# Hadron Physics
# & QCD's Dyson-Schwinger Equations

*Lectures 5 & 6: Partonic structure of nucleons and nuclei*

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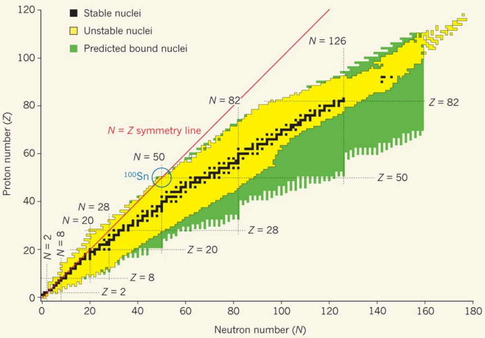
# Why are Nuclei Interesting?

- Nuclei encapsulate and accentuate much of Standard Model physics
  - QED has a dramatic affect on, e.g. the valley of stability as the number of protons increases
  - weak interactions have a dramatic affect on e.g. the stability of nuclei
  - proton decay occurs inside nuclei:

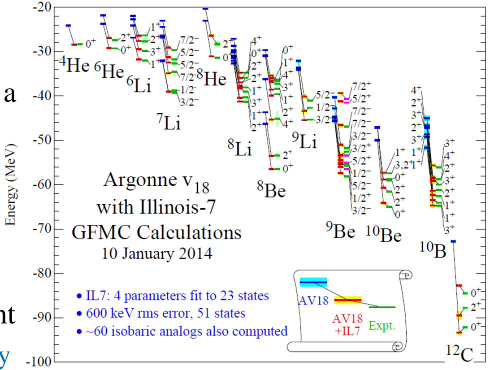
$$^{23}_{12}\text{Mg} \rightarrow {}^{23}_{11}\text{Na} + e^{+} + \nu_e$$




- However, the properties of nuclei are dominated by the strong interaction
  - understanding the properties of nuclei within QCD remains one of the most important challenges in fundamental science
  - *too understand QCD it is not sufficient to study hadrons alone*
- Nuclei are used in many searches for beyond the Standard Model physics
  - electric dipole moment in mercury, radium, etc
  - neutrinoless double $\beta$ decay
- BSM searches can be hinder by a lack of understanding of QCD and nuclei

# *Traditional Nuclear Physics*

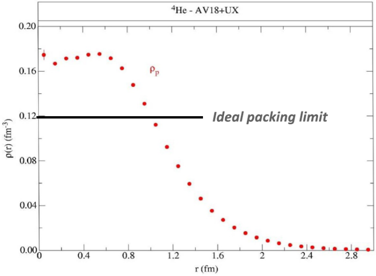
- In traditional nuclear physics the nucleus is viewed as a collection of *elementary* nucleons interacting via a phenomenological potential
  - this picture began with the discovery of the neutron in 1932
  - on firm ground with establishment of the nuclear shell model in 1940s
- Interim has seen steady improvement
  - largely independent of QCD discovery




- State-of-the-art today are sophisticated *non-relativistic* quantum-many-body approaches – VMC and GFMC – using e.g. Argonne $V_{18}$ potential
  - $V_{18}$ + IL-7 potential has 44 parameters fit to $NN$ scattering data, . . .
  - remarkably successful at describing numerous properties of light nuclei
- *A key assumption of these ab initio approaches is that the nucleons which comprise a nucleus have the same properties as those of free nucleons*

# QCD and Nuclei

- Nuclei are extremely dense – $10^{14}$ times denser that ordinary matter
  - proton rms radius is $r_p \simeq 0.85\,\text{fm}$, corresponds to hard sphere $r_p \simeq 1.15\,\text{fm}$
  - ideal packing gives $\rho = 0.12\,\text{fm}^{-3}$; nuclear matter density is $\rho \simeq 0.16\,\text{fm}^{-3}$
  - bound nucleon wave functions often overlapping




- *With the realization that QCD is the theory of the strong interaction – natural to expect that nucleon properties are modified by the nuclear medium*
  - in contradistinction to traditional nuclear physics
- Understanding validity of two viewpoints remains key challenge for NP
  - if nucleons are modified represents a new paradigm for nuclear physics
  - if nucleons are unchanged would shed light on colour confinement in QCD
- Weinberg's Third Law of Progress in Theoretical Physics:

  *you may use any degrees of freedom you like to describe a physical system, but if you choose the wrong ones, you'll be sorry*

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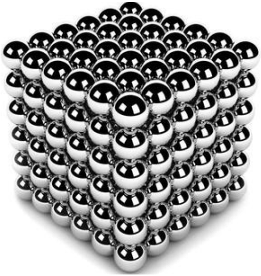

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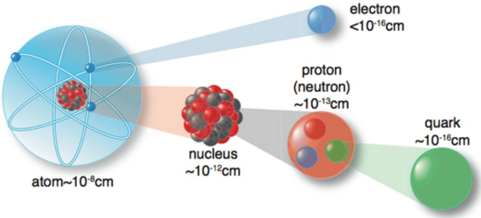
# *Nuclear Targets*

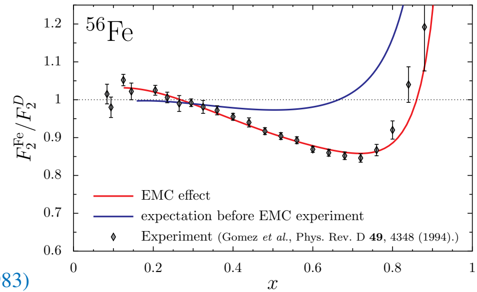
- Nuclei give access to numerous novel aspects of QCD:
  - neutron target, targets with $J \geqslant 1$
  - colour transparency, hidden colour
  - hypernuclei, gluon saturation, etc




- Important question: *How do the internal structural properties of protons and neutrons change when they form complex nuclei and what is the cause?*
- In quark level approaches *self-consistent coupling to nuclear mean-fields* naturally results in *medium modification of all nucleons in a nucleus*
  - for example, the dressed quark mass function changes with temperature and baryon chemical potential
  - very difficult to avoid medium modification in these approaches
- Unambiguous evidence for quark & gluon effects in nuclei remains elusive
  - important candidates are the EMC effect
  - Quasi-elastic scattering, the Coulomb Sum Rule & proton knockout reactions

# The EMC effect

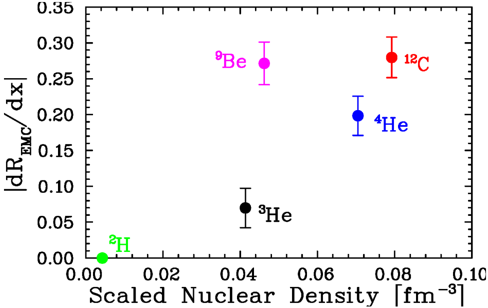
- In the early 80s physicists at CERN thought that nucleon structure studies using DIS could be enhanced (by a factor $A$) using nuclear targets
- The European Muon Collaboration (EMC) conducted DIS experiments on an iron target
  - J. J. Aubert *et al.*, Phys. Lett. B **123**, 275 (1983)

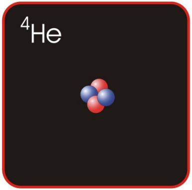


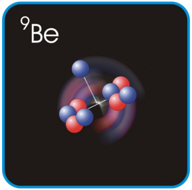

*"The results are in complete disagreement with the calculations ... We are not aware of any published detailed prediction presently available which can explain behavior of these data."*

- Measurement of the *EMC effect* destroyed a particle-physics paradigm regarding QCD and nuclear structure
  - more than 30 years after discovery a broad consensus on explanation is lacking
  - what is certain: *valence quarks in nucleus carry less momentum than in a nucleon*
- One of the most important nuclear structure discoveries since advent of QCD
  - understanding its origin is critical for a QCD based description of nuclei

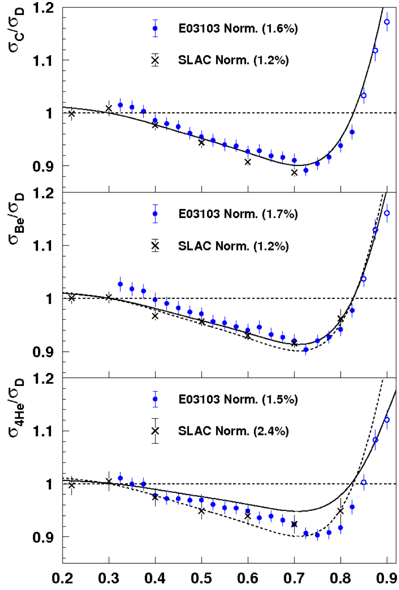
# *EMC effect in light nuclei*



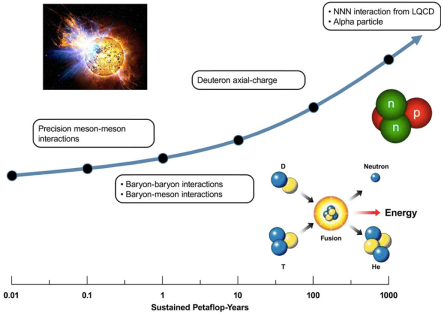

[J. Seely *et al.*, PRL **103**, 202301 (2009)]



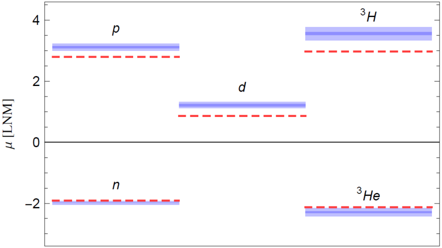

- EMC effect determined by *local density* not the *average density*: $R_{He} \sim R_{Be} \sim R_C$ [future: E12-10-008]

# *Progress using Lattice QCD*

[S. R. Beane *et al.*, Prog. Part. Nucl. Phys. **66**, 1-40 (2011)]



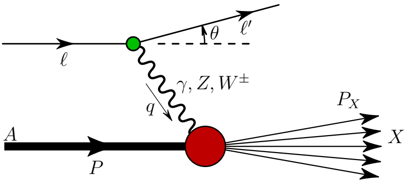

[S. R. Beane *et al.* (NPLQCD), PRL **113**, 252001 (2014)]




$[m_\pi \simeq 800\,\mathrm{MeV}]$

- Lattice QCD is beginning to make progress in the study of very light nuclei
- However calculations require huge computational resources and it will likely take 10-20 years before light nuclei studies match those of the nucleon today
- Lattice QCD can only provide limited physical insight into nuclear structure
  - it cannot tell us what the relevant degrees of freedom are in nuclei

# Deep Inelastic Scattering




$$q^2 = (k' - k)^2 = -Q^2 \leq 0, \qquad s = (\ell + P)^2$$

$$x_A \equiv A\,\frac{Q^2}{2\,P\cdot q} = A\,\frac{Q^2}{2\,M_A\,\nu}, \qquad 0 < x_A < A$$

$$y = \frac{Q^2}{x\,s}, \qquad W^2 = (P+q)^2 = Q^2\,\frac{1-x}{x}$$

- Unpolarized cross-section for DIS with single photon exchange is

$$\frac{d\sigma^\gamma}{dx_A\,dQ^2} = \frac{2\pi\,\alpha_e^2}{x_A\,Q^4}\left[\left(1+(1+y)^2\right)F_2^\gamma(x,Q^2) - y^2 F_L^\gamma(x,Q^2)\right]$$

  - $F_L^\gamma(x,Q^2) = F_2^\gamma(x,Q^2) - 2\,x\,F_1^\gamma(x,Q^2)$

- The longitudinally polarized cross-section is

$$\frac{d\,\Delta_L\sigma^\gamma(\lambda)}{dx_A\,dQ^2} = \frac{4\pi\,\alpha_e^2}{x_A\,Q^4}\left[-2\lambda\left(1-(1-y)^2\right)x\,g_1^\gamma(x,Q^2) + y^2 g_L^\gamma(x,Q^2)\right]$$

- Also structure functions for $\gamma Z$, $Z^0$ & $W^\pm$ exchange

# Bjorken Limit and Scaling

- The Bjorken limit is defined as:

$$Q^2,\, \nu \to \infty \;\; | \;\; x = \text{fixed}$$

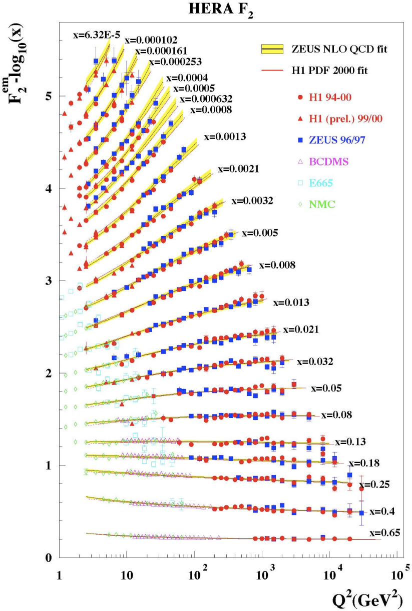
- In 1968 J. D. Bjorken argued that in this limit the photon interactions with the target constituents (partons) involves no dimensional scale, therefore

$$F_2^\gamma(x, Q^2) \to F_2^\gamma(x)$$
$$g_1^\gamma(x, Q^2) \to g_1^\gamma(x) \quad etc$$

  - Bjorken scaling

- Confirmation from SLAC in 1968 was the first evidence for pointlike constituents inside proton

- Scaling violation $\Longleftrightarrow$ perturbative QCD



# Physical meaning of Bjorken $x$

- Choose a frame where $\vec{q}_\perp = 0$ then photon moment is

$$q = \left[\nu, 0, 0, -\sqrt{\nu^2 + Q^2}\right] \xrightarrow{\text{Bjorken limit}} q = \left[\nu, 0, 0, -\nu - x\, M_N\right]$$

- Lightcone coordinates: $q^\pm = \frac{1}{\sqrt{2}}\left(q^0 \pm q^3\right) \Rightarrow a \cdot b = a^+ b^- + a^- b^+ - \vec{a}_\perp \cdot \vec{b}_\perp$
- Therefore in Bjorken limit: $q^- \to \infty \quad q^+ \to -x\, M_N/\sqrt{2}$ and

$$x = \frac{Q^2}{2\, p \cdot q} = -\frac{q^+ q^-}{q^- p^+ + q^+ p^-} \to -\frac{q^+}{p^+}$$

- The lightcone dispersion relation reads: $k^- = \dfrac{m^2 + \vec{k}_\perp^{\,2}}{2\, k^+}$
- Can only be satisfied for $k'^- \;(= k^- + q^-)$ if $k'^+ = 0 \implies k^+ = -q^+$
- *Therefore $x$ has physical meaning of the lightcone momentum fraction carried by the struck quark before it is hit by photon*

$$x = \frac{k^+}{p^+}$$

# Parton Distribution Functions

- Factorization theorems in QCD prove that the structure functions can be expressed in terms of *universal* parton distribution functions (PDFs)
  - that is, the cross-sections can be factorized into process depend perturbative pieces, determined by pQCD (Wilson coefficients) and the innately non-perturbative *universal* PDFs
- For example at LO and leading twist the structure functions are given by

$$F_2^\gamma(x,Q^2) = \sum_{q=u,d,s,\ldots} e_q^2 \left[x\, q(x,Q^2) + x\, \bar{q}(x,Q^2)\right]$$

$$g_1^\gamma(x,Q^2) = \frac{1}{2}\sum_{q=u,d,s,\ldots} e_q^2 \left[\Delta q(x,Q^2) + \Delta\bar{q}(x,Q^2)\right]$$

- These PDFs have a probability interpretation:

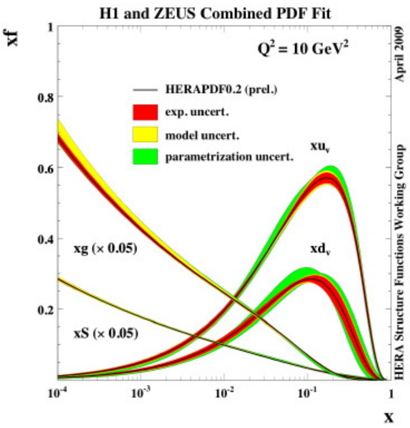
$q(x) = q_+(x) + q_-(x)$ [spin-independent PDF]

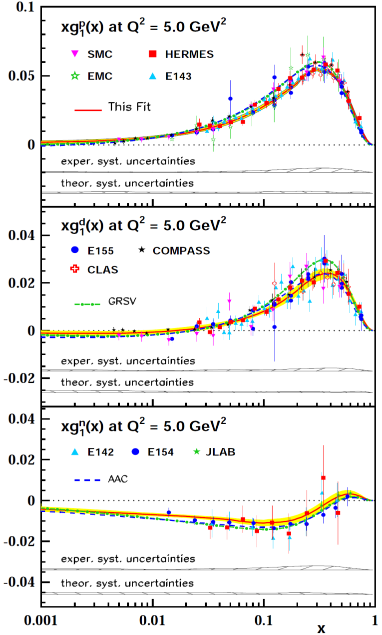
*"probability to strike a quark of flavour $q$ with lightcone momentum fraction $x$ of the target momentum"*

$\Delta q(x) = q_+(x) - q_-(x)$ [spin-dependent PDF]

*"helicity weighted probability to strike a quark of flavour $q$ with lightcone momentum fraction $x$ of the target momentum"*

# Experimental Status: Nucleon PDFs

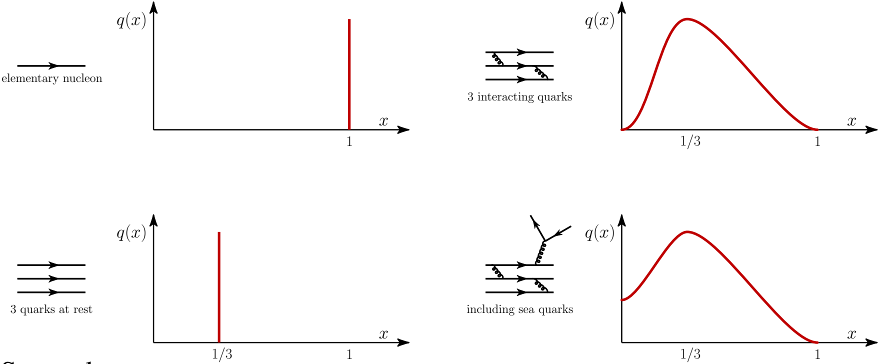



- The distance scales, $\xi$, probed in DIS are given by: $\xi \sim 1/(x\,M_N)$
  - $x = 0.5 \implies \xi = 0.4\,\text{fm}$
  - $x = 0.05 \implies \xi = 4\,\text{fm}$

# Physical Interpretation

- PDFs tells us how *particle number*, *momentum* and *spin* are distributed




- Sum rules

$$\int dx\ [q(x) - \bar{q}(x)] = N_q; \qquad \int dx\, x\, [u(x) + d(x) + \ldots] = 1; \qquad \int dx\, \Delta q(x) = \Sigma_q$$

baryon number — momentum — spin sum

- Nucleon angular momentum: $J = \frac{1}{2} = \frac{1}{2}\Sigma + L_q + J_g$

# QCD Evolution Equations

- The DGLAP evolution equations are one of the greatest successes of perturbative QCD
  - DGLAP $\Longleftrightarrow$ Dokshitzer (1977), Gribov-Lipatov (1972), Altarelli-Parisi (1977)
- These QCD evolution equations relate the PDFs at one scale, $Q_0^2$, to another scale, $Q^2$, provided $Q_0^2,\, Q^2 \gg \Lambda_{QCD}$.
- Evolution equation for minus type – $q^- \equiv q - \bar{q}$ – PDFs is

$$\frac{\partial}{\partial \ln Q^2}\, q^-(x,Q^2) = \alpha_s(Q^2)\, P(z) \otimes q^-(y,Q^2) \qquad \text{[non-singlet]}$$

  - $P(z)$: probability for quark to emit gluon leaving quark with momentum fraction $z$
  - note that the gluon PDF does not contribute to minus type PDF evolution
- Evolution equations for $q^+ \equiv q + \bar{q}$ and gluon, $g(x)$, PDFs are coupled

*The physics behind these equations is that a valence quark can radiate gluons and a gluon can become a quark–antiquark pair, therefore momentum can be shifted between the valence quarks, sea quarks and gluons. The probability of this radiation is scale, $Q^2$, dependent.*

# *Moments of PDFs*

- Low moments of PDFs are related to conservation laws and observables
  - recall baryon and momentum sum rules; spin carried by quarks
- Most PDFs moments dependent on the resolving scale $Q^2$
- PDFs are usually obtained by fitting a chosen functional form to data
  - see MRST/MSTW, GRV/GJR, CTEQ, NNPDF (neural network), etc
- Typical values for proton PDF moments $(Q^2_{0\,\mathrm{NLO}} = 0.5\,\mathrm{GeV}^2)$

$$\langle x\,u\rangle = 0.404 \quad \langle x\,d\rangle = 0.194 \quad \langle x\,\bar{u}\rangle = 0.029 \quad \langle x\,\bar{d}\rangle = 0.039 \quad \langle x\,g\rangle = 0.334$$

  - gluons carry 33% of proton momentum [GJR, Eur. Phys. J. C53 (2008) 355]
- Typical polarized PDF moments $(Q^2_{0\,\mathrm{NLO}} = 1\,\mathrm{GeV}^2)$ [LSS2010]:

$$\langle \Delta u\rangle = 0.78 \quad \langle \Delta d\rangle = -0.38 \quad \langle \Delta\bar{u}\rangle = 0.043 \quad \langle \Delta\bar{d}\rangle = -0.069 \quad \langle \Delta g\rangle \simeq 0.30$$

- For spin sum have [LSS2010]: $\Sigma = 0.42 \pm 0.19 \quad Q^2 = 4\,\mathrm{GeV}^2$
- Recall *"proton spin crisis"*: $\Sigma_{u+d} = 0.14 \pm 0.9 \pm 0.21$ [Ashman, *et al., PLB, 1987]*

# Extracting Proton Spin Content

- Ellis–Jaffe sum rule $\left[\frac{1}{2} = \frac{1}{2}\Sigma + L_q + J_g\right]$

$$\int dx\, g_{1p}^{\gamma}(x, Q^2) = \frac{1}{36}\left[3\,\Delta q_3 + \Delta q_8\right] + \frac{1}{9}\,\Delta q_0,$$

$$\Sigma = \Delta q_0 = \Delta u^+ + \Delta d^+ + \Delta s^+ \qquad \text{[singlet]}$$

$$g_A = \Delta q_3 = \Delta u^+ - \Delta d^+ \qquad \text{[triplet]}$$

$$\Delta q_8 = \Delta u^+ + \Delta d^+ - 2\,\Delta s^+ \qquad \text{[octet]}$$

- To help extract $\Sigma$ usual to use semi-leptonic hyperon decays and assume $SU(3)$ flavour symmetry to relate $\Delta q_3$ and $\Delta q_8$

$$\Delta q_3 = F + D \qquad \Delta q_8 = 3\,F - D$$

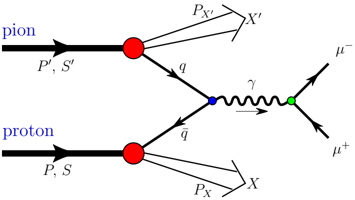
$$n\,p \to F + D, \qquad \Lambda\,p \to F + \tfrac{1}{3}\,D, \qquad \Sigma\,n \to F - D, \quad \text{etc}$$

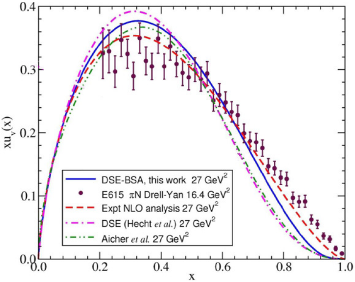
- Spin sum can also be determined via

$$\int dx\, g_{1p}^{\gamma Z}(x, Q^2) = \frac{1}{36}\left(1 - 4\,\sin^2\theta_W\right)\left[3\,\Delta q_3 + \Delta q_8\right] + \frac{2}{9}\left(1 - 2\,\sin^2\theta_W\right)\Delta q_0$$

# The Pion PDF

- In QCD alone the pion is a stable particle, however in the real world it decays via the electroweak interaction with a mean lifetime of $2.6 \times 10^{-8}$ s
- Therefore in nature there are no pion targets, however because of time dilation it is possible to create a beam of pions: e.g. $p + \text{Be} \to \pi^- + X$
- Can measure pion PDFs via a process called pion-induced Drell-Yan: $\pi\, p \to \mu^+ \mu^- X$




- There have been three experiments: CERN 1983 & 1985, Fermilab 1989

$$q_\pi(x) \overset{x\to 1}{\longrightarrow} (1-x)^{1+\varepsilon} \qquad \text{pQCD} \implies q_\pi(x) \sim (1-x)^{2+\gamma}$$

# Theory Definition of Pion PDFs

- Pion is a spin zero particle $\Longrightarrow$ only has spin-independent PDFs: $q_\pi(x, Q^2)$
- The pion quark distribution function is defined by

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

- The *moments* of PDFs are defined by

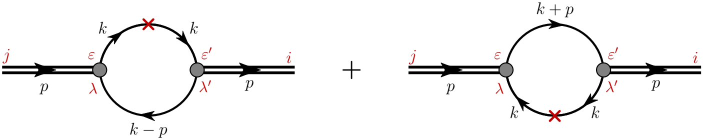
$$\left\langle x^{n-1}\, q_\pi \right\rangle = \int_0^1 dx\ x^{n-1}\ q_\pi(x)$$

- The moments of these PDFs must satisfy the baryon number & momentum sum rules
- For example the $\pi^+ = u\bar{d}$ PDFs must satisfy

$$\left\langle u_\pi - \bar{u}_\pi \right\rangle = 1 \qquad \left\langle \bar{d}_\pi - d_\pi \right\rangle = 1 \qquad \left\langle x\, u_\pi + x\, \bar{d}_\pi + \ldots \right\rangle = 1$$

baryon number sum rules — momentum sum rule

  - the baryon number sum rule is equivalent to charge conservation




- The pion quark distribution functions can be obtained from a Feynman diagram calculation
- The needed ingredients are
  - the pion Bethe-Salpeter amplitude: $\Gamma_\pi = \sqrt{Z_\pi}\,\gamma_5\,\tau_i$
  - dressed quark propagator: $S(p)^{-1} = \not{p} - M + i\varepsilon$
- The operator insertion is given by

$$\gamma^+\,\delta\!\left(x - \frac{k^+}{p^+}\right)\frac{1}{2}\,(1 \pm \tau_3)$$

  - plus sign projects out $u$-quarks and minus $d$-quarks
  - recall $x$ is the lightcone momentum fraction carried by struck quark

# Pion PDF Results in NJL

- PDFs are scale – $Q^2$ – dependent, however within the NJL model there is no way to determine the model scale $Q_0^2$
- Standard method is to fit the proton valence $u$-quark distribution to empirical results, best fit determines $Q_0^2$
- The NJL model result for $\pi^+$ PDFs at $Q^2 = Q_0^2 = 0.16\,\text{GeV}^2$

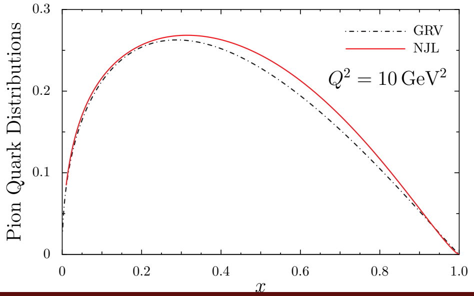
$$u_\pi(x) = \bar{d}_\pi(x) = \frac{3\,Z_\pi}{4\pi^2}\int d\tau\left[\frac{1}{\tau} + x\,(1-x)\,m_\pi^2\right] e^{-\tau\left[x(x-1)m_\pi^2+M^2\right]}.$$

- Agreement with data excellent
- At large $x$ NJL finds

$$u_\pi(x) \overset{x\to 1}{\simeq} (1-x)^1$$

- Disagrees with pQCD result

$$u_\pi(x) \overset{x\to 1}{\simeq} (1-x)^{2+\gamma}$$



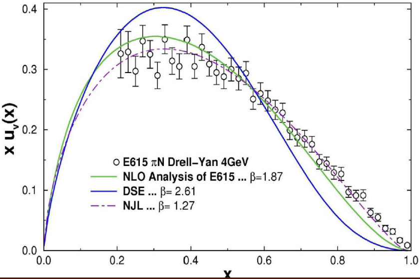
# Pion PDF in DSEs

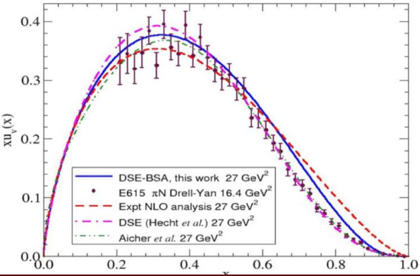
- DSE calculations – fully dressed quark propagator and BS vertex function

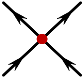
$$S(p)^{-1} = i\not{p}\, A(p^2) + B(p^2)$$

$$\Gamma_\pi(p,k) = \gamma_5\left[E_\pi(p,k) + \not{p}\, F_\pi(p,k) + \not{k}\, k\cdot p\, \mathcal{G}(p,k) + \sigma^{\mu\nu} k_\mu p_\nu\, \mathcal{H}(p,k)\right]$$

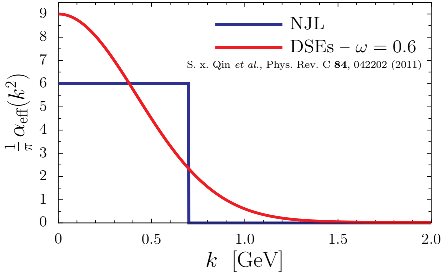
- At large $x$ DSE and pQCD results agree: $u_\pi(x) \overset{x\to 1}{\simeq} (1-x)^{2+\gamma}$
  - this 2001 result seemed to disagree with experiment for a decade
- Recent reanalysis of data by *Aicher et al.* now finds excellent agreement with DSEs

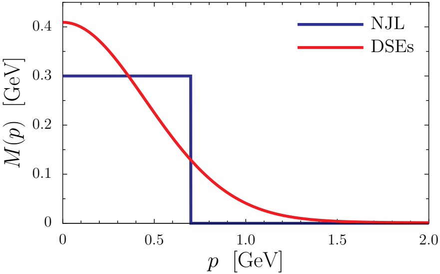


**Continuum QCD** *"integrate out gluons"* →  $\frac{1}{m_g^2}\ \Theta(\Lambda^2 - k^2)$

- this is just a modern interpretation of the Nambu–Jona-Lasinio (NJL) model
- model is a Lagrangian based covariant QFT, exhibits dynamical chiral symmetry breaking & quark confinement; elements can be QCD motivated via the DSEs

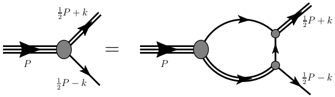


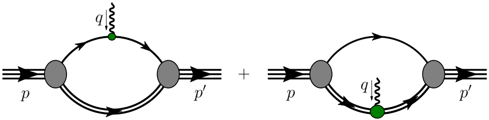

- Proper-time regularization: $\Lambda_{IR}$ & $\Lambda_{UV} \implies$ Confinement
- Quark propagator: $[\not{p} - m + i\varepsilon]^{-1} \;\rightarrow\; Z(p^2)[\not{p} - M + i\varepsilon]^{-1}$
  - wave function renormalization vanishes at quark mass-shell: $Z(p^2 = M^2) = 0$

# Proton Electromagnetic Form Factors

- Nucleon = quark+diquark

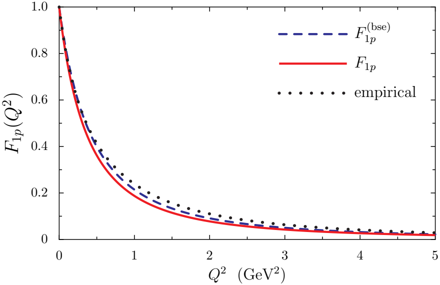


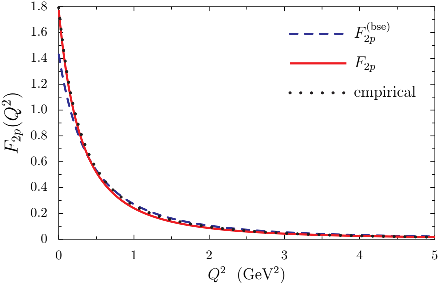

- Form factors given by Feynman diagrams:



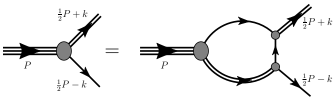

- Calculation satisfies electromagentic gauge invariance; includes
  - dressed quark–photon vertex with $\rho$ and $\omega$ contributions
  - contributions from a pion cloud

[ICC, W. Bentz and A. W. Thomas, Phys. Rev. C **90**, 045202 (2014)]

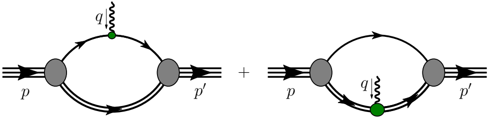


- Nucleon = quark+diquark




- Form factors given by Feynman diagrams:

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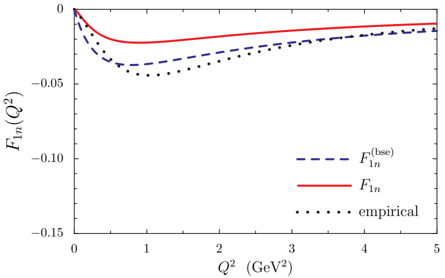
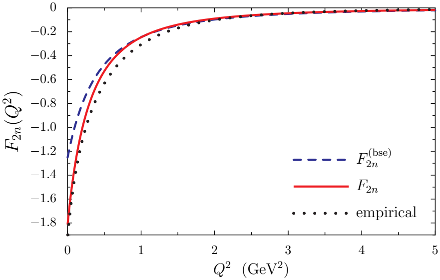
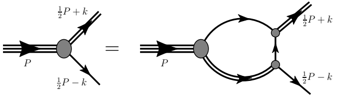
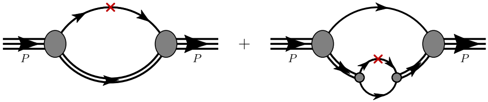


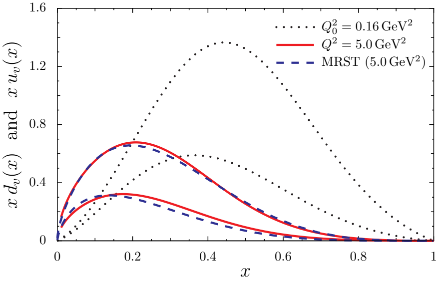
- Nucleon = quark+diquark
- PDFs given by Feynman diagrams: $\langle\gamma^+\rangle$

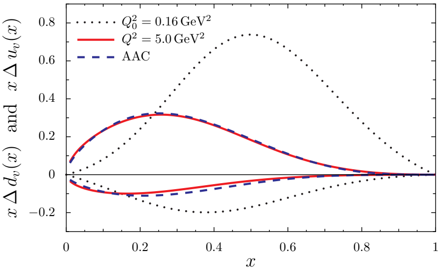


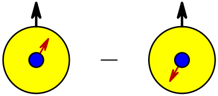

- Covariant, correct support; satisfies sum rules, Soffer bound & positivity

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



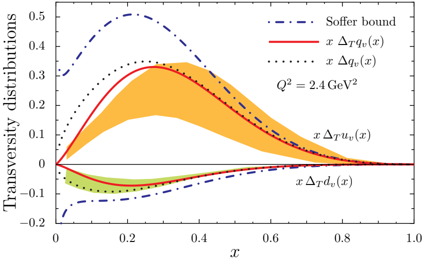

[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **621**, 246 (2005)]

$\Delta_T q(x) =$ 

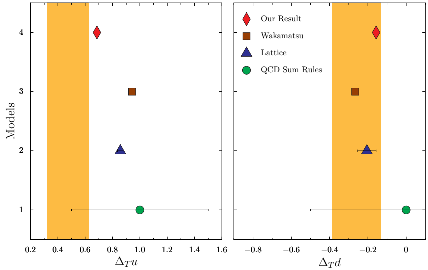
- Sum rule gives tensor charge

$$g_T = \int dx\, [\Delta_T u(x) - \Delta_T d(x)]$$

- quarks in eigenstates of $\gamma^\perp \gamma_5$
- Non-relativistically: $\Delta_T q(x) = \Delta q(x)$ – a measure of relativistic effects
- Helicity conservation: no mixing bet'n $\Delta_T q$ & $\Delta_T g$: $J \leqslant \frac{1}{2} \Rightarrow \Delta_T g(x) = 0$
- Therefore for the nucleon $\Delta_T q(x)$ is valence quark dominated
- At model scale we find: $g_T = 1.28$ *compare* $g_A = 1.267$ (input)

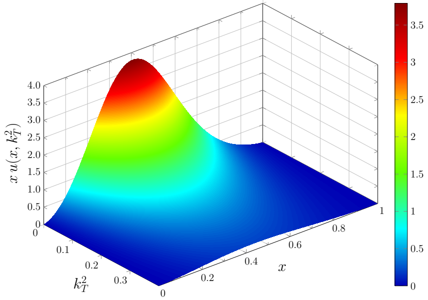


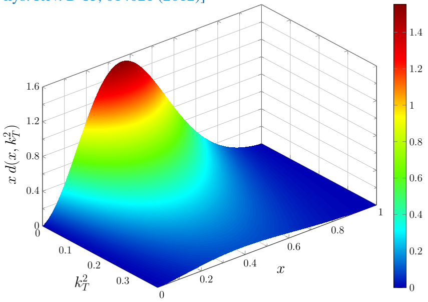

[ICC *et al.*, Phys. Lett. B **659**, 214 (2008)]




[M. Anselmino *et al*, Nucl. Phys. Proc. Suppl. **191**, 98 (2009)]

[H. H. Matevosyan, ICC *et al.*, Phys. Rev. D **85**, 014021 (2012)]




- So far only considered the simplest spin-averaged TMDs – $q(x,k_T^2)$
- In phenomenology common to work with parametrization of the form:

$$q(x,k_T^2) = q(x)\,\frac{e^{-k_T^2/\langle k_T^2\rangle_0}}{\pi\,\langle k_T^2\rangle_0}$$

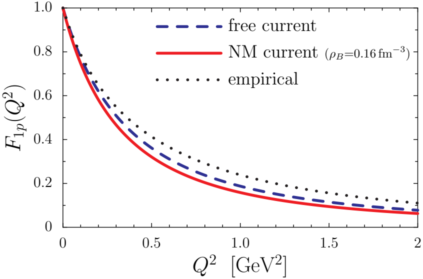
$$\langle k_T^2\rangle^{Q^2=Q_0^2} = 0.36^2\,\text{GeV}^2 \sim M^2$$

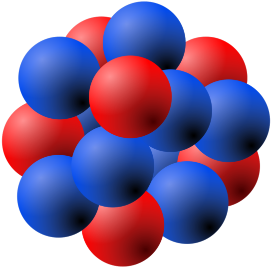
$$\langle k_T^2\rangle = 0.56^2\,\text{GeV}^2\ _{\text{[HERMES]}},\quad 0.64^2\,\text{GeV}^2\ _{\text{[EMC]}}$$

- Gaussian ansatz fits our results well
  - agreement with experiment reasonable as $\langle k_T^2\rangle$ grows with $Q^2$

# *A Nucleon in the Nuclear Medium*

- For nuclei, we find that quarks bind together into colour singlet nucleons
  - however contrary to traditional nuclear physics approaches these quarks feel the presence of the nuclear environment
  - *as a consequence bound nucleons are modified by the nuclear medium*
- Modification of the bound nucleon wave function by the nuclear medium is a *natural consequence* of quark level approaches to nuclear structure
- For a proton in nuclear matter find
  - Dirac & charge radii each increase by about $8\%$; Pauli & magnetic radii by $4\%$
  - $F_{2p}(0)$ decreases; however $F_{2p}(0)/2M_N$ almost constant; $\mu_p$ almost constant



# A Nucleon in the Nuclear Medium

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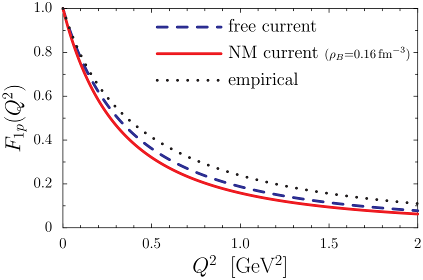
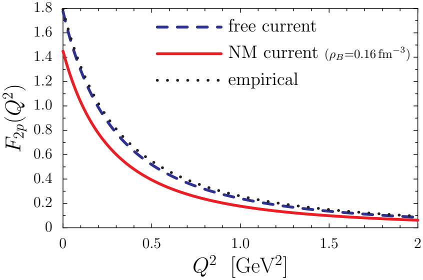
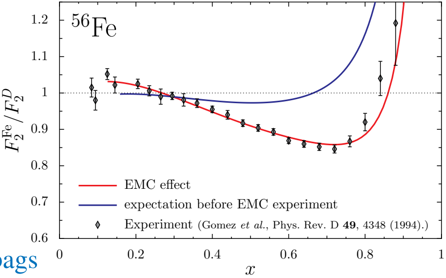
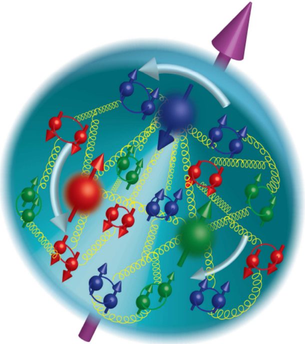


# *Explanations of the EMC effect*

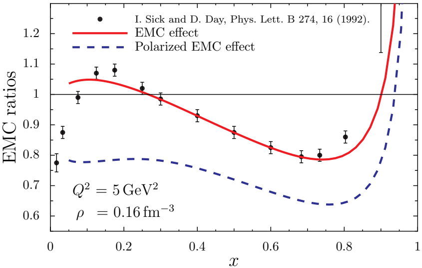
- Traditional explanations include:
  - nuclear binding and Fermi motion
  - pion excess in nuclei
- QCD motivated explanations include:
  - dynamical rescaling
  - multi-quark clusters, e.g. 6, 9, . . . quark bags
  - nucleon swelling and suppression of point-like configurations
  - medium modification of bound nucleon wave functions
- Hybrid explanations include:
  - short-range nucleon-nucleon correlations (SRCs)
- After 30 years data has ruled out almost none of these explanations!

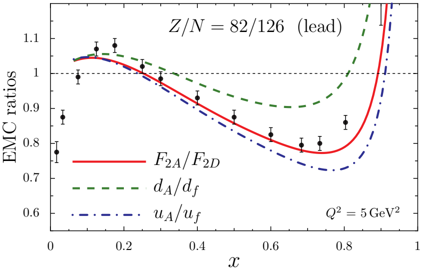


# Understanding the EMC effect

- *The puzzle posed by the EMC effect will only be solved by conducting new experiments that expose novel aspects of the EMC effect*
- Measurements must help distinguish between explanations of EMC effect; e.g. whether *all nucleons* are modified by the medium or only those in SRCs
- Important examples are measurements of the *EMC effect in polarized structure functions* & the *flavour dependence of EMC effect*
- A JLab experiment has been approved to measure the spin structure of $^{7}$Li
- Flavour dependence will be accessed via JLab DIS experiments on $^{40}$Ca & $^{48}$Ca; also parity violating DIS stands to play a pivotal role



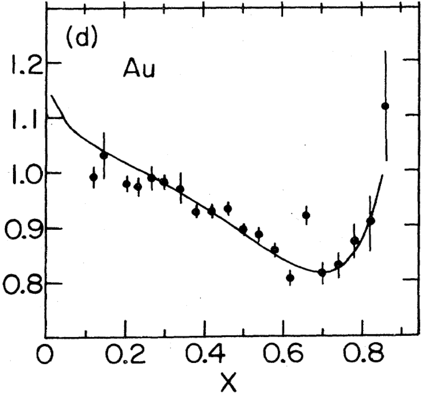



# *Sea-Quarks & Pion Excess in Nuclei*

Argonne NATIONAL LABORATORY

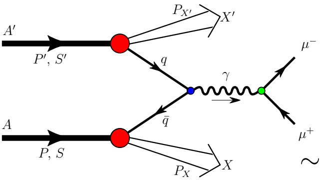
- Pions are responsible for (*inter alia*) the long range part of $NN$ interaction
- Natural to expect pions are important for the EMC effect
  [Ericson & Thomas (1983); Llewellyn Smith (1983); Berger, Coester & Wiringa (1984)]
- Pions are light – $m_\pi/M_A \ll M_N/M_A$ – so shift momentum to small $x$
  - introduce light cone distribution for pions:
    $f_\pi(y_A); \quad \int dy_A\, f_\pi(y_A) = n_\pi$

[E. L. Berger & F. Coester, Phys. Rev. D **32**, 1071 (1985)]



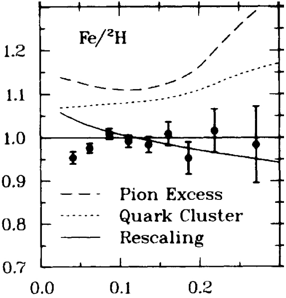

- To explain EMC effect in Gold, for example, need: $n_\pi = 0.114$
  $\Longrightarrow \quad \langle y_A \rangle = 0.061$ per-nucleon
- *A consequence of pion excess is a sizeable enhancement in the sea-quark distributions in nuclei*

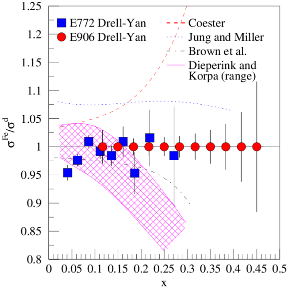
# Nuclear Sea-Quarks and Drell-Yan




$\sim \frac{\bar{u}_{Fe}}{\bar{u}_D}$

[Alde *et al.*, PRL. **64**, 2479 (1990)]




- Proposed in:

  Ericson & Thomas, PLB **148**, 191 (1984)

  Bickerstaff, Birse & Miller, PRL **53**, 2532 (1984)

- Experiment 772 at Fermilab found no anti-quark enhancement compared to the free nucleon

- *“Made a persuasive case that virtual pions with momenta greater than about 400 MeV/c are not very important in a nucleus”*

PERSPECTIVES

**Where Are the Nuclear Pions?**

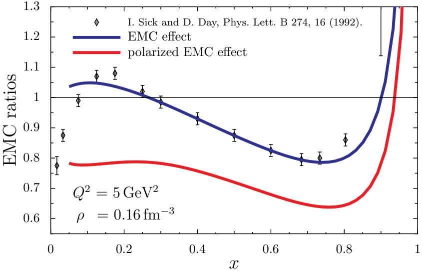
George F. Bertsch, Leonid Frankfurt, Mark Strikman

[Science, 1993]

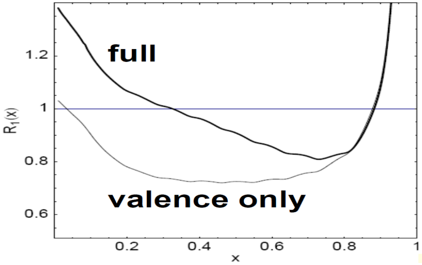
- New Fermilab Drell-Yan experiment 906 currently running

# EMC and Polarized EMC effects

[ICC, W. Bentz and A. W. Thomas, Phys. Rev. Lett. **95**, 052302 (2005)]




[J. R. Smith and G. A. Miller, Phys. Rev. C **72**, 022203(R) (2005)]

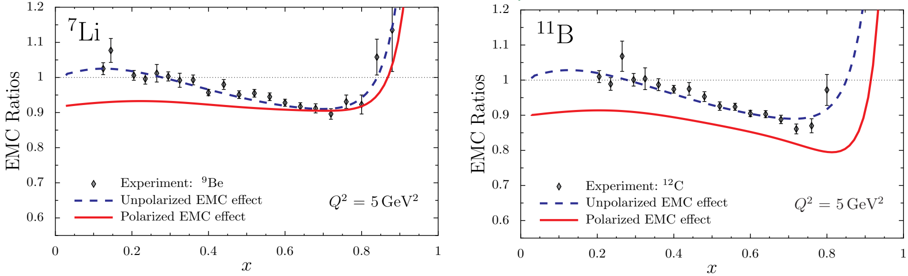



- Definition of polarized EMC effect:
  - ratio equals 1 if no medium effects

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

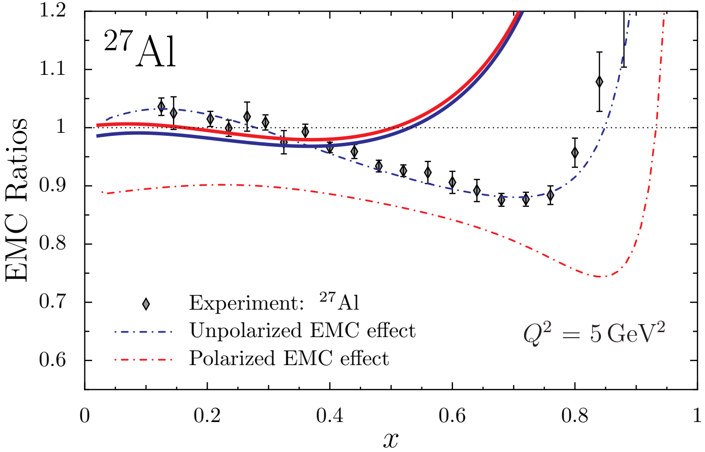
- Large polarized EMC effect results because in-medium quarks are more relativistic ($M^* < M$)
  - lower components of quark wave functions are enhanced and these usually have larger orbital angular momentum
  - *in-medium we find that quark spin is converted to orbital angular momentum*
- A large polarized EMC effect would be difficult to accommodate within traditional nuclear physics and numerous other explanations of the EMC

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




- Spin-dependent cross-section is suppressed by $1/A$
  - should choose light nucleus with spin carried by proton e.g. $\Longrightarrow$ $^7$Li, $^{11}$B, ...
- Effect in $^7$Li is slightly suppressed because it is a light nucleus and proton does not carry all the spin (simple WF: $P_p = 13/15$ & $P_n = 2/15$)
- Experiment just approved at JLab (E12-14-001) to measure spin structure functions of $^7$Li (GFMC: $P_p = 0.86$ & $P_n = 0.04$)
- *Everyone with their favourite explanation for the EMC effect should make a prediction for the polarized EMC effect in $^7$Li*

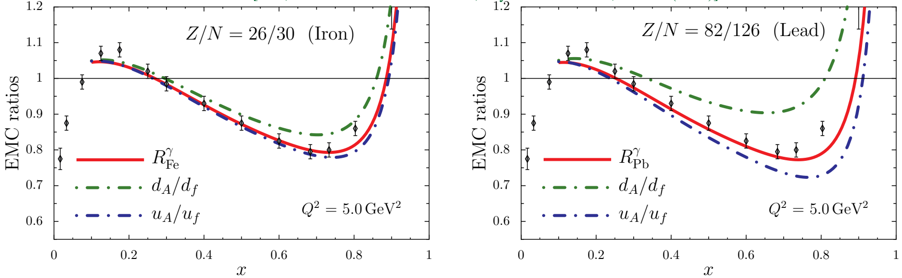
# Turning off Medium Modification




- Without medium modification both EMC & polarized EMC effects disappear
- Polarized EMC effect is smaller than the EMC effect; this is natural within standard nuclear theory and also from SRC perspective
- Large splitting very difficult without *mean-field* medium modification

# Flavour dependence of EMC effect

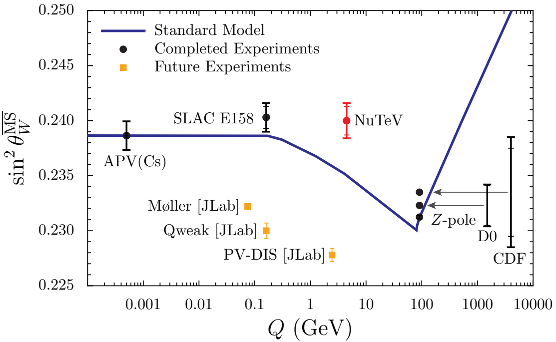
[ICC, W. Bentz and A. W. Thomas, Phys. Rev. Lett. **102**, 252301 (2009)]




- Find that EMC effect is basically a result of binding at the quark level
  - for $N > Z$ nuclei, $d$-quarks feel more repulsion than $u$-quarks: $V_d > V_u$
  - therefore $u$ quarks are more bound than $d$ quarks
- Find isovector mean-fields shift momentum *from* $u$-quarks *to* $d$-quarks

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

- Hints will be given by approved JLab DIS experiment on $^{40}$Ca and $^{48}$Ca; likely need PVDIS for conclusive result




## Fermilab 2001 press release:

"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 [$\sim$ 600 citations]
- Evidence for physics beyond the Standard Model?
- No universally accepted *complete* explanation

# Paschos-Wolfenstein ratio

- Paschos-Wolfenstein ratio motivated the NuTeV study:

$$R_{PW}=\frac{\sigma_{NC}^{\nu A}-\sigma_{NC}^{\bar{\nu} A}}{\sigma_{CC}^{\nu A}-\sigma_{CC}^{\bar{\nu} A}}=\frac{\left(\frac{1}{6}-\frac{4}{9}\sin^2\theta_W\right)\left\langle x_A\, u_A^-\right\rangle+\left(\frac{1}{6}-\frac{2}{9}\sin^2\theta_W\right)\left\langle x_A\, d_A^-+x_A\, s_A^-\right\rangle}{\left\langle x_A\, d_A^-+x_A\, s_A^-\right\rangle-\frac{1}{3}\left\langle x_A\, u_A^-\right\rangle}$$

  - $\left\langle x_A\, q_A^-\right\rangle$ fraction of target momentum carried by valence quarks of flavor $q$

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

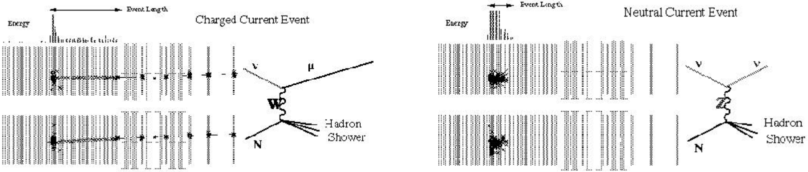
$$R_{PW}=\frac{1}{2}-\sin^2\theta_W+\Delta R_{PW};\ \ \Delta R_{PW}=\left(1-\frac{7}{3}\sin^2\theta_W\right)\frac{\left\langle x_A\, u_A^- - x_A\, d_A^- - x_A\, s_A^-\right\rangle}{\left\langle x_A\, u_A^- + x_A\, d_A^-\right\rangle}$$

- $\Delta R_{PW}$ well constrained $\Longrightarrow$ excellent way to measure weak mixing angle
- NuTeV "result" for $R_{PW}$ is smaller than Standard Model value
- Studies suggest that largest contributions to $\Delta R_{PW}$ maybe:
  - strange quarks
  - charge symmetry violation (CSV) $\Longrightarrow$ $u_p \neq d_n,\ \ d_p \neq u_n$
  - nuclear effects
- NuTeV target was 690 tons of steel $\overset{?}{\Longrightarrow}$ non-trivial nuclear corrections

# *The NuTeV experiment*

- Paschos-Wolfenstein ratio was not directly measured:

$$R_{PW} = \frac{\sigma^{\nu}_{NC} - \sigma^{\bar{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\bar{\nu}}_{CC}} \implies R^{\nu} = \frac{\sigma^{\nu}_{NC}}{\sigma^{\nu}_{CC}}, \quad R^{\bar{\nu}} = \frac{\sigma^{\bar{\nu}}_{NC}}{\sigma^{\bar{\nu}}_{CC}}; \quad R_{PW} = \frac{R^{\nu} - r\, R^{\bar{\nu}}}{1 - r}$$



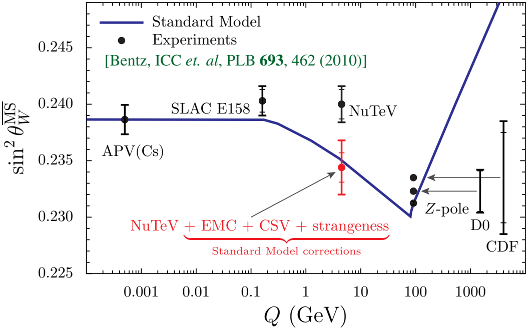

- NuTeV measured: $R^{\nu}_{\text{NuTeV}} = 0.3916(7)$ & $R^{\bar{\nu}}_{\text{NuTeV}} = 0.4050(16)$

" Corrections to $R^{\nu(\bar{\nu})}$ result from the presence of heavy quarks in the sea, the production of heavy quarks in the target, higher order terms in the cross section, and any isovector component of the light quarks in the target. In particular, in the case where a final-state charm quark is produced from a $d$ or $s$ quark in the nucleon, there are large . . .

[G. P. Zeller *et al.*, arXiv:hep-ex/0110059]

- NuTeV then performed a sophisticated Monte-Carlo analysis using constraints from the Paschos-Wolfenstein ratio

# A Reassessment of the NuTeV anomaly



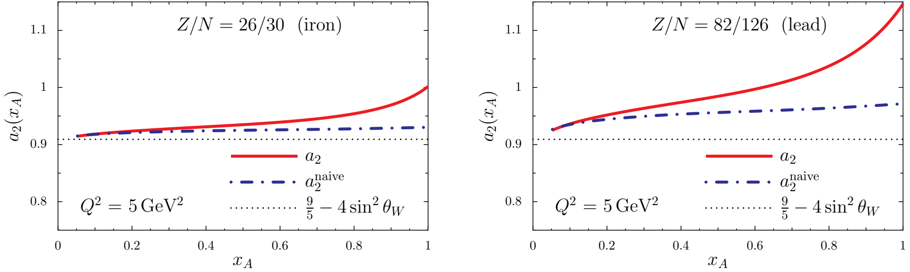

- Paschos-Wolfenstein ratio motivated NuTeV study:

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

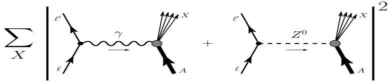
- NuTeV: $\sin^2\theta_W = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$ [Zeller *et al.* PRL. **88**, 091802 (2002)]
- Standard Model: $\sin^2\theta_W = 0.2227 \pm 0.0004$ $\Leftrightarrow 3\sigma \Longrightarrow$ "NuTeV anomaly"
- Using NuTeV *functionals*: $\sin^2\theta_W = 0.2221 \pm 0.0013(\text{stat}) \pm 0.0020(\text{syst})$
- Corrections from the EMC effect ($\sim 1.5\,\sigma$) and charge symmetry violation ($\sim 1.5\,\sigma$) brings NuTeV result into agreement with the Standard Model
  - consistent with mean-field expectation – momentum shifted *from u to d*-quarks

# *Parity-Violating DIS*

[ICC, W. Bentz and A. W. Thomas, Phys. Rev. Lett. **109**, 182301 (2012)]




- PV DIS – $\gamma\, Z$ interference:

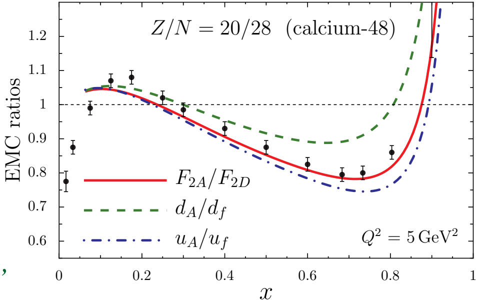



$$A_{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} \propto a_2(x) = -2g_A^e \frac{F_2^{\gamma Z}}{F_2^{\gamma}} \overset{N\sim Z}{=} \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+(x) - d_A^+(x)}{u_A^+(x) + d_A^+(x)}$$

- Deviation from naive expectation: momentum shifted *from* $u$ *to* $d$*-quarks*
- $F_2^{\gamma Z}(x)$ has markedly different flavour dependence compared with $F_2^{\gamma}(x)$
  - a measurement of both enables an extraction of $u(x)$ and $d(x)$ separately
- Proposal to measure $a_2$ of $^{48}$Ca was deferred – will likely be approved soon

# Conclusion

- Understanding the EMC effect is a another critical step towards a QCD based description of nuclei
  - approved JLab experiments will measure the polarized EMC effect in $^7$Li; PVDIS also important!
- QCD town meeting: "... *must solve problem posed by the EMC effect ...*"




- *In these lecture I have endeavored to convey that the DSEs are a powerful tool with which to study Hadron Physics; numerous benchmark results:*
  - illustrated how DCSB generates infrared masses for the quarks and gluons, thereby producing 98% of the mass in the visible Universe
  - demonstrated that dressed quarks are not Dirac particles but instead have a non-trival electromagnetic structure
  - provided the deepest insights into the structure of the pion and nucleon form factos at large $Q^2$; *etc!!*