Measurement of F_2^n/F_2^p and d/u in Deep Inelastic Electron scattering off ^{3}H and ^{3}He.

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PAC 18
Jefferson Lab
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DRAFT version

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– Typeset by FoilTEX –

Measurement of the F_2^n/F_2^p and d/u ratios in Deep Inelastic Electron Scattering off ^{3}H and ^{3}He.

Jefferson Lab 12 GeV White Paper Proposal

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DIS and Quark Parton Model

- Cross Section - Nucleon Structure Functions

$$\sigma_{eN} = \frac{\alpha^2}{4E^2\sin^4\left(\frac{\theta}{2}\right)}\left[\frac{F_2}{\nu}\cos^2\left(\frac{\theta}{2}\right) + \frac{2F_1}{M}\sin^2\left(\frac{\theta}{2}\right)\right]$$

$$\begin{aligned} Q^2 &= 4EE'\sin^2\left(\frac{\theta}{2}\right) \\ \nu &= E - E' \\ R &= \frac{\sigma_L}{\sigma_T} = \frac{F_2 M}{F_1 \nu}\left(1 + \frac{\nu^2}{Q^2}\right) - 1 \end{aligned}$$

- Quark Parton Model

$$\begin{aligned} F_1(x) &= \frac{1}{2}\sum_i e_i^2 q_i(x) \\ F_2(x) &= x\sum_i e_i^2 q_i(x) \end{aligned}$$

$$Q^2 \to \infty,\ \nu \to \infty,\ x = \frac{Q^2}{2M\nu}\ \text{fixed}$$

F$_2^n$/F$_2^p$ in Quark Parton Model

- Assume isospin symmetry:

$$\begin{aligned} u^p(x) &\equiv d^n(x) \equiv u(x) \\ d^p(x) &\equiv u^n(x) \equiv d(x) \\ s^p(x) &\equiv s^n(x) \equiv s(x) \end{aligned}$$

(Similarly for antiquarks)

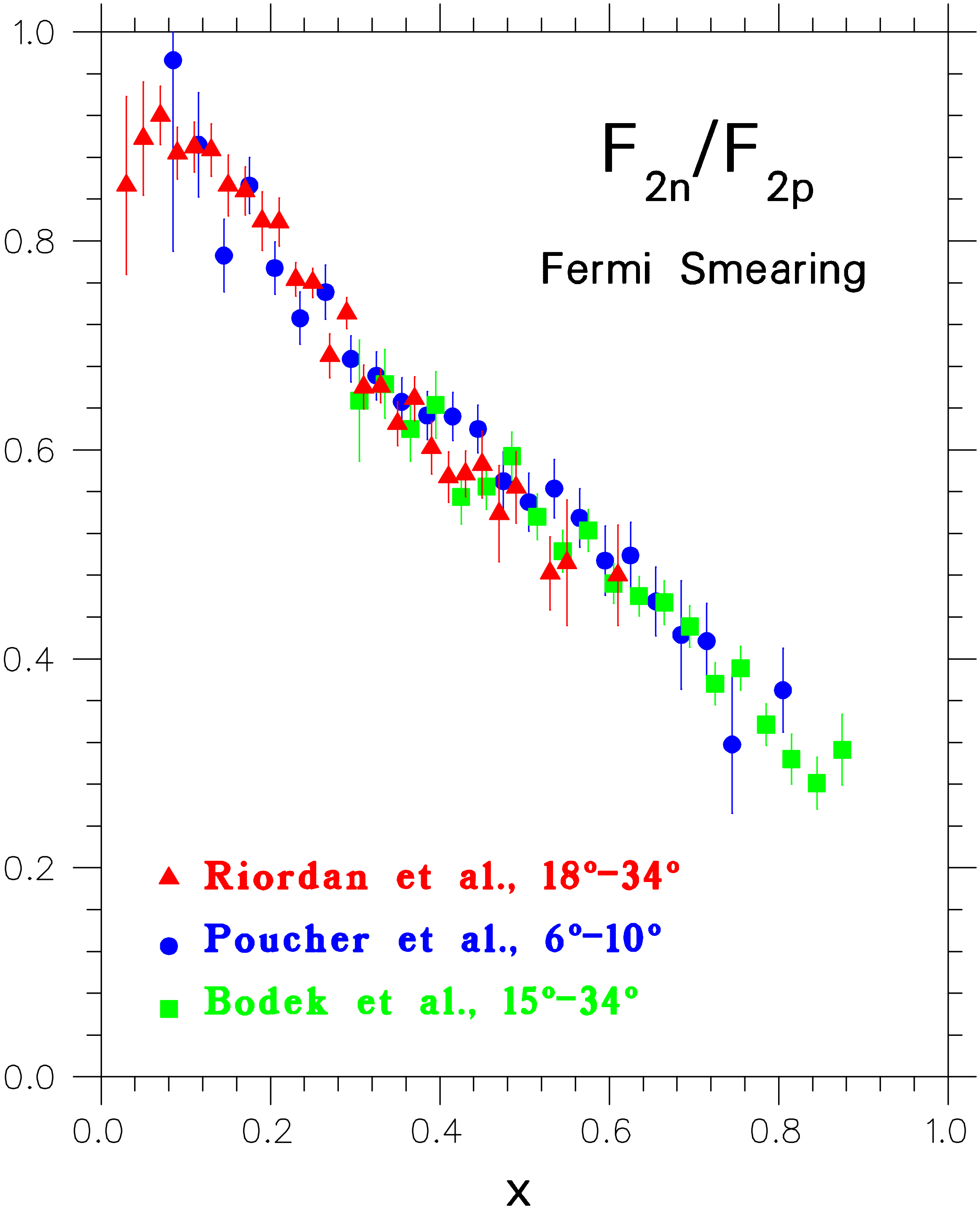
- Proton and neutron structure functions:

$$F_2^p = x\left[\left(\frac{4}{9}\right)(u+\bar{u}) + \left(\frac{1}{9}\right)(d+\bar{d}) + \left(\frac{1}{9}\right)(s+\bar{s})\right]$$

$$F_2^n = x\left[\left(\frac{4}{9}\right)(d+\bar{d}) + \left(\frac{1}{9}\right)(u+\bar{u}) + \left(\frac{1}{9}\right)(s+\bar{s})\right]$$

- Nachtmann Inequality:

$$\frac{1}{4} \leq F_2^n/F_2^p \leq 4$$


F_{2n}/F_{2p}
Fermi Smearing
▲ Riordan et al., 18°–34°
● Poucher et al., 6°–10°
■ Bodek et al., 15°–34°
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
x

SLAC/MIT and CERN data

- Nachtmann inequality satisfied

$$\frac{1}{4} \leq F_2^n/F_2^p \leq 4$$

- $x \to 0 \ : F_2^n/F_2^p \simeq 1$

Sea quarks dominate with
$u + \bar{u} = d + \bar{d} = s + \bar{s}$

- $x \to 1 \ : F_2^n/F_2^p \simeq \frac{1}{4}$

High momentum partons in proton (neutron) are up (down) quarks and $s + \bar{s} = 0$.

SU(6) Symmetry

- Wave function for a polarized proton:

$$\begin{aligned} p\uparrow &= \frac{1}{\sqrt{2}} u\uparrow (ud)_{S=0} + \frac{1}{\sqrt{18}} u\uparrow (ud)_{S=1} \\ &- \frac{1}{3} u\downarrow (ud)_{S=1} \quad - \frac{1}{3} d\uparrow (uu)_{S=1} \\ &- \frac{\sqrt{2}}{3} d\downarrow (uu)_{S=1} \end{aligned}$$

- $u(x)$, $d(x)$ have same shape:

$$u(x) = 2d(x)$$

- F_2 ratio and $A_1^{n,p}$ asymmetries:

$$\left\{ F_2^n / F_2^p = \frac{2}{3} \right\} , \left\{ A_1^p = \frac{5}{9} , \quad A_1^n = 0 \right\}$$

Quark Model with Broken SU(6) *

- Diquark configuration with $s = 1$ suppressed relative to $s = 0$

$$\begin{aligned} F_2^n &\sim \psi_0(x) + 3\psi_1(x) \\ F_2^p &\sim 4\psi_0(x) + 2\psi_1(x) \end{aligned}$$

- If $\psi_1(x) \to 0$ as $x \to 1$ then :

$$\left\{ \begin{array}{ll} F_2^n/F_2^p & \to \frac{1}{4} \\ d/u & \to 0 \end{array} \right\}$$

- Spin asymmetries

$$\begin{aligned} A_1^p(x) &= \frac{4 - \frac{2}{3}\psi_1(x)/\psi_0(x)}{4 + 2\psi_1(x)/\psi_0(x)} \\ A_1^n(x) &= \frac{1 - \psi_1(x)/\psi_0(x)}{1 + 3\psi_1(x)/\psi_0(x)} \end{aligned}$$

- If $\psi_1(x) \to 0$ as $x \to 1$ then :

$$\{A_1^p, A_1^n \to 1\}$$

*Close (1973)

Regge Theory

- Probability to find single valence quark with $x \simeq 0$ is (Feynman):

$$P[q(x \simeq 0)] \sim x^{-\alpha}, \qquad 1 < \alpha < 1.5$$

- Consider probability to find pair of valence quarks with $x \simeq 0$:

$$\frac{F_2^n(x)}{F_2^p(x)} = \frac{1+3\alpha(1-x)}{4+2\alpha(1-x)}$$

For $x \rightarrow 1$: $$\left\{ \begin{array}{ll} F_2^n/F_2^p & \rightarrow \frac{1}{4} \\ d/u & \rightarrow 0 \end{array} \right\}$$

Carlitz (1975)

- Extend model to spin asymmetries

For $x \rightarrow 1$: $$\{A_1^p, A_1^n \rightarrow 1\}$$

Kaur (1975)

Hyperfine-Perturbed Quark Model*

- Hyperfine interaction perturbs proton's energy
- Perturbation results in mixed symmetry distributions that allow the d quark to have a different probability than the two u quarks
- Quark pairs with spin 1 have their energies raised
  Quark pairs with spin 0 have their energies lowered
- Up quarks acquire higher average energy than down quarks
- As $x \to 1$:

$$\left\{ \begin{array}{ll} F_2^n/F_2^p & \to \frac{1}{4} \\ d/u & \to 0 \end{array} \right\} , \; \{A_1^p, A_1^n \to 1\}$$

(Similar predictions to older SU(6) breaking mechanisms)

*Isgur (1999)

Perturbative QCD*

- When diquark spins aligned, only exchange of longitudinal gluons is permitted
- Compton amplitude suppressed by $(1-x)^{\frac{1}{2}}$
- Quark carrying nearly all momentum of nucleon ($x \simeq 1$) must have same helicity as nucleon
- Predictions for $x \to 1$:

$$\begin{array}{rcll} F_2^n/F_2^p & \to & 3/7 & (\text{not } 1/4!) \\ d/u & \to & 1/5 & (\text{not } 0!) \\ A_1^n,\ A_1^p & \to & 1 & \end{array}$$

- Note different F_2^n/F_2^p and d/u predictions !!
- Quark Counting Rules result in same predictions [Brodsky et al. (95)]

*Farrar and Jackson (75)

Limits for x $\rightarrow 1$

	F_2^n/F_2^p	d/u	A_1^n	A_1^p
SU(6)	2/3	1/2	0	5/9
Scalar Diquark Model	1/4	0	1	1
H-P Quark Model	1/4	0	1	1
pQCD	3/7	1/5	1	1
Counting Rules	3/7	1/5	1	1

Reviews : Isgur, Phys. Rev. D59, 34013 (1999)

Brodsky et al., Nucl. Phys. B441, 197 (1995)

Melnitchouk and Thomas,
Phys. Lett. B377, 11 (1996)

Binding/EMC Effect in Deuteron

- Deuteron structure function convolution:

$$\begin{aligned} F_2^d(x,Q^2) &= \int dy f(y) F_2^N(x,Q^2) \\ F_2^N &= F_2^p + F_2^n \end{aligned}$$

$f(y)$: accounts for Fermi motion AND binding

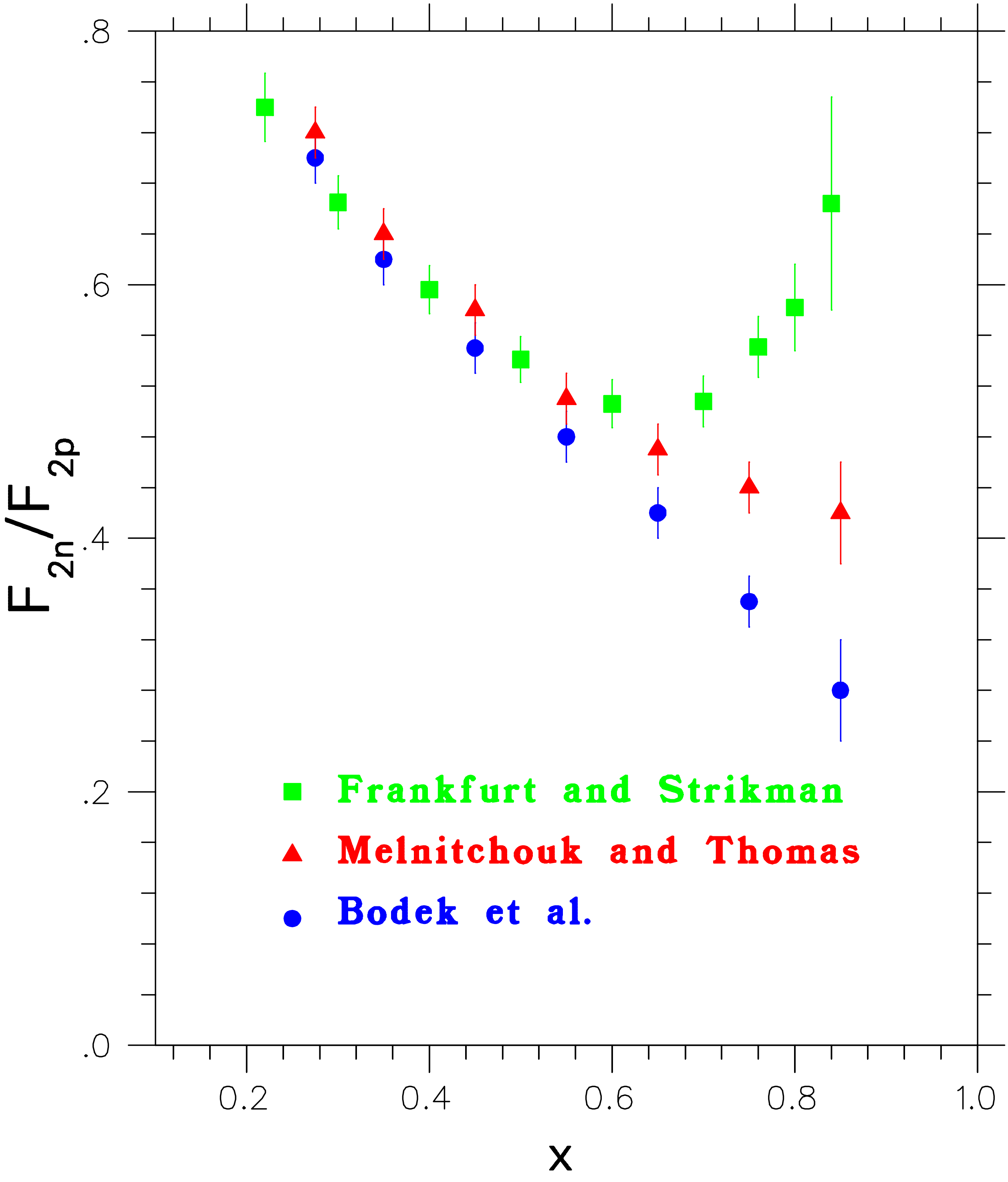
$f(y)$ calculated using relativistic deuteron wave function within a covariant framework

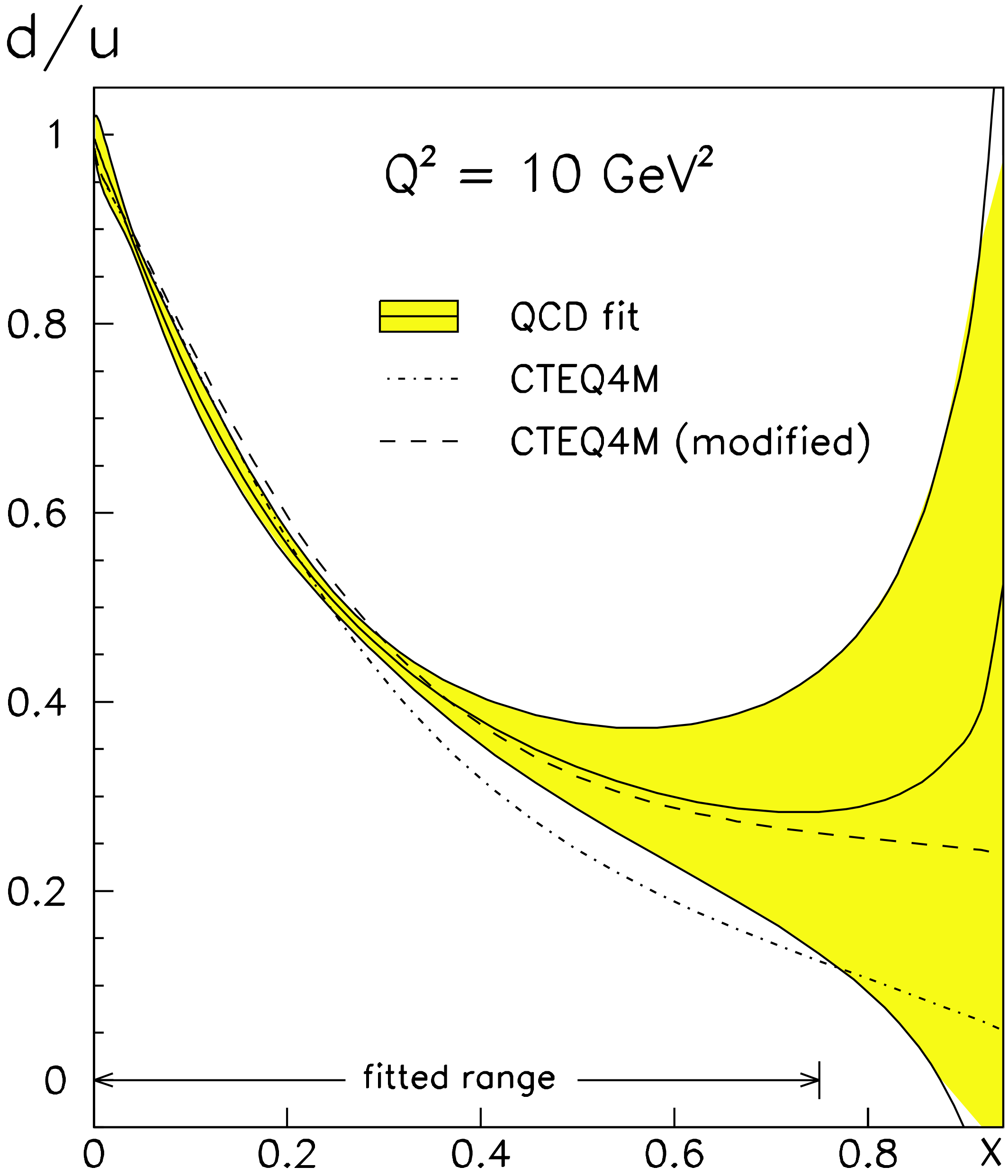
Melnitchouk and Thomas

- Density model :
  EMC effect for deuteron scales with nuclear density as for heavy nuclei

$$\frac{F_2^d}{F_2^p+F_2^n} = 1 + \frac{\rho_d}{\rho_A-\rho_d}\left[\frac{F_2^A}{F_2^d} - 1\right]$$

Frankfurt and Strikman


F_{2n}/F_{2p}
.8
.6
.4
.2
.0
0.2
0.4
0.6
0.8
1.0
x
■ Frankfurt and Strikman
▲ Melnitchouk and Thomas
● Bodek et al.



M. Botje, Eur. Phys. J. C14, 285-297, 2000

^{3}He and ^{3}H Structure Functions

- Nuclear structure function in impulse approximation :

$$F_2^{A=3}(x) \approx \int dy\, f_{N/A}(y)\, F_2^N(x/y) \equiv f_{N/A} \otimes F_2^N$$

- For ^{3}He:

$$F_2^{^3He} = 2\, f_p \otimes F_2^p + f_n \otimes F_2^n$$

- With isospin symmetry:

$$f_{n/^3H} = f_{p/^3He} \equiv f_p$$
$$f_{p/^3H} = f_{n/^3He} \equiv f_n$$

- Then for ^{3}H:

$$F_2^{^3H} = f_n \otimes F_2^p + 2\, f_p \otimes F_2^n$$

F_2^n/F_2^p Extraction from $F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}}$

- Compare EMC ratios for $A = 3$ mirror nuclei:

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

$$\mathcal{R} = R(^3He)/R(^3H) \ \ \text{(from theory model)}$$

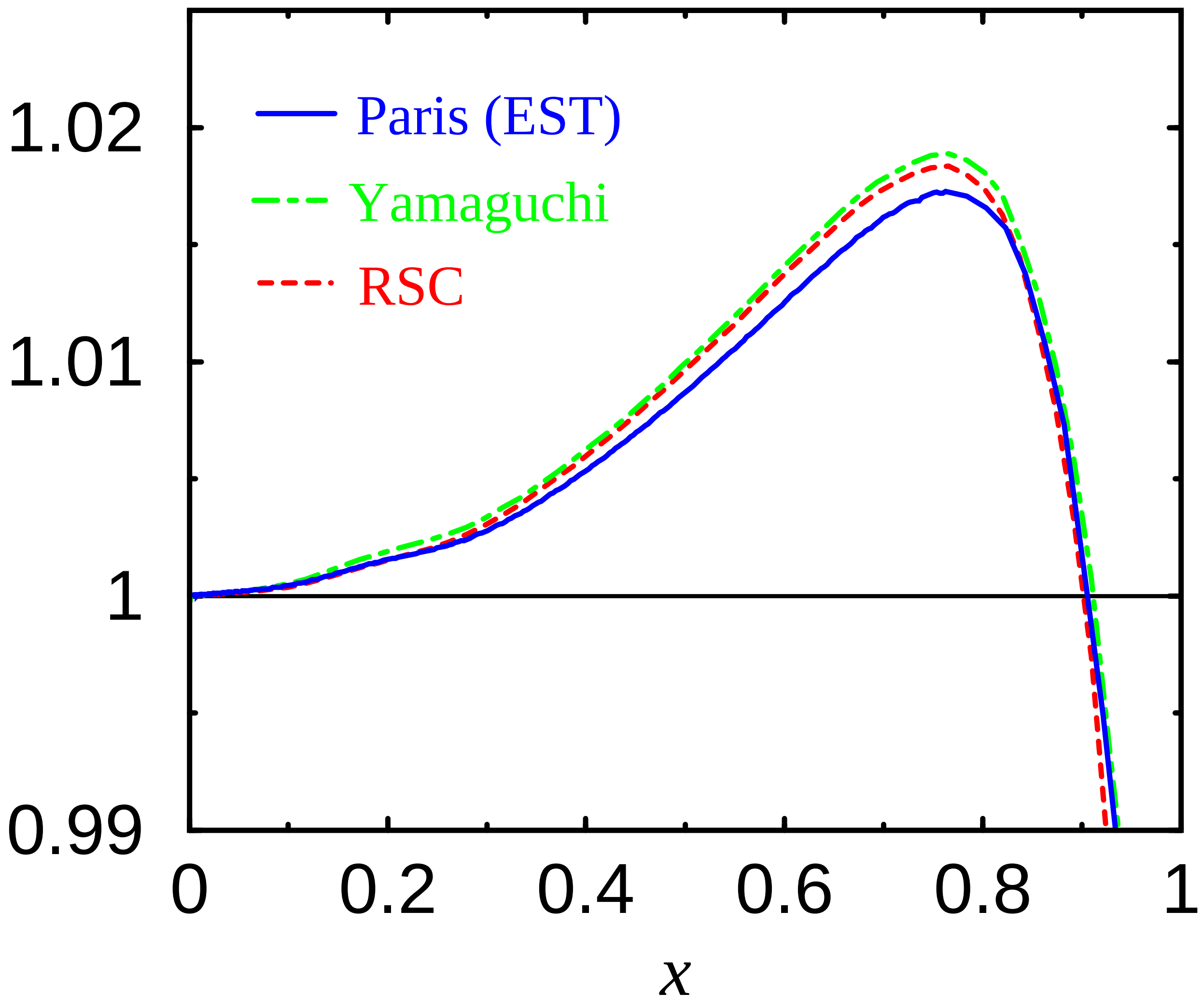
- Measured ^{3}He/^{3}H ratio:

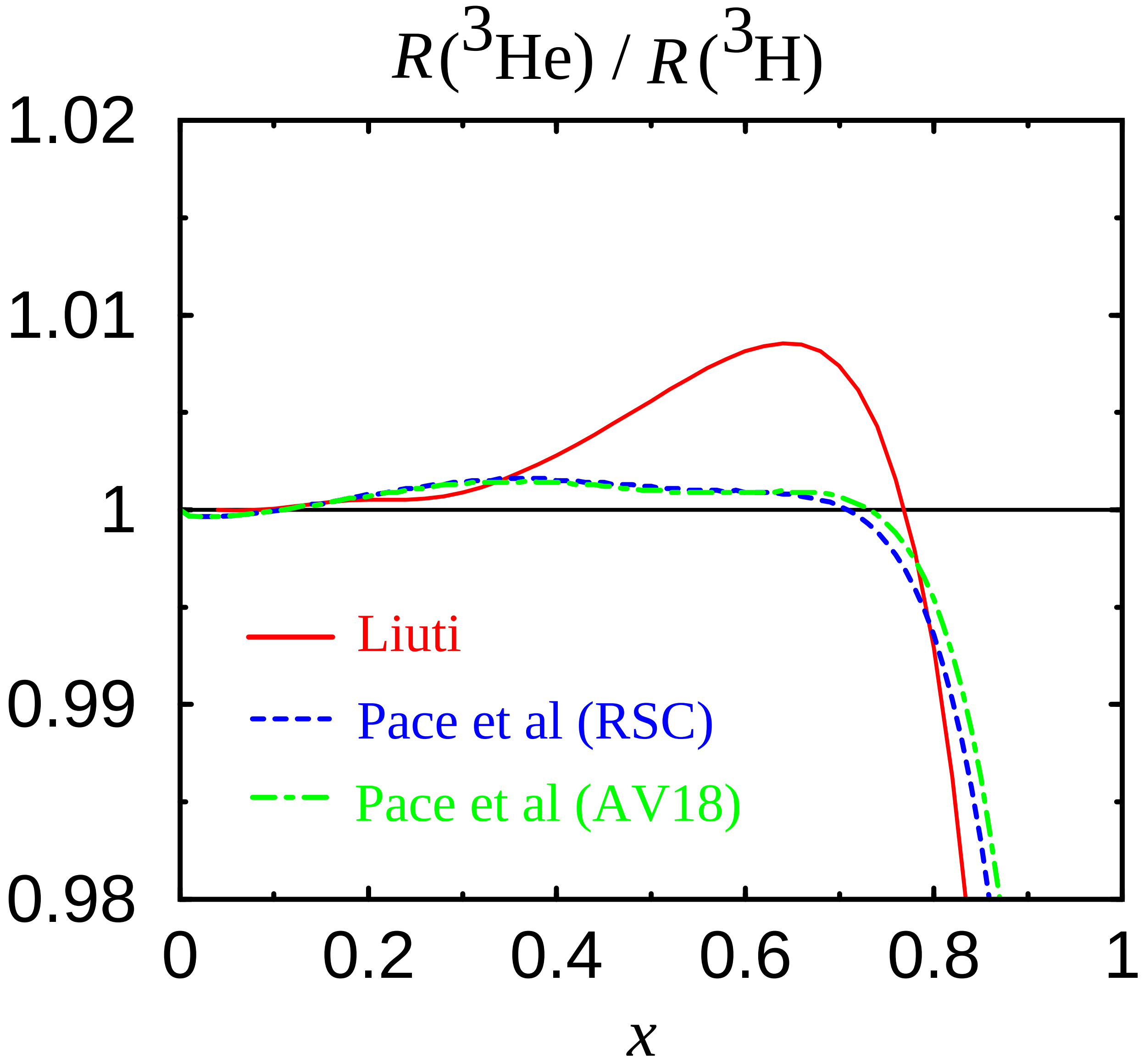
$$\frac{F_2^{^3He}}{F_2^{^3H}} = \mathcal{R}\,\frac{2F_2^p + F_2^n}{F_2^p + 2F_2^n}$$

- F_2^n/F_2^p ratio extracted via:

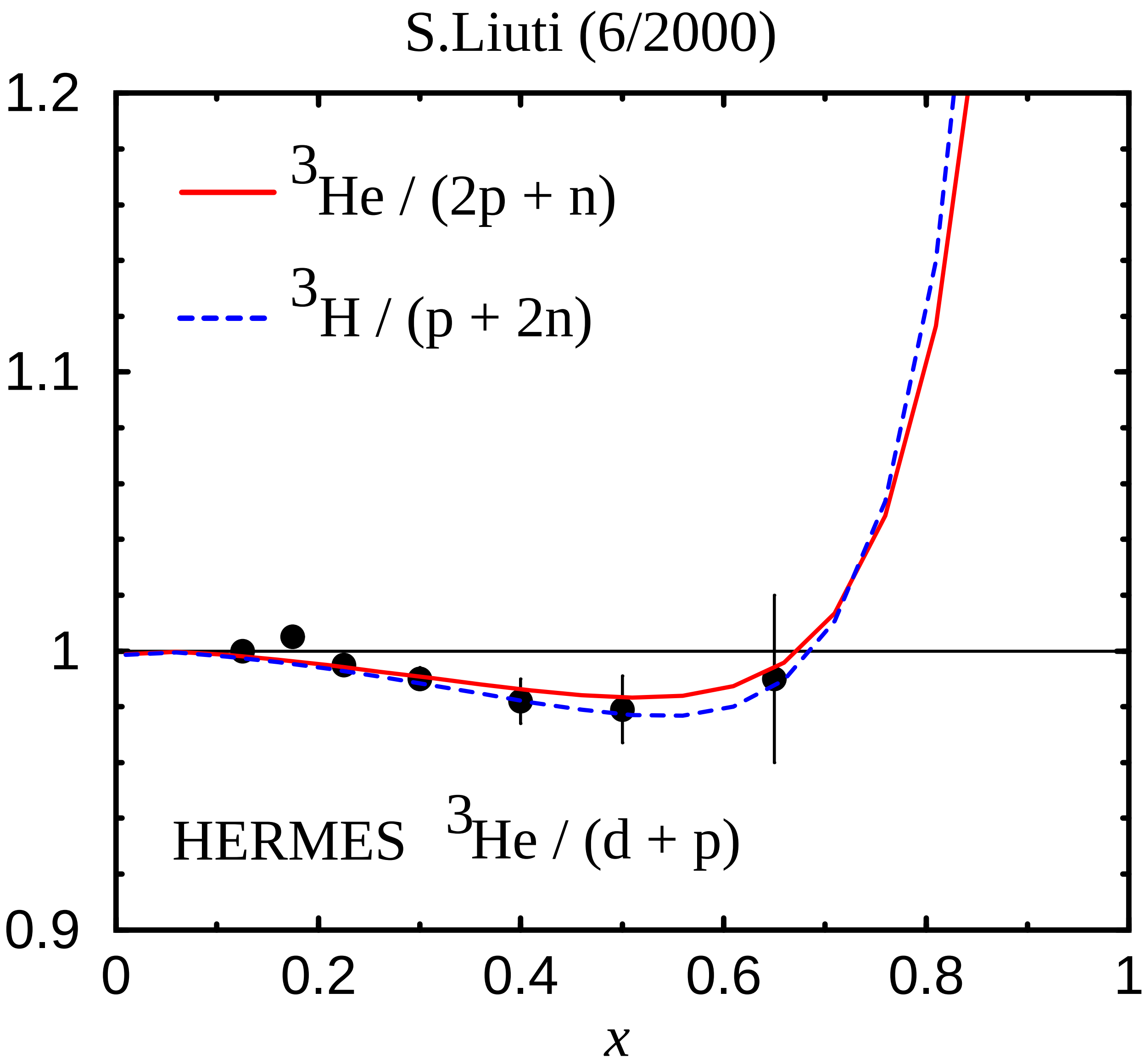
$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3He}/F_2^{^3H}}{2F_2^{^3He}/F_2^{^3H} - \mathcal{R}}$$

$R(^3\mathrm{He}) / R(^3\mathrm{H})$





$R(^3\mathrm{He}) / R(^3\mathrm{H})$
1.02
1.01
1
0.99
0.98
0
0.2
0.4
0.6
0.8
1
x
Liuti
Pace et al (RSC)
Pace et al (AV18)


S.Liuti (6/2000)
^{3}He / (2p + n)
^{3}H / (p + 2n)
HERMES ^{3}He / (d + p)
1.2
1.1
1
0.9
0
0.2
0.4
0.6
0.8
1
x

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JLAB-THY-00-17
PCCF RI 00-11
KSUCNR-107-00

Neutron Structure Function and $A = 3$ Mirror Nuclei

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Abstract

We demonstrate that the free neutron structure function can be extracted in deep-inelastic scattering from $A = 3$ mirror nuclei, with nuclear effects canceling to within 2% for $x \lesssim 0.85$.

(Submitted to Phys. Lett. B)

Tritium Target

- Gas at 45 K, 225 psi
- Density 0.028 g/cm^3
- Maximum current 80 μA
- Density change with beam 0.1$\%/\mu$A
- $\sim$ 30 cm length, $\sim$ 2 cm diameter cell
- Luminosity $\sim 5 \times 10^{37}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Total activity $\sim$ 20 kCi
- Measure density by using replica cell at higher temperature ($\sim$ ideal gas)
- ^{3}He cells in same structure

Spectrometer

- MAD is the IDEAL spectrometer to cover (x, Q^2) plane* with 11 GeV.
  - 30 msr solid angle
  - 25 $\%$ momentum byte
  - 1-6 GeV central momentum
  - Standard electron detector package:
    - Calorimeter
    - Threshold Cherenkov
    - Drift Chambers
    - Scintillators
- Systematics studies (MAD helps!)
  - Check that $R = \sigma_L/\sigma_T$ is same for ^{3}He and ^{3}H
  - Measure target densities
  - Cover maximum W^2 and Q^2 range possible

* Similar to SLAC experiments on nuclear R and EMC effect (E139, E140, E140X)

Cross Section ^{3}He/^{3}H Ratio

- High statistics capability $\leq 0.25\%$
- Most corrections cancel out
  - Solid angle
  - Detector efficiencies
  - Beam current
  - Radiative corrections (partially)
- Systematics errors dominated by:

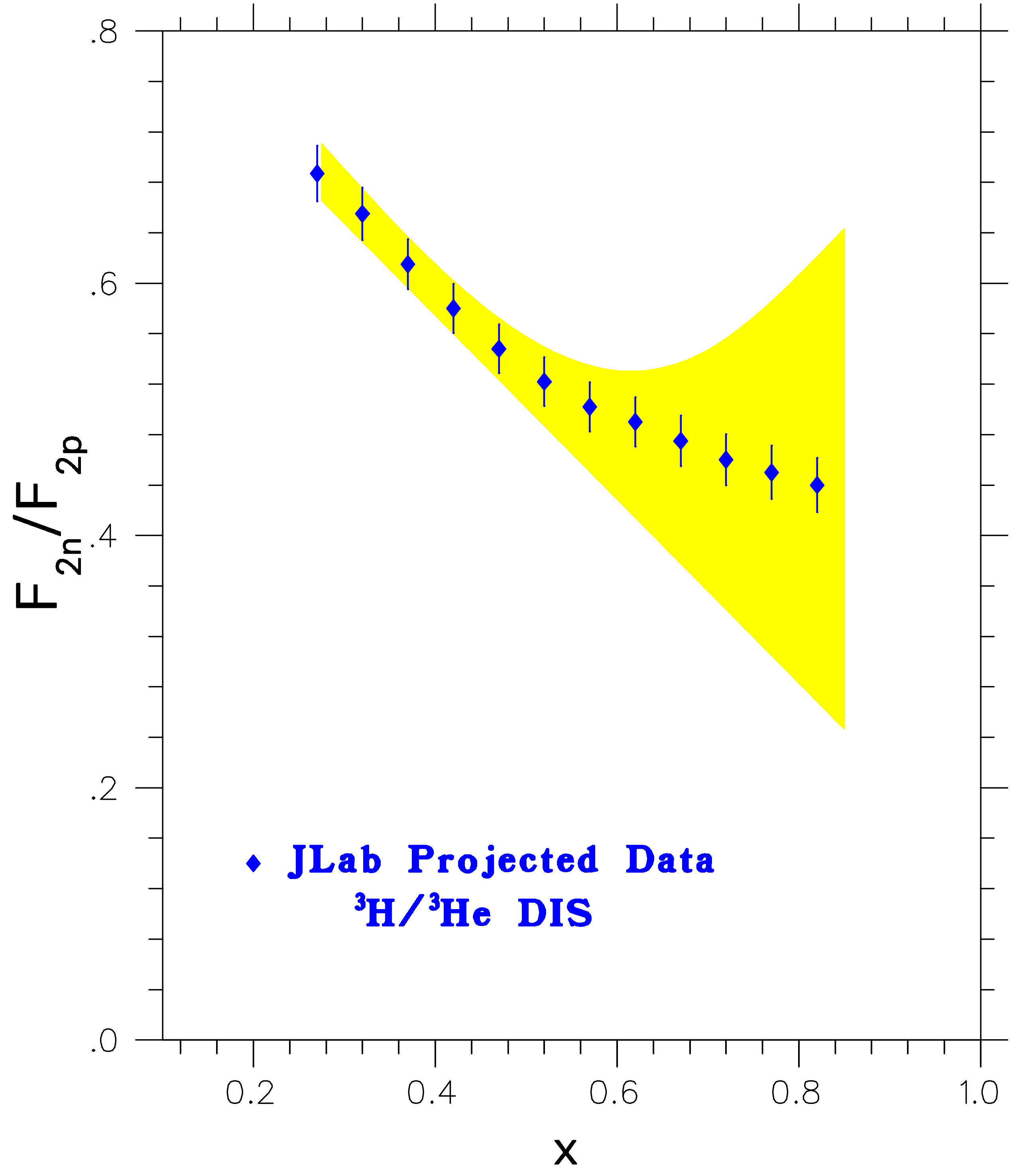
  $\sim 0.5\%$ target densities
  $\sim 0.5\%$ radiative corrections
  $\sim 1\%$ total systematic (comparable to SLAC)
- Theory error 0 -1 %
- Total error 1-1.5 %

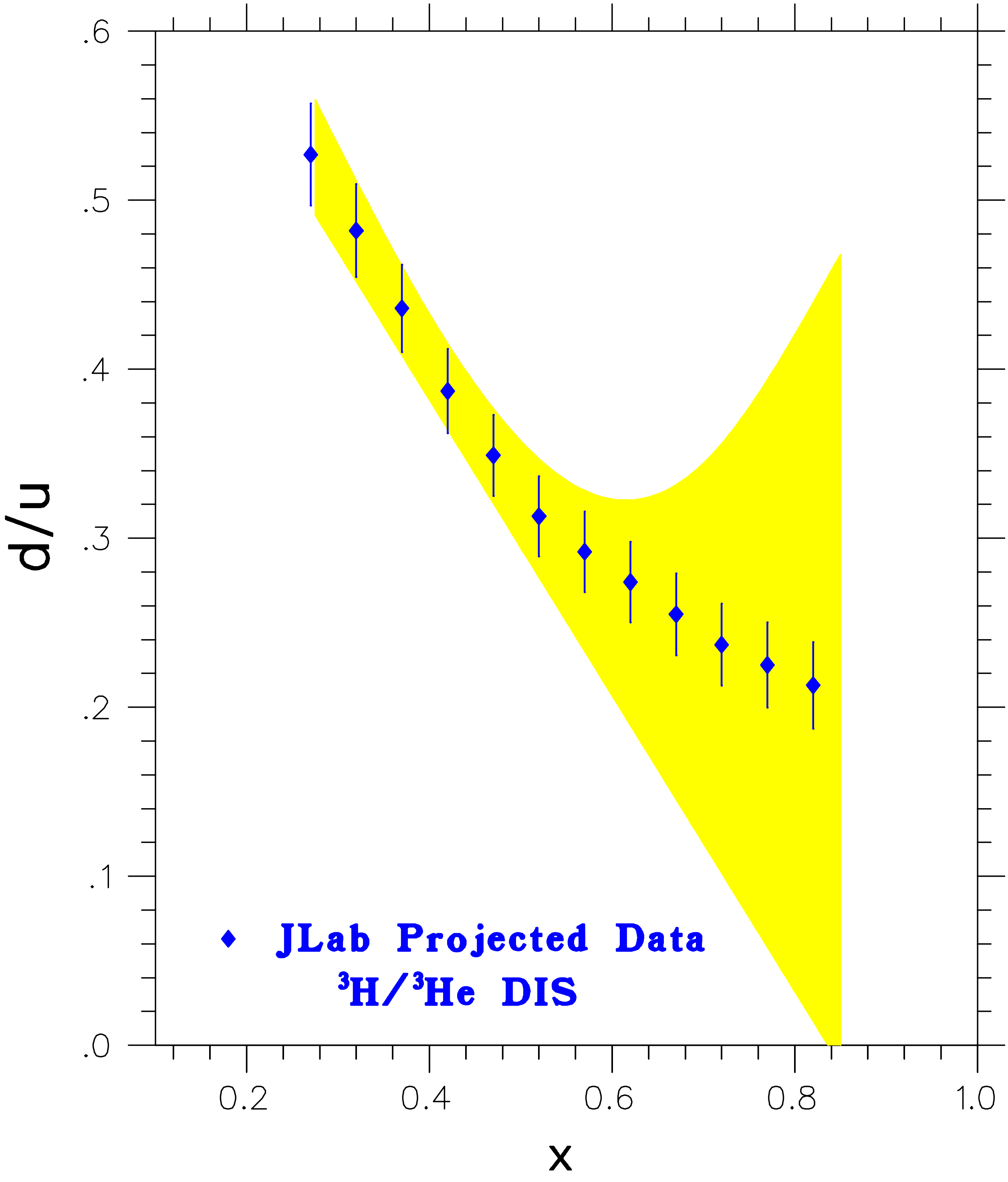
Helium/Tritium E = 11 GeV DIS Kinematics

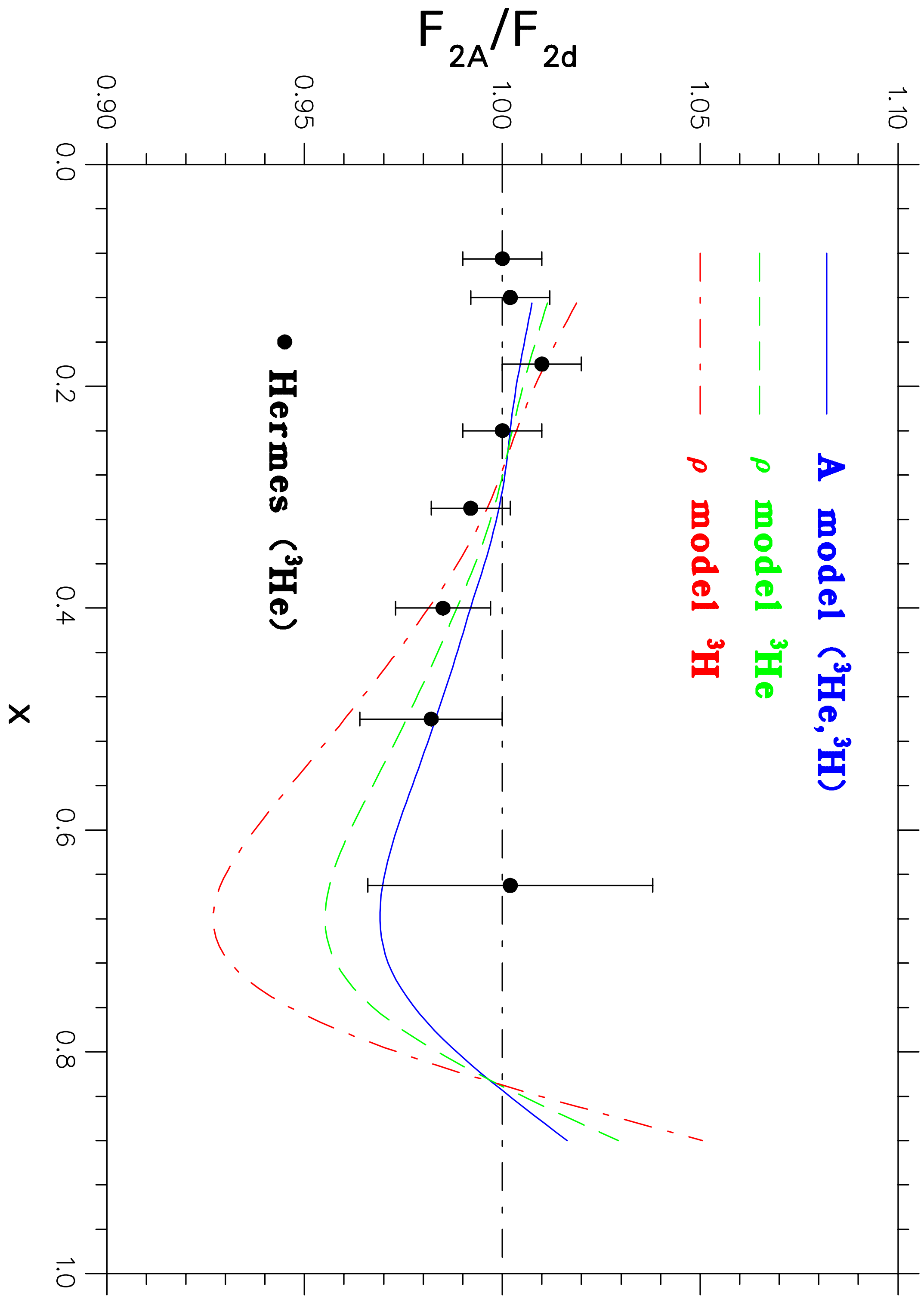
x	W^2 [(GeV)^2]	Q^2 [(GeV)^2]	E' (GeV)	θ (deg)	π/e
0.82	4.0	13.8	2.00	46.6	52
0.77	4.7	12.9	2.10	43.8	43
0.72	5.5	11.9	2.20	41.0	36
0.67	6.2	10.9	2.35	37.8	27
0.62	6.9	9.8	2.55	34.4	19
0.57	7.6	8.9	2.65	32.1	19
0.52	8.3	8.1	2.75	29.9	18
0.47	9.0	7.2	2.85	27.7	19
0.42	9.6	6.3	3.00	25.2	18
0.37	10.2	5.5	3.10	23.1	19
0.32	10.7	4.6	3.30	20.6	18
0.27	11.2	3.8	3.50	18.1	18
0.22	11.6	3.0	3.65	15.8	19

Helium/Tritium E = 11 GeV DIS σ's and Times

x	$\sigma(^3\text{He})$ (nb/sr/GeV)	$\sigma(^3\text{H})$ (nb/sr/GeV)	$t(^3\text{He})$ (h)	$t(^3\text{H})$ (h)
0.82	0.0146	0.0117	10.3	12.8
0.77	0.0308	0.0240	4.5	5.8
0.72	0.0639	0.0491	2.0	2.6
0.67	0.130	0.0996	0.9	1.2
0.62	0.261	0.202	0.5	0.5
0.57	0.463	0.364	0.5	0.5
0.52	0.801	0.639	0.5	0.5
0.47	1.35	1.10	0.5	0.5
0.42	2.35	1.95	0.5	0.5
0.37	3.89	3.30	0.5	0.5
0.32	7.00	6.07	0.5	0.5
0.27	12.8	11.3	0.5	0.5
0.22	23.3	21.1	0.5	0.5


.8
.6
.4
.2
.0
0.2
0.4
0.6
0.8
1.0
x
F_{2n}/F_{2p}
◆ JLab Projected Data
^{3}H/^{3}He DIS


.6
.5
.4
.3
.2
.1
.0
d/u
0.2
0.4
0.6
0.8
1.0
x
◆ JLab Projected Data
$^3H/^3He$ DIS


F_{2A}/F_{2d}
0.90
0.95
1.00
1.05
1.10
0.0
0.2
0.4
0.6
0.8
1.0
x
A model (^{3}He,^{3}H)
ρ model ^{3}He
ρ model ^{3}H
● Hermes (^{3}He)

Summary

- DIS from ^{3}He and ^{3}H at 11 GeV at JLab can provide:
  - Best measurements of

$$F_2^n/F_2^p \text{ and } d/u$$
$$0.1 < x < 0.82$$

  - Distinguish between different predictions of Quark Model and pQCD/Counting Rules
  - Crucial $A = 3$ data for EMC effect study
  - Input to light nuclei structure theory
  - Input to structure function parametrizations,* and Gottfried Sum Rule
- Need ^{3}H/^{3}He in one cryotarget !

* d/u needed to predict hard scattering cross sections of ep, pp, p$\bar{\text{p}}$ collisions