Hadron Phenomenology and QCDs DSEs

Lecture 6: *Nuclear Structure in Continuum Strong QCD*

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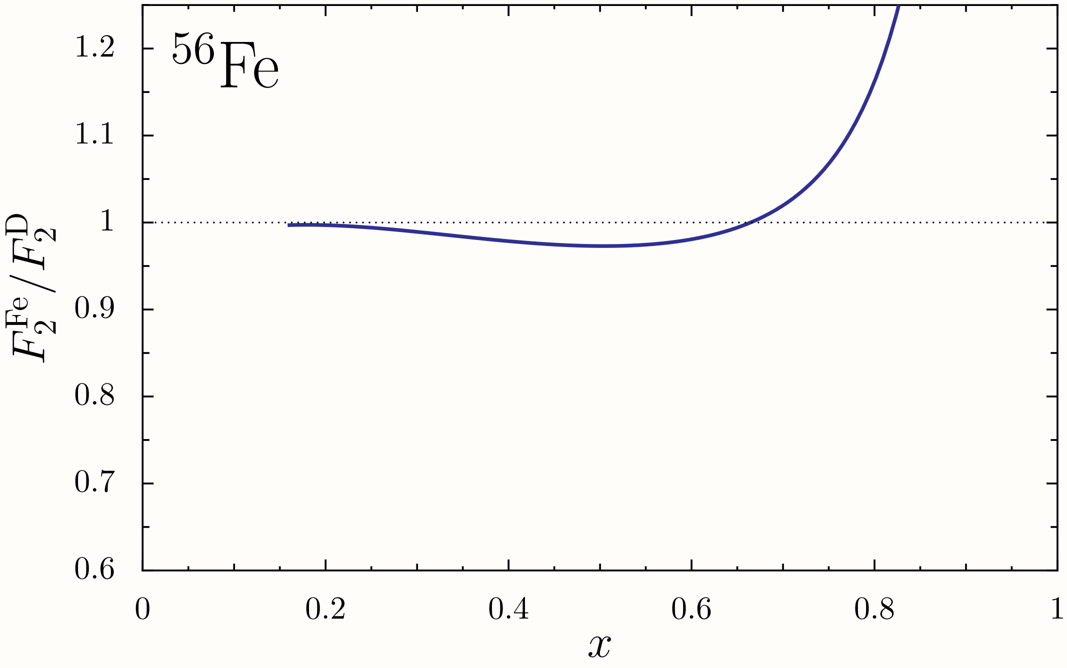
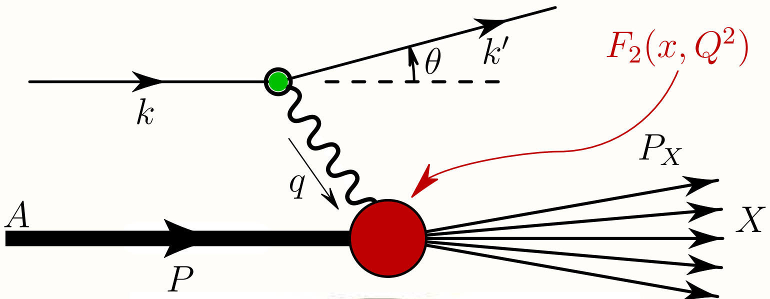
Why Nuclear Targets

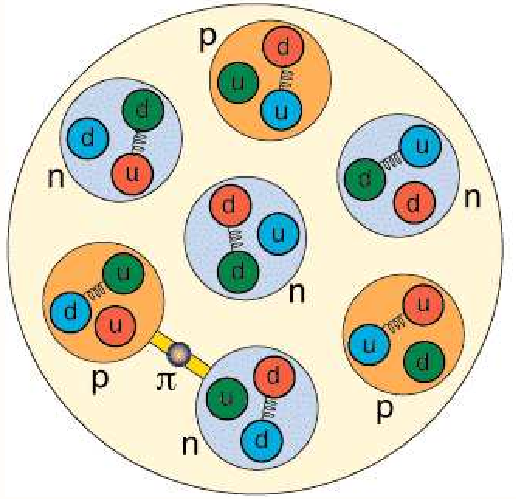
- One of the greatest challenges confronting nuclear physics is to understand how quarks and gluons give rise to nucleons and nuclei
  - need a deeper understanding than traditional nuclear physics
- What do we know?
  - no macroscopic coloured objects – quarks in nuclei seem to cluster within colour singlet objects
  - effective description in terms of bound nucleons and mesons works fairly well
  - “nucleons” held apart by short-range repulsion:
    - $d_s \sim 1.8$ fm & $r_p \sim 0.8$ fm
- Many open questions, for example:
  - what is the role of gluons in nuclei
  - when do non-nucleonic dof play an important role e.g. Δ’s
  - are off-shell effects important, etc . . .

EMC effect



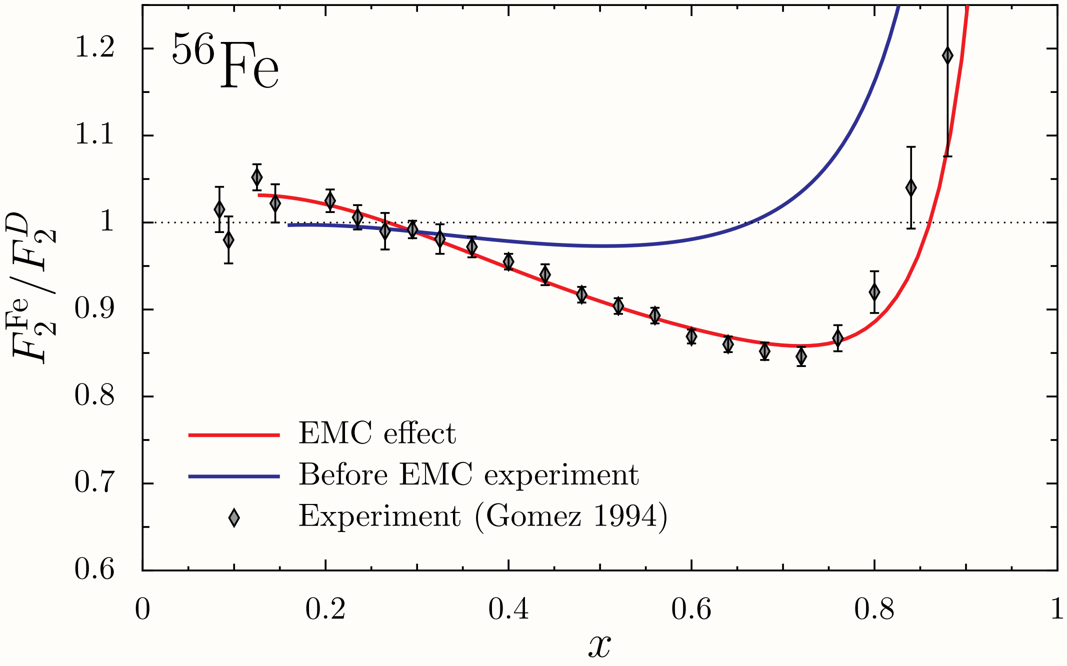
[J. J. Aubert *et al.* [European Muon Collaboration], Phys. Lett. B **123**, 275 (1983)]





- Fundamentally challenged our understanding of nuclear structure
- Immediate parton model interpretation:
  - ✦ valence quarks in nucleus carry less momentum than in nucleon
- What is the mechanism? After almost 30 years still no consensus
- *nuclear structure, pion excess, SR correlations, medium modification*
- Understanding EMC effect critical for QCD based description of nuclei

EMC effect



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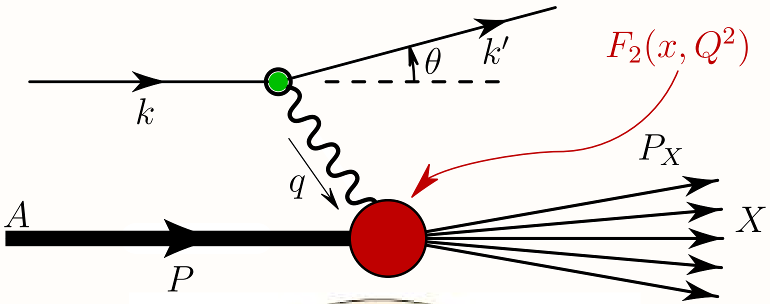

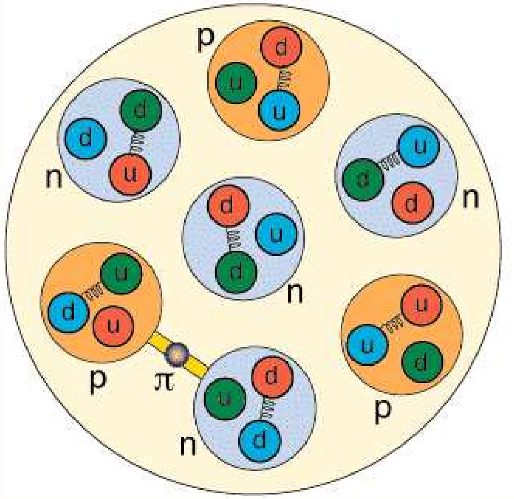

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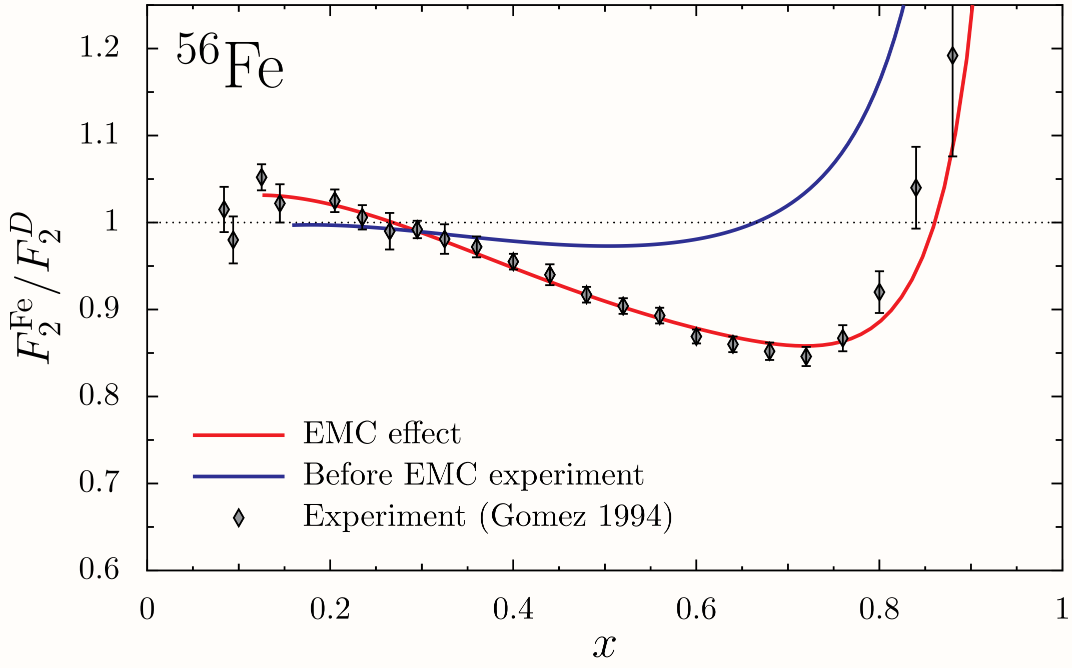

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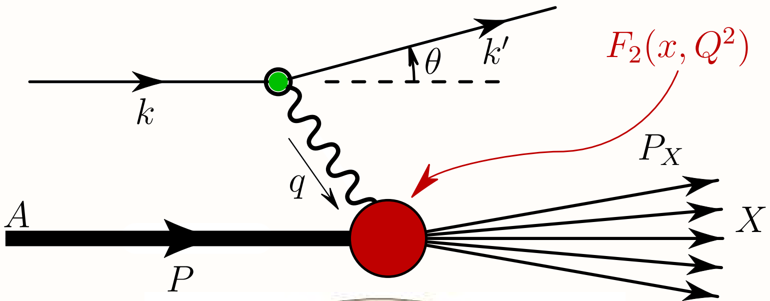
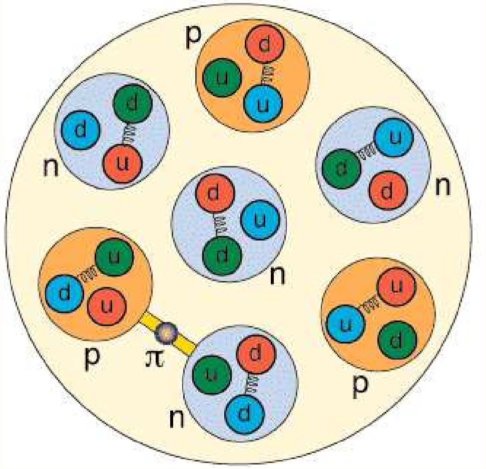




- Need new experiments accessing different aspects of the EMC effect
- Important near term measurements
  - flavour decomposition – SIDIS, PVDIS, Drell-Yan
  - spin-dependent nuclear PDFs – polarized DIS
  - in-medium form factors, response functions – quasi-elastic scattering
- To increase our understanding of the EMC effect, model builders should make robust predictions that can be tested in future experiments

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 – e.g.
  - ✦ 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

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

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

Medium Modification

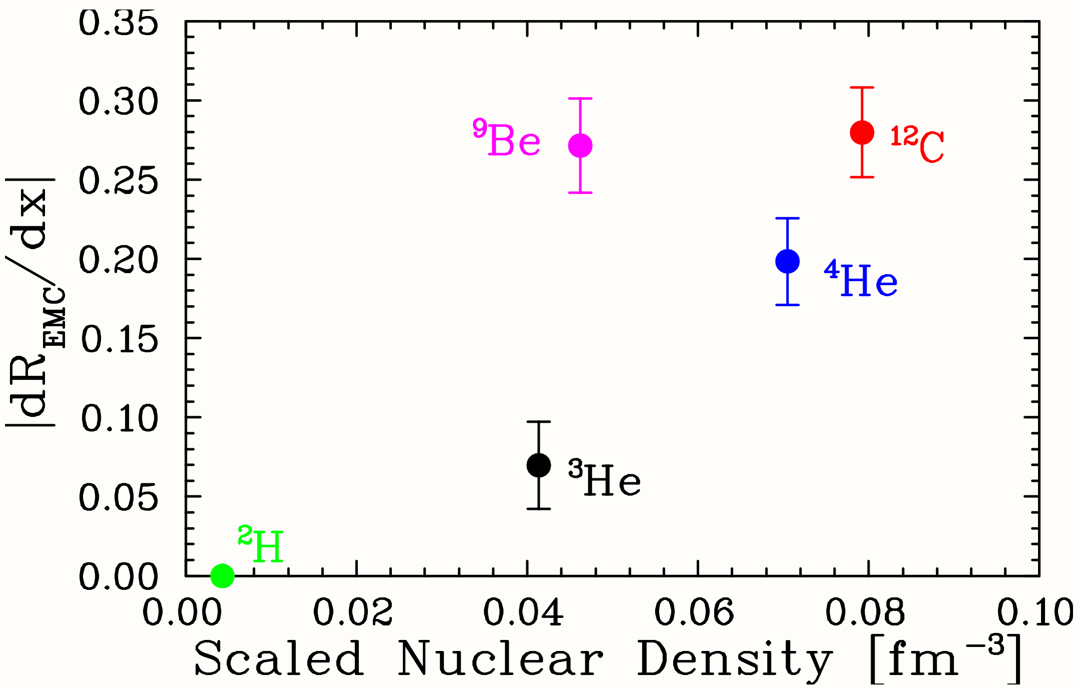
- 50 years of traditional nuclear physics tells us that the nucleus is composed of nucleon-like objects
- However if a nucleon property is not protected by a symmetry its value may change in medium – for example:
  - mass, magnetic moment, size
  - quark distributions, form factors, GPDs, etc
- There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

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

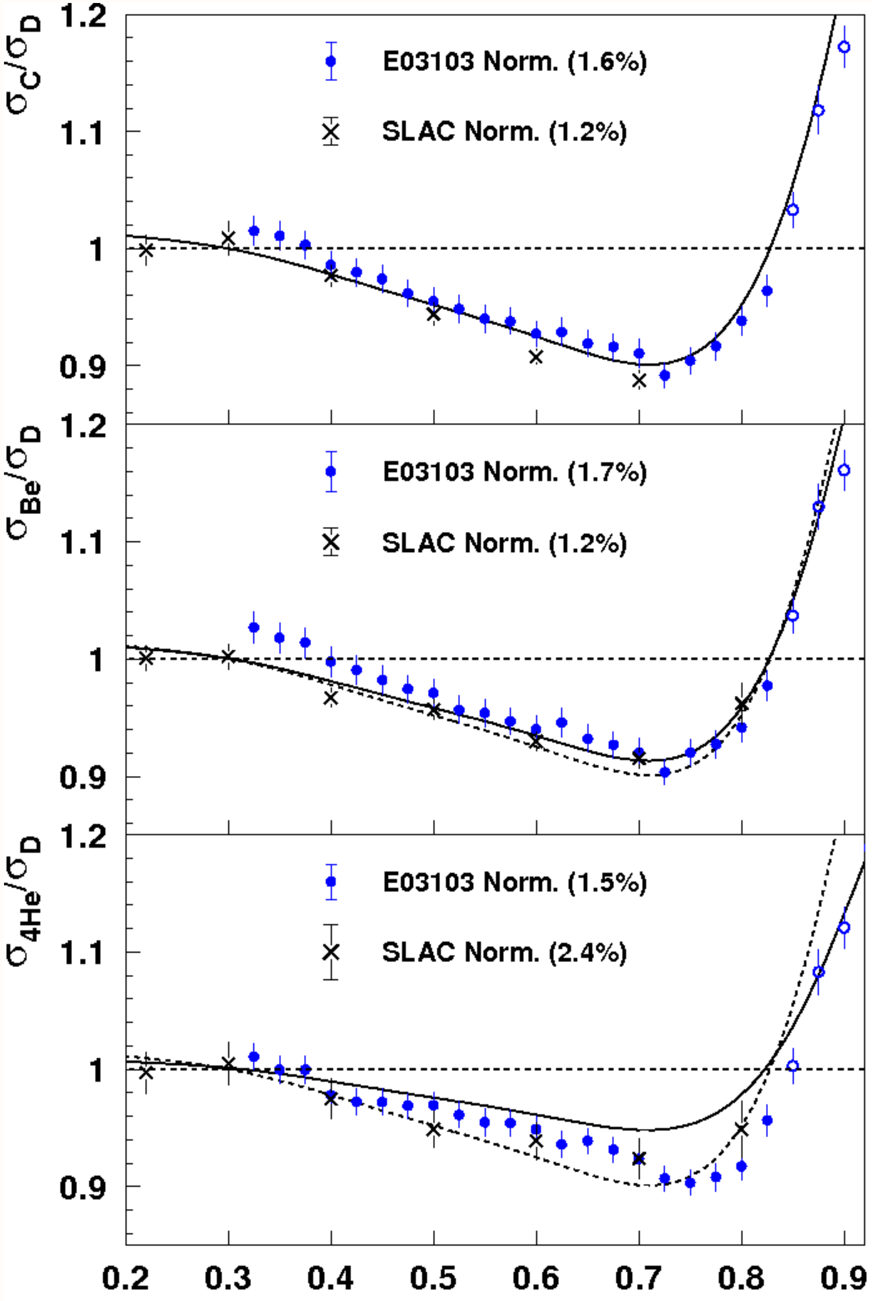
- Need to understand these effects as first step toward QCD based understanding of nuclei

EMC effect in light nuclei

- For theory to confront these results need sophisticated few & many body techniques
- Size of EMC effect determined by the *local density* not the average density or A: $R_{\text{He}} \simeq R_{\text{Be}} \simeq R_{\text{C}}$



[J. Seely *et al.*, Phys. Rev. Lett. **103**, 202301 (2009)]



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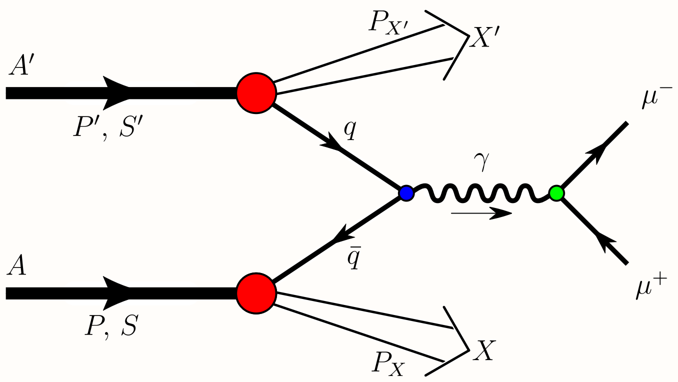
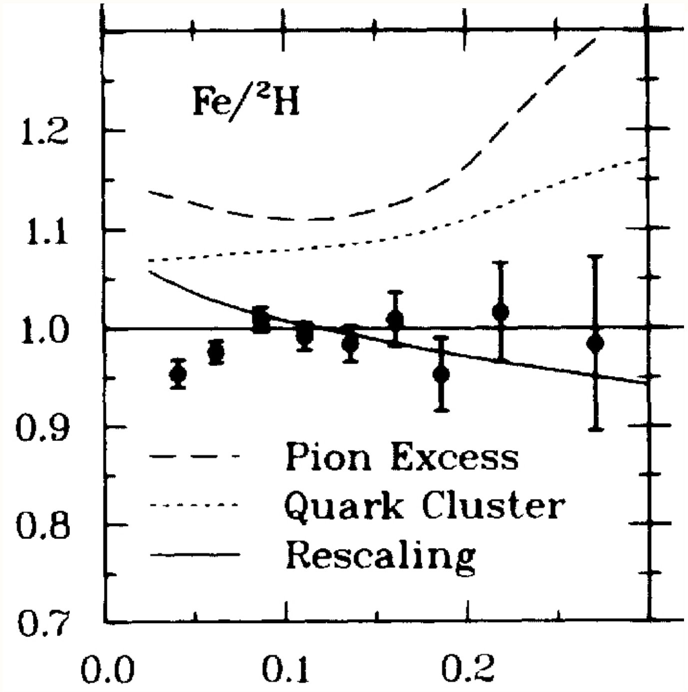
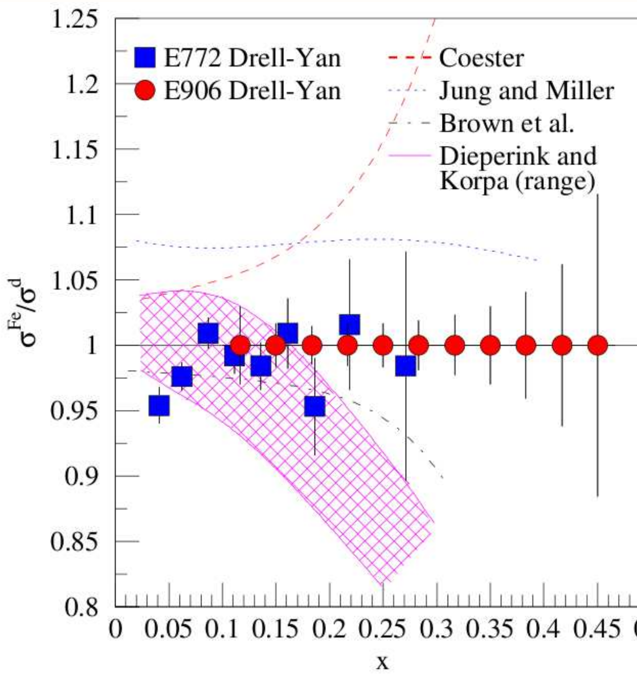
Anti-quarks in nuclei and Drell-Yan



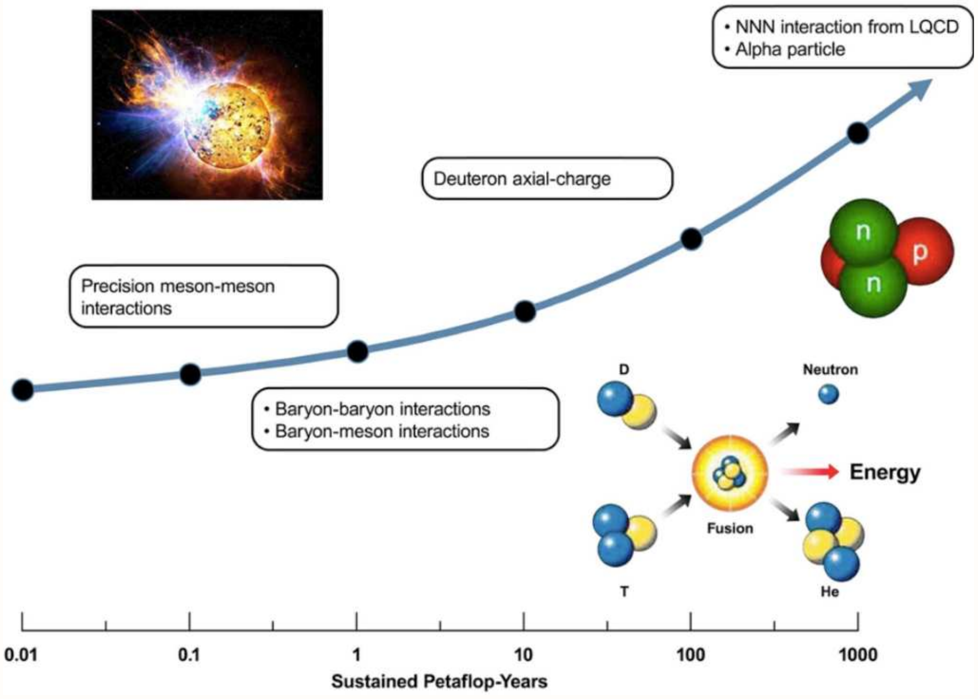


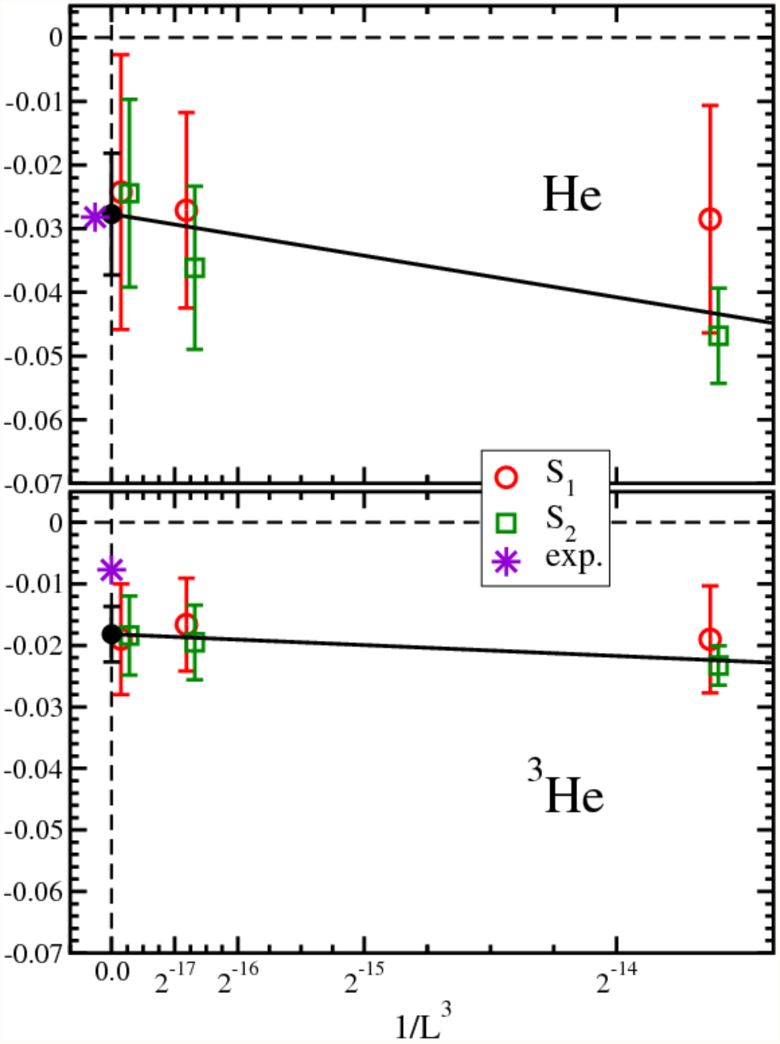


- Pions play a fundamental role in traditional nuclear physics
  - ✦ expect pion (anti-quark) enhancement in nuclei compared to nucleon
- Drell-Yan experiment set up to probe anti-quarks in target nucleus
  - ✦ $\bar{q}q \to \mu^+\mu^-$ – E906: running FNAL, [E772: Alde *et al.*, PRL. **64**, 2479 (1990).]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

Lattice QCD and nuclear physics

- Lattice QCD is beginning to make inroads into nuclear physics
  - ✦ primarily binding energies
- Calculations require huge computational resources $\gtrsim$ 10yrs





- Quenched, $m_\pi \sim 800$ MeV
- S. R. Beane, *et al.*, Prog. Part. Nucl. Phys. **66**, 1-40 (2011).
- PACS-CS Collaboration, Phys. Rev. **D81**, 111504 (2010).

DIS on Nuclear Targets

- Why nuclear targets?
  - ✦ only targets with $J > \frac{1}{2}$ 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: $-J \leqslant H \leqslant J$ [$2J+1$ DIS 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]

$$g^H_{1A}(x_A) = \tfrac{1}{2} \sum\nolimits_q e_q^2 \left[\Delta q^H_A(x_A) + \Delta \bar{q}^H_A(x_A) \right]; \quad \text{parity} \implies g^H_{1A} = -g^{-H}_{1A}$$

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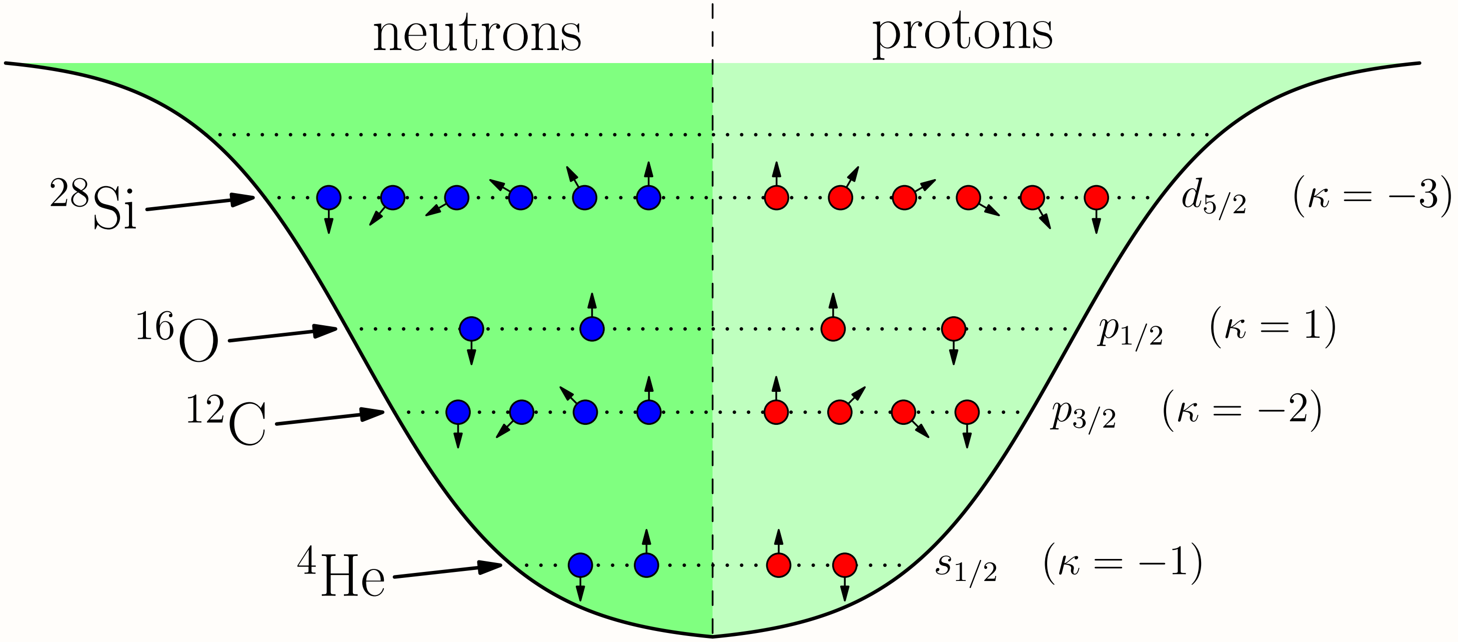
Finite nuclei quark distributions

- Definition of finite nuclei quark distributions

$$\Delta q_A^H(x_A) = \frac{P^+}{A}\int \frac{d\xi^-}{2\pi} e^{iP^+ x_A \xi^-/A}\langle A, P, H|\overline{\psi}_q(0)\,\gamma^+\gamma_5\,\psi_q(\xi^-)|A, P, H\rangle$$

- Approximate using a modified convolution formalism

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



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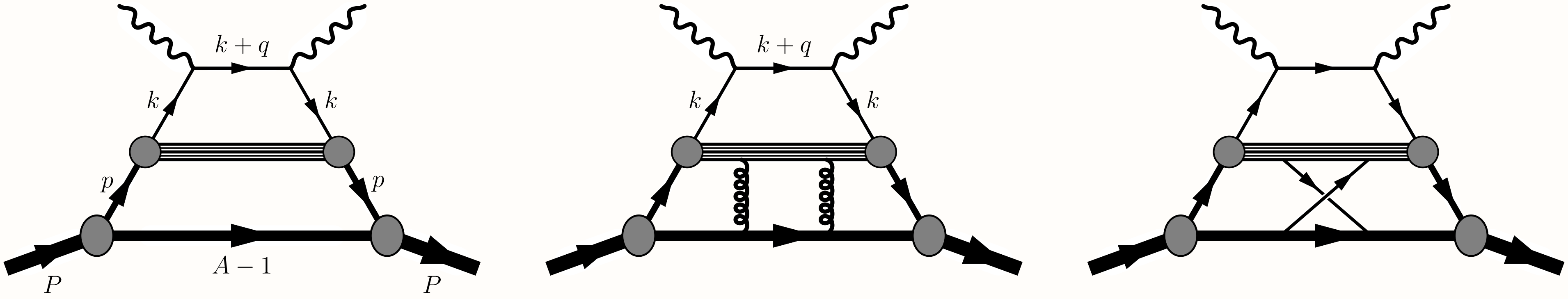
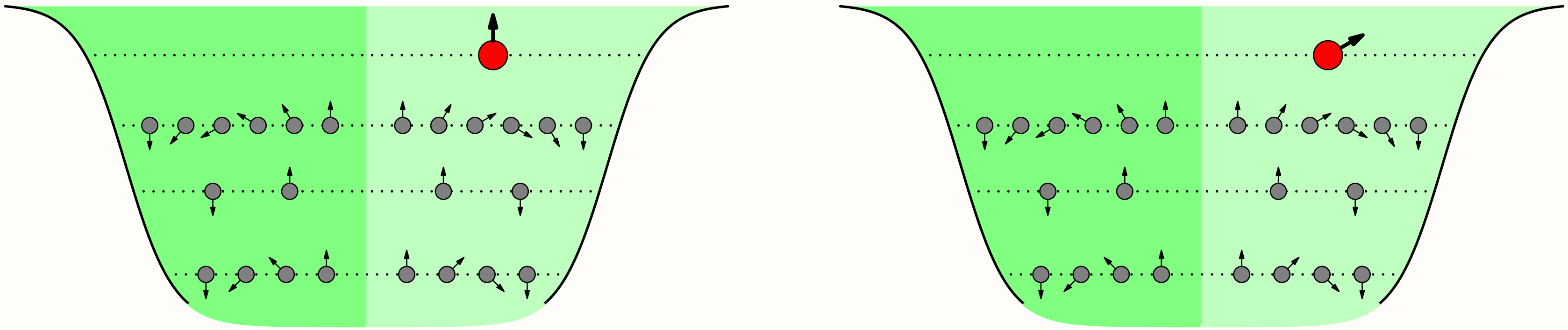
- Convolution formalism diagrammatically:



Convolution Formalism: implications

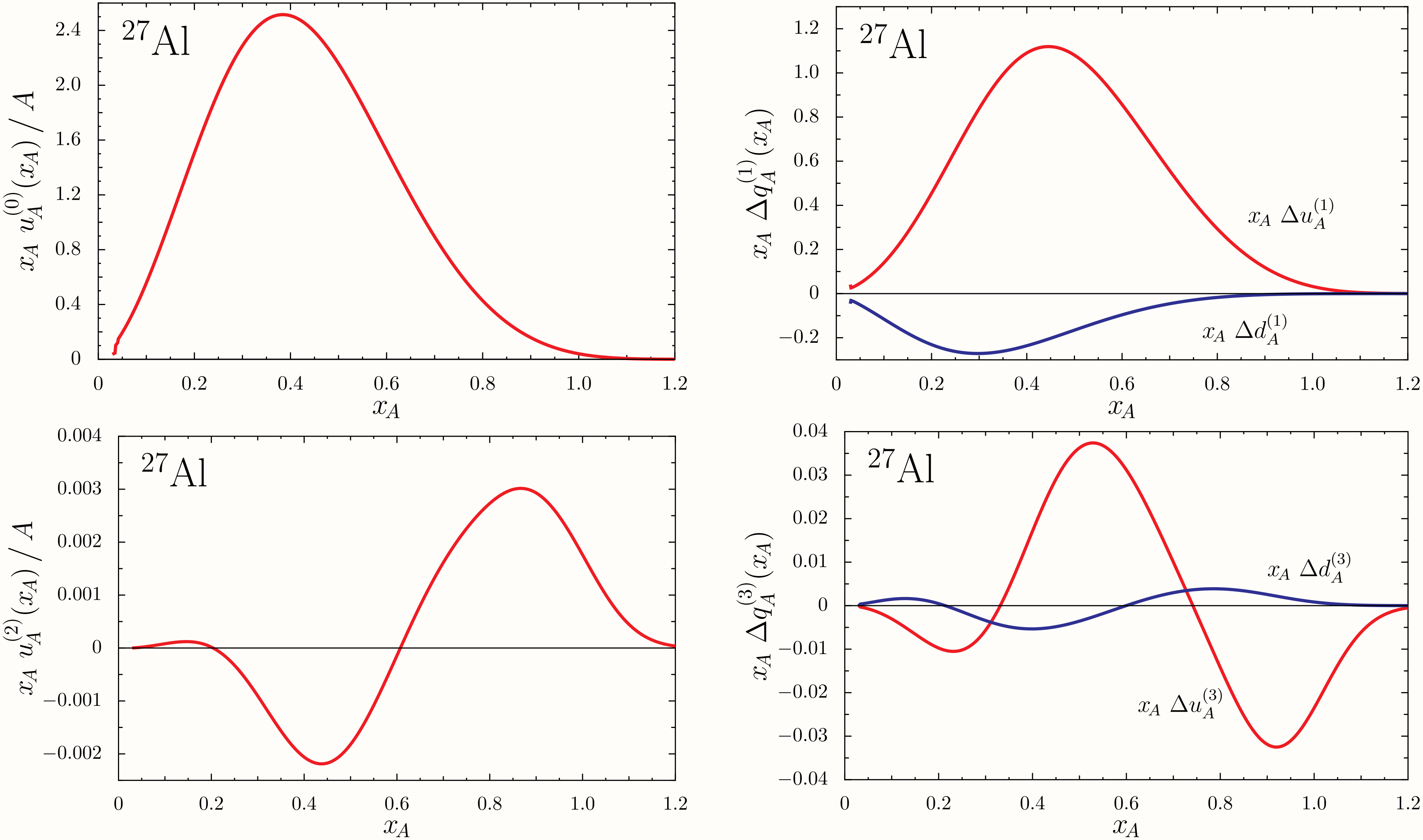


- Assume all spin is carried by the valence nucleons
  - ✦ if $A \gtrsim 8$ and for example if: $J = \frac{3}{2} \quad \Longrightarrow \quad F_{2A}^{3/2} \simeq F_{2A}^{1/2}$
- Basically a model independent result within the convolution formalism
- Introduce multipole quark distributions

$$q^{(K)}(x) \equiv \sum_H (-1)^{J-H} \sqrt{2K+1} \begin{pmatrix} J & J & K \\ H & -H & 0 \end{pmatrix} q^H(x), \quad K = 0, 2, \ldots, 2J$$

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

Multipole quark distributions results



- 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:

$$J = \tfrac{3}{2} \implies \Big\langle \Delta q^{(3)}(x) \Big\rangle = 0$$

$$J = 2 \implies \Big\langle q^{(4)}(x) \Big\rangle = \Big\langle \Delta q^{(3)}(x) \Big\rangle = 0$$

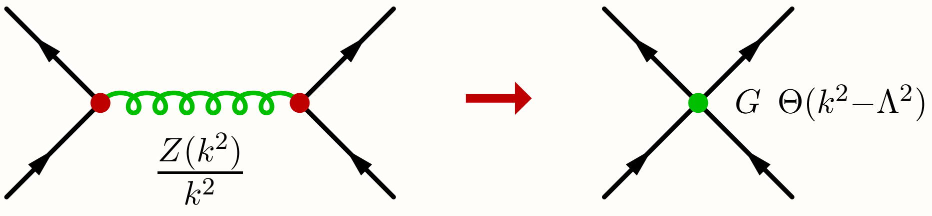
$$J = \tfrac{5}{2} \implies \Big\langle q^{(4)}(x) \Big\rangle = \Big\langle \Delta q^{(3)}(x) \Big\rangle = \Big\langle \Delta q^{(5)}(x) \Big\rangle = \Big\langle x^2\, \Delta q^{(5)}(x) \Big\rangle = 0$$

- 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

- A low energy chiral effective theory of QCD

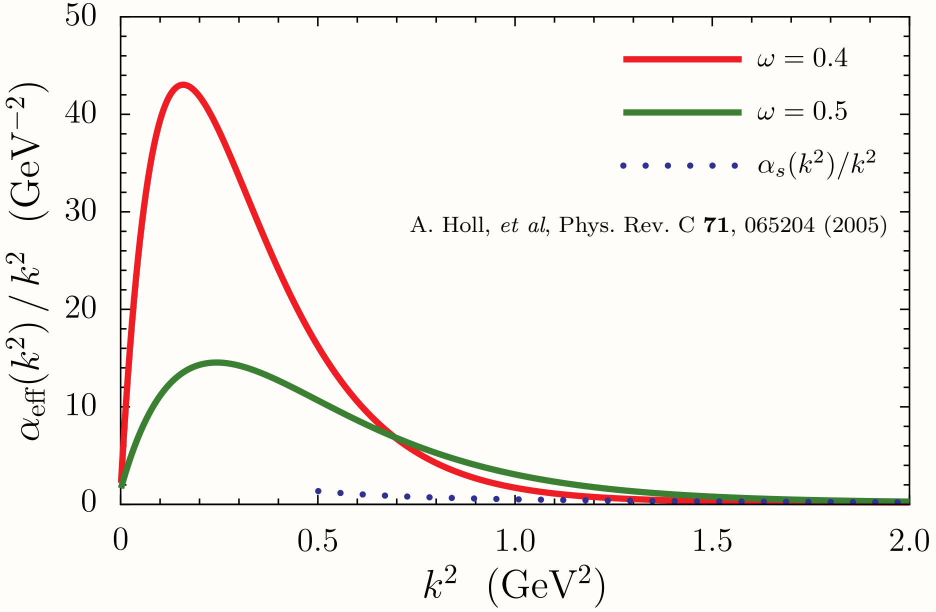


$$\mathcal{L} = \bar{\psi}_q\left(i\not{\partial} - m\right)\psi_q + G\left(\bar{\psi}_q\,\Gamma\,\psi_q\right)^2$$

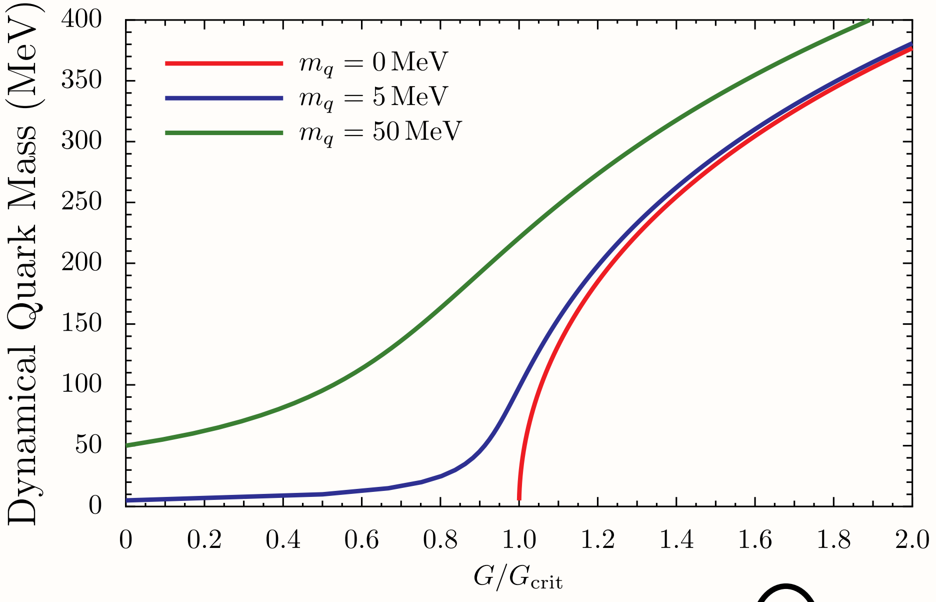
- Dynamically generated quark masses $\Leftrightarrow$ $\langle\bar{\psi}\psi\rangle \neq 0$ $\Leftrightarrow$ DCSB
- Proper-time regularization: Λ_{IR} & Λ_{UV} $\Longrightarrow$ Confinement
- For example: quark propagator

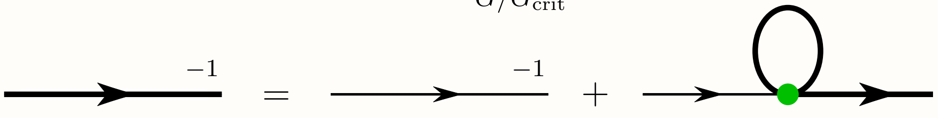
$$\frac{1}{\not{p} - m + i\varepsilon} \rightarrow \frac{Z(p^2)}{\not{p} - M + i\varepsilon}$$

✦ on mass-shell: $Z(p^2 = M^2) = 0$



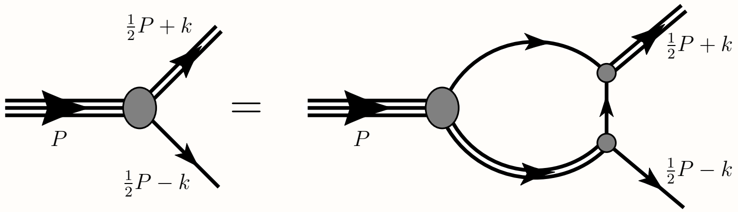
A. Holl, *et al*, Phys. Rev. C **71**, 065204 (2005)



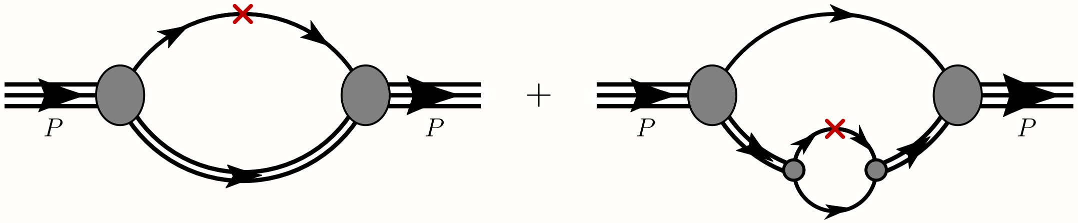


Nucleon quark distributions

- Nucleon $=$ quark+diquark



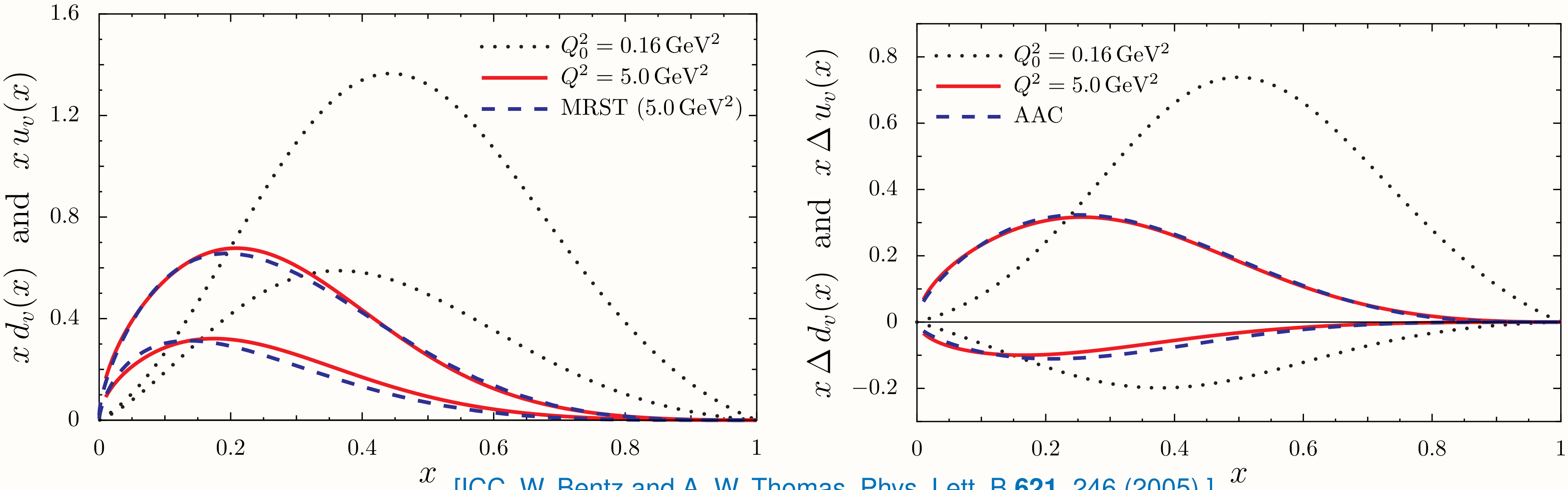
- PDFs given by Feynman diagrams: $\langle\gamma^+\rangle$



- Covariant, correct support; satisfies sum rules, Soffer bound & positivity

$$\langle q(x) - \bar{q}(x)\rangle = N_q, \quad \langle x\, u(x) + x\, d(x) + \ldots\rangle = 1, \quad |\Delta q(x)|\,,\ |\Delta_T q(x)| \leqslant q(x)$$

- $q(x)$: probability strike quark of favor q with momentum fraction x of target



[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **621**, 246 (2005).]

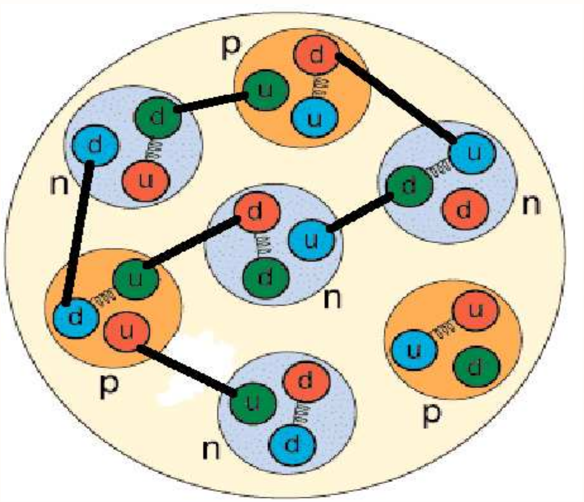
Asymmetric nuclear matter

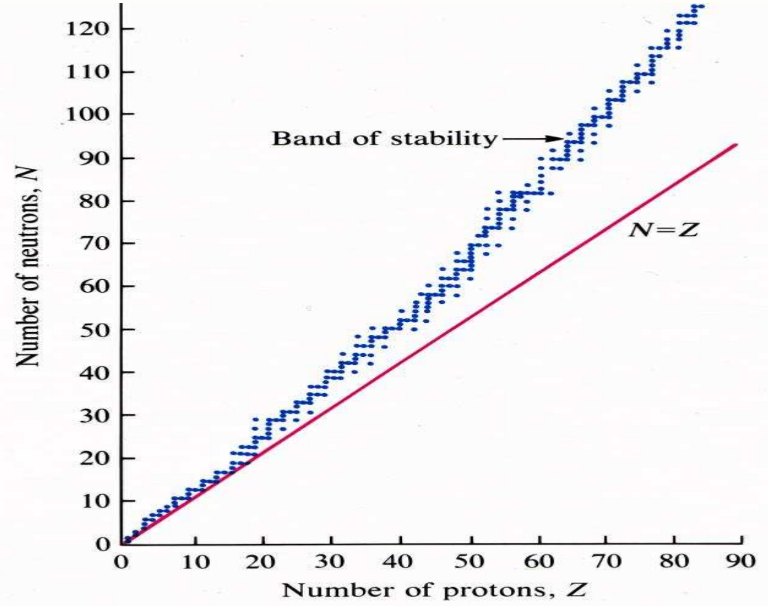
- Finite density Lagrangian: $\bar{q}q$ interaction in $\sigma,\ \omega,\ \rho$ channels

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

[W. Bentz, A.W. Thomas, Nucl. Phys. A **696**, 138 (2001)]

Fundamental idea: mean-fields couple to quarks in bound nucleons



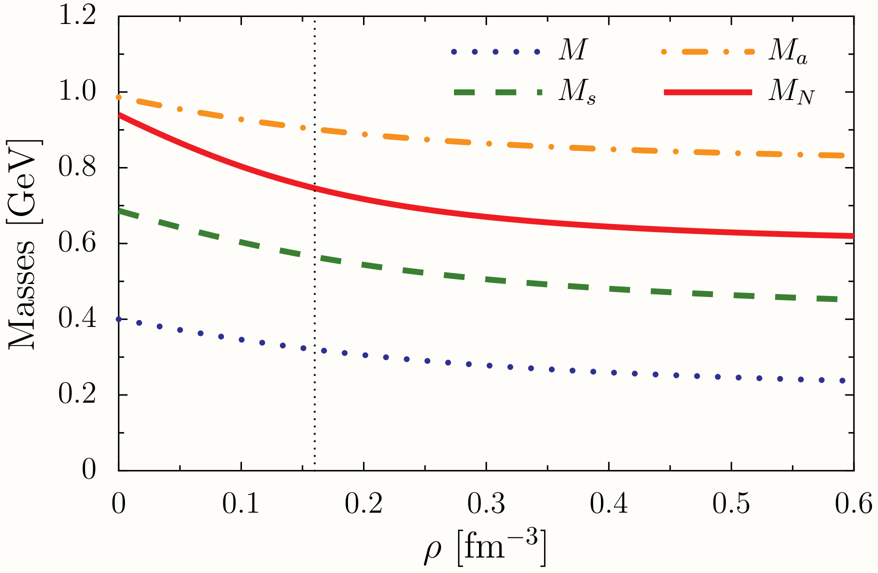


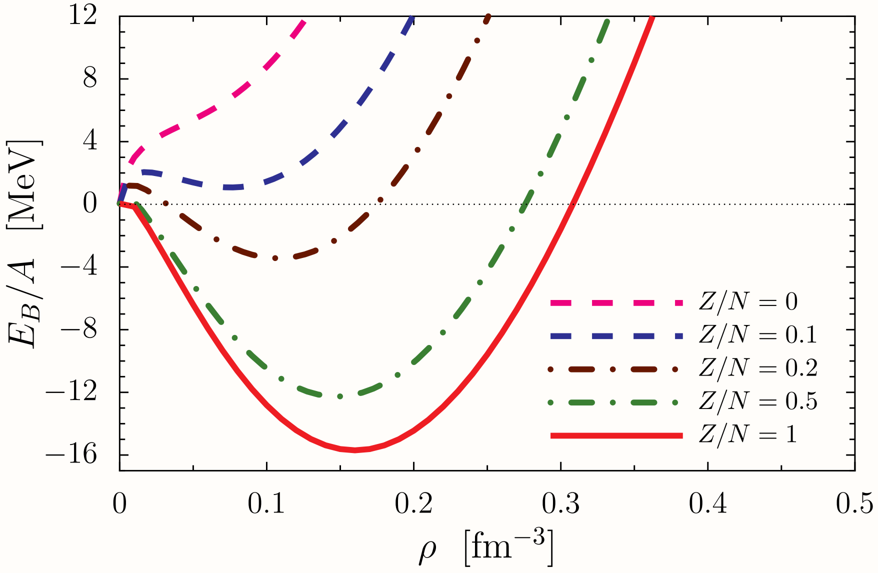
- Quark propagator: $S^{-1} = \not k - M + i\varepsilon \ \rightarrow\ S_q^{-1} = \not k - M^* - \not V_q + i\varepsilon$
- Hadronization + mean–field $\Longrightarrow$ effective potential

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

✦ $G_\omega \Longleftrightarrow Z = N$ saturation & $G_\rho \Longleftrightarrow$ symmetry energy

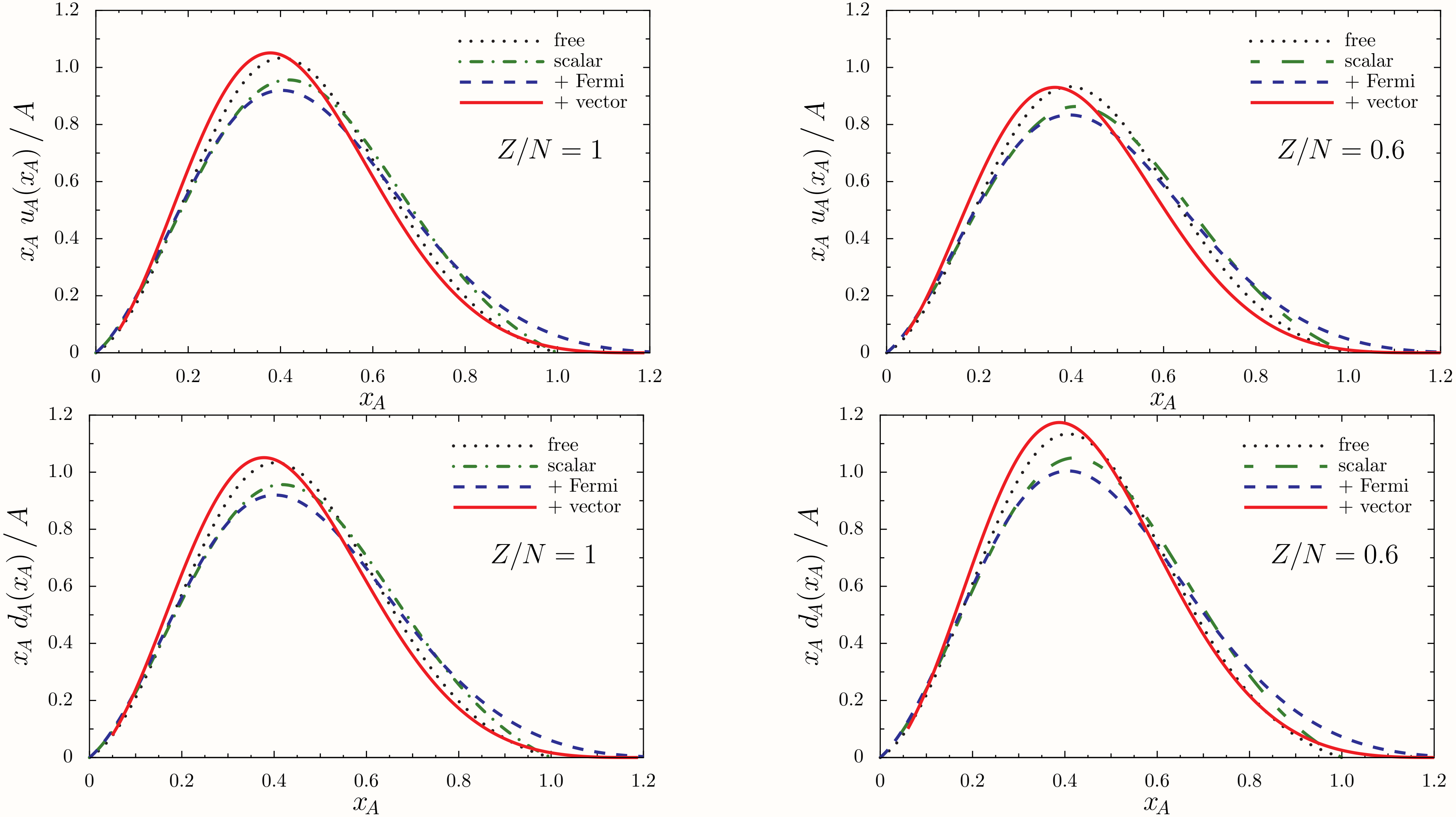
Nuclear matter results





- Constituent mass: $M^* = m - 2\,G_\pi \langle\overline{\psi}\psi\rangle^*$
  - small restoration of chiral symmetry: $|\langle\overline{\psi}\psi\rangle^*| < |\langle\overline{\psi}\psi\rangle|$
- Curvature [“scalar polarizability”] important for saturation
  - prevents chiral collapse
- 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 $\sigma,\ \omega,\ \rho$ mean-fields

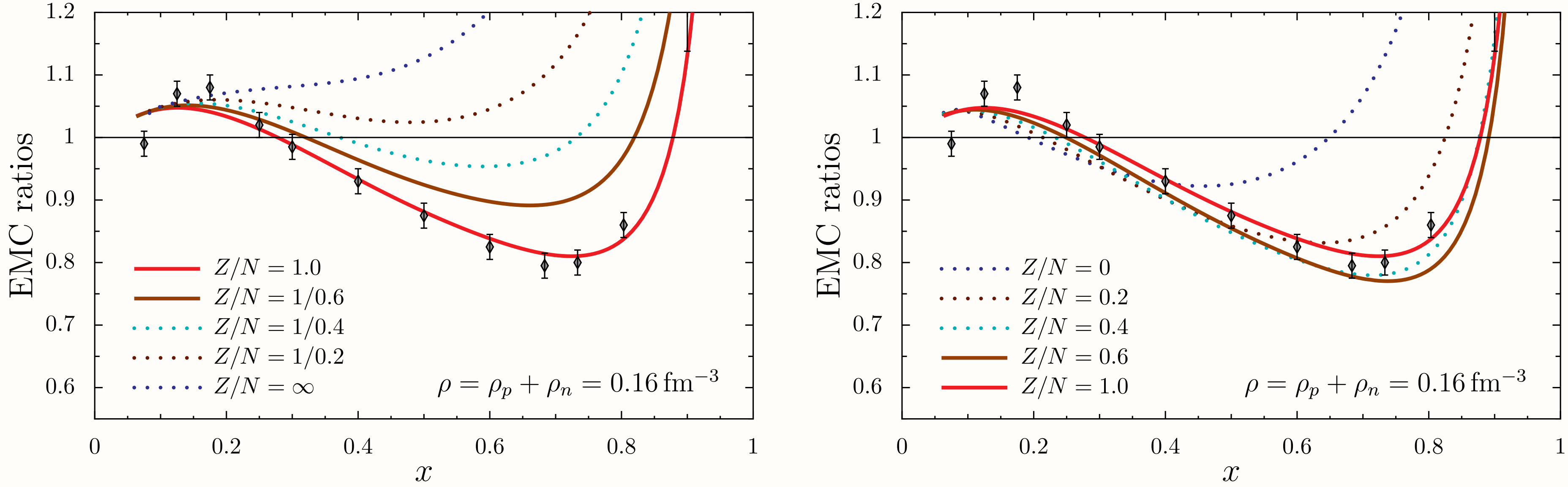
Nuclear matter PDFs



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

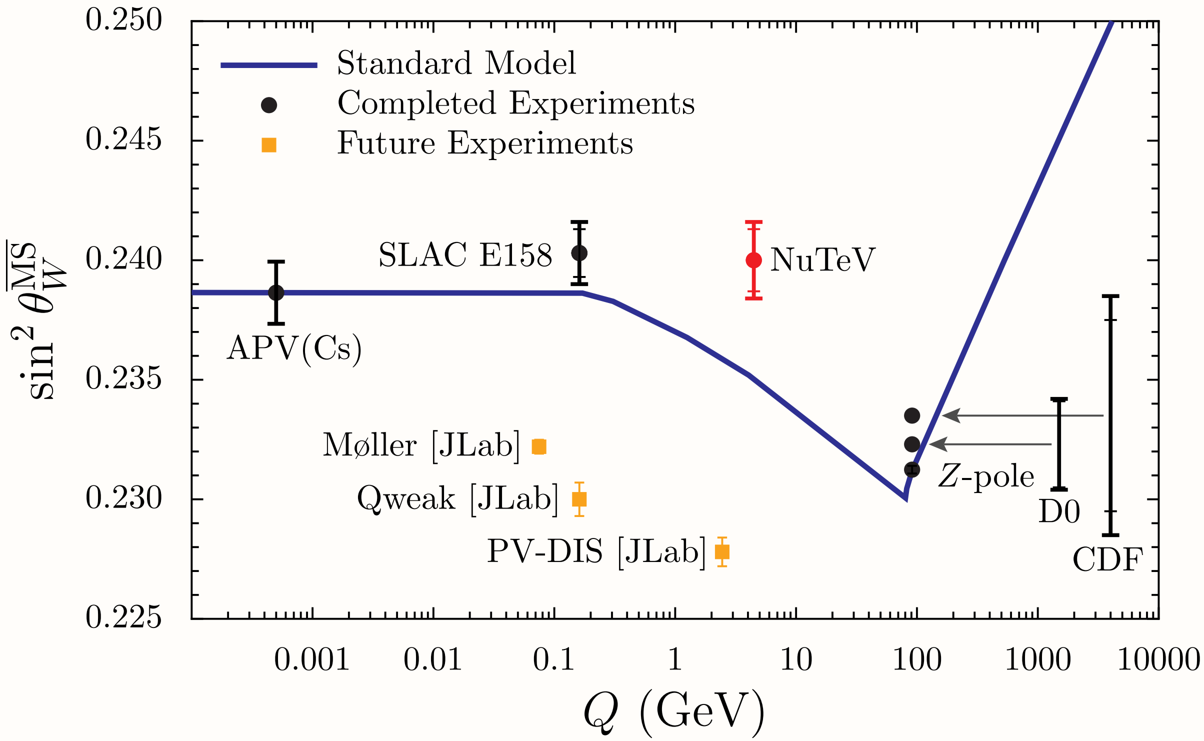
Isovector EMC effect

[ICC, W. Bentz and A. W. Thomas, Phys. Rev. Lett. **102**, 252301 (2009).]



- EMC ratio: $R = \dfrac{F_{2A}}{F_{2A,\text{naive}}} = \dfrac{F_{2A}}{Z\,F_{2p} + N\,F_{2n}} \simeq \dfrac{4\,u_A(x) + d_A(x)}{4\,u_f(x) + d_f(x)}$
- Density is fixed only changing Z/N ratio [therefore only ρ_0 is changing]
- 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



Fermilab press conference

"The predicted value was 0.2227. The value we found was 0.2277, a difference of 0.0050. It might not sound like much, but the room full of physicists fell silent when we first revealed the result"

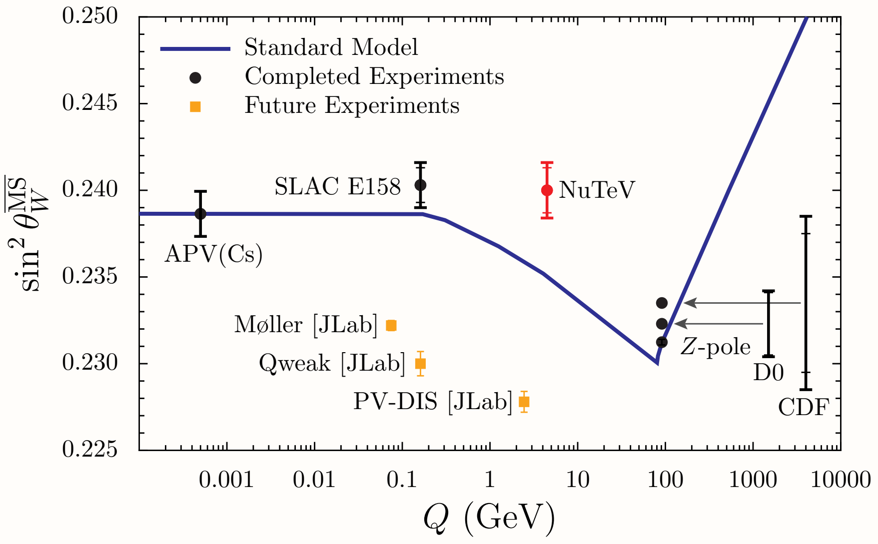
"99.75% probability that the neutrinos are not behaving like other particles . . . only 1 in 400 chance that our measurement is consistent with prediction"

- 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)]

- Standard Model: $\sin^2\theta_W = 0.2227 \pm 0.0004$ $\Leftrightarrow 3\sigma \Longrightarrow$ "NuTeV anomaly"
- Huge amount of experimental & theoretical interest [500+ citations]
- No universally accepted *complete* explanation
- Z-pole (LEP & SLC) $e^+e^- \to X$, D0 & CDF at Fermilab: $\bar{p}p \to e^+e^-$

Weak mixing angle and the NuTeV anomaly



- NuTeV: $\sin^2\theta_W = 0.2277 \pm 0.0016$

[G. P. Zeller *et al.* Phys. Rev. Lett. **88**, 091802 (2002).]

- SM: $\sin^2\theta_W = 0.2227 \pm 0.0004$
- Evidence for physics beyond the Standard Model?

- Paschos-Wolfenstein ratio motivated NuTeV study:

$$R_{PW} = \frac{\sigma^{\nu A}_{NC} - \sigma^{\bar\nu A}_{NC}}{\sigma^{\nu A}_{CC} - \sigma^{\bar\nu A}_{CC}} \overset{N\sim Z}{=} \frac{1}{2} - \sin^2\theta_W + \left(1 - \frac{7}{3}\sin^2\theta_W\right)\frac{\langle x\, u^-_A - x\, d^-_A\rangle}{\langle x\, u^-_A + x\, d^-_A\rangle}$$

- NuTeV used a steel target – $Z/N \simeq 26/30$
  - ✦ correct for neutron excess ⟺ flavour dependent EMC effect

- Use our medium modified *Iron* quark distributions

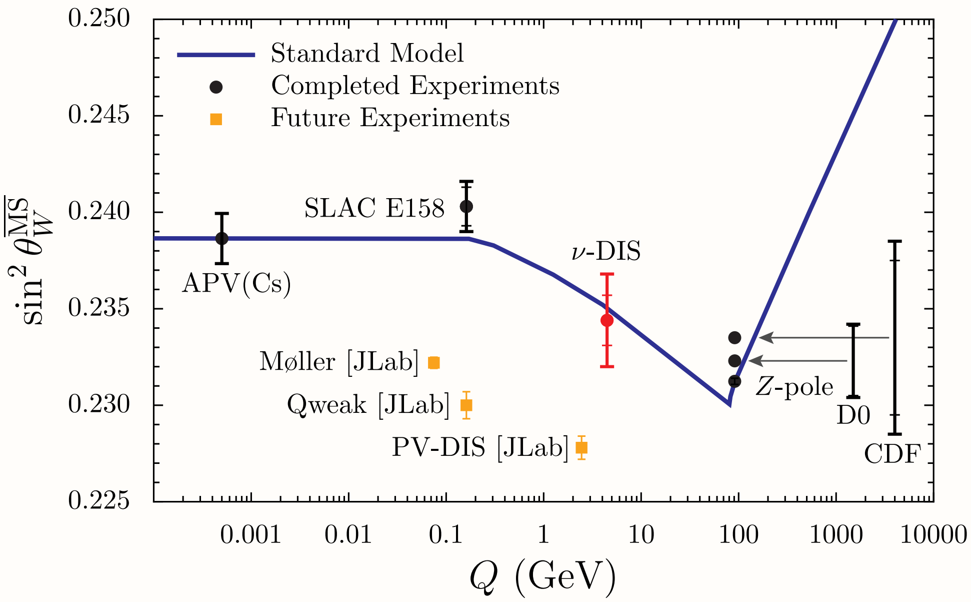
$$\Delta R_{PW} = \Delta R_{PW}^{\text{naive}} + \Delta R_{PW}^{\text{EMC effect}} = -\left(0.0107 + 0.0032\right).$$

- Flavour dependent of EMC effect explains up to 65% of anomaly

Reassessment of the NuTeV anomaly

- Also include corrections:
  - charge symmetry violation:

    $m_u \neq m_d \quad \& \quad e_u \neq e_d$
  - strange quarks
- Use NuTeV functionals
- "NuTeV anomaly" is evidence for medium modification

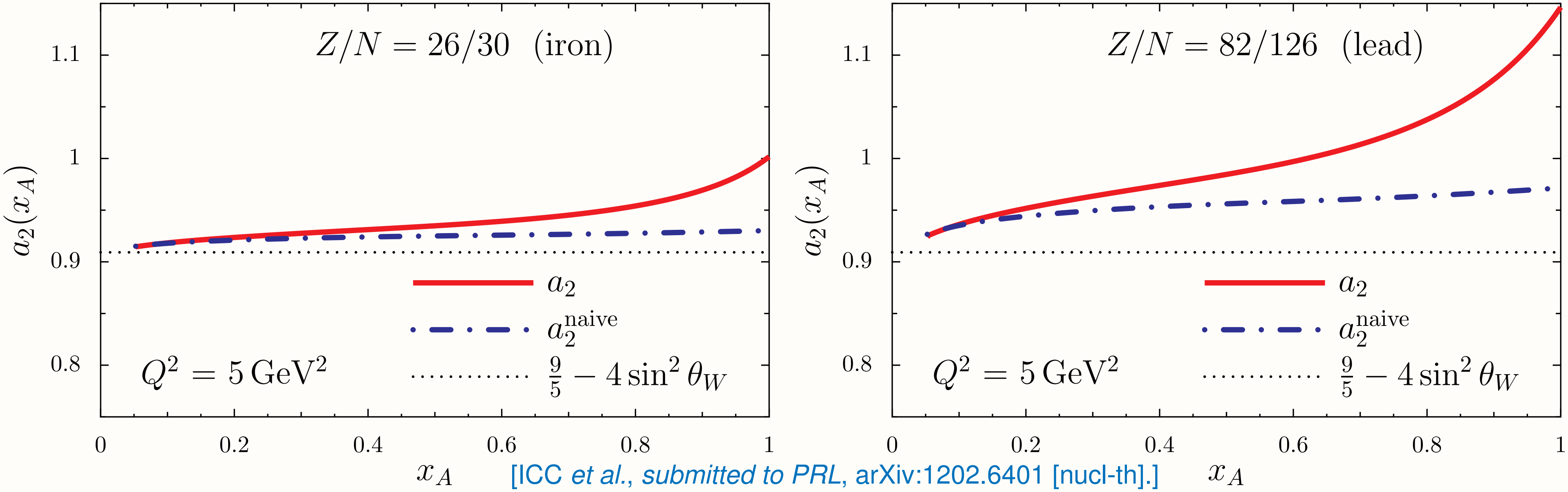


[ICC, J. T. Londergan *et al.*, Phys. Lett. B **693**, 462 (2010).]

- Model dependence?
  - sign of correction is fixed by nature of vector fields

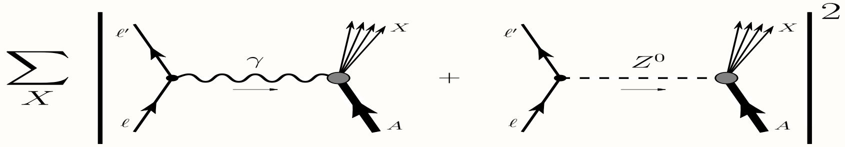
    $$q(x) = \frac{p^+}{p^+ - V^+}\, q_0\left(\frac{p^+}{p^+ - V^+}\, x - \frac{V_q^+}{p^+ - V^+}\right), \qquad N > Z \implies V_d > V_u$$
  - ρ^0-field shifts momentum from u to d quarks
  - R_{PW} correction term negative $\implies \sin^2\theta_W$ decreases
  - size of correction is constrained by nuclear matter symmetry energy
- ρ_0 vector field reduces NuTeV anomaly – model independent!

Parity Violating DIS: Iron & Lead



[ICC *et al.*, *submitted to PRL*, arXiv:1202.6401 [nucl-th].]

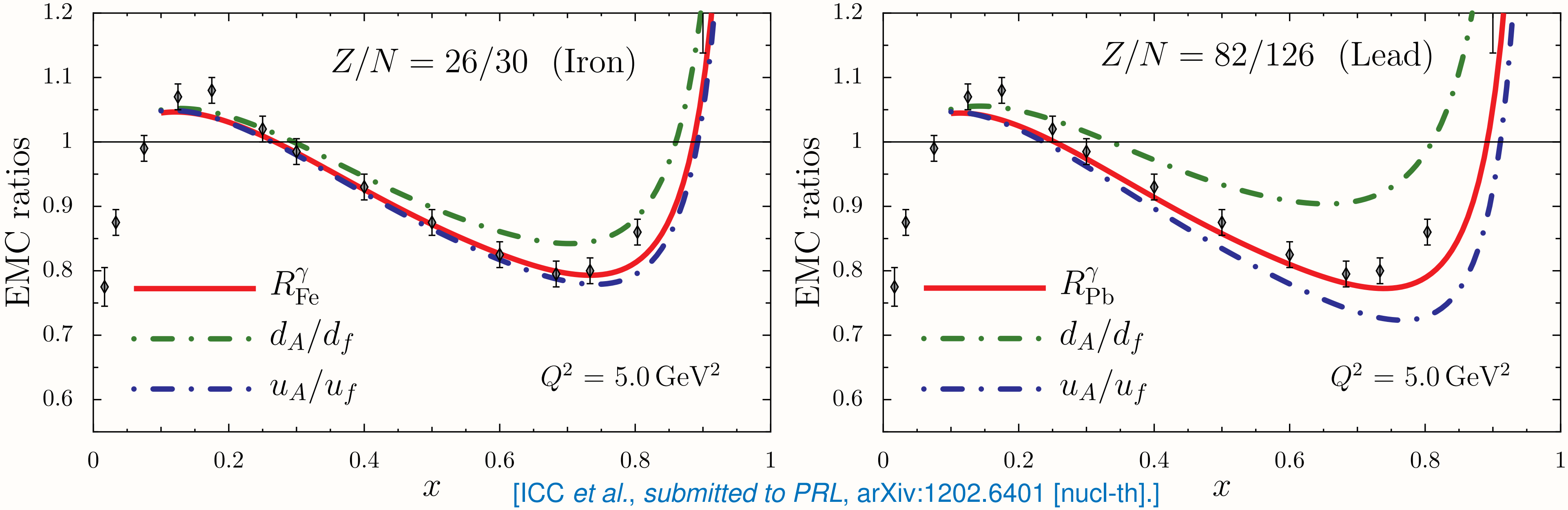
- PV DIS – $\gamma\, Z$ interference:



$$A_{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} \propto a_2(x) = -\,2 g_A^e\, \frac{F_2^{\gamma Z}}{F_2^{\gamma}} \overset{N\sim Z}{=} \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\, \frac{u_A^+(x) - d_A^+(x)}{u_A^+(x) + d_A^+(x)}$$

- Same mechanism explains ~1.5σ of NuTeV result
- Large x dependence of $a_2(x)$ → evidence for medium modification
- $a_2(x)$ is also a excellent way to measure $\sin^2\theta_W$
- Predictions will be tested at Jefferson Lab

Flavour dependence of EMC effect



[ICC *et al.*, *submitted to PRL*, arXiv:1202.6401 [nucl-th].]

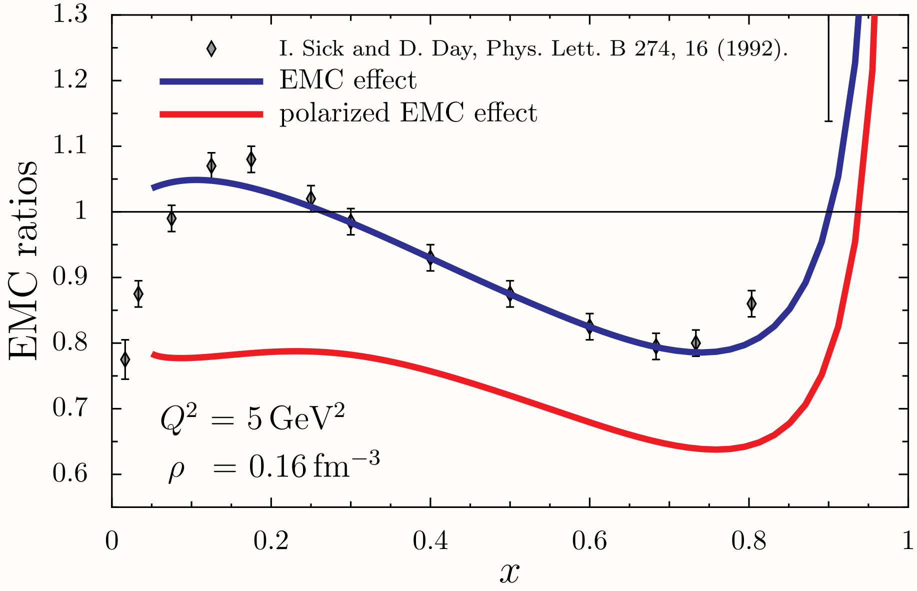
- Flavour dependence: $F_2^{\gamma} = \sum e_q^2\, x\, q^+(x), \quad F_2^{\gamma Z} = 2\sum e_q\, g_V^q\, x\, q^+(x)$
- $N > Z \implies d$-quarks feel more repulsion than u-quarks: $V_d > V_u$
  - ✦ u quarks are more bound than d quarks
  - ✦ ρ^0 field shifts momentum from u to d quarks

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

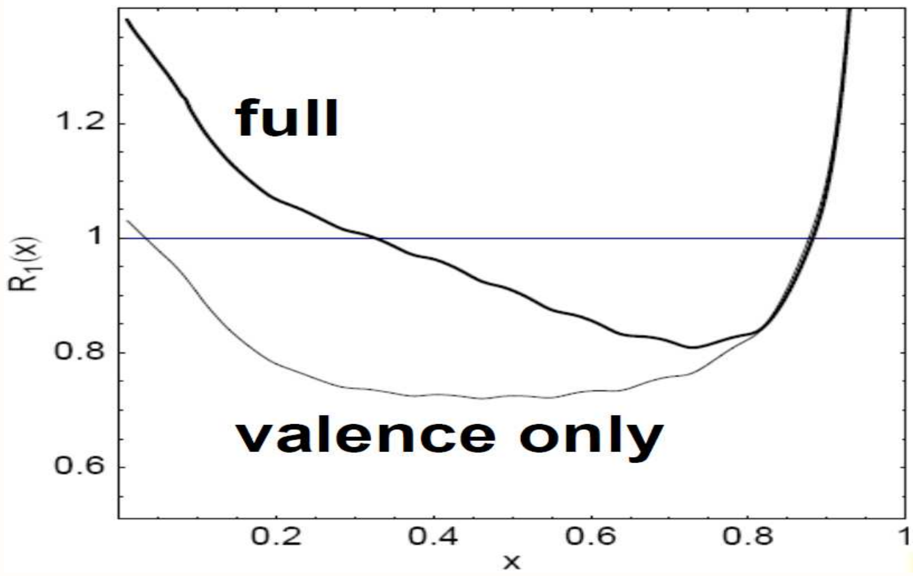
- If observed, would be strong evidence for medium modification

Polarized EMC effect

[ICC *et al.*, Phys. Rev. Lett. **95**, 052302 (2005)]

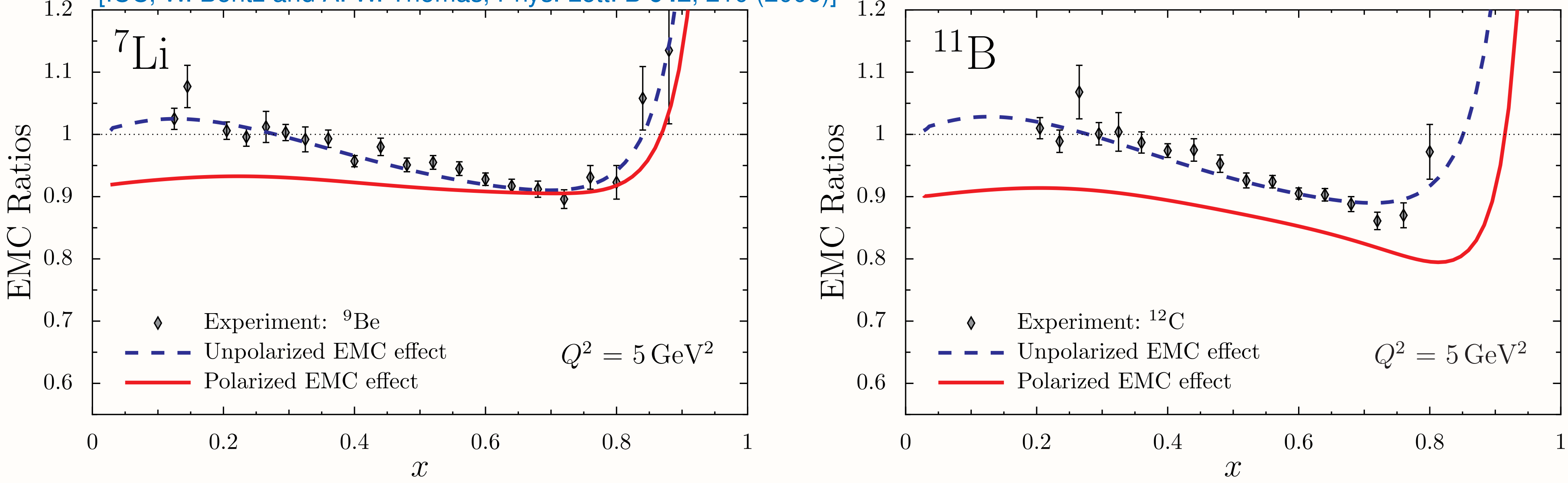


[J. R. Smith and G. A. Miller, PRC 72, 022203(R) (2005)]



- Polarized EMC ratio: $$\Delta R = \frac{g_{1A}}{g_{1A}^{\text{naive}}} = \frac{g_{1A}}{P_p\, g_{1p} + P_n\, g_{1n}}$$
- 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, ...
- Ideal nucleus is probably ^{7}Li
  - from Quantum Monte–Carlo: $P_p = 0.86$ & $P_n = 0.04$
- Ratios equal 1 in limit of no nuclear effects

Polarized EMC effect



[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **642**, 210 (2006)]

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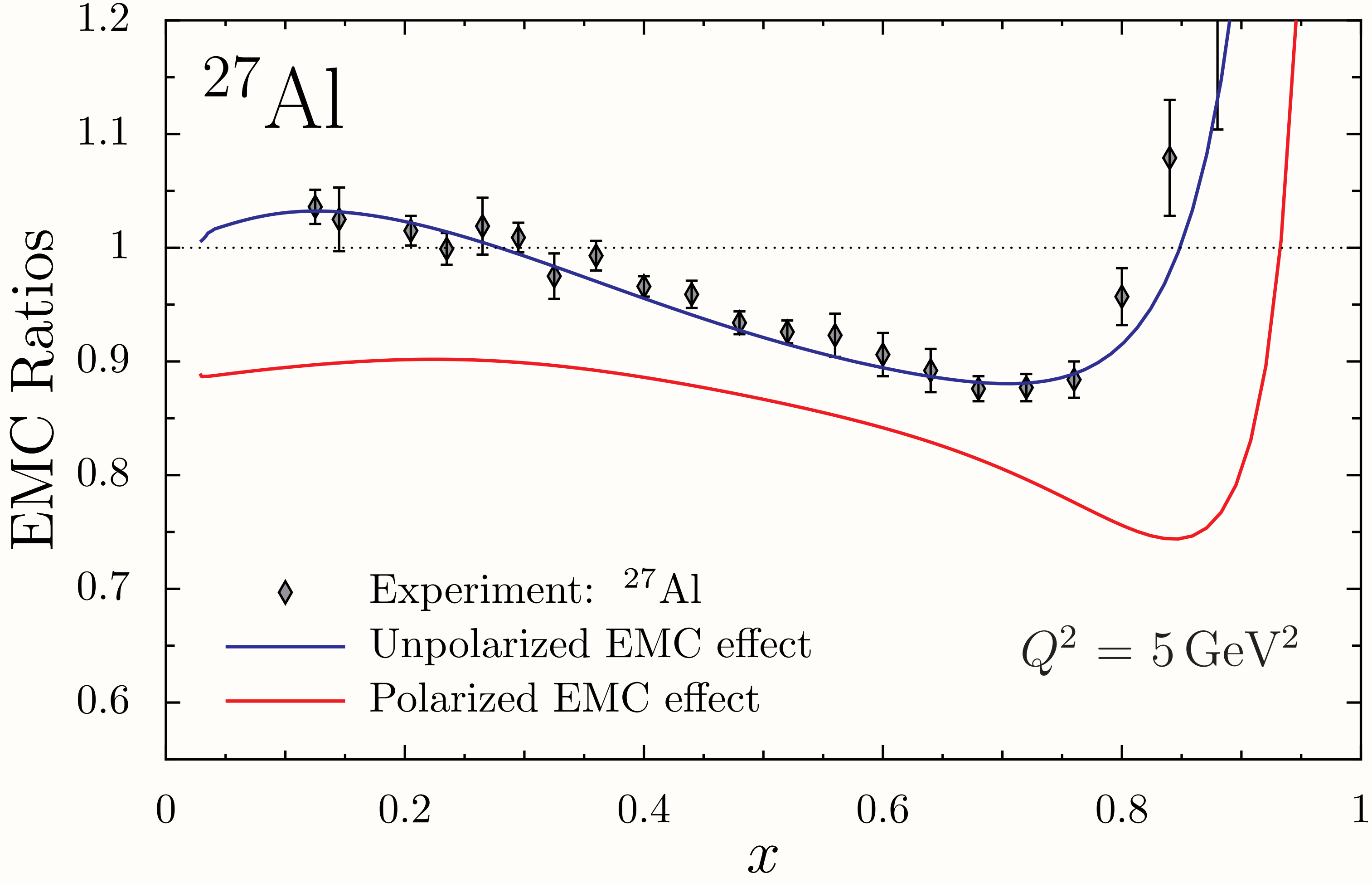
Is there medium modification

[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **642**, 210 (2006)]



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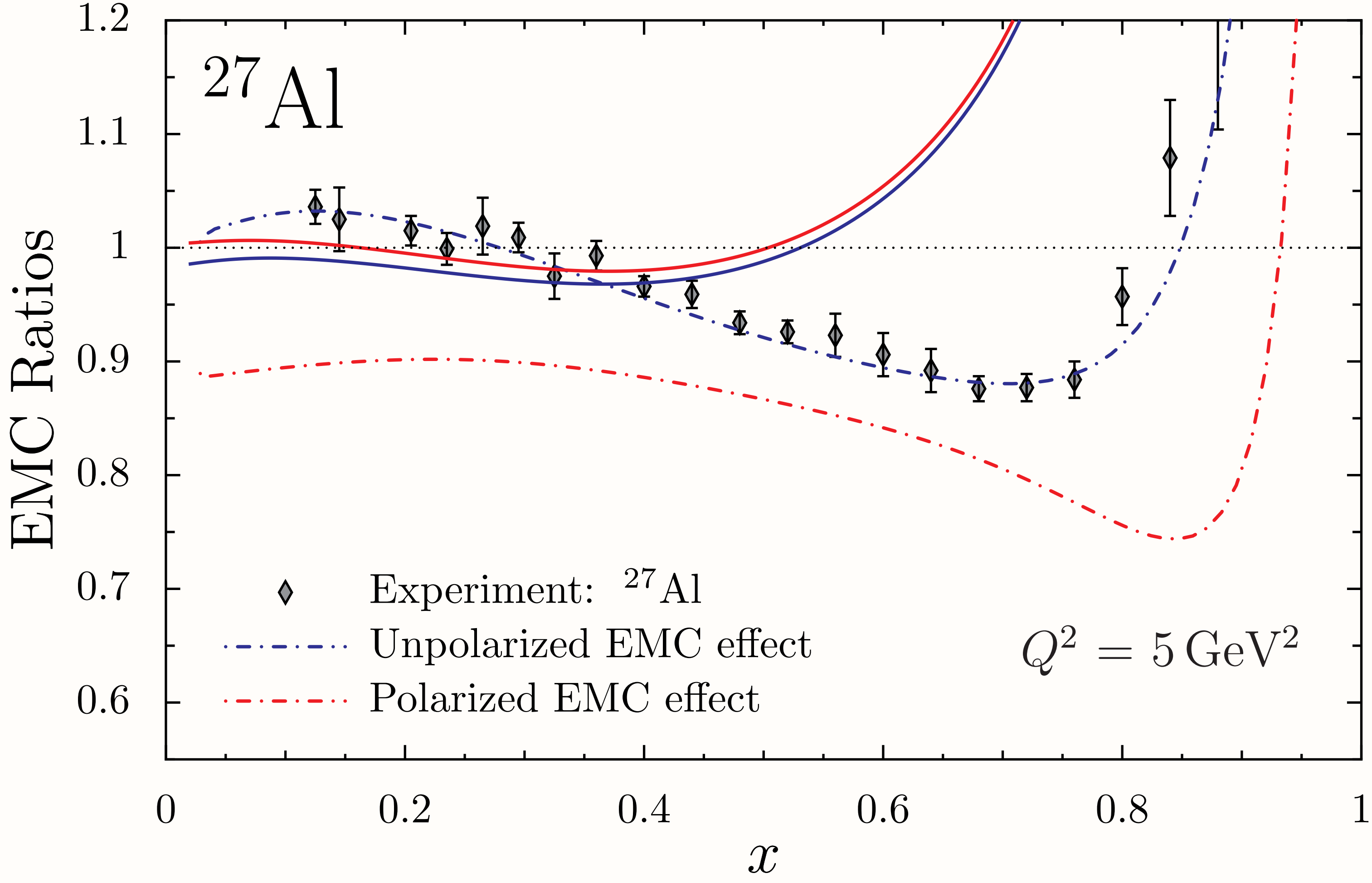


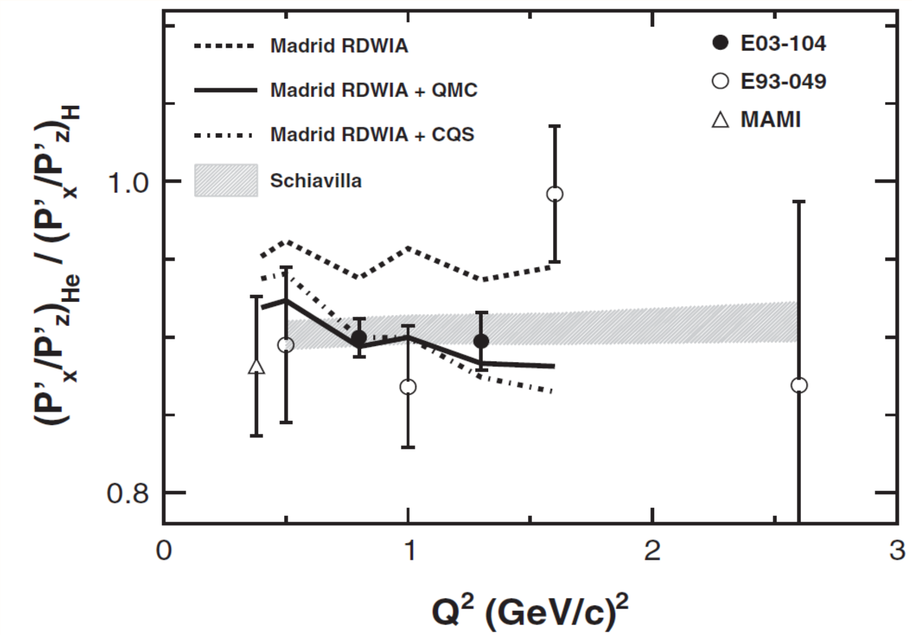
- Medium modification of nucleon has been switched off
- Relativistic effects remain
- Large splitting very difficult without medium modification

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

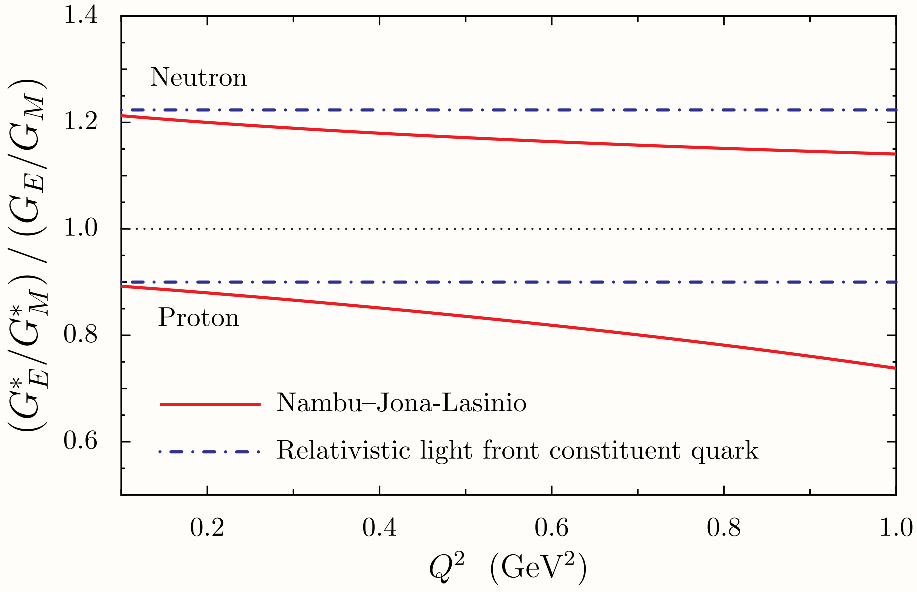
- Angular momentum of nucleon: $J = \frac{1}{2} = \frac{1}{2}\,\Delta\Sigma + L_q + J_g$
  - ✦ in medium $M^* < M$ and therefore quarks are more relativistic
  - ✦ lower components of quark wavefunctions are enhanced
  - ✦ quark lower components usually have larger angular momentum
  - ✦ $\Delta q(x)$ very sensitive to lower components
- Therefore, in-medium quark spin → orbital angular momentum

Form factors of a bound nucleon



[S. Strauch, *et al.*, Phys. Rev. Lett. **91**, 052301 (2003)]

[M. Paolone, *et al.*, Phys. Rev. Lett. **105**, 072001 (2010)]



[ICC *et al.*, Phys. Rev. Lett. **103**, 082301 (2009)]

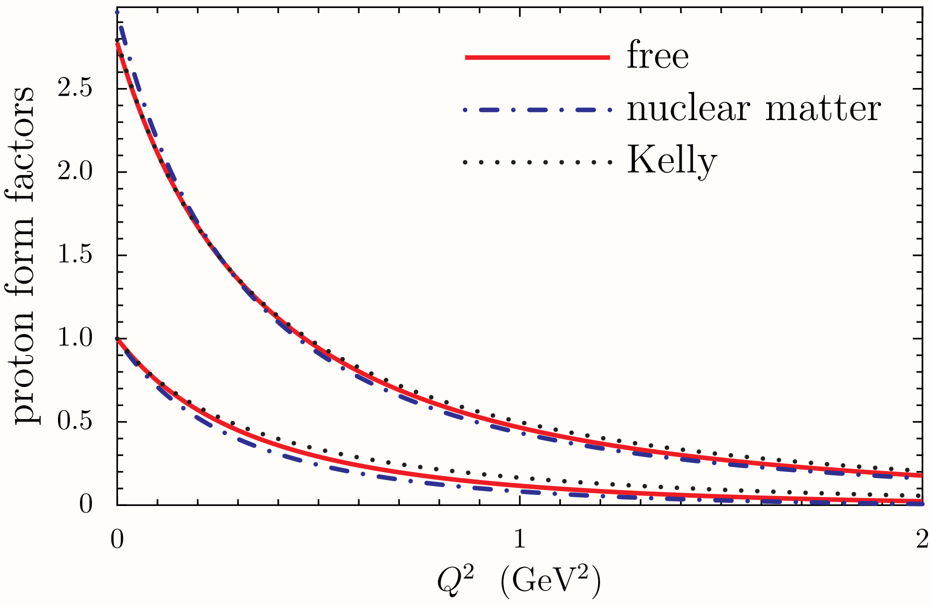
- Reaction $^4\text{He}\,(\vec{e}, e'\vec{p})\,^3\text{H}$ sensitive to G_E/G_M of bound proton
- Assume bound neutron is almost on-shell & Foldy term $\left[\frac{3}{2\,M_N^2}\,\kappa_n\right]$ remains dominate contribution to bound neutron charge radius

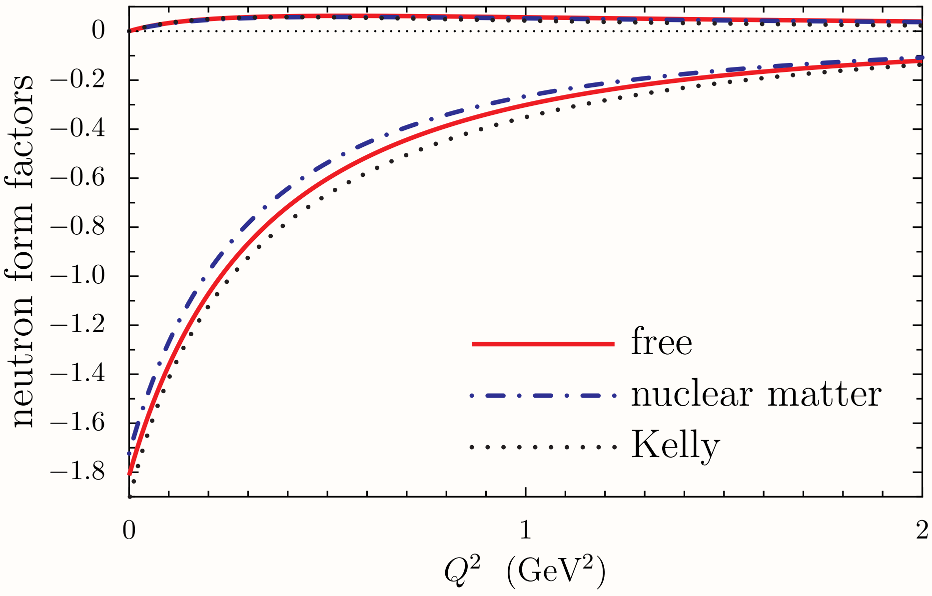
$$\frac{\mathcal{R}_n^*}{\mathcal{R}_n} \simeq \left(\frac{M_N}{M_N^*}\right)^2, \qquad \mathcal{R}_n \equiv G_{En}/G_{Mn} \simeq -\frac{1}{\mu_n}\,\frac{1}{6}\,Q^2\,\hat{R}_{En}^2, \quad \text{for} \quad Q^2 \ll 1$$

- An almost model independent result

In-medium nucleon form factors

- Nucleon form factors are modified in-medium
- Free and in-medium nucleon magnetic moments $[\mu_N]$
  - ✦ $\mu_p = 2.78, \quad \mu_n = -1.81, \quad \mu_p^* = 2.96, \quad \mu_n^* = -1.72$
- Free and in-medium radii [fm] – $r_i \equiv \sqrt{\langle r_i^2 \rangle}$
  - ✦ $r_{Cp} = 0.858, \quad r_{Cn} = -0.336, \quad r_{Mp} = 0.835, \quad r_{Mn} = 0.861$
  - ✦ $r_{Cp}^* = 0.926, \quad r_{Cn}^* = -0.324, \quad r_{Mp}^* = 0.878, \quad r_{Mn}^* = 0.891$





Conclusion

Hopefully I have demonstrated that the DSEs are a powerful tool with which to study QCD and hadron structure

Thank you!

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