Nuclear EMC effect

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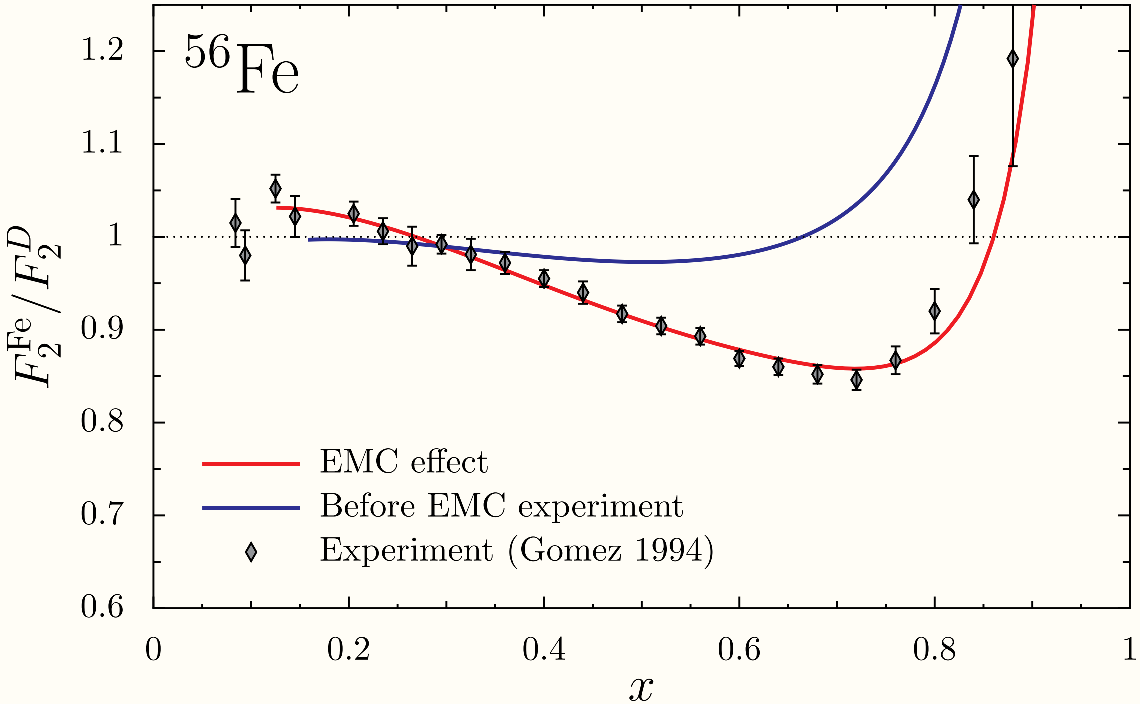
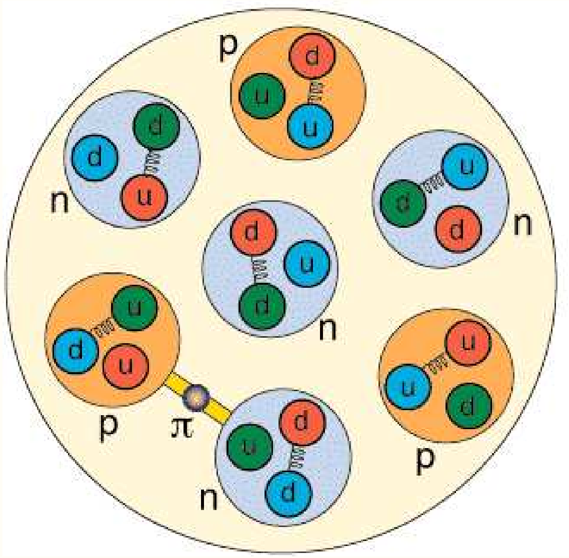
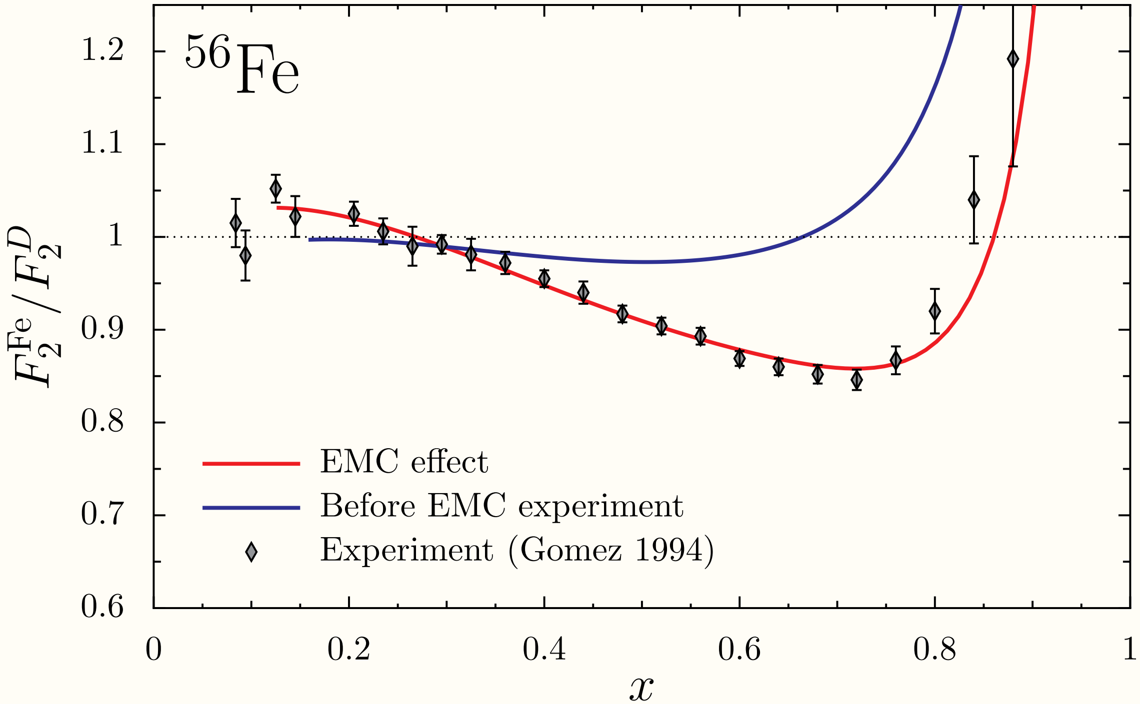
EMC Effect

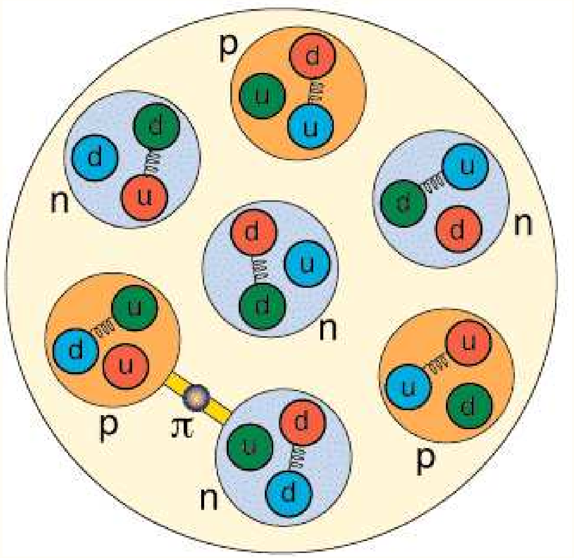




- J. J. Aubert *et al.* [European Muon Collaboration], Phys. Lett. B **123**, 275 (1983).
- Fundamentally challenged our understanding of nuclei
- Immediate parton model interpretation:
  - valence quarks in nucleus carry less momentum than in nucleon
- What is the mechanism? After more than 25 years no consensus
- *nuclear structure, pions, 6 quark bags, rescaling, medium modification*

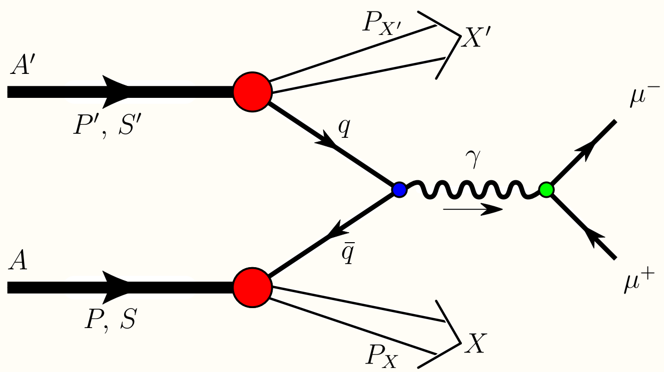
EMC Effect

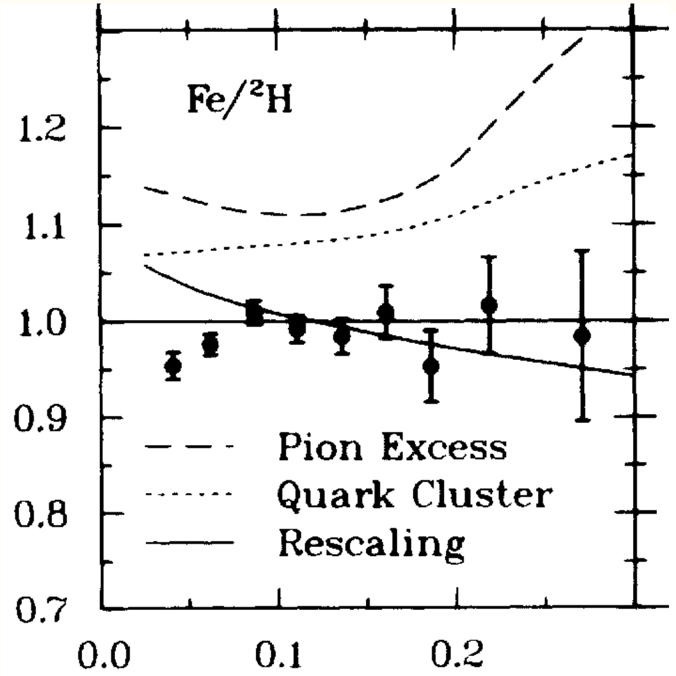


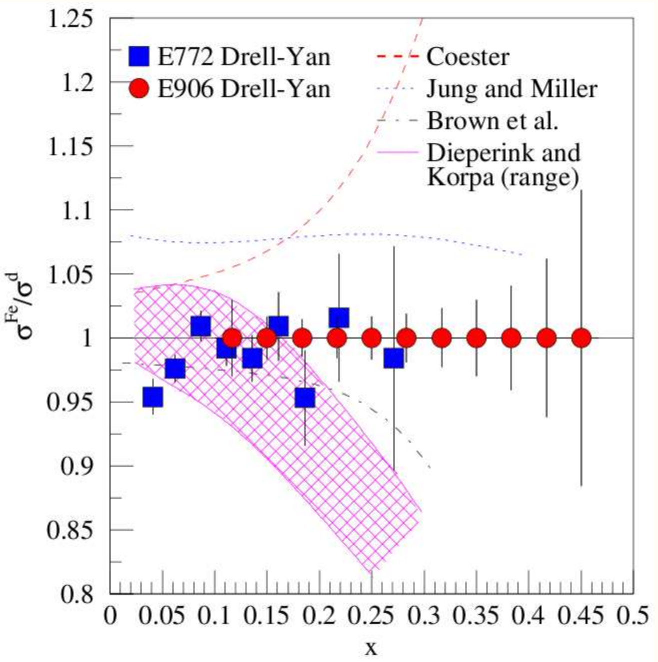


- Understanding EMC effect critical for QCD based description of nuclei
- Need new experiments accessing different aspects of the EMC effect
- Important near term measurements
  - flavour decomposition & spin dependence of nuclear PDFs
- New experiments
  - SIDIS, parity violating DIS, polarized DIS, νDIS, Drell-Yan

Anti-quarks in Nuclei and Drell-Yan



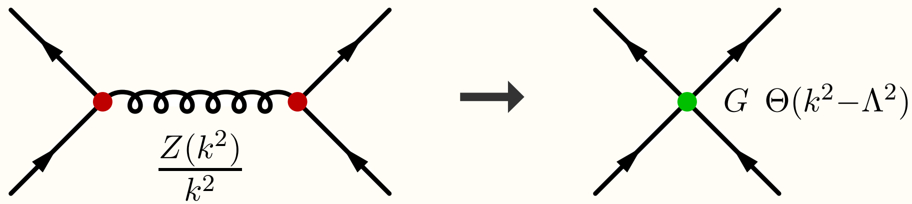




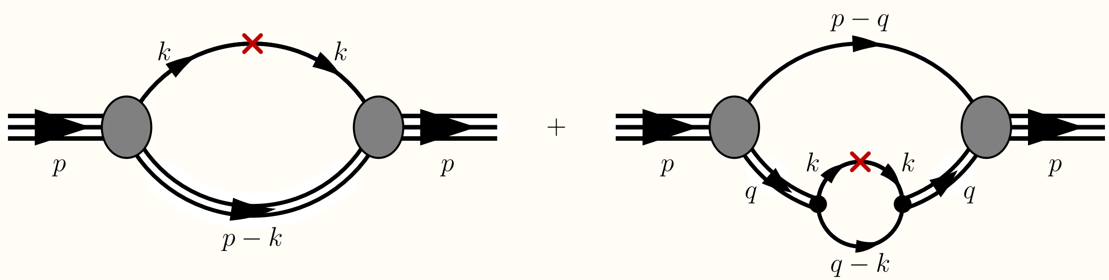
- Pions play a fundamental role in traditional nuclear physics
  - therefore expect pion (anti-quark) enhancement in nuclei
- Drell-Yan experiment set up to probe anti-quarks in target nucleus
  - $\bar{q}q \to \mu^+\mu^-$ – E906: run ∼2011 FNAL, E772: Alde *et al.*, PRL. **64**, 2479 (1990).
  - no pionic enhancement – very unexpected – energy loss?
- Important to understand anti-quarks in nuclei: Drell-Yan & PV DIS

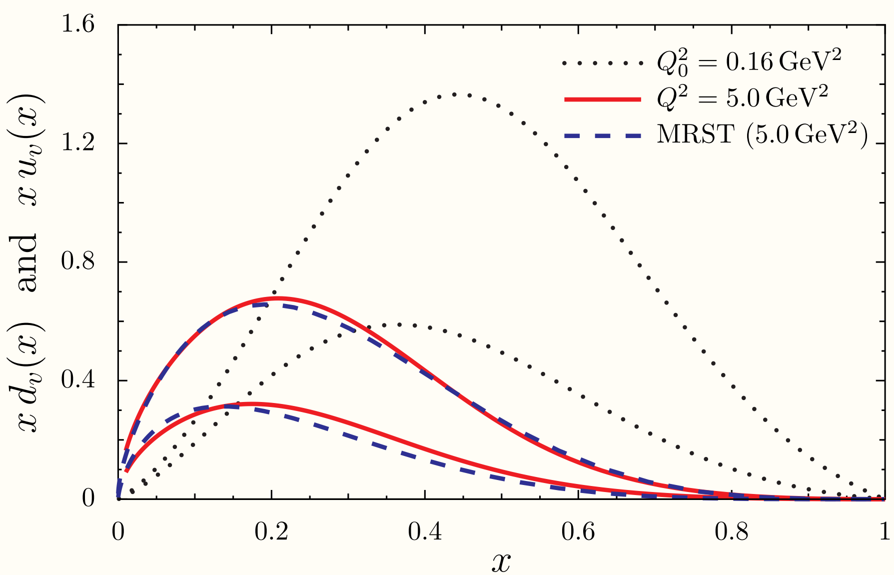
Nambu–Jona-Lasinio Model and PDFs

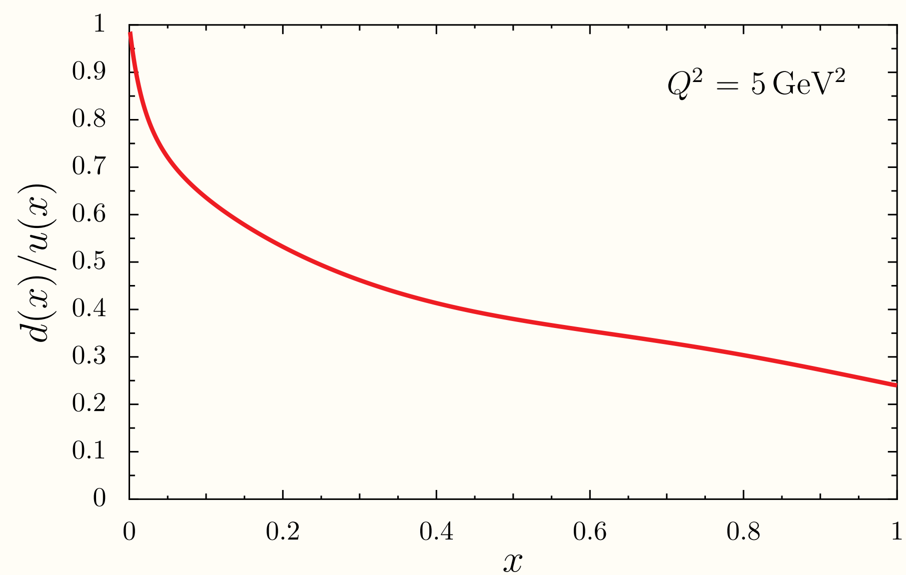
- NJL model interpreted as low energy chiral effective theory of QCD



- Quark distributions given by Feynman diagram calculation

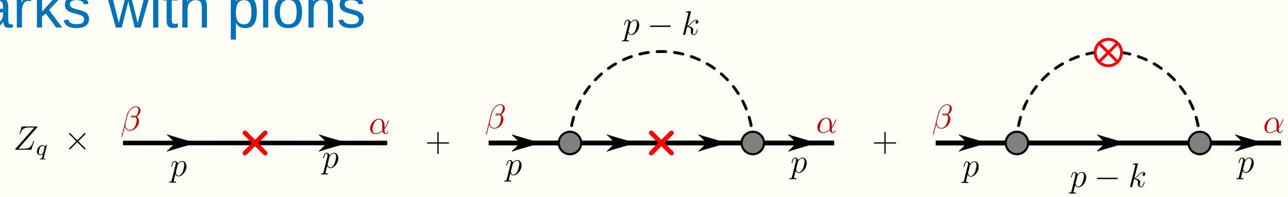


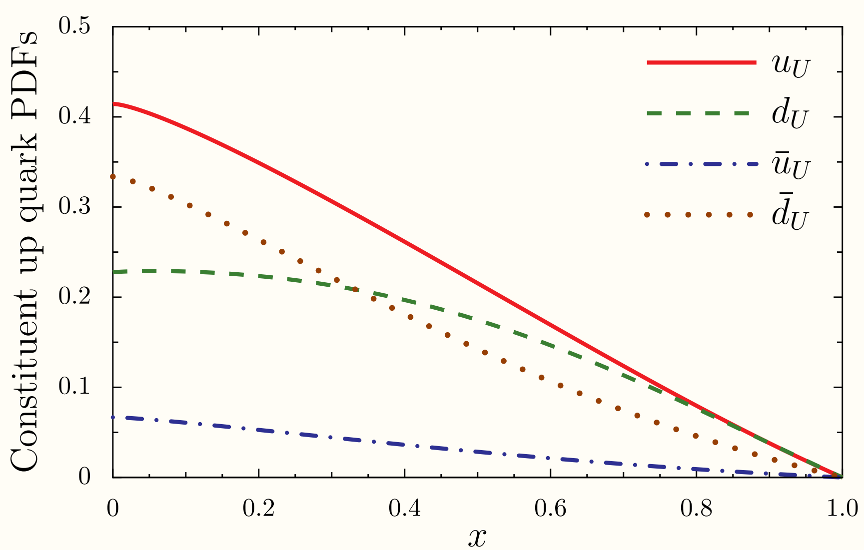


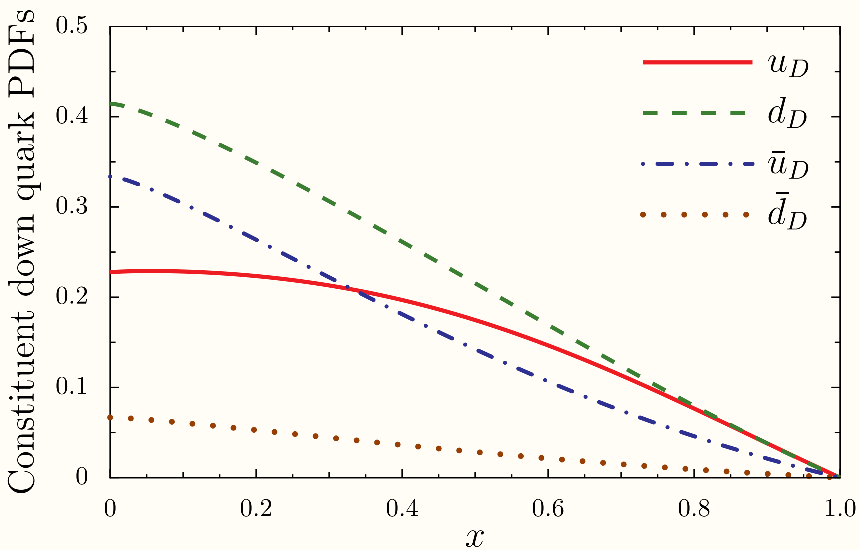


Constituent Quark PDFs

- Dress quarks with pions







- Gottfried Sum Rule: NMC 1994: $S_G = 0.258 \pm 0.017\ [Q^2 = 4\,\text{GeV}^2]$

$$S_G = \int_0^1 \frac{dx}{x}\,[F_{2p}(x) - F_{2n}(x)] = \frac{1}{3} - \frac{2}{3}\int_0^1 dx\,\left[\bar{d}(x) - \bar{u}(x)\right]$$

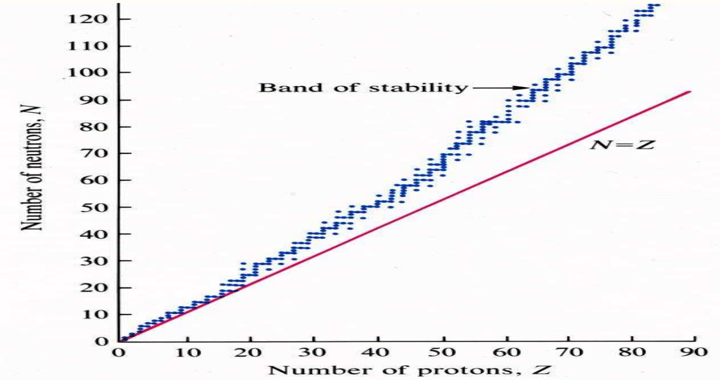
- We find: $S_G = \frac{1}{3} - \frac{4}{9}(1 - Z_q) = 0.252 \qquad [Z_q = 0.817]$

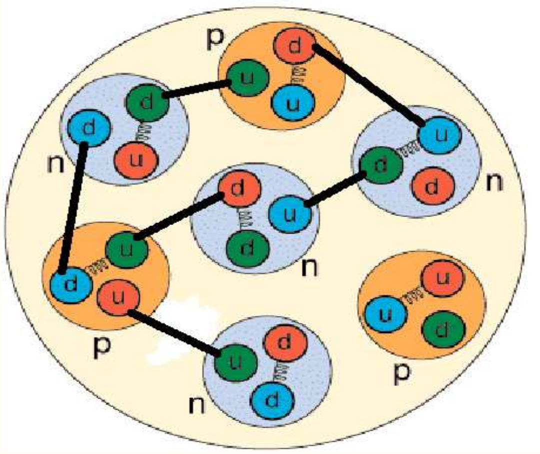
Asymmetric Nuclear Matter

- Finite density Lagrangian: $\bar{q}q$ interaction in $\sigma,\ \omega,\ \rho$ channels

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

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





- Finite density quark propagator

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

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

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

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

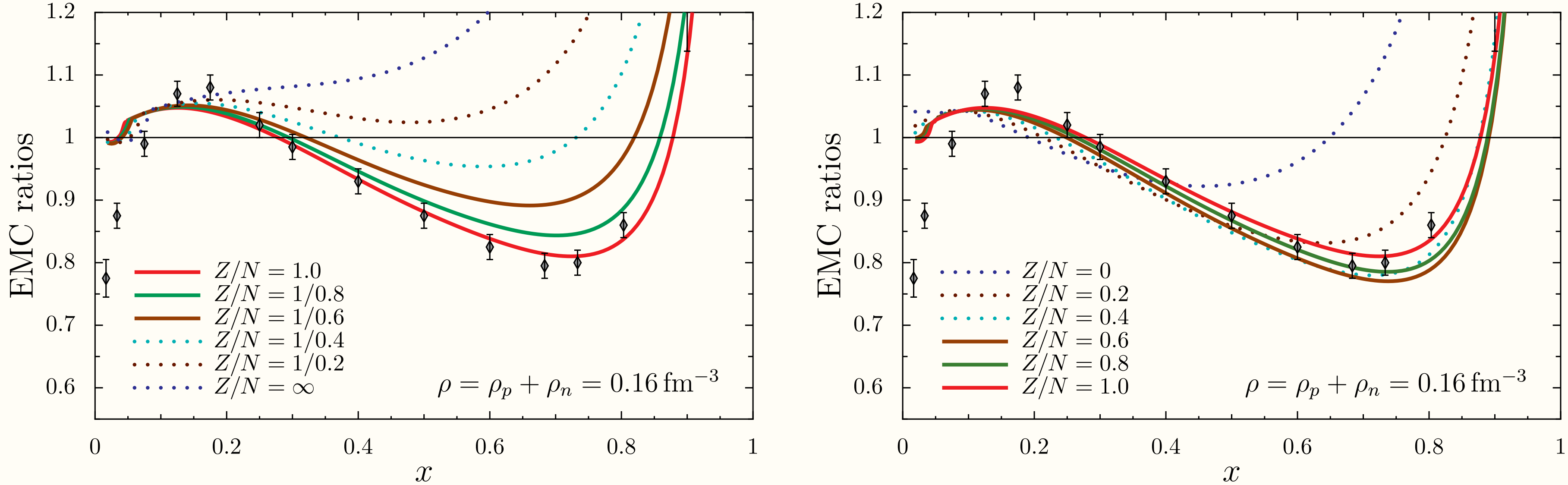
Model Independent Results?

- The effect of vector-field is model independent under assumptions
  - quarks feel nuclear medium
  - struck quark does not feel vector-field (asymptotic freedom)
- Result [Thomas 1998, Bentz 2003, Miller 2005]

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

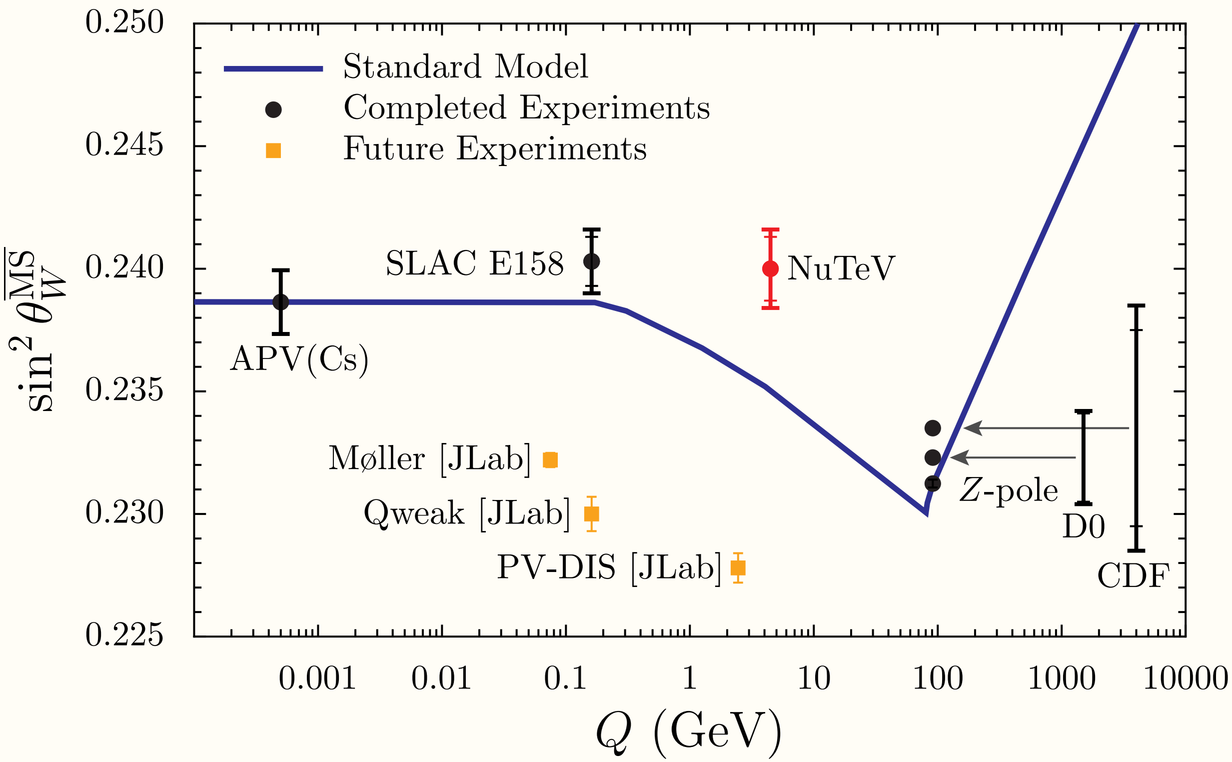
- All medium modification models should obey this result
- Important observation
  - For $N > Z$ ρ^0-field $\implies$ $V_d > V_u$
  - ρ^0-field shifts momentum from u- to d-quarks
- As we will see this result has important testable consequences
  - large flavour dependence of EMC effect for $N > Z$ nuclei

Isovector EMC effect



- EMC ratio: $$R = \frac{F_{2A}}{F_{2A,\text{naive}}} = \frac{F_{2A}}{Z\,F_{2p} + N\,F_{2n}} \simeq \frac{4\,u_A(x) + d_A(x)}{4\,u_f(x) + d_f(x)}$$
- Density is fixed only changing Z/N ratio
- EMC effect essentially a consequence of binding at the quark level
- proton excess: u-quarks feel more repulsion than d-quarks $(V_u > V_d)$
- neutron excess: d-quarks feel more repulsion than u-quarks $(V_d > V_u)$

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 $s_A \ll u_A + d_A$

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

- NuTeV "measured" R_{PW} on an Fe target ($Z/N \simeq 26/30$)
- Correct for neutron excess $\Leftrightarrow$ flavour dependent EMC effect
- Use our medium modified "Fe" quark distributions

$$\Delta R_{PW} = \Delta R_{PW}^{\text{naive}} + \Delta R_{PW}^{\text{Fermi}} + \Delta R_{PW}^{\rho^0} = -\,(0.0107 + 0.0004 + 0.0028)\,.$$

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

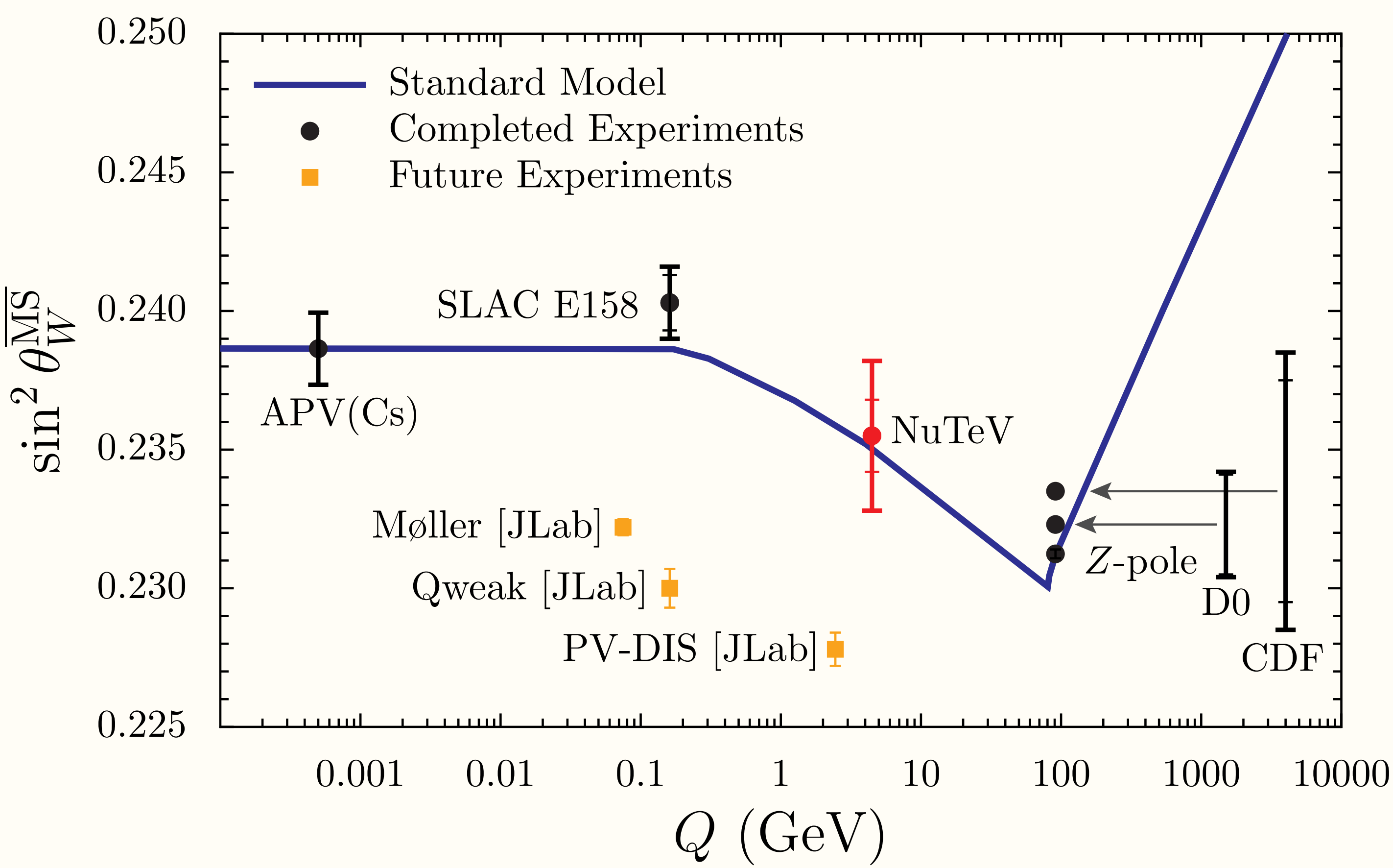
NuTeV anomaly cont'd

- 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

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

  - 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

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

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

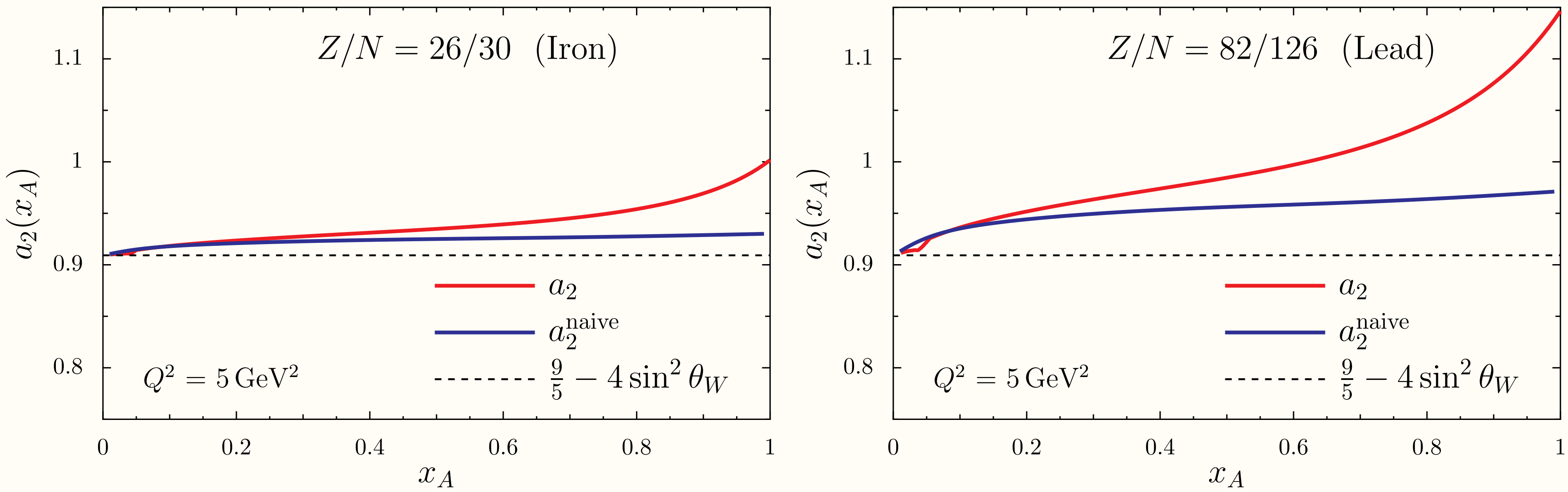
$$a_3(x) = -2g_V^e\, \frac{F_3^{\gamma Z}}{F_2^{\gamma}} = 3\left(1 - 4\sin^2\theta_W\right) \frac{2\,u^- + d^-}{4\,u^+ + d^+}$$

- 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: Iron & Lead

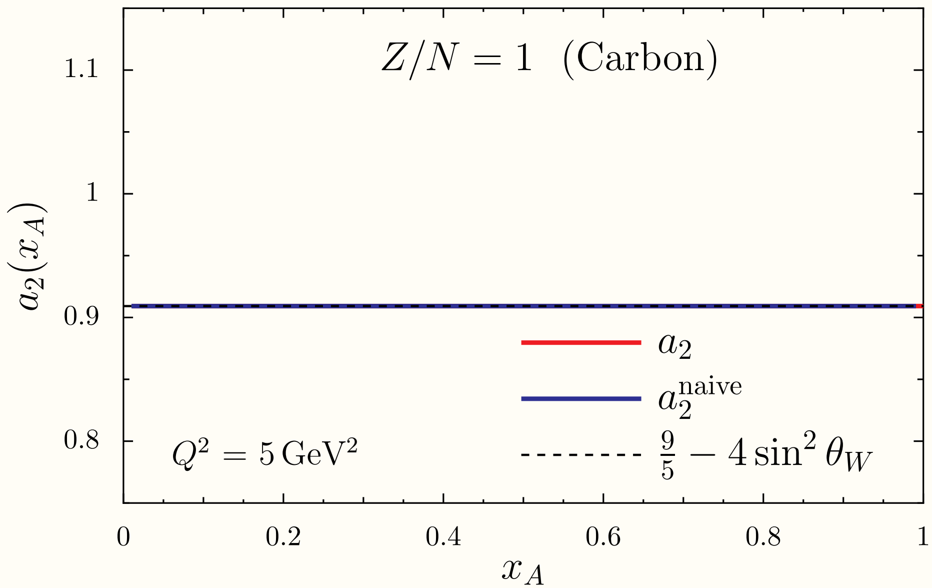


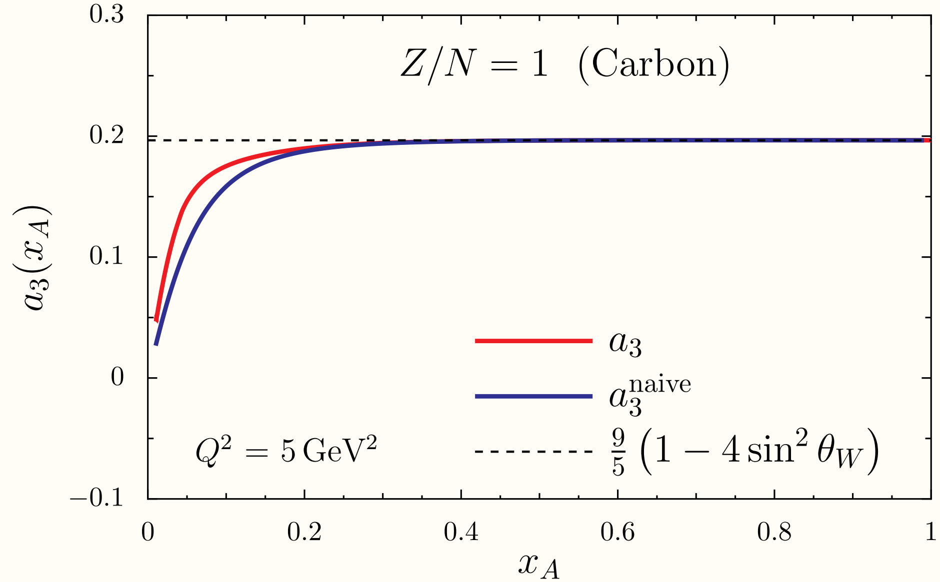
- For a $N \simeq Z$ target:

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

- “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

PVDIS: Carbon (with anti-quarks) Preliminary





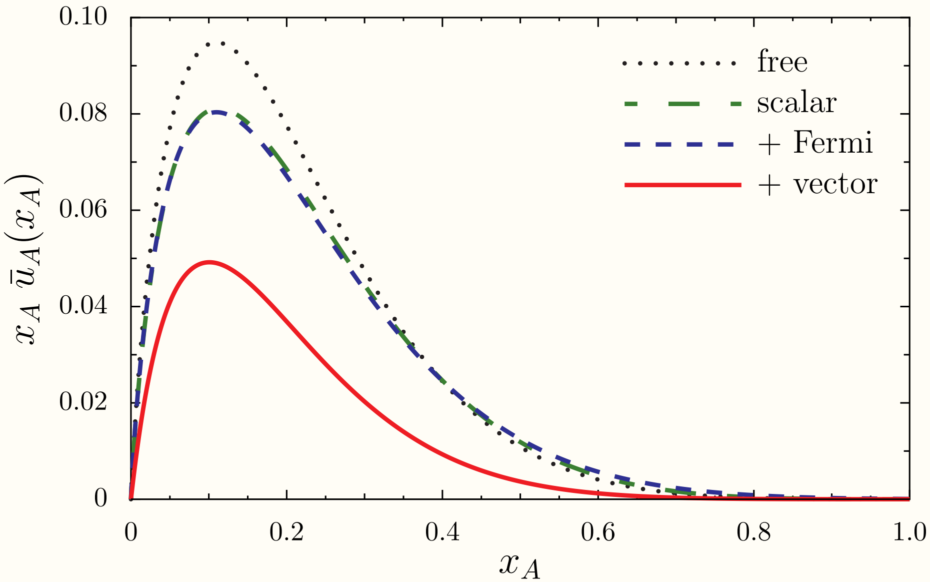
- Ignoring quark mass differences, s-quarks and EW corrections
  - For a $N = Z$ target:

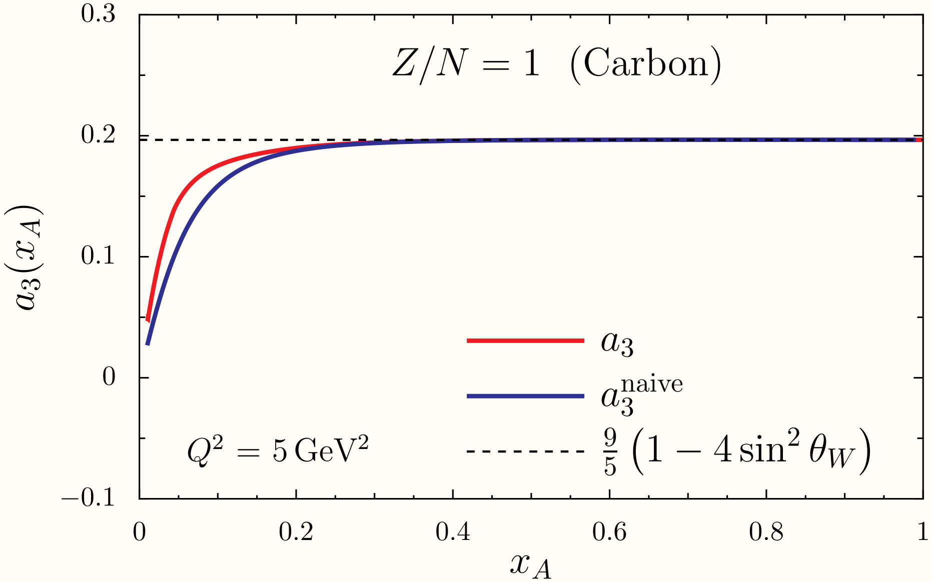
$$a_2(x) = \frac{6u_A^+ + 3d_A^+}{4\,u_A^+ + d_A^+} - 4\sin^2\theta_W \to \frac{9}{5} - 4\sin^2\theta_W$$

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

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

PVDIS: Carbon (with anti-quarks) Preliminary





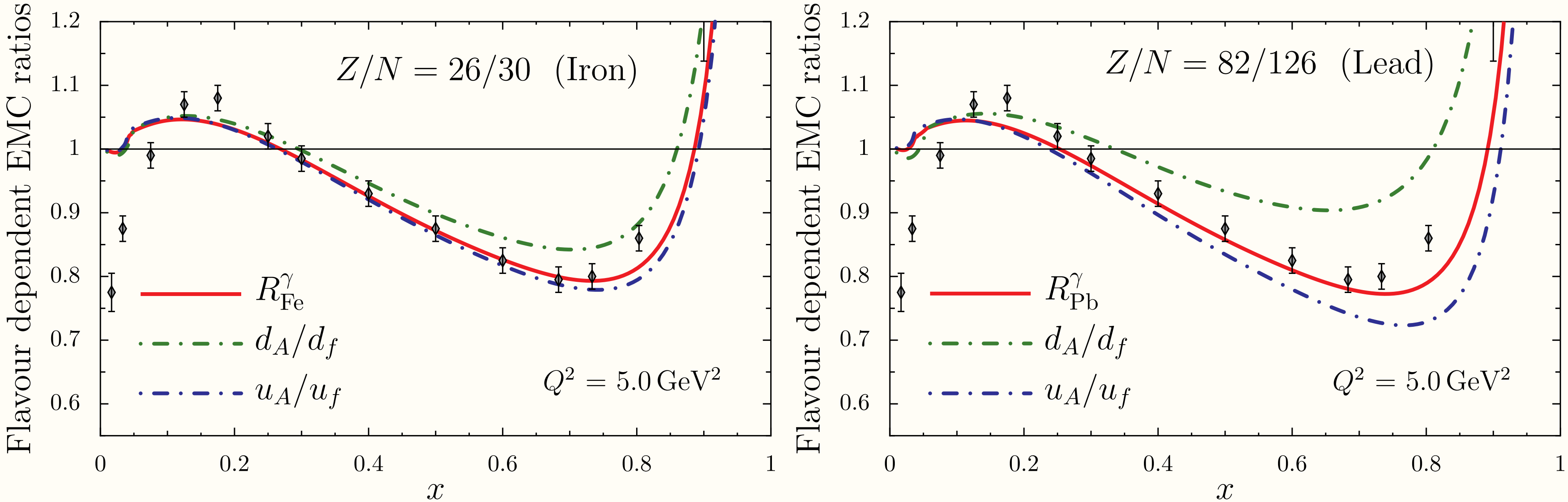
- Ignoring quark mass differences, s-quarks and EW corrections
  - For a $N = Z$ target:

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

$$\bar{q}(x) = \frac{p^+}{p^+ - V^+}\;\bar{q}_0\left(\frac{p^+}{p^+ - V^+}\,x + \frac{V_q^+}{p^+ - V^+}\right)$$

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

Flavour Dependence of EMC effect



- Flavour dependence determined by measuring F_{2A}^{γ} and $F_{2A}^{\gamma Z}$
- $N > Z \implies$ 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 has shifted momentum from u to d quarks
  - u quarks are more bound than d quarks
- If observed $\implies$ very strong evidence for medium modification

Finite nuclei EMC effects

- EMC ratio

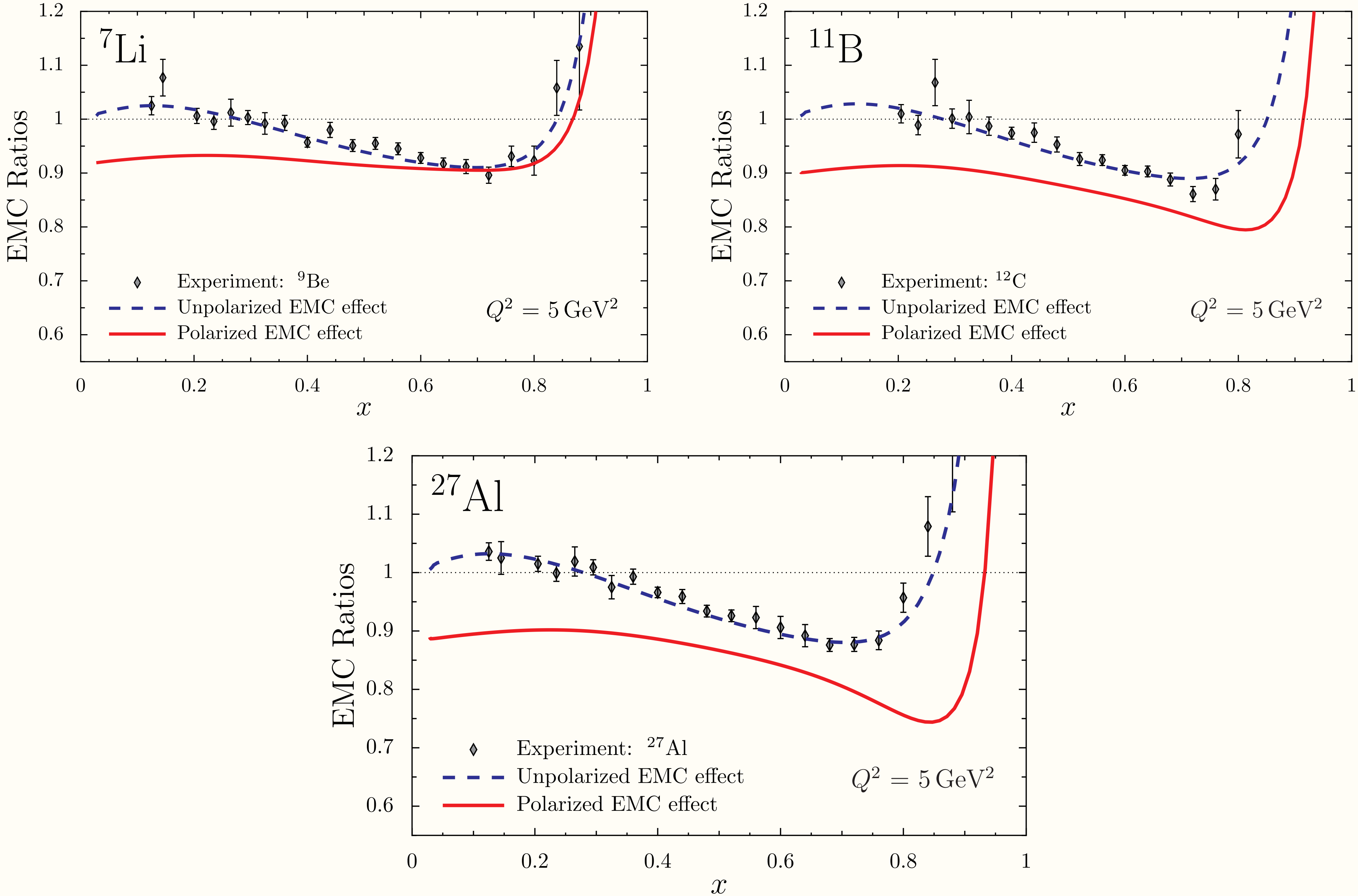
$$R = \frac{F_{2A}}{F_{2A}^{\text{naive}}} = \frac{F_{2A}}{Z\, F_{2p} + N\, F_{2n}}$$

- Polarized EMC ratio

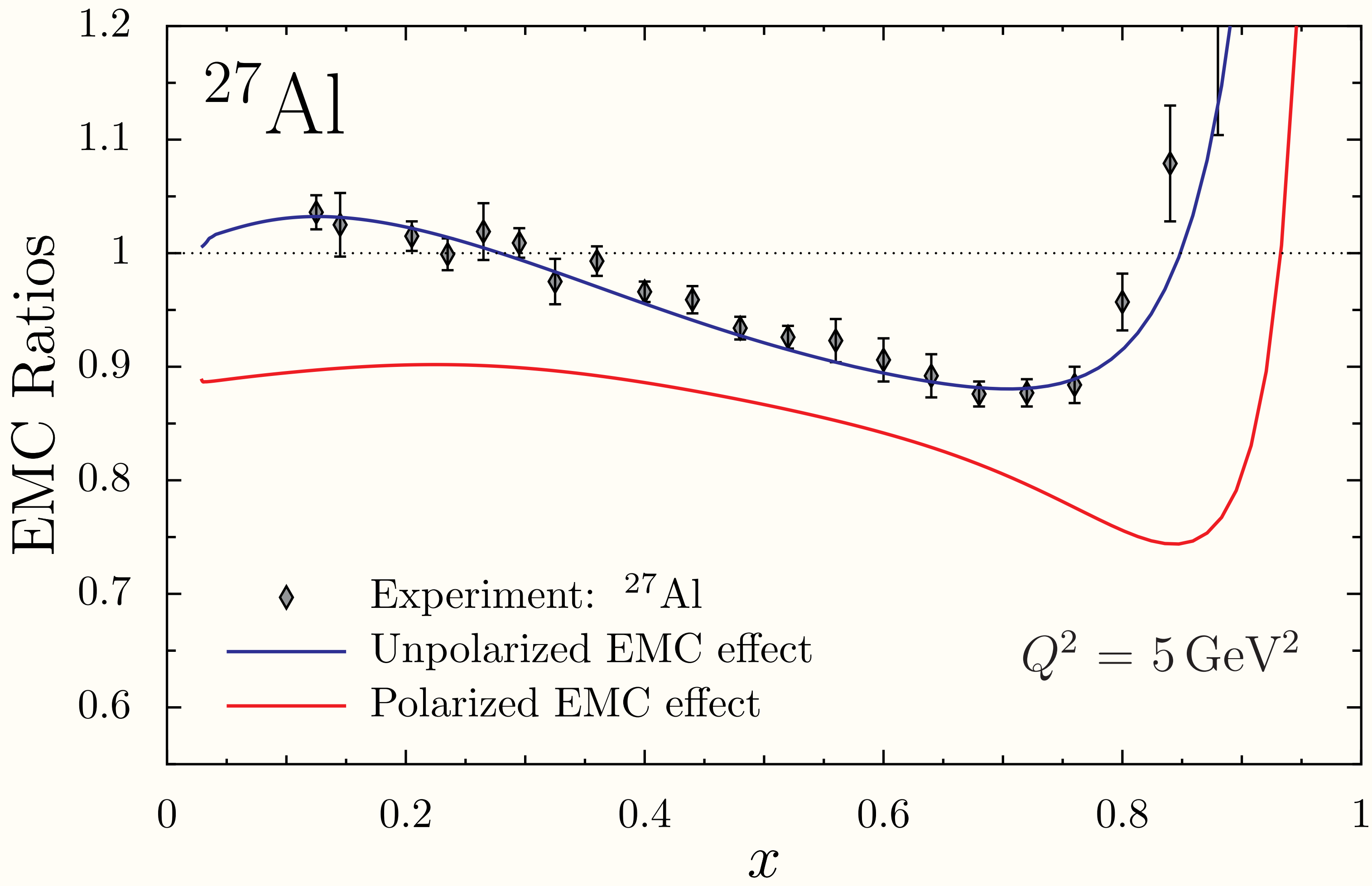
$$R_s^H = \frac{g_{1A}^H}{g_{1A}^{H,\text{naive}}} = \frac{g_{1A}^H}{P_p^H\, g_{1p} + P_n^H\, g_{1n}}$$

- 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

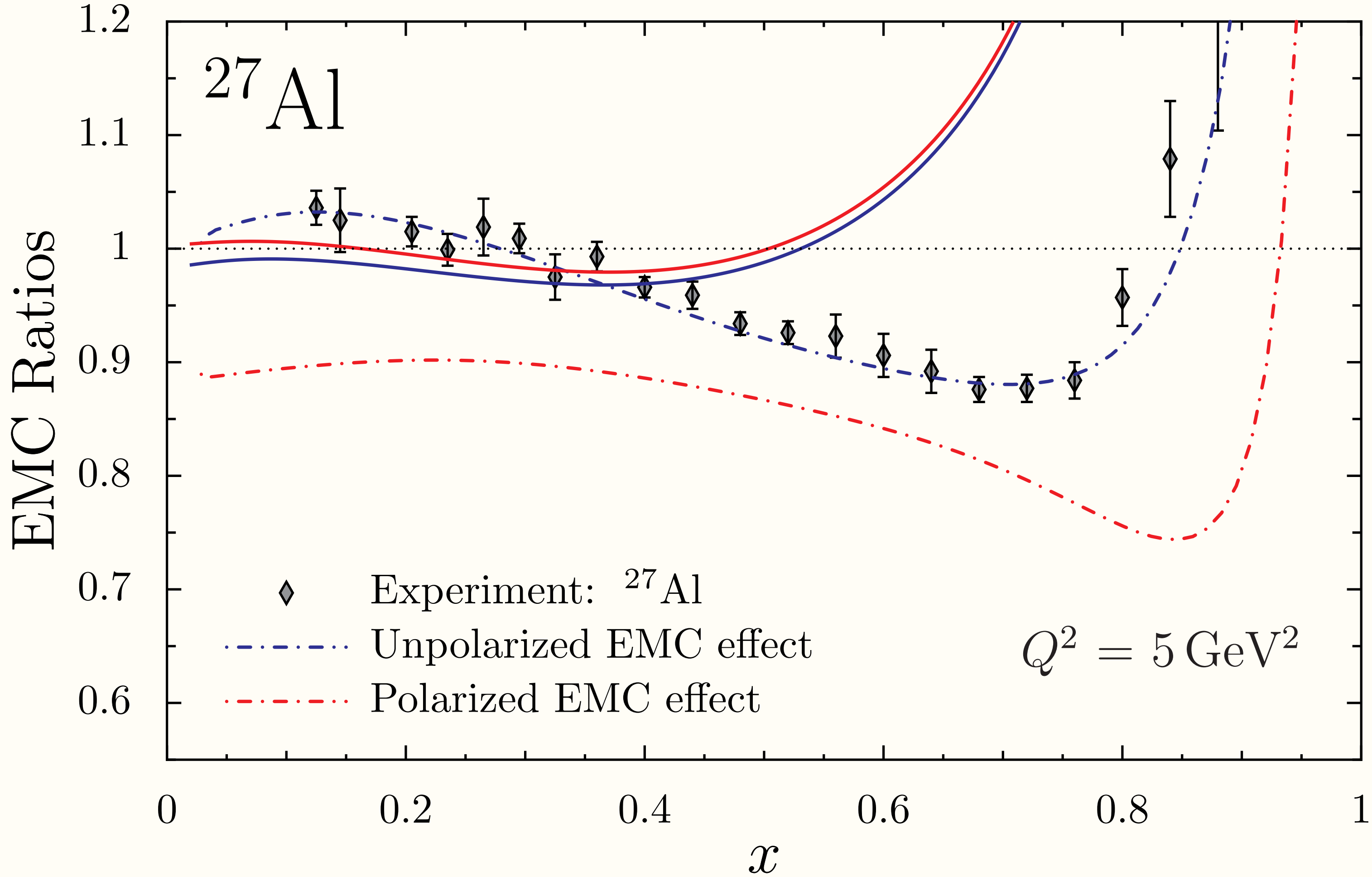
EMC ratio ^7Li, ^{11}B and ^{27}Al



Is there medium modification



Is there medium modification



- Medium modification of nucleon has been switched off
- Relativistic effects remain
- Large splitting very difficult without 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
- Major discrepancy with SM 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
  - result can be tested using PV DIS
- Some important remaining challenges:
  - polarized EMC effect [quark spin converted $\rightarrow L_q$ in nuclei]
  - flavour dependence of EMC effect
- Exciting new experiments:
  - PV DIS, pion induced Drell-Yan, neutron knockout
- Slowly building a QCD based understanding of nuclear structure