MeAsurement of F_2^n/F_2^p, d/u RAtios and $A=3$ EMC Effect in Deep Inelastic Electron Scattering Off the Tritium and Helium MirrOr Nuclei

JLab MARATHON Experiment

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Overview and Goals of the Experiment

- MARATHON will use deep inelastic scattering to measure the cross section ratio of the 3H and 3He mirror nuclei using the Hall A spectrometer facility of JLab.
- Using a new novel method that exploits the isospin symmetry of the $A=3$ nuclei, will measure ratio of the neutron to proton structure functions F_2^n / F_2^p, and the ratio of the proton d/u quark distribution functions.
- New data will be almost free of nuclear structure theoretical uncertainties that dominate the previous SLAC data, extracted from proton and deuteron deep inelastic scattering (DIS) measurements.
- Expt. will also measure the EMC effect for 3H and 3He. $A=3$ EMC data are considered crucial for the effect understanding.

Deep Inelastic Scattering and Quark Parton Model

- DIS cross section - Nucleon structure functions F_1 and F_2:

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

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

$$\nu = E - E'$$

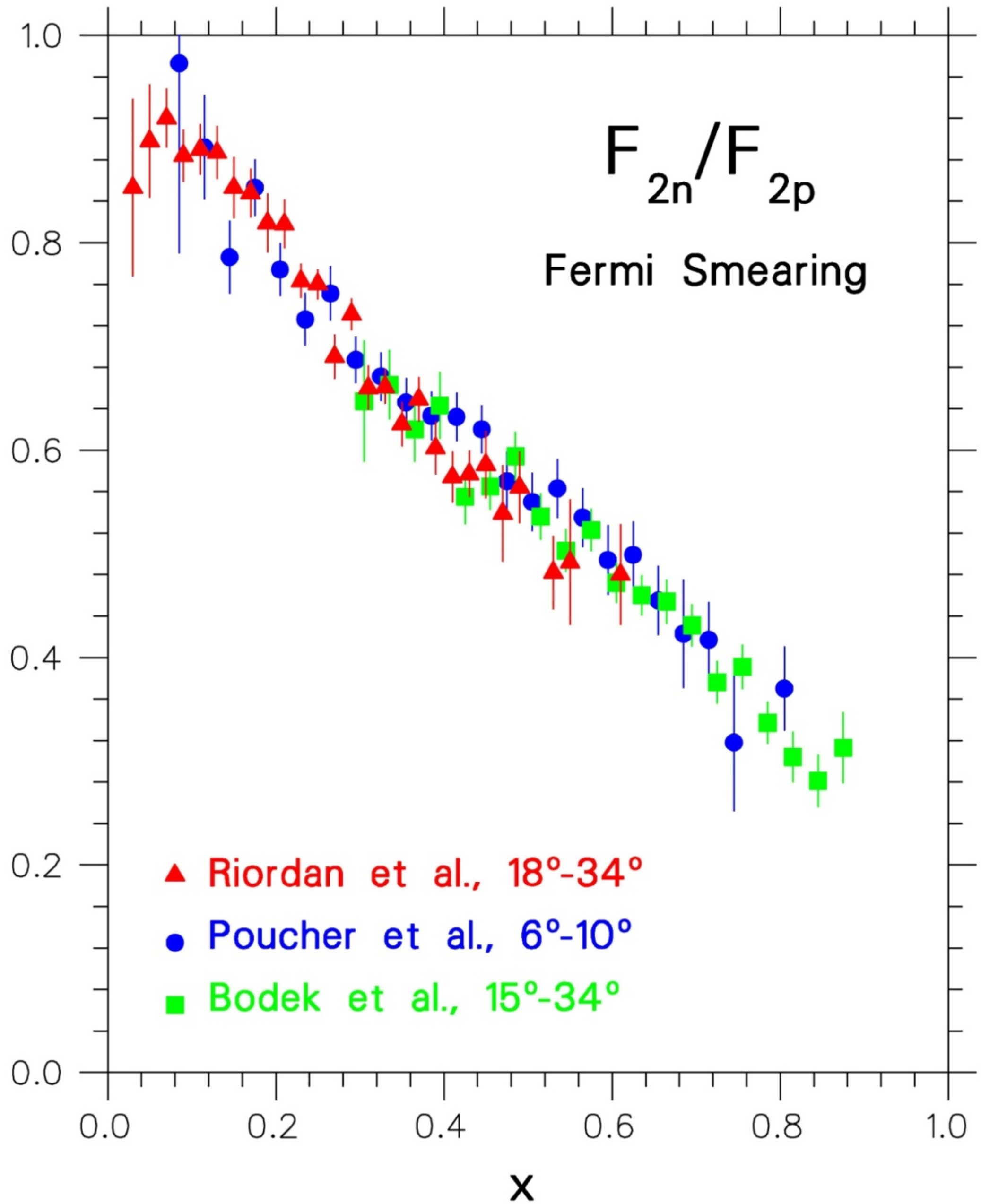
$$Q^2 = 4EE'\sin^2(\theta/2)$$

- QPM interpretation in terms of quark momentum probability distributions $q_i(x)$ (large Q^2 and ν, fixed x):

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

- Bjorken x: fraction of nucleon momentum carried by struck quark:

$$x = Q^2/2M\nu$$



SLAC 1968-1972

Friedman, Kendall, Taylor

Nobel 1991

F_2^n/F_2^p extracted from *p* and *d* DIS using a Fermi-smearing model and a non-relativistic *N-N* potential

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

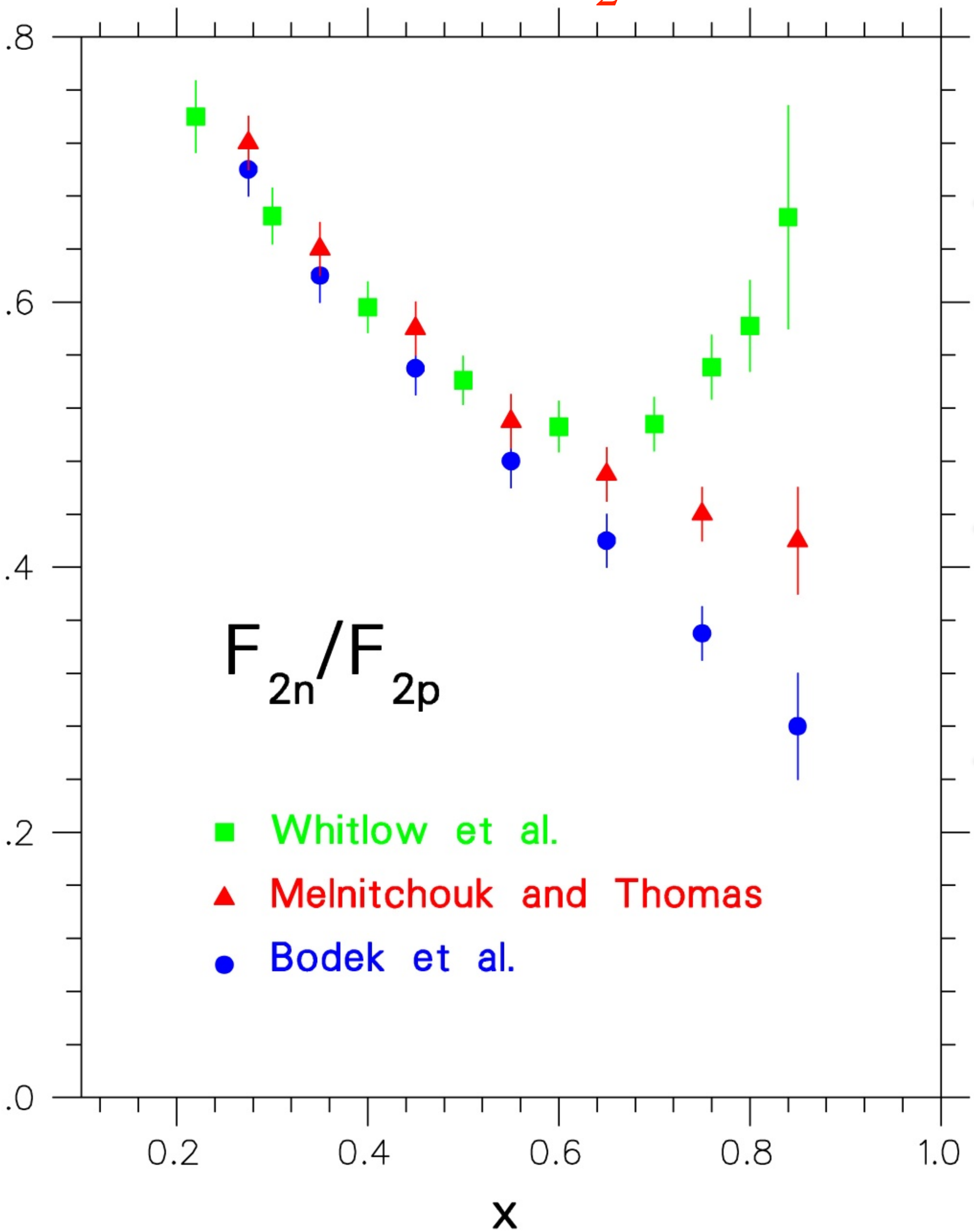
Data consistent with di-quark model by Feynman and others

High momentum quarks in *p(n)* are *u(d)* valence quarks

There are no high momentum strange quarks in *p* and *n*

Sea quarks dominate at small *x*

Nucleon F_2 Ratio Extraction Revisited



SU(6)

$F_2^n / F_2^p \rightarrow \frac{2}{3}$ $\quad d/u \rightarrow \frac{1}{2}$

pQCD / Quark Counting Rules

$F_2^n / F_2^p \rightarrow \frac{3}{7}$ $\quad d/u \rightarrow \frac{1}{5}$

Diquark / Quark Model

$F_2^n / F_2^p \rightarrow \frac{1}{4}$ $\quad d/u \rightarrow 0$

Nucleon F_2 Ratio Extraction from $^3He/^3H$

- Binding of nucleons in the two nuclei is of same nature. Differences between bound and free nucleons in the two nuclei is calculable, summarized, for their ratio, by some parameter R^* (W. Melnitchouk *et al.*).

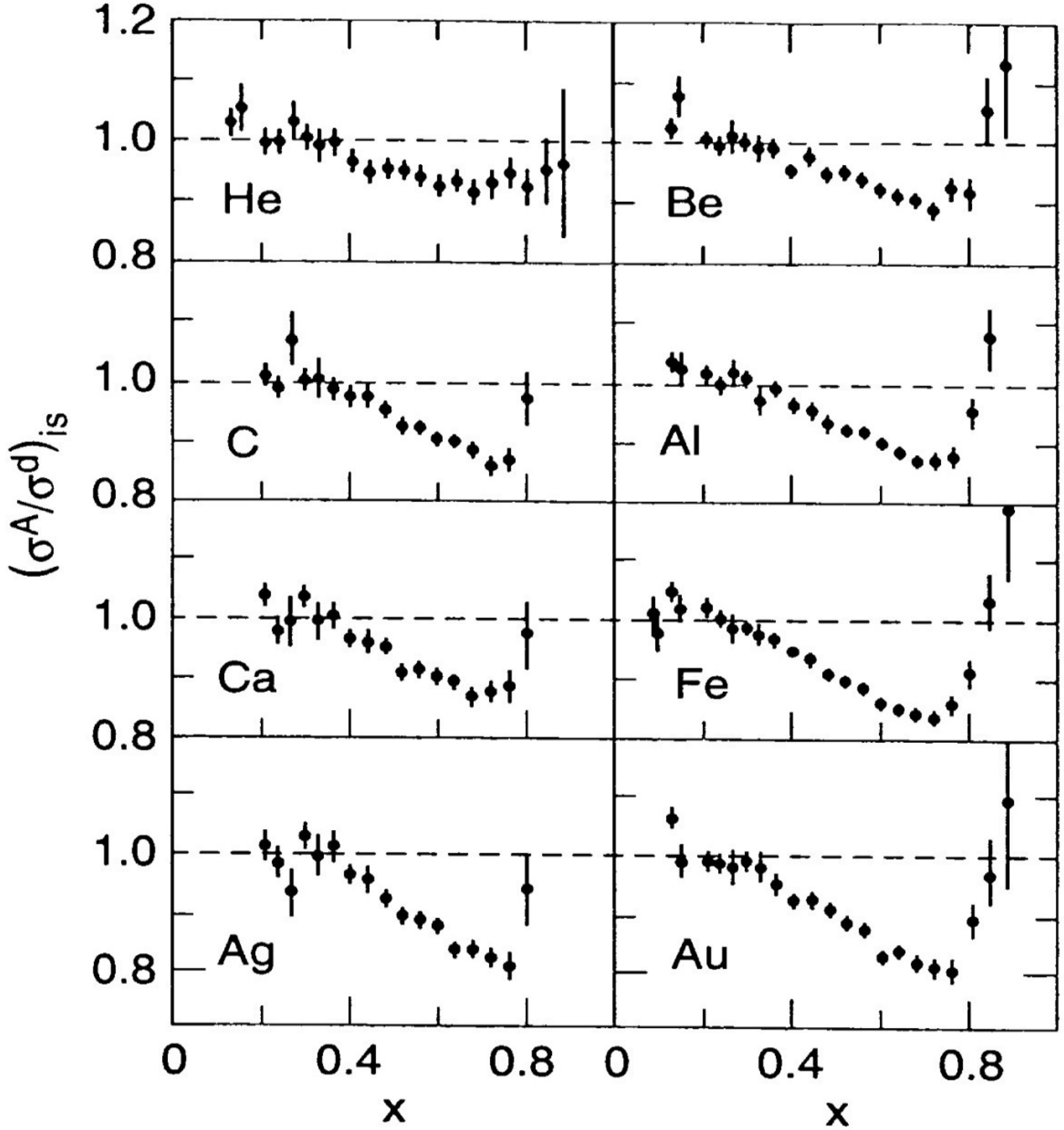
$$R^* = \frac{R(^3He)}{R(^3H)} \quad \text{where} \quad R(^3He) = \frac{F_2^{3He}}{2F_2^p + F_2^n} \qquad R(^3H) = \frac{F_2^{3H}}{F_2^p + 2F_2^n}$$

- If $R=\sigma_L/\sigma_T$ is the same for ^3He and ^3H, measured DIS cross section ratio must be equal to the F_2 structure function ratio as calculated using R^*:

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

- Determine nucleon F_2 ratio using $A=3$ DIS cross section data and $R^*(\approx 1)$ from theory:

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



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

EMC Effect

- Nuclear F_2 structure function per nucleon is different than that of deuterium: large dependence on Bjorken *x* and mass *A*.
- No universally accepted theory for the effect explanation.
- *A*=3 data will be pivotal for understanding the EMC effect.

Experimental Plan and Requirements (I)

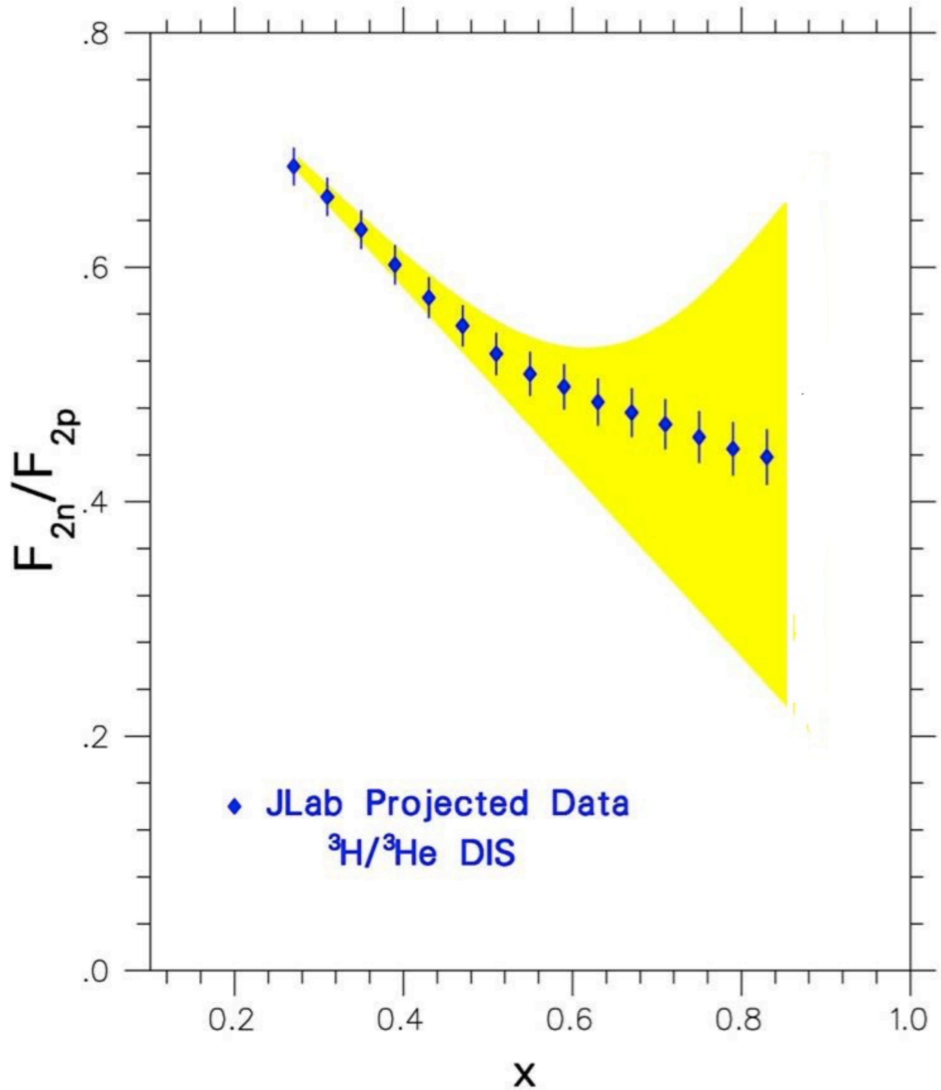
- Proposal was based on using the Left High Resolution Spectrometer (HRS) for low-x measurements and the Big Bite Spectrometer (BBS) for high-x measurements.
- *Change of plans after successful final target safety review that took place in the fall of 2015!*
- For safety reasons, the target review committee had to impose severe:
  - Restrictions in the BBS movement (change of angle)
  - Limitations in accessing the BBS components and detectors for checkout & repair purposes. Access from the front was to be totally forbidden!
- MARATHON requested to take the data with both the HRS spectrometers (instead of the Left HRS and BBS) at the expense of:
  - Eliminating the highest-x point (x=0.87) in the resonance region
  - Reducing the W^2 value of the highest-x DIS point (x=0.83) from 4.0 to about 3.5 GeV^2.

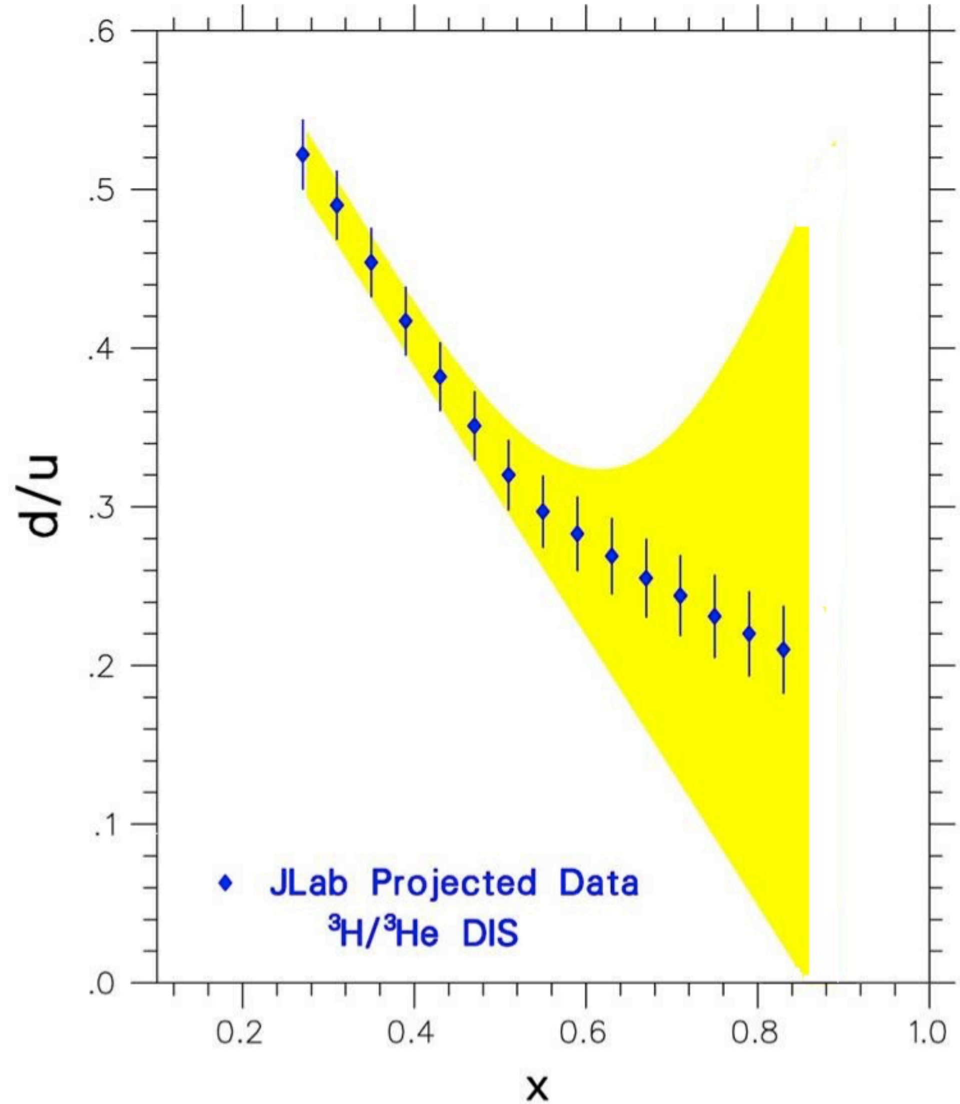
- Request has been approved!

Experimental Plan and Requirements (II)

- Experiment requires (unpolarized) electron beam with the highest energy available (11 GeV). Beam current will be limited to 20 μA for target safety reasons.
- Target system is under construction. Ladder structure will have helium, tritium, deuterium, and hydrogen high pressure cells [25 cm long, 1.25 cm diameter, 14 atm (^{3}H), 30 atm (^{1}H, ^{2}H, ^{3}He)].
- HRS Systems will operate in angular range between 15^o and 60^o, and in momentum range between 0.5 and 4.0 GeV.
- Experiment will use the existing detector packages of the HRS systems, and standard Hall A data acquisition and online analysis and monitoring software.

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

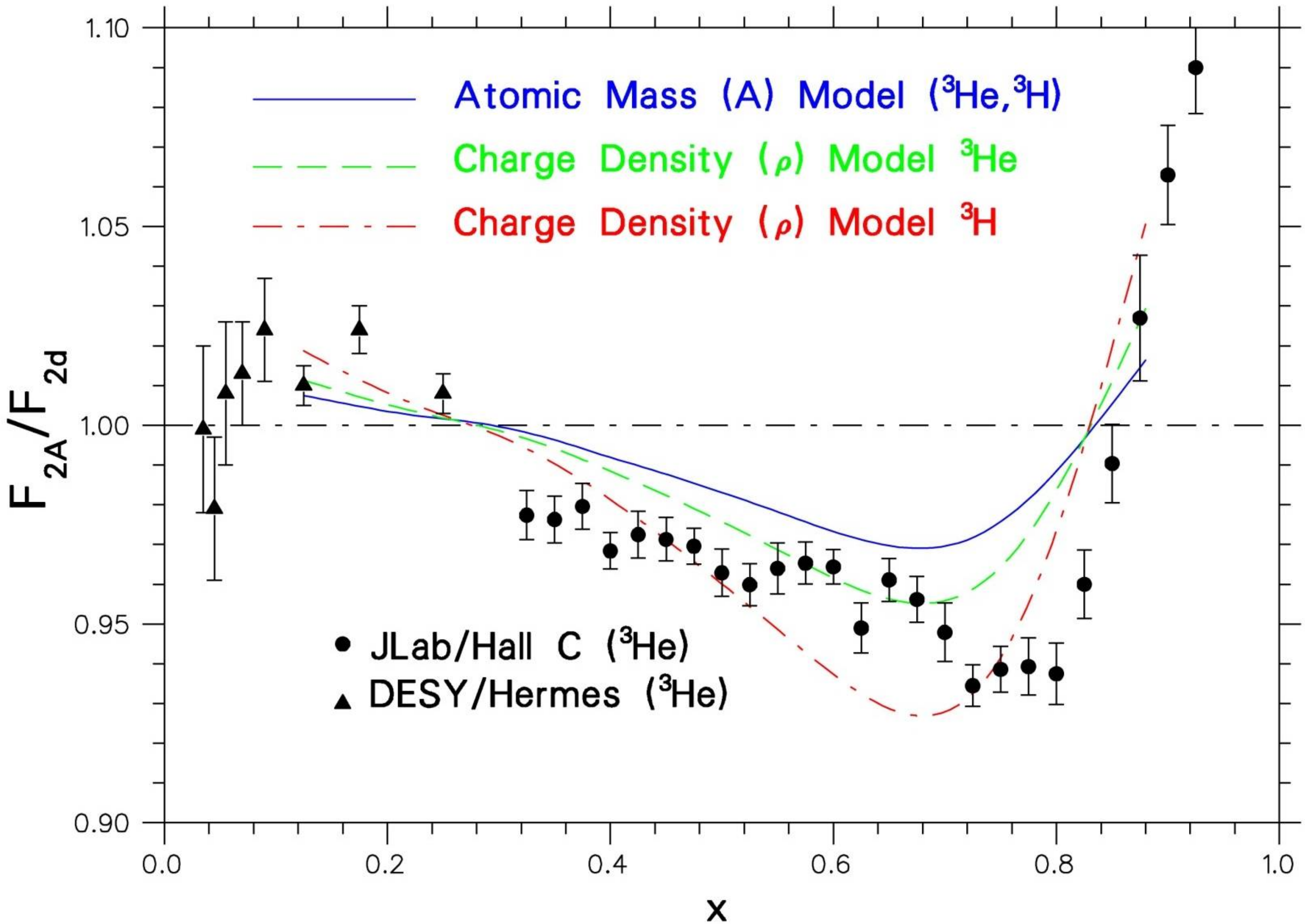




11 GeV beam; Left and Right High Resolution Hall A Spectrometers

3H and 3He gas target system; 42 days of data taking

EMC Effect for *A=3* Mirror Nuclei



Hall A data on ^{3}H, ^{3}He will be of similar precision to Hall C data

Summary

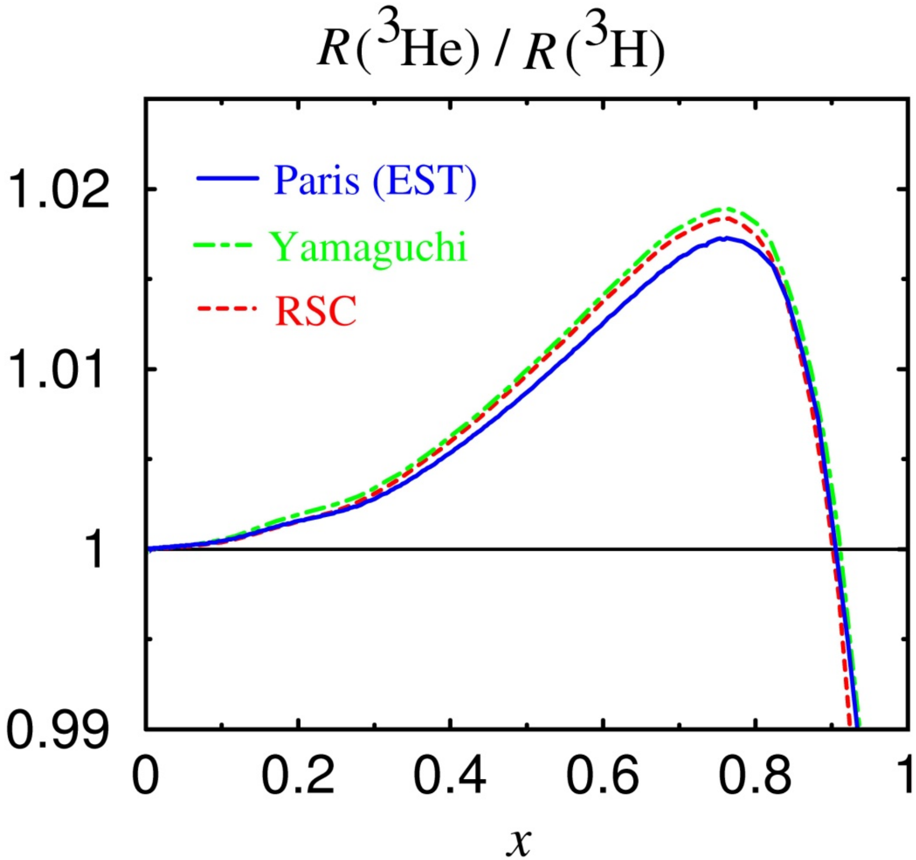
- JLab Hall A MARATHON experiment target system has passed safety review.
- Experiment passed recently readiness review.
- Will use the two HRS's as electron detection systems.
- Is scheduled to take data in the spring of 2017.
- Will provide data on F_2^n/F_2^p and *d/u* with minimal theoretical uncertainties, and input for parton distribution parametrizations.
- Will provide precision data on the EMC effect for the $A=3$ nuclear systems.

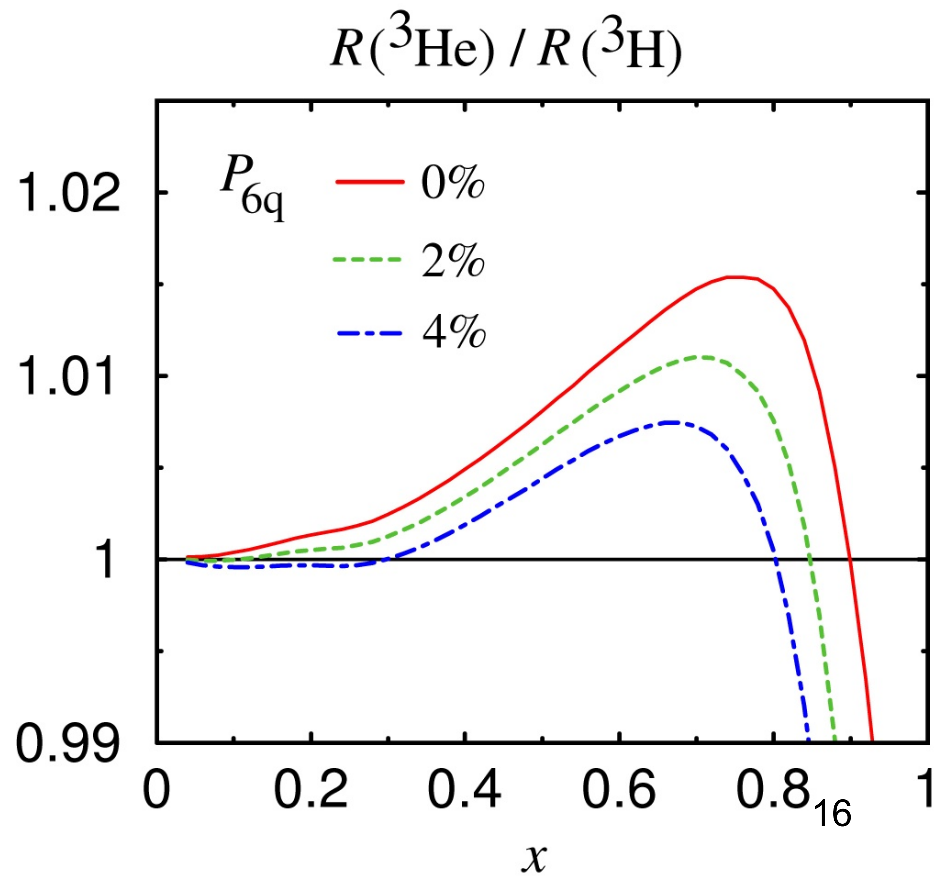
Thanks!

Back Up Slides

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)





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:

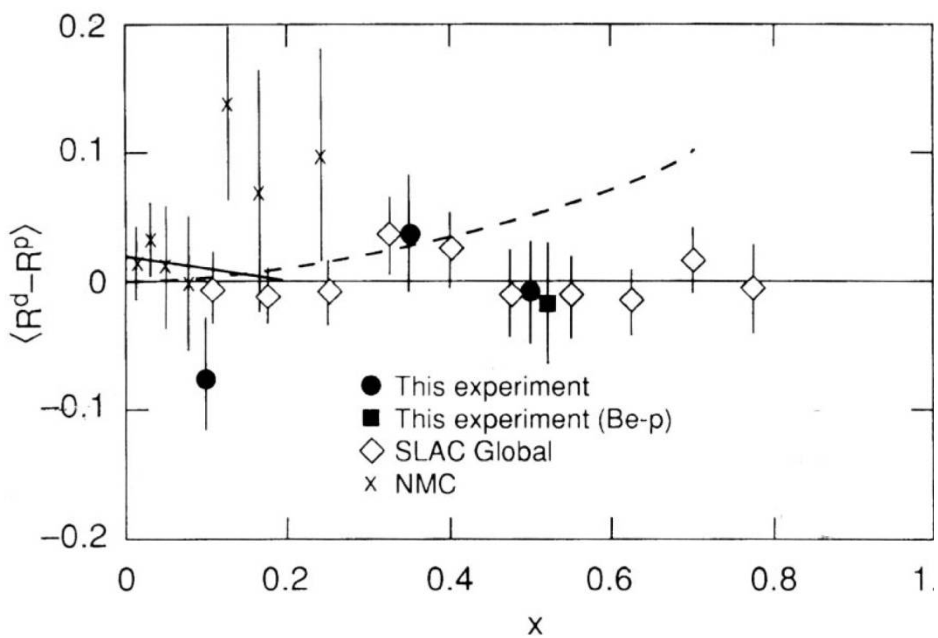
$$F_2^p = x\left[\frac{4}{9}(u+\bar{u}) + \frac{1}{9}(d+\bar{d}) + \frac{1}{9}(s+\bar{s})\right]$$

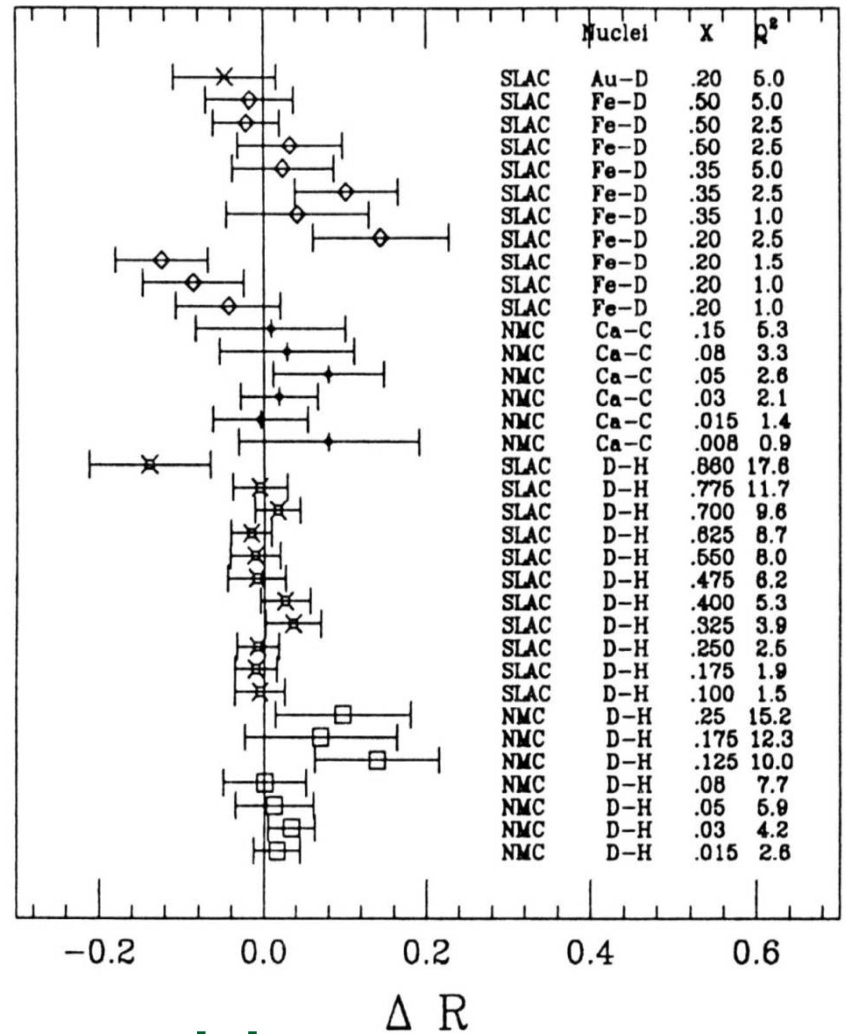
$$F_2^n = x\left[\frac{4}{9}(d+\bar{d}) + \frac{1}{9}(u+\bar{u}) + \frac{1}{9}(s+\bar{s})\right]$$

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

$R=\sigma_L/\sigma_T$ Measurements

SLAC/CERN data show that the ratio $R=\sigma_L/\sigma_T$ is the same for all nuclei within experimental errors





$^3He/^3H$ JLab data will be of better precision than SLAC data [wider angular range!]

F_2^n / F_2^p Deuteron Extraction Uncertainties

- Theoretically, F_2^d is a convolution of the "free nucleon" F_2^p and F_2^n functions with the deuteron wave function. Uncertainty in knowledge of the nucleon-nucleon potential introduces a large uncertainty in the determination of F_2^n (and F_2^n/F_2^p).
- Realistic relativistic calculations also show a large sensitivity in the F_2^n extraction on the nucleon binding effects in the deuteron (W. Melnitchouk and A. Thomas).
- Existence of an EMC effect in the deuteron (if the nucleon $q_i(x)$ in the deuteron are different than those of the free nucleon) would alter significantly the extracted F_2^n value. Note: recent JLab data support the existence of the EMC effect in the deuteron!

F_2^n / F_2^n, d/u Ratios and A_1 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
Diquark/Feynman	1/4	0	1	1
Quark Model/Isgur	1/4	0	1	1
Perturbative QCD	3/7	1/5	1	1
Quark Counting Rules	3/7	1/5	1	1

A_1: Asymmetry measured with polarized electrons and nucleons. QPM probability that the quark spins are aligned with the nucleon spin.

A_1^p, A_1^n: Extensive experimental programs at CERN, SLAC, DESY and JLab (6 GeV and 12 GeV Programs)

EMC Effect

- Nuclear F_2 structure function per nucleon is different than that of deuterium: large dependence on Bjorken *x* and mass *A*.
- Quark distribution functions modified in the nuclear medium.
- Possible explanations include:
  - Binding effects beyond nucleon Fermi motion
  - Enhancement of pion field with increasing *A*
  - Influence of possible multi-quark clusters
  - Change in the quark confinement scale in nuclei
  - Local environment and density dependence
- No universally accepted theory for the effect explanation.
- *A*=3 data will be pivotal for understanding the EMC effect.
- Theorists: Ratio of EMC effect for ^3H and ^3He is the best quantity for quantitative check of the theory, free of most uncertainties.

Deep Inelastic Scattering and Quark Parton Model

- DIS cross section - Nucleon structure functions F_1 and F_2:

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

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

$$\nu = E - E'$$
$$Q^2 = 4EE'\sin^2(\theta/2)$$
$$x = Q^2/2M\nu$$

$$\frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2}{Q^4}\cos^2\left(\tfrac{\theta}{2}\right)F_2(\nu,Q^2)\left[\frac{1}{\nu} + \frac{(1+Q^2/\nu^2)}{xM(1+R)}\tan^2\left(\tfrac{\theta}{2}\right)\right]$$

- QPM interpretation in terms of quark momentum probability distributions $q_i(x)$ (large Q^2 and ν, fixed x):

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

SLAC/CERN Data Interpretation in QPM

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

- 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):

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

Theory Overview (I)

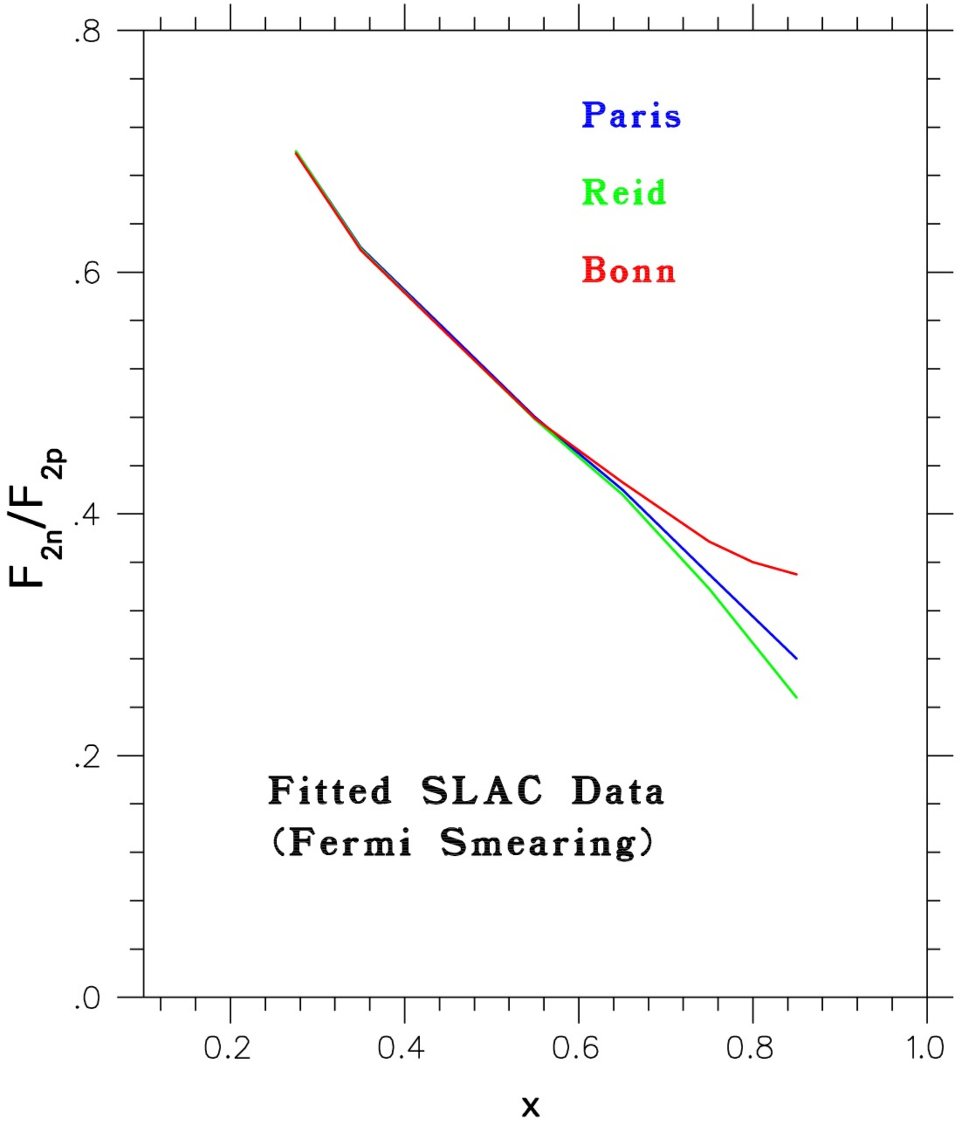
- SU(6)-breaking Diquark Model (Close/Feynman, 1970's)
  - Phenomenological explanation: fall off of F_2^n/F_2^p and its $x=1$ limit easily explainable using SU(6) nucleon wave function (Close, 1973) or Regge theory (Feynman, 1975) and assuming that the spectator diquark configuration with total spin $s=1$ is suppressed relative to that with $s=0$.
  - Limit at $x=1$ in agreement with the SLAC/CERN data.
- Constituent Quark Model (Isgur and Carl, 1980-2000)
  - Suppression fully understood in the hyperfine-perturbed quark model: color-magnetic hyperfine interaction generated by gluon exchange is proportional to quark spin dot products $\mathbf{s}_i \cdot \mathbf{s}_j$. Force is repulsive(attractive) for parallel(antiparallel) spins and allows the $u(x)$ and $d(x)$ quark momentum distributions to be different.
  - Limit for $x=1$ in agreement with the diquark model and data.

Theory Overview (II)

- Perturbative QCD (Farrar and Jackson, 1975)
  - Simple consideration of isospin and helicity structure of nucleon's quark wave function within perturbative QCD dictates that for diquark spin alignment (*s=1*) only exchange of longitudinal gluons is permitted, resulting in suppression of Compton scattering amplitude, which causes the F_2^n/F_2^p fall off.
  - Problem: pQCD $x=1$ limit different than that of quark/diquark model!
- QCD Counting Rules (Brodsky *et al*., 1995)
  - Early pQCD findings substantiated within first-principles calculations of Counting Rules of QCD predicting the high-x behavior of quark distributions: $q(x) \sim (1-x)^{2n-1+2\Delta h}$, where n is the minimum number of not interacting (spectator) quarks and Δh is the difference in helicity between the struck quark and the nucleon.
  - Same $x=1$ limit as pQCD.

The Tritium Target System

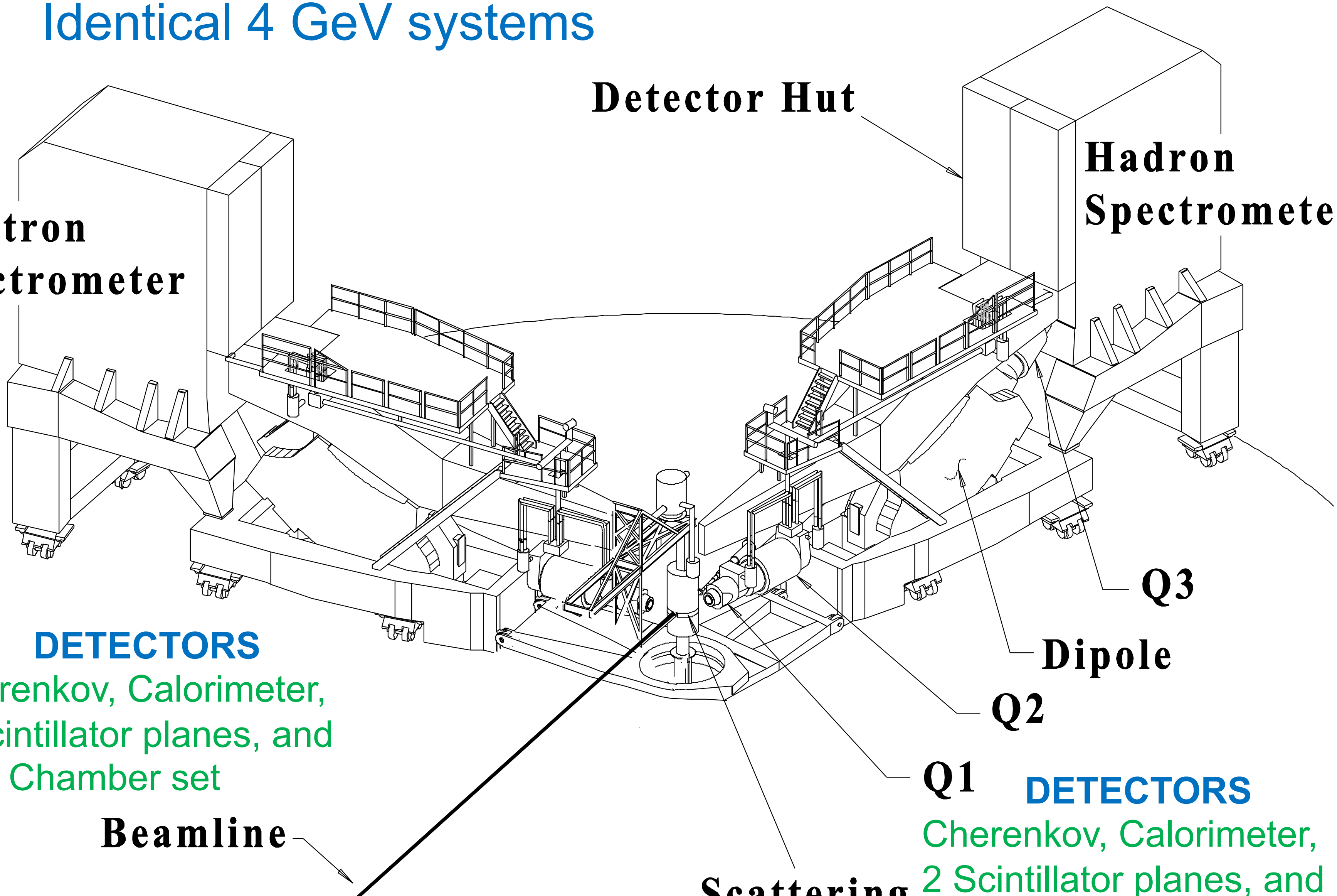
- Five-cell target structure (^{1}H, ^{2}H, ^{3}H, ^{3}He, Al Dummy):
  - All cells: 25 cm long, 1.25 cm diameter, 20 μA max current
  - ^{3}H cell: 10 atm, 1100 Ci activity
  - ^{1}H, ^{2}H, ^{3}He cells: 25 atm
- Cells will be filled at the Savannah River National Laboratory.
- Target will be shipped to JLab using commercial services.
- System will be enclosed in secondary “sealed” containment vessel (no reliance on fast valves).
- A catastrophic leak will be vented through stack above Hall A.
- Resulting emission will keep tritium levels at the JLab site boundary below regulatory limits.
- Tritium target project has passes a safety review.



Standard analysis of F_2^n/F_2^p from proton and deuteron data shows large uncertainty at high-x values depending on nucleon-nucleon potential used.

JLab Hall A High Resolution Spectrometers

Identical 4 GeV systems



DETECTORS
Cherenkov, Calorimeter,
2 Scintillator planes, and
Drift Chamber set

DETECTORS
Cherenkov, Calorimeter,
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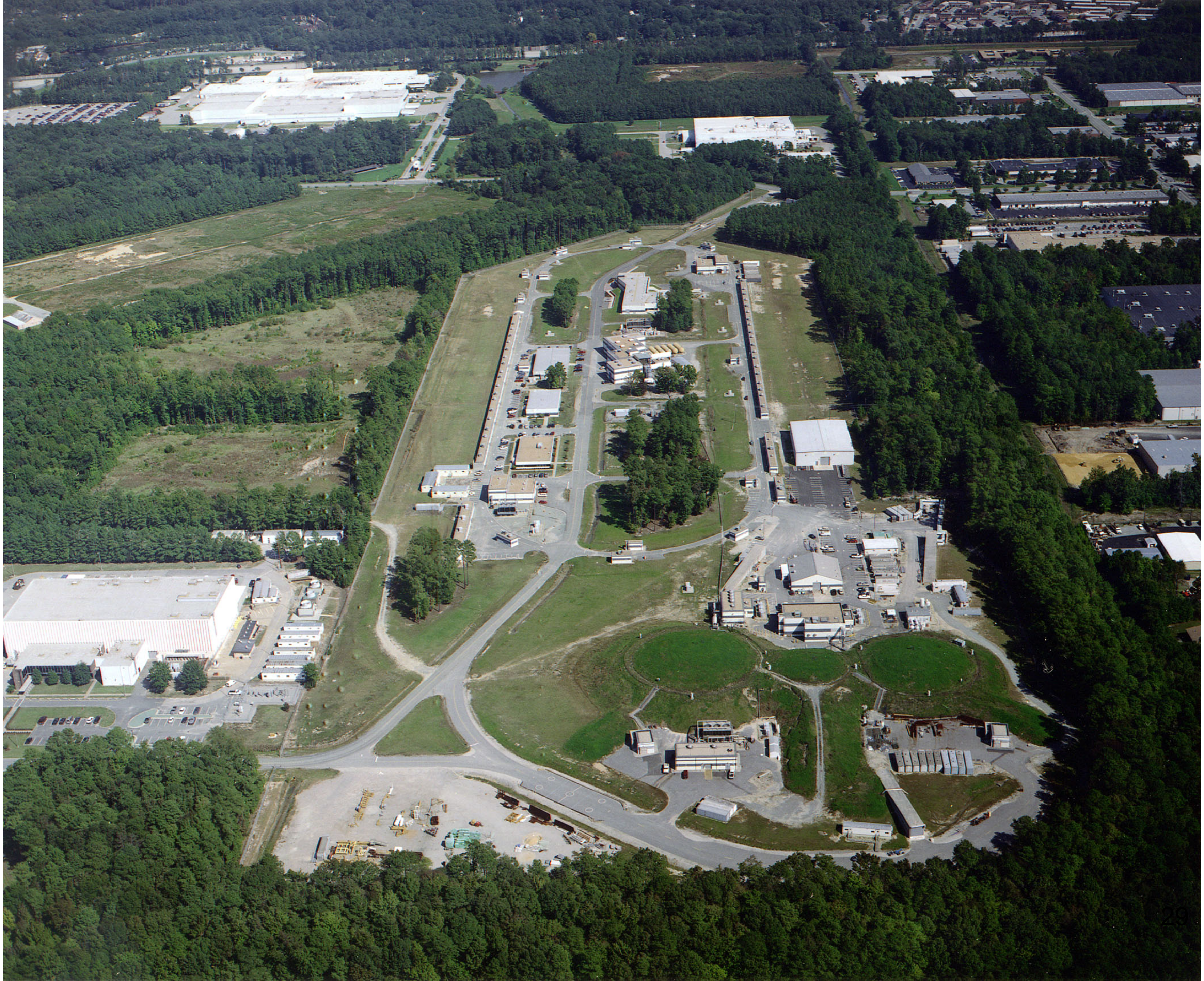
11 GeV Beam - Tritium/Helium targets



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

- Nucleon structure function in nucleus *A* in the Impulse Approximation: extension of deuteron model (Melnitchouk and Thomas):

$$F_2^{NA}(x) = \int dy\,[f(y)]_{N/A}\, F_2^N(x/y) \equiv f_{N/A} \otimes F_2^N$$

- For ^{3}He: $$F_2^{^3He} = 2 f_{p/^3He} \otimes F_2^p + f_{n/^3He} \otimes F_2^n$$

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

- Charge symmetry breaking effects are small!