The structure of a bound nucleon

Ian Cloët

(University of Washington)

Collaborators

Wolfgang Bentz

(Tokai University)

Anthony Thomas

(Adelaide University)

Tony's 60–Fest

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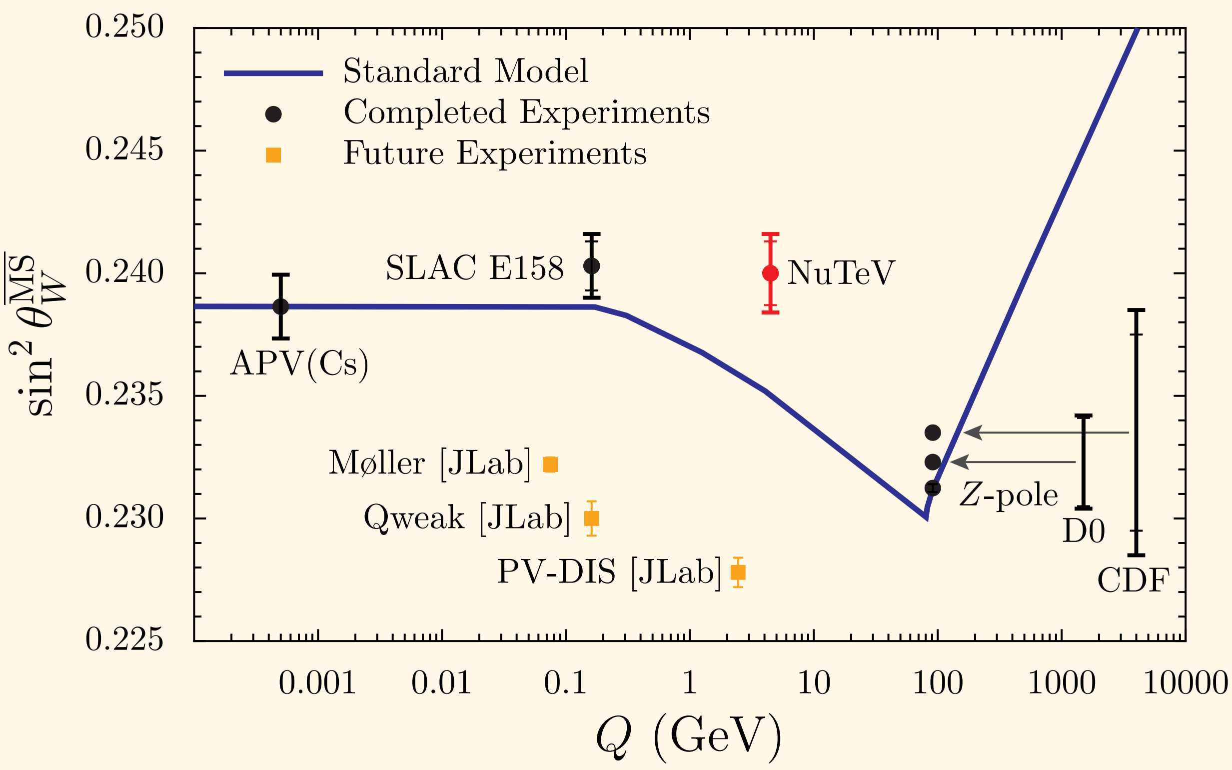
Theme

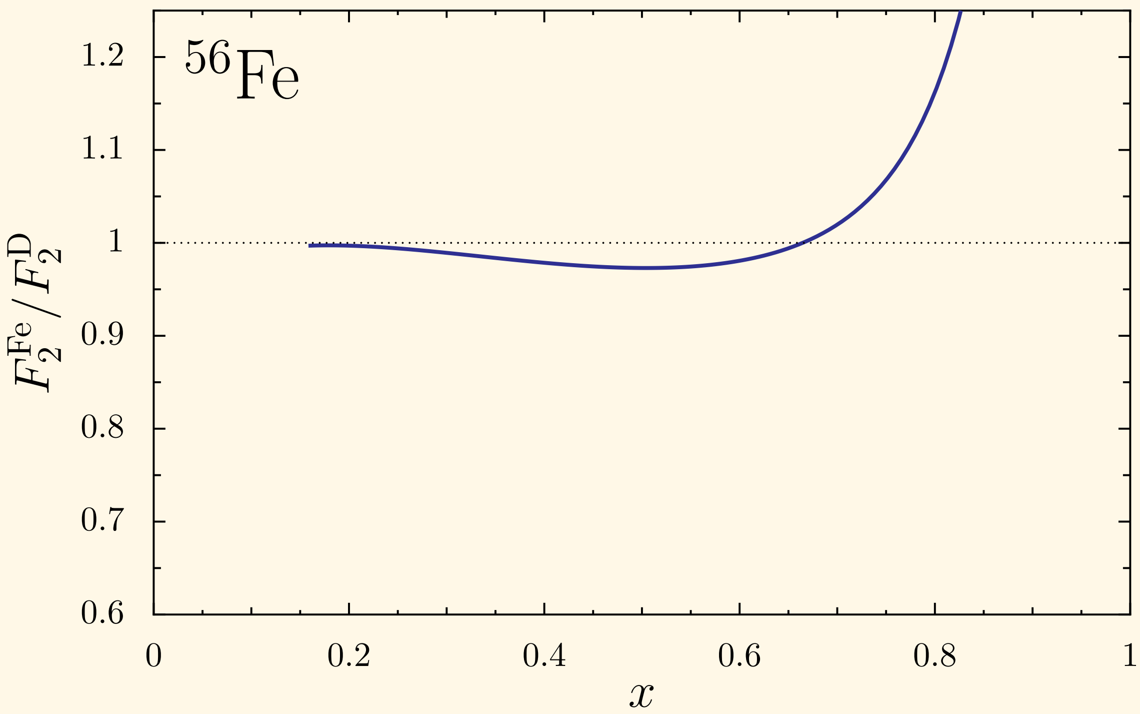
- Gain insights into nuclear structure from a QCD viewpoint
- Highlight opportunities provided by nuclear systems to study QCD
- Present complementary approach to traditional nuclear physics
  - formulated as a covariant quark theory
  - grounded in good description of mesons and baryons
  - at finite density self-consistent mean-field approach
- Fundamental difference
  - bound nucleons differ from free nucleons
  - medium modification – effects typically $\sim$10–20%
- Possible answers to many long standing questions: we address
  - the EMC effect [European Muon Collaboration]
  - the NuTeV anomaly [Neutrinos at the Tevatron]

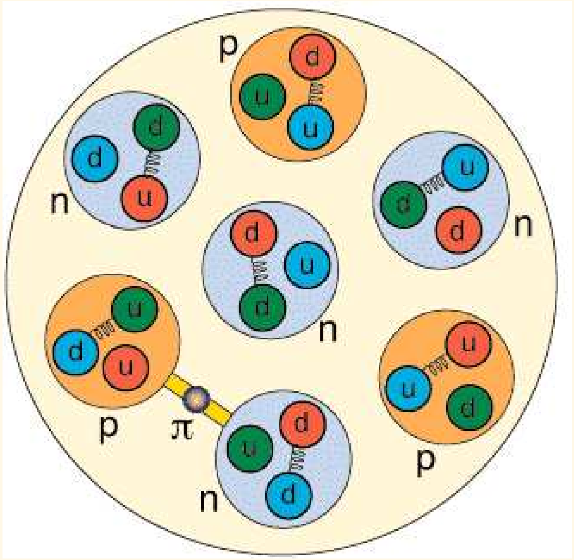
Weak mixing angle and the NuTeV anomaly



- 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

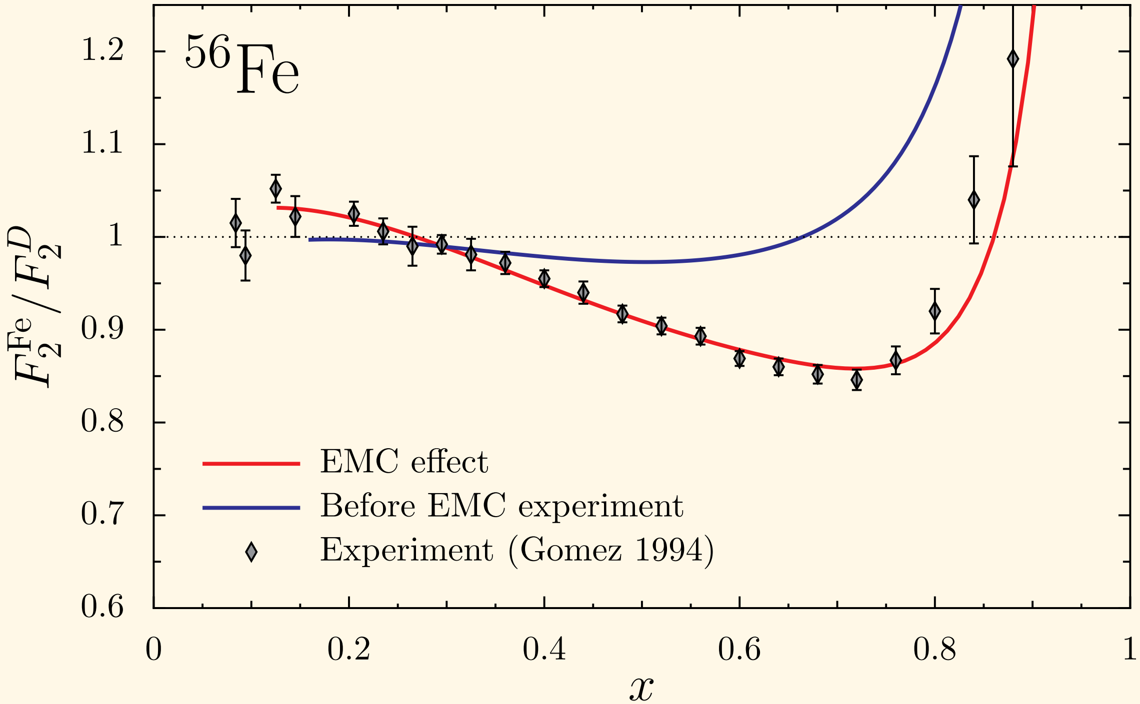
EMC Effect

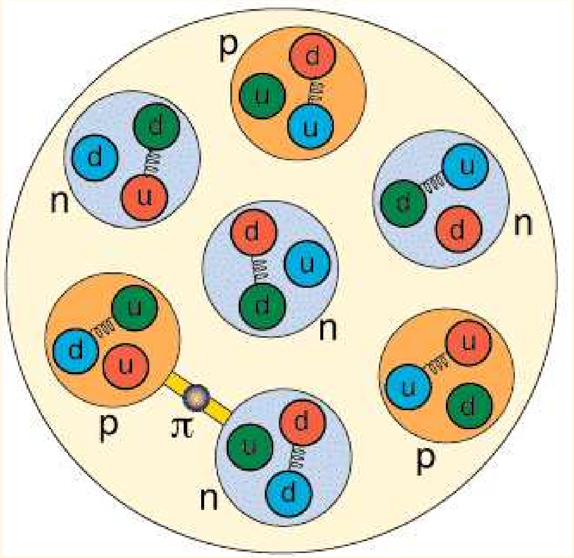




- Pre–1983: before the EMC experiment
- Nucleon quark distributions unchanged in medium
- Long distance nuclear effects not expected to influence "short distance" quark physics
- Fermi motion of nucleons dominate at large x

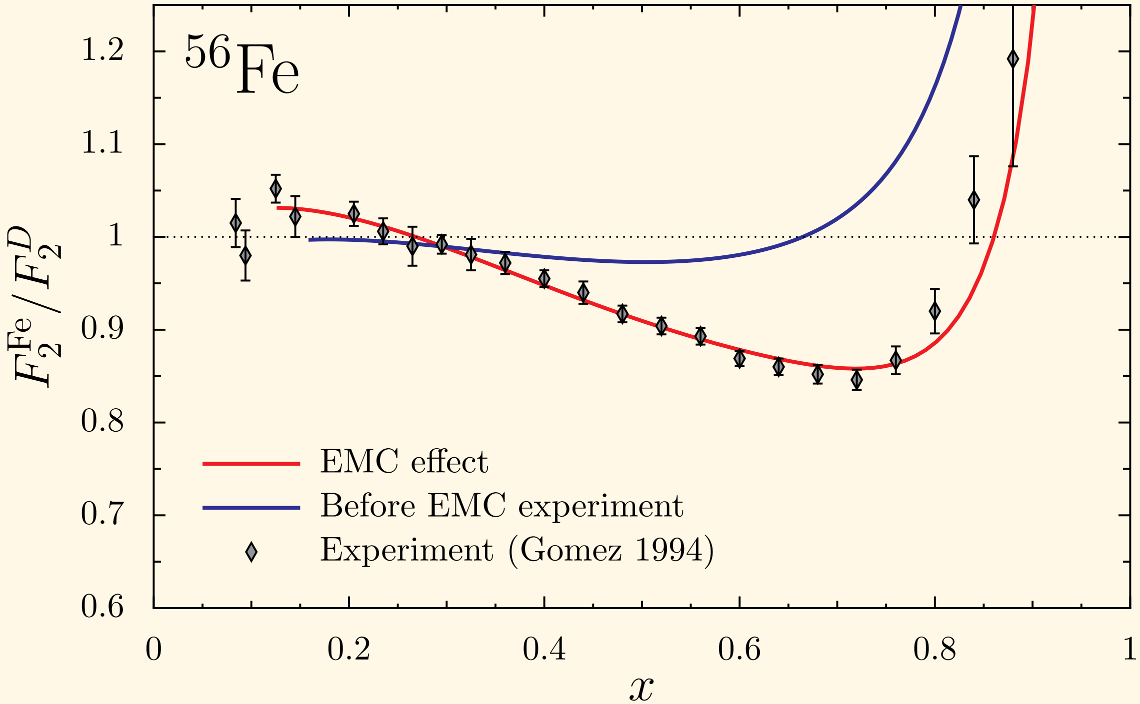
EMC Effect

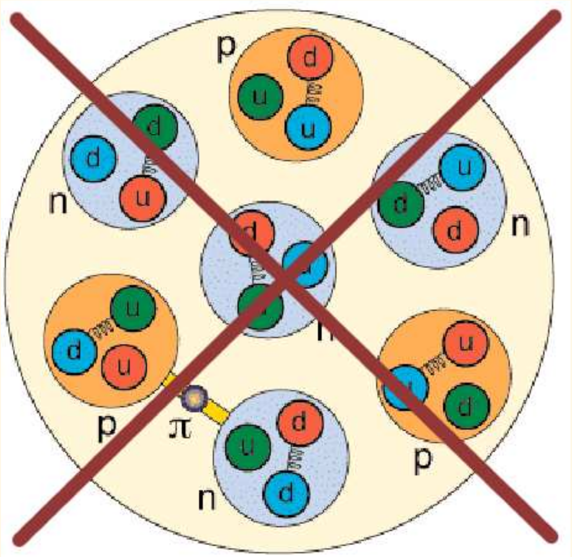




- J. J. Aubert *et al.* [European Muon Collaboration], Phys. Lett. B **123**, 275 (1983).
- Immediate parton model interpretation:
  - valence quarks in nucleus carry less momentum than in nucleon
- Nuclear effects do influence quark physics
- What is the mechanism? After 25 years no consensus
- EMC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

EMC Effect





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Medium Modification

- What does this mean?
- 50 years of traditional nuclear physics tells us that the nucleus is composited of nucleon-like objects
- However if a nucleon property is not protected by a symmetry its value may change in medium e.g.
  - mass, magnetic moments, radii
  - quark distributions, form factors, GPDs, etc
- There must be medium modification:
  - nucleon propagator is changed in medium
  - off-shell effects: in-medium nucleon has 12 form factors
    - consequently for example $F_{1p}(Q^2 = 0) \neq 1$
- Need to understand these effects as first step toward QCD based understanding of nuclei

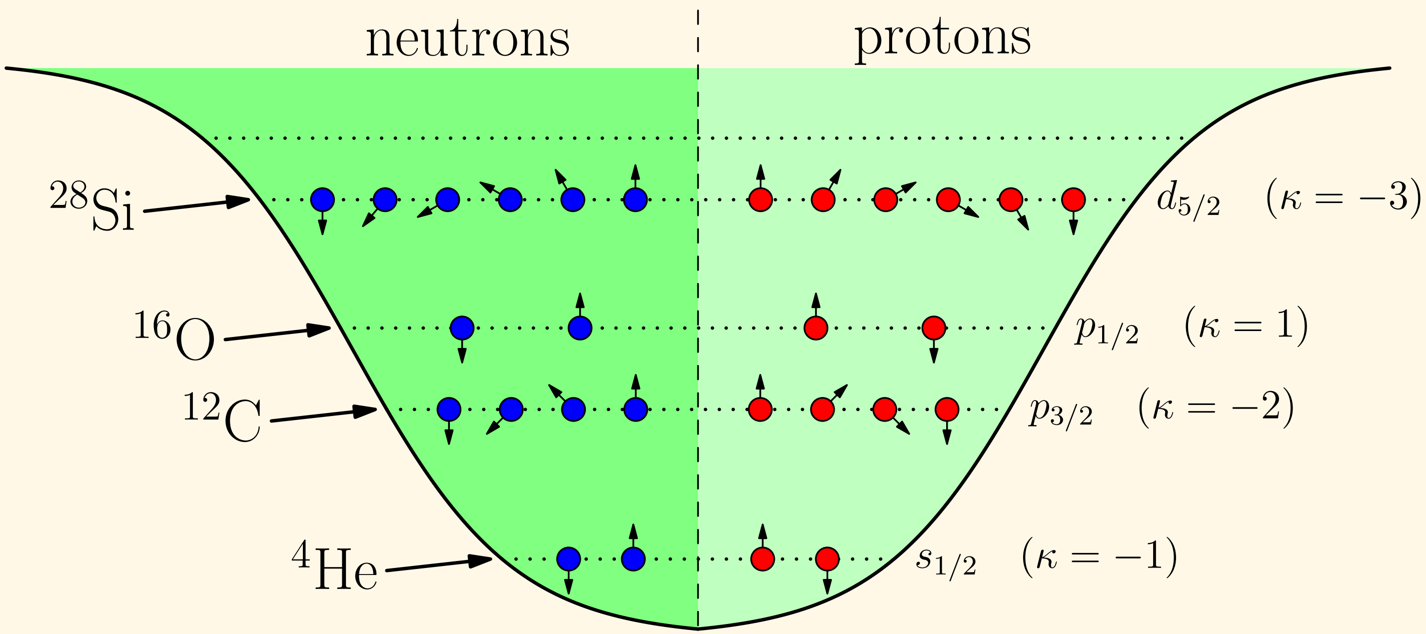
Finite Nuclei quark distributions

- Definition of finite nuclei quark distributions

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

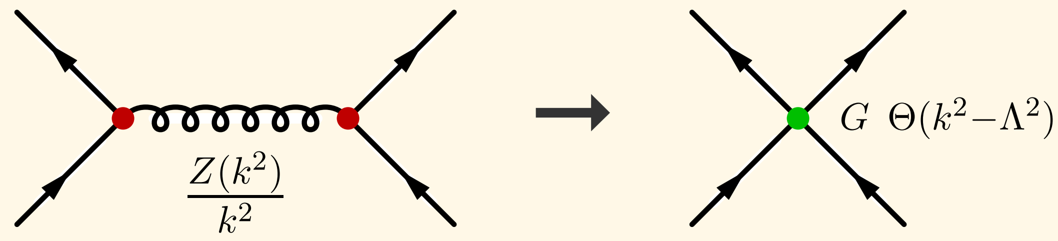
- Approximate using a modified convolution formalism

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

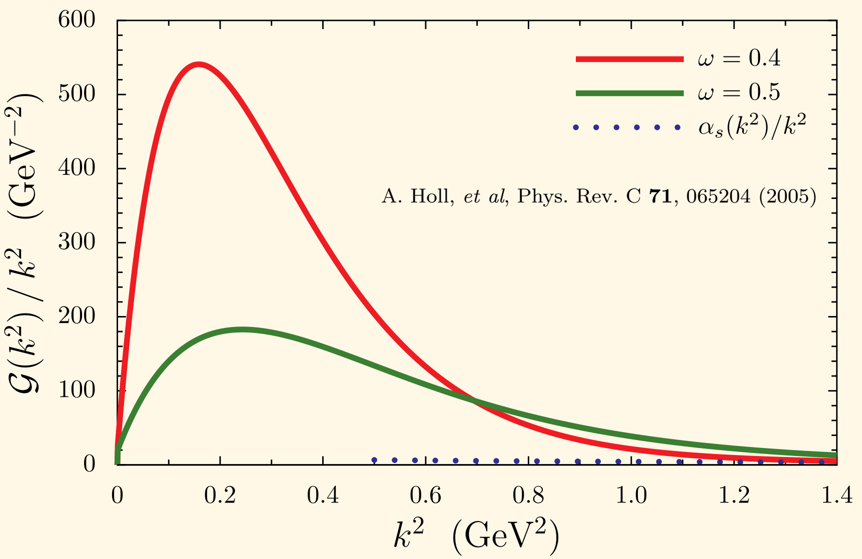


Nambu–Jona-Lasinio Model

- Interpreted as low energy chiral effective theory of QCD



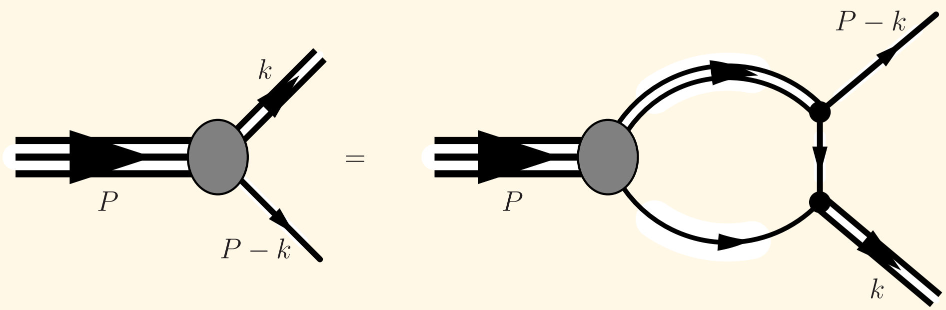
- Can be motivated by infrared enhancement of gluon propagator e.g. DSEs and Lattice QCD



- 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

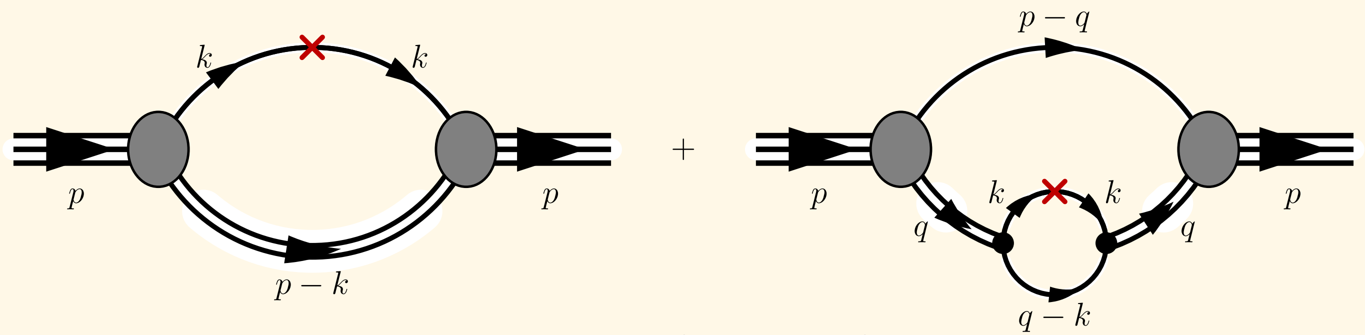
- Nucleon approximated as quark-diquark bound state.
- Use relativistic Faddeev approach:



- Nucleon quark distributions

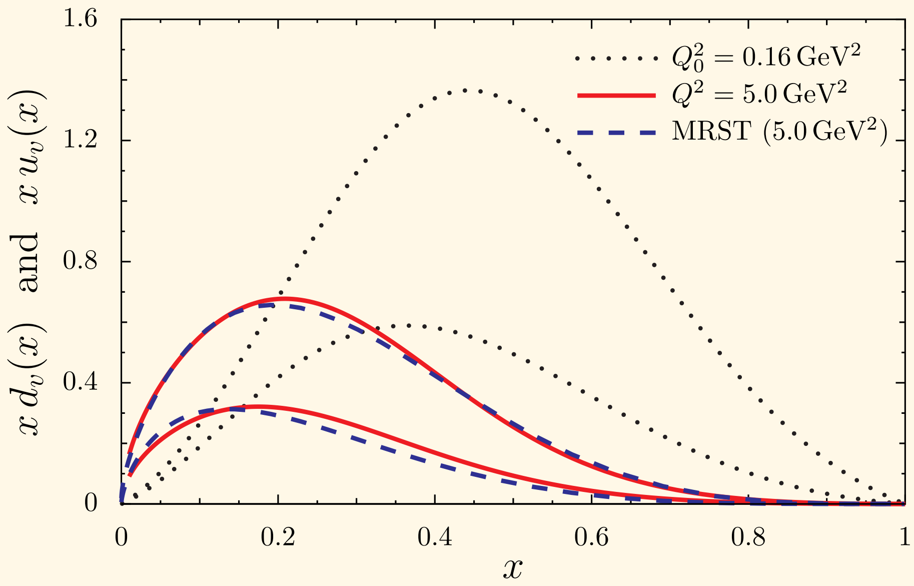
$$q(x) = p^+ \int \frac{d\xi^-}{2\pi} e^{i\,x\,p^+\xi^-} \langle p,s|\overline{\psi}_q(0)\gamma^+\psi_q(\xi^-)|p,s\rangle_c, \quad \Delta q(x) \; = \langle \gamma^+\gamma_5 \rangle$$

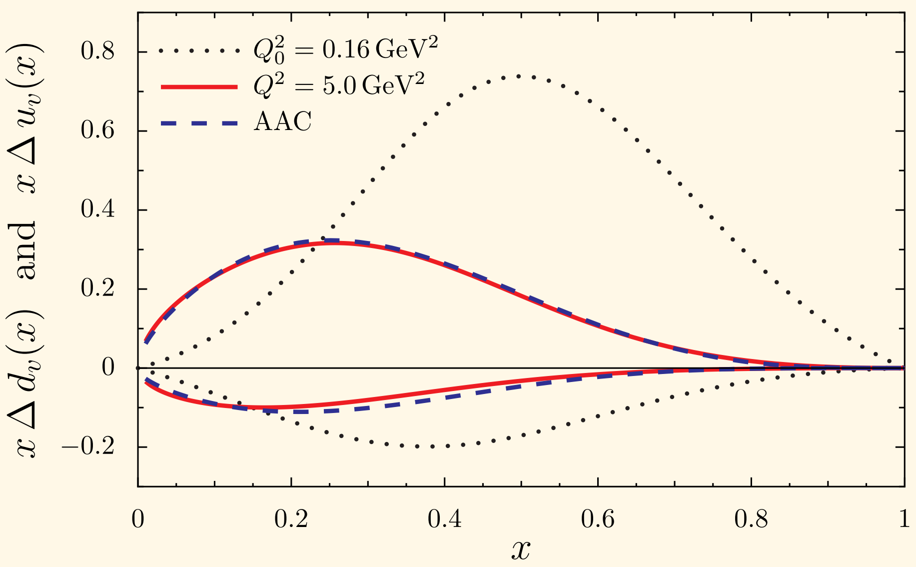
- Associated with a Feynman diagram calculation



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

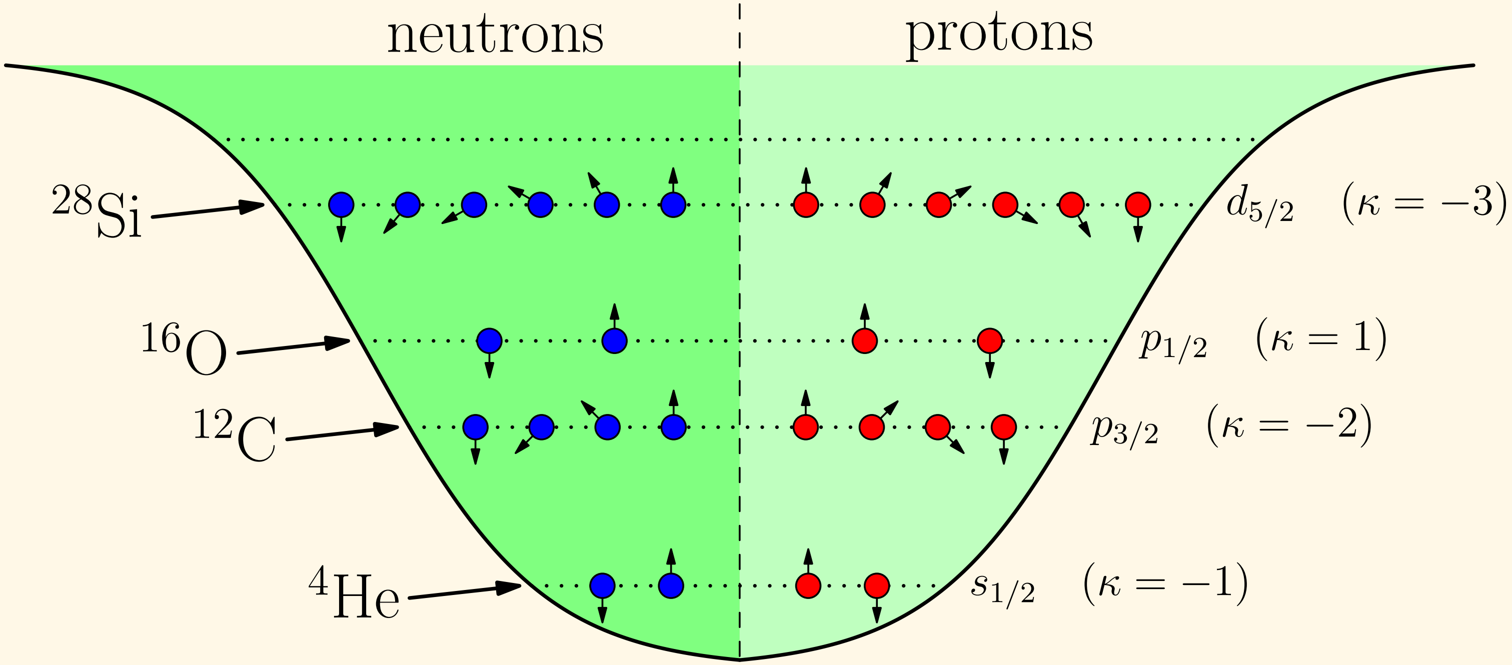
Results: proton quark distributions





- Empirical spin-independent distributions:
  - Martin, Roberts, Stirling and Thorne, Phys. Lett. B **531**, 216 (2002).
- Empirical helicity:
  - M. Hirai, S. Kumano and N. Saito, Phys. Rev. D **69**, 054021 (2004).
- Dotted line $\Longrightarrow$ model result, Solid line $\Longrightarrow$ evolved model result
  Dashed line $\Longrightarrow$ empirical result
- Approach is covariant, satisfies all sum rules & positivity constraints

Recall: Shell Model Picture



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

- We now discuss κ or density dependence
- For nuclear matter $f_{\alpha,\kappa,m}(y_A)$ & hence $\sum_{\alpha,\kappa,m}$ greatly simplify

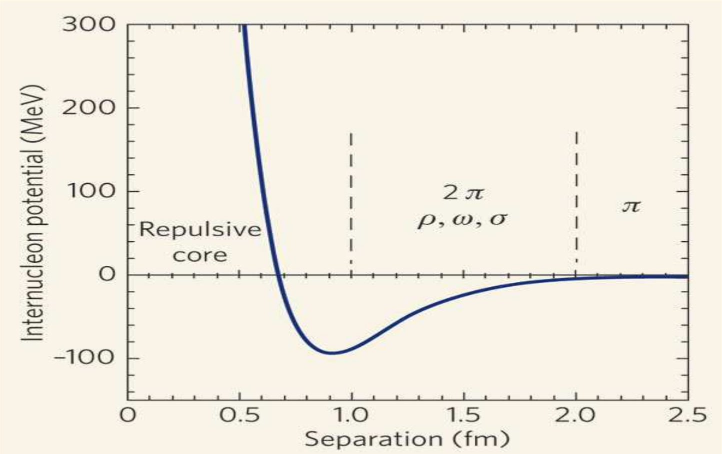
Asymmetric Nuclear Matter: Lagrangian

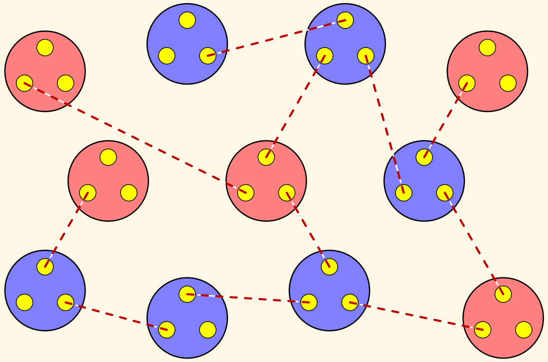
- Finite Density Lagrangian: $\sigma,\ \omega,\ \rho$ mean fields

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

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

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





- Finite density quark propagator

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

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

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

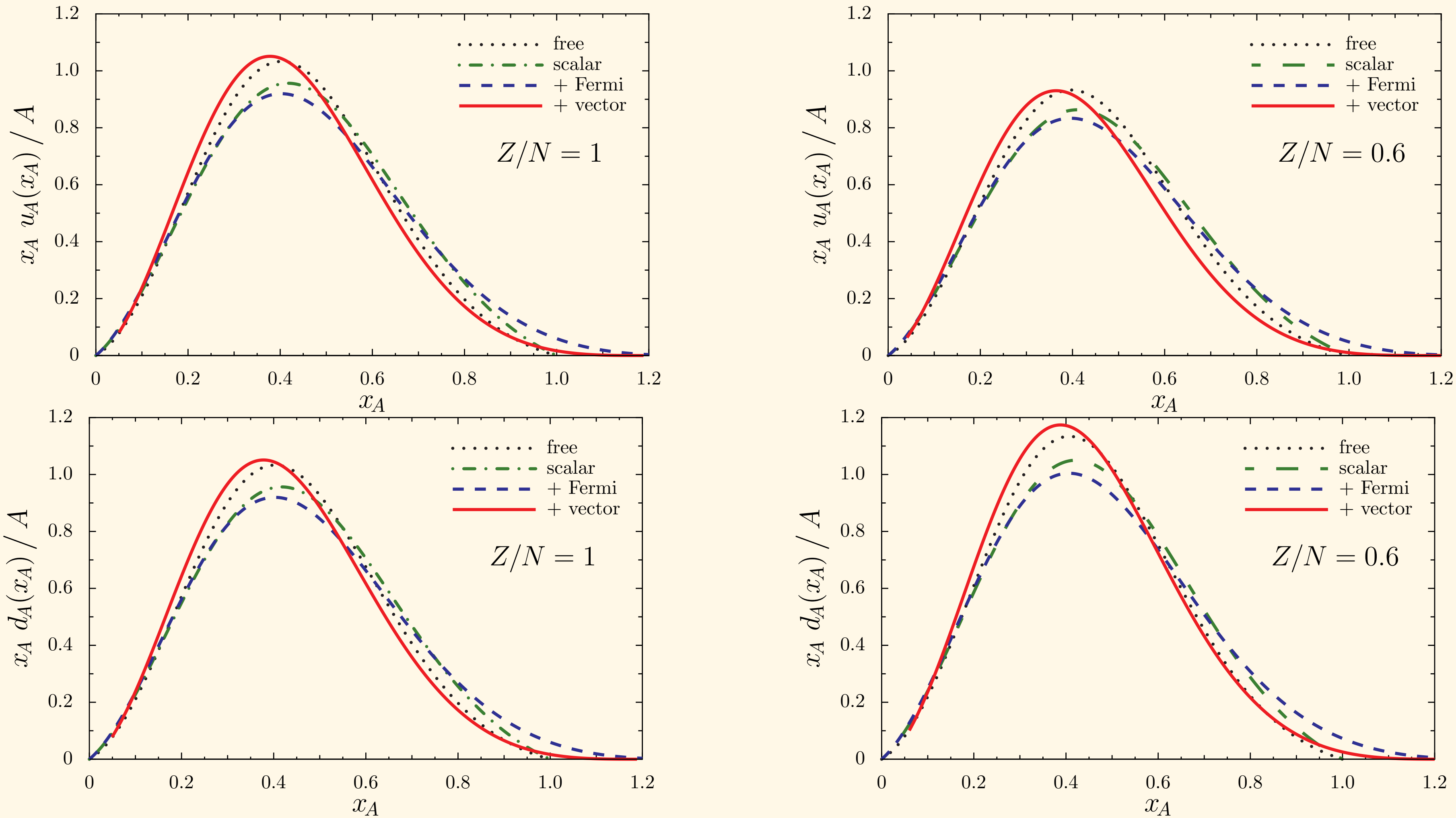
  - $G_\omega \Leftrightarrow Z = N$ saturation & $G_\rho \Leftrightarrow$ symmetry energy

- Vector potentials:

$$V_{u(d)} = \omega_0 \pm \rho_0 \qquad V_{p(n)} = 3\omega_0 \pm \rho_0$$

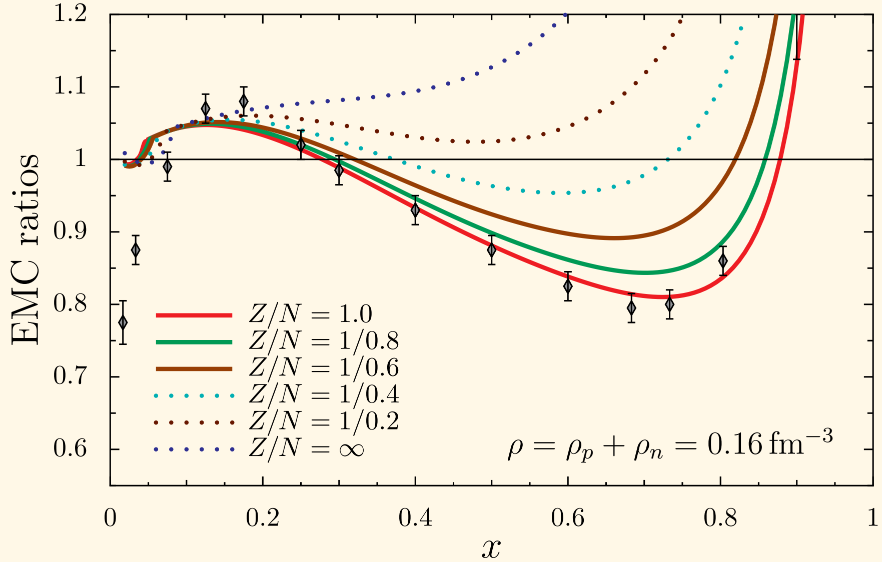
- Recall: quark propagator: $S_q(k) = \left[\not{k} - M^* - \not{V}_q\right]^{-1}$

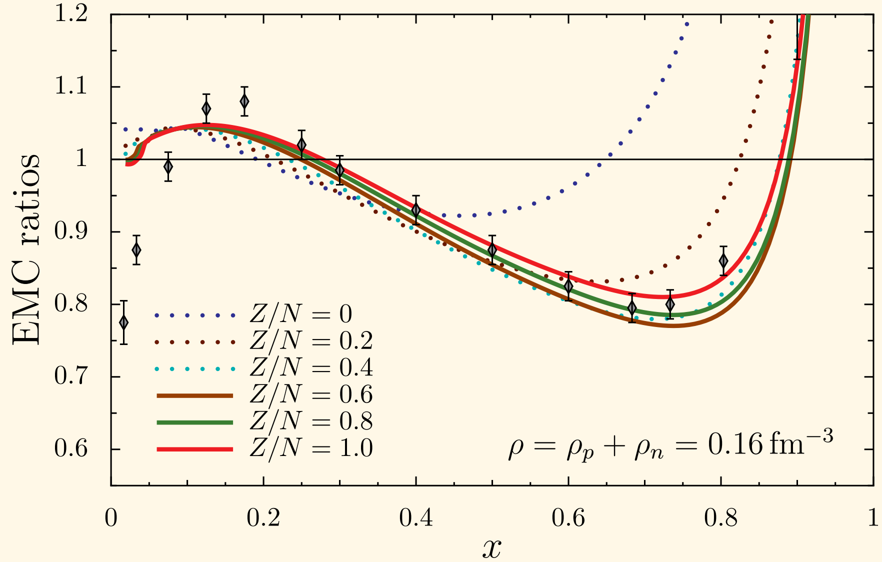
Results: Nuclear Matter



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

Isovector EMC Effect





- EMC ratio: $R^\gamma = \frac{F_{2A}}{F_{2A}^{\text{naive}}} \sim \frac{4\ u_A(x)+d_A(x)}{4\ u_0(x)+d_0(x)}, \quad u(x)=\frac{Z}{A}u_p(x)+\frac{N}{A}u_n(x)\ \ldots$
- Effect comes largely from the changing ρ_0 field
- Proton rich: $u(x) > d(x)$ and $V_u > V_d$
- Neutron rich: $u(x) < d(x)$ and $V_u < V_d$
- Density is fixed, only Z/N changes $\Longrightarrow$ non-trivial isospin dependence

Paschos-Wolfenstein ratio

- Paschos-Wolfenstein ratio motivated the NuTeV study:

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

- 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 ⇔ 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

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

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

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

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

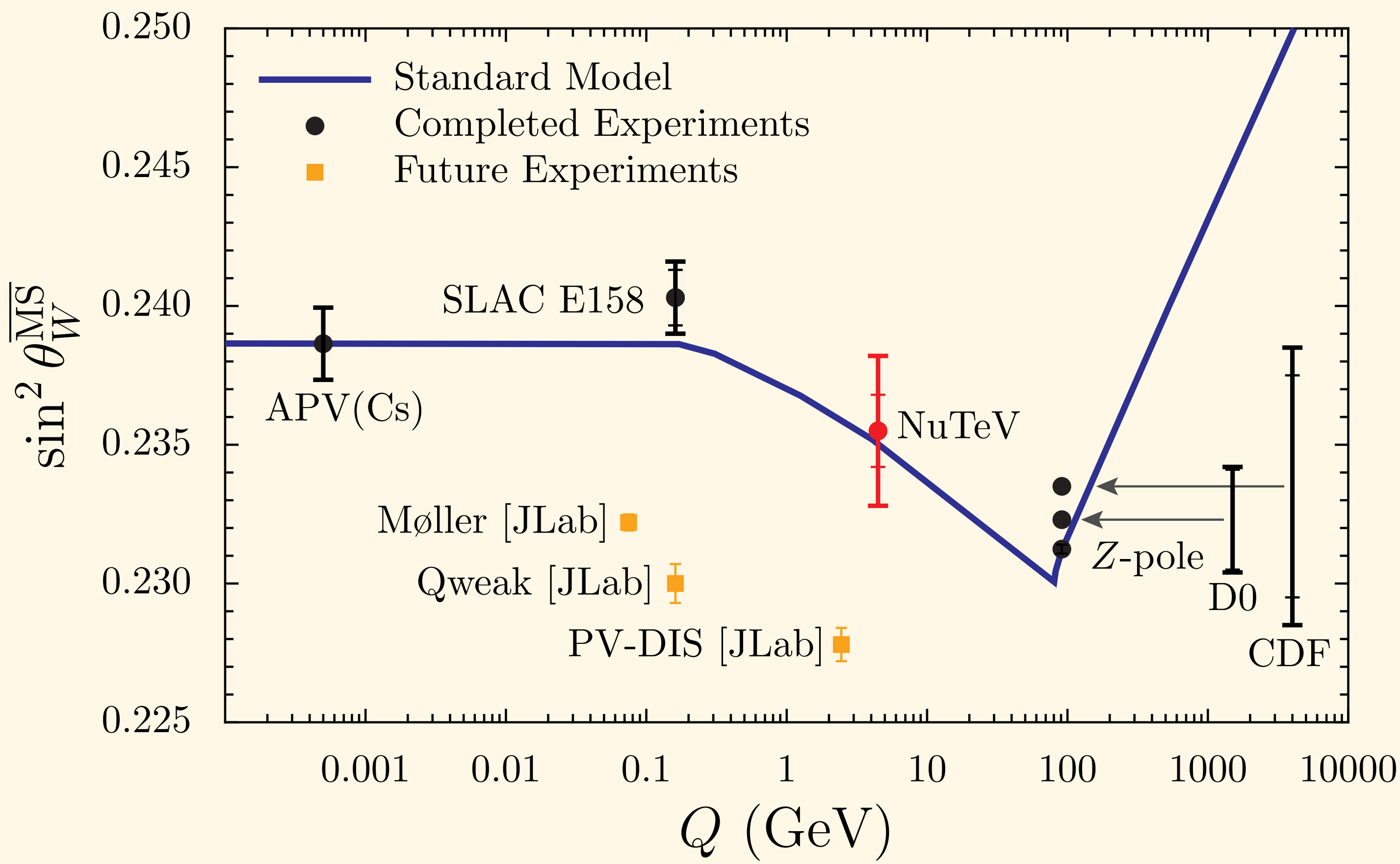
NuTeV anomaly cont'd

- 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

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

  - 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



- 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
  - but can this mechanism be observed elsewhere?
- Yes!! Parity violating DIS – Z^0 interaction violates parity

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

- Parton model expressions

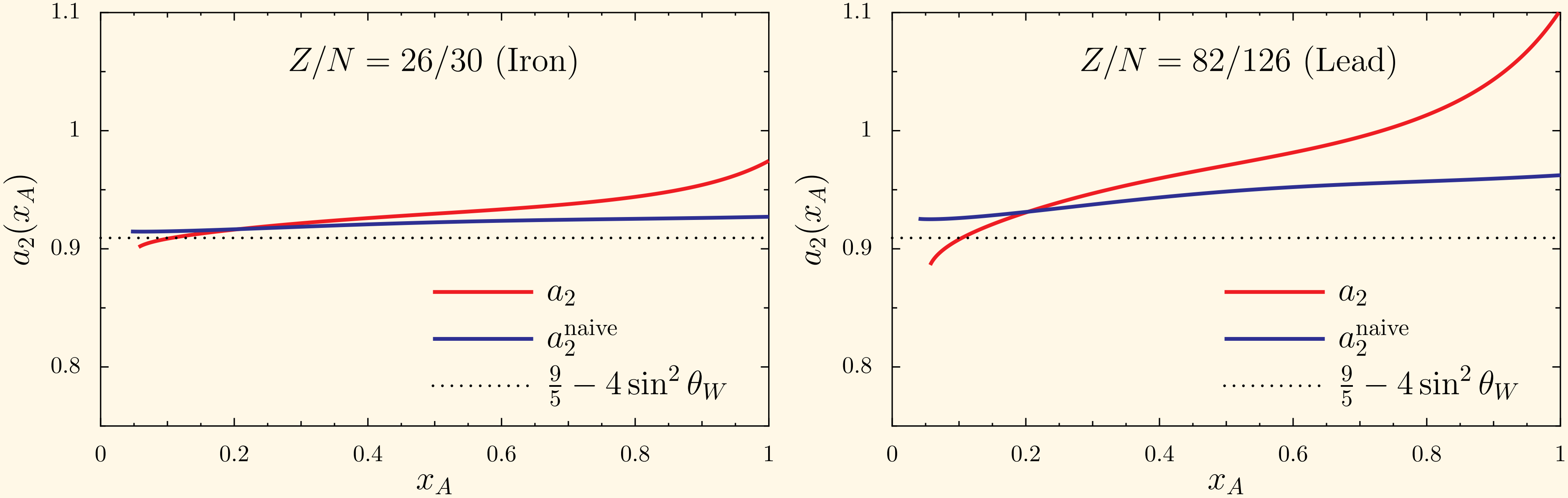
$$F_2^{\gamma Z} = 2x \sum e_q\, g_V^q\, (q + \bar{q})\,, \qquad g_V^q = \pm\frac{1}{2} - 2e_q \sin^2\theta_W$$

- Measuring $a_2 \Longrightarrow F_2^{\gamma Z}$ or $\sin^2\theta_W$
- For $N \simeq Z$ target

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

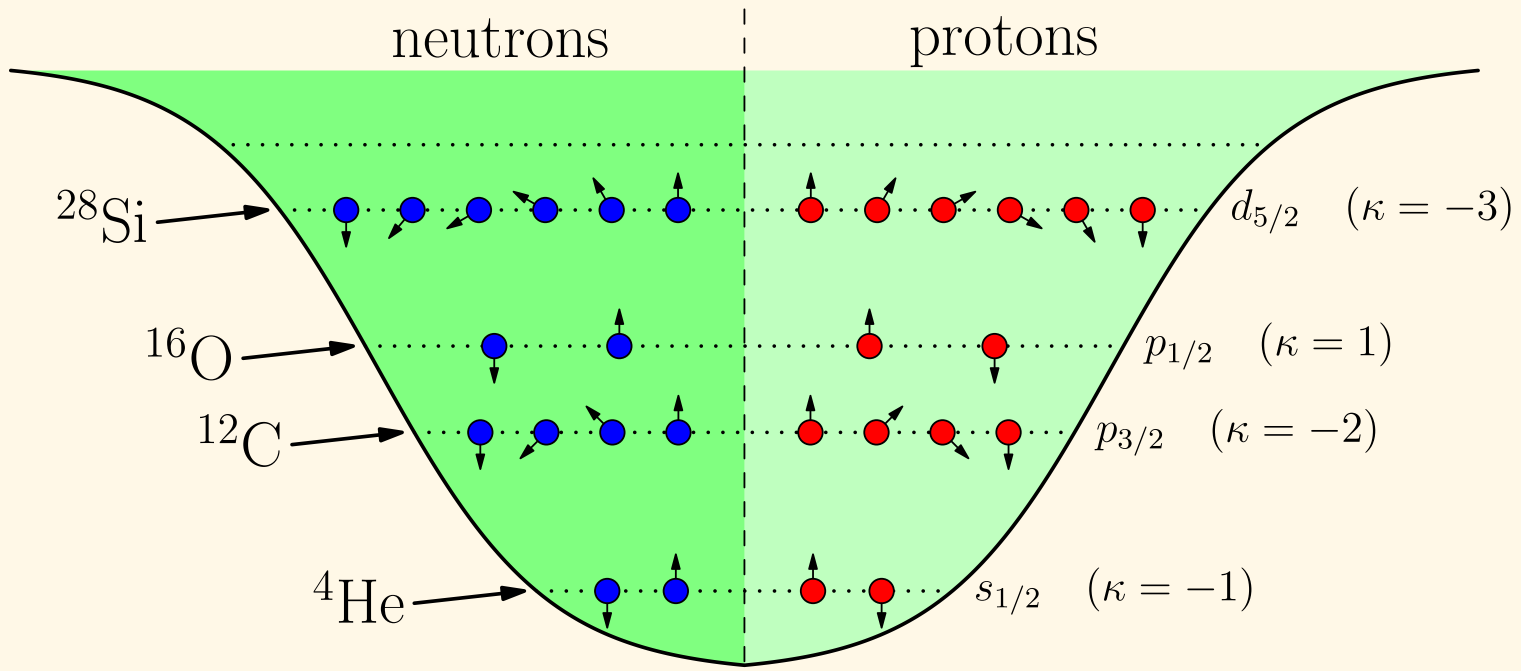
- Measurement of $a_2(x)$ at each $x \Longrightarrow$ a NuTeV experiment!!

Parity Violating DIS: a_2 ratios



- $$a_2(x) \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\,\frac{u_A^+(x) - d_A^+(x)}{u_A^+(x) + d_A^+(x)}$$
- Isoscalarity corrections are independent of $\sin^2\theta_W$
  - An advantage over Paschos-Wolfenstein ratio
- After naive isoscalarity corrections medium effects still very large
- Large x dependence of $a_2(x)$, even after naive correction
  → Cannot be from $\sin^2\theta_W$
  → Evidence for medium modification

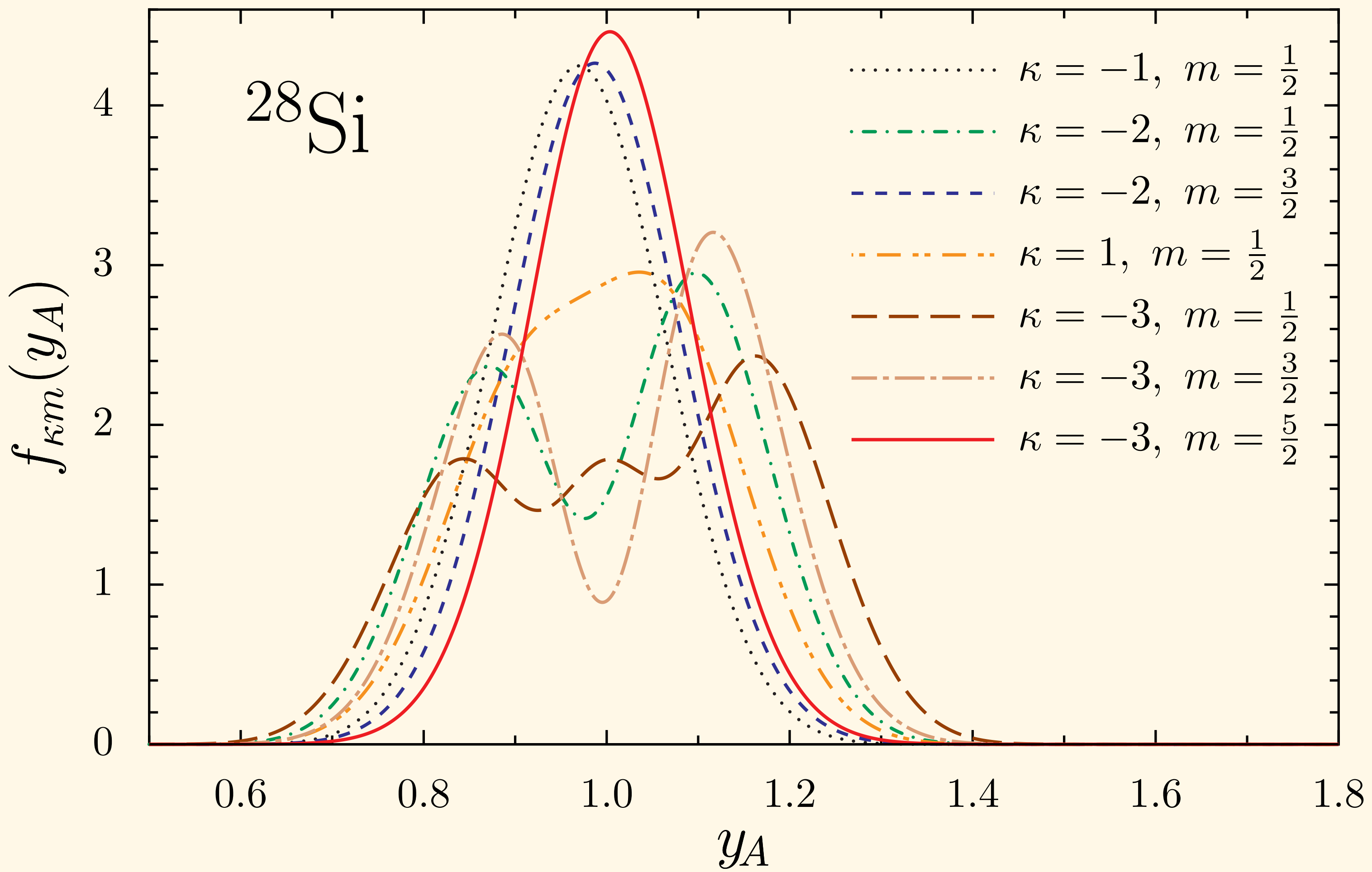
Recall Shell Model Picture



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

- Finite nucleus calculation

Nucleon distributions: ^{28}Si



EMC effects

- EMC ratio

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

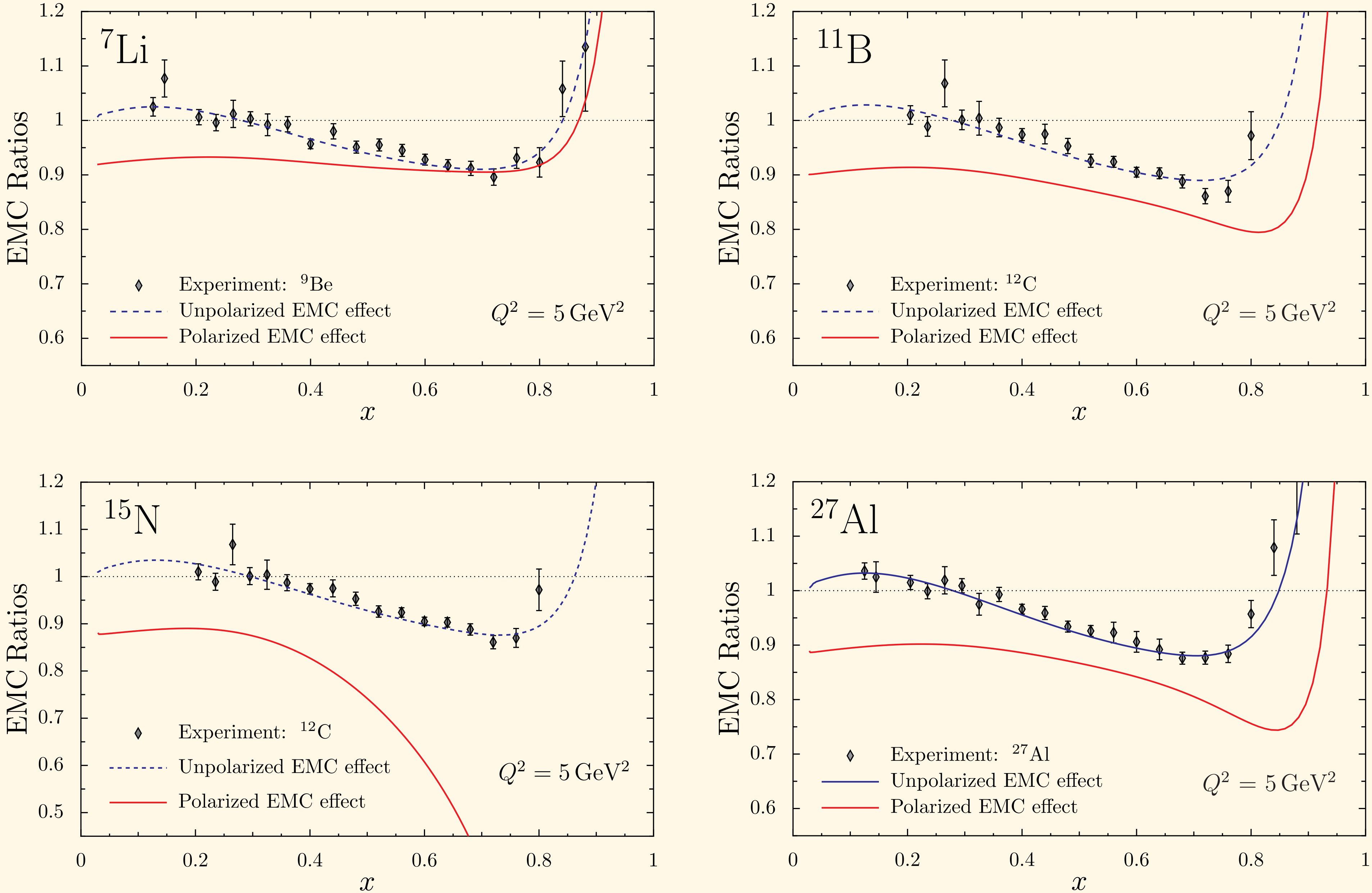
  - Least model dependent way to definite EMC effect

- Polarized EMC ratio

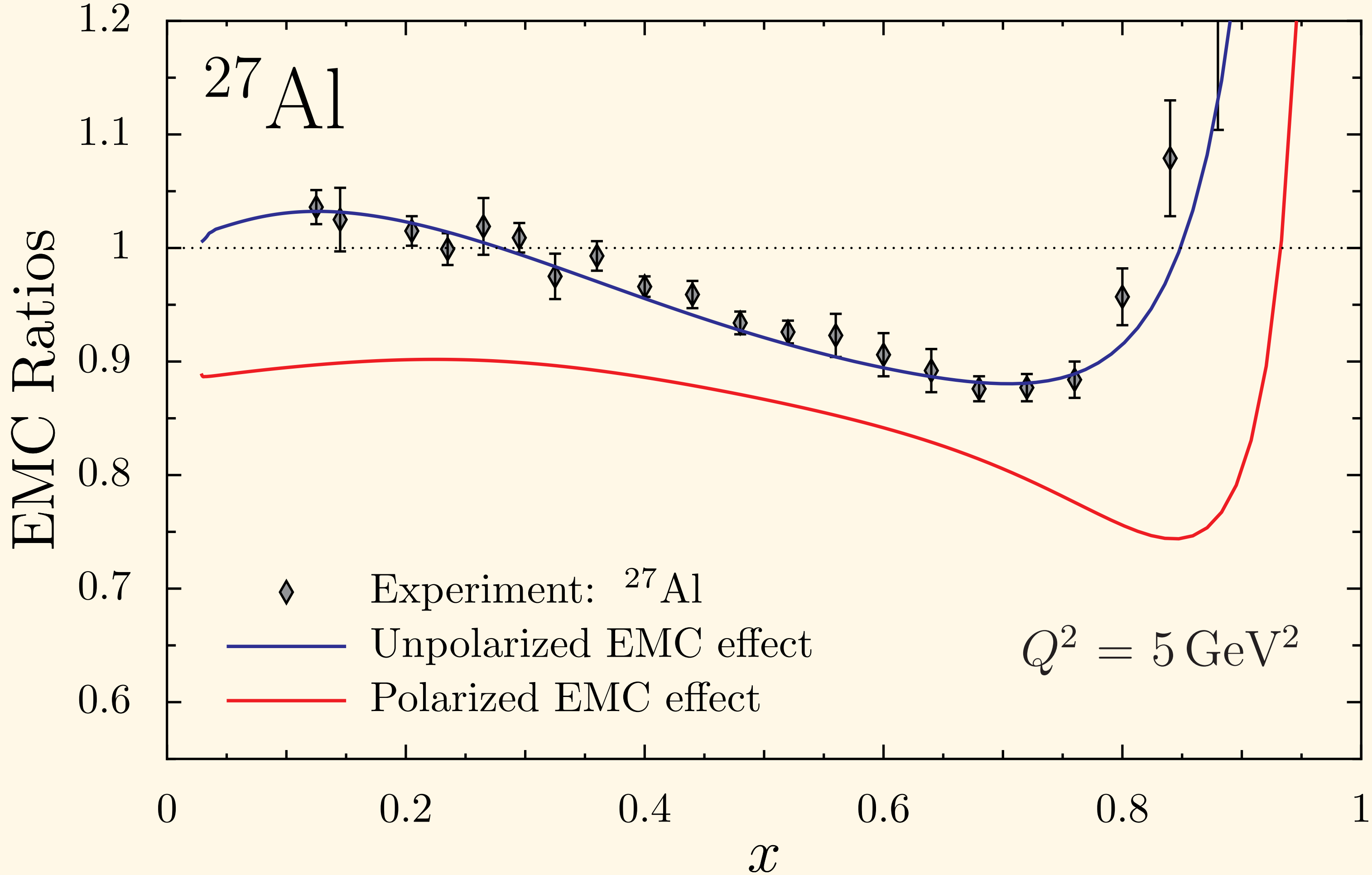
$$R_s^{JH} = \frac{g_{1A}^{JH}}{g_{1A,\text{naive}}^{JH}} = \frac{g_{1A}^{JH}}{P_p^{JH}\, g_{1p} + P_n^{JH}\, g_{1n}}$$

- 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: $P_p^{JJ} = 0.86$ & $P_n^{JJ} = 0.04$
- 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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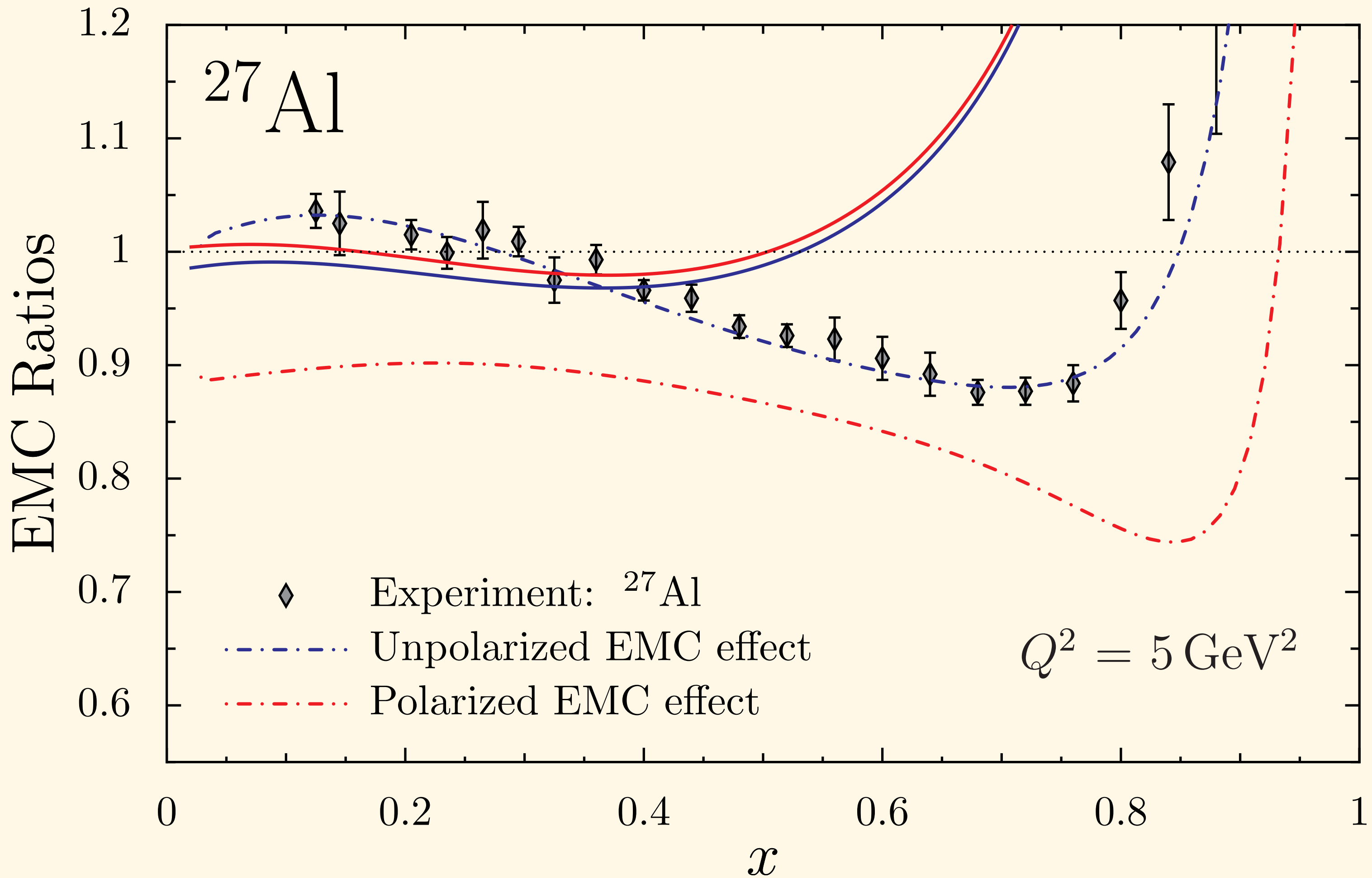


- Medium modification of nucleon has been switched off

Nuclear Spin Sum

	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 lower components of quark wavefunctions are enhanced
  - since $M^* < M$ and therefore quarks are more relativistic
  - lower components have $L = 1$
  - $\Delta q(x)$ very sensitive to lower components because of γ_5
- Conclusion: quark spin → orbital angular momentum in-medium

Conclusion

- Effective quark theories can be used to incorporate quarks into a traditional description of nuclei
  - fundamentally different approach to nuclear physics
- The major outstanding discrepancy with Standard Model predictions for Z^0 was NuTeV anomaly
  - 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
- Important implications for nuclear physics

Model Parameters

- Free Parameters:

  $$\Lambda_{IR},\ \Lambda_{UV},\ M_0,\ G_\pi,\ G_s,\ G_a,\ G_\omega \text{ and } G_\rho$$

- 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

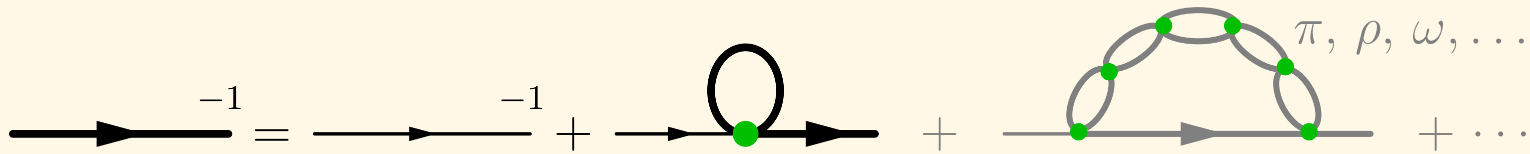
- Proper-time regularization

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

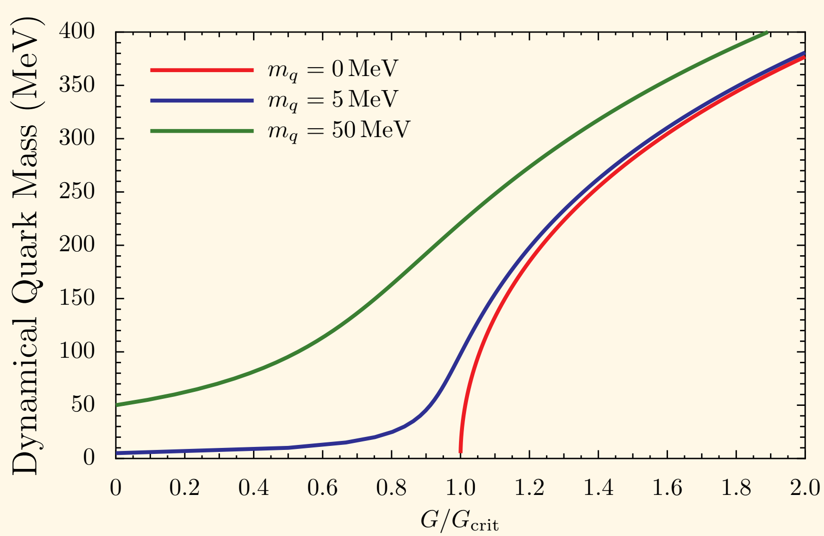
$$\longrightarrow \quad \frac{1}{(n-1)!}\int_{1/(\Lambda_{UV})^2}^{1/(\Lambda_{IR})^2} d\tau\, \tau^{n-1}\, e^{-\tau X}$$

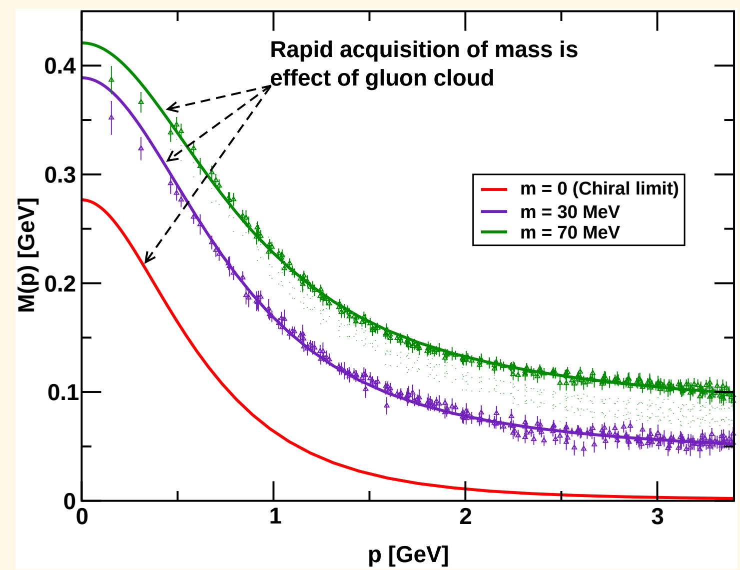
- Λ_{IR} eliminates unphysical thresholds for the nucleon to decay into quarks: $\rightarrow$ simulates confinement
  - D. Ebert, T. Feldmann and H. Reinhardt, Phys. Lett. B **388**, 154 (1996).
- E.g.: Quark wave function renormalization
  - $Z(k^2) = e^{-\Lambda_{UV}(k^2-M^2)} - e^{-\Lambda_{IR}(k^2-M^2)}$
  - → $Z(k^2 = M^2) = 0 \quad \Longrightarrow$ 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 $\Longleftrightarrow$ $\langle\bar{\psi}\psi\rangle \neq 0$ $\Longleftrightarrow$ DχSB
- Proper-time regularization: Λ_{IR} and Λ_{UV}

  → No free quarks $\Longrightarrow$ Confinement $[Z(k^2 = M^2) = 0]$

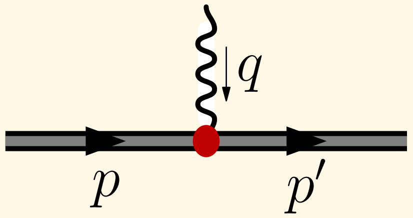
Off-Shell Effects

- 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

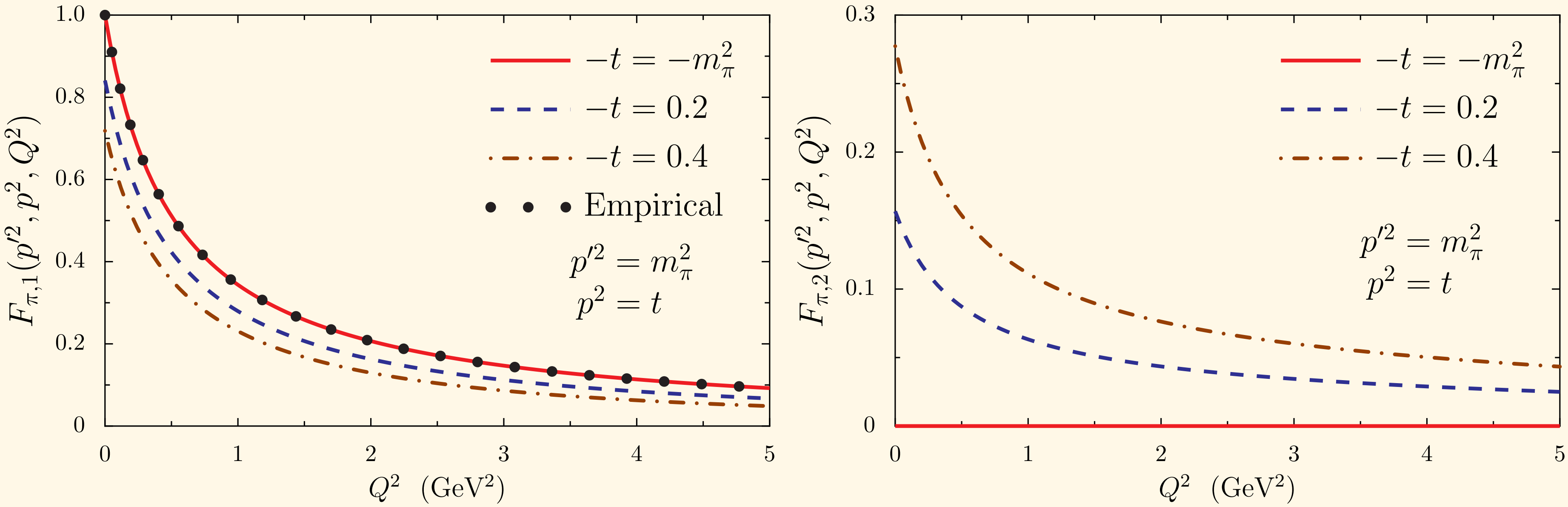
- Simpler system: off-shell pion form factors
  - relax on-shell constraint $p'^2 = p^2 = m_{\pi}^2$
  - Very difficult to calculate in many approaches, e.g. Lattice QCD



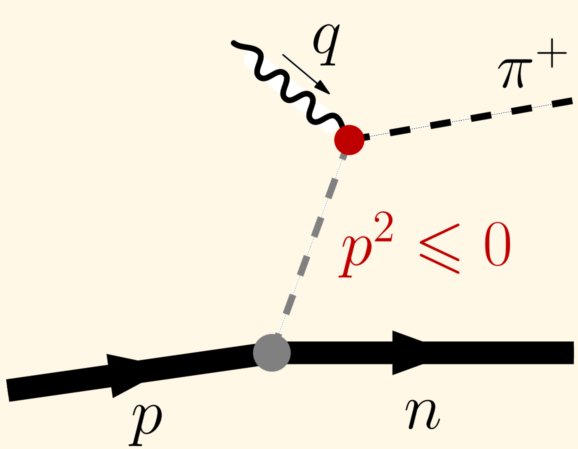
$$= (p'+p)^{\mu}\, F_{\pi,1}(p'^2, p^2, Q^2) + (p'-p)^{\mu}\, F_{\pi,2}(p'^2, p^2, Q^2)$$

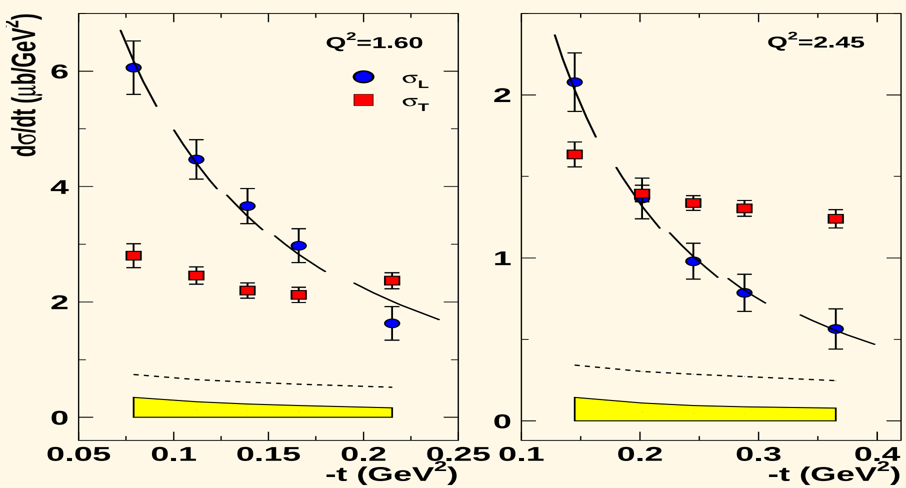
- For $p'^2 = p^2 = m_{\pi}^2$ we have $F_{\pi,1} \to F_{\pi}$ and $F_{\pi,2} = 0$

Pion Off-Shell Form Factors



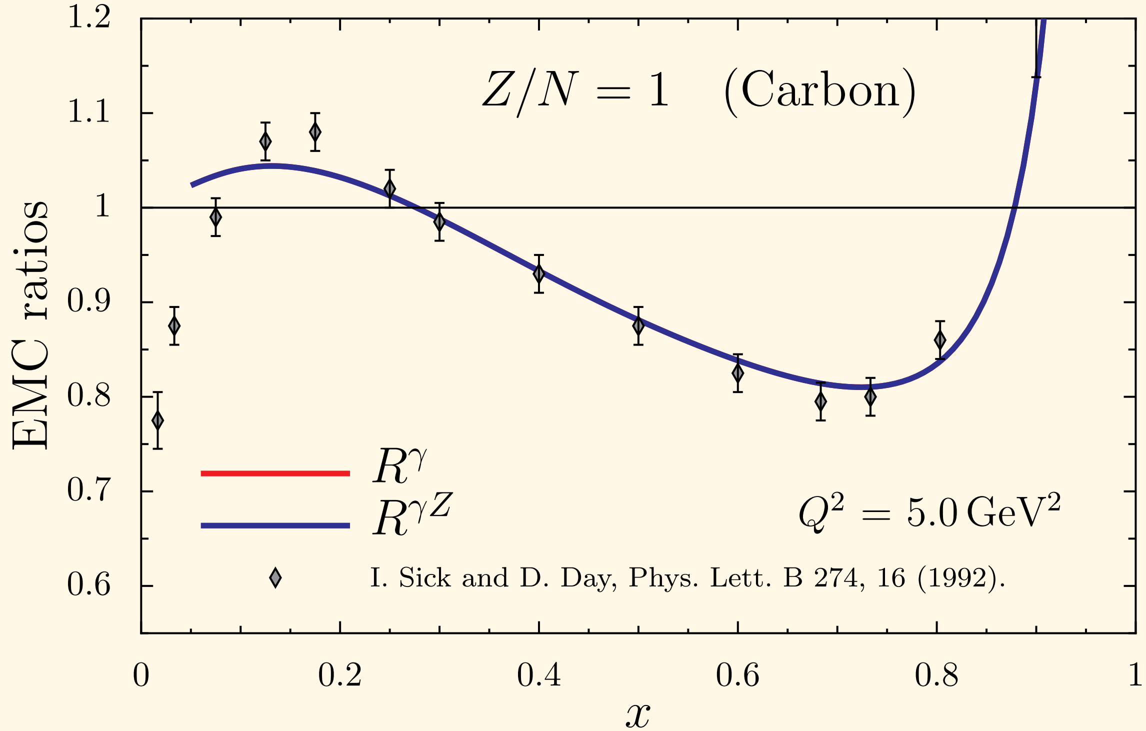
- Potentially important for experimental extraction of F_π





- May also be important for extracting G_E/G_M ratio from ^{4}He(e,e'p)^{3}H

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

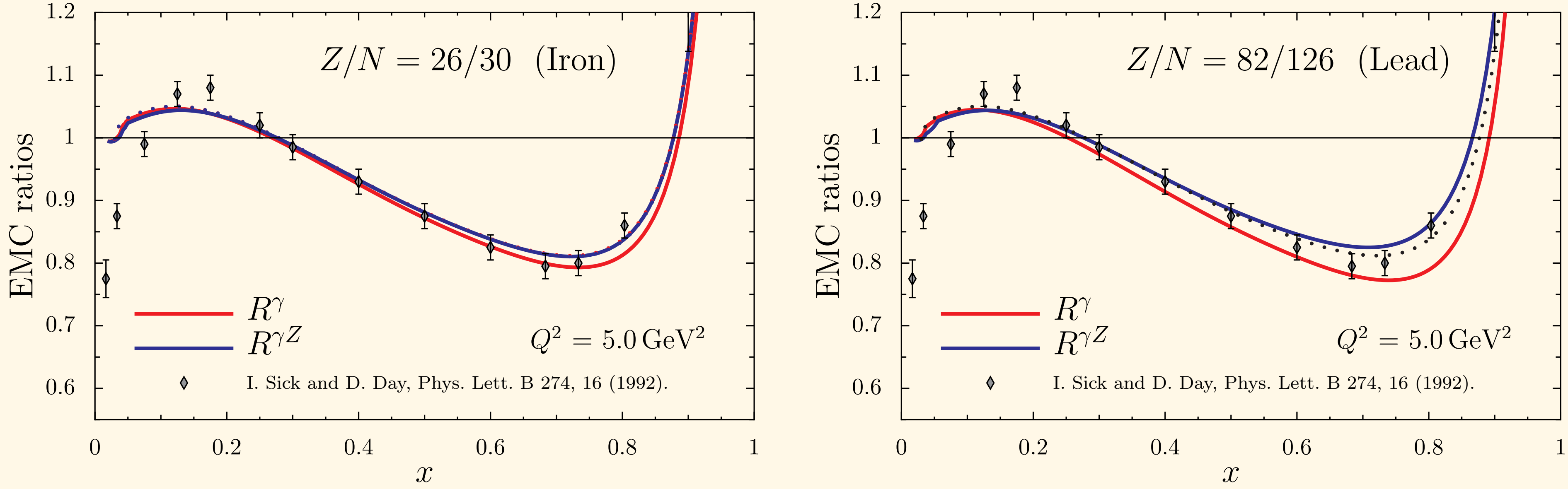


- Recall EMC ratio:

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

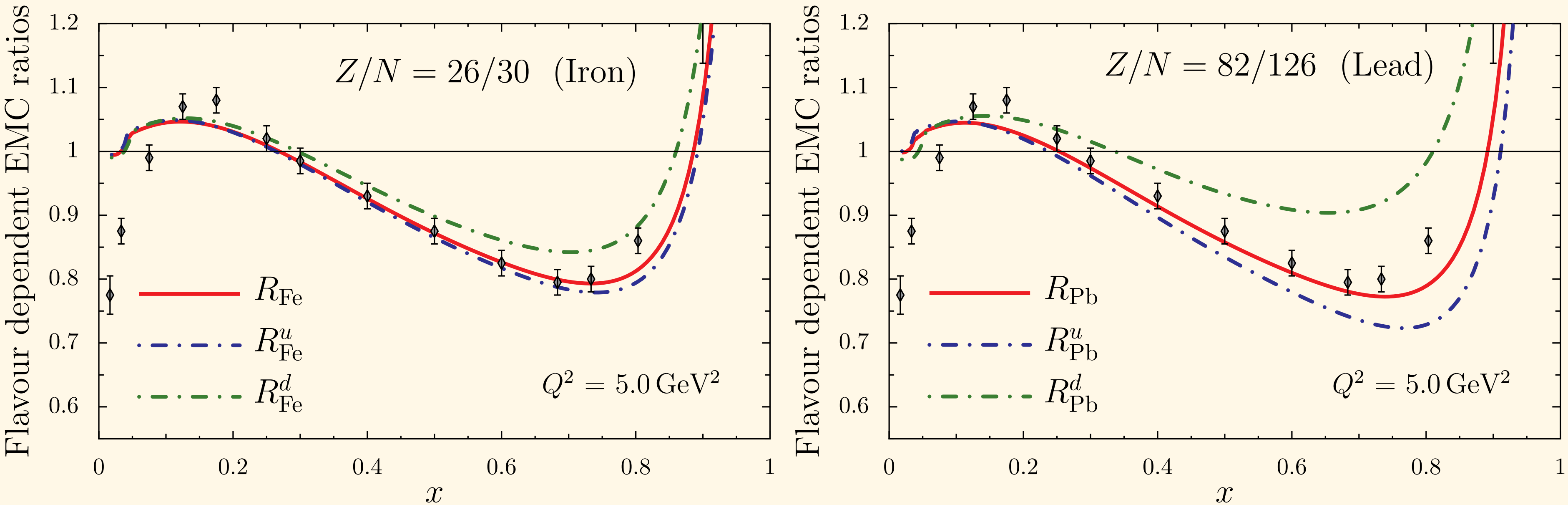
$$R^{\gamma} \sim \frac{4\,u_A(x) + d_A(x)}{4\,u_0(x) + d_0(x)}, \qquad R^{\gamma Z} \sim \frac{1.16\,u_A(x) + d_A(x)}{1.16\,u_0(x) + d_0(x)}$$

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



- $R^{\gamma} \sim \frac{4\,u_A(x)+d_A(x)}{4\,u_0(x)+d_0(x)}$ & $R^{\gamma Z} \sim \frac{1.16\,u_A(x)+d_A(x)}{1.16\,u_0(x)+d_0(x)}$
- Neutron rich – $Z/N < 1$:
  - $u_A(x) < d_A(x)$
  - medium modification of u_A increases & d_A decreases
- u_A dominates R^{γ} – however $R^{\gamma Z}$ almost isoscalar ratio
- ρ_0-field $\Longrightarrow R^{\gamma Z} > R^{\gamma}$ – Model Independent

Flavour Dependence of EMC effect



- Flavour dependence is defined above by

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

- Flavour dependence determined by measuring e.g. F_A^γ and $F_A^{\gamma Z}$
- If observed $\Longrightarrow$ strong evidence for medium modification