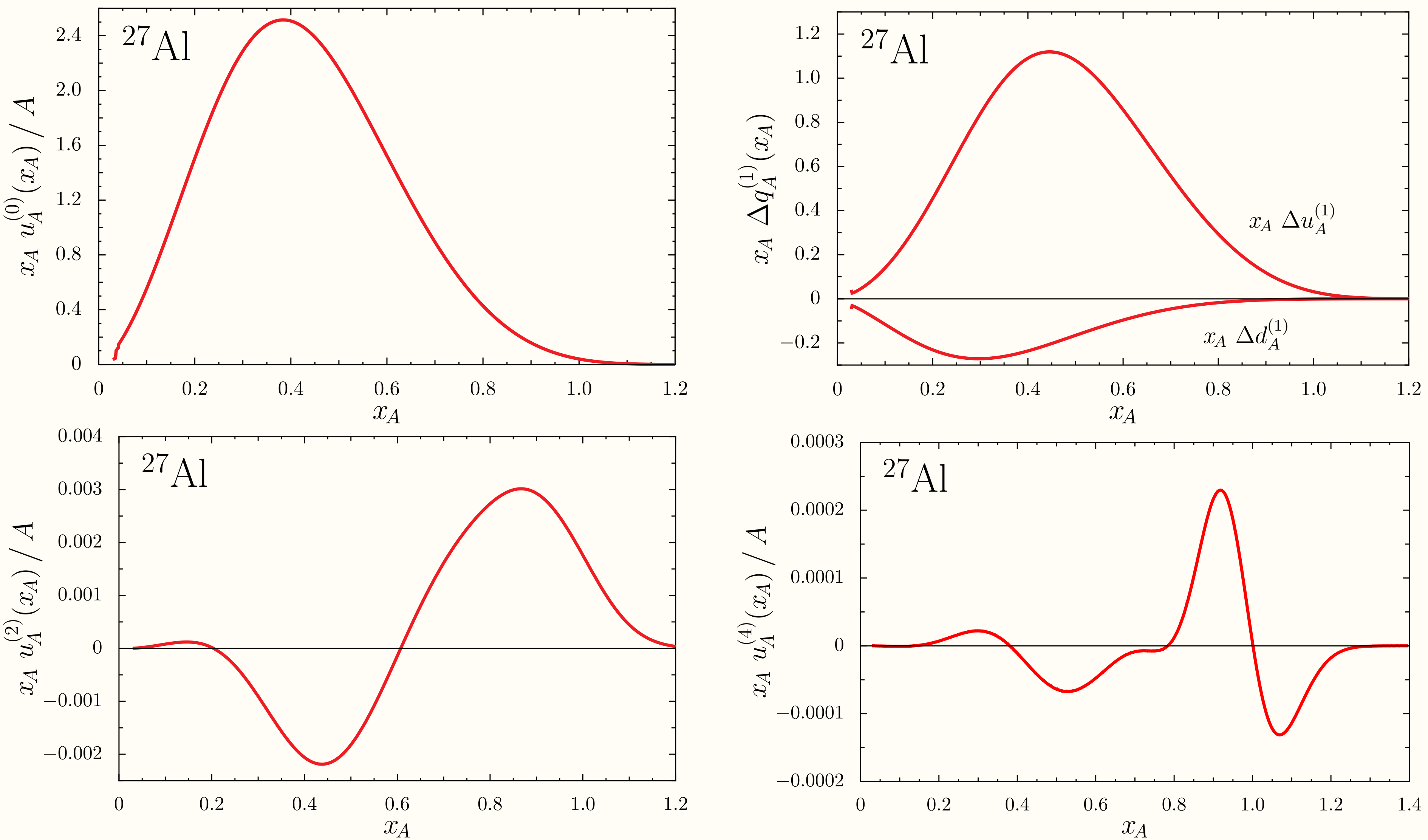


- Assume all spin is carried by the valence nucleons
  - ❖ If $A \gtrsim 8$ and for example if: $J = \frac{3}{2} \quad \Longrightarrow \quad F_{2A}^{3/2} \simeq F_{2A}^{1/2}$
- This is a model independent result within the convolution formalism
- Introduce multipole quark distributions

$$q^{(K)}(x) \equiv \sum\nolimits_H (-1)^{J-H} \sqrt{2K+1} \left(\begin{smallmatrix} J & J & K \\ H & -H & 0 \end{smallmatrix}\right) q^H(x), \quad K = 0, 2, \ldots, 2J$$

- Example: $J = \frac{3}{2} \quad \longrightarrow \quad q^{(0)} = q^{\frac{3}{2}} + q^{\frac{1}{2}} \qquad q^{(2)} = q^{\frac{3}{2}} - q^{\frac{1}{2}}$
- Higher multipoles encapsulate difference between helicity distributions

Some multipole quark distributions result



- Large $K > 1$ multipole PDFs would be very surprising
  - $\Longrightarrow$ large off-shell effects &/or non-nucleon components, etc

New Sum Rules

- Sum rules for multipole quark distributions

$$\int dx\, x^{n-1}\; q^{(K)}(x) \;= 0, \quad K, n \text{ even}, \quad 2 \leqslant n < K,$$
$$\int dx\, x^{n-1}\, \Delta q^{(K)}(x) = 0, \quad K, n \text{ odd}, \quad 1 \leqslant n < K.$$

- Examples:

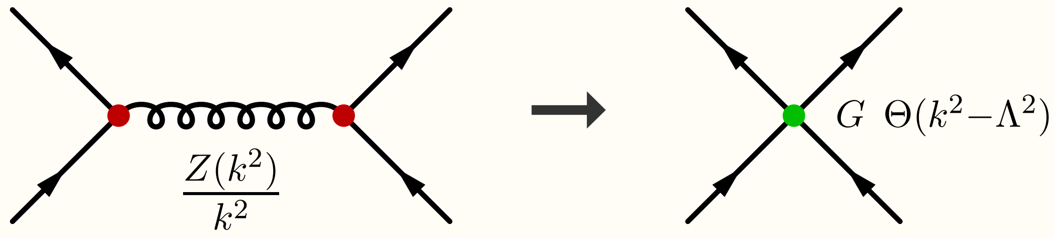
$$J = \tfrac{3}{2} \implies \left\langle \Delta q^{(3)}(x) \right\rangle = 0$$
$$J = 2 \implies \left\langle \Delta q^{(3)}(x) \right\rangle = \left\langle q^{(4)}(x) \right\rangle = 0$$
$$J = \tfrac{5}{2} \implies \left\langle \Delta q^{(3)}(x) \right\rangle = \left\langle q^{(4)}(x) \right\rangle = \left\langle \Delta q^{(5)}(x) \right\rangle = \left\langle x^2\, \Delta q^{(5)}(x) \right\rangle = 0$$

- Sum rules place tight constraints on multipole PDFs

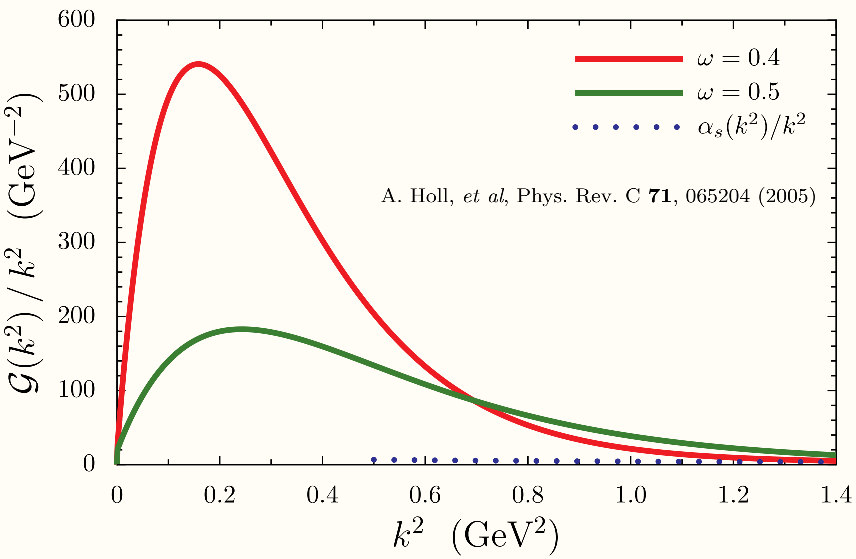
- Jaffe and Manohar, *DIS from arbitrary spin targets*, Nucl. Phys. B **321**, 343 (1989).

Nambu–Jona-Lasinio Model

- Interpreted as low energy chiral effective theory of QCD



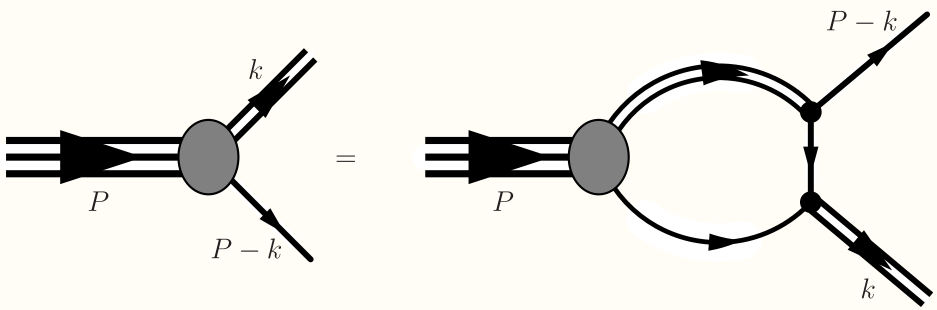
- Can be motivated by infrared enhancement of gluon propagator e.g. DSEs and Lattice QCD



- 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

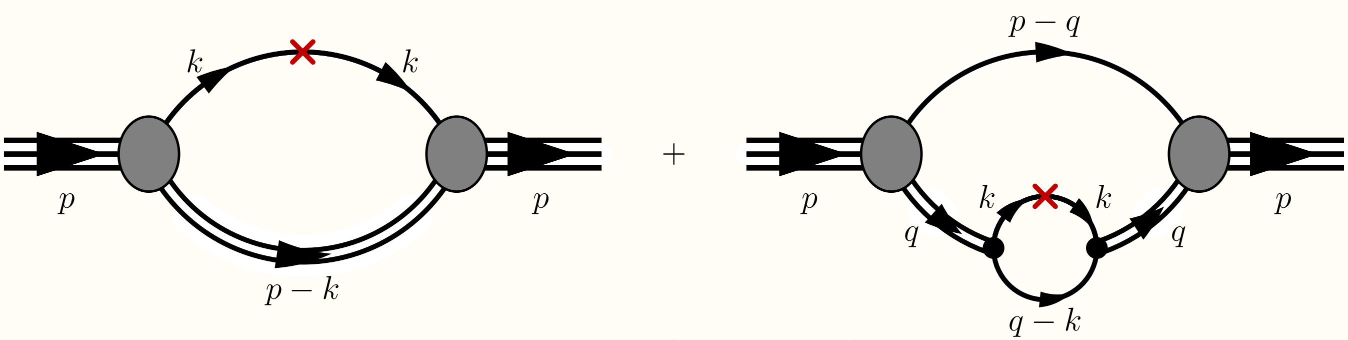
- Nucleon approximated as quark-diquark bound state
- Use relativistic Faddeev approach:



- Nucleon quark distributions

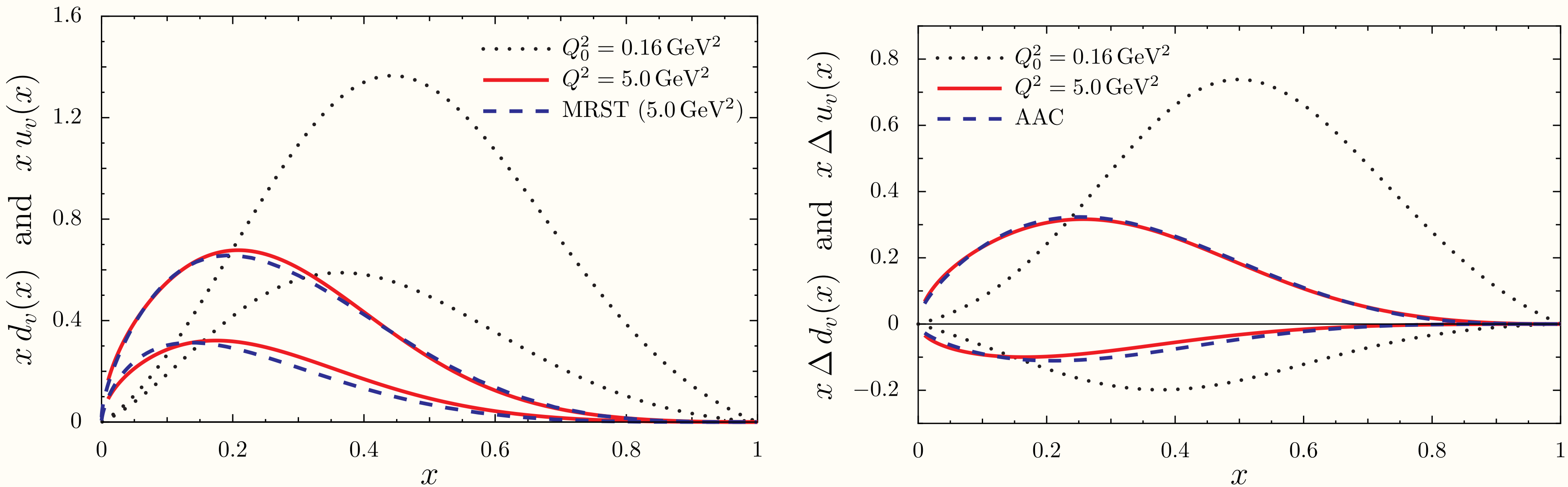
$$q(x) = p^+ \int \frac{d\xi^-}{2\pi} e^{i\,x\,p^+\xi^-} \langle p, s|\overline{\psi}_q(0)\gamma^+\psi_q(\xi^-)|p, s\rangle_c, \quad \Delta q(x) \quad = \langle\gamma^+\gamma_5\rangle$$

- Associated with a Feynman diagram calculation



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

Results: proton quark distributions

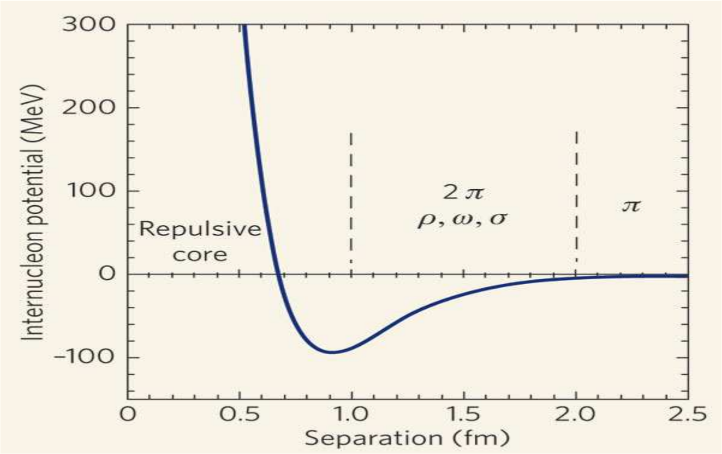


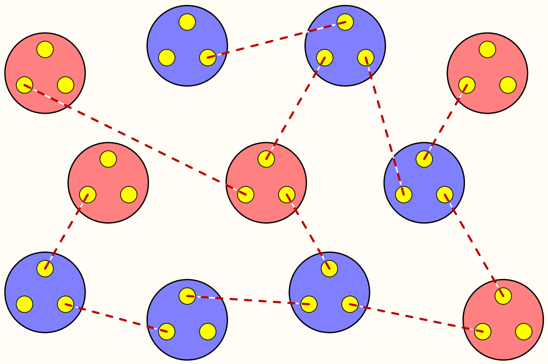
- Empirical distributions:
  - Martin, Roberts, Stirling and Thorne, Phys. Lett. B **531**, 216 (2002).
  - M. Hirai, S. Kumano and N. Saito, Phys. Rev. D **69**, 054021 (2004).
- NJL model gives good description of free nucleon quark distributions
- Approach is covariant, satisfies all sum rules & positivity 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 $\rightarrow$ 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

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

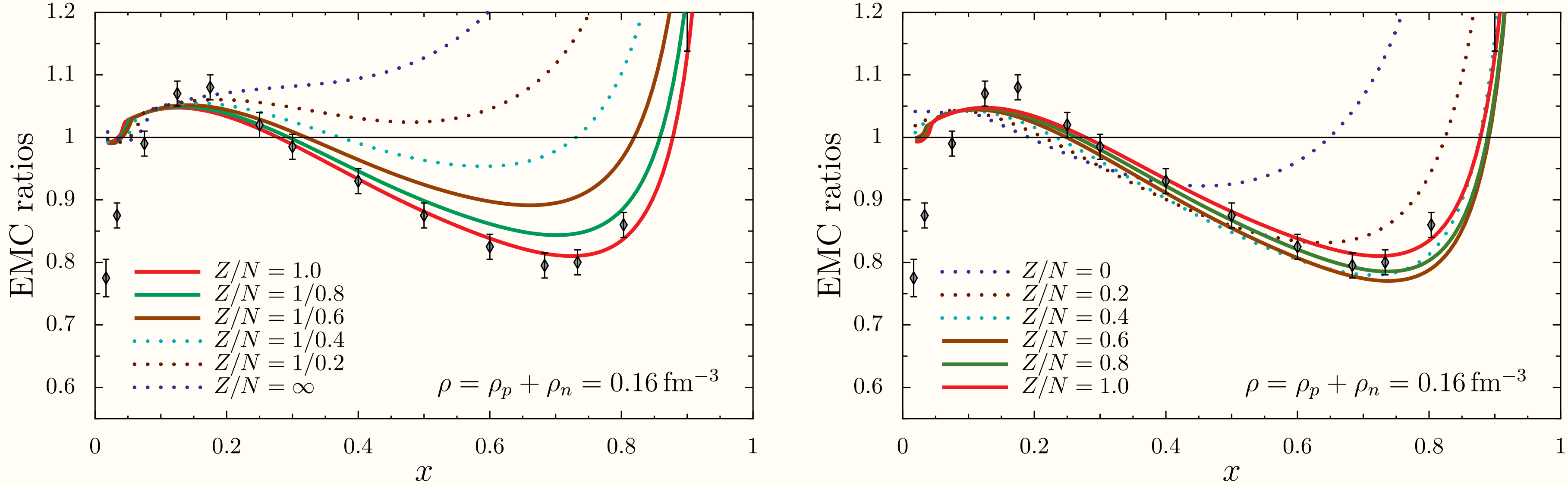
  - $G_\omega \Leftrightarrow Z = N$ saturation & $G_\rho \Leftrightarrow$ symmetry energy

- Quark vector fields:

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

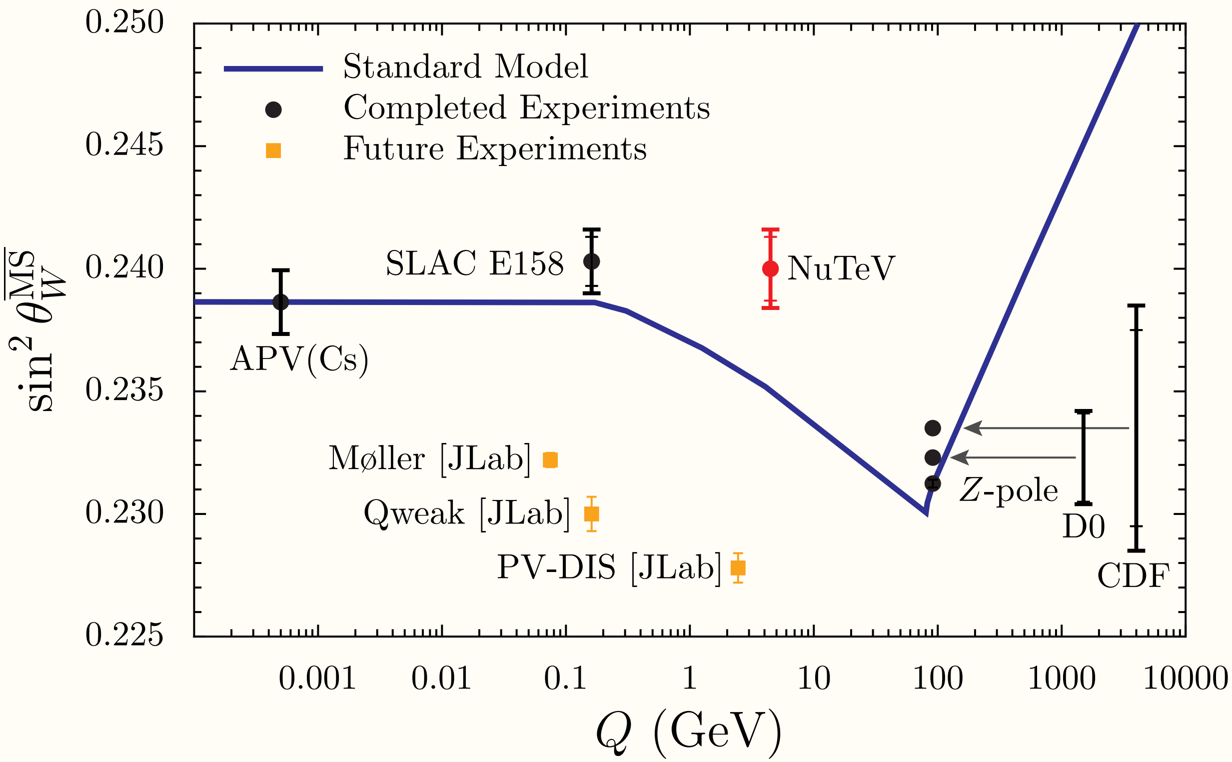
- Recall: quark propagator: $S_q(k) = \left[\not{k} - M^* - \not{V}_q\right]^{-1}$

Isovector EMC effect



- EMC ratio: $R = \dfrac{F_{2A}}{F_{2A}^{\text{naive}}} = \dfrac{F_{2A}}{Z\,F_{2p} + N\,F_{2n}} \sim \dfrac{4\,u_A(x) + d_A(x)}{4\,u_0(x) + d_0(x)}$
- 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: $\boxed{\sin^2\theta_W = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})}$
  - G. P. Zeller *et al.* Phys. Rev. Lett. **88**, 091802 (2002)
- World average $\boxed{\sin^2\theta_W = 0.2227 \pm 0.0004}$: 3 $\sigma \implies$ "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:

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

- Expressing R_{PW} in terms of quark distributions:

$$R_{PW} = \frac{\left(\frac{1}{6}-\frac{4}{9}\sin^2\theta_W\right)\langle x\,u_A^-\rangle+\left(\frac{1}{6}-\frac{2}{9}\sin^2\theta_W\right)\langle x\,d_A^-+x\,s_A^-\rangle}{\langle x\,d_A^-+x\,s_A^-\rangle-\frac{1}{3}\langle x\,u_A^-\rangle}$$

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

$$R_{PW} = \frac{1}{2} - \sin^2\theta_W + \Delta R_{PW}$$

- NuTeV measured R_{PW} on an Fe target ($Z/N \simeq 26/30$)
- Correct for neutron excess $\Leftrightarrow$ isoscalarity corrections

Isovector EMC correction to NuTeV

- General form of isoscalarity corrections

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

- NuTeV assumed nucleons in Fe are like free nucleons
  - Ignored some medium effects: Fermi motion & ρ^0-field
- Use our medium modified “Fe” quark distributions

$$\begin{aligned}\Delta R_{PW} &= \Delta R_{PW}^{\text{naive}} + \Delta R_{PW}^{\text{Fermi}} + \Delta R_{PW}^{\rho^0} \\ &= -\left(0.0107 + 0.0004 + 0.0028\right).\end{aligned}$$

- Recall NuTeV requires $\Delta R_{PW} = -0.005$

$$\begin{aligned}R_{PW}^{\text{SM}} &= 0.2773 \pm \ldots \quad \left(= \tfrac{1}{2} - \sin^2\theta_W\right) \\ R_{PW}^{\text{NuTeV}} &= 0.2723 \pm \ldots\end{aligned}$$

- Isoscalarity ρ^0 correction can explain up to 65% of anomaly

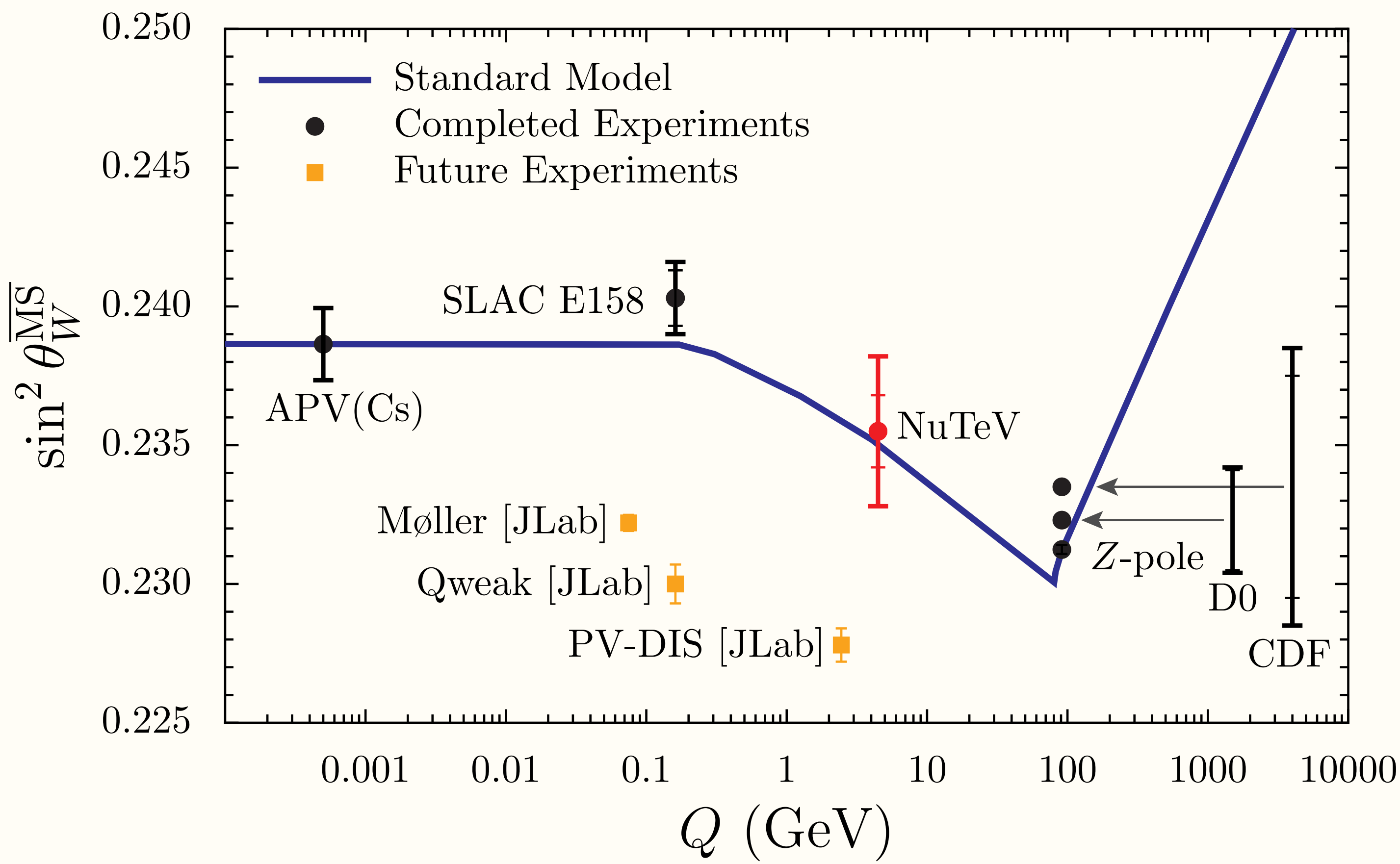
NuTeV anomaly cont'd

- Also correction from $m_u \neq m_d$ - Charge Symmetry Violation
  - CSV + $\rho_0 \implies$ no NuTeV anomaly
  - No evidence for physics beyond the Standard Model
- Instead "NuTeV anomaly" is evidence for medium modification
  - Equally interesting
  - EMC effect has over 850 citations [J. J. Aubert *et al.*, Phys. Lett. B **123**, 275 (1983).]
- Model dependence?
  - sign of correction is fixed by nature of vector fields

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

  - ρ^0-field shifts momentum from u- to d-quarks
  - size of correction is constrained by Nucl. Matt. symmetry energy
- ρ_0 vector field reduces NuTeV anomaly – Model Independent!!

Total NuTeV correction



- Includes NuTeV functionals
- Small increase in systematic error
- NuTeV anomaly interpreted as evidence for medium modification
- Equally profound as evidence for physics beyond Standard Model

Consistent with other observables?

- We claim isovector EMC effect explains $\sim$1.5σ of NuTeV result
  - is this mechanism observed elsewhere?
- Yes!! Parity violating DIS: $\gamma\, Z^0$ interference

$$A_{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} \propto \left[a_2(x) + \frac{1-(1-y)^2}{1+(1-y)^2}\, a_3(x)\right]$$

$$a_2(x) = -2g_A^e\, \frac{F_2^{\gamma Z}}{F_2^{\gamma}} = \frac{6u^+ + 3d^+}{4\,u^+ + d^+} - 4\sin^2\theta_W$$

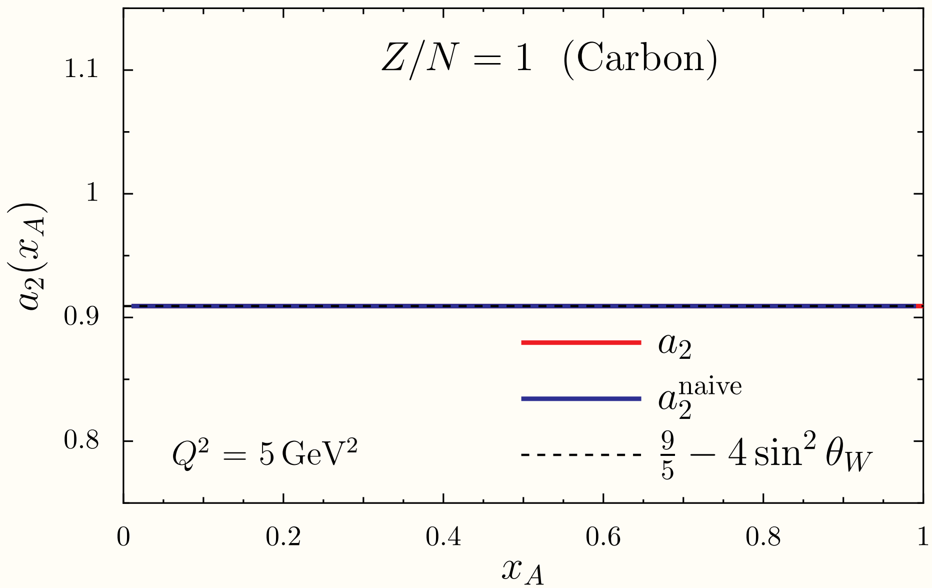
$$a_3(x) = -2g_V^e\, \frac{F_3^{\gamma Z}}{F_2^{\gamma}} = 3\left(1 - 4\sin^2\theta_W\right) \frac{2\,u^- + d^-}{4\,u^+ + d^+}$$

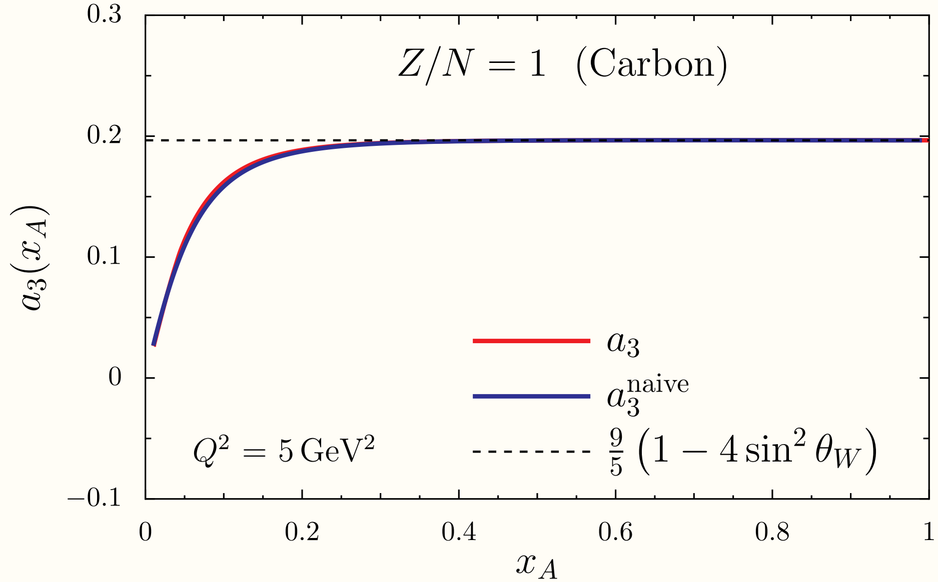
- Parton model expressions

$$F_2^{\gamma Z} = 2\sum e_q\, g_V^q\; x\,(q+\bar{q})\,, \qquad g_V^q = \pm\tfrac{1}{2} - 2e_q \sin^2\theta_W$$

$$F_3^{\gamma Z} = 2\sum e_q\, g_A^q\; (q-\bar{q})\,, \qquad g_A^q = \pm\tfrac{1}{2}$$

Parity Violating DIS: Carbon





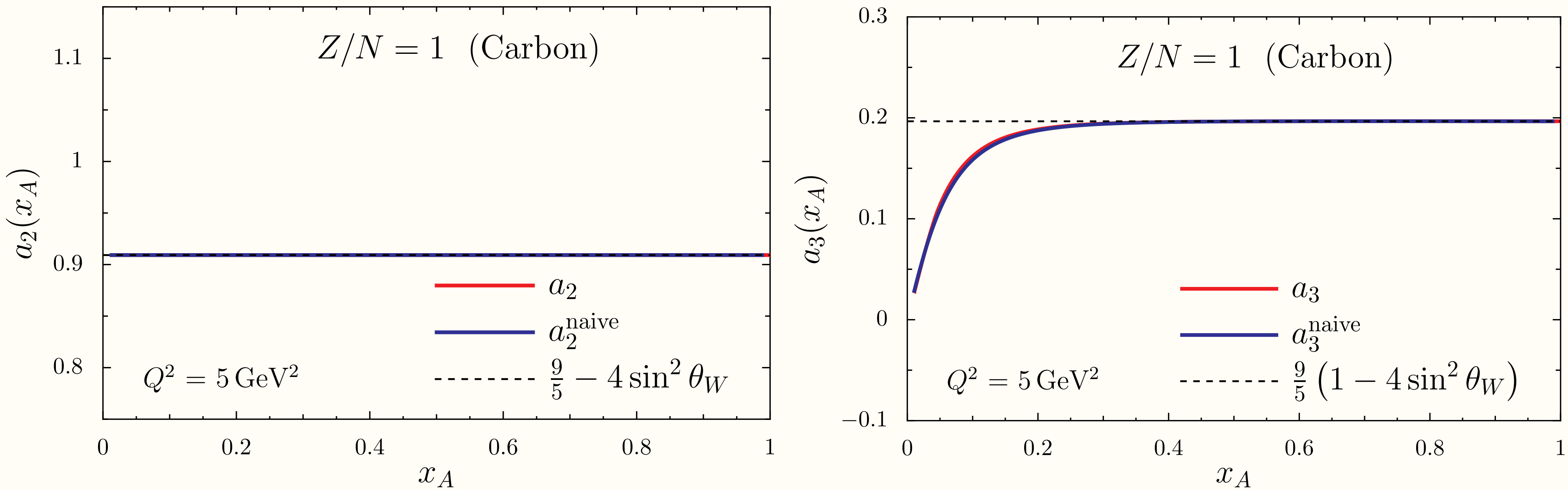
- Ignoring quark mass differences, s-quarks and EW corrections
  - For a $N = Z$ target:

$$a_2(x) = \frac{6u_A^+ + 3d_A^+}{4\,u_A^+ + d_A^+} - 4\sin^2\theta_W \to \frac{9}{5} - 4\sin^2\theta_W$$

$$a_3(x) = 3\left(1 - 4\sin^2\theta_W\right)\frac{2\,u^- + d^-}{4\,u_A^+ + d_A^+} \to \frac{9}{5}\left(1 - 4\sin^2\theta_W\right)\frac{u_A^- + d_A^-}{u_A^+ + d_A^+}$$

- Measurement of $a_2(x)$ at each $x \Longrightarrow$ a NuTeV experiment!

Parity Violating DIS: Carbon



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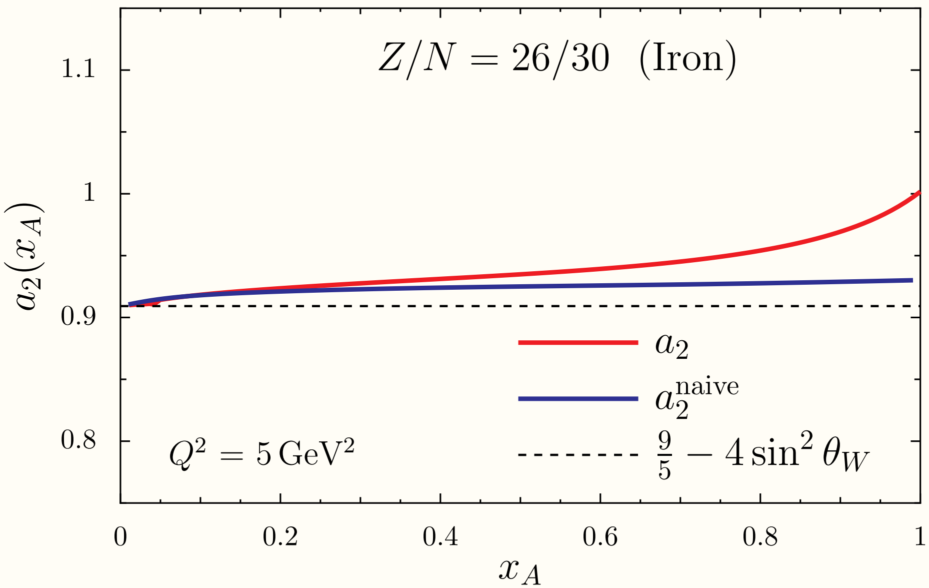
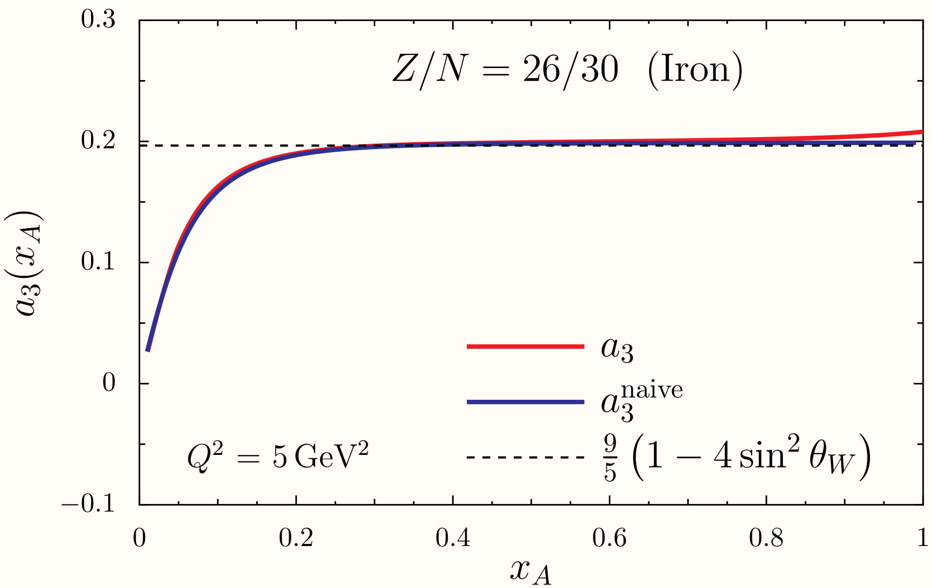
$$a_3(x) \to \frac{9}{5}\left(1 - 4\sin^2\theta_W\right)\frac{u_A^- + d_A^-}{u_A^+ + d_A^+} = \frac{9}{5}\left(1 - 4\sin^2\theta_W\right)\left[1 + 2\,\frac{\bar{u}_A + \bar{d}_A}{u_A^- + d_A^-}\right]^{-1}$$

- Measurement of $a_2(x)$ at each $x \Longrightarrow$ a NuTeV experiment!

Parity Violating DIS: Iron





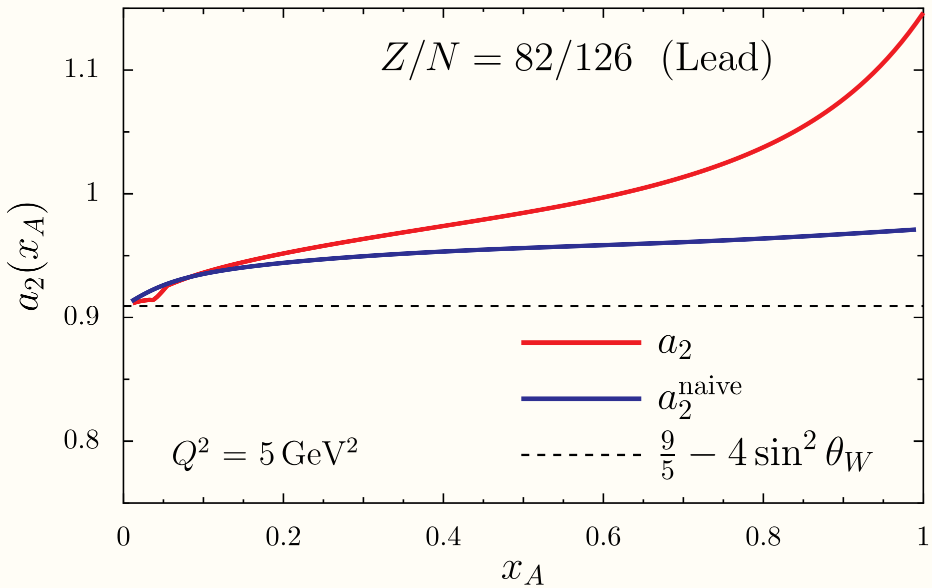
- For a $N \simeq Z$ target:

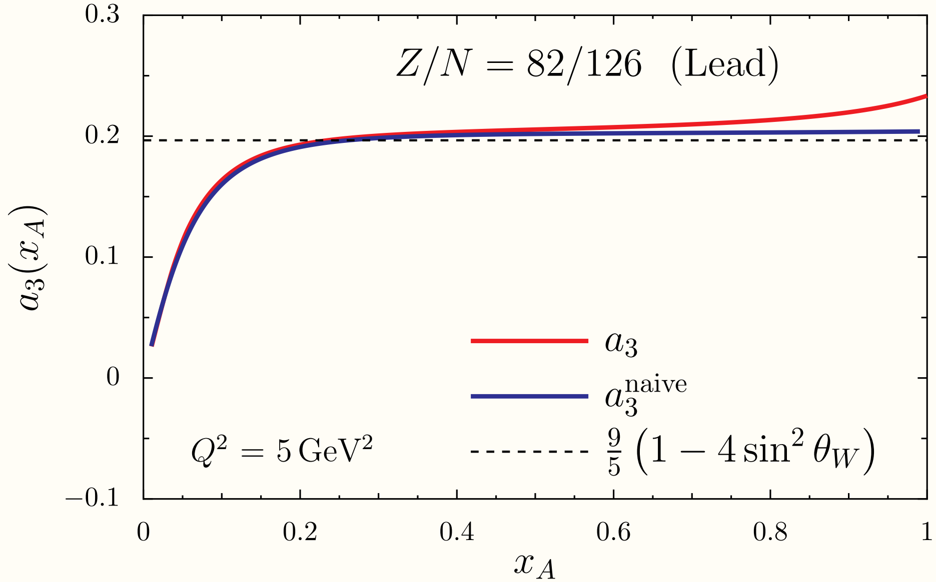
$$a_2(x) = \frac{9}{5} - 4\sin^2\theta_W \; - \; \frac{12}{25}\,\frac{u_A^+(x) - d_A^+(x)}{u_A^+(x) + d_A^+(x)}$$

$$a_3(x) = \frac{9}{5}\left(1 - 4\sin^2\theta_W\right)\left\{\frac{u_A^- + d_A^-}{u_A^+ + d_A^+} - \frac{1}{3}\left[\frac{12}{5}\,\frac{u_A^- + d_A^-}{u_A^+ + d_A^+}\,\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+} - \frac{u_A^- - d_A^-}{u_A^+ + d_A^+}\right]\right\}$$

- “Naive” result has no medium corrections
- Sizeable medium effects in $a_2(x)$

Parity Violating DIS: Lead





- For a $N \simeq Z$ target:

$$a_2(x) = \frac{9}{5} - 4\sin^2\theta_W \;-\; \frac{12}{25}\,\frac{u_A^+(x) - d_A^+(x)}{u_A^+(x) + d_A^+(x)}$$

$$a_3(x) = \frac{9}{5}\left(1 - 4\sin^2\theta_W\right)\left\{\frac{u_A^- + d_A^-}{u_A^+ + d_A^+} - \frac{1}{3}\left[\frac{12}{5}\,\frac{u_A^- + d_A^-}{u_A^+ + d_A^+}\,\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+} - \frac{u_A^- - d_A^-}{u_A^+ + d_A^+}\right]\right\}$$

- After naive isoscalarity corrections medium effects still very large
- Large x dependence of $a_2(x)$ → evidence for medium modification

Finite nuclei EMC effects

- EMC ratio

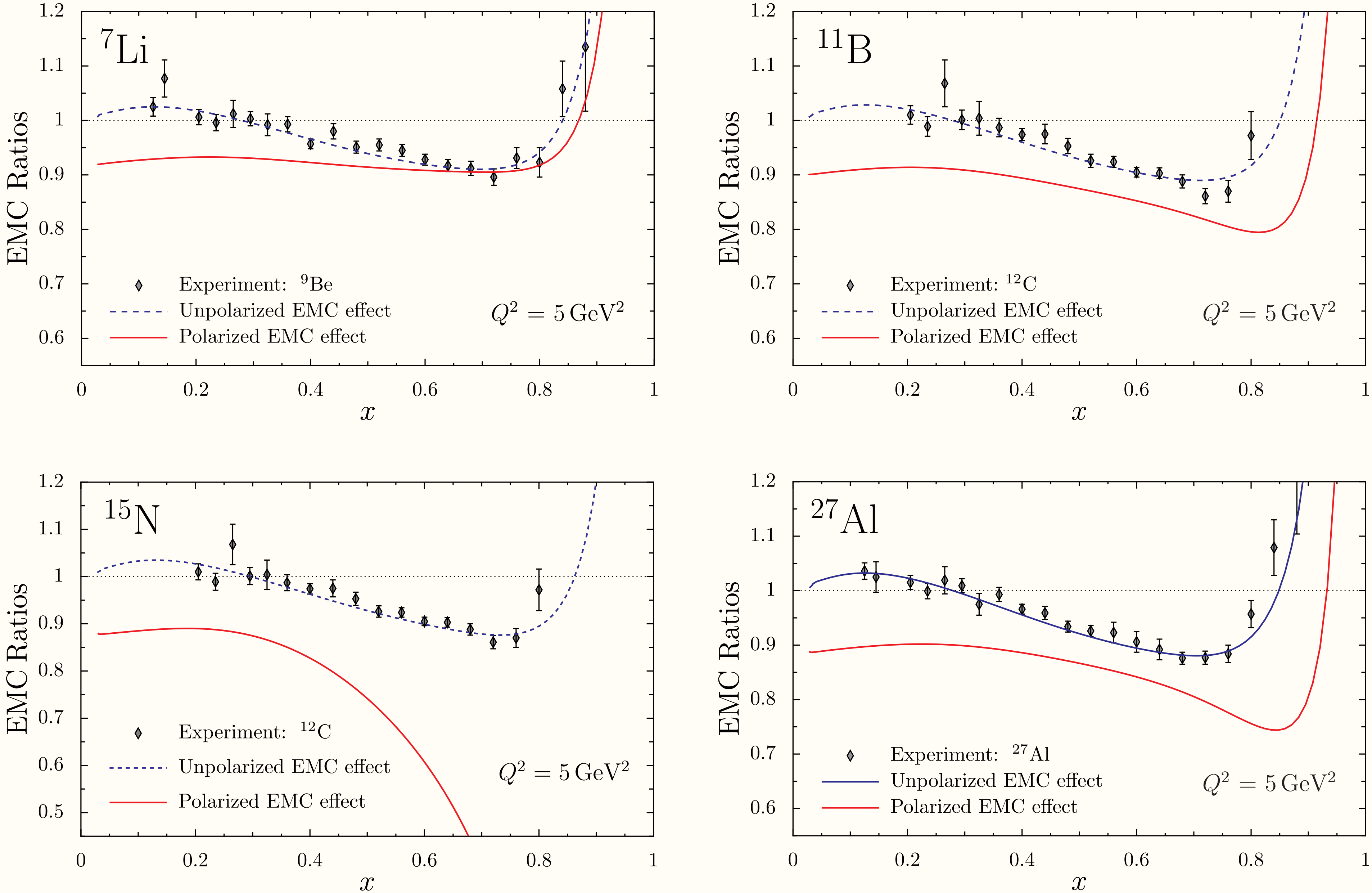
$$R = \frac{F_{2A}}{F_{2A}^{\text{naive}}} = \frac{F_{2A}}{Z\,F_{2p} + N\,F_{2n}}$$

- Polarized EMC ratio

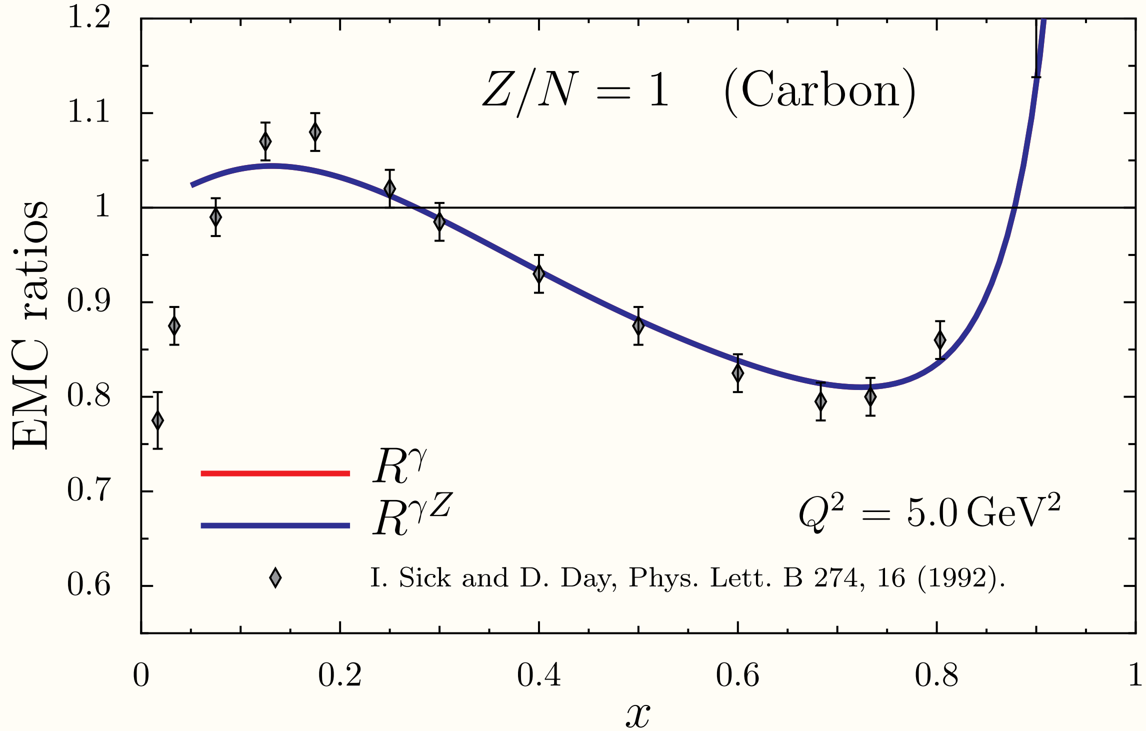
$$R_s^H = \frac{g_{1A}^H}{g_{1A}^{H,\text{naive}}} = \frac{g_{1A}^H}{P_p^H\,g_{1p} + P_n^H\,g_{1n}}$$

- 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



F_2^γ and $F_2^{\gamma Z}$ EMC ratios – "Carbon"

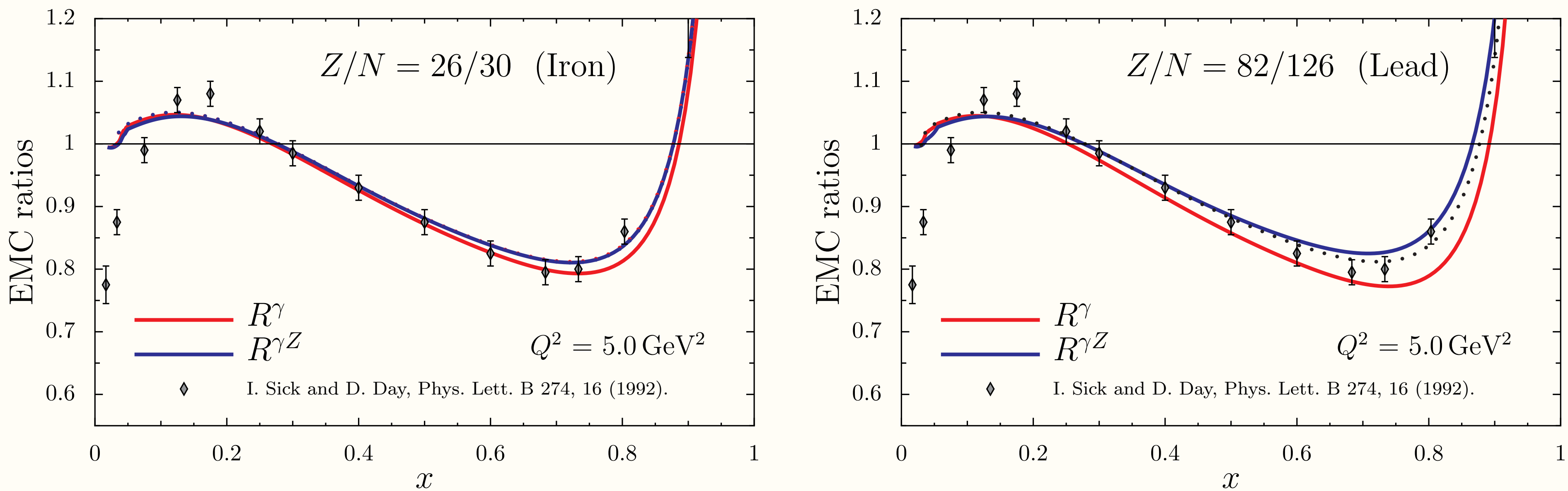


- Recall EMC ratio:

$$R^i = \frac{F_{2A}^i}{F_{2A}^{i,\text{naive}}} = \frac{F_{2A}^i}{Z\,F_{2p}^i + N\,F_{2n}^i} \qquad i \in \gamma,\ \gamma Z,\ \ldots$$

$$R^\gamma \sim \frac{4\,u_A(x) + d_A(x)}{4\,u_0(x) + d_0(x)}, \qquad R^{\gamma Z} \sim \frac{1.16\,u_A(x) + d_A(x)}{1.16\,u_0(x) + d_0(x)}$$

F_2^γ and $F_2^{\gamma Z}$ EMC ratios – "Iron" & "Lead"

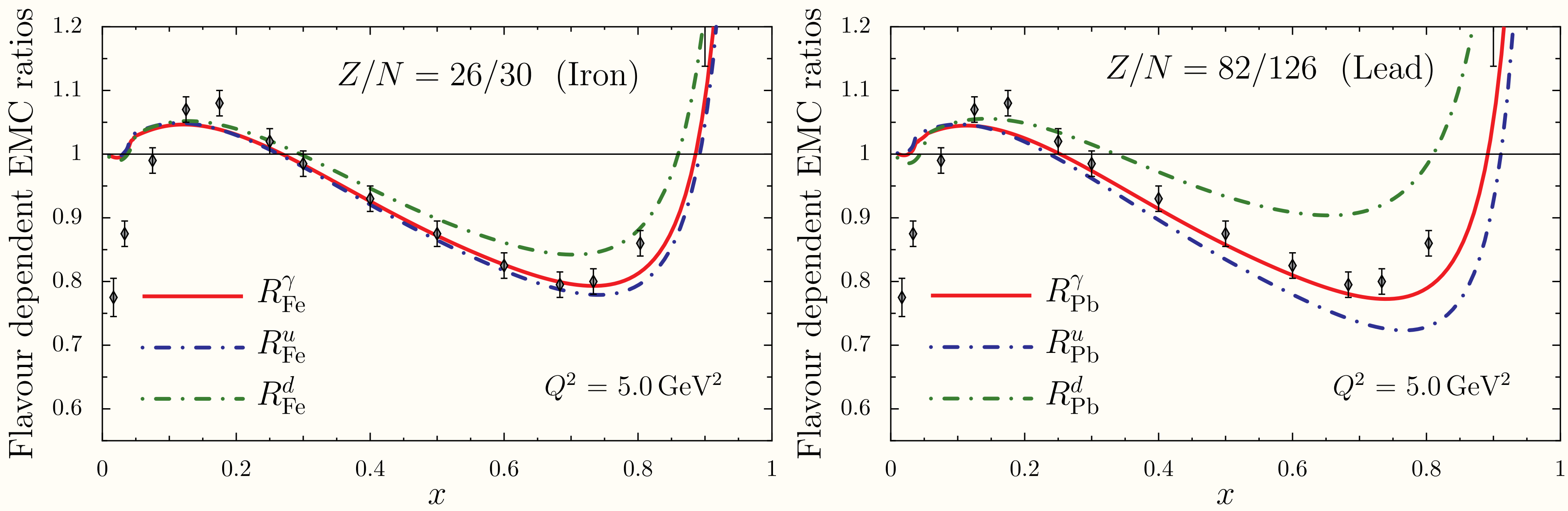


- $$R^\gamma \sim \frac{4\,u_A(x)+d_A(x)}{4\,u_0(x)+d_0(x)} \quad \& \quad R^{\gamma Z} \sim \frac{1.16\,u_A(x)+d_A(x)}{1.16\,u_0(x)+d_0(x)}$$
- u_A dominates R^γ where $R^{\gamma Z}$ almost isoscalar ratio
- $N > Z$: d-quarks feel more repulsion than u-quarks: $V_d > V_u$

$$q(x) = \frac{p^+}{p^+ - V^+}\, q_0\left(\frac{p^+}{p^+ - V^+}\, x - \frac{V_q^+}{p^+ - V^+}\right)$$

- ρ_0-field $\Longrightarrow R^{\gamma Z} > R^\gamma$ – Model Independent

Flavour Dependence of EMC effect

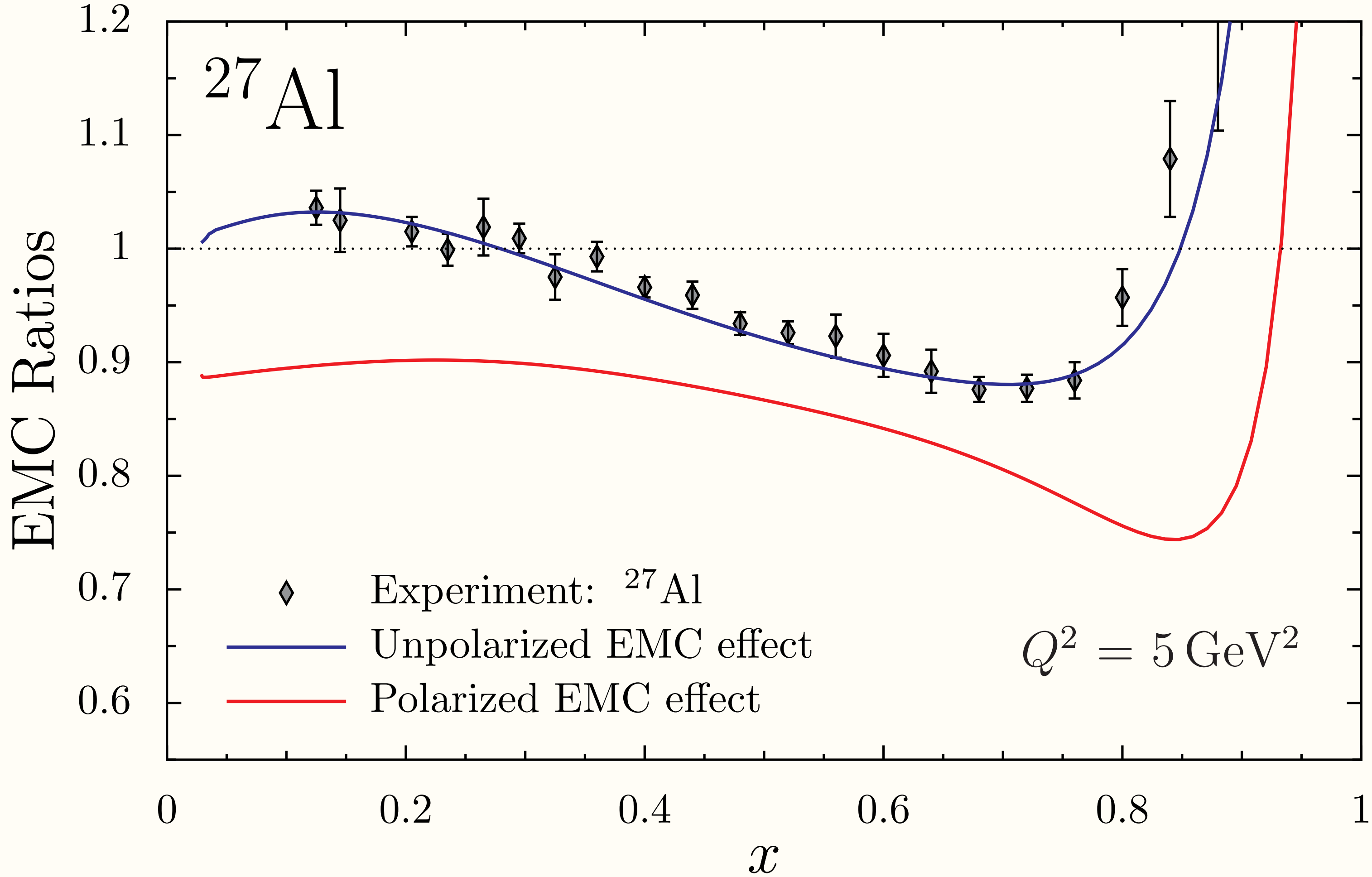


- Flavour dependence determined by measuring F_{2A}^{γ} and $F_{2A}^{\gamma Z}$
- Defined above by

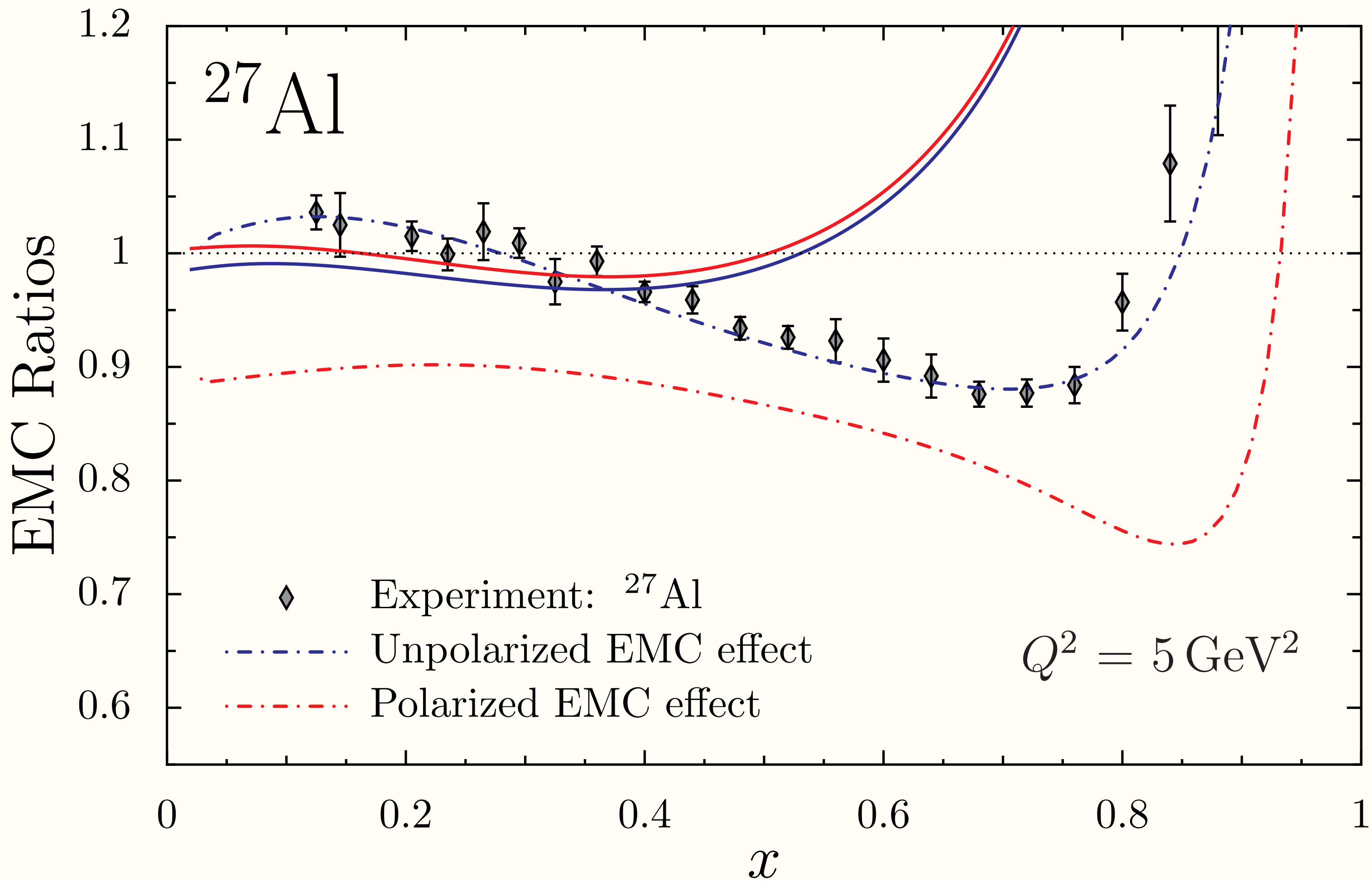
$$R_A^q = \frac{F_{2A}^q}{F_{2A}^{q,\,\text{naive}}} \simeq \frac{q_A}{q_0}$$

- If observed $\Longrightarrow$ very strong evidence for medium modification

Is there medium modification



Is there medium modification



- 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: $\boxed{J = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g}$
  - 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
- Tried to demonstrate that PV DIS is a very powerful tool with which to study the parton structure of nuclei – at JLab or an EIC

Model Parameters

- Free Parameters:

  Λ_{IR}, Λ_{UV}, M_0, G_π, G_s, G_a, G_ω and G_ρ

- Constraints:
  - $f_\pi = 93$ MeV, $m_\pi = 140$ MeV & $M_N = 940$ MeV
  - $\int_0^1 dx\ (\Delta u_v(x) - \Delta d_v(x)) = g_A = 1.267$
  - $(\rho, E_B/A) = (0.16\,\text{fm}^{-3}, -15.7\text{ MeV})$
  - $a_4 = 32$ MeV
  - $\Lambda_{IR} = 240$ MeV
- We obtain [MeV]:
  - $\Lambda_{UV} = 644$
  - $M_0 = 400, \quad M_s = 690, \quad M_a = 990, \quad \ldots$
- Can now study a very large array of observables:
  - e.g. meson and baryon: quark distributions, form factors, GPDs, finite temp. and density, neutron stars

Regularization

- Proper-time regularization

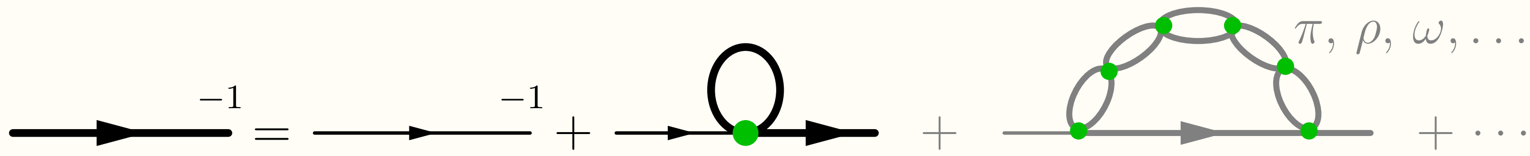
$$\frac{1}{X^n} = \frac{1}{(n-1)!} \int_0^\infty d\tau\, \tau^{n-1}\, e^{-\tau\, X}$$
$$\longrightarrow \quad \frac{1}{(n-1)!} \int_{1/(\Lambda_{UV})^2}^{1/(\Lambda_{IR})^2} d\tau\, \tau^{n-1}\, e^{-\tau\, X}$$

- Λ_{IR} eliminates unphysical thresholds for the nucleon to decay into quarks: $\rightarrow$ simulates confinement
  - D. Ebert, T. Feldmann and H. Reinhardt, Phys. Lett. B **388**, 154 (1996).
- E.g.: Quark wave function renormalization
  - $Z(k^2) = e^{-\Lambda_{UV}(k^2-M^2)} - e^{-\Lambda_{IR}(k^2-M^2)}$

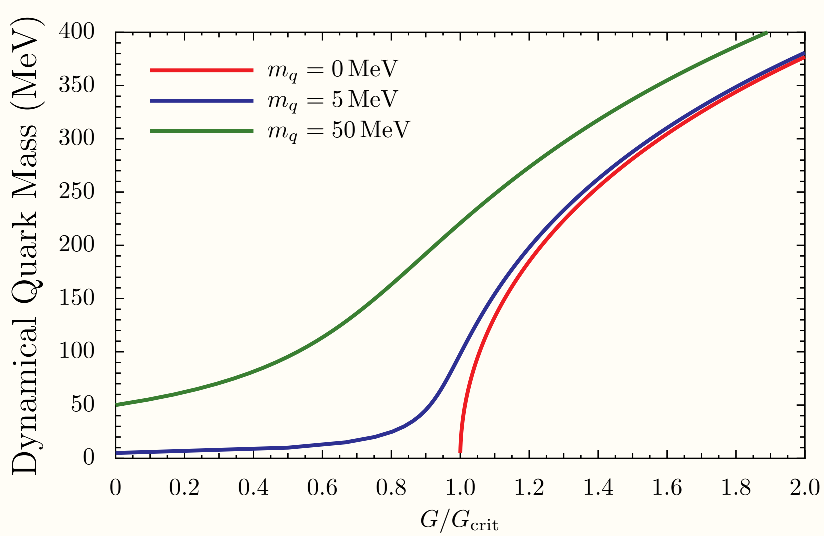
  → $Z(k^2 = M^2) = 0 \quad \Longrightarrow$ no free quarks

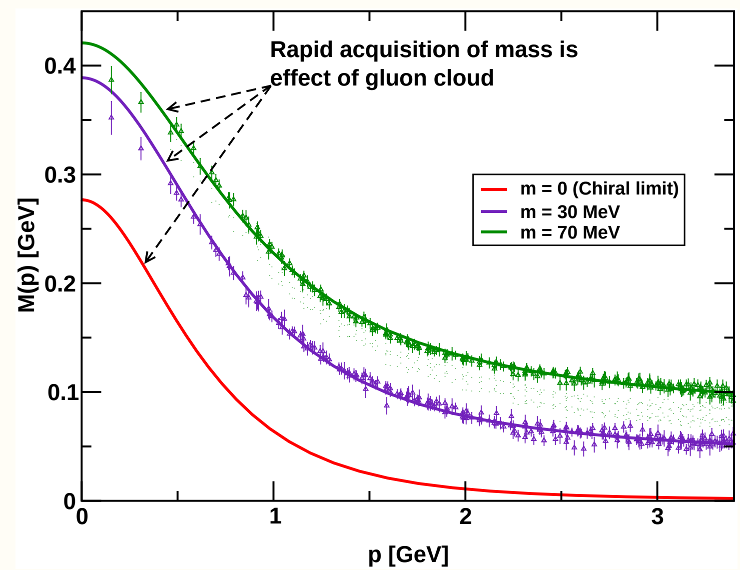
- Needed for: nuclear matter saturation, Δ baryon, etc
  - W. Bentz, A.W. Thomas, Nucl. Phys. A **696**, 138 (2001)

Gap Equation & Mass Generation



- Quark Propagator: $\dfrac{1}{\not p - m + i\varepsilon} \rightarrow \dfrac{1}{\not p - M + i\varepsilon}$
- Mass is generated via interaction with vacuum





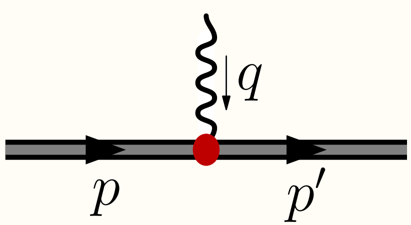
- Dynamically generated quark masses $\Longleftrightarrow$ $\langle\overline{\psi}\psi\rangle \neq 0$ $\Longleftrightarrow$ DχSB
- Proper-time regularization: Λ_{IR} and Λ_{UV}
  - ➞ No free quarks $\Longrightarrow$ Confinement $\quad [Z(k^2 = M^2) = 0]$

Off-Shell Effects

- For an off-shell nucleon, photon–nucleon vertex given by

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

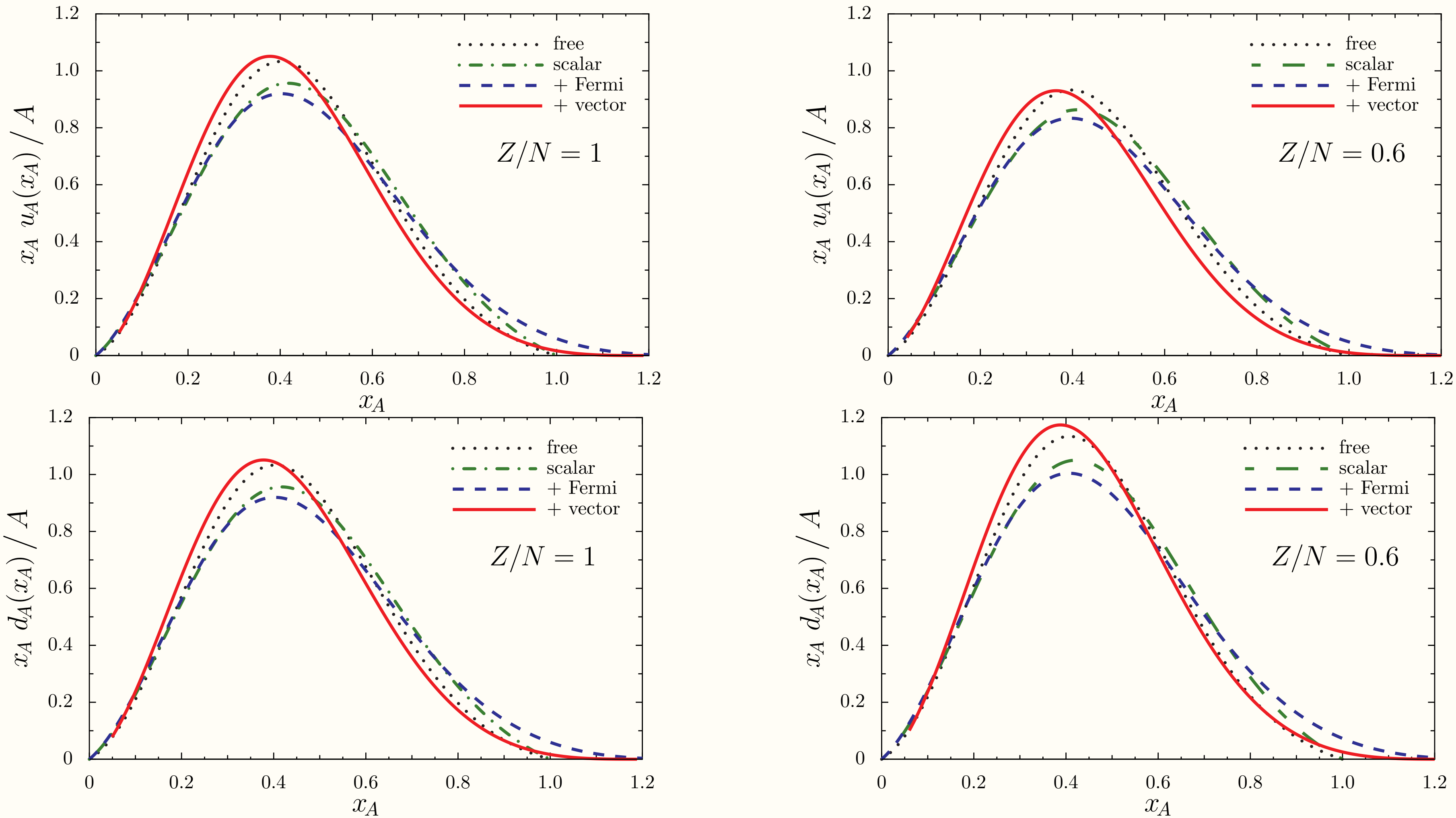
- In-medium nucleon is off-shell, extremely difficult to quantify effects
  - However must understand to fully describe in-medium nucleon
- Simpler system: off-shell pion form factors
  - relax on-shell constraint $p'^2 = p^2 = m_\pi^2$
  - Very difficult to calculate in many approaches, e.g. Lattice QCD



$$= (p'+p)^\mu\, F_{\pi,1}(p'^2, p^2, Q^2) + (p'-p)^\mu\, F_{\pi,2}(p'^2, p^2, Q^2)$$

- For $p'^2 = p^2 = m_\pi^2$ we have $F_{\pi,1} \to F_\pi$ and $F_{\pi,2} = 0$

Results: Nuclear Matter



- $\rho_p + \rho_n = \text{fixed}$ – Differences arise from:
  - naive: different number protons and neutrons
  - medium: p & n Fermi motion and $V_{u(d)}$ differ $\rightarrow u_p(x) \neq d_n(x), \ldots$