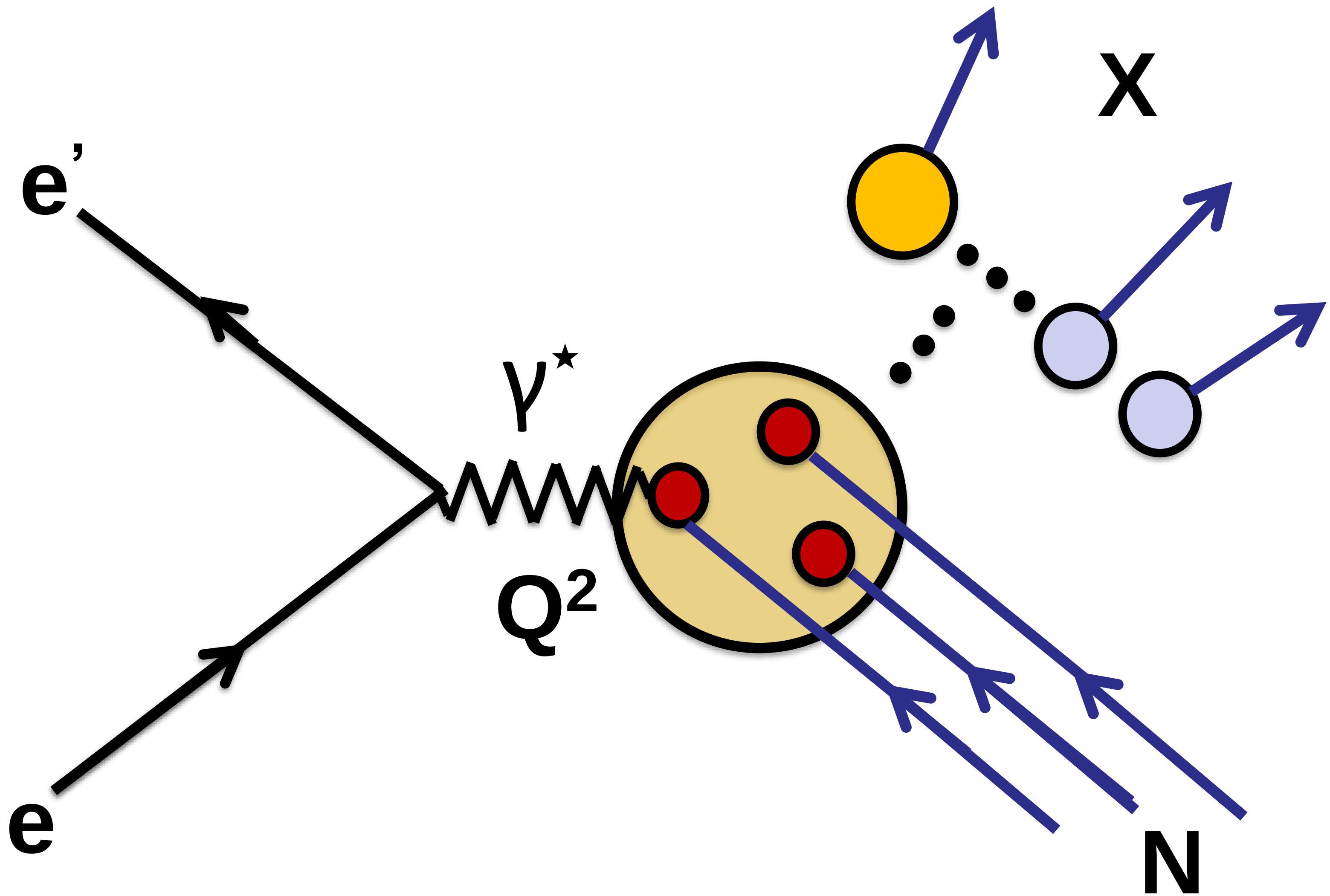
The Quark-Parton Model of the Nucleon Missing Links*

Gerassimos (Makis) Petratos
Kent State University, Ohio, USA

6th International Conference on New Frontiers in Physics
Kolymbari, Crete
August 2017

* Work Supported by US National Science Foundation Grants PHY-1405814/1714809

Electron-Nucleon (Nucleus) Inelastic Scattering: Interaction is mediated via exchange of a virtual photon absorbed by one of the constituent quarks. Nucleon (Nucleus) breaks up into X hadrons. A typical experiment detects only scattered electrons.



Electron-Nucleus Inelastic Scattering

- Cross section for inelastic electron-nucleus scattering [*E* (*E'*): incident (scattered) electron energy, θ: electron scattering angle, *M*: nucleon mass] in terms of nuclear F_1 and F_2 structure functions:

$$\frac{d\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2 \sin^4\left(\frac{\theta}{2}\right)} \left[\frac{F_2(\nu, Q^2)}{\nu} \cos^2\left(\frac{\theta}{2}\right) + \frac{2F_1(\nu, Q^2)}{M} \sin^2\left(\frac{\theta}{2}\right) \right]$$

$$R = \frac{F_2 M}{F_1 \nu}\left(1 + \frac{\nu^2}{Q^2}\right) - 1$$

$$\nu = E - E'$$

$$Q^2 = 4EE' \sin^2(\theta / 2)$$

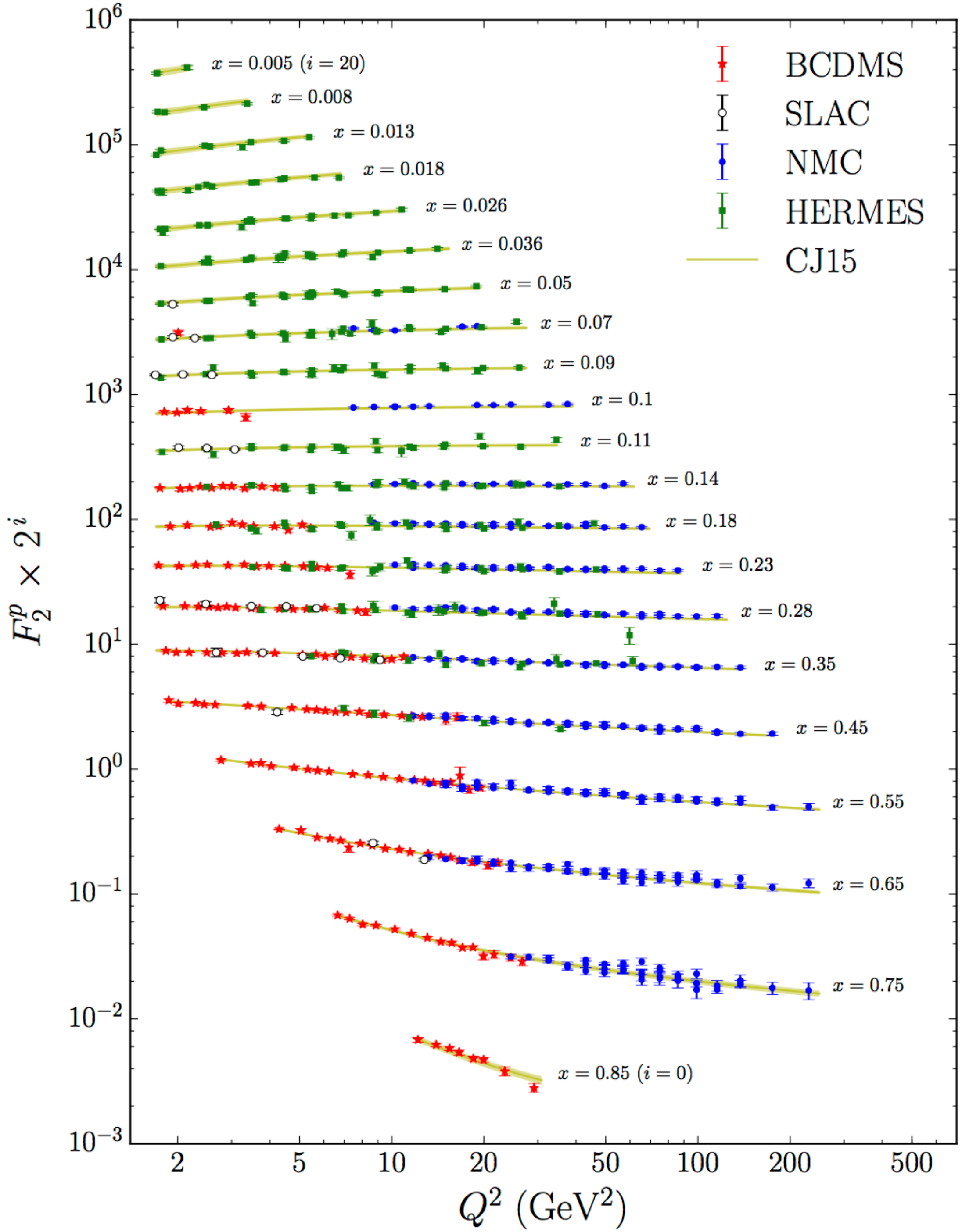
- *R* has been measured to be the same for all nuclei. Therefore, the cross section ratio for any two nuclei, *e.g*. 3H and 3He, becomes equal to ratio of their F_2 structure functions:

$$\left[\frac{d\sigma(3H)}{d\Omega dE'} \Big/ \frac{d\sigma(3He)}{d\Omega dE'} \right] = \left[F_2(3H) / F_2(3He) \right]$$

Deep Inelastic Scattering and Quark Parton Model

- In the Quark Parton Model (QPM) of the nucleon, as established from the SLAC experiments, the electron scatters from one of its 3 valence quarks, which interact through exchange of massless gluons, the carriers of the strong force in nature.
- In Deep Inelastic Scattering (DIS), where both Q^2 and ν are large, the structure functions depend only on the Bjorken scaling variable $x=Q^2/2M\nu$, which is the fraction of the nucleon momentum carried by the struck quark.
- QPM interpretation of the nucleon structure functions in terms of the probability distribution functions, $q_i(x)$, of the i quarks [up $u(x)$, down $d(x)$, and strange $s(x)$] and their electric charges e_i:

$$F_1(x) = \frac{1}{2}\sum_i e_i^2 q_i(x) \qquad F_2(x) = x\sum_i e_i^2 q_i(x)$$



BCDMS
SLAC
NMC
HERMES
CJ15
$x = 0.005$ ($i = 20$)
$x = 0.008$
$x = 0.013$
$x = 0.018$
$x = 0.026$
$x = 0.036$
$x = 0.05$
$x = 0.07$
$x = 0.09$
$x = 0.1$
$x = 0.11$
$x = 0.14$
$x = 0.18$
$x = 0.23$
$x = 0.28$
$x = 0.35$
$x = 0.45$
$x = 0.55$
$x = 0.65$
$x = 0.75$
$x = 0.85$ ($i = 0$)
$F_2^p \times 2^i$
Q^2 (GeV^2)

F_2^n/F_2^p in Quark Parton Model

- Assume isospin symmetry:

$$u^p(x) \equiv d^n(x) \equiv u(x) \qquad \bar{u}^p(x) \equiv \bar{d}^n(x) \equiv \bar{u}(x)$$

$$d^p(x) \equiv u^n(x) \equiv d(x) \qquad \bar{d}^p(x) \equiv \bar{u}^n(x) \equiv \bar{d}(x)$$

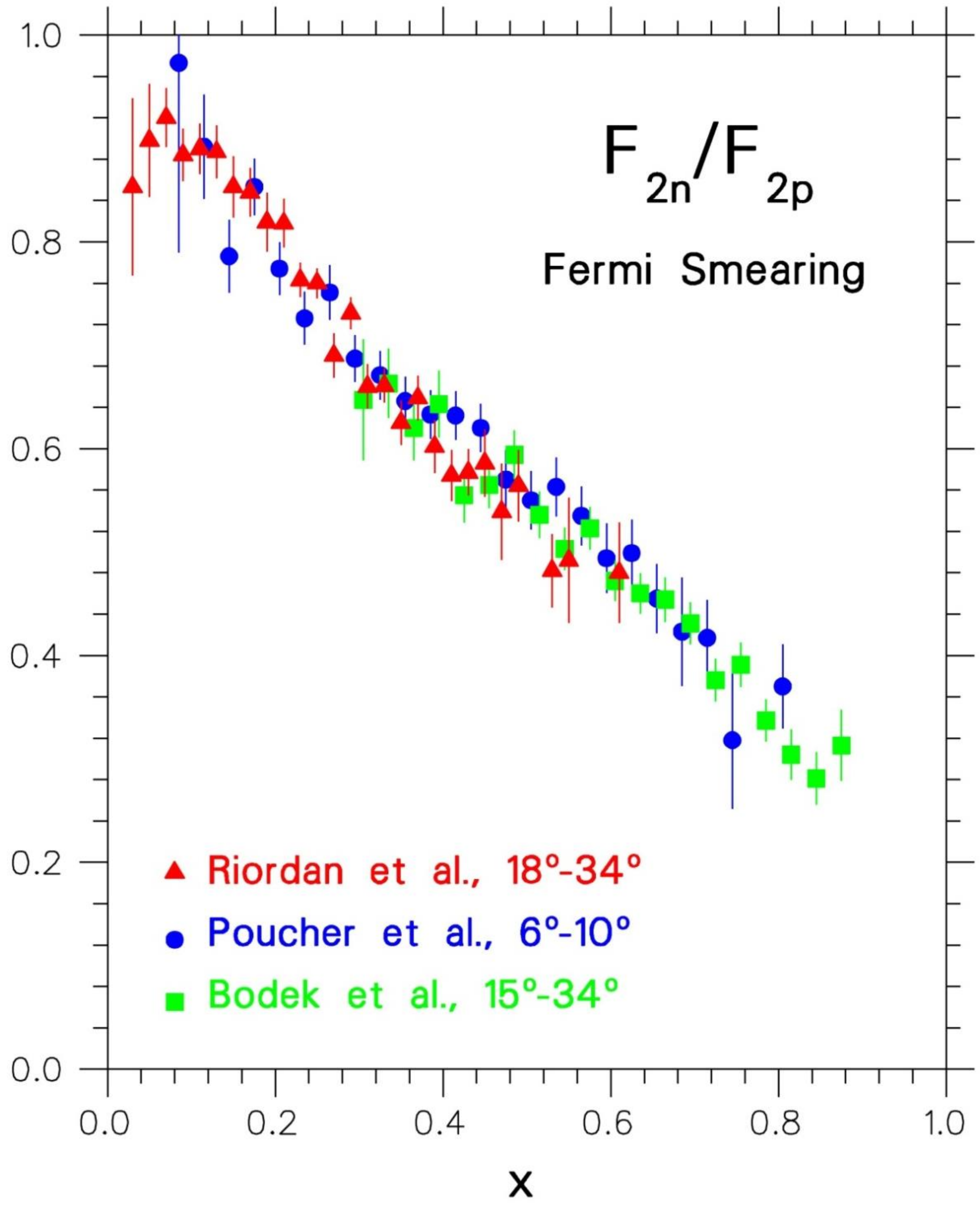
$$s^p(x) \equiv s^n(x) \equiv s(x) \qquad \bar{s}^p(x) \equiv \bar{s}^n(x) \equiv \bar{s}(x)$$

- Proton and neutron structure functions (from definition):

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

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

- Nachtmann inequality: $1/4 \le F_2^n / F_2^p \le 4$



SLAC Measurements
End Station A
1968-1972

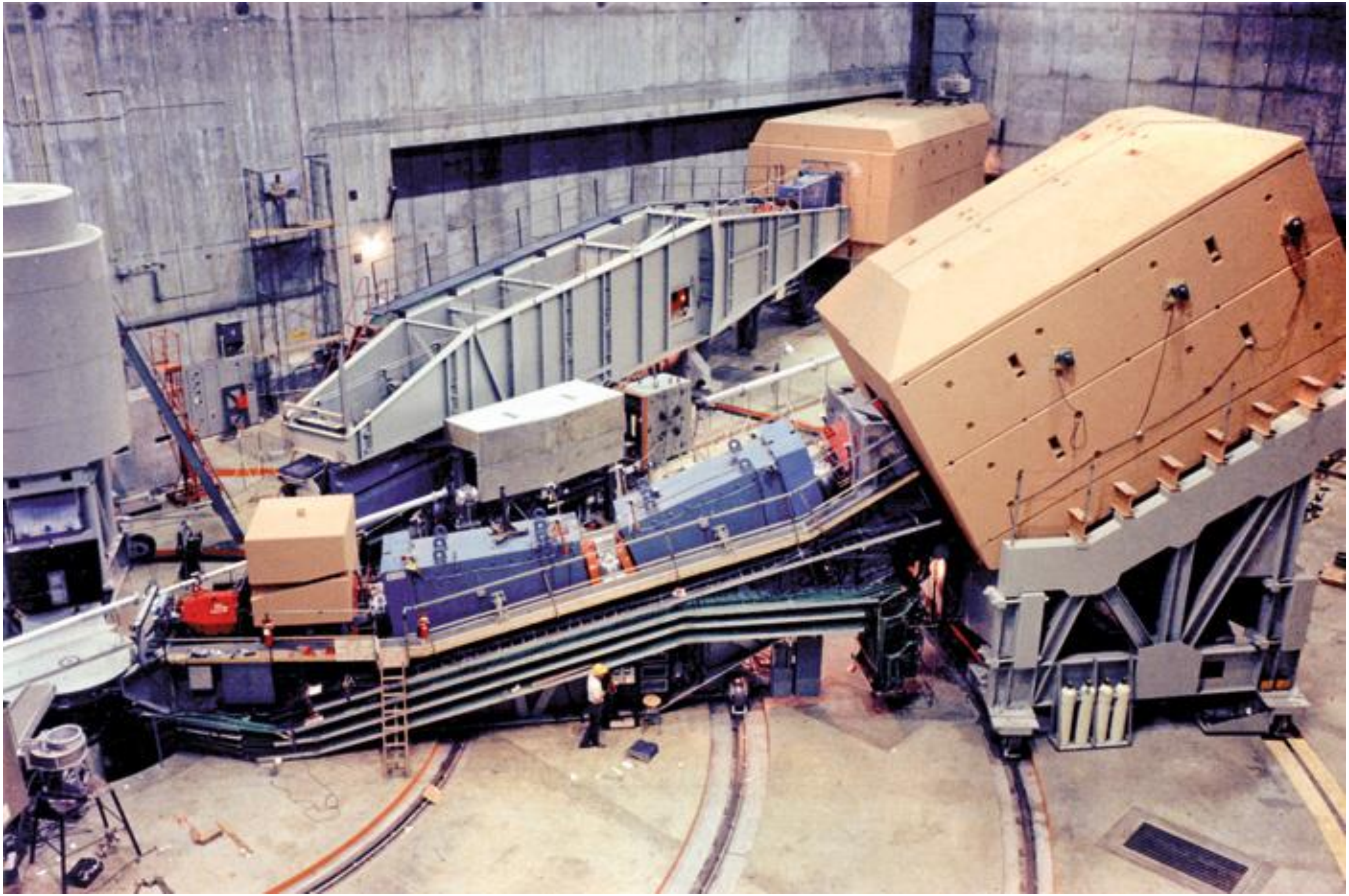
Friedman, Kendal, Taylor
Nobel 1991

F_2^n/F_2^p extracted from proton and deuterium deep inelastic data using Hamada-Johnston potential with a non-relativistic Fermi-smearing model.

Data in disagreement with *SU(6)* prediction: 2/3=0.67!

SLAC End Station A

1.6, 8, and 20 GeV/c Magnetic Spectrometers



SLAC/CERN Data Interpretation in QPM

- Nachtmann inequality satisfied: $1/4 \leq F_2^n / F_2^p \leq 4$

- For $x \to 0$: $F_2^n/F_2^p \to 1$: Sea quarks dominate with:

$$u + \bar{u} = d + \bar{d} = s + \bar{s}$$

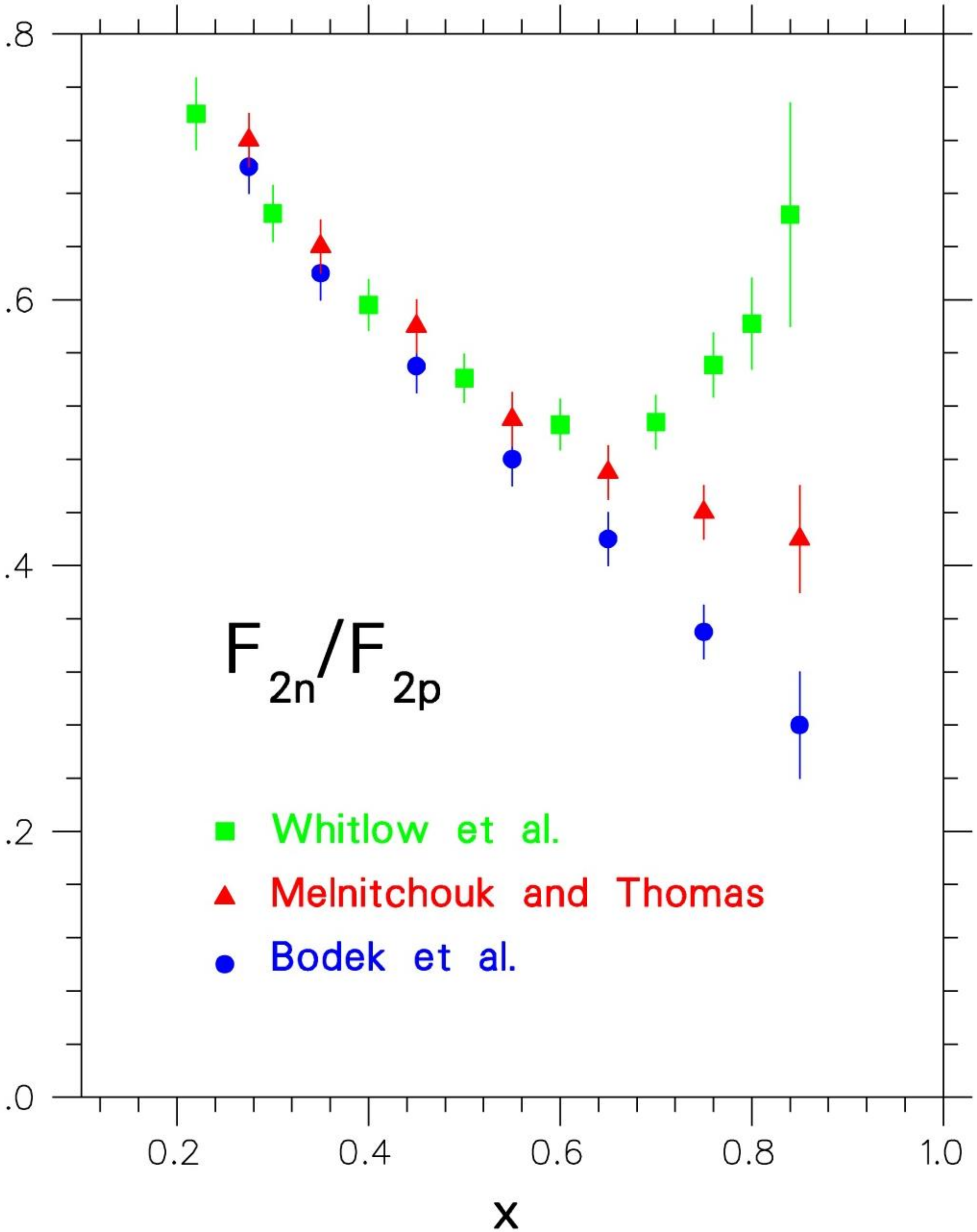
- For $x \to 1$: $F_2^n/F_2^p \to 1/4$: High momentum partons in proton (neutron) are up (down) quarks, and:

$$s + \bar{s} = 0$$

- For medium and high x, safe to assume that (with d and u denoting now quark **plus** antiquark distributions):

$$\frac{F_2^n}{F_2^p} = \frac{[1 + 4(d/u)]}{[4 + (d/u)]}$$

Nucleon F_2 Ratio Extraction Revisited



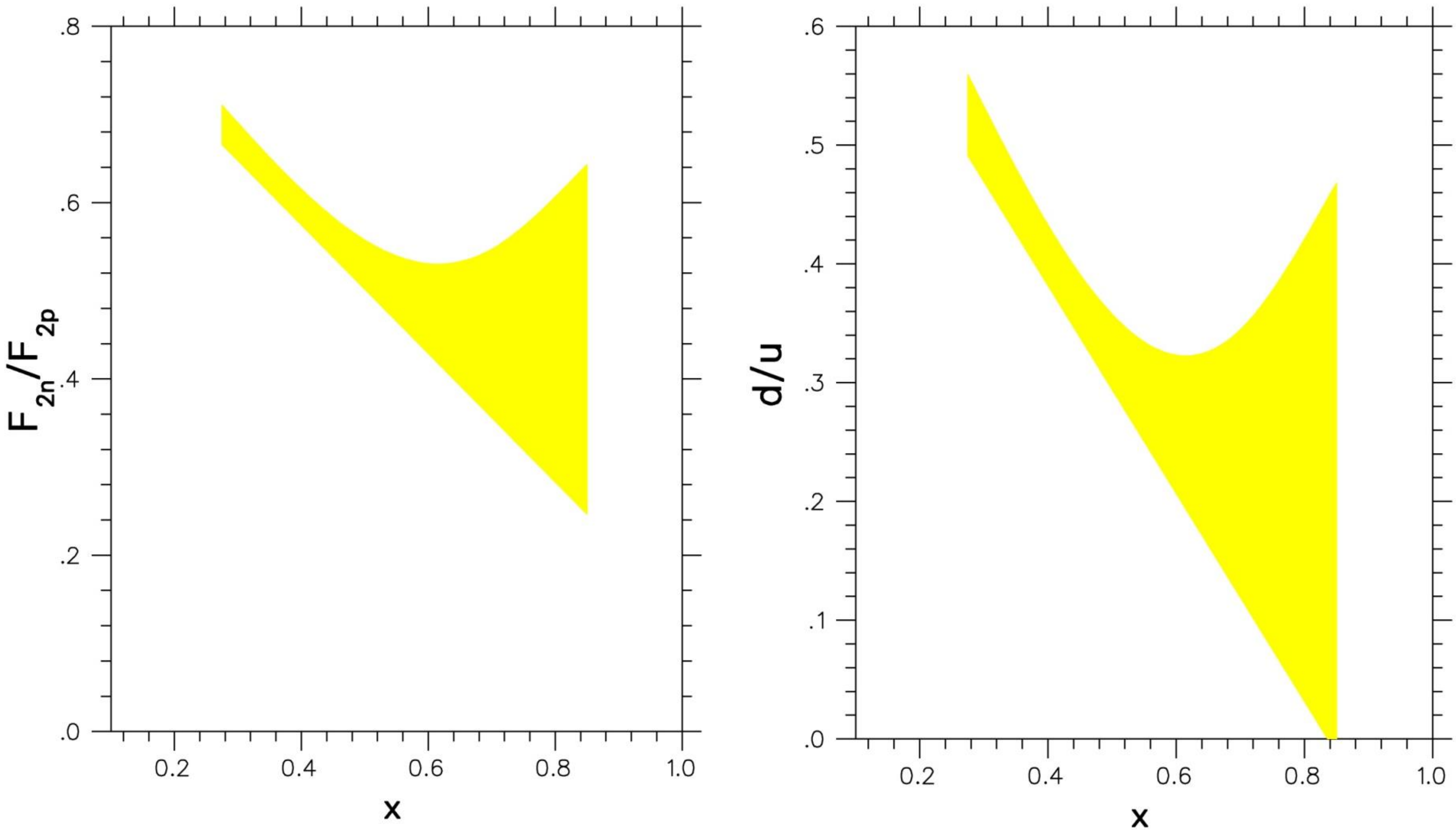
SLAC DIS Data

Bodek: Non-relativistic Fermi-smearing-only model with Paris nucleon-nucleon potential (1972).

Melnitcouk &Thomas: Relativistic convolution model with empirical binding effects (1996).

Whitlow: Assumes EMC effect in deuteron (Frankfurt and Strikman data-based Density Model) (1993).

Theoretical uncertainties introduce tremendous uncertainties in high-*x* behavior of F_2^n/F_2^p and *d/u* ratios … *d/u* essentially unknown at large *x*!



Knowledege of *d/u* ratio is essential for Quark Model and perturbative QCD tests, and for the interpretation of high energy hadron collider data.

Polarized Electron-Nucleus Inelastic Scattering

- DIS cross section asymmetry is given for longitudinally (→ or ←) or transversely (↑ or ↓) polarized electrons and nuclear targets in terms of the nuclear polarized g_1 and g_2 structure functions, and the degree of the longitudinal polarization, ε, of the virtual photon:

$$A_P = \frac{1-\varepsilon}{(1+\varepsilon R)\nu F_1}\left[g_1(\nu,Q^2)(E+E'\cos\theta) - \frac{Q^2}{\nu} g_2(\nu,Q^2) \right]$$

$$A_T = \frac{(1-\varepsilon)E'}{(1+\varepsilon R)\nu F_1}\left[\left[g_1(\nu,Q^2) + 2\frac{E}{\nu} g_2(\nu,Q^2) \right]\sin\theta\right]$$

- *Parallel* and *Transverse* Asymmetries, A_P and A_T, are standard ratios for different incident electrons and target nuclei spin orientations:

$$A_P = \left[\frac{\sigma(\uparrow\uparrow)-\sigma(\uparrow\downarrow)}{\sigma(\uparrow\uparrow)+\sigma(\uparrow\downarrow)}\right] \quad A_T = \left[\frac{\sigma(\uparrow\rightarrow)-\sigma(\uparrow\leftarrow)}{\sigma(\uparrow\rightarrow)+\sigma(\uparrow\leftarrow)}\right]$$

Polarized DIS and QPM

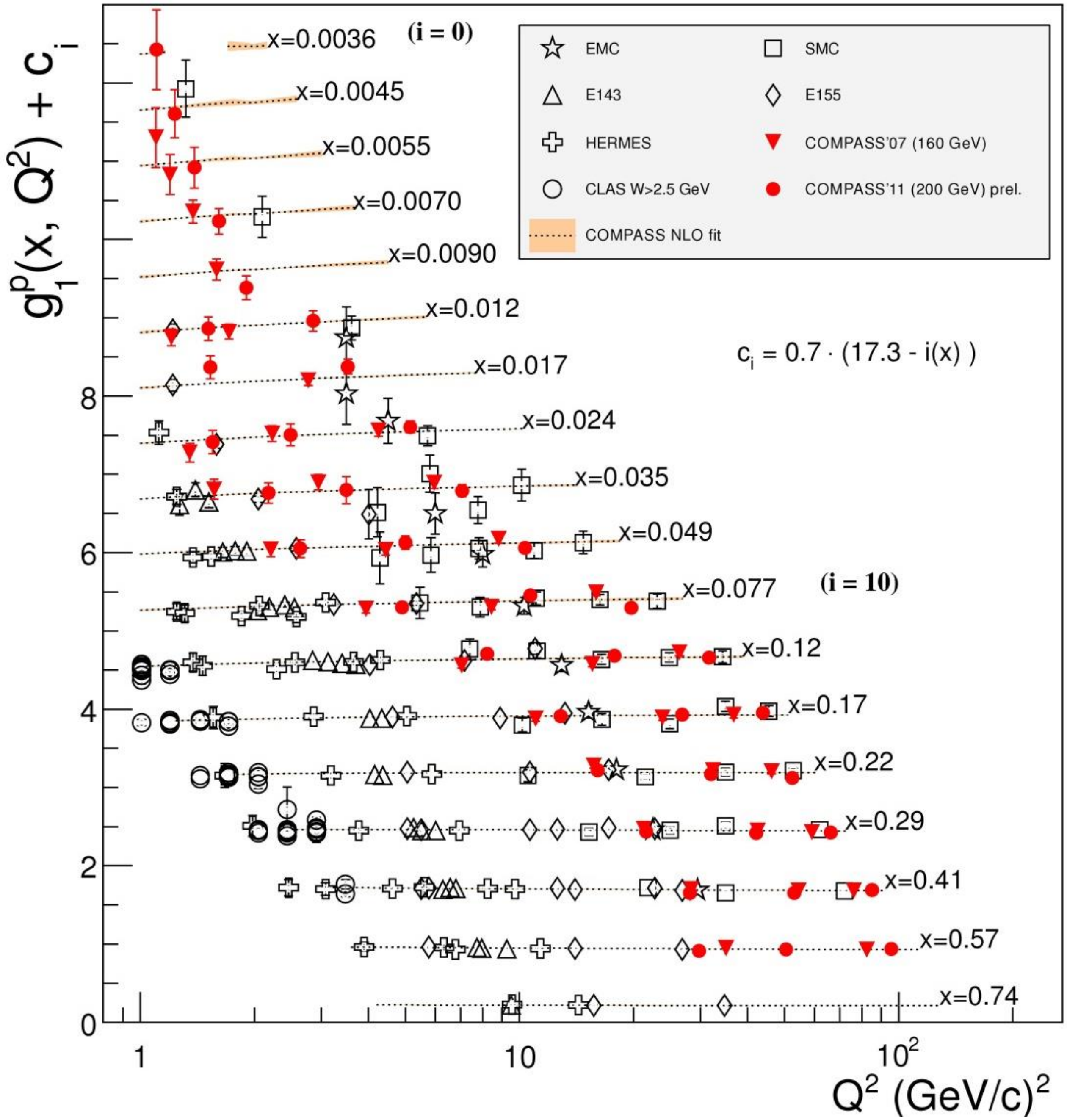
- In the Bjorken scaling limit, the nucleon g_1 and g_2 structure functions should also become functions only of the Bjorken *x*. If *L (T)* stands for a longitudinally (transversely) polarized nucleon, and + (-) denotes quarks with spin parallel (antiparallel) to the nucleon spin:

$$g_1(x) = \frac{1}{2}\sum_i e_i^2\left[q_i^{+L}(x) - q_i^{-L}(x)\right]$$

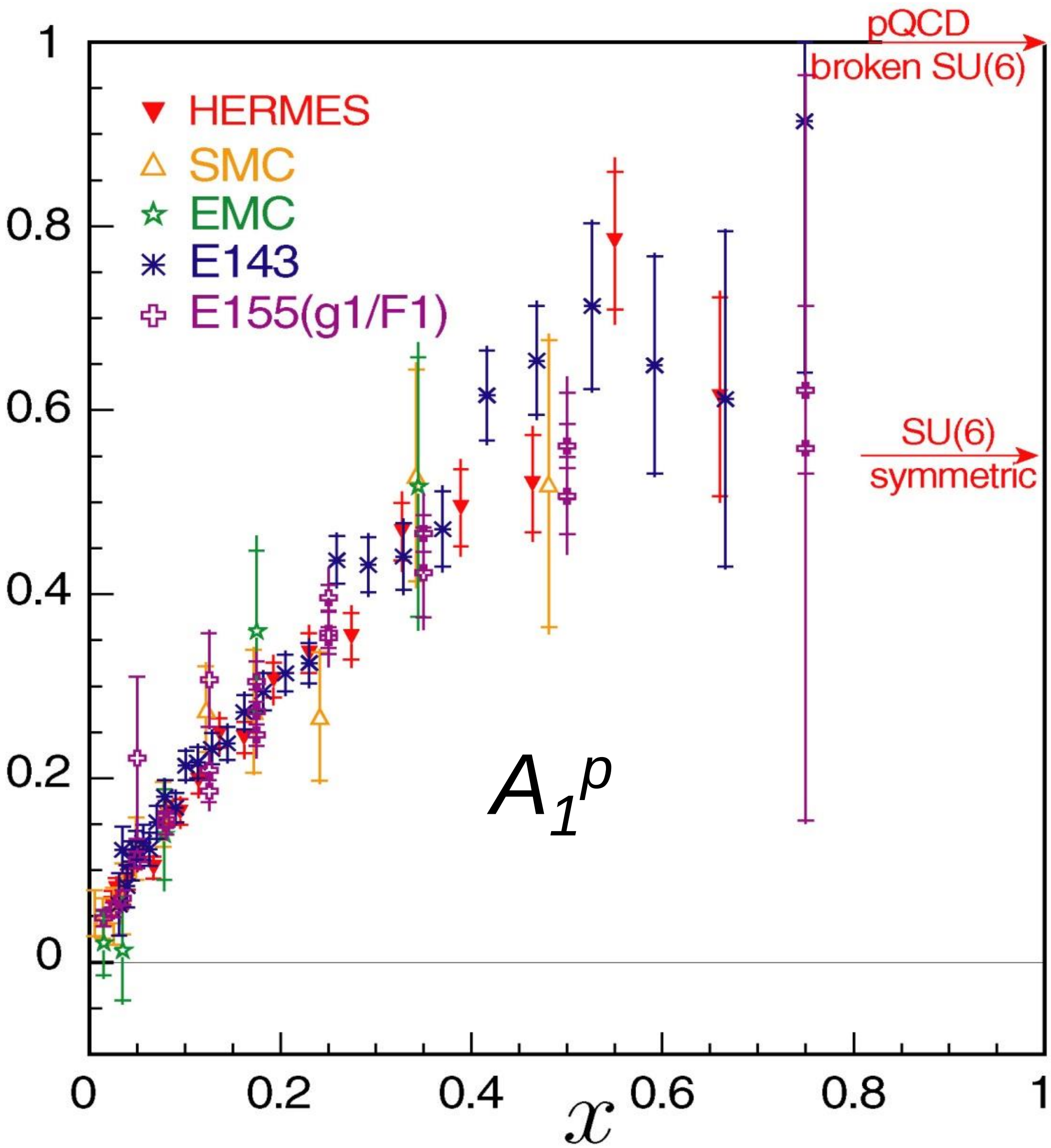
$$g_1(x) + g_2(x) = \frac{1}{2Mx}\sum_i e_i^2 m_i\left[q_i^{+T}(x) - q_i^{-T}(x)\right]$$

- Of particular interest is the asymmetry A_1, which is a measure of the probability that the quark spins are aligned with the nucleon spin:

$$A_1(x) = \frac{g_1(x)}{F_1(x)} = \frac{\sum_i e_i^2\left[q_i^{+L}(x) - q_i^{-L}(x)\right]}{\sum_i e_i^2\left[q_i(x) - q_i(x)\right]}$$

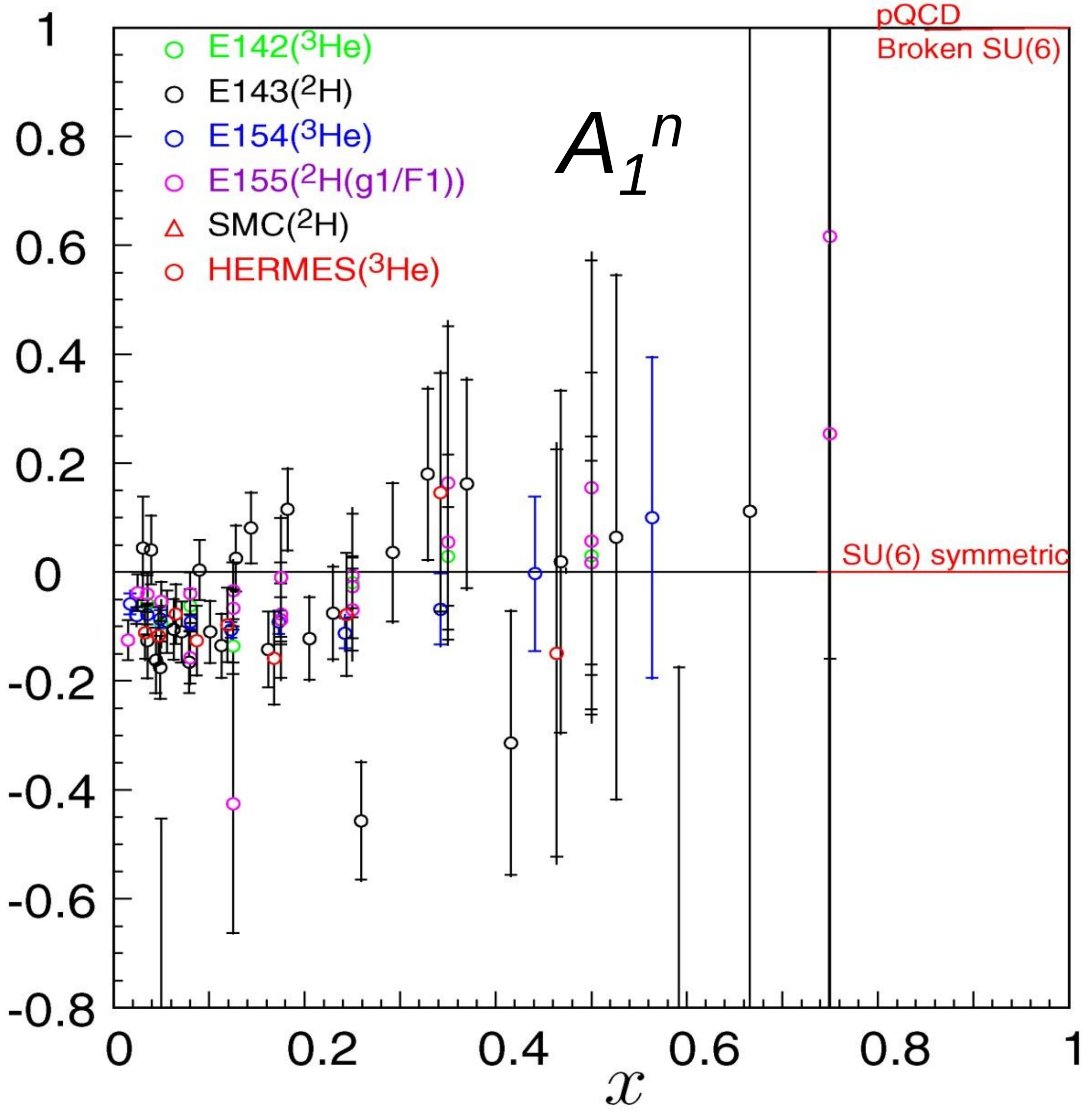


$g_1^p(x, Q^2) + c_i$
Q^2 (GeV/c)^2
x=0.0036
(i = 0)
x=0.0045
x=0.0055
x=0.0070
x=0.0090
x=0.012
x=0.017
x=0.024
x=0.035
x=0.049
x=0.077
(i = 10)
x=0.12
x=0.17
x=0.22
x=0.29
x=0.41
x=0.57
x=0.74
EMC
SMC
E143
E155
HERMES
COMPASS'07 (160 GeV)
CLAS W>2.5 GeV
COMPASS'11 (200 GeV) prel.
COMPASS NLO fit
$c_i = 0.7 \cdot (17.3 - i(x))$



Experimental data on the proton A_1 asymmetry from experiments with polarized electrons/positrons or muons, and polarized protons (hydrogen, ammonia or butanol).

As x increases, the spins of the proton's quarks tend to be aligned with the proton spin. High-*x* quarks in the proton are highly polarized!



Experimental data on the neutron A_1 asymmetry from experiments with polarized electrons/positrons or muons. and polarized neutrons (helium-3, deuterated butanol or ammonia).

Low-*x* neutron quarks are mildly polarized in a direction opposite to the neutron spin. Medium-*x* quarks seem to be unpolarized. But, we cannot say anything about the polarization of the high-*x* quarks In the neutron!

F_2^n / F_2^p, d/u Ratios and A_1 Limits for $x \to 1$

THEORY MODEL	F_2^n/F_2^p	d/u	A_1^n	A_1^p
SU(6) Symmetry	2/3	1/2	0	5/9
Diquark Feynman Model	1/4	0	1	1
Quark Model/Isgur	1/4	0	1	1
Perturbative QCD	3/7	1/5	1	1
See E12-10-103, E12-06-109, E12-06-110 JLab Proposals				

Nucleon F_2 Ratio Extraction from ^{3}He/^{3}H

- Form the "SuperRatio" of EMC-type ratios for A=3 mirror nuclei:

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

- Solve above equations for the *A=3* structure function ratio:

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

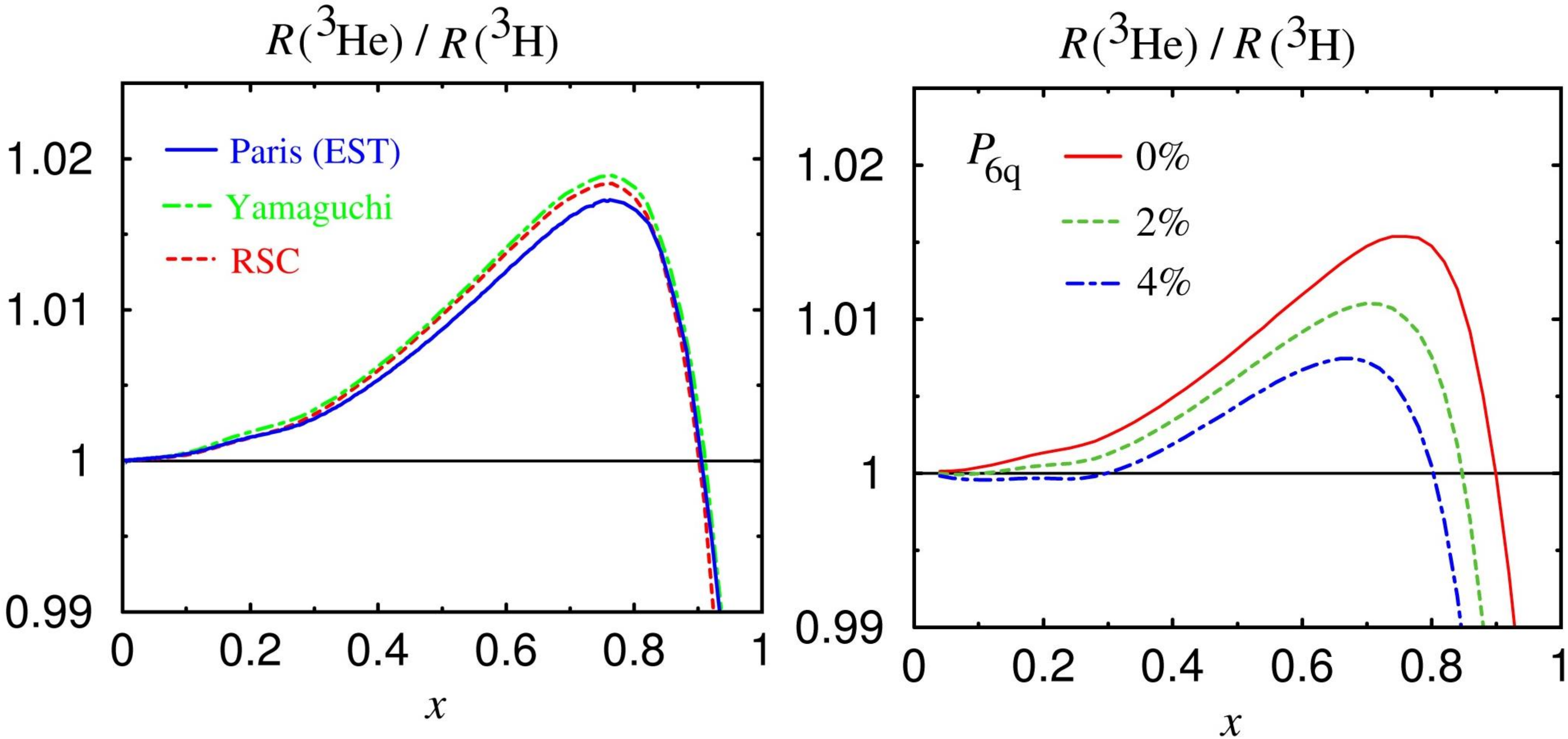
- Solve for the nucleon F_2^n/F_2^p ratio and extract it, using R^* from a reliable theoretical model (value of R^* is very close to unity with an uncertainty of *1-2%*), and the measured *A=3* cross sections:

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

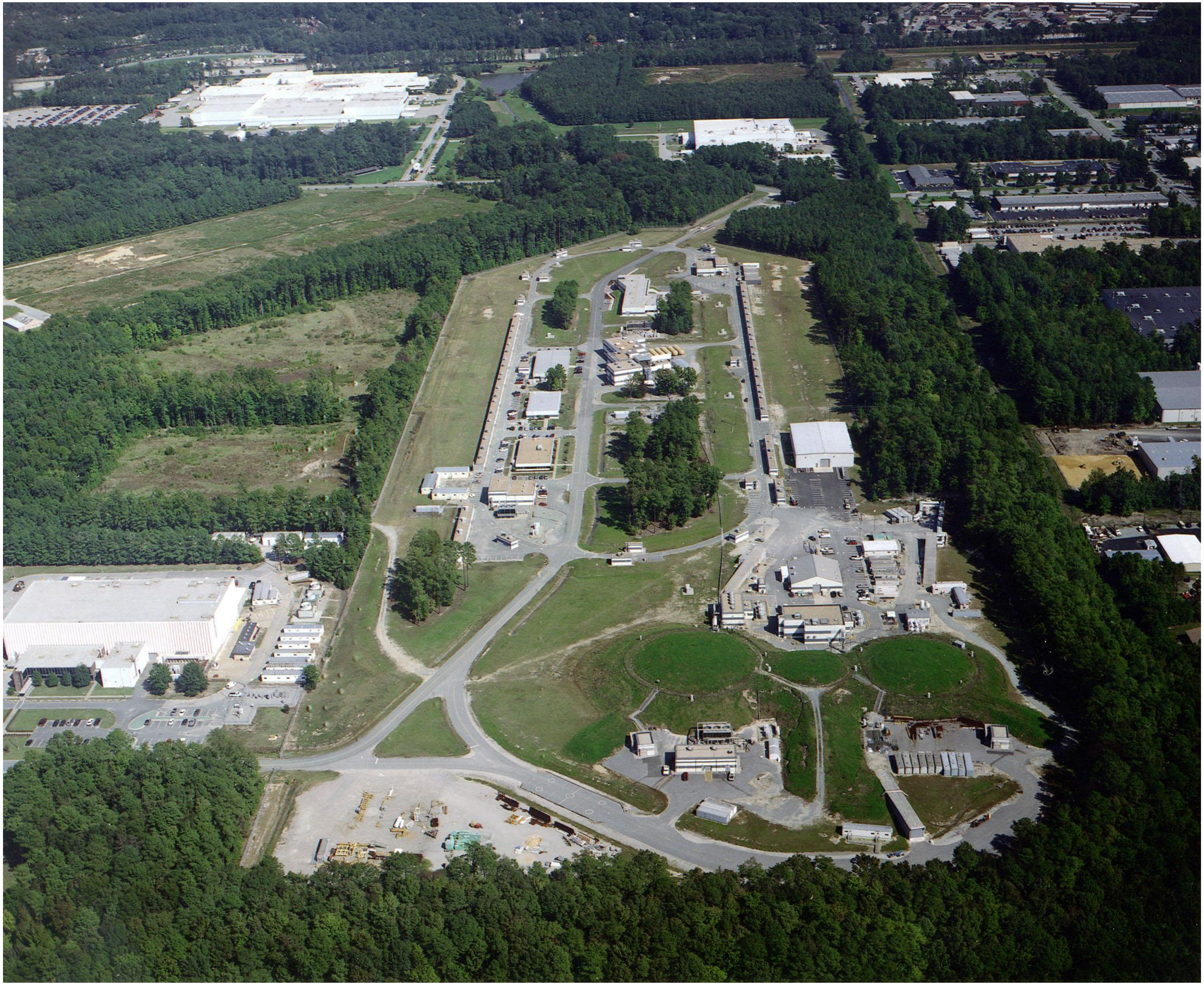
- **Note:** The F_2^n/F_2^p (and *d/u*) ratio at high *x* can also be extracted by employing proton-spectator tagging in electron-deuteron DIS (forthcoming JLab BoNuS experiment). The *d/u* ratio at high *x* can also be extracted directly from parity-violating electron-proton DIS (forthcoming JLab SOLID experiment).

SuperRatio $R^* = R(^3He)/R(^3H)$ has been calculated by three expert groups to deviate from 1 only up to ~1.5% taking into account all possible effects:

* I. Afnan et al., Phys. Lett. B493, 36 (2000); Phys. Rev. C68, 035201 (2003)
* E. Pace, G Salme, S. Scopetta, A. Kievsky, Phys. Rev. C64, 055203 (2001)
* M. Sargsian, S. Simula, M. Strikman, Phys. Rev. C66, 024001 (2002)

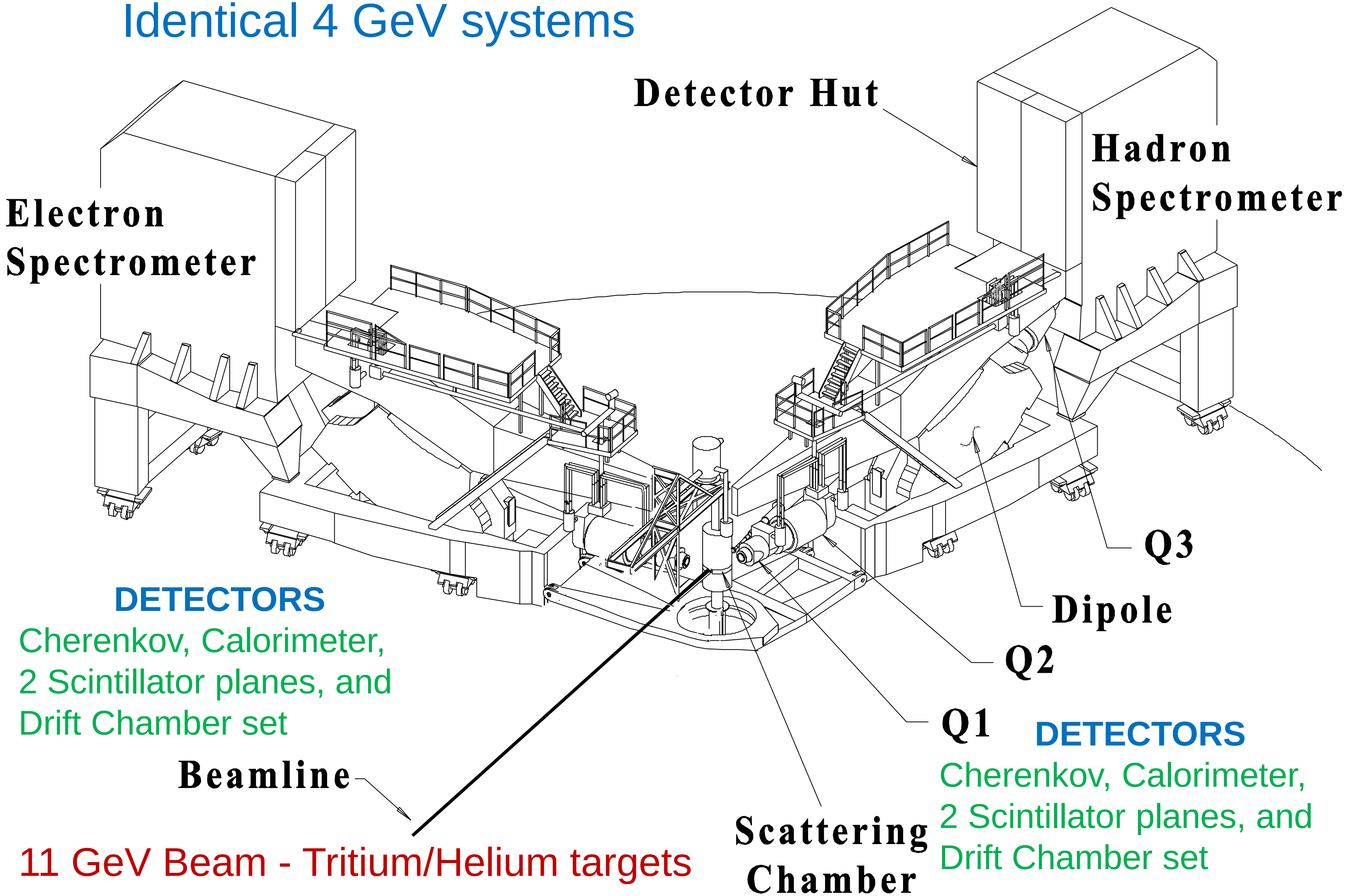


The Jefferson Lab Electron Accelerator

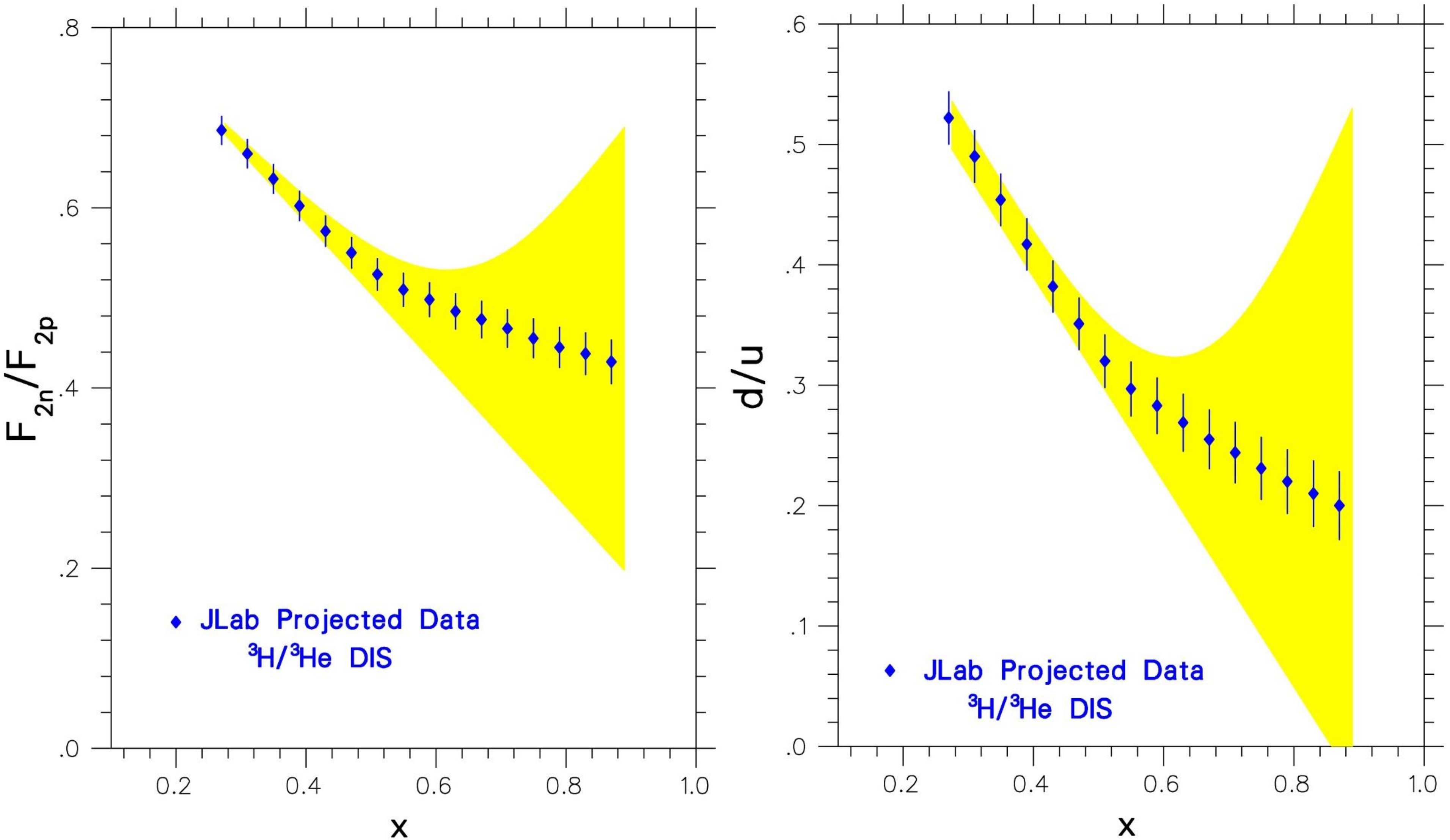


JLab Hall A High Resolution Spectrometers

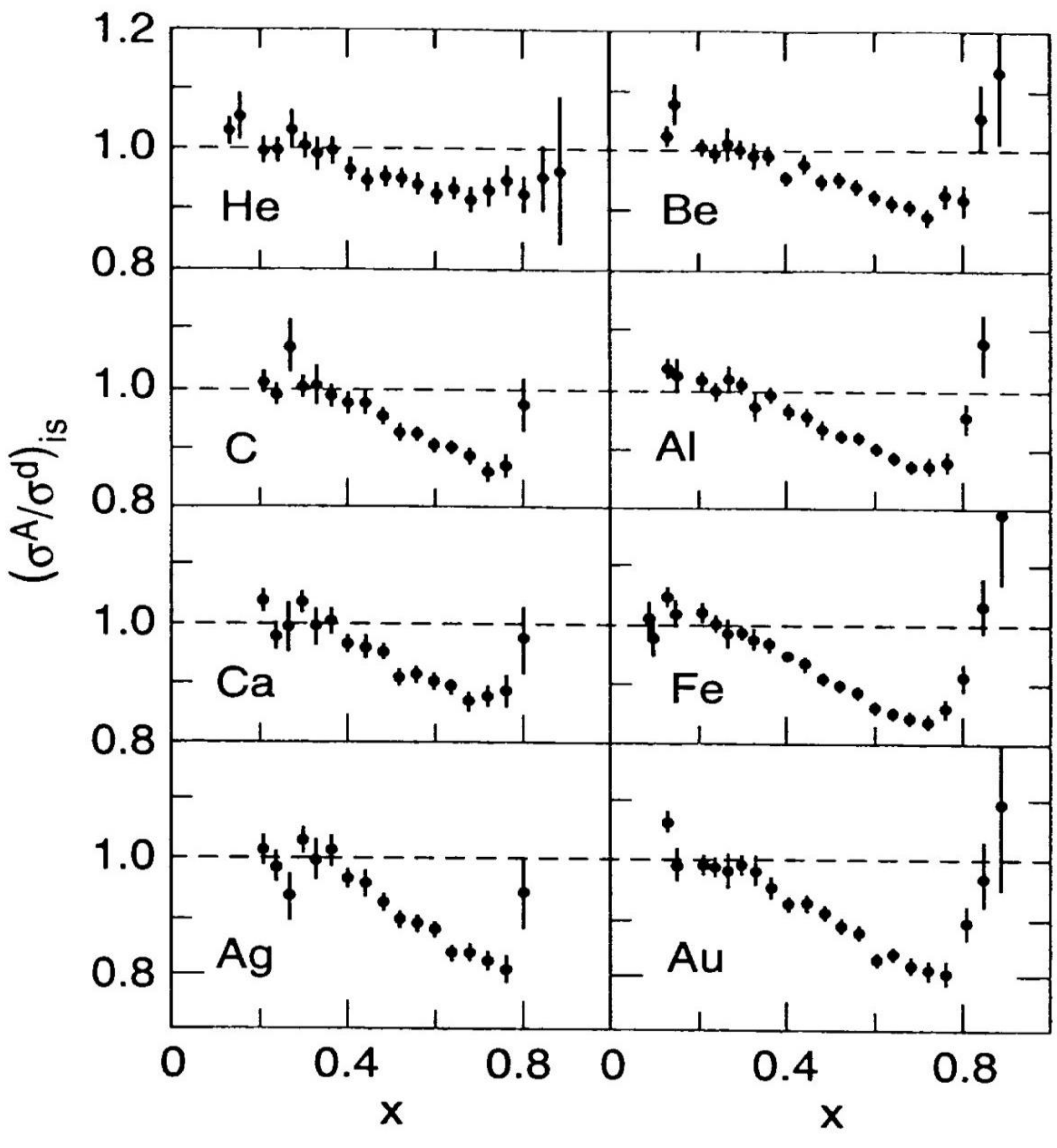
Identical 4 GeV systems



Projected JLab Hall A Data for F_2^n/F_2^p and d/u Ratios



11 GeV beam; Left and Right High Resolution Hall A Spectrometers;
^3H and ^3He gas target system; 3 months of data taking (**E12-10-103**)

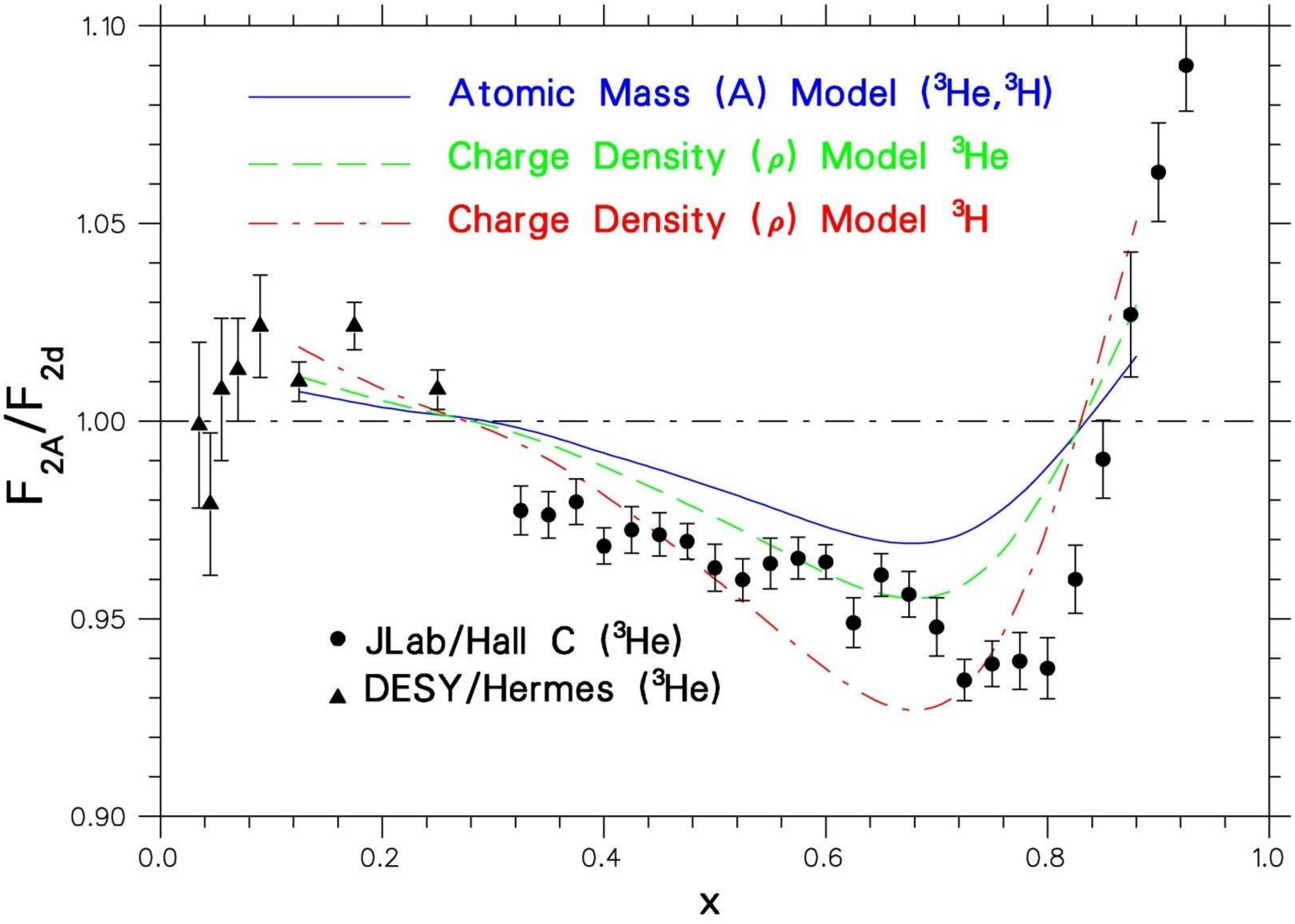


A Dependence EMC Effect

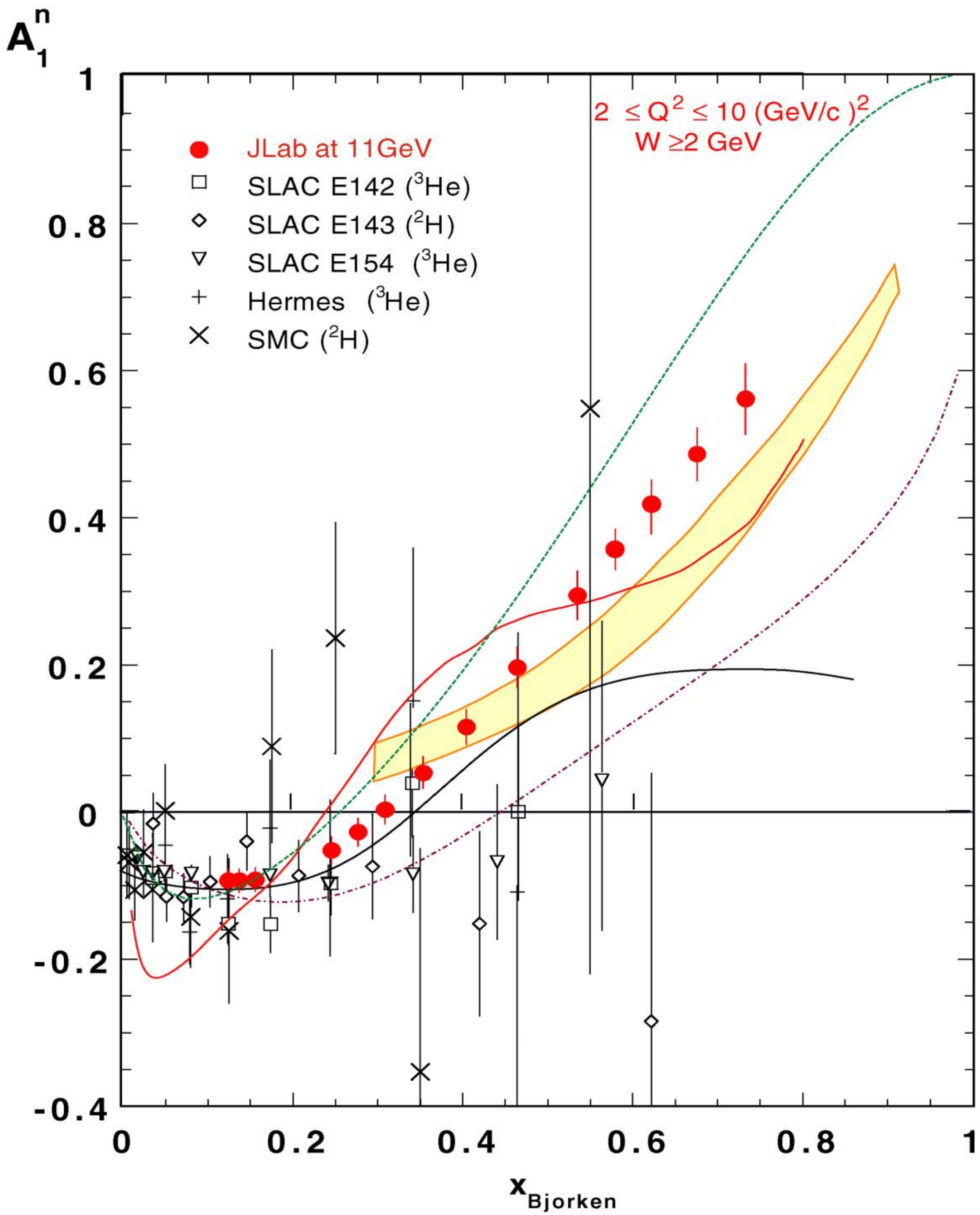
SLAC E-139, 1984
J. Gomez et al.

Quark momentum probability distributions in nuclei different from those in deuterium. Effect increases with mass number *A*.

EMC Effect for *A=3* Mirror Nuclei



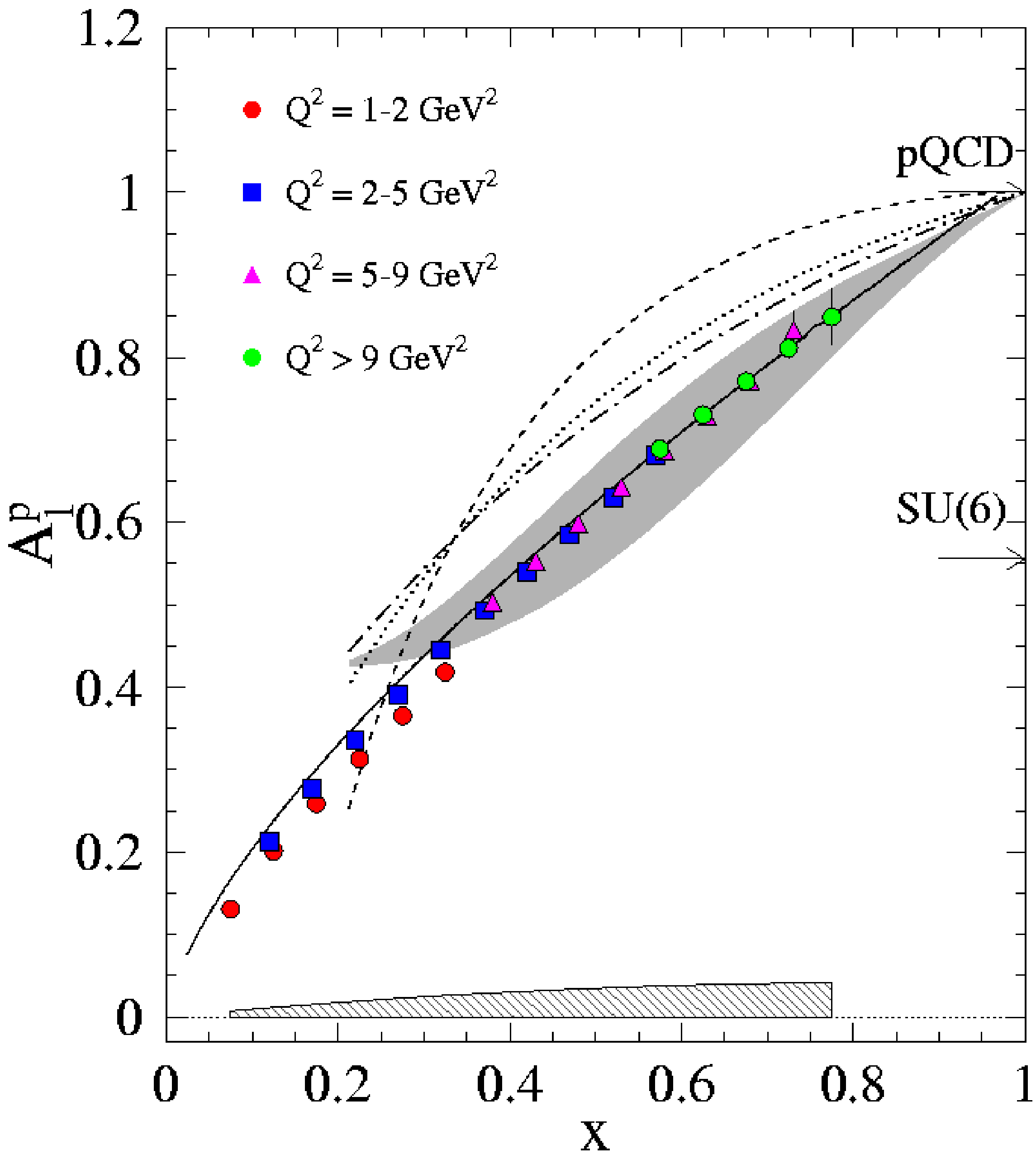
Hall A JLab expected EMC effect data on ^{3}H, ^{3}He (**E12-10-103**) will be of **similar precision** to the shown ^{3}He JLab Hall C data.



PROJECTED JLab DATA on the Neutron A_1 Asymmetry

Experiment E12-06-110

Experiment to be performed in the **Hall C** Facility using the new SHMS electron detection system and a helium-3 polarized target.



PROJECTED JLab DATA on the Proton A_1 Asymmetry

Experiment E12-06-109

Experiment to be performed in the **Hall B** Facility using the new CLAS-12 electron detection system and a polarized ammonia target.

Summary - Outlook

- Upcoming Jefferson Lab experiments will perform unpolarized and polarized DIS electron scattering from nuclear targets to measure unpolarized and polarized structure functions of the nucleon at large values of the Bjorken-*x* (valence quark region).
- A new novel technique using a tritium target with an 11 GeV electron beam in the JLab Hall A Facility can provide:
  - Best measurements of F_2^n/F_2^p and d/u ratios
  - Discrimination between differing predictions of Quark Model and Quantum Chromodynamic
  - Reliable data for structure function parametrizations, needed for interpretation of high energy hadron collider data
- Hall B/C experiments using established methods of polarizing nucleons in nuclear targets will also provide complementary high-*x* data for the proton and neutron A_1 asymmetries.