Recent developments in the nuclear EMC effect

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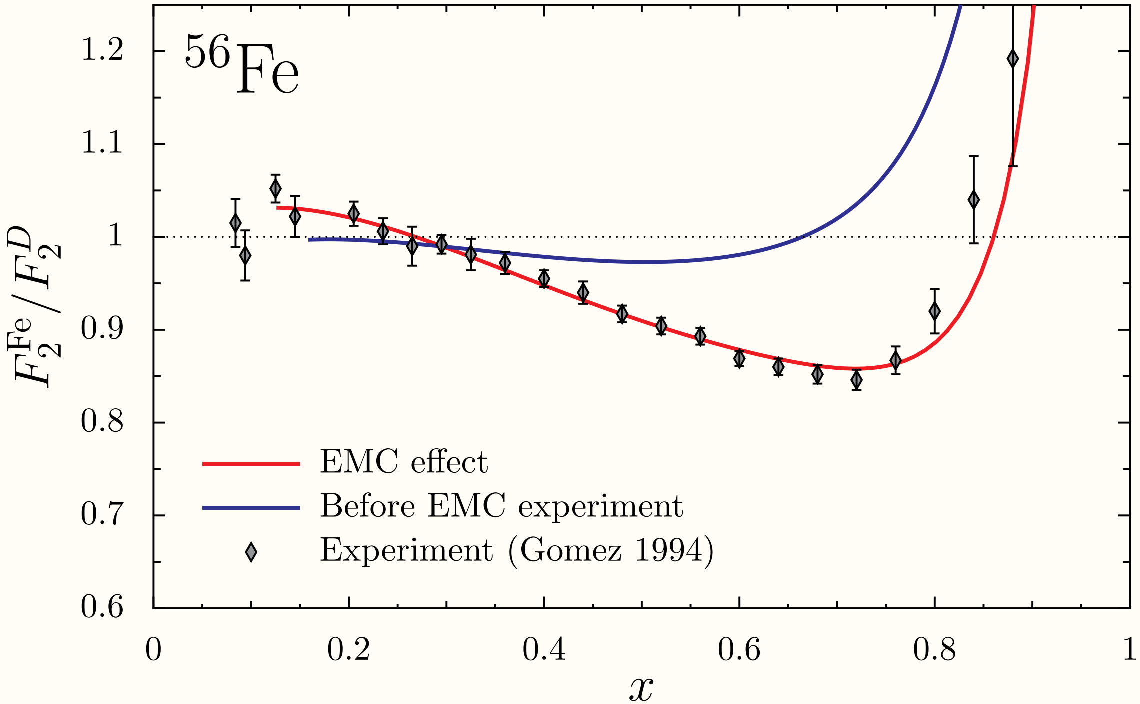
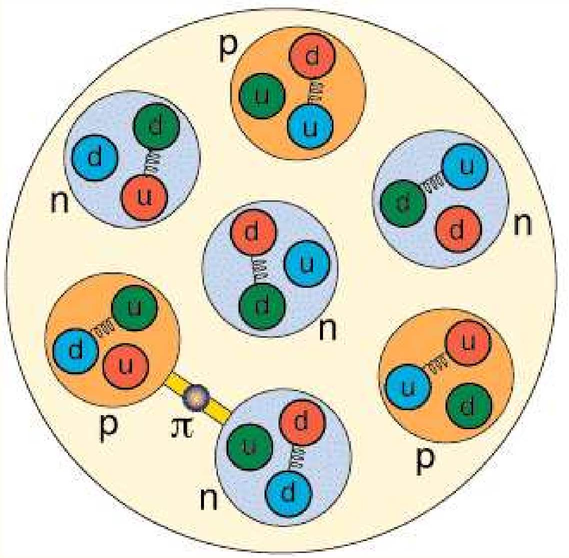
Meson-Nucleon Physics and the Structure of the Nucleon

William & Mary   June 2010

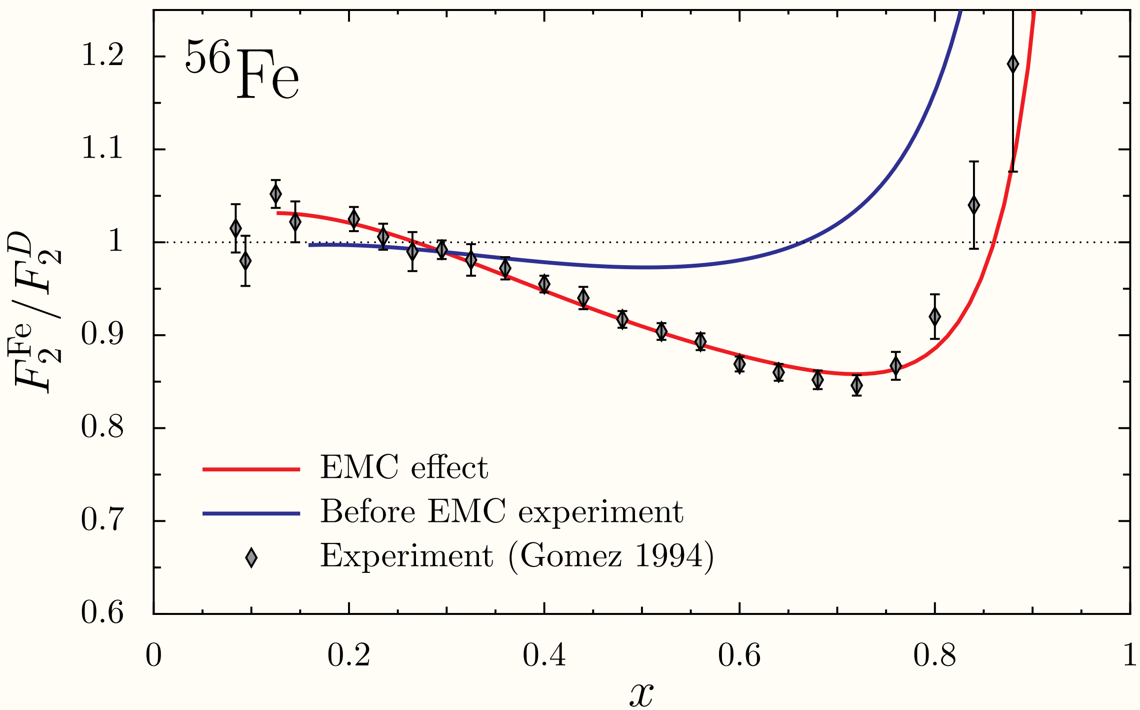
EMC Effect

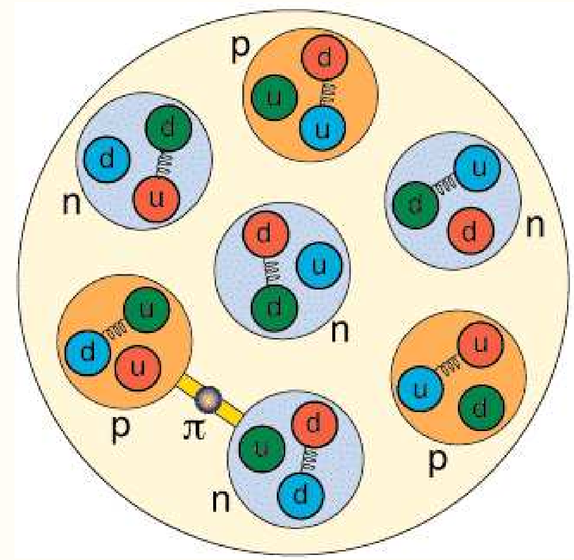




- J. J. Aubert *et al.* [European Muon Collaboration], Phys. Lett. B **123**, 275 (1983).
- Fundamentally changed our understanding of nuclear structure
- Immediate parton model interpretation:
  - valence quarks in nucleus carry less momentum than in nucleon
- What is the mechanism? After 25 years no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

EMC Effect





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- Fundamentally changed our understanding of nuclear structure
- What is the mechanism? After 25 years no consensus
- EMC $\Longrightarrow$ medium modification of the bound nucleons
- Need new experiments accessing different aspects of EMC effect
  - Drell–Yan, Parity Violating DIS, . . .

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

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

- 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 an on-shell nucleon

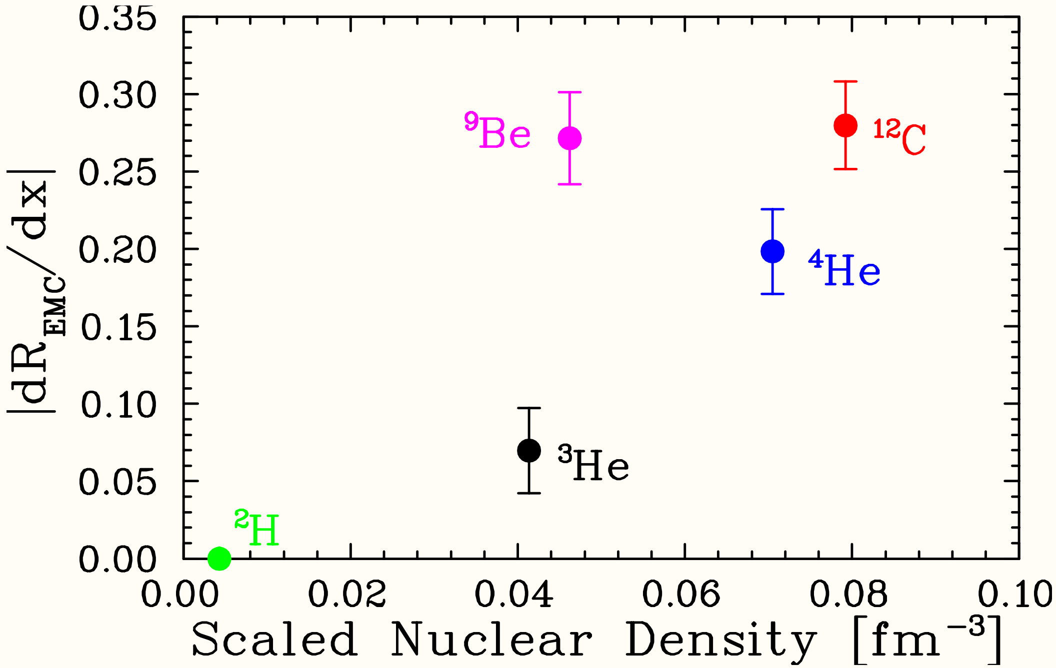
$$\langle J^\mu \rangle = \bar{u}(p') \left[\gamma^\mu \, F_1(Q^2) + \frac{1}{2M} i\sigma^{\mu\nu} q_\nu \, F_2(Q^2) \right] u(p)$$

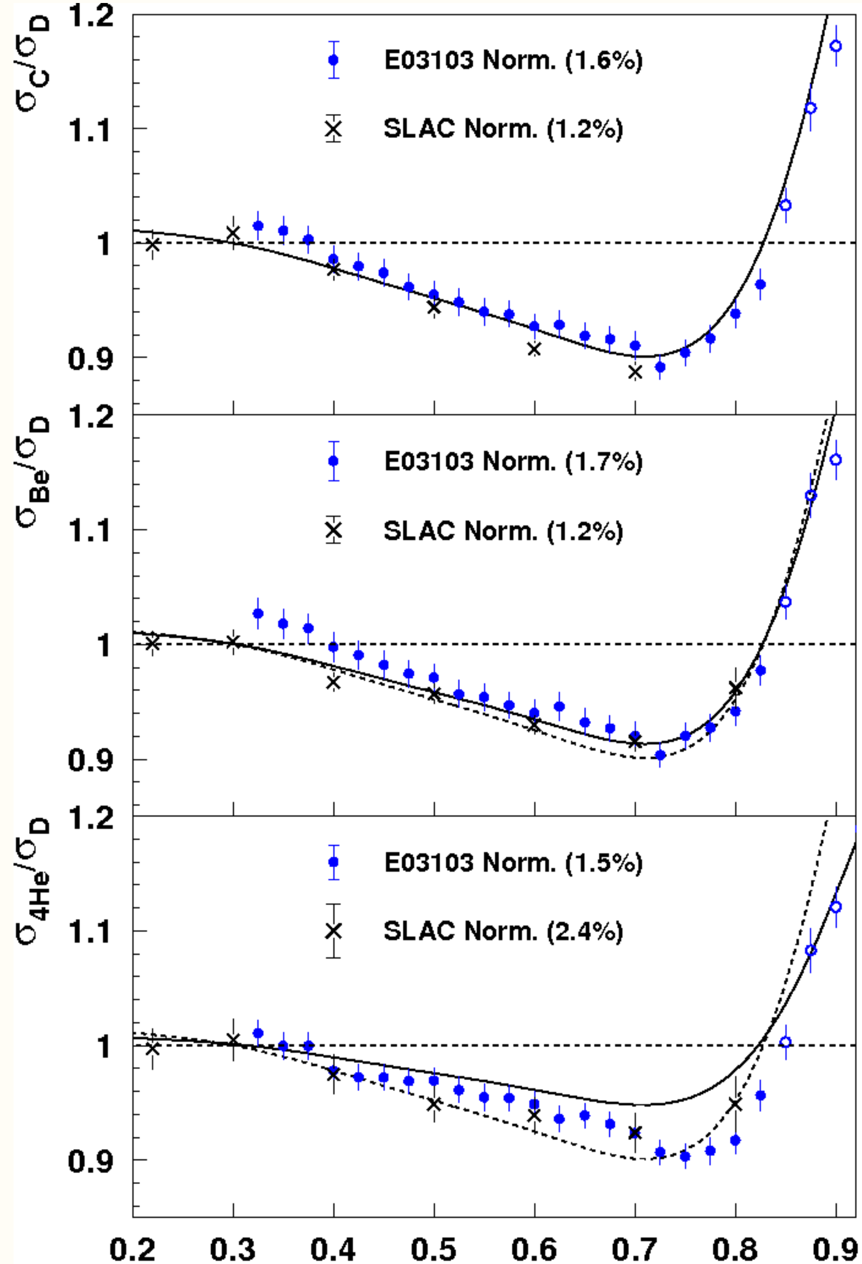
- Need to understand these effects as first step toward QCD based understanding of nuclei

EMC effect in light nuclei

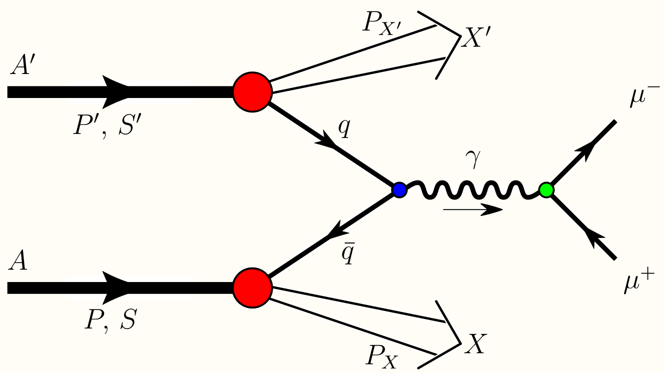
- J. Seely *et al.*, Phys. Rev. Lett. **103**, 202301 (2009).
- To confront these results need sophisticated N-body techniques
- Size of EMC effect appears to be determined by the *local density*, not the average density or A

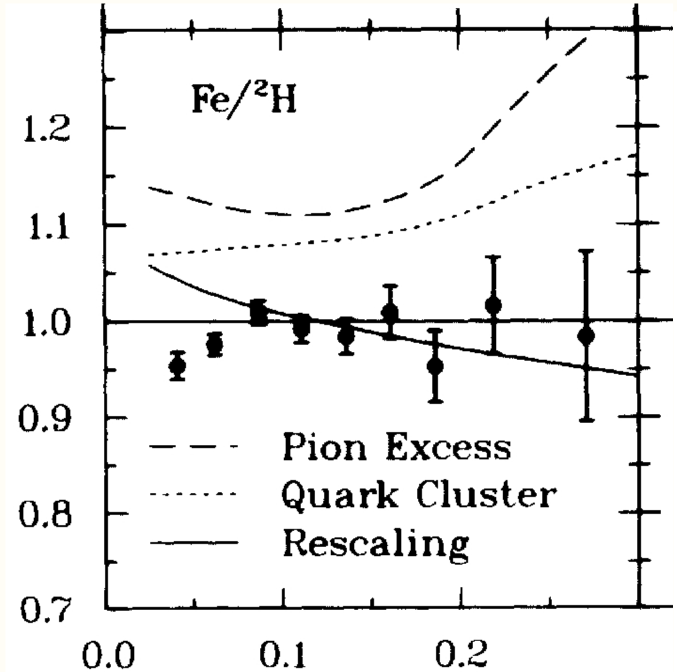
$$R_{\text{He}} \simeq R_{\text{Be}} \simeq R_{\text{C}}$$

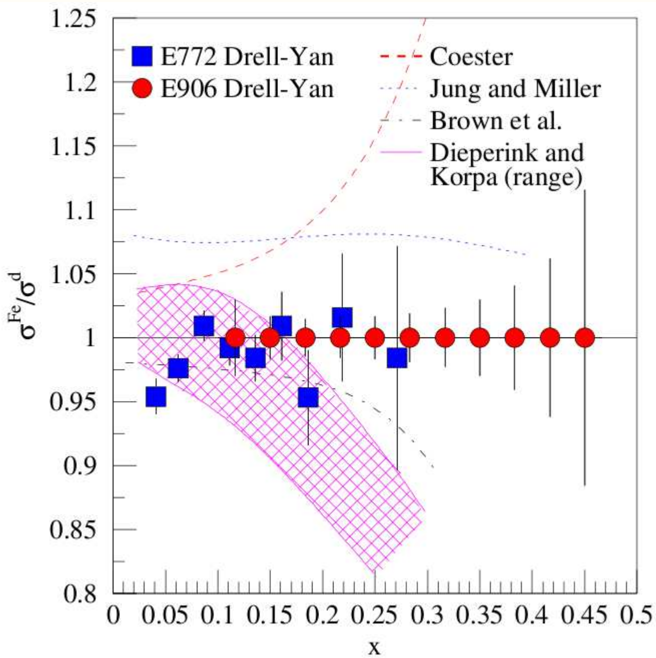




Anti-quarks in Nuclei and Drell-Yan







- Pions play a fundamental role in traditional nuclear physics
  - therefore expect pion (anti-quark) enhancement in nuclei
- Drell-Yan experiment set up to probe anti-quarks in target nucleus
  - $\bar{q}q \to \mu^+\mu^-$ – E906: running FNAL, E772: Alde *et al.*, PRL. **64**, 2479 (1990).
  - sees no pion enhancement compared to free nucleon
- Important to understand anti-quarks in nuclei: Drell-Yan & PV DIS

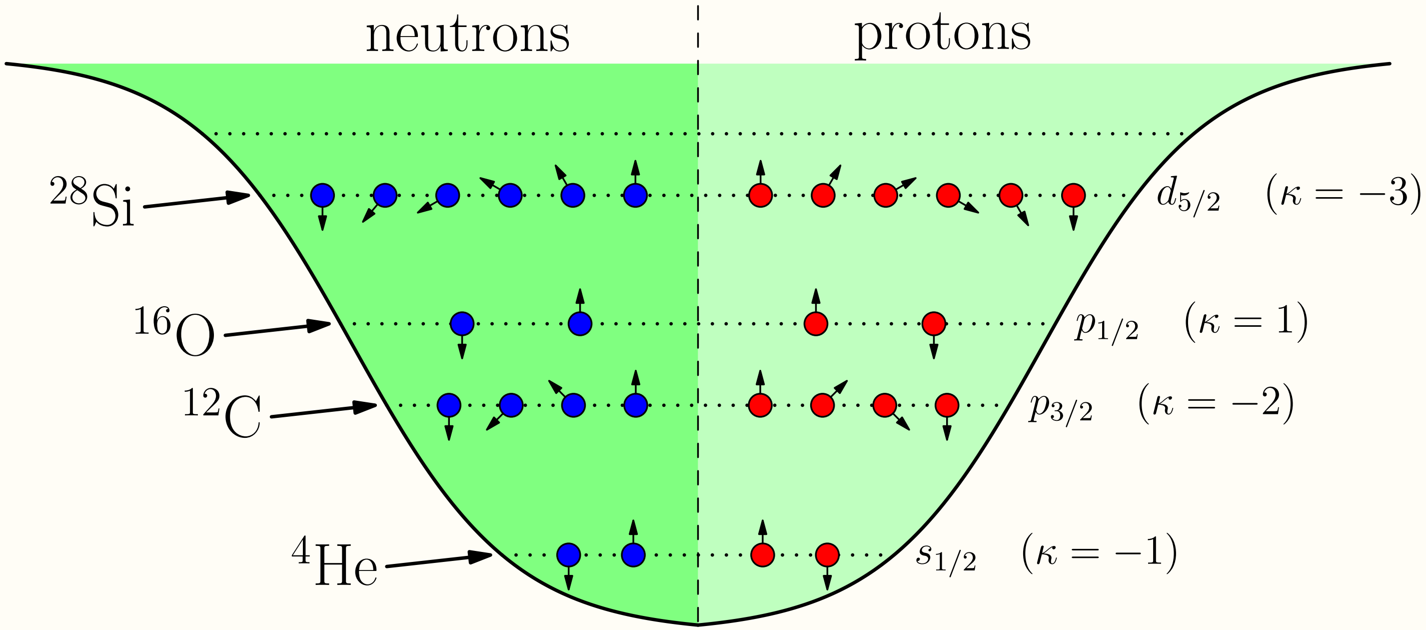
Finite nuclei quark distributions

- Definition of finite nuclei quark distributions

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

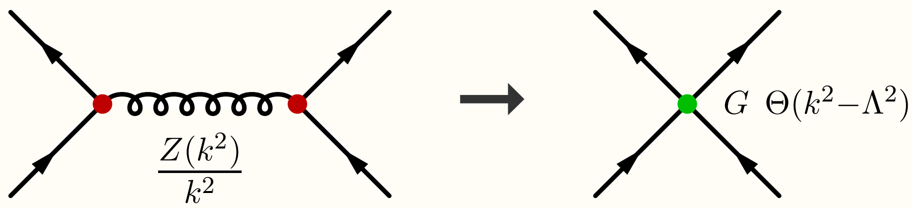
- Approximate using a modified convolution formalism

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

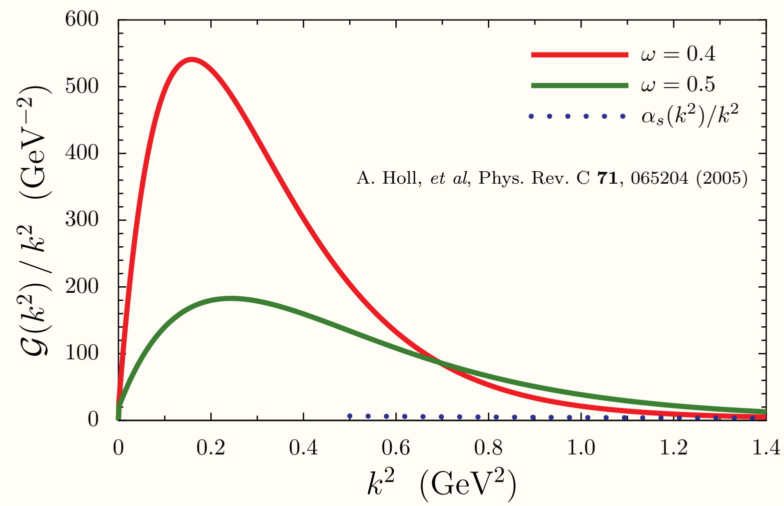


Nambu–Jona-Lasinio Model

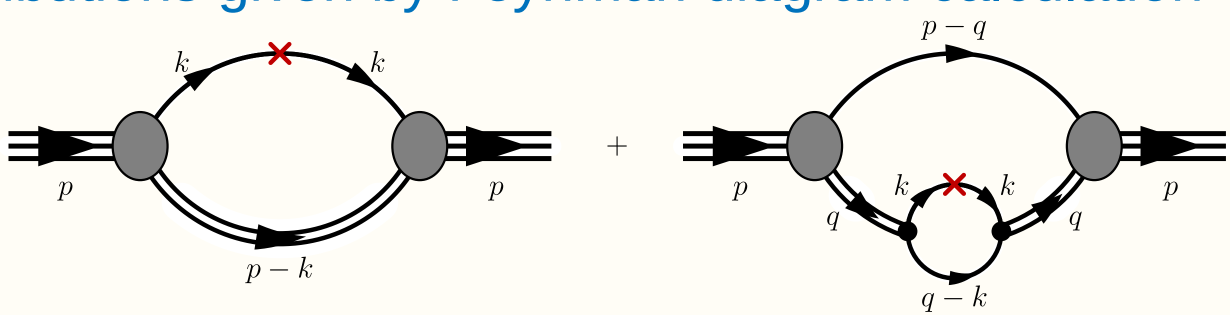
- Interpreted as low energy chiral effective theory of QCD



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

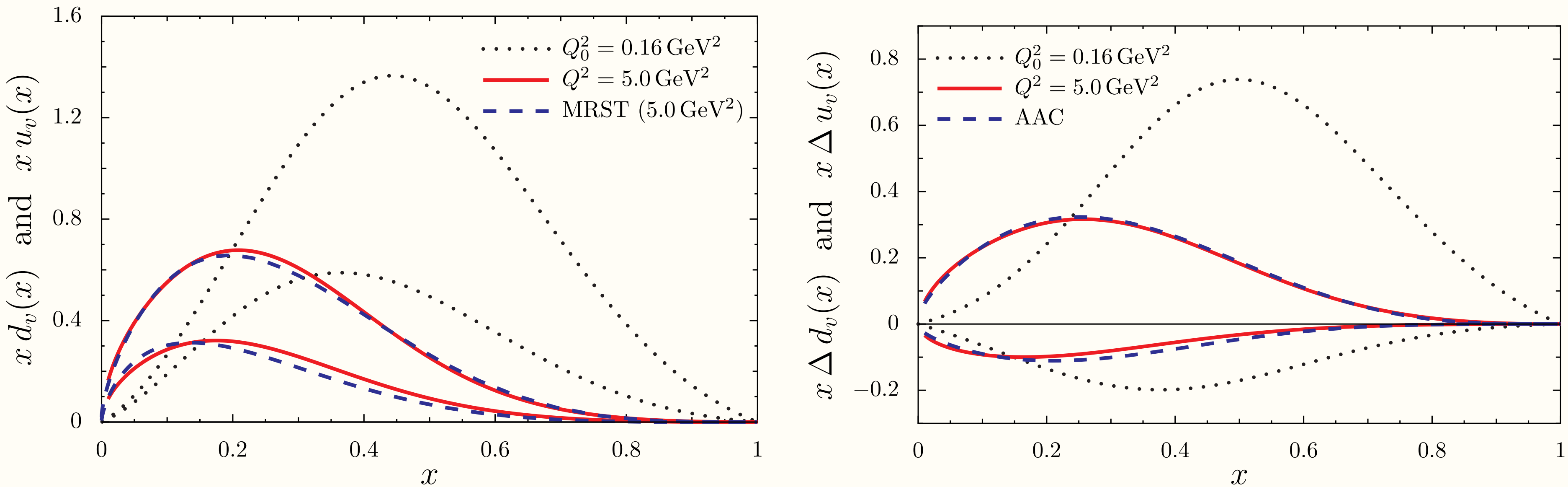


- Quark distributions given by Feynman diagram calculation



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

Results: proton quark distributions

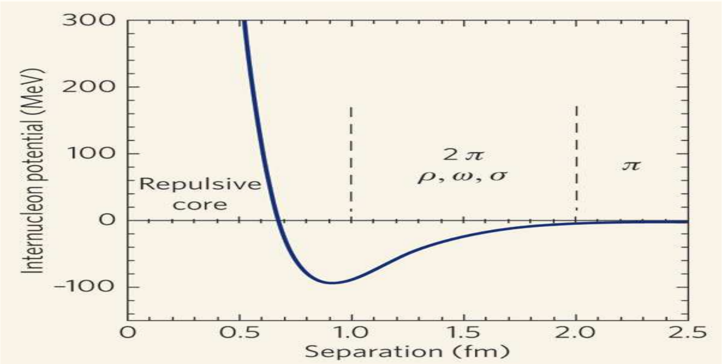


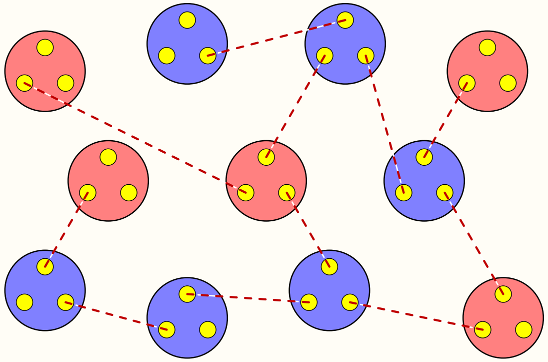
- Empirical distributions:
  - Martin, Roberts, Stirling and Thorne, Phys. Lett. B **531**, 216 (2002).
  - M. Hirai, S. Kumano and N. Saito, Phys. Rev. D **69**, 054021 (2004).
- NJL model gives good description of free nucleon quark distributions
- Approach is covariant, satisfies all sum rules & positivity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

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

- Hadronization + mean–field $\Longrightarrow$ effective potential that provides

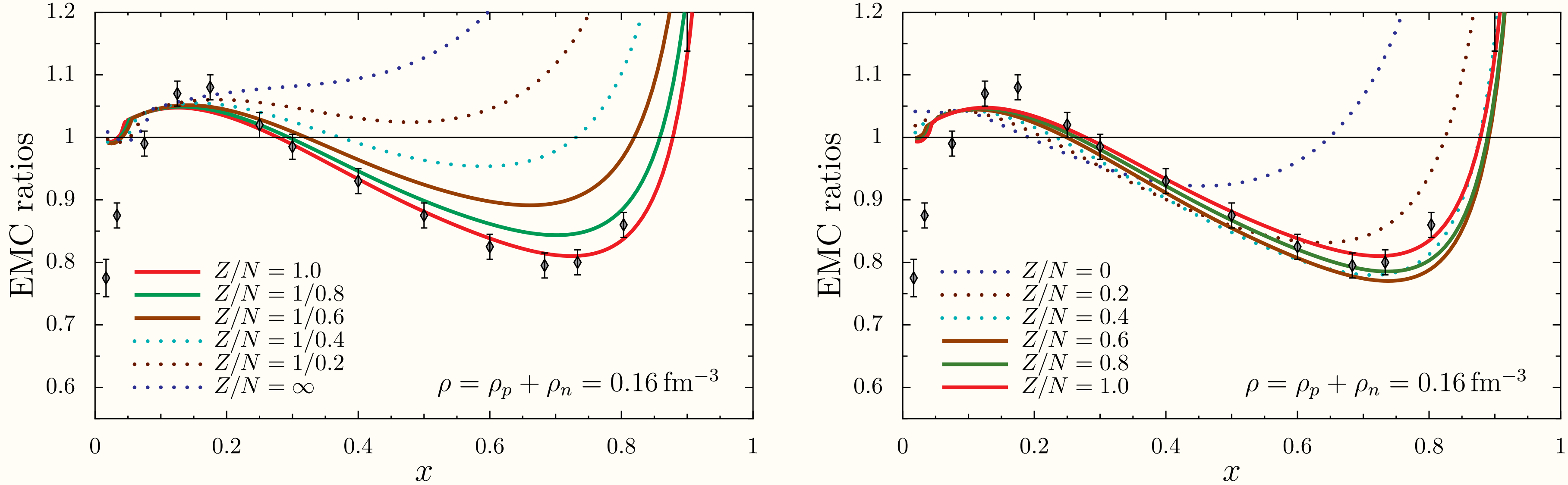
$$\omega_0 = 6\,G_\omega\,(\rho_p + \rho_n)\,, \qquad \rho_0 = 2\,G_\rho\,(\rho_p - \rho_n)\,, \qquad V_{u(d)} = \omega_0 \pm \rho_0$$

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

- Finite density quark propagator

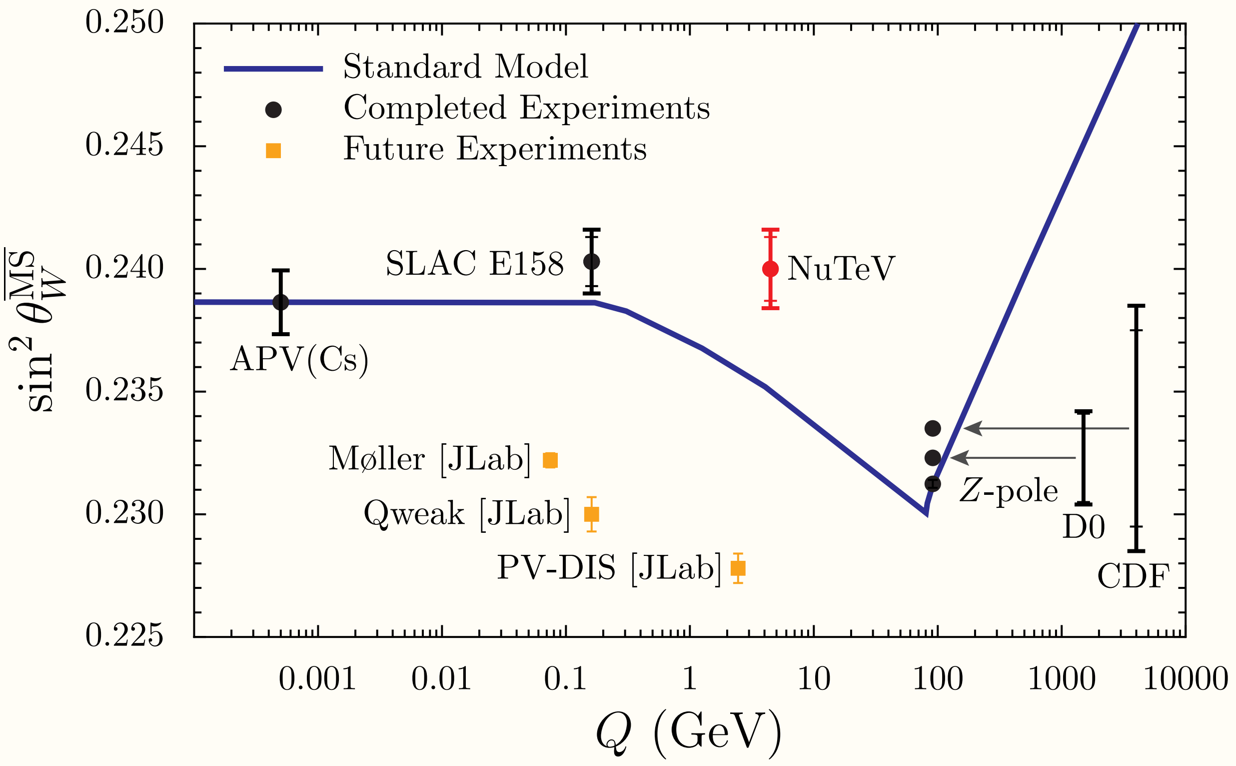
$$S(k)^{-1} = \not k - M - i\varepsilon \quad \rightarrow \quad S_q(k)^{-1} = \not k - M^* - \not V_q - i\varepsilon$$

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
- EMC effect essentially a consequence of binding at the quark level
- 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:

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

- 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

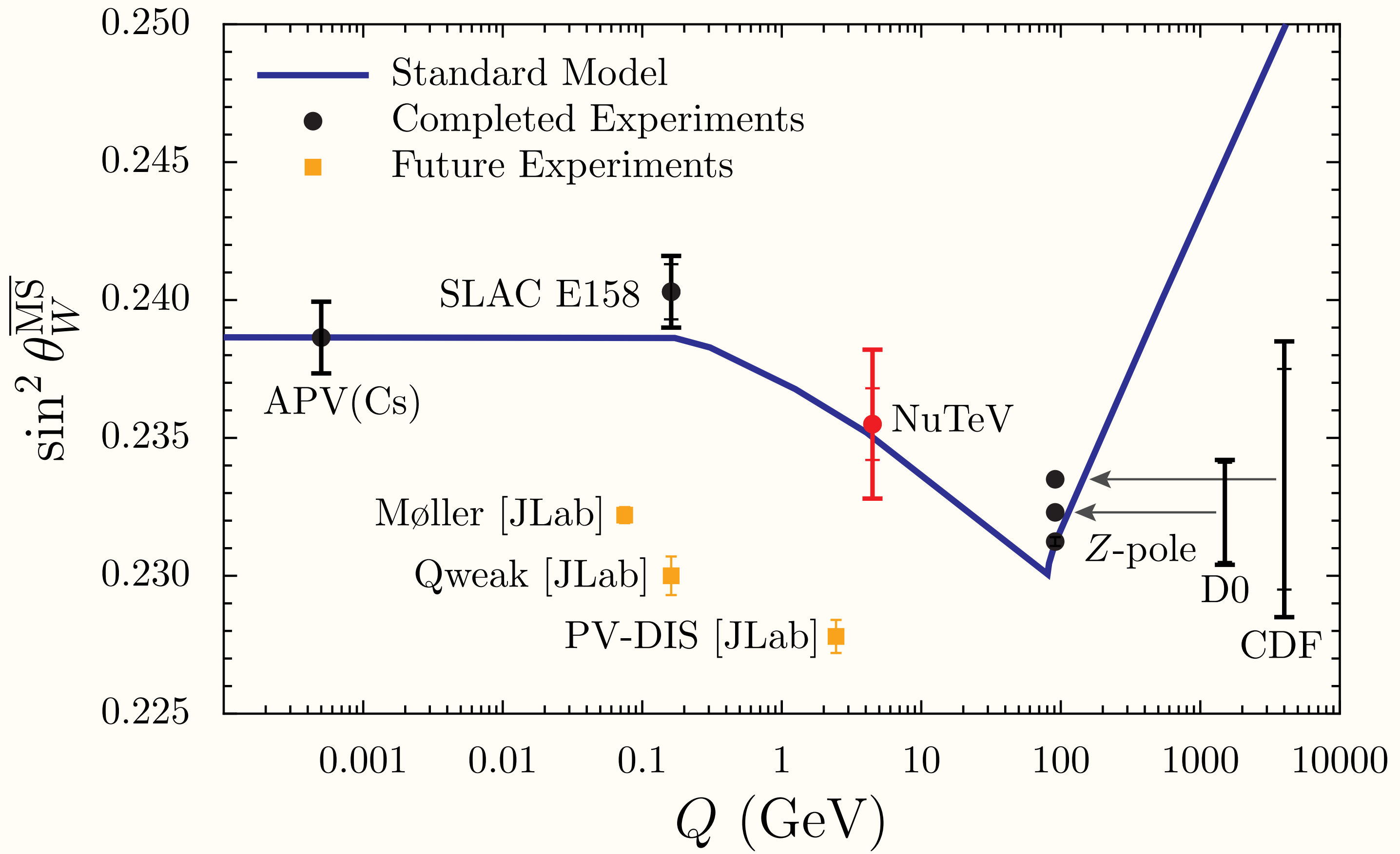
NuTeV anomaly cont'd

- 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!!

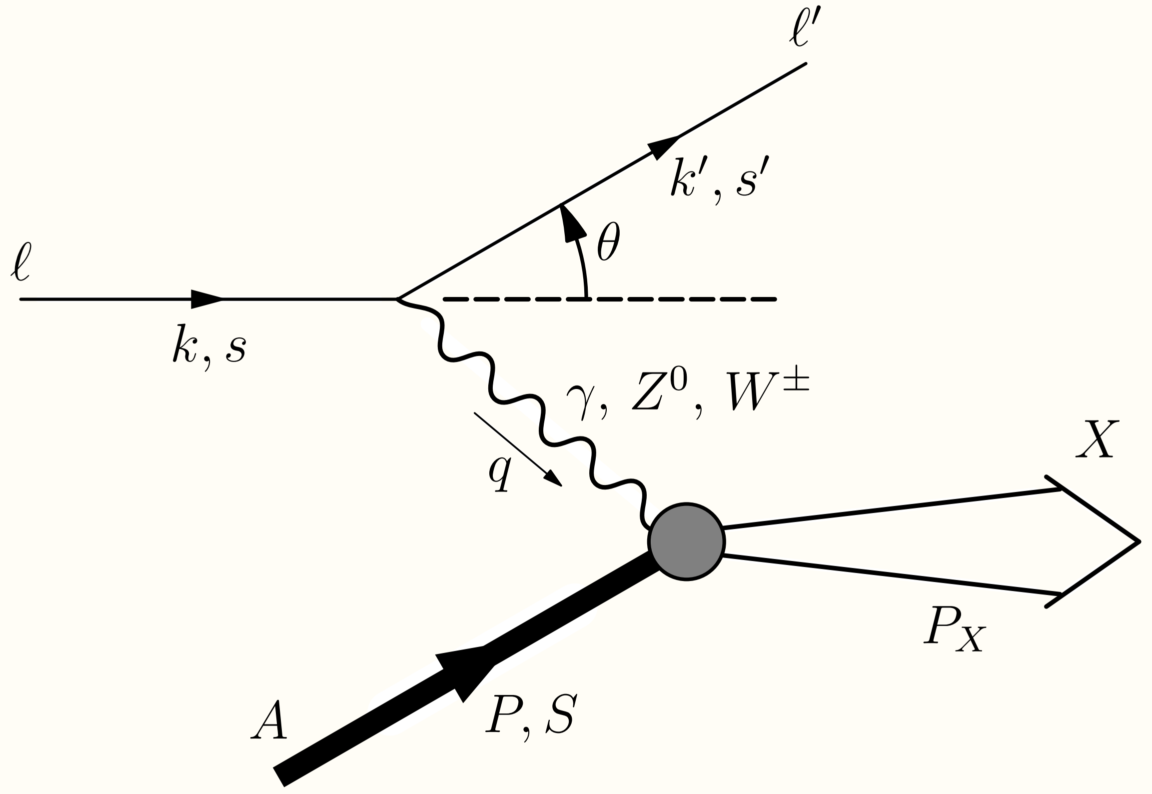
Total NuTeV correction



- 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 $\sim 1.5\sigma$ of NuTeV result
  - is this mechanism observed elsewhere?
- Yes!! Parity violating DIS: $\gamma\, Z$ interference
  - Z^0 interaction violates parity



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

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

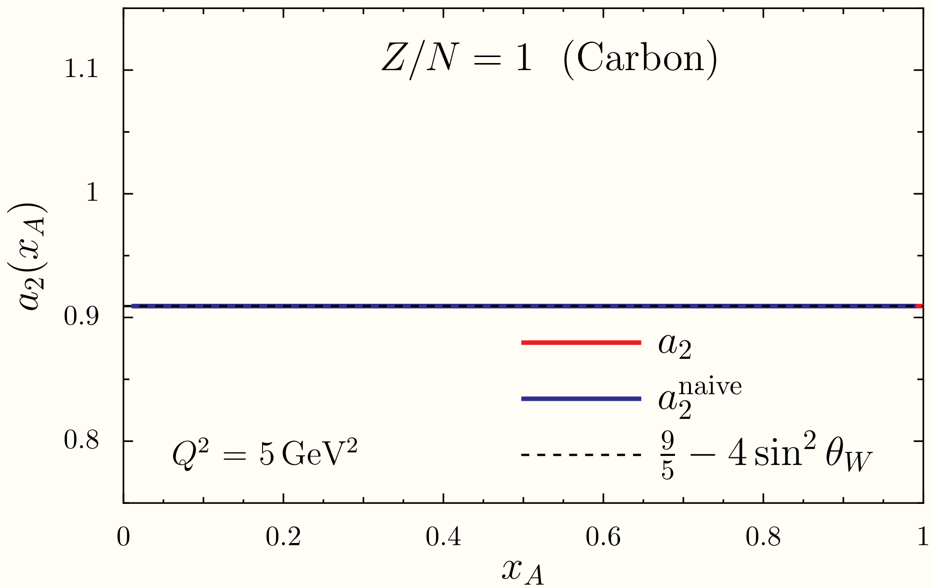
$$a_3(x) = -2g_V^e \frac{F_3^{\gamma Z}}{F_2^{\gamma}} = 3\left(1 - 4\sin^2\theta_W\right) \frac{2\,u^- + d^-}{4\,u^+ + d^+}$$

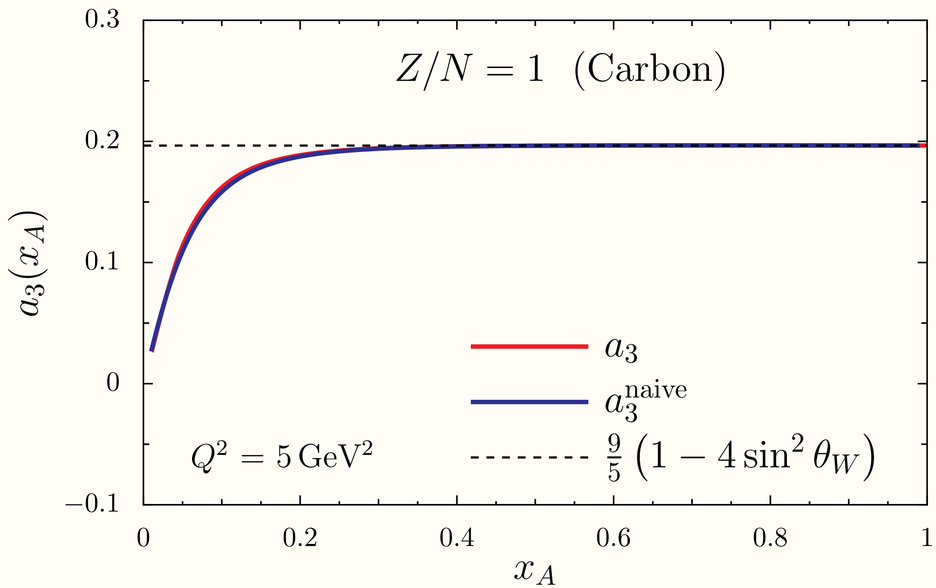
- Parton model expressions

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

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

Parity Violating DIS: Carbon





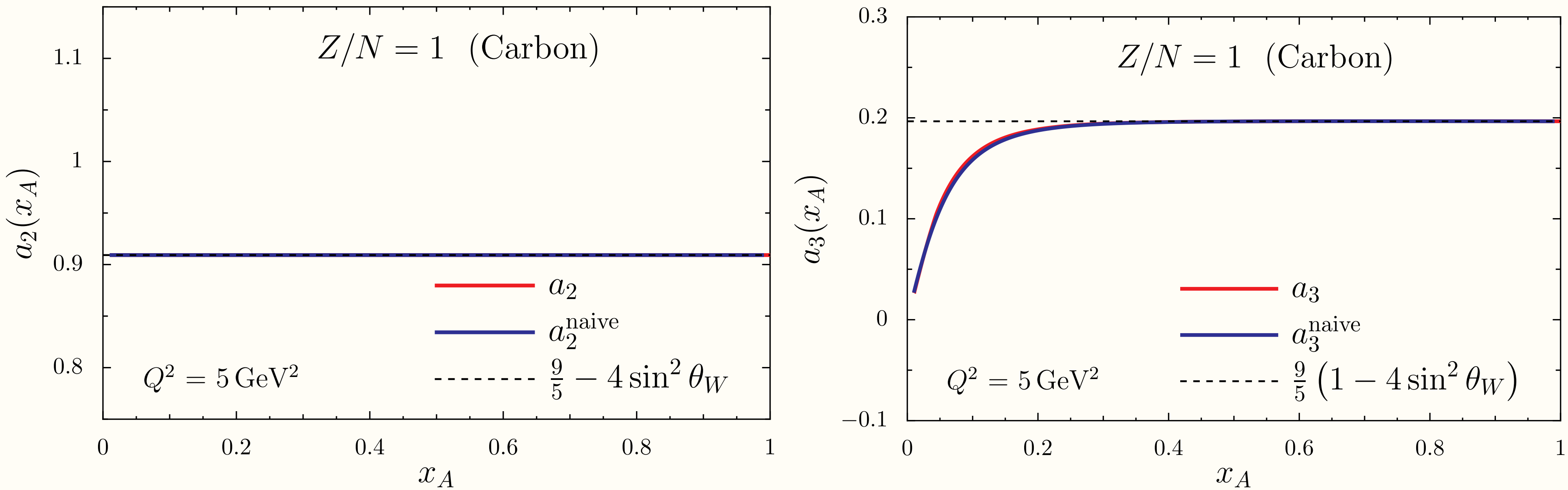
- Ignoring quark mass differences, s-quarks and EW corrections
  - For a $N = Z$ target:

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

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

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

Parity Violating DIS: Carbon



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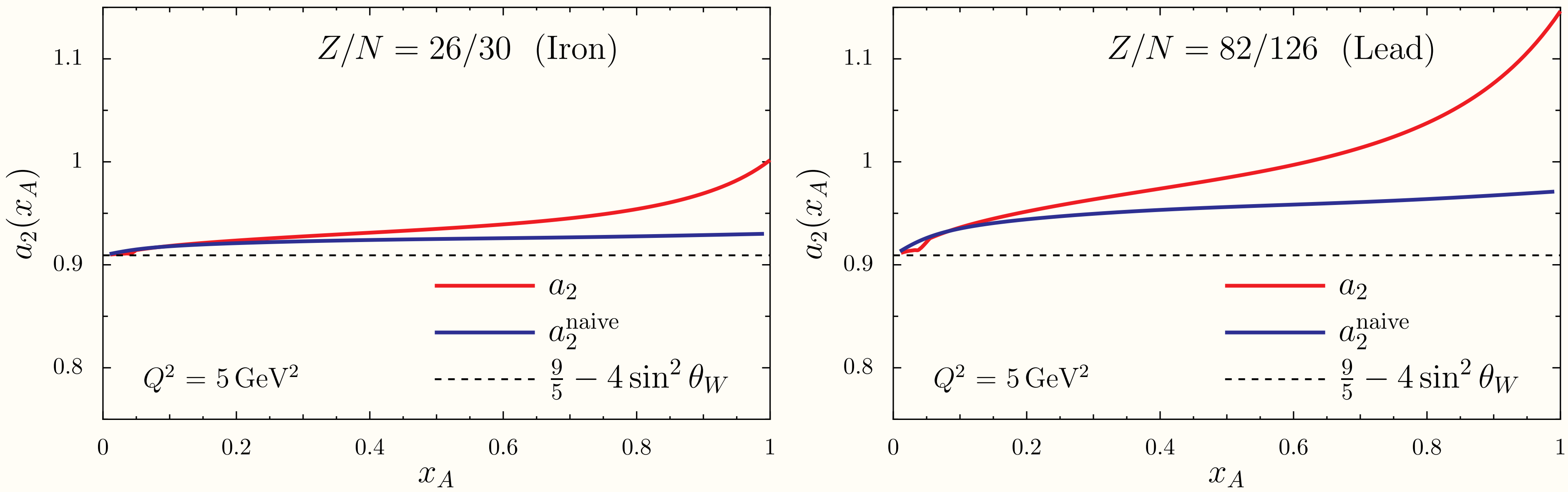
$$a_2(x) = \frac{6u_A^+ + 3d_A^+}{4\,u_A^+ + d_A^+} - 4\sin^2\theta_W \to \frac{9}{5} - 4\sin^2\theta_W$$

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

- $a_3(x)$ sensitive to anti-quarks in nuclei, complements Drell-Yan

Parity Violating DIS: Iron & Lead

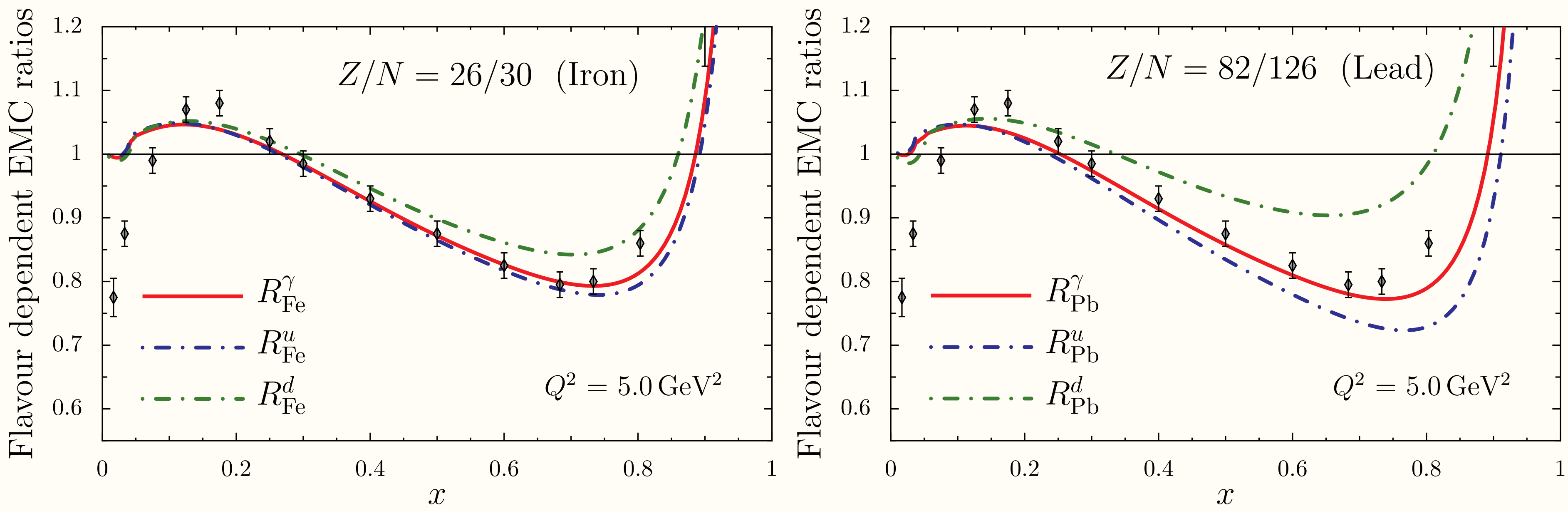


- For a $N \simeq Z$ target:

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

- “Naive” result has no medium corrections
- After naive isoscalarity corrections medium effects still very large
- Large x dependence of $a_2(x)$ → evidence for medium modification

Flavour Dependence of EMC effect



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

$$F_2^{\gamma} = \sum e_q^2\, x\,(q+\bar{q})\,, \quad F_2^{\gamma Z} = 2\sum e_q\, g_V^q\, x\,(q+\bar{q})\,, \qquad R_A^q \simeq \frac{q_A}{q_0}$$

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

Finite nuclei EMC effects

- EMC ratio

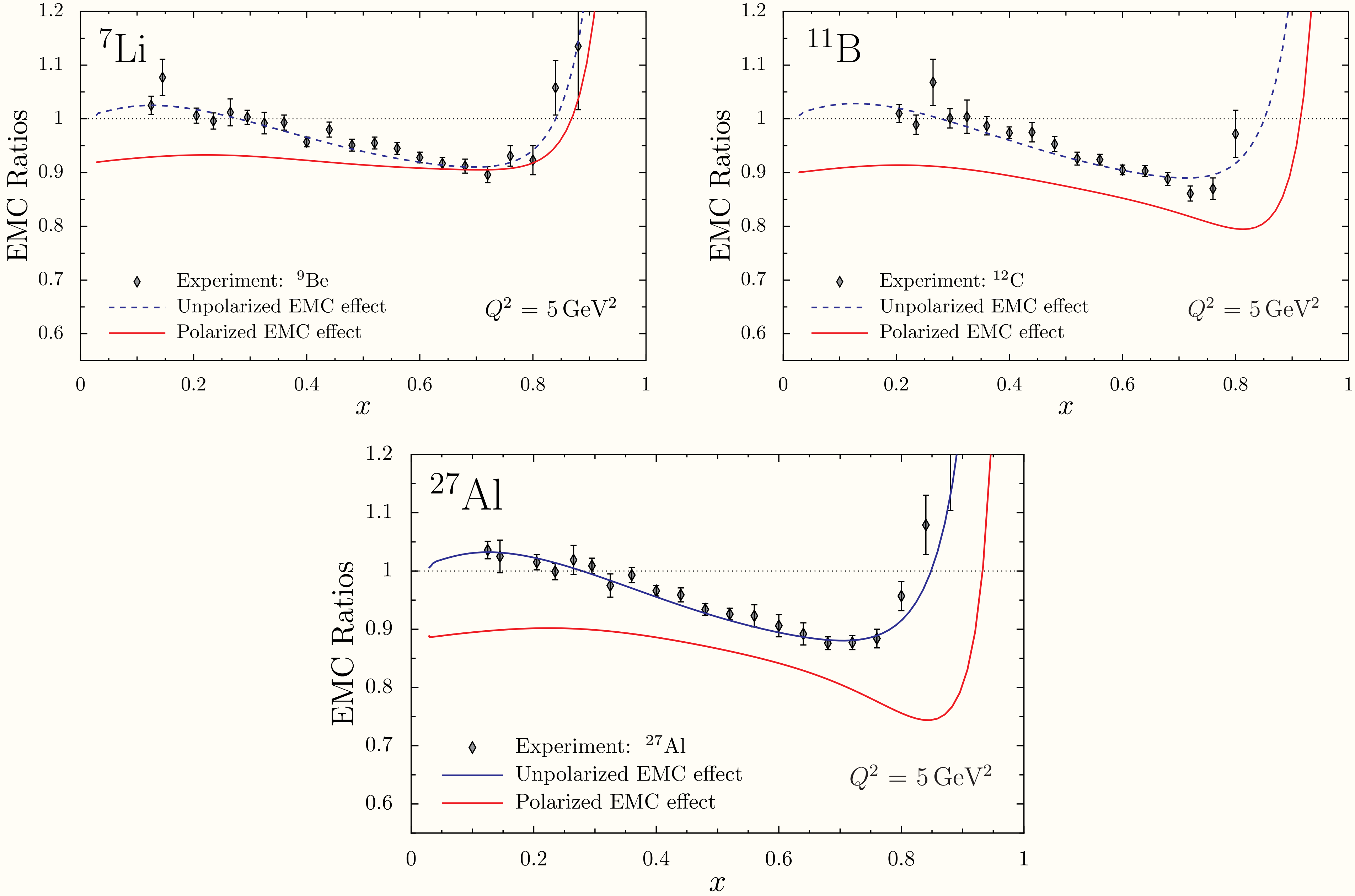
$$R = \frac{F_{2A}}{F_{2A}^{\text{naive}}} = \frac{F_{2A}}{Z\,F_{2p} + N\,F_{2n}}$$

- Polarized EMC ratio

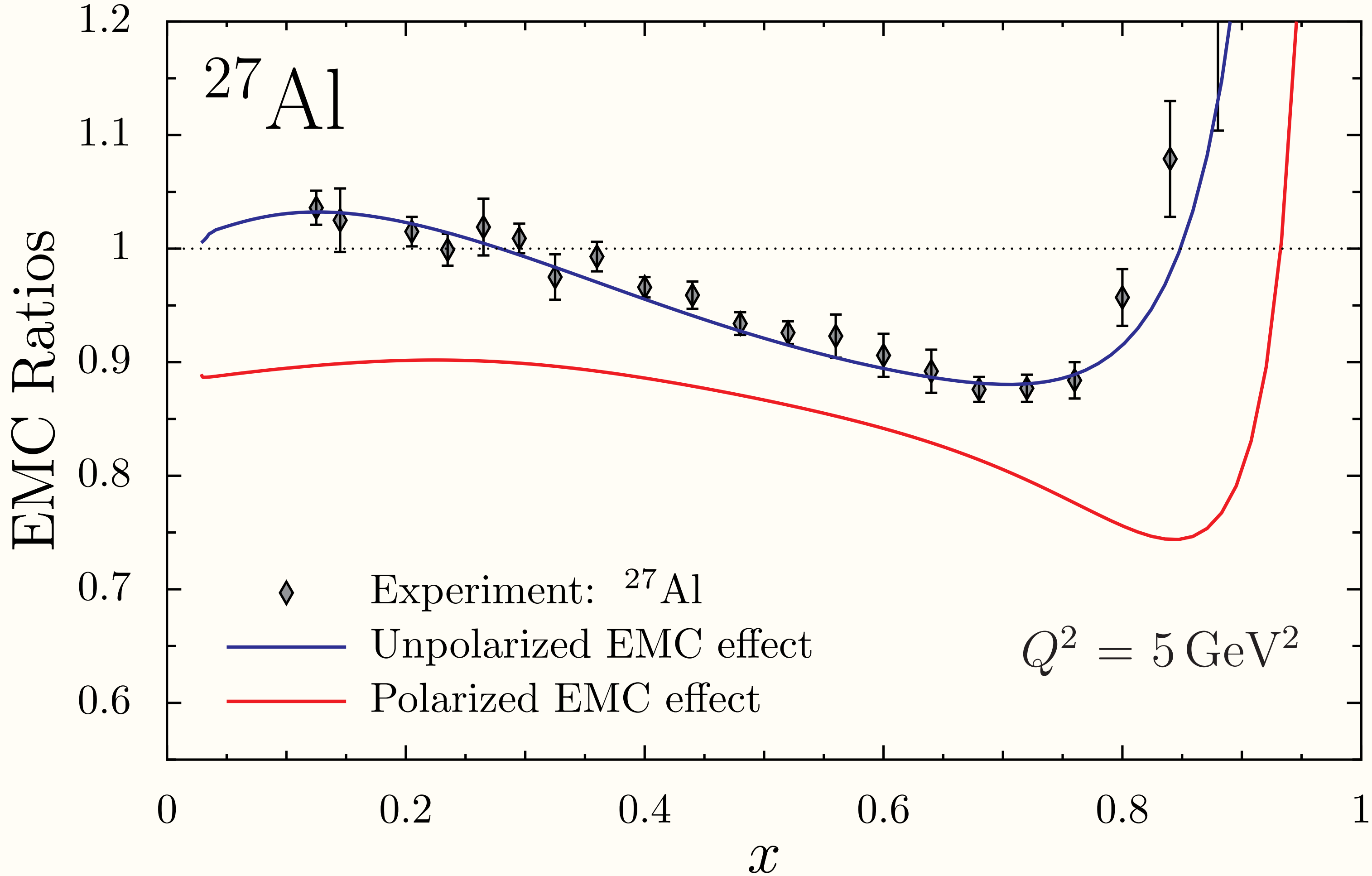
$$R_s^H = \frac{g_{1A}^H}{g_{1A}^{H,\text{naive}}} = \frac{g_{1A}^H}{P_p^H\,g_{1p} + P_n^H\,g_{1n}}$$

- 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 and ^{27}Al



Is there medium modification



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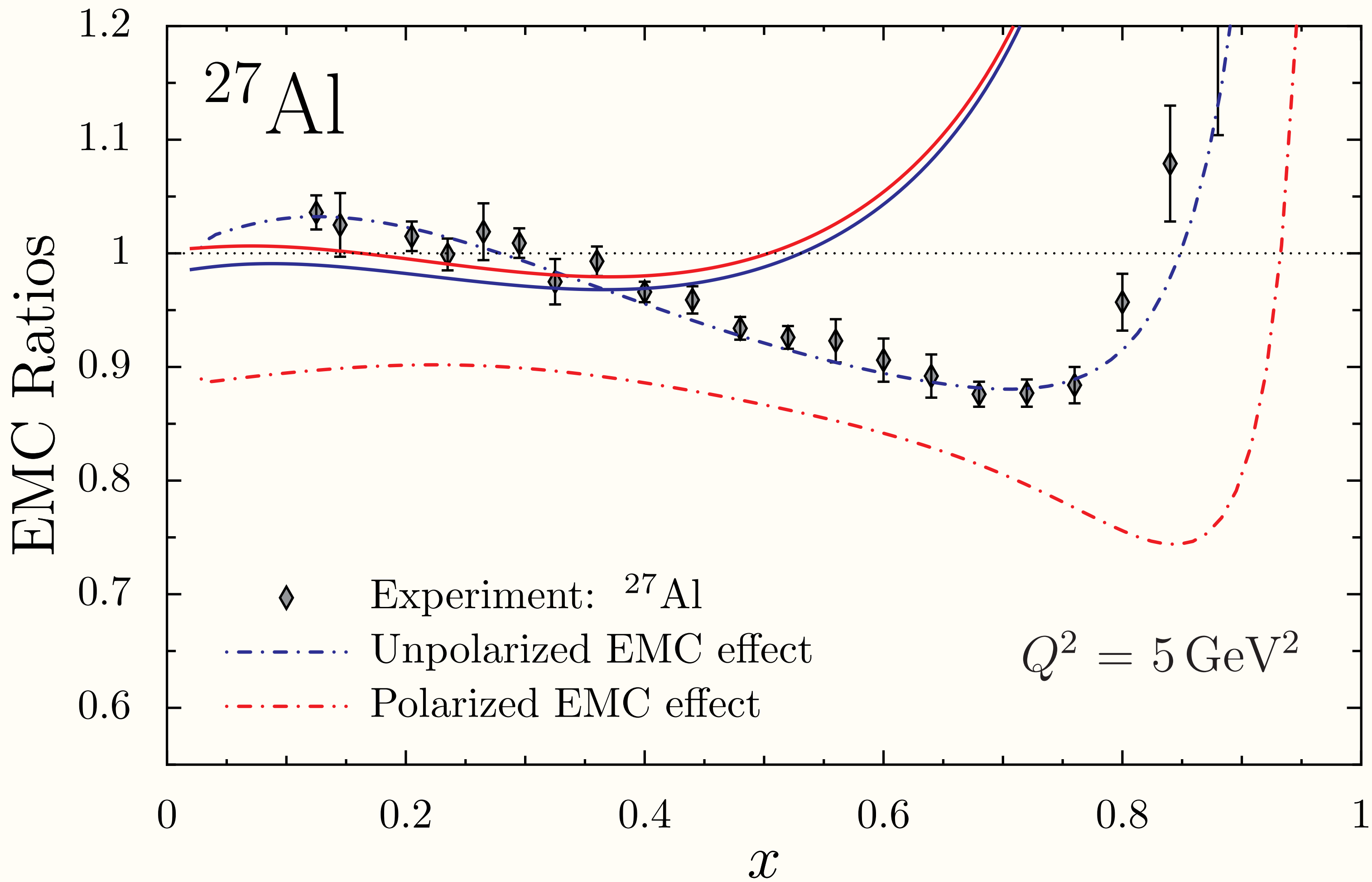

- Medium modification of nucleon has been switched off
- Relativistic effects remain
- Large splitting would be strong evidence for medium modification

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

- Illustrated the inclusion of quarks into a traditional description of nuclei
  - complementary approach to traditional nuclear physics
- EMC effect and NuTeV anomaly are interpreted as evidence for medium modification of the bound nucleon wavefunction
  - result can be tested using PV DIS
- Some important remaining challenges:
  - polarized EMC effect [quark spin converted → L_q in nuclei]
  - flavour dependence of EMC effect and anti-quarks in nuclei
- Exciting new experiments:
  - PV DIS, pion induced Drell-Yan, neutron knockout
- Significant omissions: quasi-elastic scattering
  - in-medium form factors [Strauch], Coulomb sum rule [Meziani], etc
- Slowly building a QCD based understanding of nuclear structure