Three-body dynamics in hadron structure & hadronic systems:
A symposium in celebration of Iraj Afnan's 70th birthday
Jefferson Lab, July 24, 2009

Deep-inelastic scattering on the tri-nucleons

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Jefferson Lab

Outline

- Motivation: neutron structure at large x
  - → d/u ratio, duality in the neutron

- Status of large-x quark distributions
  - → nuclear corrections
  - → new global analysis of *inclusive* DIS data (CTEQx)

- DIS from A=3 nuclei
  - → model-independent extraction of neutron F_2
  - → plans for helium-3/tritium experiments

Quark distributions at large x

Parton distributions functions (PDFs)

- provide basic information on structure of hadronic systems

- needed to understand backgrounds in searches for *new physics* beyond the Standard Model in high-energy colliders, neutrino oscillation experiments, ...

$\longrightarrow$ DGLAP evolution feeds low x, high Q^2 from high x, low Q^2

$$\frac{dq(x,t)}{dt} = \frac{\alpha_s(t)}{2\pi} \int_x^1 \frac{dy}{y} \left[P_{qq}\left(\frac{x}{y}\right) q(y,t) + P_{qg}\left(\frac{x}{y}\right) g(y,t) \right]$$

$$t = \log Q^2 / \Lambda^2_{\rm QCD}$$

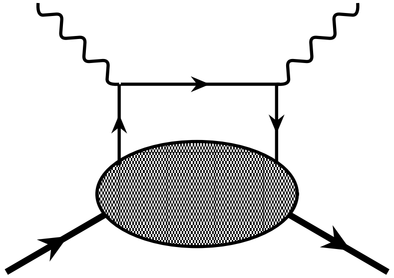
- Ratio of d to u quark distributions at large x particularly sensitive to quark dynamics in nucleon

- SU(6) spin-flavor symmetry

proton wave function

$$p^\uparrow = -\frac{1}{3}d^\uparrow(uu)_1 - \frac{\sqrt{2}}{3}d^\downarrow(uu)_1$$

$$+ \frac{\sqrt{2}}{6}u^\uparrow(ud)_1 - \frac{1}{3}u^\downarrow(ud)_1 + \frac{1}{\sqrt{2}}u^\uparrow(ud)_0$$



interacting quark

spectator diquark

diquark spin

- Ratio of d to u quark distributions at large x particularly sensitive to quark dynamics in nucleon

- SU(6) spin-flavor symmetry

proton wave function

$$p^{\uparrow} = -\frac{1}{3}d^{\uparrow}(uu)_1 - \frac{\sqrt{2}}{3}d^{\downarrow}(uu)_1 + \frac{\sqrt{2}}{6}u^{\uparrow}(ud)_1 - \frac{1}{3}u^{\downarrow}(ud)_1 + \frac{1}{\sqrt{2}}u^{\uparrow}(ud)_0$$

$\longrightarrow$ $u(x) = 2\ d(x)$ for all x

$$\longrightarrow \frac{F_2^n}{F_2^p} = \frac{2}{3}$$

🟥 scalar diquark dominance

$M_\Delta > M_N \quad \Longrightarrow \quad (qq)_1$ has larger energy than $(qq)_0$

$\Longrightarrow$ scalar diquark dominant in $x \to 1$ limit

since only u quarks couple to scalar diquarks

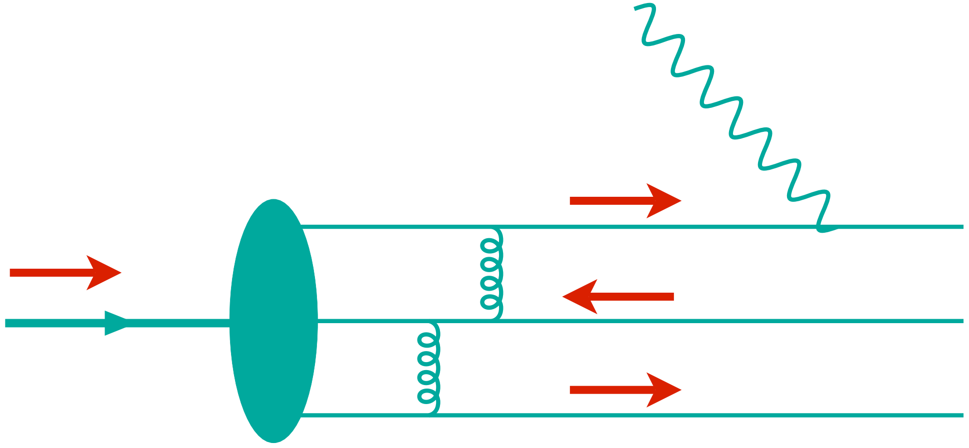
$$\longrightarrow \quad \boxed{\frac{d}{u} \to 0}$$

$$\longrightarrow \quad \frac{F_2^n}{F_2^p} \to \frac{1}{4}$$

Feynman 1972, Close 1973, Close/Thomas 1988

- hard gluon exchange

at large x, helicity of struck quark = helicity of hadron



$$q^{\uparrow} \gg q^{\downarrow}$$

$\Longrightarrow$ helicity-zero diquark dominant in $x \to 1$ limit

$$\longrightarrow \boxed{\frac{d}{u} \to \frac{1}{5}}$$

$$\longrightarrow \frac{F_2^n}{F_2^p} \to \frac{3}{7}$$

Farrar, Jackson 1975

- At large x, valence u and d distributions extracted from p and n structure functions

$$F_2^p \approx \frac{4}{9} u_v + \frac{1}{9} d_v$$

$$F_2^n \approx \frac{4}{9} d_v + \frac{1}{9} u_v$$

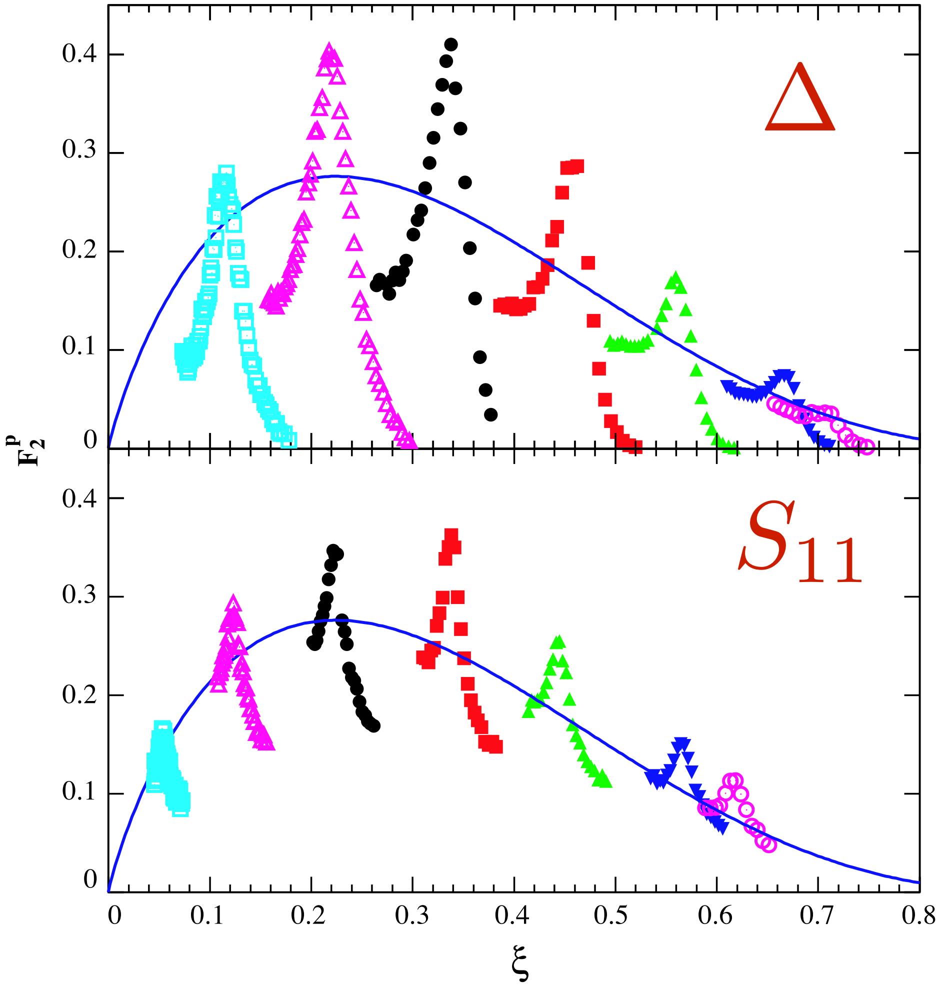
- u quark distribution well determined from p data

- d quark distribution requires n structure function

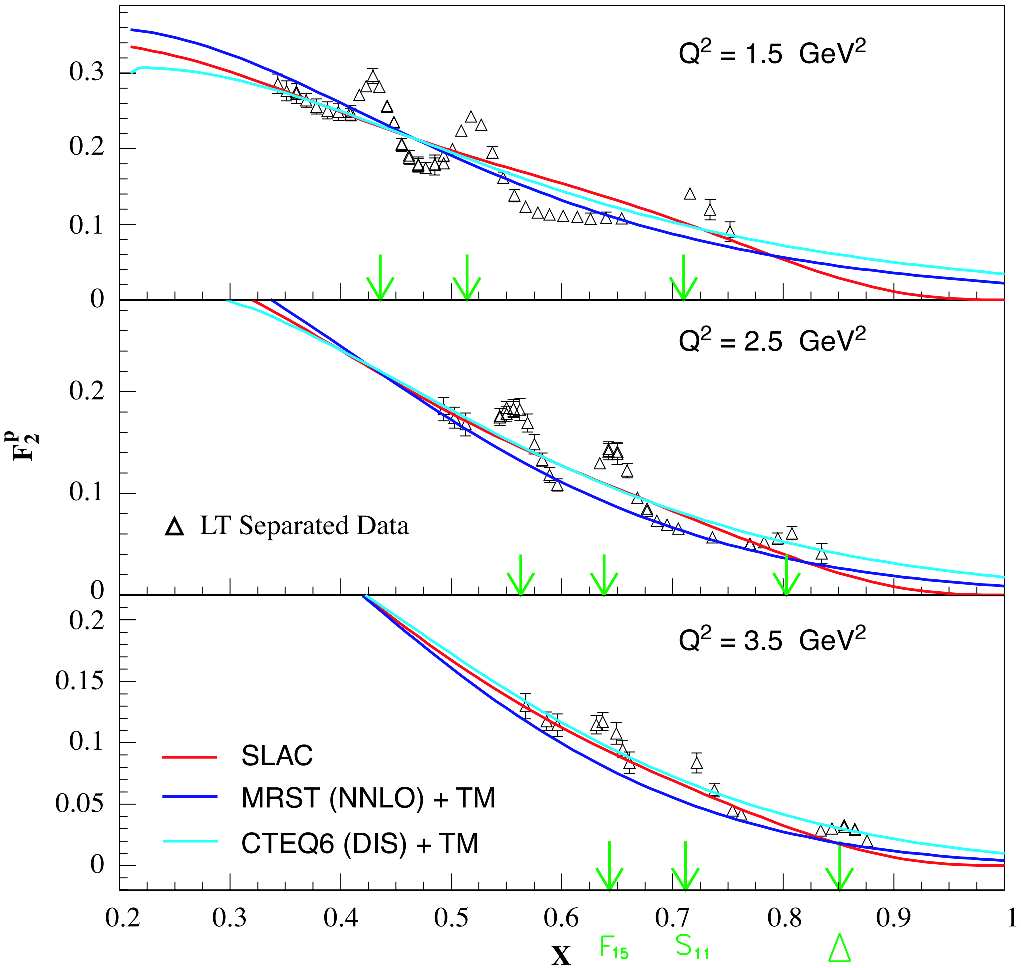
$$\Longrightarrow \quad \frac{d}{u} \approx \frac{4 - F_2^n / F_2^p}{4 F_2^n / F_2^p - 1}$$

Duality in the neutron?

Bloom-Gilman duality well established for the *proton*

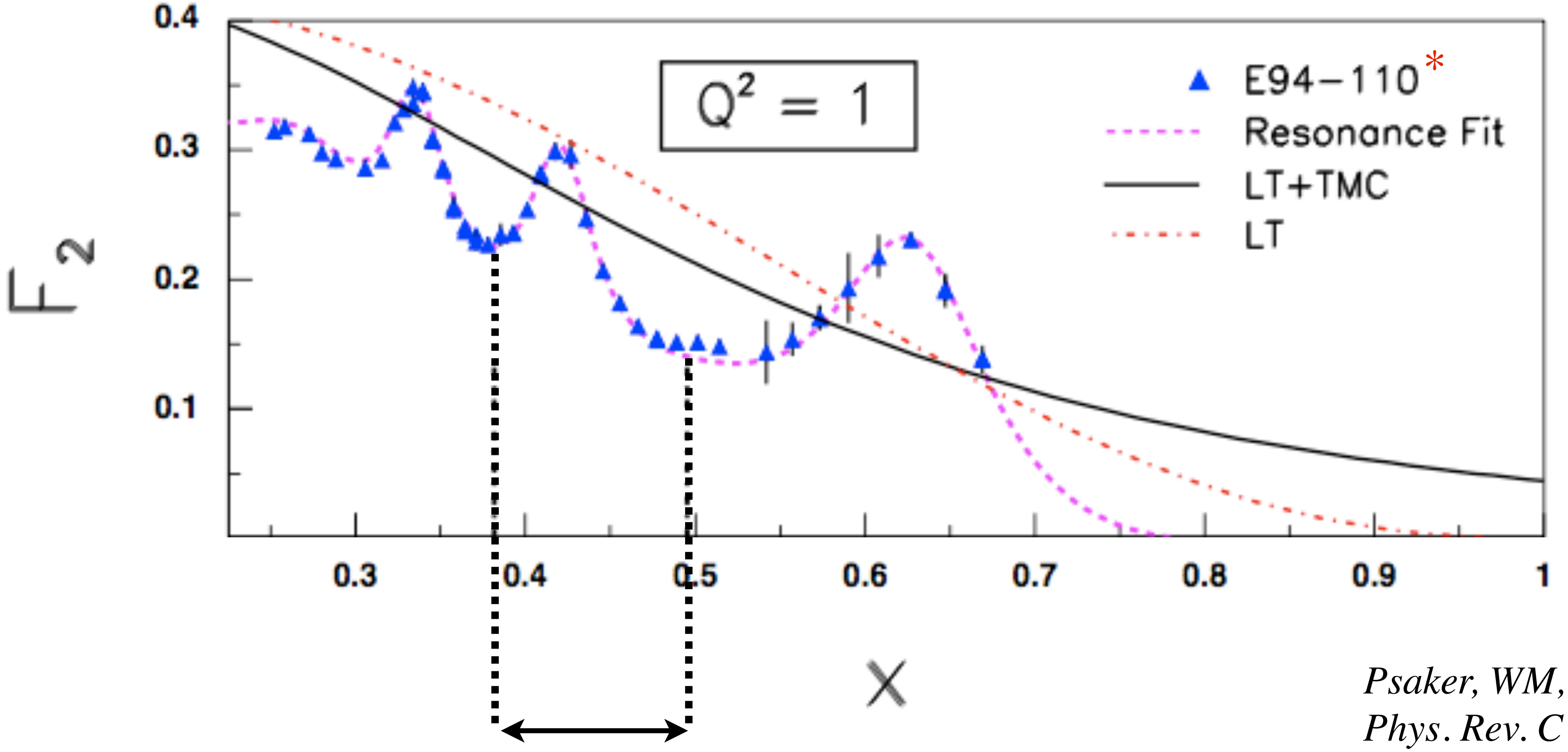


*Niculescu et al., PRL **85** (2000) 1182, 1185*



Christy et al. (2005)

F_2^p resonance spectrum



* JLab Hall C

Psaker, WM, Christy, Keppel, Phys. Rev. C ***78*** *(2008) 025206*

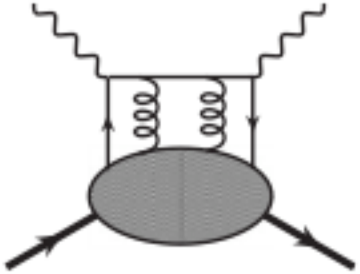
how much of this region is *leading twist* ?

Higher twists

- $1/Q^2$ expansion of structure function moments

$$M_n(Q^2) = \int_0^1 dx\ x^{n-2}\ F_2(x,Q^2)\ = A_n^{(2)} + \frac{A_n^{(4)}}{Q^2} + \frac{A_n^{(6)}}{Q^4} + \cdots$$

matrix elements of operators with specific "twist" (= dimension − spin)

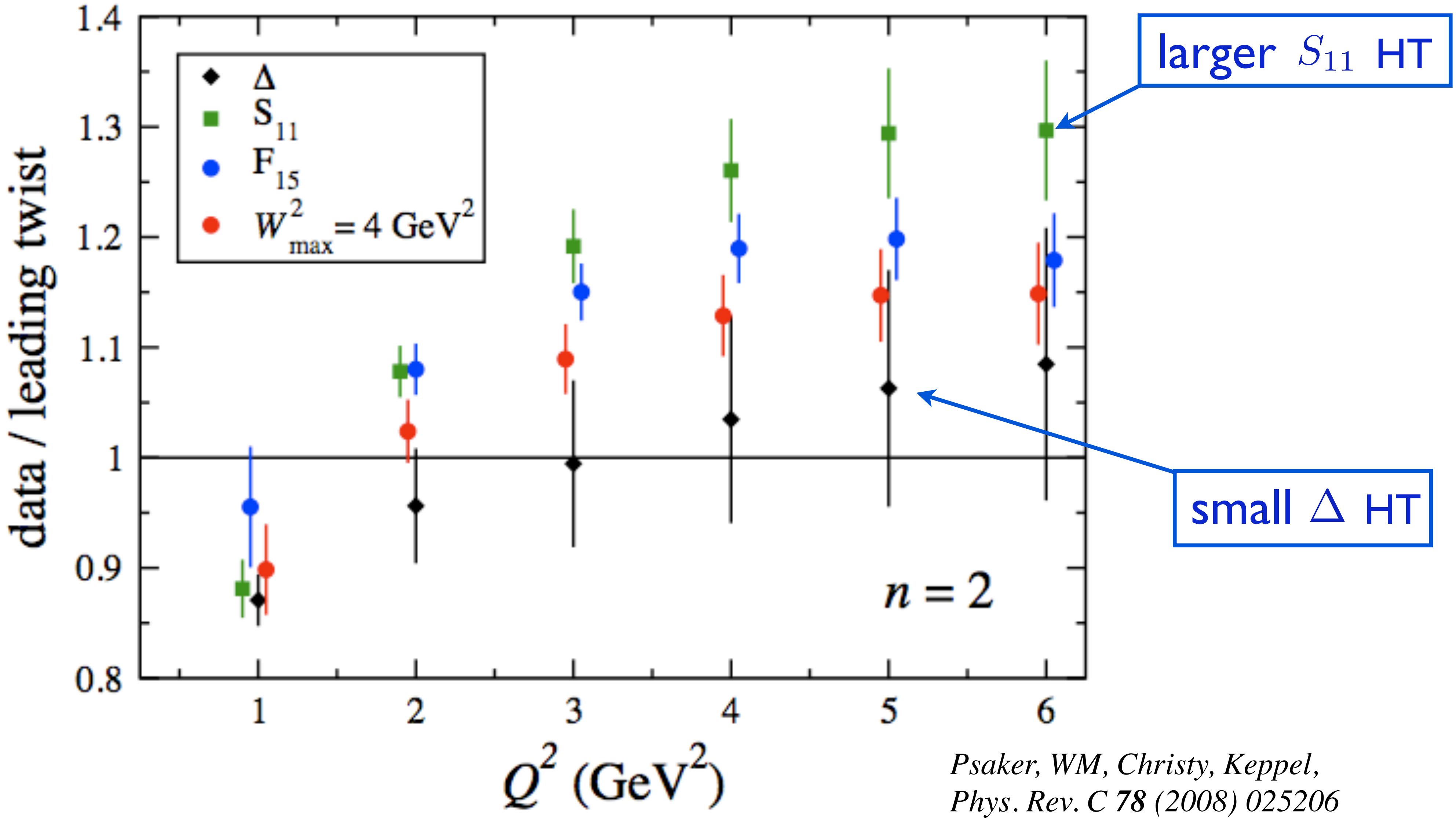


→ twist > 2 reveals long-range q-g correlations

- phenomenologically important at low Q^2 and large x

→ parametrize x dependence by

$$F_2(x,Q^2) = F_2^{\rm LT}(x,Q^2)\left(1 + \frac{C(x)}{Q^2}\right)$$

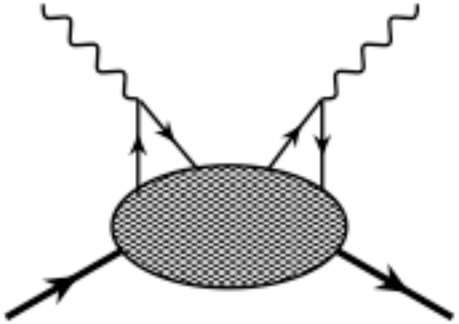


*Psaker, WM, Christy, Keppel, Phys. Rev. C **78** (2008) 025206*

→ higher twists $< 10–15\%$ for $Q^2 > 1\ \mathrm{GeV}^2$

Is duality in the proton a coincidence?

→ consider symmetric nucleon wave function



cat's ears diagram (4-fermion higher twist $\sim 1/Q^2$)

$$\propto \sum_{i \neq j} e_i \, e_j \sim \Big(\sum_i e_i\Big)^2 - \sum_i e_i^2$$

coherent *incoherent*

- *proton* $\mathrm{HT} \sim 1 - \left(2 \times \frac{4}{9} + \frac{1}{9}\right) = 0 \, !$
- *neutron* $\mathrm{HT} \sim 0 - \left(\frac{4}{9} + 2 \times \frac{1}{9}\right) \neq 0$

→ need to test duality in the neutron!

- No **FREE** neutron targets

  (neutron half-life ~ 12 mins)

  → use deuteron as "effective" neutron target

- **BUT** deuteron is a nucleus, and $F_2^d \neq F_2^p + F_2^n$

  → nuclear effects (nuclear binding, Fermi motion, shadowing) *obscure neutron structure* information

  → need to correct for "nuclear EMC effect"

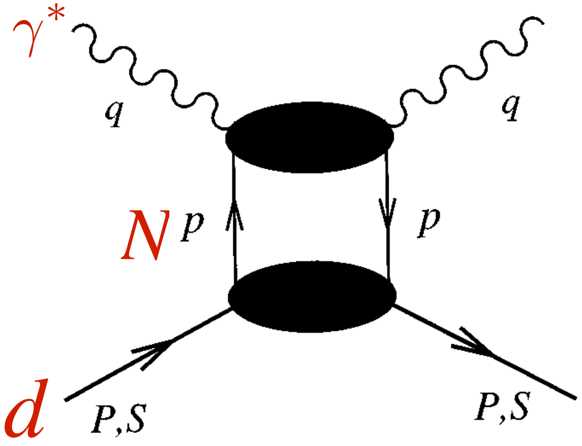
Nuclear effects in the deuteron

- nuclear "impulse approximation"

→ incoherent scattering from individual nucleons in d

(good approx. at $x >> 0$)

N=p+n



$$F_2^d(x,Q^2) = \int_x dy\ f(y,\gamma)\ F_2^N(x/y,Q^2)$$
$$+\ \delta^{(\mathrm{off})} F_2^d$$

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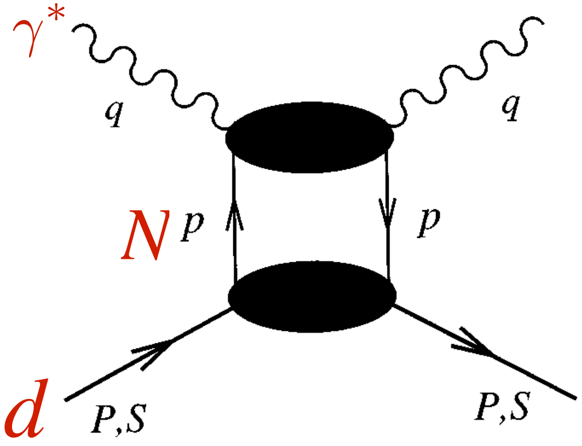


N=p+n

$$F_2^d(x,Q^2) = \int_x dy\ f(y,\gamma)\ F_2^N(x/y,Q^2)$$

$$+\ \delta^{(\mathrm{off})} F_2^d$$

nucleon momentum
distribution in d
("smearing function")

off-shell
correction
(~1%)

→ at finite Q^2, smearing function depends also on parameter

$$\gamma = |\mathbf{q}|/q_0 = \sqrt{1 + 4M^2x^2/Q^2}$$

N momentum distributions in d

- weak binding approximation (WBA): expand amplitudes to order $\vec{p}^{\,2}/M^2$

$$\boxed{\begin{aligned} f(y,\gamma) &= \int \frac{d^3p}{(2\pi)^3}\, |\psi_d(p)|^2\, \delta\Big(y - 1 - \frac{\varepsilon + \gamma p_z}{M}\Big) \\ &\times \frac{1}{\gamma^2}\Big[1 + \frac{\gamma^2 - 1}{y^2}\Big(1 + \frac{2\varepsilon}{M} + \frac{\vec{p}^{\,2}}{2M^2}(1 - 3\hat{p}_z^2)\Big)\Big] \end{aligned}}$$

Kulagin, Petti, NPA ***765****, 126 (2006); Kahn, WM, Kulagin, PRC* ***79****, 035205 (2009)*

→ deuteron wave function $\psi_d(p)$

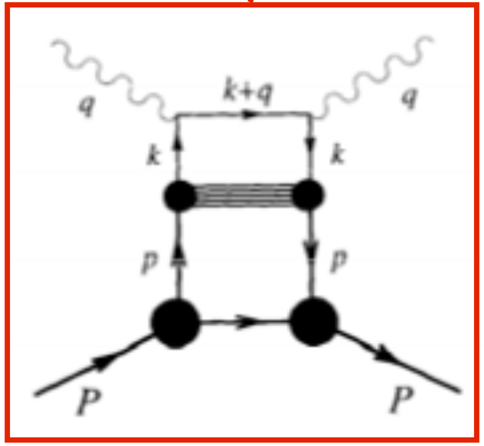
→ deuteron separation energy $\varepsilon = \varepsilon_d - \dfrac{\vec{p}^{\,2}}{2M}$

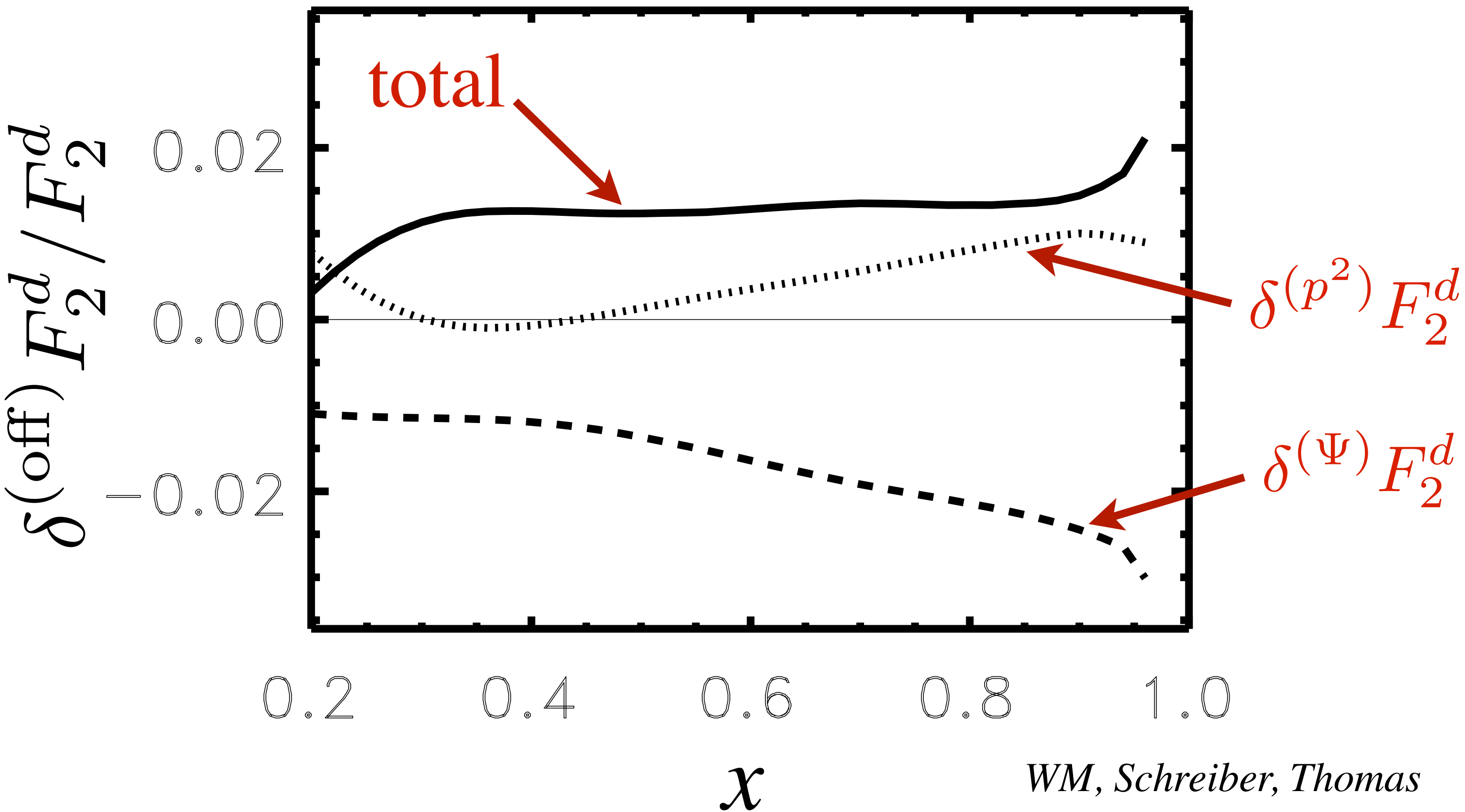
→ approaches usual nonrelativistic momentum distribution in $\gamma \to 1$ limit

Off-shell correction

$\delta^{(\mathrm{off})} F_2^d$ → $\delta^{(\Psi)} F_2^d$ negative energy components of ψ_d

→ $\delta^{(p^2)} F_2^d$ off-shell N structure function

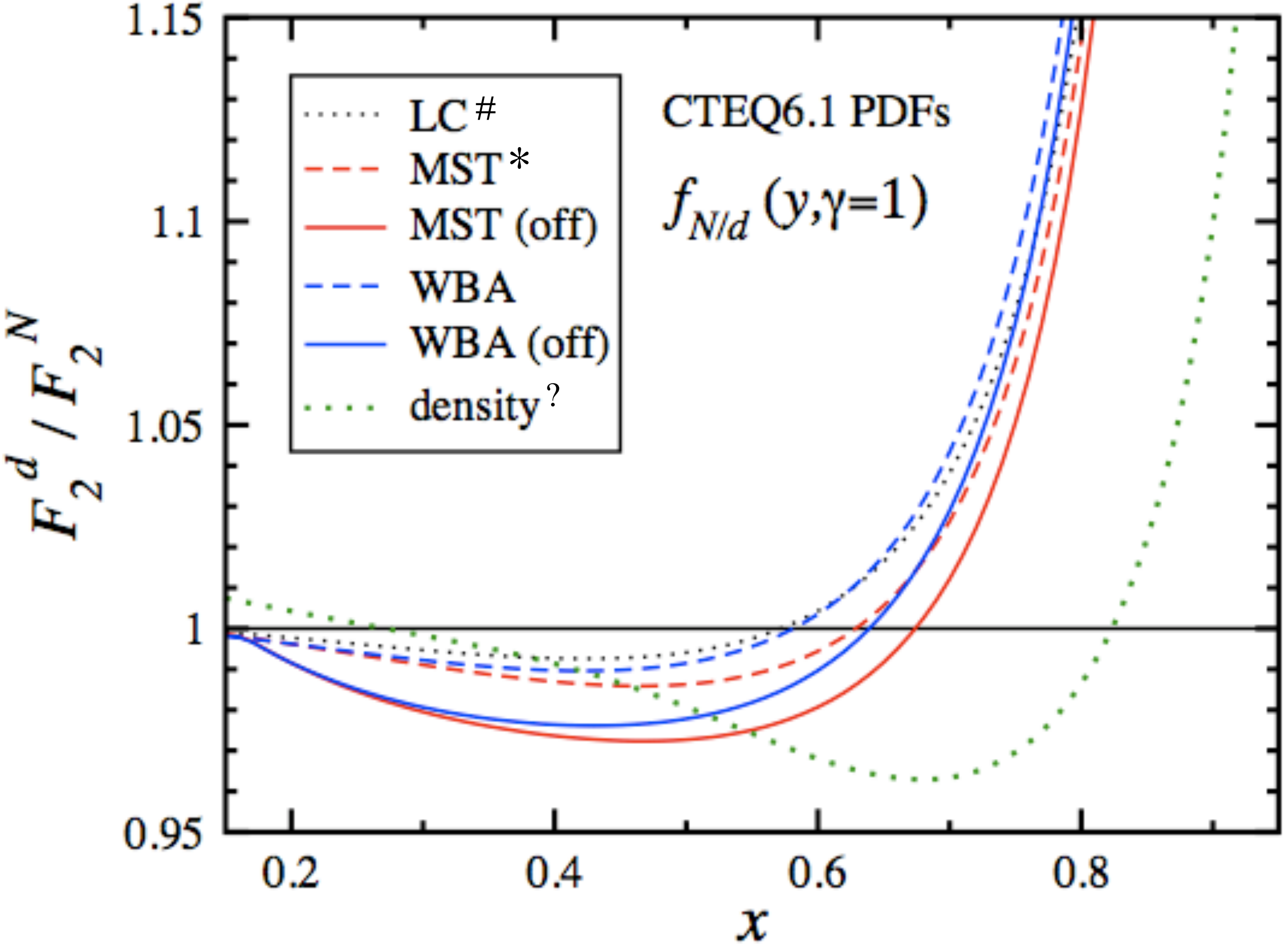




WM, Schreiber, Thomas
PLB ***335*** *(1994) 11*

→ $\leq 1-2\ \%$ effect

EMC effect in deuteron



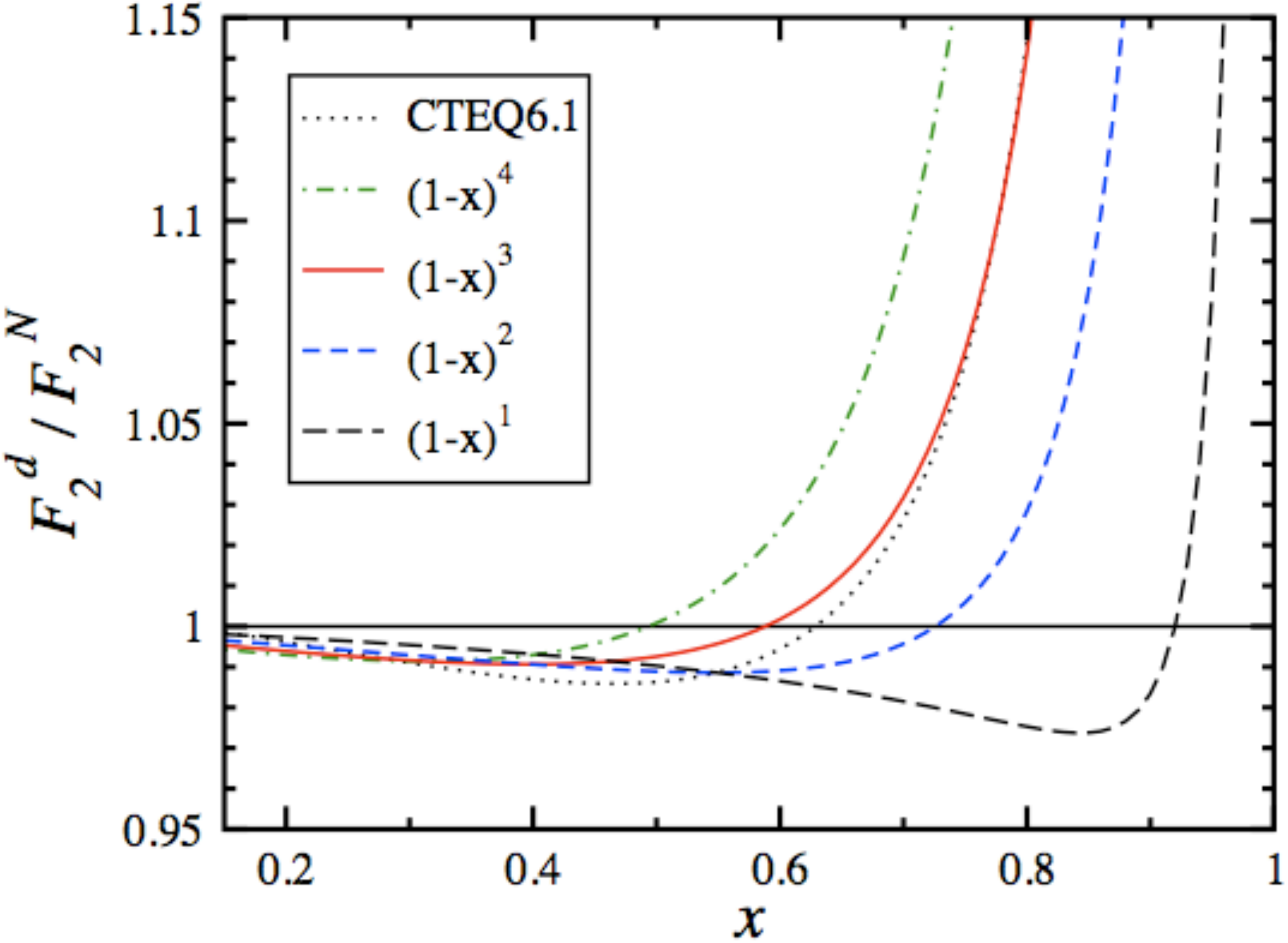
\# *Light-cone model (Frankfurt, Strikman)*

* *Relativistic model (WM, Schreiber, Thomas)*

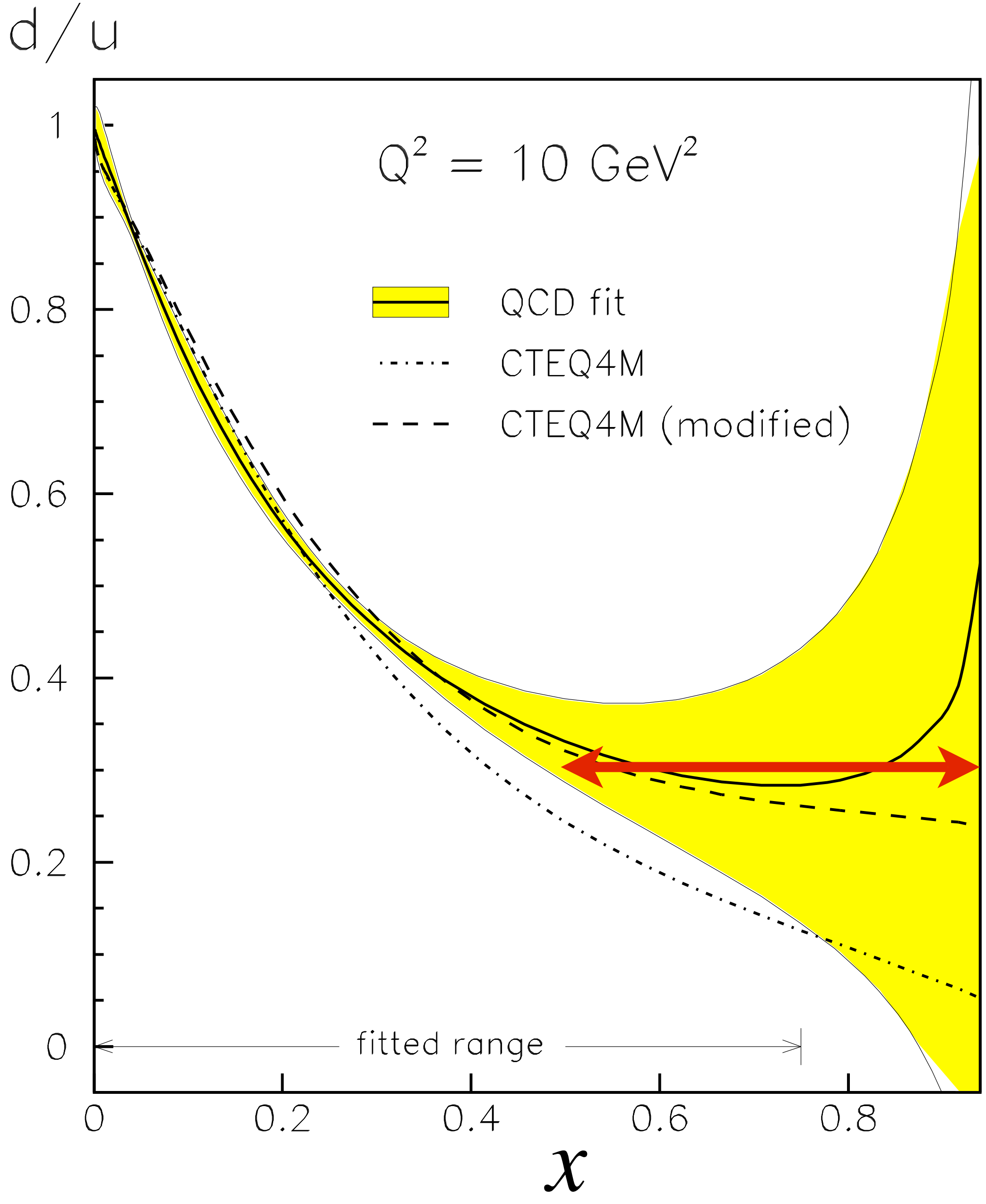
? *Nuclear density model (Frankfurt, Strikman)*

→ larger EMC effect (smaller d/N ratio) at $x \sim 0.5\text{–}0.6$ with binding + off-shell corrections

EMC effect in deuteron



→ EMC ratio depends also on *input nucleon* SFs; need to iterate when extracting F_2^n



large uncertainty from nuclear effects in deuteron

(range of nuclear models*)

beyond $x \sim 0.5$

→ symmetry breaking mechanism remains unknown!

* most PDFs assume *no* nuclear corrections

New global analysis
(“CTEQx”)

[with Accardi, Christy, Keppel, Monaghan, Morfin, Owens]

Global questions

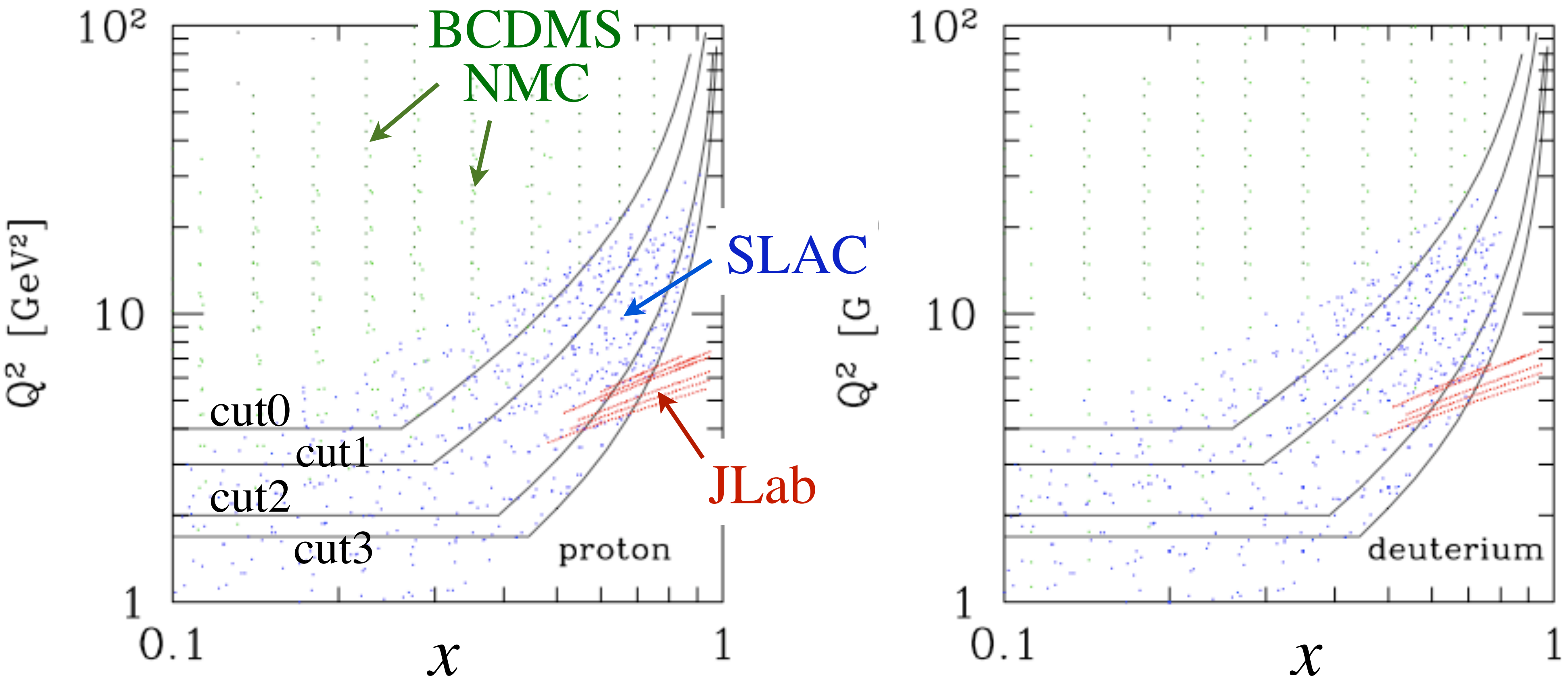
- Can one obtain stable fits including low-Q^2, low-W data?
  - $\longrightarrow$ how do large-x data affect PDFs?
  - $\longrightarrow$ to what extent can uncertainties be reduced?

- Are subleading, $1/Q^2$ corrections under control?
  - $\longrightarrow$ how large are higher twists?

- How do nuclear corrections affect d/u ratio?
  - $\longrightarrow$ what uncertainties do nuclear effects introduce?

➡ New analysis of <u>proton</u> & <u>deuteron</u> data includes effects of Q^2/W *<u>cuts</u>*, *<u>TMCs</u>*, *<u>higher twists</u>*, *<u>nuclear corrections</u>*

Kinematic cuts



cut0: $Q^2 > 4\ \mathrm{GeV}^2, \quad W^2 > 12.25\ \mathrm{GeV}^2$

cut1: $Q^2 > 3\ \mathrm{GeV}^2, \quad W^2 > 8\ \mathrm{GeV}^2$

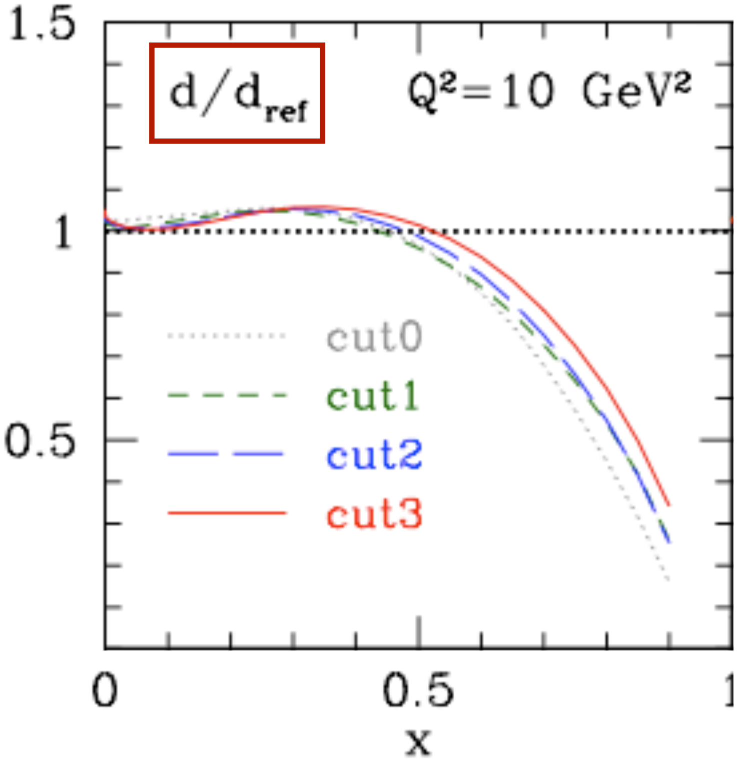
cut2: $Q^2 > 2\ \mathrm{GeV}^2, \quad W^2 > 4\ \mathrm{GeV}^2$

cut3: $Q^2 > m_c^2\ , \quad W^2 > 3\ \mathrm{GeV}^2$

~ 2 times more data for cut3 *cf*. cut0

Effect of Q^2 & W cuts

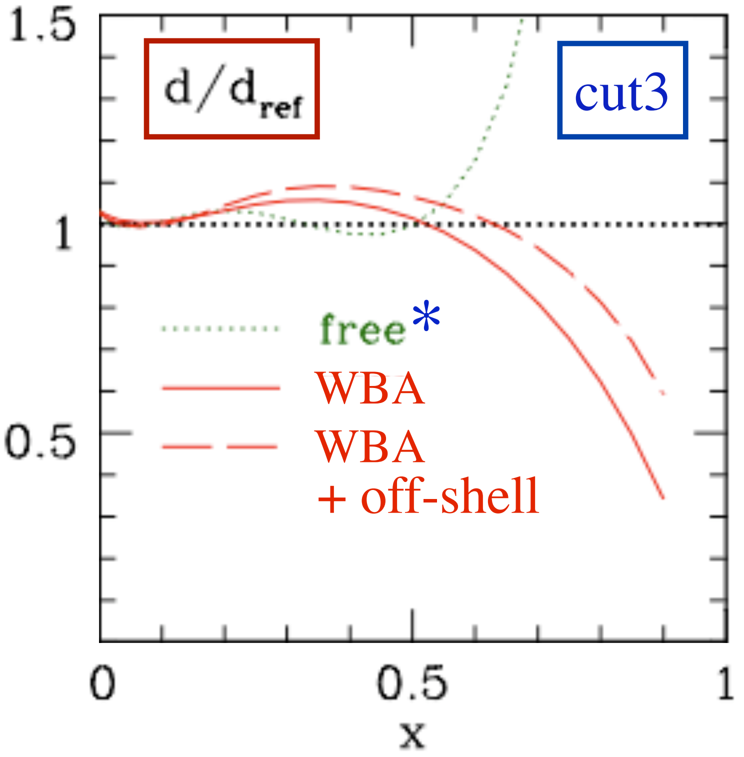
- Systematically reduce Q^2 and W cuts
- Fit includes target mass, higher twist & nuclear corrections (WBA)



→ d suppressed by $\sim 50\%$ for $x > 0.5$

→ driven mostly by nuclear corrections

Effect of nuclear corrections



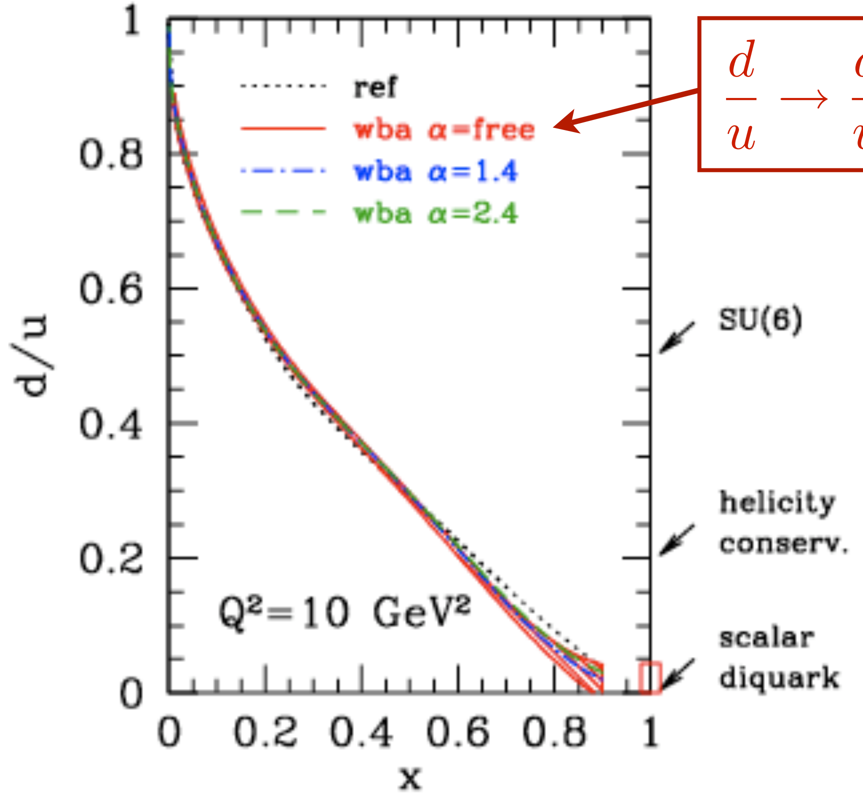
* assumes $F_2^d = F_2^p + F_2^n$ as in CTEQ6.1 and most other global fits

→ dramatic effect of nuclear corrections: *decrease* in d distribution for $x > 0.6$

→ modest increase with (additive) off-shell correction (since EMC ratio has deeper "trough")

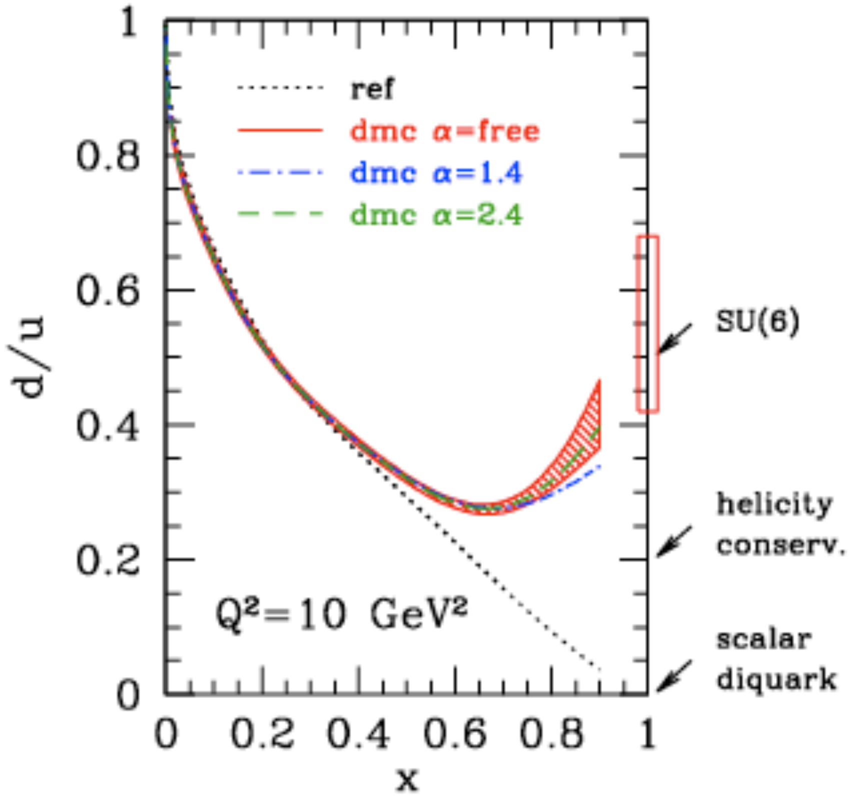
d/u PDF ratio

nuclear smearing



$$\frac{d}{u} \to \frac{d}{u} + c\,x^{\alpha}$$

density model

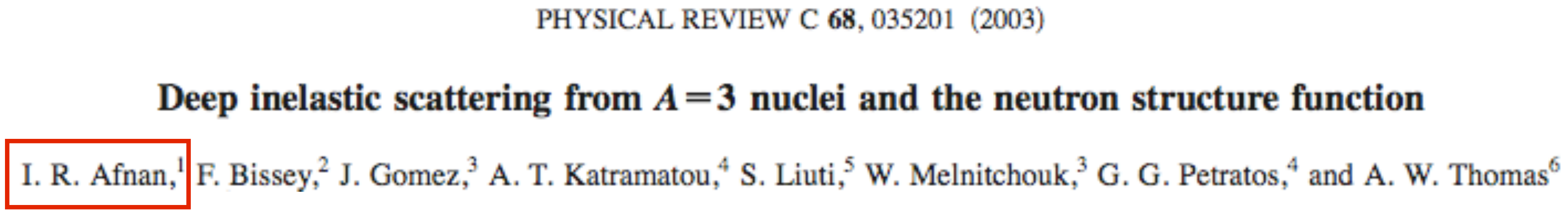


→ full fits favors *smaller* d/u ratio

→ dominance of nonperturbative physics?

→ critical need for neutron SF at $x > 0.6$

How to extract neutron without nuclear uncertainties?



PHYSICAL REVIEW C **68**, 035201 (2003)

Deep inelastic scattering from $A=3$ nuclei and the neutron structure function

I. R. Afnan,[1] F. Bissey,[2] J. Gomez,[3] A. T. Katramatou,[4] S. Liuti,[5] W. Melnitchouk,[3] G. G. Petratos,[4] and A. W. Thomas[6]

- EMC ratios for A=3 mirror nuclei

$$R(^3\mathrm{He}) = \frac{F_2^{^3\mathrm{He}}}{2F_2^p + F_2^n} \qquad R(^3\mathrm{H}) = \frac{F_2^{^3\mathrm{H}}}{F_2^p + 2F_2^n}$$

- Extract n/p ratio from measured ^{3}He-^{3}H ratio

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}}}{2F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}} - \mathcal{R}} \qquad \mathcal{R} = \frac{R(^3\mathrm{He})}{R(^3\mathrm{H})}$$

theory input

Nucleon distribution function in A=3 nucleus

$$f_{N/A}(y,\gamma) = \int d^4p \left(1+\frac{p_z}{p_0}\right) S_A(p)\,\mathcal{F}(p,\gamma)\,\delta\left(y-\frac{p_0+p_z}{M}\right)$$

$$\mathcal{F}(p,\gamma) = \left(1+\frac{4Mp_zx^2\gamma}{yQ^2}\right) - (2p^2-p_z^2)\frac{\gamma^2x^2}{y^2Q^2}$$

→ nucleon spectral function

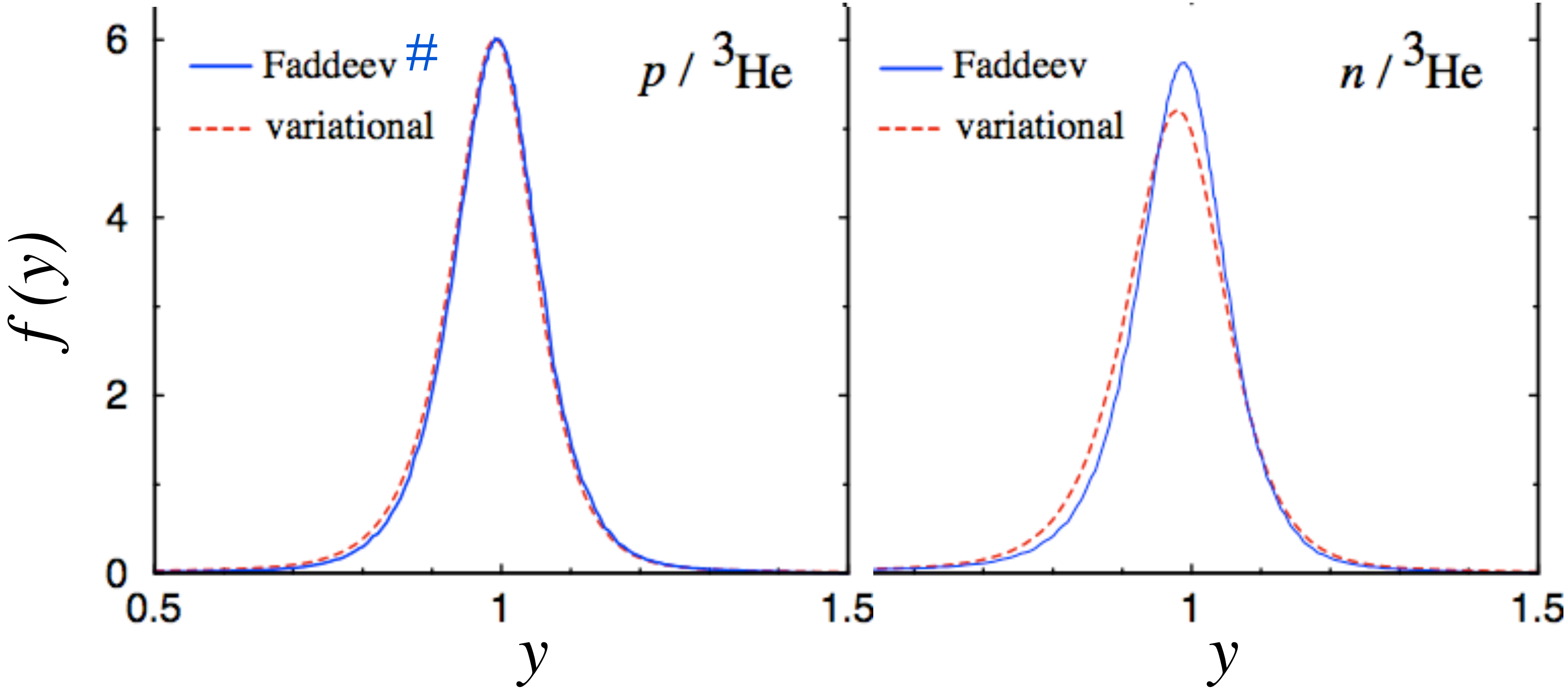
$$S_A(p) = \frac{1}{(2\pi)^3}\sum_f \left|\int d^3r\, e^{i\vec{p}\cdot\vec{r}} G_{fi}(\vec{r})\right|^2 \delta(E_3 - E_2^f - E)$$

$$S_{^3\mathrm{He}} = \frac{2}{3}S_{p/^3\mathrm{He}} + \frac{1}{3}S_{n/^3\mathrm{He}}\,, \qquad S_{^3\mathrm{H}} = \frac{1}{3}S_{p/^3\mathrm{H}} + \frac{2}{3}S_{n/^3\mathrm{H}}$$

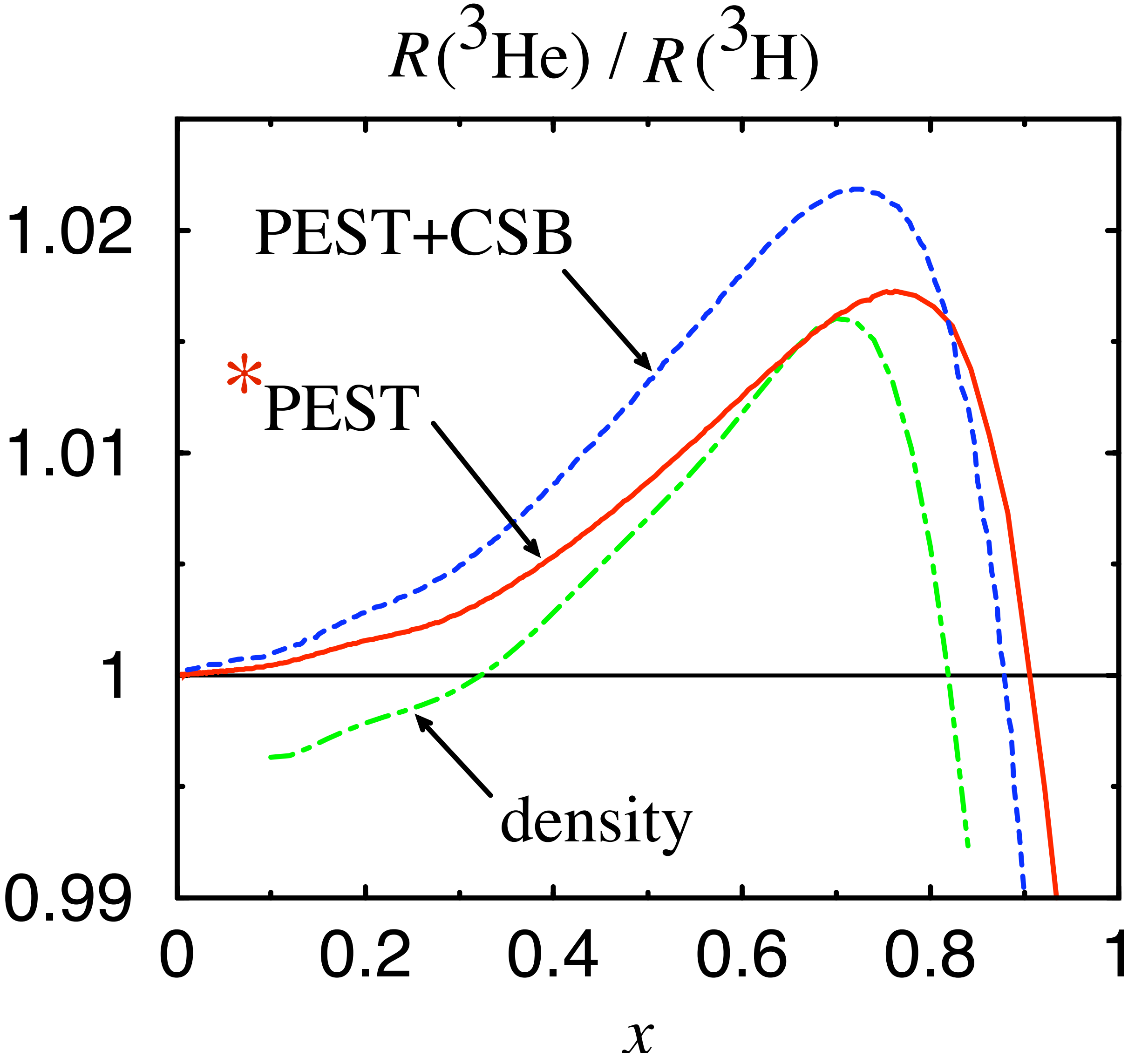
d + *np* **break-up**

pp **break-up**

Nucleon distribution function in A=3 nucleus

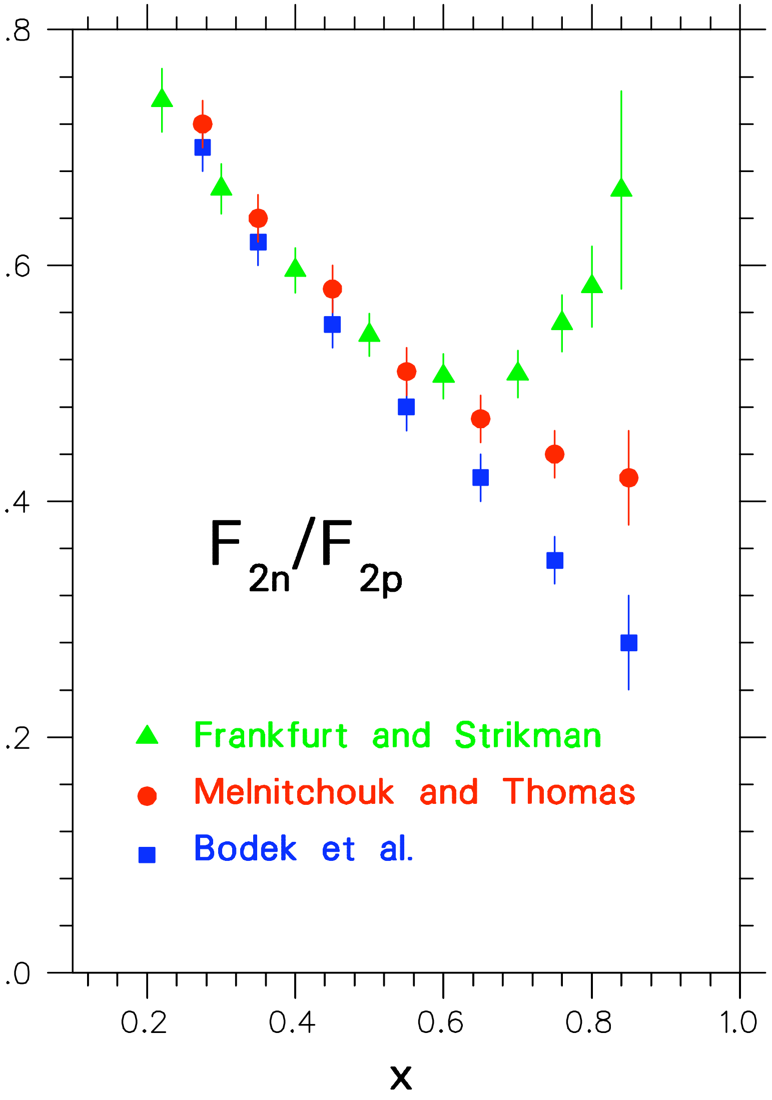


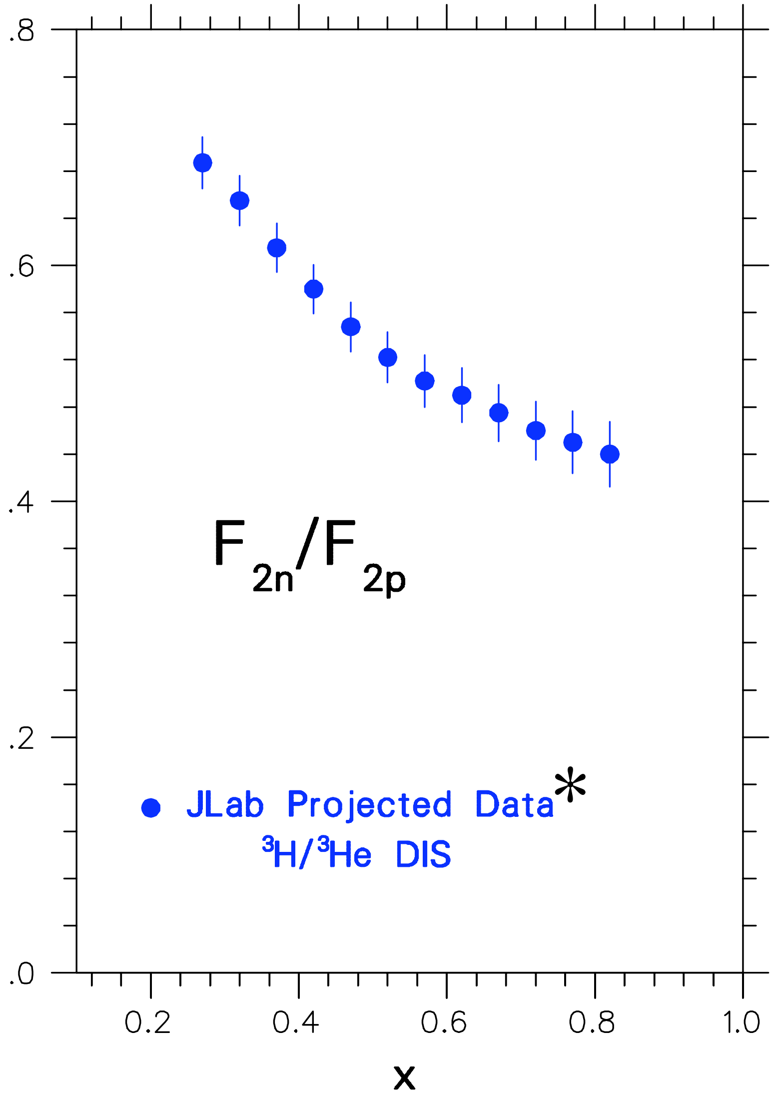
Bissey, Thomas, Afnan, *Phys. Rev.* **C64**, 024004 (2001)



* Ernst-Shakin-Thaler separable approx. to Paris potential

→ nuclear effects cancel to $< 1\%$ level





*theoretical uncertainty integrated into total error

Tritium Target at JLab

Roy J. Holt

Tritium Target Task Force:

E. J. Beise (Univ. of Maryland), R. J. Holt (ANL),
W. Korsch (Univ. of Kentucky) , T. O'Connor (ANL),
G. Petratos (Kent State Univ.), R. Ransome (Rutgers Univ.) ,
P. Solvignon (ANL) , and B. Wojtsekhowski (JLab)

- 12 GeV experiment: E12-06-118, conditionally approved
    - d/u ratio
    - EMC effect in ^3H
- "… the PAC considers the physics goals of this experiment as highlights of the 12 GeV physics program."
- Condition: "A special JLab Management review of the safety aspects of the tritium target is the condition for approval."

Summary

- Scientific stage being set at JLab for d/u ratio and EMC measurements
- Totally sealed, passively-cooled target, triple containment, exhaust fan, interlocks
- All tritium gas handling performed at STAR* Facility at INL
- Additional independent interlock on beam raster
- Target concept is ready for engineering design

* *Safety and Tritium Applications Research (STAR) Facility*
Idaho National Laboratory

Conclusion: A safe tritium target is possible at JLab.

Thank you, Iraj, for your critical contributions!