*Joint Town Meeting on QCD*
*Temple University*
*September 15, 2014*

# Parton distributions in nuclei

*Wally Melnitchouk*

Jefferson Lab

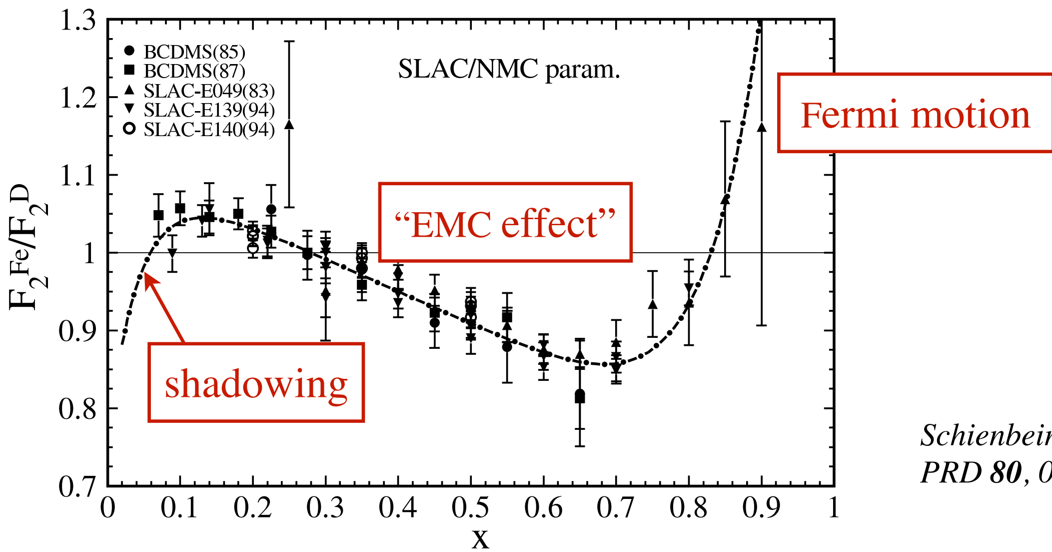
# Outline

- New insights into nuclear EMC effect from precision measurements
- Flavor dependence of nuclear effects
- Nuclear modification of spin & orbital angular momentum
- Gluons in nuclei
- Deuteron tensor structure function $b_1$

- Ultimate goal of nuclear physics: describe nuclei in terms of quarks & gluons

"Looking for quarks in the nucleus is like looking for the Mafia in Sicily – everybody *knows* they're there, but it's hard to find the evidence!"

- Fact: PDFs in nuclei are not the same as PDFs in the nucleon

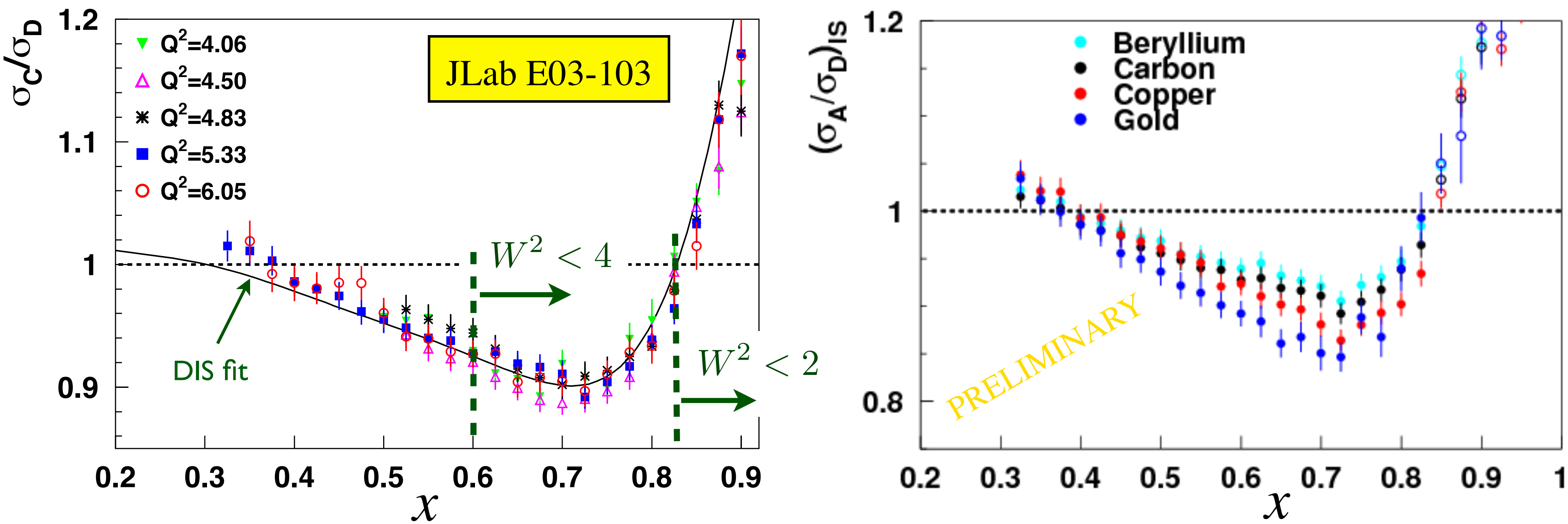



*Schienbein et al., PRD* ***80****, 094004 (2009)*

- No unique (undisputed) theoretical explanation

→ after 30 years of the nuclear EMC effect, have we learned anything more than just that *bound nucleons are not free*?

# Nuclear EMC effect: new insights



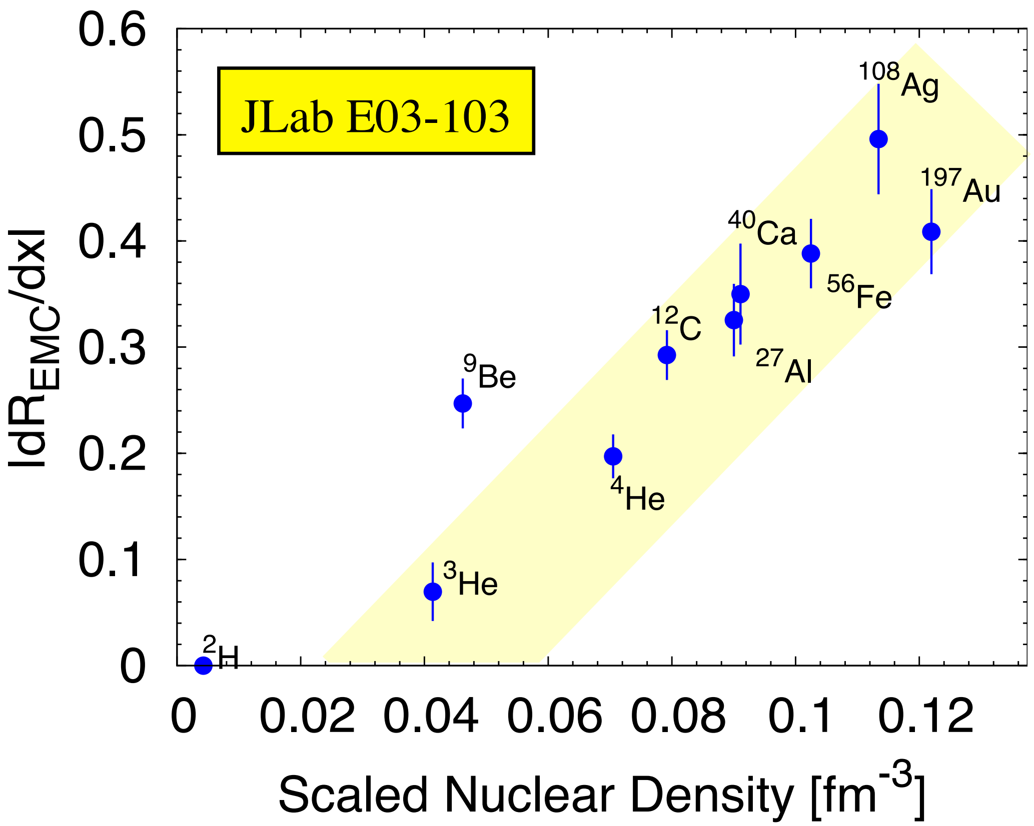

*Seely et al., PRL* ***103****, 202301 (2009)*

→ *precision* measurements of $A/D$ ratios established
EMC effect to low $Q^2$ and $W^2$

→ similarity of DIS & resonance regions (duality at nuclear level!)

→ accurate extraction of *slopes* of EMC ratios

# Nuclear EMC effect: new insights

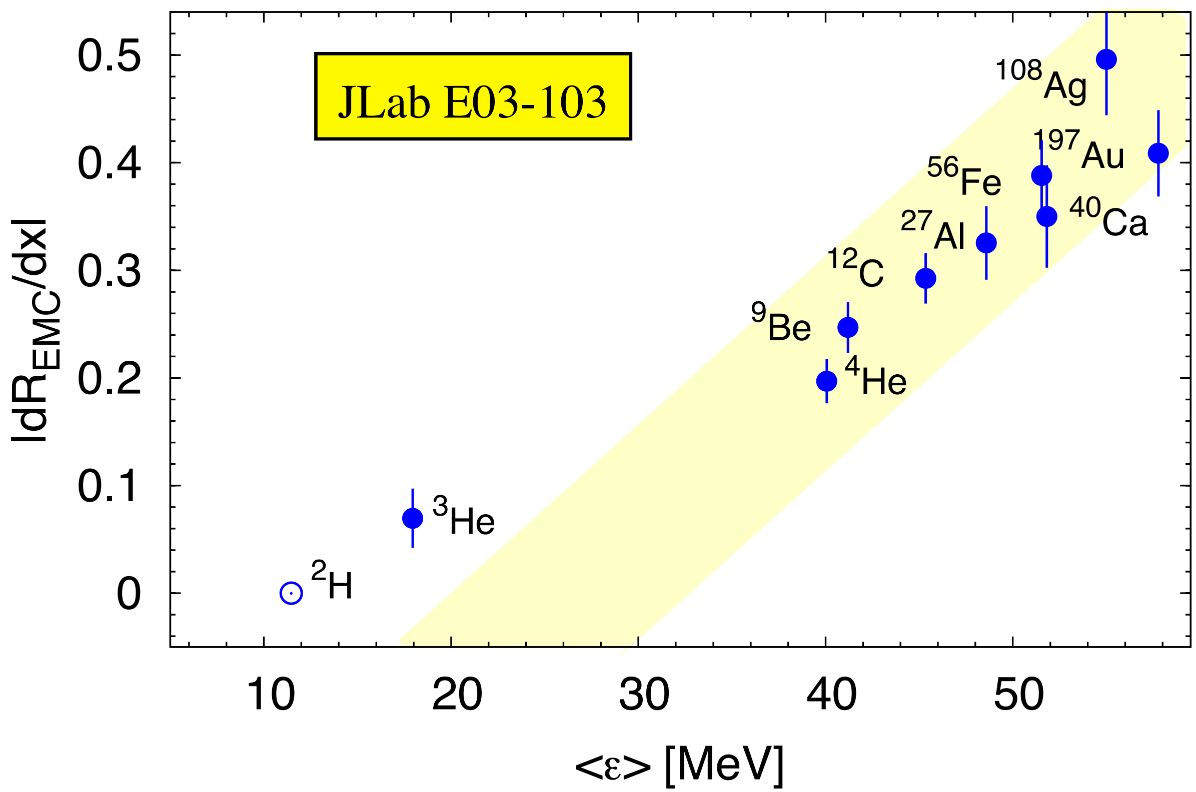



*Arrington, Fomin et al.*
*PRC* ***86****, 065204 (2012)*

→ correlation between EMC slope and *nuclear density* for a range of nuclei (related to short-range correlations?)

→ mean-field description fails for light nuclei ($^{2}$H,$^{9}$Be)

# Nuclear EMC effect: new insights

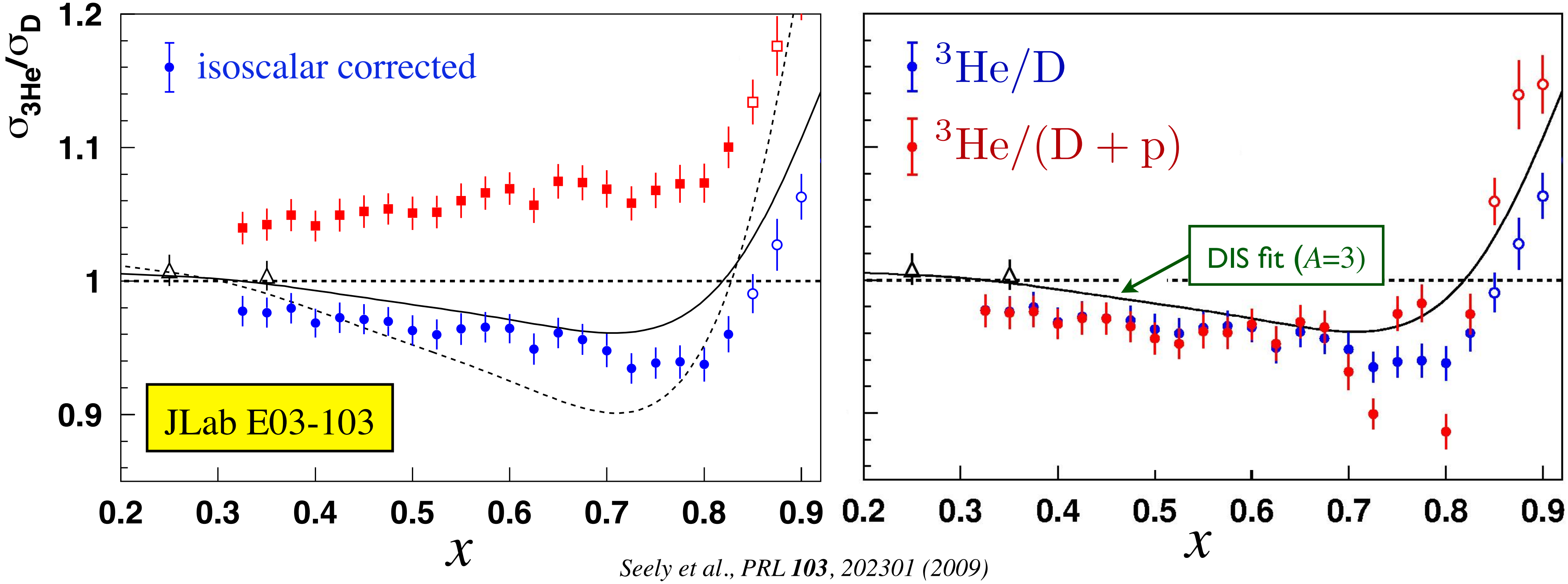



*Arrington, Fomin et al.*
*PRC* ***86****, 065204 (2012)*

⟶ correlation between EMC slope and *separation energy* for a range of nuclei $\langle \varepsilon \rangle = 2E_{\rm B} - \langle p^2 \rangle / 2M$

⟶ mean-field description fails for light nuclei $(^2\text{H}, ^3\text{He})$

# EMC effect in light nuclei



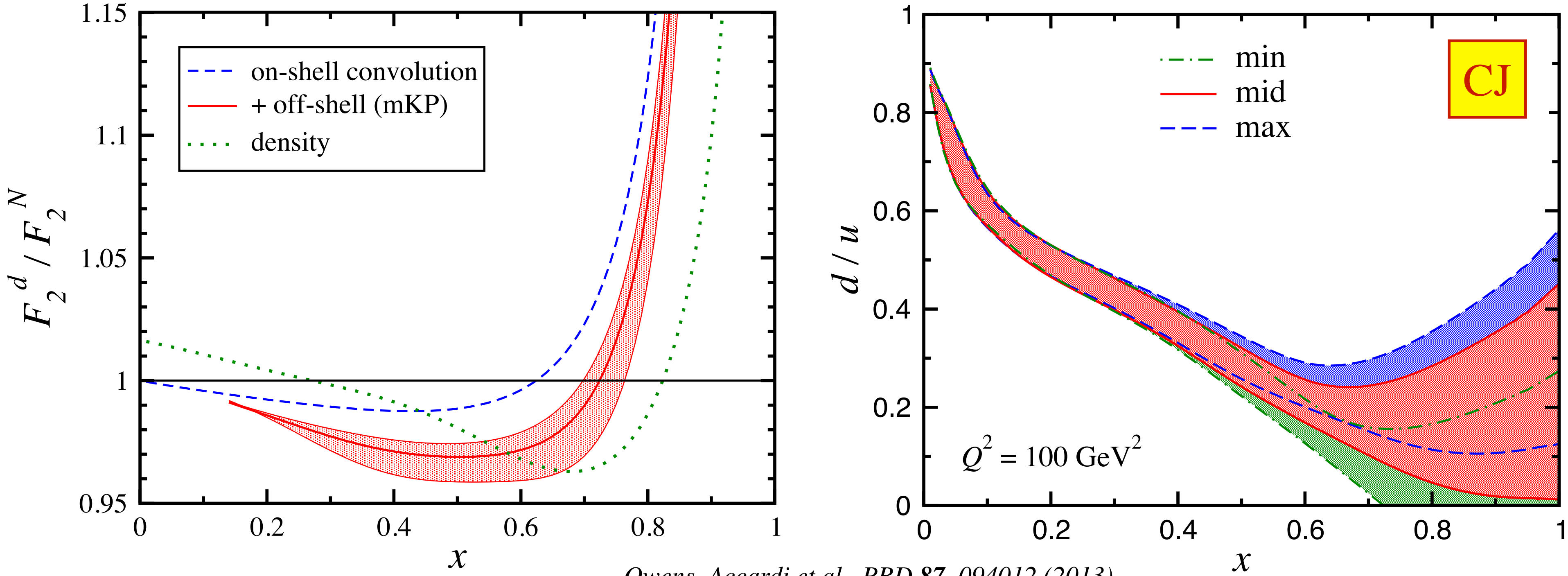

*Seely et al., PRL **103**, 202301 (2009)*

→ first measurement of EMC effect in $^3$He

→ large isoscalar correction due to proton "excess"
– assumes $F_2^n / F_2^p = 1 - 0.8\, x$

... but what about EMC effect in deuteron?

# EMC effect in deuterium




*Owens, Accardi et al., PRD* ***87****, 094012 (2013)*

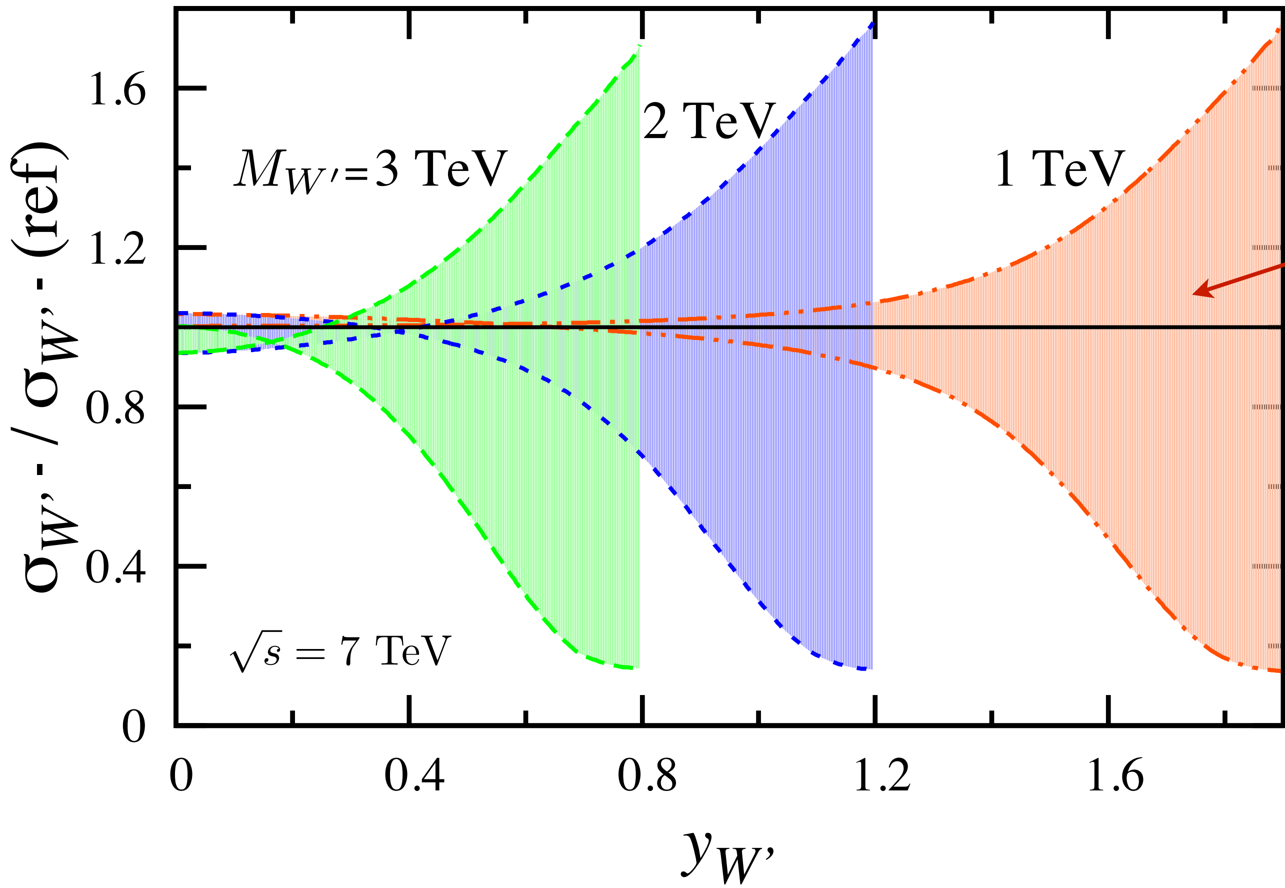
→ expect ~ 2–4% difference between $F_2^d$ & $F_2^{p+n}$ for $x < 0.7$

→ nuclear corrections (& uncertainties) systematically incorporated into CTEQ-JLab (CJ) global PDF analysis (www.jlab.org/cj)

→ significant effect on $d/u$ ratio at large $x$

$$d/u \to 0.22 \pm 0.20\,(\mathrm{PDF}) \pm 0.10\,(\mathrm{nucl}) \quad \text{as} \quad x \to 1$$

# EMC effect in deuterium




~ 100% uncertainty at large rapidity (for min−max range)

*Brady et al.*
*JHEP* ***1206**, 019 (2012)*

→ important also for BSM physics at LHC!

*e.g.* heavy boson production $p\,p \to W'^- + X$

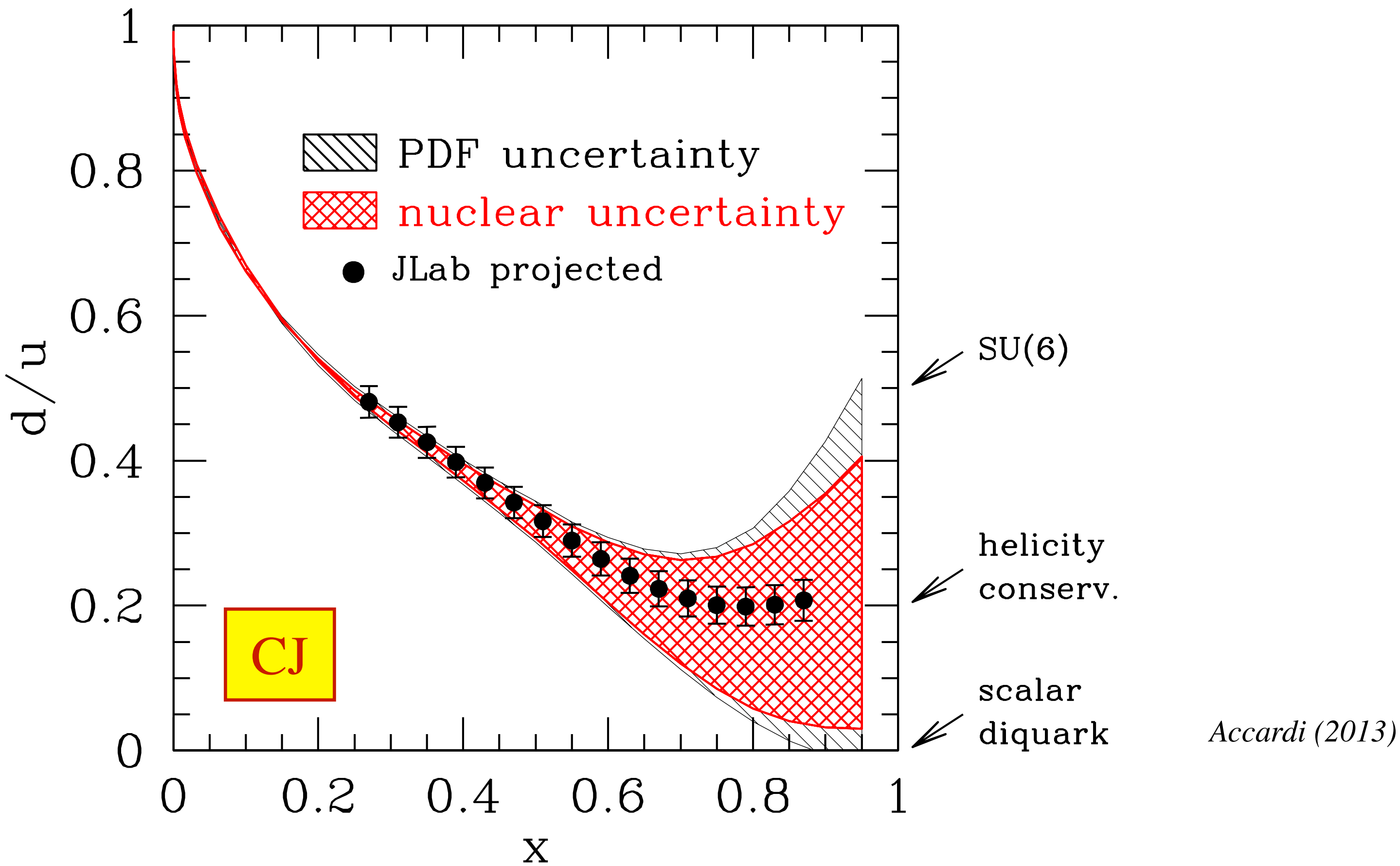
$\to \bar{\nu}\, l^-$

dominated by $d * \bar{u}$

# EMC effect in deuterium

- Empirical constraints on $d/u$ ($\rightarrow D/N$) from JLab experiments

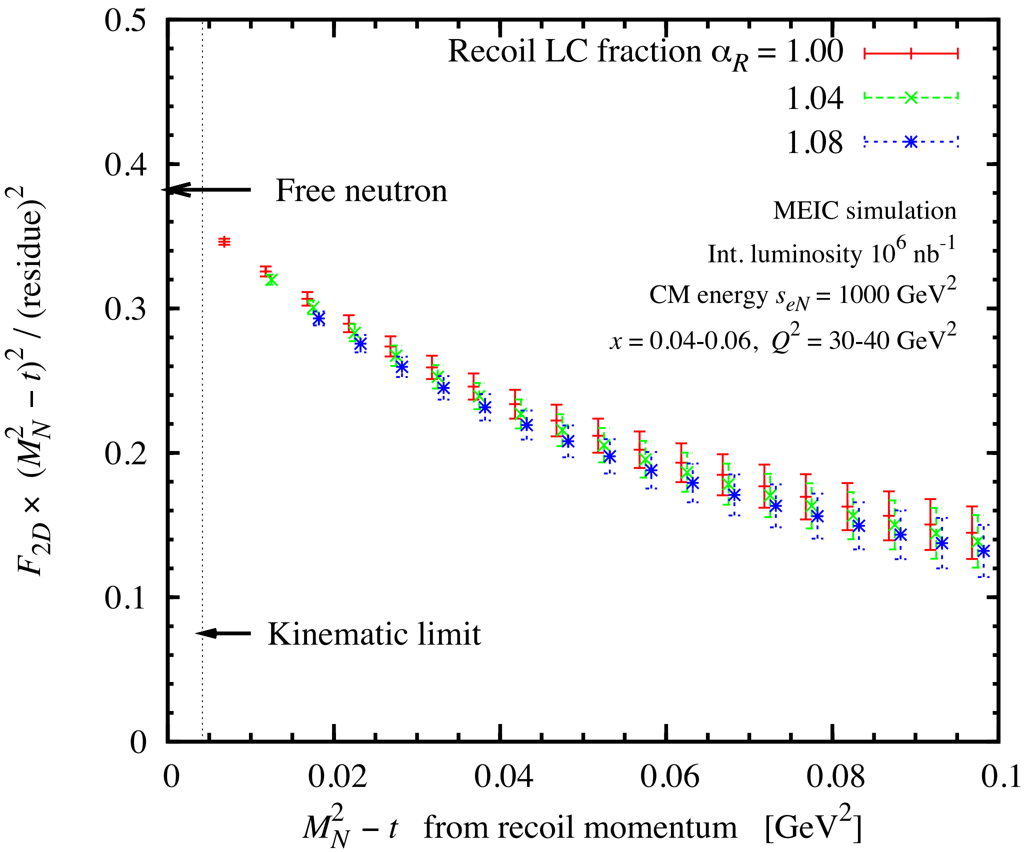
→ at 12 GeV, up to $x \sim 0.85$ from BONuS12;
DIS from $^3$He / $^3$H DIS (MARATHON); PVDIS from H (SoLID)




→ will settle decades-old problem ("rewrite textbooks")

# EMC effect in deuterium

- Beyond $12\,\mathrm{GeV}$, study free neutron structure at EIC via conditional (SIDIS) structure functions in $e\,D \to e\,p\,X$

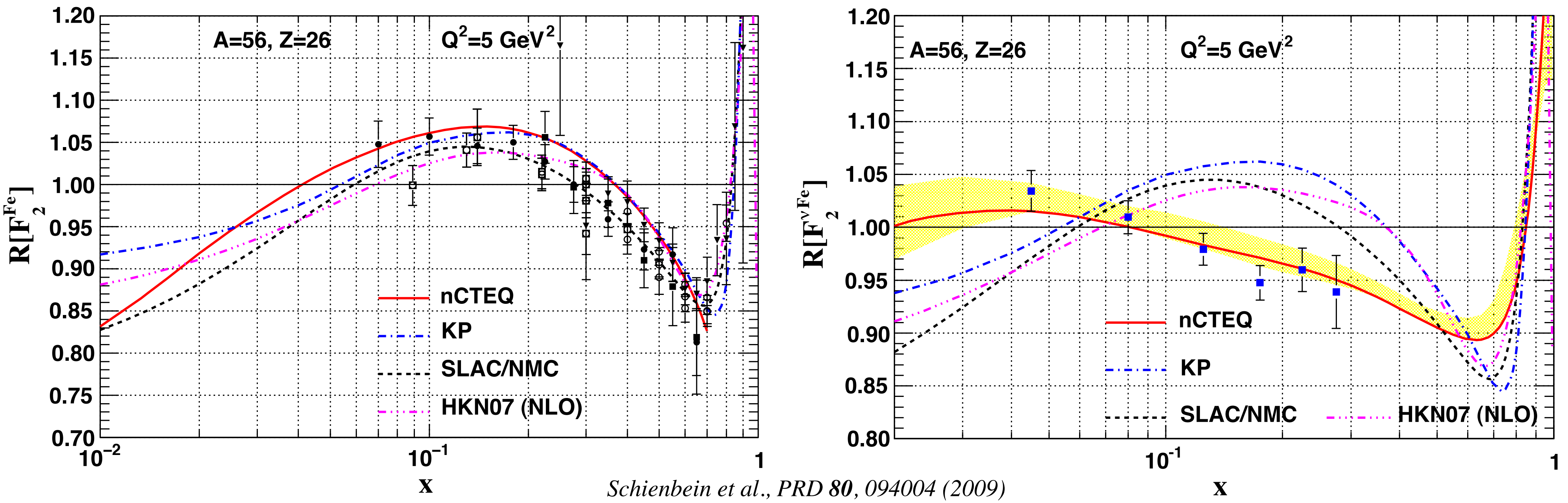



*Weiss (2014)*

→ controlled extrapolation to neutron pole

# Flavor dependence of nuclear PDFs

- nCTEQ* global NLO analysis of nuclear PDFs




*Schienbein et al., PRD **80**, 094004 (2009)*

→ good description ($\chi^2$/dof = 0.946) of PDFs for $A$=1−207

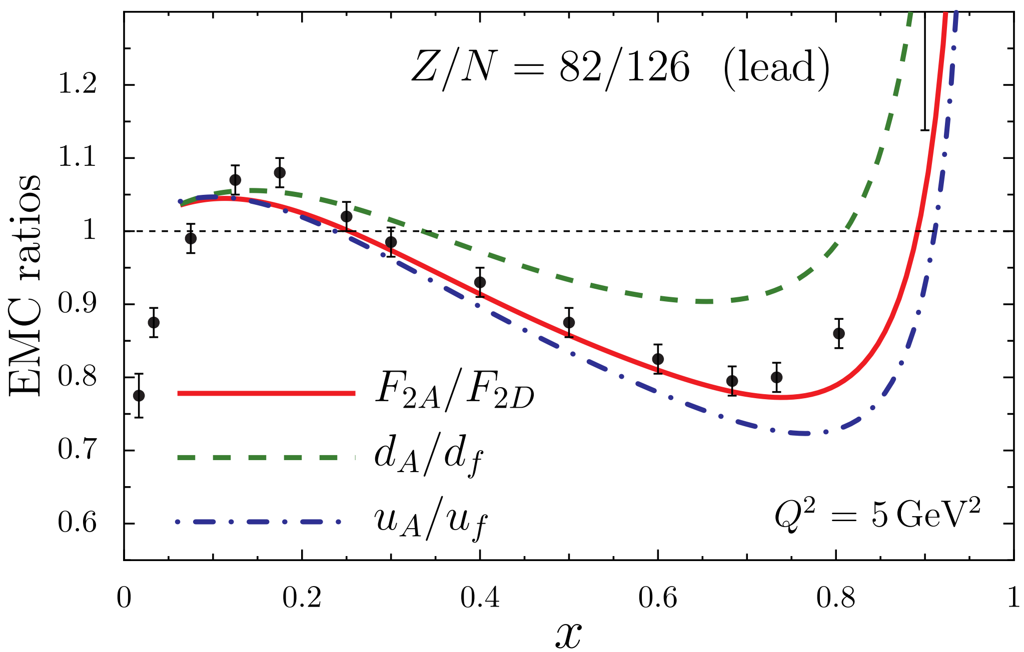
→ nuclear effects in $\nu$-Fe DIS data (NuTeV) not compatible with those derived from charged-lepton DIS & DY!

→ future $\nu$ data on $A$ dependence from MINERvA may clarify whether corrections different for e.m. & weak probes

* nuclear−CTEQ (SMU-FSU-JLab-FNAL-Grenoble)

# Flavor dependence of nuclear PDFs

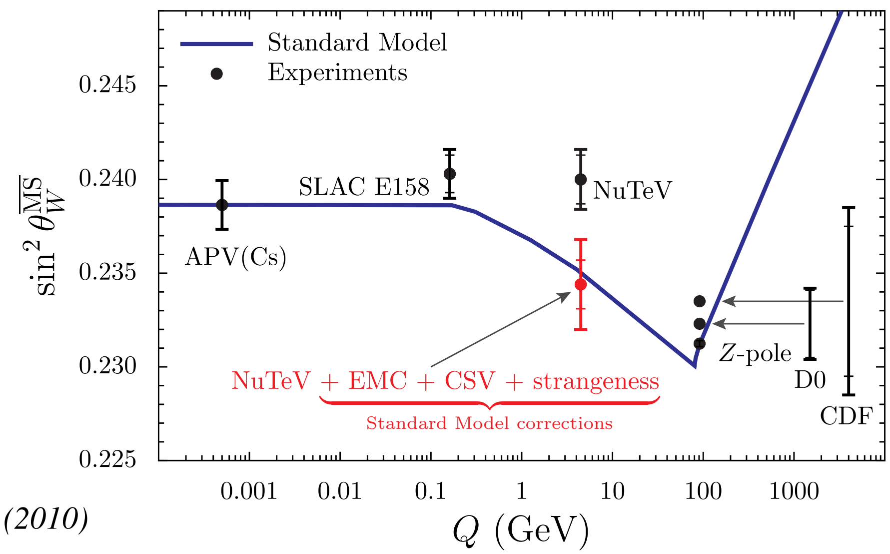
- Interaction of quarks with isovector-vector mean-field $\rho^0$ induces differences between $u$ & $d$ medium modifications




$u$ feels vector *attraction*,
$d$ feels additional *repulsion*

*Cloet et al.*
*PRL* ***102****, 252301 (2009)*

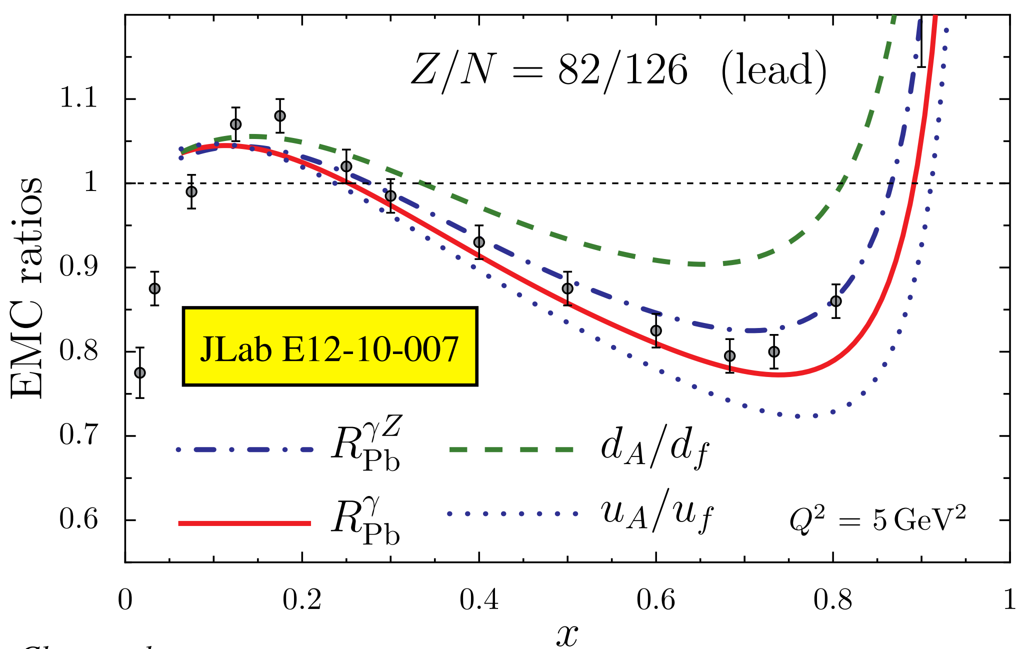
→ important implications for NuTeV "anomaly"

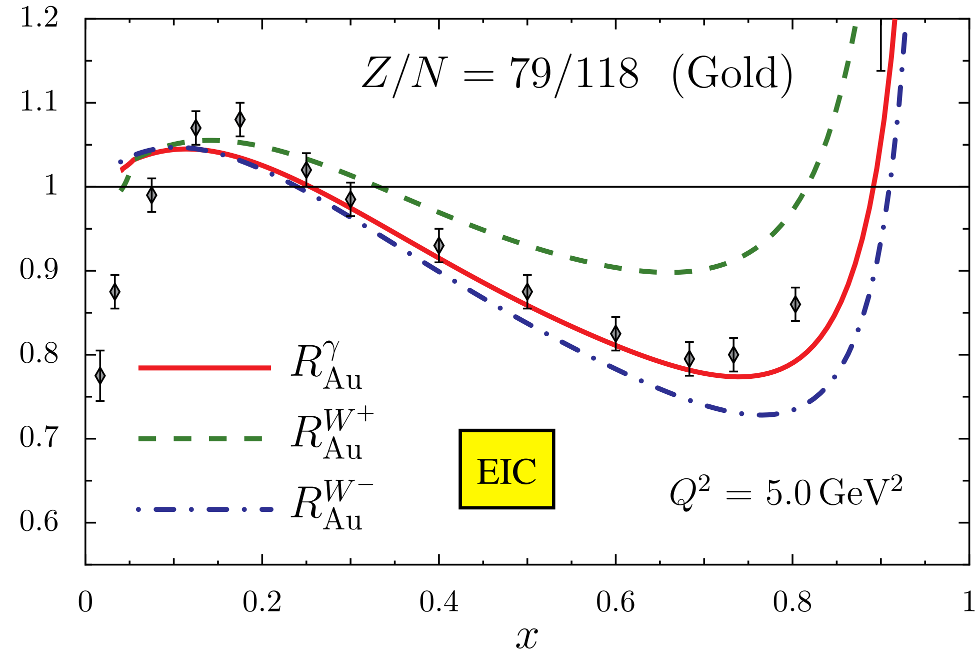



*Bentz et al.*
*PLB* ***693****, 462 (2010)*

# Flavor dependence of nuclear PDFs

- Can be tested in parity-violating DIS at JLab ($\gamma Z$ interference); charged-current DIS at EIC




*Cloet et al.*
*PRL **109**, 182301 (2012)*

$$R^i_A = \frac{F_2^A}{ZF_2^p + NF_2^n}, \quad i = \gamma,\, \gamma Z,\, W^\pm$$

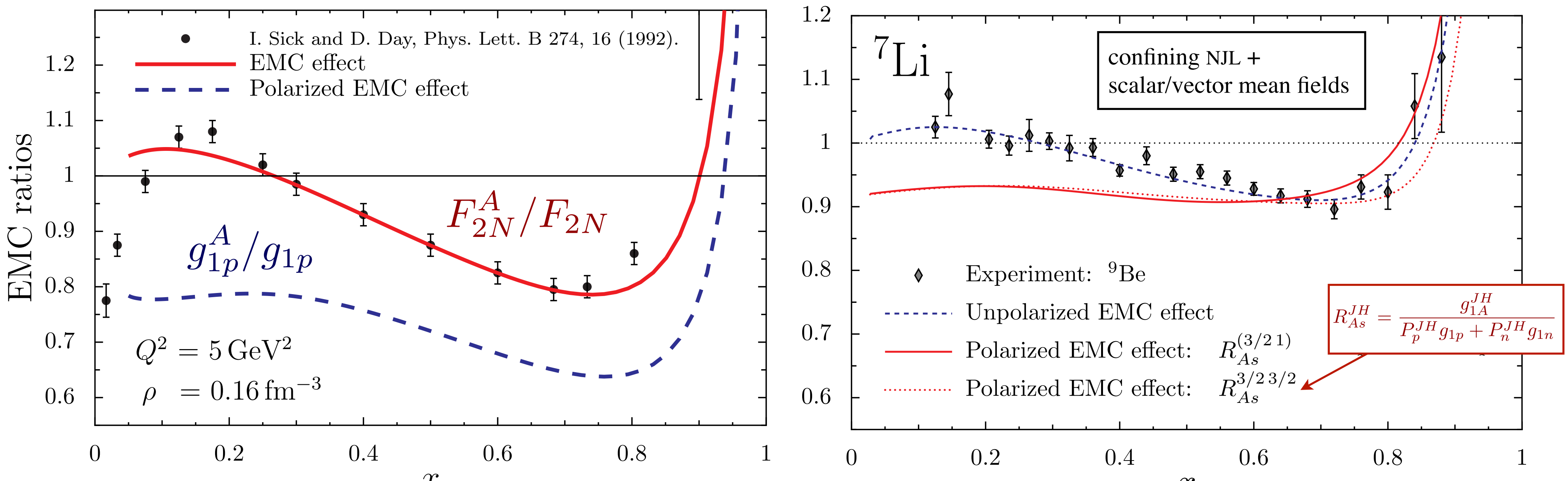
→ $\sim 5\%$ effect in $^{208}$Pb feasible with SOLiD

→ $e^\mp A \to \nu(\bar{\nu})\, X$
$\nu$ energy reconstructed from hadronic final state

# Nuclear modification of spin PDFs

- Quark interactions with scalar mean-fields in nuclei *reduce* dynamical quark mass (~ 20% at nuclear matter density)

  → lower components of quark spinors enhanced



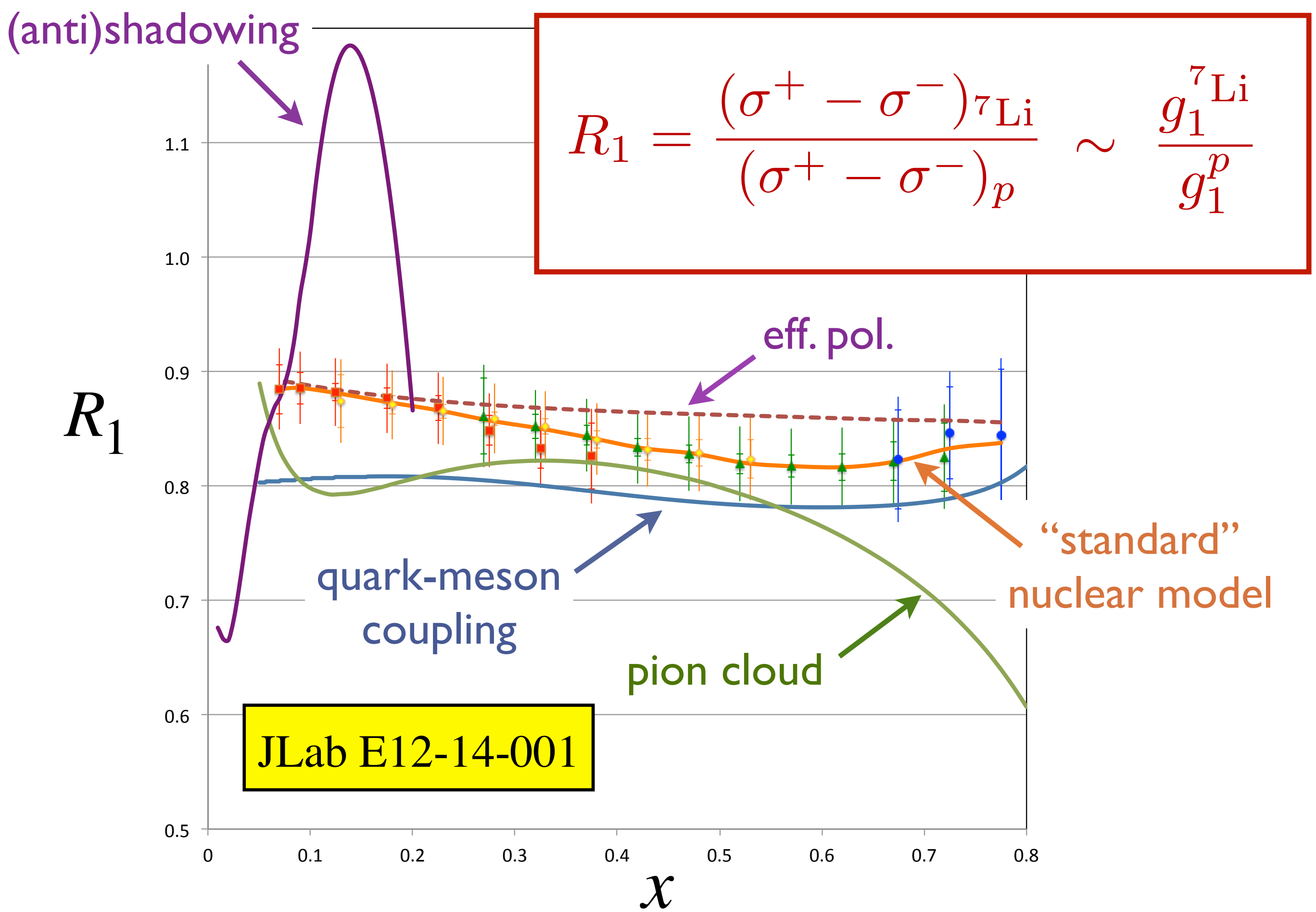

*Cloet et al., PRL* ***95****, 052302 (2005); PLB* ***642****, 210 (2006)*

→ spin EMC effect predicted to be *larger* than unpolarized

→ spin of carried by quarks *decreases* in nuclei
(orbital angular momentum in medium expected to *increase*)

# Nuclear modification of spin PDFs

- Approved JLab experiment E12-14-001 on $^7$LiD

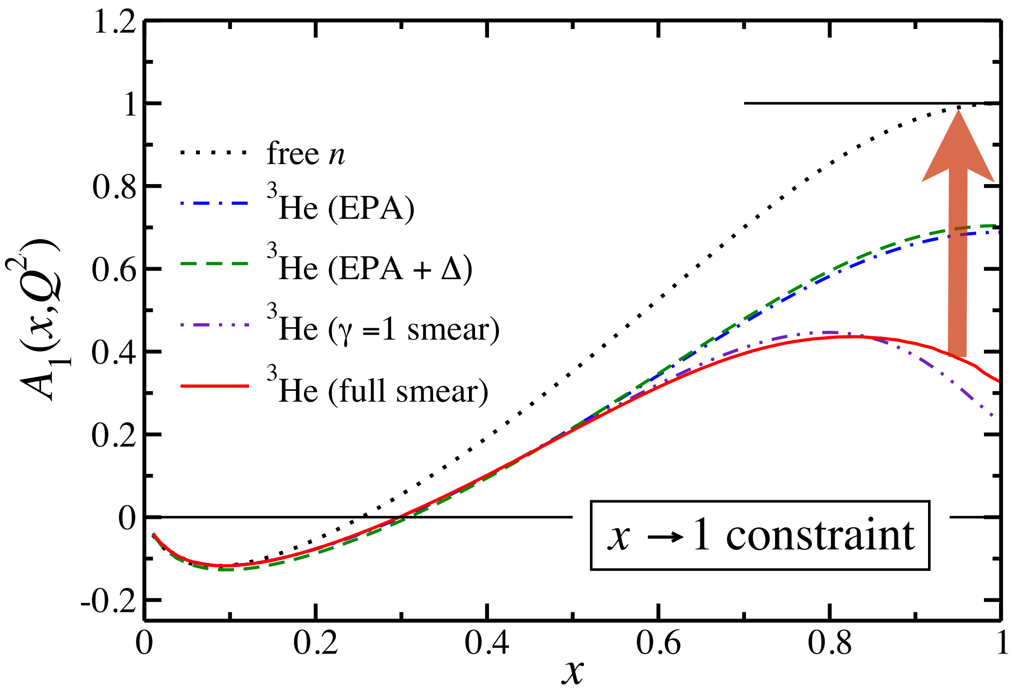



$$R_1 = \frac{(\sigma^+ - \sigma^-)_{^7\mathrm{Li}}}{(\sigma^+ - \sigma^-)_p} \sim \frac{g_1^{^7\mathrm{Li}}}{g_1^p}$$

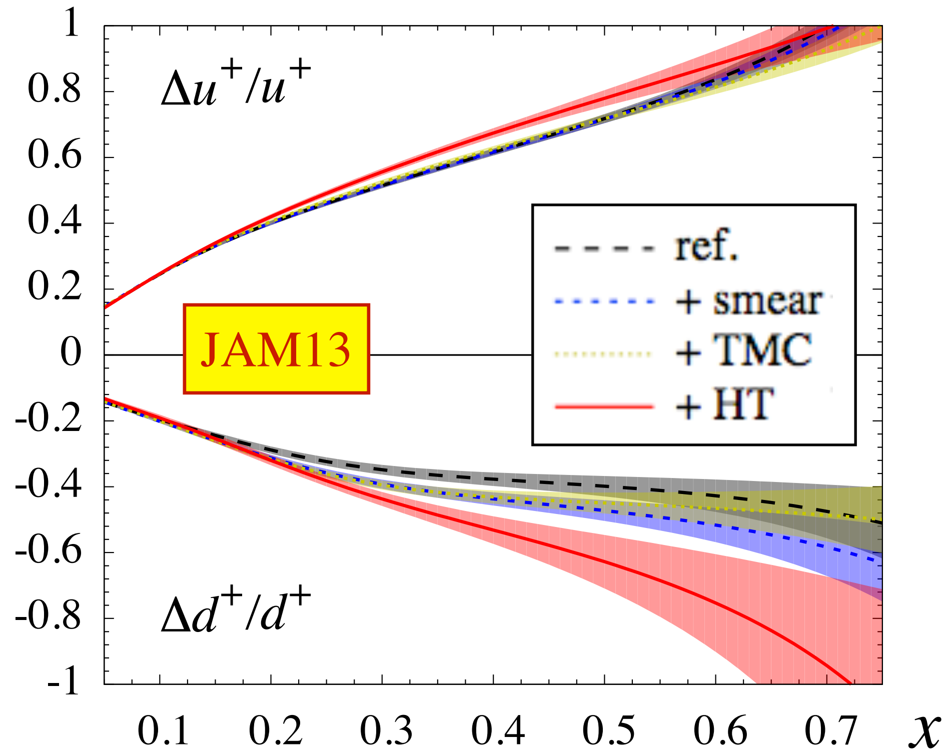
→ quantify role of quark d.o.f. in nuclear environment

# Nuclear modification of spin PDFs

- Nuclear corrections in extracting polarized $n$ from $^3$He




*Ethier et al., PRC* ***88****, 5 (2013)*




*Jimenez-Delgado et al., PRD* ***89****, 034025 (2014)*

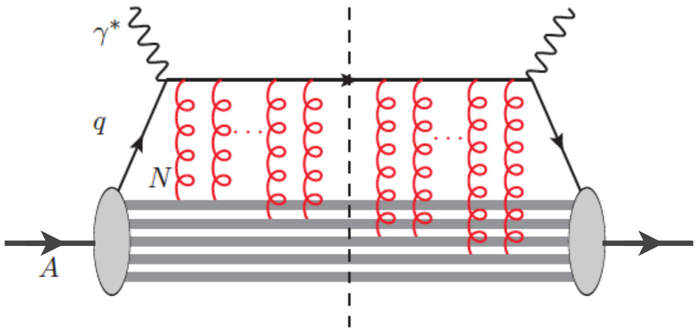
→ systematically included in JAM (Jefferson Lab Angular Momentum) global PDF analysis (www.jlab.org/jam)

→ crucial for reliable extraction of large-$x$ PDFs

# Nuclear modification of spin TMDs

- Medium effects larger for spin-dependent distributions

→ observables sensitive to orbital motion (TMD / SSA) should have enhanced medium modifications




parton $\langle k_\perp^2 \rangle$ from soft gluon exchange

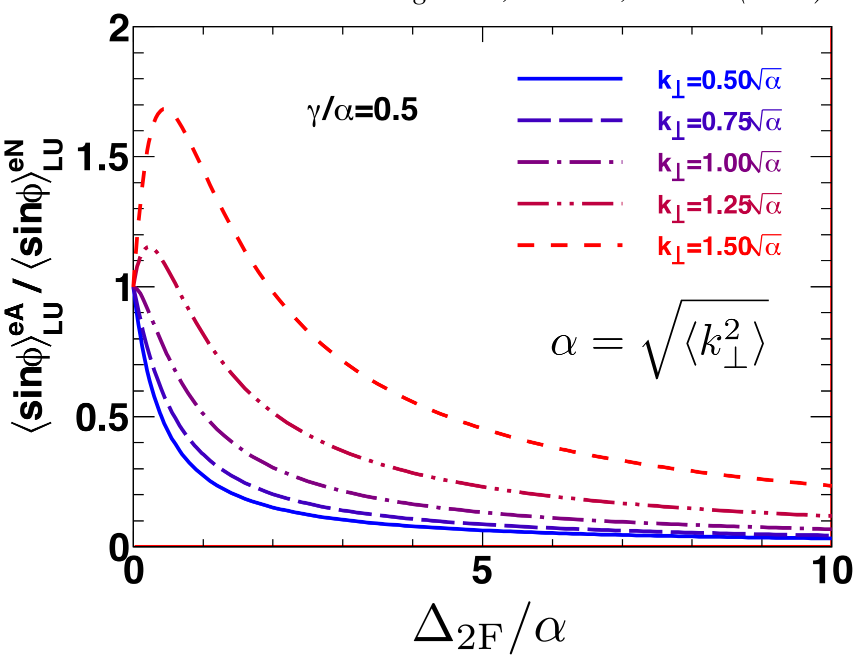
→ beam longitudinal single-spin asymmetry

$$\langle \sin\phi \rangle_{LU} \propto \frac{k_\perp}{Q} \frac{g^\perp(x,k_\perp)}{f_1(x,k_\perp)}$$

twist-3, T-odd

$$\frac{\left(A_{LU}^{\sin\phi}\right)^{eA}}{\left(A_{LU}^{\sin\phi}\right)^{eN}} \approx \frac{\langle k_\perp^2 \rangle}{\langle k_\perp^2 \rangle + \Delta_{2F}}$$

*Tang et al., PRD 77, 125010 (2008)*

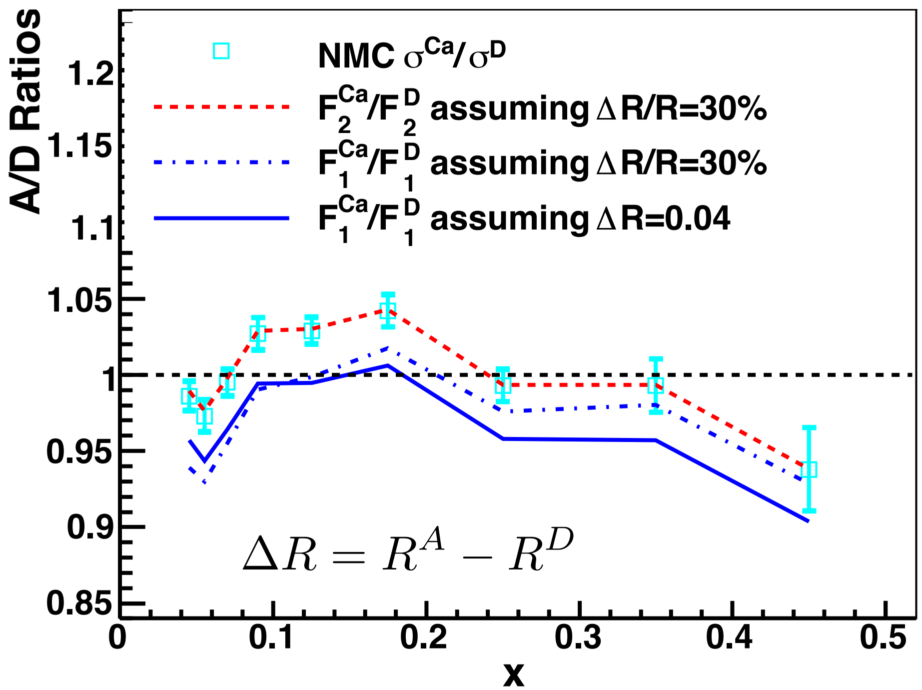


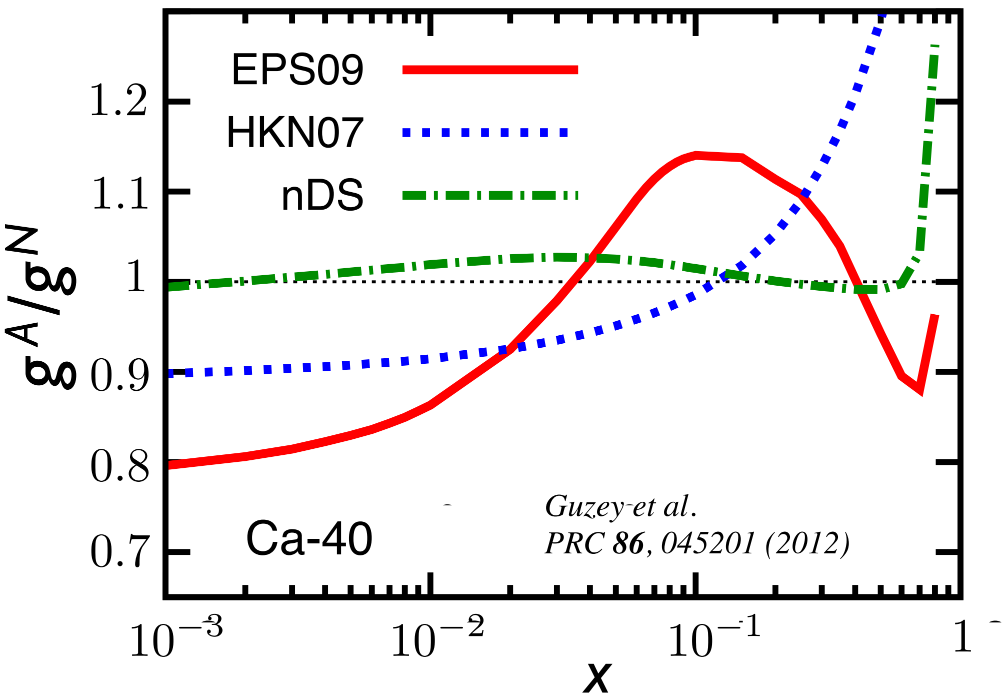

$k_\perp$ broadening

→ can be measured @ JLab12 *Avakian (2014)*

# Gluons in nuclei

- Influence of $R = \sigma_L/\sigma_T$ on EMC ratios




→ nuclear modification of $R$ gives significant reduction of antishadowing for $F_1$ *cf.* $F_2$

→ antishadowing dominated by gluons *cf.* (anti)quarks?

→ $L$–$T$ separation at JLab12 for $A$=1–78 (PR12-14-002)
(prompt-$\gamma$ production at EIC?)

# Deuteron $b_1$ structure function

- Tensor polarized $D$ structure function gives *unique* opportunity to study non-nucleonic effects in nuclei

→ no free−nucleon analog

→ in parton model

$$b_1 = \frac{1}{2} \sum_q e_q^2 \left(\delta_T q + \delta_T \bar{q}\right) \qquad \delta_T q = q^{(0)} - \frac{q^{(+1)} + q^{(-1)}}{2}$$

$$\rightarrow \int_0^1 dx\, b_1 = \frac{1}{18} \int_0^1 dx\, \left(8\delta_T \bar{u} + 2\delta_T \bar{d} + \delta_T \bar{s}\right)$$

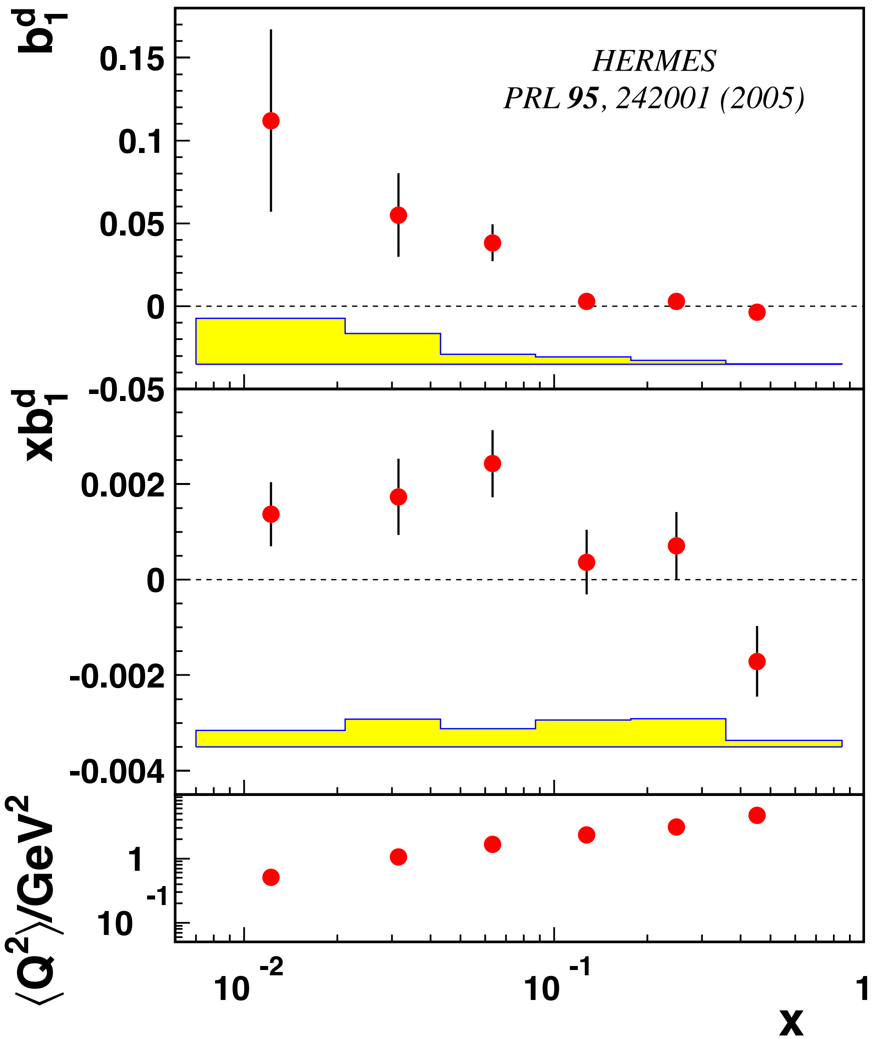
$\longrightarrow\ 0$ for tensor-unpolarized sea

(*cf*. Gottfried sum rule)

*Close, Kumano*
*PRD* ***42****, 2377 (1990)*

→ in convolution model, $b_1$ vanishes for nucleons in $S$-state; small nonzero $D$-state contribution

# Deuteron $b_1$ structure function




→ HERMES data suggest polarization of tensor sea!

$$\int_{0.02}^{0.85} dx\, b_1 = (0.35 \pm 0.10 \pm 0.18) \times 10^{-2}$$

→ theoretical situation unclear:
(anti)shadowing, pion exchange,
$6q$ configs, final-state interactions, ... ?

→ JLab12 experiment E12-13-110 will cover $0.15 < x < 0.5$ (→ E. Long)
– EIC would settle question of CK sum rule

# Summary

- Precision measurements of EMC ratios
  → systematics of $A$ dependence, slopes
  - need to establish theoretical basis for correlations
- First measurement of EMC effect for $A$=3
  - determine EMC effect for $A$=2 (free neutron structure)
  - impact QCD backgrounds at colliders
- Discrepancy between $\ell^{-}A$ & $\nu A$ data?
  - important for neutrino oscillation studies
  - flavor dependence of EMC effect in PVDIS at JLab12; CC at EIC
- Prediction of spin EMC effect to be tested at JLab12
  - nuclear corrections in $^3$He vital for extraction of $A_1^n$ at $x \to 1$
- Suggestion of gluonic origin of antishadowing
  - $A$ dependence of $R$ at JLab12 will reveal role of nuclear gluons
- $b_1$ measurements (at JLab12, EIC) may reveal non-trivial tensor polarization of sea